



Oil spill detection in the Kazakhstan sector of the Caspian Sea with the help of ENVISAT ASAR data

Alexander Holstein¹ · Martin Kappas¹ · Pavel Propastin¹ · Tsolmon Renchin²

Received: 8 September 2016 / Accepted: 18 February 2018 / Published online: 2 March 2018
© The Author(s) 2018. This article is an open access publication

Abstract

Oil pollution in the world's oceans is predominantly caused by operational discharges from tankers (predominant oil dumped during cleaning operations). These discharges result in over 2 million tons of oil which are introduced annually comparable to one full-tanker disaster per week. Land-based sources such as urban waste and industrial discharges, which compass the ocean via rivers, are also a major contamination factor. The Caspian Sea is the largest inland water body on Earth without a direct connection to the world's oceans, which makes it a unique water reservoir. This fact makes the Caspian Sea particularly vulnerable and subject to human influence, for example, pollution from shipping activities and oil transports by ships. The research study shows results from a monitoring campaign in northern and central parts of the Caspian Sea (Kazakhstan sector) for the period from 2005 to 2012 (April–October), based on visual interpretation of radar images from ASAR ENVISAT. Radar data (529 radar images) such as ASAR_WSM_1P and ASAR_IM_1P were obtained from the archives of the European Space Agency. In 529 ASAR ENVISAT images, 160 images were selected, on which 329 oil spills were detected. Examples of individual slicks were analyzed by visual image interpretation. The total surface of contamination for the entire study period was estimated by 822.66 km². The average size of the oil spills ranged from 1.09 to 10.62 km², in different years. The monitoring of oil spills over the Kazakhstan sector of the Caspian Sea could show that it is possible to state with certainty that the main source of oil pollution is shipping (confirmed by analysis of slicks form and clusters along shipping routes) and the most contaminated area is its southern part, where there is more intensive navigation in the direction of Aktau–Baku (Azerbaijan), Aktau–Turkmenbashi (Turkmenistan), and Aktau–Neka (Iran). In the northern part of the Caspian Sea, it was determined that a low number of spills could have been caused by fishing and marine activities in the development area of the Kashagan oil field. The result is based on comparing the contamination map and the map of navigation, as well as through an analysis of the geometry of the slicks. Monitoring results largely coincided with the results of work carried out in the region, and at different times for some of its sites. These findings based on the radar data showed advantages of ASAR ENVISAT satellite monitoring for the control of oil pollution on the sea surface.

Keywords Oil spill detection · Caspian Sea · ENVISAT ASAR data exploitation

Introduction

The Caspian Sea is the largest (378,000 km²) totally enclosed sea in the world without a direct connection to the global ocean. The GIWA (Global International Water Assessment) contains the Caspian Sea more than 40% of the world's inland waters (GIWA 2006). Geographically situated at the crossroads of Europe and Asia, the Caspian Sea is an important and strategic hub of water routes between the two continents.

Considerable energy resources (natural gas and oil reserves in offshore fields and onshore on the coast of the sea) in the Caspian basin make it one of the richest

✉ Alexander Holstein
alexander.holstein@stud.uni-goettingen.de

Martin Kappas
mkappas@gwdg.de

Tsolmon Renchin
tsolmonren@gmail.com

¹ Department of Cartography, GIS and Remote Sensing, Georg-August University, Göttingen, Germany

² Remote Sensing and Space Science Laboratory, National University of Mongolia (NUM), Ulaanbaatar, Mongolia

hydrocarbon provinces in the world. The Caspian Sea region is one of the oldest oil-producing areas in the world and is an increasingly significant source of global energy production. In the last 20 years, it was discovered that Kazakhstan sector of the Caspian Sea contains huge oil deposits, including the giant Kashagan field, which, according to experts, has reserves of 35 billion barrels. Estimates of recoverable reserves amount to billions of barrels (9–13 billion barrels) (Oil and Gas Journal 2013). Despite considerable oil resources, the Caspian region faces challenges to oil production and transportation. The Caspian's hydrocarbon resources are located relatively far from export markets, requiring infrastructure to move oil to ports where it can go to international markets.

Any offshore oil activity, whether it is development, extraction, or transportation, is much more difficult than on land and is always associated with a high risk of accidents. Fortunately, major disasters with oil tankers or drilling platforms do not often happen, and actually, ships are the main source of oil pollution. According to statistics, operatives discharge from ships is a reason for 45% of oil pollution in the world's oceans, while offshore oil production is a source of only 2% (ESA 1998b, 2000b; Kostianoy et al. 2007; Patin 2009). Transportation of oil products, the shipping activity, as well as various activities in the ports that result any of which could lead to an oil spill in the sea. Oil spills in the marine environment can have serious biological and economic impacts.

