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Oil spills distribution in the Middle and Southern Adriatic Sea as a result of intensive ship traffic

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Oil slick detection by synthetic aperture radars (SAR) is a proven and commonly used operational technique, which showed that the seas of the Mediterranean are often polluted by oil and oily products. For the period 2003-2011, the Envisat and Radarsat-1 SAR images were available for analysis, thanks to the several projects. About 300 SAR images have been analysed over the Middle and Southern Adriatic Sea, in order to detect marine oil spills and other phenomena causing similar signatures. Analysing many oil spills detected in the Adriatic Sea, their sizes were determined between 0.1 km^2 and 108 km^2. Most of the spills were located along the main shipping routes, especially in the ship corridor along the Adriatic Sea axis. They were, most probably deliberate slicks released from ships during transportation or fishing operations, while suspected source of the largest spills is tank washing or illegal discharges.

Key words: Adriatic Sea, oil pollution, oil spills, SAR Images, geo-information approach

INTRODUCTION

For its small size (138,595 km^2; LUŠIĆ & KOS, 2006) and location as a semi-enclosed sea of the Mediterranean, the Adriatic Sea is especially endangered from oil pollution. It exchanges the waters through the Otranto Strait with the greater Mediterranean Sea with the approximate rate of 1-5 years (MOSETTI, 1983; LUŠIĆ & KOS 2006). General circulation in the Adriatic Sea is cyclonic (BULJAN & ZORE-ARMANDA, 1976), with a three smaller cyclonic gyres (Northern, Middle and Southern Adriatic gyre) occurring within in different seasons (ARTEGIANI *et al.,* 1997).

One large oil spill accident in the Adriatic Sea could put down economies of surrounding coastal countries, especially in Croatia and Italy, which are based mainly on tourism, fisheries and aquaculture. These branches are potentially endangered due to ever increasing traffic, existing oil transport and future oil exploitation in the Adriatic Sea.

With exception of a few smaller accidents, so far the Adriatic Sea was rather lucky regarding the oil spill accidents. Several ports in Italy (Venezia, Trieste), Croatia (Rijeka, Omišalj, Ploče), Slovenia (Koper), Montenegro (Bar) and Albania (Vlore) serve as terminals for tankers, where from oil is transported to other countries. The Joint Research Centre (JRC, 2006) study as the first oil slicks monitoring project (FERRARO *et al.,* 2007; JRC, 2006; FERRARO *et al.,* 2009) provided statistics of oil discharges in the Adriatic Sea, reporting increasing frequency of ship-made oil slicks. A number of projects like RAMSES, AESOP, GAIANET, VASCO, CLEOPATRA and JRC studies (http://ec.europa.eu/dgs/jrc) also demonstrated constant violation of International Convention for the Prevention of Pollution from Ships – MARPOL 73/78 (MARPOL, 2009).

With so far unknown quantities, these evidences point that there is a constant input of oil and oily products to the sea, on a daily basis, which in the long run could have unforeseen consequences to the marine ecosystem (CORNER *et al.,* 1976) even through the marine food web (ORTMANN, 2012). Impact to marine species including plankton, fish, fish eggs and larvae, seabirds, molluscs, crustaceans, sea turtles, and marine mammals could be very different. Some products enter the species and can be metabolized with unknown further fate, from lethal like cancer of liver and lungs in sea mammals to instantaneous death. In case of British Petroleum disaster the spill waters had 40 times more Polycyclic aromatic hydrocarbons (PAHs) than before the spill, containing carcinogens and chemicals that pose various health risks to humans and all marine life (SCHNEYER, 2010).

To obtain a proper assessment on the frequency, size, type and causes of oil slicks in the Adriatic Sea, the use of satellite remote sensing data, particularly synthetic aperture radar (SAR) images together with data of the Ship Automatic Identification systems (AIS) would be indispensable. In MOROVIĆ *et al.,* 2011, the needs and possibilities of such oil spill monitoring in the Adriatic Croatian waters were proposed and demonstrated. Our intention in this paper is to give an overview of the last years of larger oil spills through analysis the SAR images acquired over the Adriatic Sea by the European Envisat and the Canadian Radarsat-1 satellites, and to attempt to understand their sources and nature.

MATERIAL AND METHODS

It is possible to recognize the oil slicks on SAR images as a dark patches, because these locally decrease the sea surface roughness, which contrasts with the brightness of the surrounding sea, and, in turn, the radar backscatter of the sea surface, practically under all weather and is eventually limited by the wind conditions (BREKKE & SOLBERG, 2005). However, automatic detection is hardly possible, and the complex nature of slicks requires experienced operator (TOPOUZELIS 2007; TOPOUZELIS 2008).

First task of an operator is to distinguish oil slicks from look-alikes. Additional information like the shape of slicks, location relative to the shore, borders of national and territorial waters, location of oil production infrastructure, ships, wind and wind history data may help distinguishing the nature of slicks (ESPEDAL & JOHANNESSEN, 2000).