Oil and oil products come into the sea as a result of small accidents, routine manufacturing operations, illegal discharges from ships ballast and bilge water, fishing activity (fishery waste), as a result of washing tanks, river runoff, accidents involving oil tankers, or during the oil offshore exploration and production (Bernem and Lübbe 1997; Alpers 2002, Brekke and Solberg 2005). It should be noted that crude oil intrusion into the water is quite rare, as it only happens because of accidents on oil rigs and tankers, leaking pipelines as well natural seeps. Other events in the sea introduce more toxic petroleum products. Independence of Kazakhstan has resulted in increasing oil production, which has led to an escalating volume of traffic, including sea transport. There has been an expansion of ports and terminals, a growth in operations due to new deposits on the shelf and in the coastal zone, and an increase in the number of ships in the Caspian Sea (Ports of Ukraine 2012; Mintranskom RK 2013).

Present-day monitoring of oil pollution at sea is done through widely used satellite radar images. Known as ASAR (advanced synthetic aperture radar), it is well established due to a number of advantages it has over other sources. Radar images do not depend on weather conditions, cloud cover, or light conditions and, at the same time, have a sufficiently good spatial resolution and cover

large areas (Fiscella et al. 2000; Ivanov and Zatyagalova 2008; Kamagate 2011).

Crude oil and oil products that enter the sea, depending on their physical and chemical parameters, form surface films on the water of various thicknesses (from a few centimeters to only fractions of millimeters). This distinguishes them from films, such as biological surfactants (produced by plankton and fish), that are able to spread monomolecular layers. This means that the more viscous and difficult oily mixture can be observed on radar images at higher wind speeds as well, while the surfactant films will disappear (Ivanov et al. 2004a, b; Brekke and Solberg 2005).

Due to its high sensitivity to the surface roughness of the sea, the radar images are very good at fixating on floating oil. Under wind conditions from 2.5–3 m/s to 10–12 m/s, oil dampens ripple waves and forms a smooth layer on the surface, which, in turn, appears on radar images as dark patches on the brighter water surface (ESA 1998b; Ivanov and Zatyagalova 2008).

The main objective of this research study is to assess the level of oil pollution based on radar satellite images ASAR (ENVISAT), for the period 2005–2012, in the Kazakhstan sector of the Caspian Sea. The tasks included are as follows: detection of oil slicks, identification of possible sources of contamination, identification of areas of the greatest conglomeration of oil slicks, and digitalization of oil spills and creation of an overall pollution map. Further, a robust framework to monitor oil spills using radar data and additional GIS data is developed and explained in the data/method section.

Study area

The research area belongs to Central Asia and extends to the northern and central part of the Caspian Sea (Fig. 1).

The investigated region is located at the crossroads of two continents, Europe and Asia. The Kazakh sector of the Caspian Sea is bordered by Russia to the north and borders Azerbaijani and Turkmen to the south. The Kazakhstan section comprises of about 30% of the total amount of the Caspian Sea, with a long coastline of more than 2300 km. The Caspian Sea is the largest enclosed water body, which has no connection with the global oceans. The Caspian Sea level is approximately – 27 m below sea level (Brockhaus 2006), with characteristic variations of the hydrological regime.

Oil production in the northern Caspian Sea is connected with certain difficulties, such as the harsh environmental conditions (temperature difference between the coldest month in January and the warmest month in July is 33 °C), ice cover (from November to March, with thickness of ice up to 70 cm), shallow waters (average depth of 70% of the northern Caspian Sea is only 5 m), daily (wind-induced surges) and long-term fluctuations of the sea, the presence of conservation protected areas rich in biodiversity (including