Considering all these, oil slicks detected in the open sea can be classified to three main categories: natural biogenic oil films, ship-made oil spills and natural seepage slicks (IVANOV, 2011).

Natural biogenic oil films are products of marine flora and fauna, and they appear as filaments, very thin 2-3 nm dark colourless strips. These are found especially in coastal waters and can be visible in calm wind conditions (2-4 m/s).

Ship-made oil spills form films of thin to moderate thickness and are mainly linear shapes. These may occur everywhere but prevail along the ship lanes. They could be produced accidentally or deliberately during routine ship operations, and could contain ballast, tank washing, engine room, sludge and foul bilge waters or different waste waters which all can contain mixtures of oily and chemical products, emulsifiers, residuals of fuel and lubrications, industrial, biogenic or crude mineral oils, and even vegetable oils and animal fat (fish oil).

Seepage films have approximate thickness between 0.04 x 10^{-3} and 5 x 10^{-3} mm because formed by light fractions of crude oil and their slicks range in shapes from linear to complex like: zigzags, sickles, corkscrews, loops, etc. They can be usually recognised at low wind conditions due to accurate repeatability at the same places, the good example of marine regions with seep activity are Gulf of Mexico and South-Western Caspian Sea. In this case detail information on bottom topography and local geophysics is very useful.

The large ESA archive of Envisat SAR images gave us a good opportunity, and it was available over the area of interest in the Adriatic Sea through the EOLISA catalogue for the years 2000-2011. Some of these images were made available through the ESA research project. After examining the quick-looks, suitable images with pronounced oil spills were further collected for analysis. Obtained selected SAR images were first manually analysed using such characteristics as size, shape and contrast taking into account context of surrounding and wind conditions, and then were processed (georeferenced) with the NEST ESA SAR ToolBox. The raw raster images were imported to NEST program and reprojected to geographical grid. The images were than exported to GeoTIFF format. Each image from the data set is initially screened to determine oil slicks and enlarged to obtain clear view of a particular slick. The SAR images after being georeferenced in NEST were imported in the GeoMixer application (http://geomixer.ru). For more comprehensive analysis we also used data set of Radarsat-1 images acquired in September-November 2011 in the framework of the pilot project between P.P. Shirshov Institute of Oceanology RAS/SCANEX and Institute of Oceanography and Fisheries.

It is well-known that main contribution to oil pollution of the inland and semi-closed seas originates not from ship accidents but from transportation and routine ship operations, including tank washings and illegal discharges of different ship-produced liquid wastes (LEAN & HEINRICHSEN, 1992). In order to help the oil spill experts to complete manual identification work, a GIS approach has been proposed by IVANOV & ZATYAGALOVA (2008). This approach implies collection of additional and supplementary data about a marine basin and its man-made offshore infrastructure in a single application or in an oil spill monitoring system (IVANOV & ZATYAGALOVA, 2008; MOROVIĆ & IVANOV 2011; IVANOV *et al.,* 2014). It consists of the further integration of geographic, oceanographic, geophysical data and information within one envelope that allows effective management during the identification process. This approach has already been implemented into the GeoMixer application by RDC SCANEX (http://www.scanex.ru) in order to provide new geoinformation solutions and internet technologies for operational maritime monitoring (IVANOV *et al.,* 2014). The GeoMixer is an API (Application Programming Interface) application for storage, integration, visualization, interactive analysis, and publishing of RS/SAR data and results of analysis using on-line GIS.

To integrate all the data, i.e., SAR images and geospatial data, GeoMixer, an on-line GIS application consisting of software and a geoportal for operation, was used. In its frameworks data about oceanography and offshore oil-and-gas infrastructure, digital nautical charts with bottom topography, marine boundaries and ship lines, and other useful information have been integrated. Collection as many data and information about marine basin as possible in a such application allows identification of oil spills and discrimination of them from look-alikes, mainly biogenic slicks, with high confidence level, say, 90-95%. Of course, there are several uncertainties in oil spill identification on SAR images, and there is still a probability of false alarms without airborne survey and sampling.

Moreover, analysis of SAR image permits simultaneous and effective ship detection using small bright spots visible on the SAR images; this has been done during a pilot phase of the project for Radarsat-1 data (Fig. 1). Information about detected ships together with oil slicks/spills collected in GIS applications is of high value for monitoring tasks.

Finally, we also took into account wind conditions during image acquisitions, because the ability to detect oil slicks on SAR images

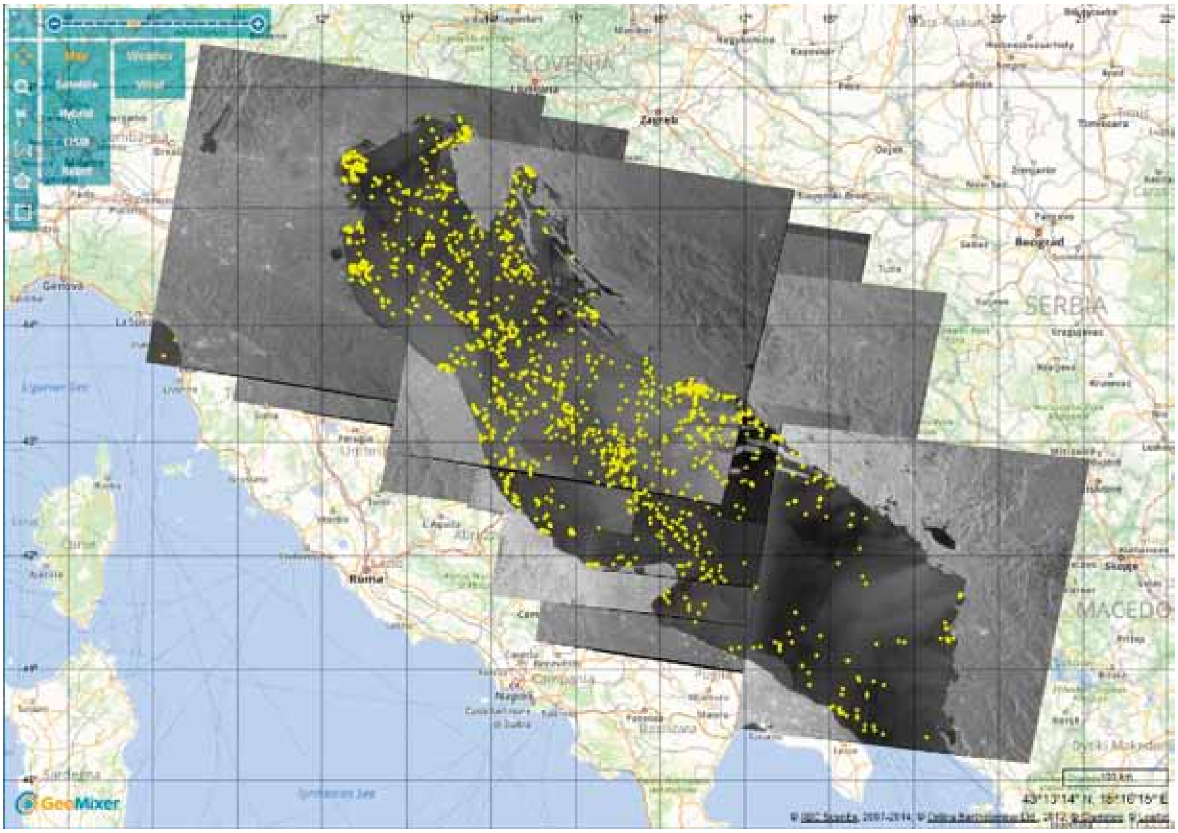

Fig. 1. Coverage of the Adriatic Sea by operative Radarsat-1 SAR images acquired in September-November 2011 (ships detected on SAR images are shown by yellow dots which marked main ship routes). © MDA, SCANEX

strongly depends on the wind speed at the sea surface. The wind data from several stations in the Adriatic islands were available. From State Hydro- meteorological office in Zagreb, 10 min averaged wind speed, direction and gust data were obtained (for details see MOROVIĆ *et al.,* 2014). If the wind speed over most of the area of interest was either too low or too high, the images were rejected as being unsuitable for oil detection and were not used in analysis.

RESULTS AND DISCUSSION

From the total of about 300 examined quick-looks of SAR images, we selected for analysis 30 images by Radarsat-1 and 29 by Envisat, with clearly visible radar signatures of marine oil slicks. The coverage of the Adriatic Sea by Radarsat-1 SAR images used in our analysis is shown on Fig. 1, where a large number of ships were visible along the main transport routes and fishing areas. Transport routes concentrate along the long Adriatic axis, and fishing areas are dispersed both in the coastal and open sea. The coverage by Envisat SAR images from our analysis is shown on Fig. 2.

Examples of Envisat SAR images with detected large oil spills are presented on Fig. 3. Here also some smaller slicks are visible as well as the ships wakes. On Fig. 3a, seen is one large slick (24 km^2), with feathered edges caused by the wind, but is interrupted like that another ship passed over perpendicularly to it. On the Fig. 3b seen is the one long (9 km^2) rather fresh slick modified a little, probably by local currents. On the Fig. 3c one very large and long slick (74 km^2) is observed with feathered edges caused by a longer action of the wind. On the Fig. 3d one large slick (46 km^2) is observed, prolonged in a thin slick towards south east, indicating the ship direction.