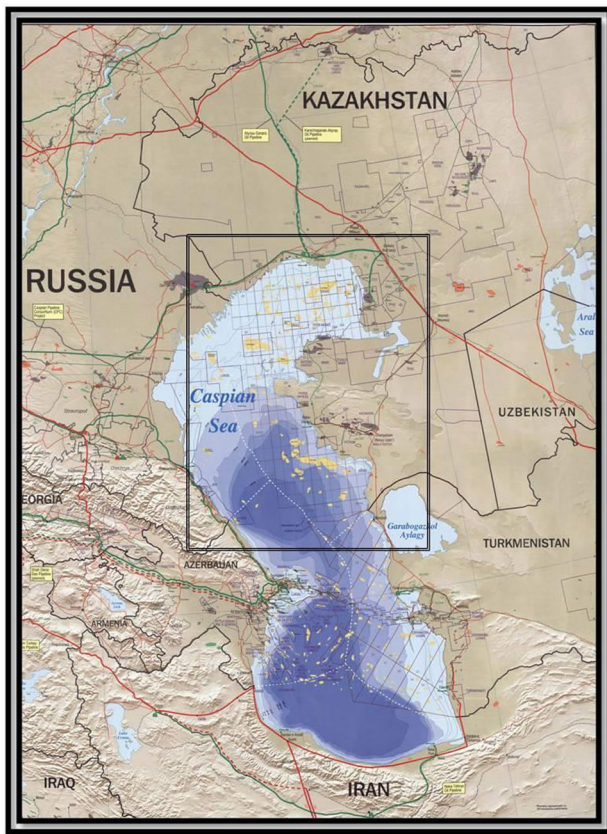


Fig. 1 Study area northern and central part of the Caspian Sea. (Source: CIA 2001)

representatives of the relict flora and fauna), high reservoir pressure occurrence of oil (800–1100 atm.), and a high content of sulfur in the oil (Reshetnjak et al. 2000; Nurushev and Diarov 2010; Zhindarev et al. 2013).

Furthermore, there are a large number of suspended wells within the coastal zone, which may be susceptible to flooding with sea-level fluctuations. All of these factors increase the risk of accidents and environmental disasters. A disaster, such as occurred in the Gulf of Mexico, would cause irreparable damage to the Caspian Sea. Offshore oil production, oil transport in the tankers, and shipping are risk factors for the marine environment and the coastal ecology. The valuation and control of oil pollution are therefore of high importance.

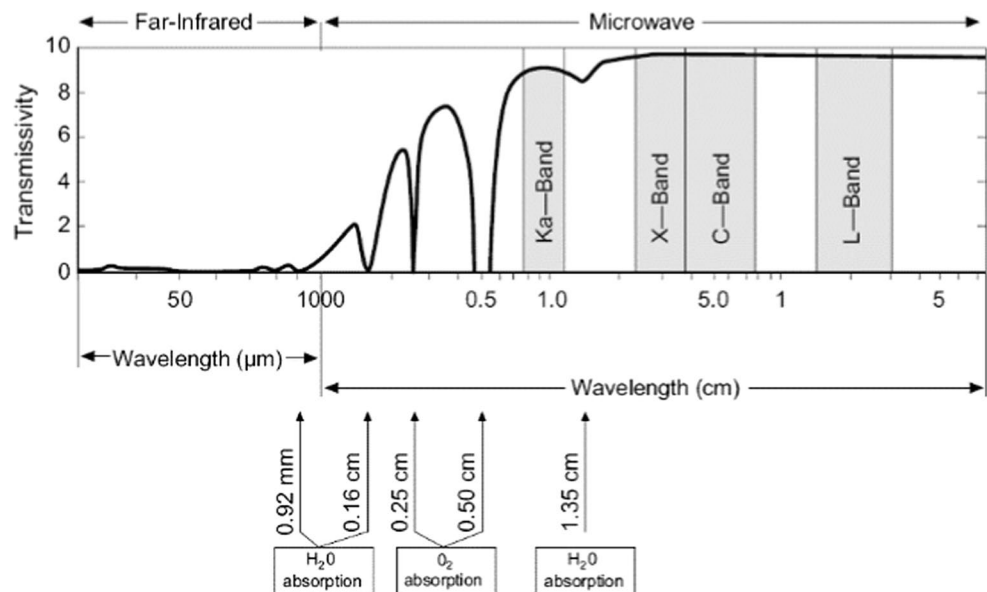
Data and methods

Radar systems

The optical satellite sensors are dependent on reflected sunlight and are among the “passive” remote sensing systems, and the radar systems with their own radiation source belong to the “active” systems, as reflected signals are recorded to the sensor. The radar sensors are due to their active lighting and the ability of microwaves to penetrate clouds, haze, fog, and smoke, regardless of the light conditions and the weather (Albertz 2001; Soergel 2006). In addition, the microwave range of the electromagnetic spectrum with a wavelength of 7 mm is affected by weather conditions (Lusch 1999) (Fig. 2).

The process of radar recording depends on several individual parameters, such as:

Fig. 2 Microwave atmospheric permeability. (Reproduced with the permission from Lusch 1999)



- Parameters of the recording system (wavelength of radiation, polarization, depression, intensity, duration, phase, and strength of radiation between sending and receiving the returned impulse)
- Parameters of the terrain surface (the roughness, the shape of the surface, and the electrical properties of the materials) (Walzog 2013; Albertz 2001; ESA 2007, 2014)

A radar satellite image is carried out in ultra-microwave areas in three bands X, C, and L. The pulses sent by a radar antenna to the area to be transmitted are scattered back from the illuminated surface and converted into a digital image after processing (Hagemeister 2001). In contrast to longer microwaves, which have the ability to penetrate deep in various superficial materials, the shorter waves are already reflected from the surface (Ramminger 2004).

ENVISAT (ASAR)

The satellite ENVISAT, with 10 instruments on board, was launched in March 2002, and served until April 2012. The satellite had a 35-day repeating cyclical orbit, but due to the wide scope of the instrument, it could cover certain areas of the Earth at intervals ranging from a few days up to several hours (ESA 2005; Kostianoy et al. 2007).

The instrument ASAR, with a size of 1.3 m × 10 m, is the largest instrument the satellite ENVISAT carries. This is a further developed and improved synthetic aperture radar (SAR), which differs from the SAR sensor due to its

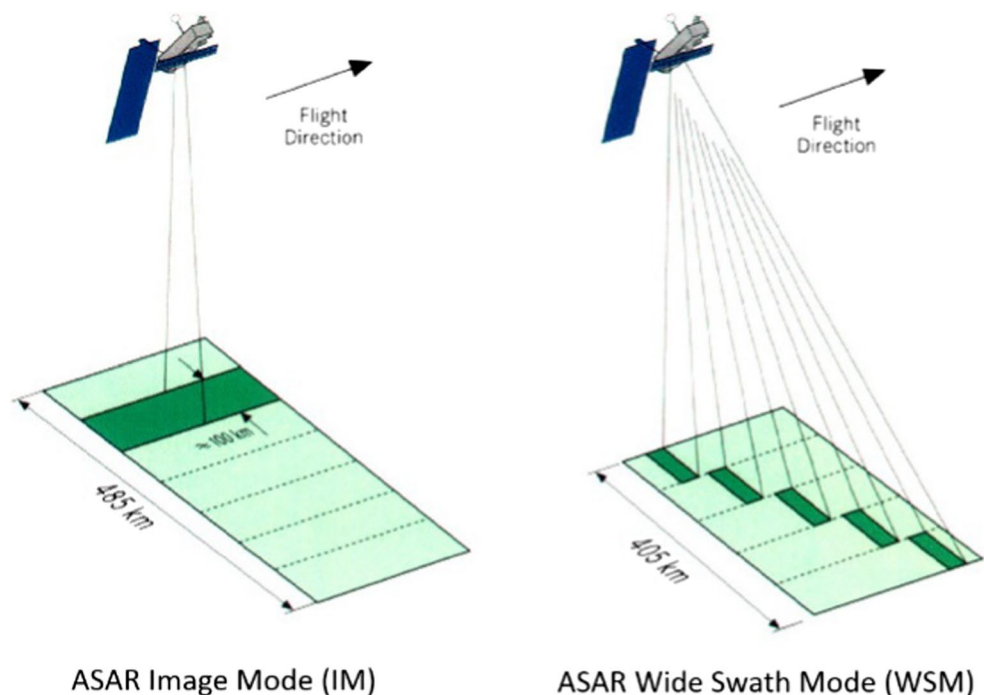
active phased array antenna, which can record images from various angles (15°–45°) (ESA 2000a, 2007). Its matrix consists of 320 transmit/receive modules (ESA 1998a). The high-resolution active radar ASAR works in C-band (5331 GHz, 5.623 cm) and is suitable for global as well as regional observations of land and water surfaces. The ASAR recording system is mainly used for observing the sea (wave strength, coastal dynamics, ice and spreading, oil pollution, shipping) and the land surface (topography, geology, land cover, agriculture, deforestation, devastation) (ESA 2000a, 2007; Airbus Defence and Space 2012).

The ASAR sensor, carried by ENVISAT, operates in five modes (recording mode): image mode medium resolution (IMM), alternating polarization mode (APM), wide swath mode (WSM), global monitoring mode (GM), and wave mode (WM).

This work was based on the analysis of radar data such as wide swath standard image (WSM) and image mode medium resolution image (IM) from synthetic aperture radar ASAR (ENVISAT) (Fig. 3). The improved ASAR antenna allows one image to capture an area of 400 × 400 km which, in the WSM-mode, covered almost the entire study area, with a geometrical resolution of 150 m. The image mode medium resolution image (IM) has a geometric resolution of 30 m with a swath of 100 km (ESA 2002). The coverage of the Caspian Sea in period from April 01, 2010 to October 31, 2010 by the ENVISAT ASAR WSM and IM products is shown in Fig. 4.