Summary maps of all large and medium oil slicks having different man-made nature detected in 2003-2011 in the Adriatic Sea, created

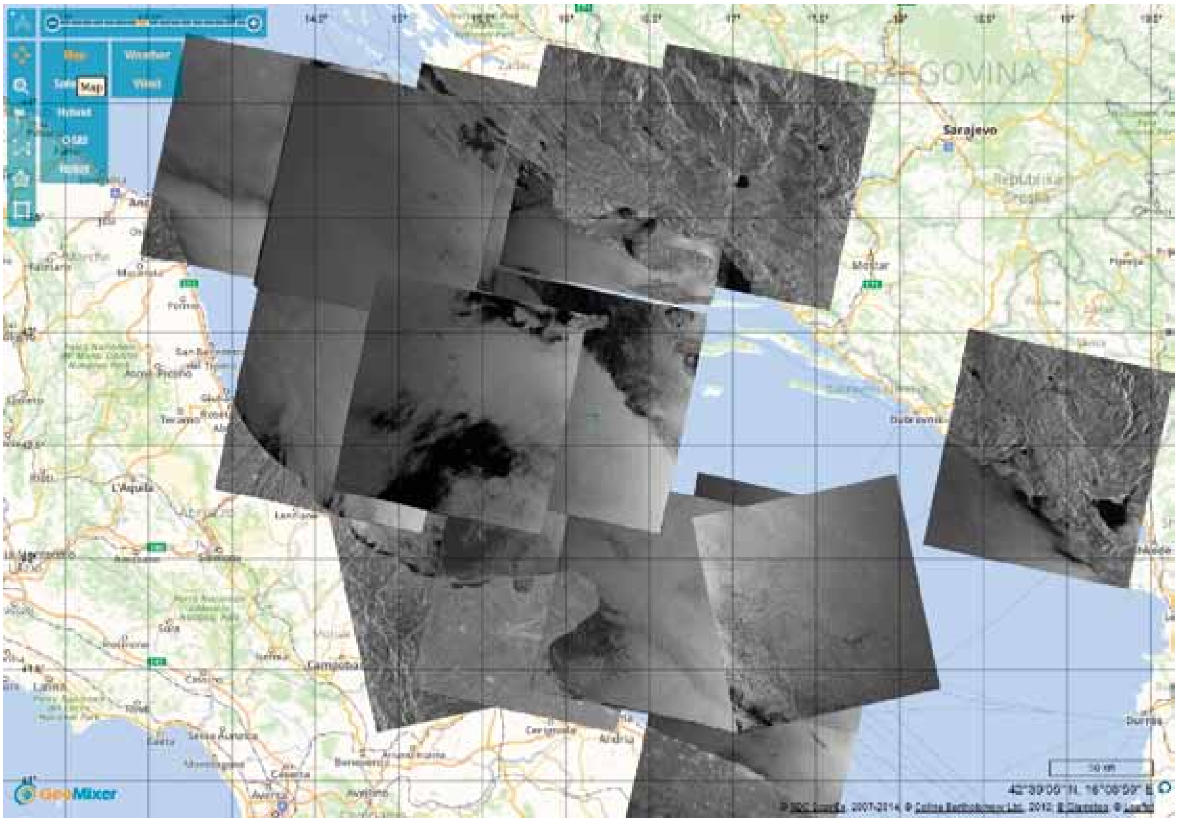

Fig. 2. Coverage of the Adriatic Sea by archived Envisat SAR images acquired in 2003-2010. © ESA, SCANEX

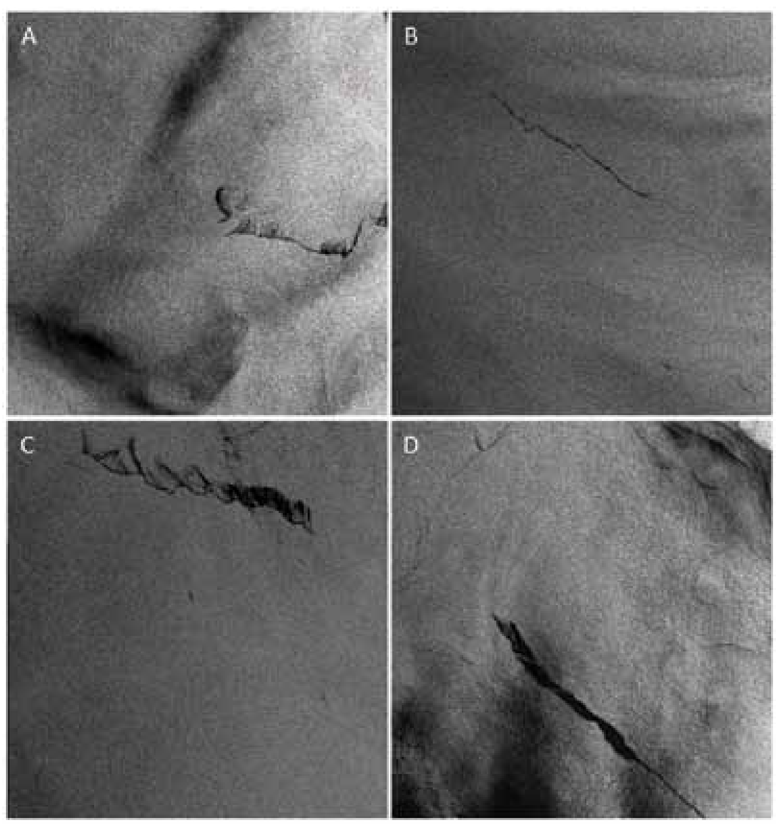

Fig. 3. Sub-scenes of Envisat SAR images acquired in Image Mode with large ship-made oil spills on 15 April 2003 (A) on 10 May 2008 (B), on 19 July 2008 (C) and 11 Sept. 2008 (D). Wind smearing of the patches (so-called, feathered edge) indicates the presence of different fractions of the oil in the releases during tank washing (see their locations on fig. 6) ©ESA.