The methods of identification of oil spills using radar images are confirmed by many studies (Fingas and Brown

Fig. 3 ENVISAT ASAR IM and WSM operation modes for oil spill detection. (Reproduced with the permission from ESA 2007)



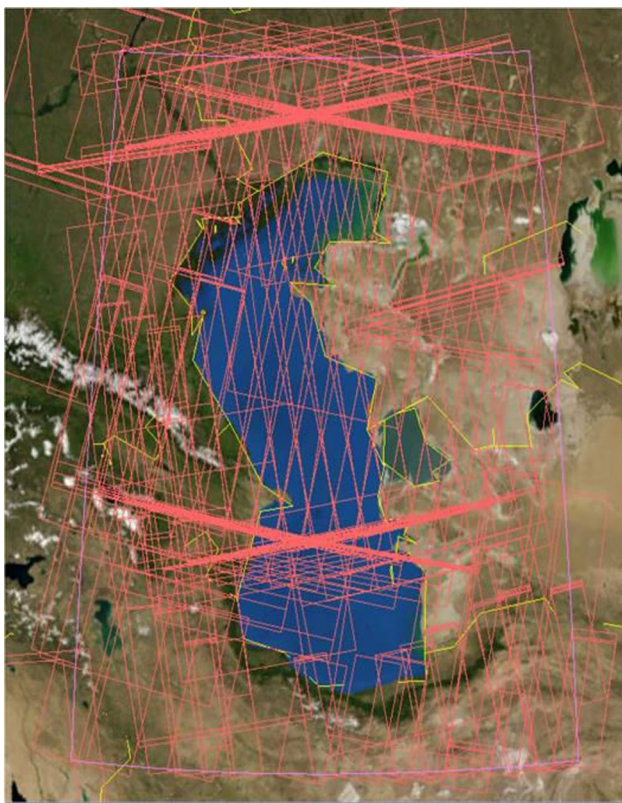


Fig. 4 Coverage of the Caspian Sea by ASAR WSM and IMM products in period of 2010 (April–October). (Source: EOLi-SA)

1997; Fiscella et al. 2000; Kostianoy and Lobkovskij 2004; Zatyagalova et al. 2008; Baschek 2010; Kamagate 2011; Morovic and Ivanov 2011; Santilli et al. 2011; Mityagina and Lavrova 2012). Radar data, due to a number of advantages (all weather, any time, good resolution, and spatial

coverage) as compared to other satellite data, have proven themselves in recent years.

Oil films on the sea surface damp the capillary waves and smooth the roughness of the water surface. These differences in backscatter signals from the water surface allow the radar to detect oil pollution. Despite the numerous advantages of radar images, however, there are still a number of limitations that cause the identification of oil spills to be difficult or impossible. Thus, the basic conditions for successful detection of oil on the sea surface are the wind conditions.

When wind conditions of up to 2.5 m/s exist, a calm zone is formed, and the oil slick is drained from the water surface. Conversely, in wind speeds greater than 12 m/s oil slicks mix with water. In both cases, identification is not possible (Fig. 5). The most optimal conditions are wind speeds of 3–8 m/s, when the oil is clearly seen on the radar image as dark patches on a bright background water surface (Ivanov and Zatyagalova 2007; Kamagate 2011). The area under consideration is characterized by wind speed of 5–8 m/s, which are the most favorable conditions for the detection of oil slicks.

Another limitation is the existence of *look-alike* effects and processes on the water surface and in the lower atmosphere, which also cause dark patches in radar images (Espedal 1998). These may be low wind areas, shear zones, grease ice, upwelling, rain cells, biological films (surfactants), algae blooms or the internal and atmospheric gravity waves etc. The main problem in the identification of oil pollution is to discriminate these natural effects from the oil pollution (Brekke and Solberg 2005). For this purpose, the oil slick properties (shape, size, location relative to infrastructure, contrast, texture, form of the boundaries of slicks) can be used as well, as meteorological and oceanographic information or satellite data in the visible and infra-red ranges (Ivanov and Zatyagalova 2008).

Fig. 5 Wind conditions for oil spill detection with the radar sensors. (Reproduced with the permission from Baldenhofer K.)

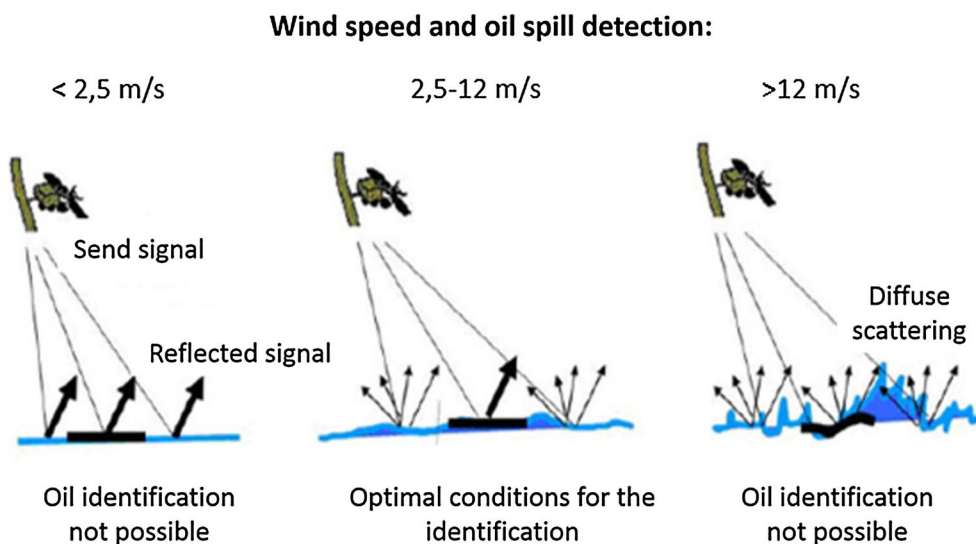
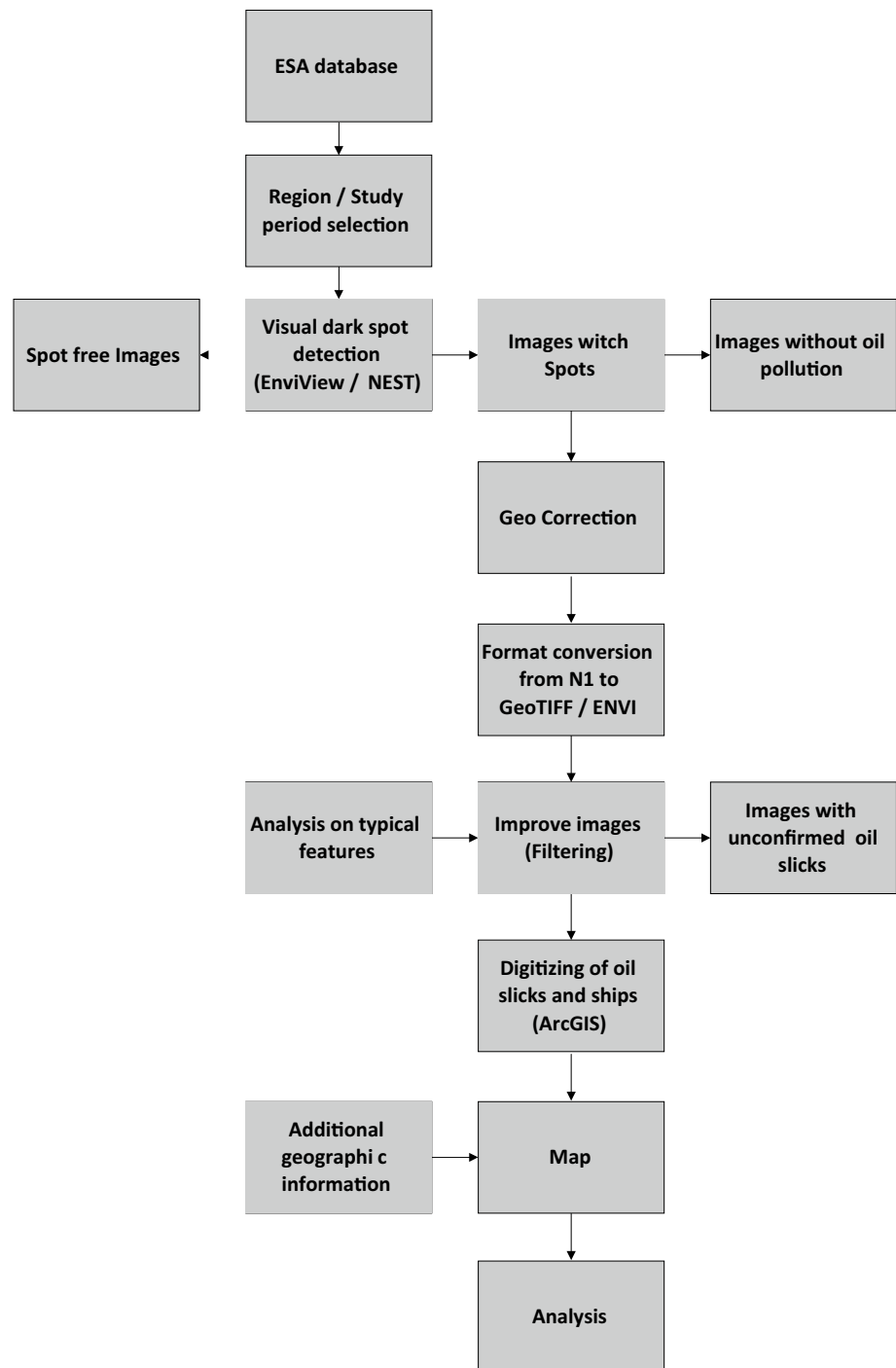