and analyzed using GeoMixer technology, are shown on Figs. 4. & 5. On the Fig. 6, presented is distribution of the oil spills detected in the central part of the Adriatic Sea along the main shipping routes. Here one very large spill of 108 km^2, the largest observed throughout analysis, is visible. For the largest oil spills dates and sizes are indicated on the callouts. Main ship routes (hatch blue lines), boundaries (shadowed light blue lines) of the territorial waters and ZERP (Zaštićeno ekološko ribarsko područje; in English: Croatian Fishery and Ecological Zone) (dark blue line) are shown.

For convenience, the boundaries of the ZERP, territorial waters and shipping routes are plotted on the maps. The results of our scrupulous analysis of SAR images and maps (Figs. 4-6) revealed that:

- Many large oil slicks have been detected in the Adriatic Sea, especially in its central part with area of individual patches ranged from 9 to 108 km^2. The feathered edges of a number of patches indicate the presence of different fractions of oil (from heavy to light) in a release, which can come into the water during routine tank washing operations (Figs. 3, 5) and is dispersed in the course of time and under the action of wind.

- Most of oil spills are detected along the main shipping routes, among them are those international, following from the SE to NW along the coastline of Croatia (to the ports of Trieste, Venice, Ancona, Bari, Pula, Rijeka, etc.), and ferry lines crossing the sea, such as Dubrovnik-Bari, Split-Ancona, Durres-Bari, etc. Moreover, as clearly seen from Fig. 6, large oil spills are mostly observed in the Croatian ZERP.

- All oil spills have been released during night time, because most of them were detected in SAR images acquired in the morning time at 05:00-09:00 UTC (07:00-11:00 local time) during descending (morning) satellite passes. At