Fig. 6 Framework for oil spill detection processing steps



The process of interpreting radar images consists of several stages. Figure 6 shows the entire process, from the initial stages to the final stages of building the maps and analyzing the oil pollution.

All images received from the ESA archive (529) were visually examined for the presence of dark patches on a bright background of the water surface using programs EnviView (Application to open ENVISAT data file) and

NEST (Next ESA SAR Toolbox). As a result, all images with the specific dimming have been selected.

Afterward, selected images were geo-corrected and converted from the format N1 (ENVISAT) in GeoTIFF or ENVI format using NEST for follow-up processing in ArcGIS. These images were analyzed in ArcGIS by integrating additional information (boundaries, bathymetry, coastline, infrastructure, etc.). The filtering was performed if better

imaging was necessary. At this stage, all the images were selected that contained dark patches that were within the boundaries of the Kazakhstan sector of the Caspian Sea, and that held a high probability of being caused by oil pollution.

To differentiate oil slicks from the *look-alikes*, a method of qualitative (visual) analysis was utilized, and for this procedure a combination of following features was analyzed: form of slick, size of slick, texture of slick, outlines of slick, form and clarity of borders of slick, brightness characteristics of slick, and location (with respect to shipping lanes, ports, and infrastructure) of slick.

The final processing, analysis, and calculation of individual slicks area were carried out in the program ArcGIS, which provided additional geographical information about the study region.

Results

The result of the analysis revealed 529 radar images of the sea surface (ASAR WSM, ASAR IM) in the study area for the period 2005–2012 (April–October). Only research satellite surveys from April to October were chosen, as throughout the remaining period, most of the study area was ice covered, which made the identification of oil pollutions impossible. Uneven numbers of images obtained in different years for the study area made it impossible to analyze the pattern of an increase or decrease in the number of slicks for different periods of time. Therefore, the total assessment of oil pollution was undertaken in the study area.

A total of 160 images were selected, which were attended by 329 oil spills. Examples of individual slicks are shown in Figs. 7, 8, 9, 10, and 11. The total area of contamination for the entire study period was 822.66 km². The average size of the spills ranged from 1.09 to 10.62 km², in different years. The largest spill (about 59.8 km²) was discovered on July 16, 2006, in the southern part of Kazakhstan water (Fig. 7). Oil spills in the areas of ship activity are mainly marine spills, oily foods that fall into the sea, or illegal discharges of ballast, bilge water, and fish processing waste (Fig. 8).

Many ship slicks have a very distinctive line appearance. Pictures taken during the discharge of oil or immediately after the reset can be reviewed and the probable polluter can be quickly identified (The picture shows the ship as a bright point of light located in the immediate vicinity of the spill.). Thus, Fig. 9 reflects oil dumping with moving ships, repeated in the southwest direction (discontinuous band stretching for many kilometers with a bright point at the beginning of conformity of the ship). If necessary, the use of an automated system of tracking ships AIS (automatic identification system) can determine the type and identity of the ship, and, furthermore, can bring the perpetrators to justice.

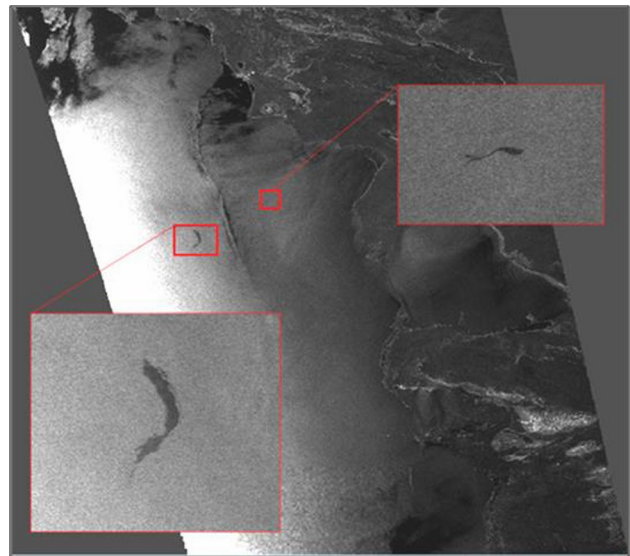


Fig. 7 Oil spills in the southern part of the Kazakhstan sector of the Caspian Sea (large oil spill (left)—total surfaces—59.8 km²). Fragment of WSM ENVISAT radar images from July 16, 2006