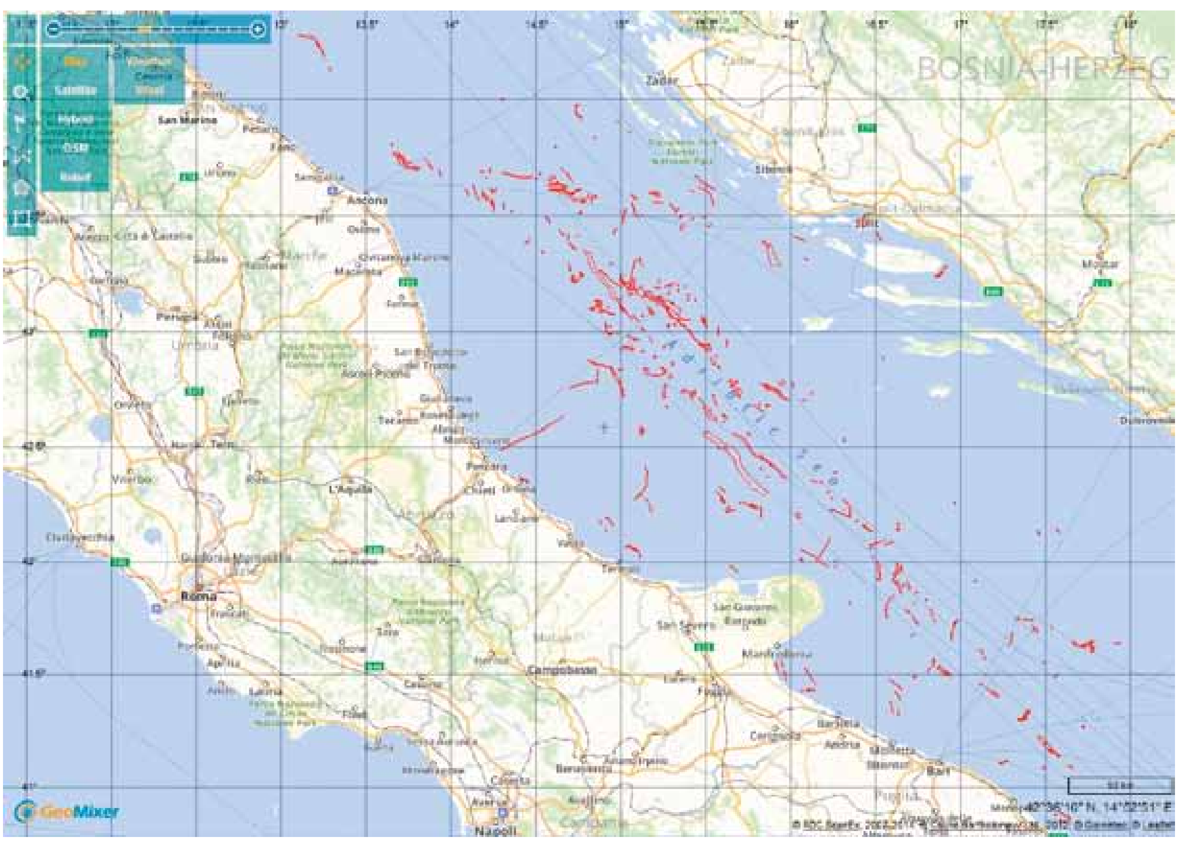

Fig. 4. Summary map of oil slicks of different nature detected in the SAR imagery of the Adriatic Sea. Extension of oil pollution along the main shipping routes is clearly seen. © SCANEX

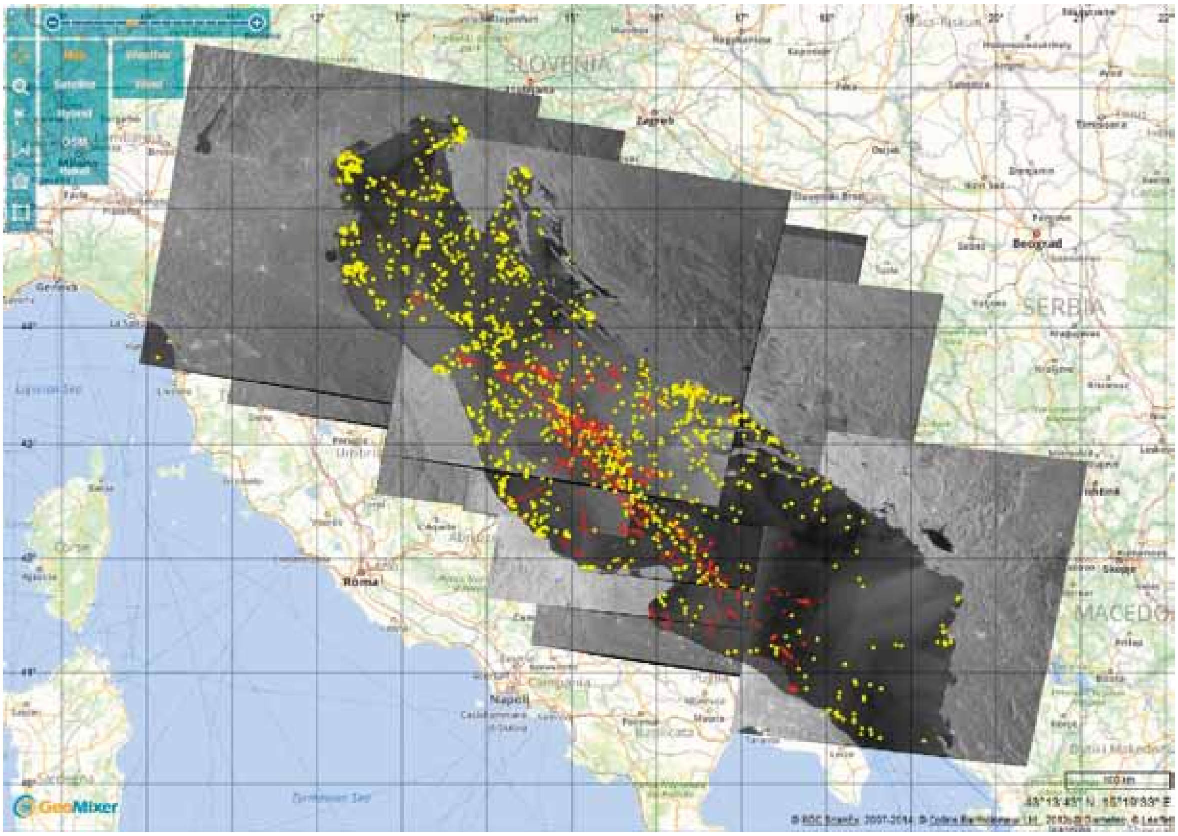

Fig. 5. Map of all oil slicks/spills, detected on SAR images, collocated with the detected ships (yellow dots). © MDA, ESA, SCANEX

Fig. 6. Distribution of the oil spills detected in the central part of the Adriatic Sea along the main shipping routes. For largest spills date and size are indicated on the callouts. Main ship routes (hatch blue lines), boundaries (shadowed light blue lines) of the territorial waters and ZERP (dark blue line) are shown. © SCANEX

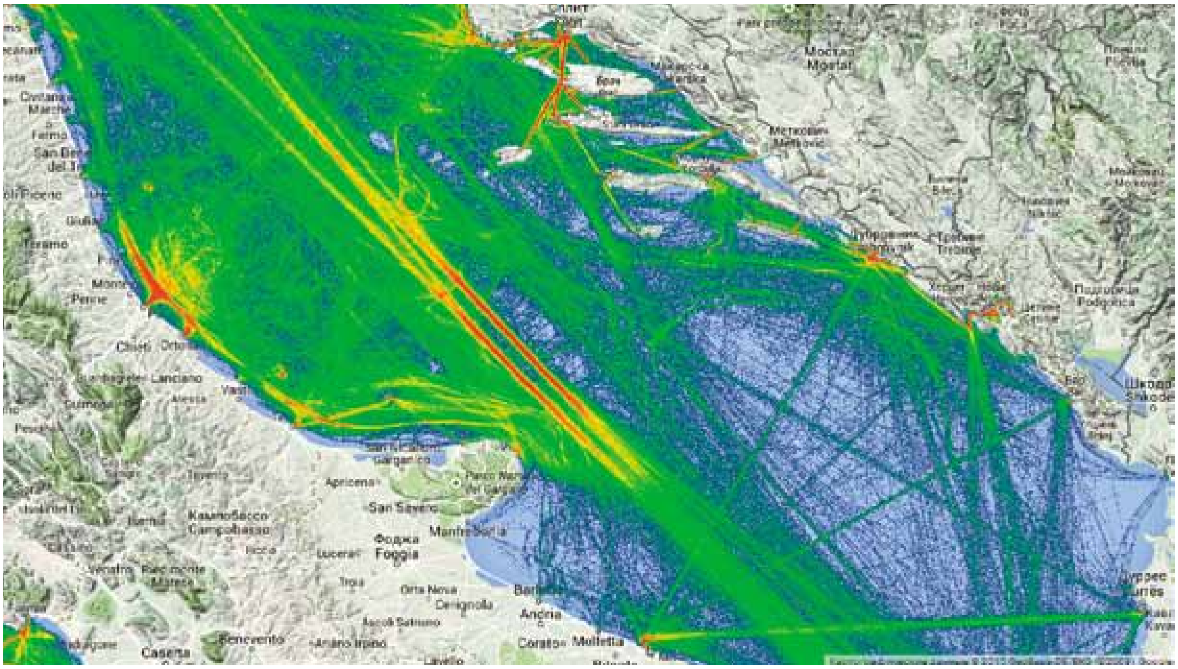

Fig. 7. The density traffic map for the Central Adriatic Sea showing all vessels tracks recorded by MarineTraffic during the last semester of 2013. Ó www.marinetraffic.com

the moments of SAR image acquisitions the oil patches have underwent a change of their forms under action of local currents and wind, and got feathered edges under action of wind (Fig. 5).

- Analysis of distribution of large oil spills suggests that tank washing from time to time occurred in the central part of the Adriatic Sea (it seems the same way like in the Central Black Sea (IVANOV & KUCHEIKO, 2014). It is assumed these patches were produced by multipurpose chemical tankers, which transport liquid substances of different toxicity including crude oil and oil products. These liquids together with emulsifiers and surface active substances used for tank cleaning are able to form different surface-active films on the sea surface. Despite the Adriatic Sea is selected as Special zone according to the MARPOL Convention, however, tank washings are possible there, even during transportation of oil products. This may be acceptable under certain regulations and conditions (see MARPOL, 2009). The highest amount of oil spills with the largest areas were detected on SAR images in open sea at the boundaries of the Italian and Croatian sectors, sometimes starting in Italian sector and ending in Croatian one. It can be considered to be other fact confirming frequent routine tank washing.

- It is quite obvious that these films are not necessary pollution by crude oil, and it is possible they are made legally in the frameworks of the MARPOL regulations. Other medium ship-made oil spills can represent their ballast waters, tank washing residues and other oil mixtures from the engine room and bilge waters and even oily fish wastes. They are produced during routine ship operations from transport ships or fishing boats. Unfortunately, there was no possibility to get the AIS data in the port authority of Split for these outrageous cases (Figs. 5, 6). In this connection a question, what ships and what oily substances forms oil pollution in the Central Adriatic Sea, requires additional investigations.

On Fig. 7 the density map of ship traffic in the Central Adriatic Sea, where all vessels tracks recorded by marinetraffic.com during the last semester of 2013, is shown. The ship traffic, which intensity is represented by color, in particular the most intensive by red-yellow, clearly marks the ship routes. First of all, attention should be paid to two international lines, where usually most intensive oil pollution is detected in SAR imagery (Fig. 3). As seen, from comparison of figs. 4-6 and fig.7, the largest oil spills are related to these lines, one of them, 108 km^2 has been detected on 21.06.2003. There is other place with intensive ship traffic near the Italian coast; that is a set of oil production sites with oil rigs installed in the sea (over Rospo Mare and Elsa and other oil and gas fields) and also is the site with high ship traffic. In this marine region oil pollution was represented by middle to small oil slicks or spills (usually less than several km^2), which can be associated either with oil & gas production/transportation or with service shipping. Finally, the local and international ferry lines should be noted; these are local lines connecting Rijeka, Zadar, Šibenik, Split, Makarska and Dubrovnik with the Croatian islands and Split, Zadar and Dubrovnik with Italian ports. Of course, small oil spills associated with routine ship operations can be found there from time to time.

These analysis of Envisat and Radarsat-1 SAR images and oil spill distribution maps further proves former findings by GADE & ALPERS (1999), PAVLAKIS *et al.* (2001), EUROPEAN COMMISSION (2001), FERRARO *et al.,* (2008, 2009), TOPOUZELIS (2009), IVANOV (2011), IVANOV & KUCHEIKO (2014), showing that most oil pollution occurs along the main ship routes (see figs. 5-7). This finding also agrees well with results by IVANOV & KUCHEIKO (2014) recently obtained for the Black Sea.

CONCLUSIONS

Analysis of the ESA archive as well as the SAR images acquired during pilot project allowed again looking at the level and sources of oil pollution of the Adriatic Sea. The sea has extensive marine traffic giving access to the local ports of six countries (Fig. 7); much of this traffic is oil and chemical tankers. As reported by mass media the amount of transported oil can reach up to many million tonnes per year (OCEANA). The result of such traffic is a high risk of oil pollution and even environmental disaster, worsened by the fact that it is a semi-closed sea within the inland Mediterranean Sea. Despite the Adriatic Sea is selected as a Special Area according to the MARPOL Convention, tank washing occurs often in the Adriatic the most important findings from this study can be summarized as follows:

(1) Most of oil spills were detected along the main international shipping routes at the boundaries of the Italian and Croatian sectors, while large oil spills are mostly observed in the Croatian ZERP.
(2) The sizes of the detected oil spills varied between 0.1 km^2 and 108 km^2,
(3) Feathered edges of oil slicks indicate heavy and middle fractions of oil in a slick that also can be a sign of routine tank washing operations or illegal discharges,
(4) The number and the total area of detected oil spills depended on the particular time/season and ship traffic.
(5) Most of oil spills have been released during night time, and were detected during descending (morning) satellite passes.
(6) Oil spills have been more often detected on SAR images in the open parts of the sea beyond the territorial waters, rather than in the coastal waters.
(7) Other, not estimated yet source of oil pollution may be bottom seepage.

Oil spill detection using remote sensing is a very good affair, but there is one executive problem. According to EUROPEAN COMMISSION (2001), it remains very difficult to carry out effective sanctions on the national level, other than against illegal actions that take place in national waters and specific protected areas. Coastal states have limited jurisdiction over passing ships flagged by other states. Beyond territorial waters, the role of coastal states is restricted to monitoring and collecting "sufficient evidences" of pollution events, for reporting to the administrative state of the culprit ship (flag state). While the flag states are bound by international law to investigate such reports and punish polluters, what constitutes "sufficient evidence" is their own decision. Thus the vast number of pollution incidents takes place just beyond the territorial waters.

It is finally concluded that the Central Adriatic Sea from time to time is seriously polluted with oil, mostly as a result of heavy ship traffic. Oil pollution along the shipping lanes is especially heavy and has been shown to be caused mainly by tank washing operations and illegal discharges. The SAR imagery collected and analyzed provides both new insights into oil spill problems in this Mediterranean Sea and new information for use in understand the nature of oil pollution. Moreover, more study and efforts are further needed to gathering information on types and sources of oil pollution of the Adriatic Sea.

Due to the fact that there is recently increasing interest in investigation of undersea oil and gas resources in the Adriatic Sea, this topic should raise awareness for continuous monitoring of oil slicks to be up to date with potential accidents during future exploitation and transportation of oil. Nevertheless, these results can lead to special actions and particular measures for protection of the marine environment of the Adriatic Sea against oil pollution.

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Raspodjela uljnih mrlja u srednjem i južnom Jadranu i intenzivan pomorski promet

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SAŽETAK

Detekcija uljnih mrlja sintetičkim satelitskim radarom (SAR) provjerena je i najčešće korištena operativna tehnika, koja je pokazala kako je Sredozemno more često zagađeno uljem i sličnim proizvodima. Zahvaljujući nekolicini projekata Envisat i Radarsat-1 SAR slike su za razdoblje 2003-2011 bile dostupne za analizu. Analizirano je oko 300 SAR slika srednjeg i južnog Jadrana, kako bi se otkrile pojave naftnih mrlja i druge pojave koje imaju sličan signal na satelitskim snimcima.

Otkrivena su mnoga izlijevanja nafte u Jadranu, čije su površine bile između 0,1 km^2 i 108 km^2. Većina izlijevanja je smještena uz glavne brodske rute, osobito u brodskom koridoru duž osi Jadranskog mora. To su vjerojatno ulja namjerno izlivena s brodova tijekom prijevoza ili ribolovnih operacija, a najčešći slučajevi izlijevanja su pranje brodskih spremnika ili nedozvoljena pražnjenja tankova.

Ključne riječi: Jadransko more, uljno zagađenje, uljne mrlje, SAR satelitski smimci, geoinformacijski pristup

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