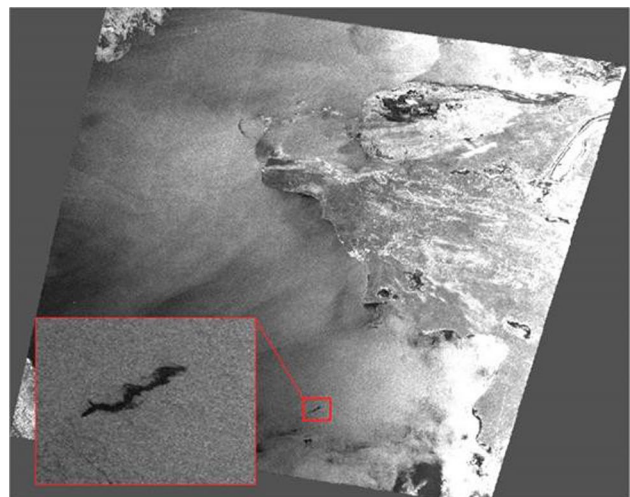


Fig. 8 Oil spill (surface—20 km²) in the area of the middle of the Caspian Sea. Fragment of WSM ENVISAT radar images from June 25, 2008

After identification, the slicks were digitized in a vector layer placed on their cartographical basis. Figure 12a shows the shipping situation in the region for the year. Figure 12b shows a map of the distribution of oil slicks. Joint analysis of maps to navigation and oil pollution shows that the majority of slicks are concentrated mainly along the shipping routes southbound from the port of Aktau, pointed in the directions of Baku (Azerbaijan), Neka (Iran), and Turkmenbashi (Turkmenistan), which may indicate a greater intensity of navigation in this direction, as well as in the proximity of the port of

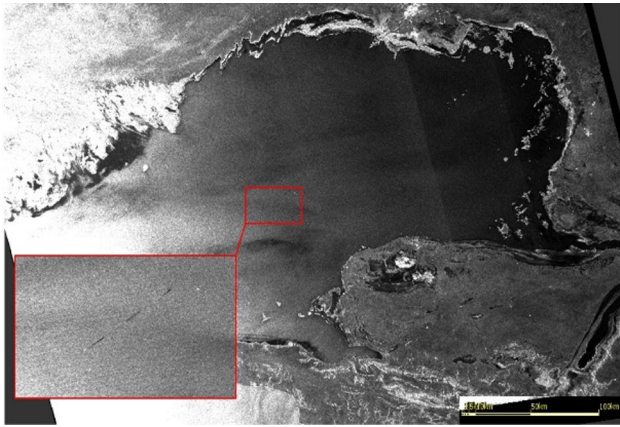


Fig. 9 Northern Caspian Sea. The discharge from the vessel produced during filming. The photograph shows the ship (bright spot)—presumably the originator of oil dumping. The nature and form of spills indicate repeated reset during movement of the ship in a SW direction. The total surface of the spills is 1.87 km². Fragment of WSM ENVISAT radar images from September 13, 2009

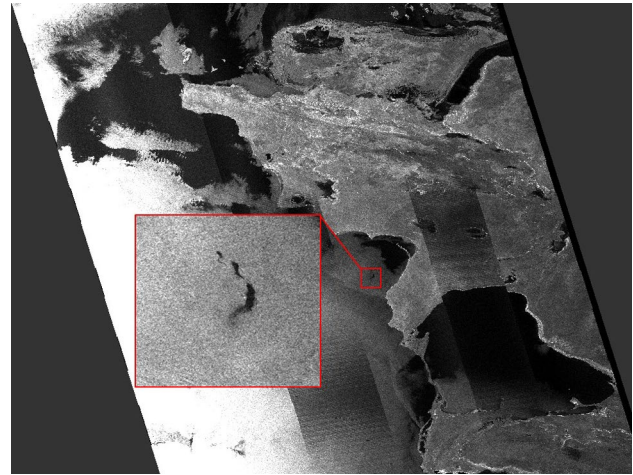


Fig. 11 Three oil spills of the Gulf of Kazak (Kazakhstan) (size of 9.6, 2.3, and 1.05 km²). The bright point in the vicinity of oil spill may indicate the ship responsible for the spill. Fragment of WSM ENVISAT radar images from April 22, 2007

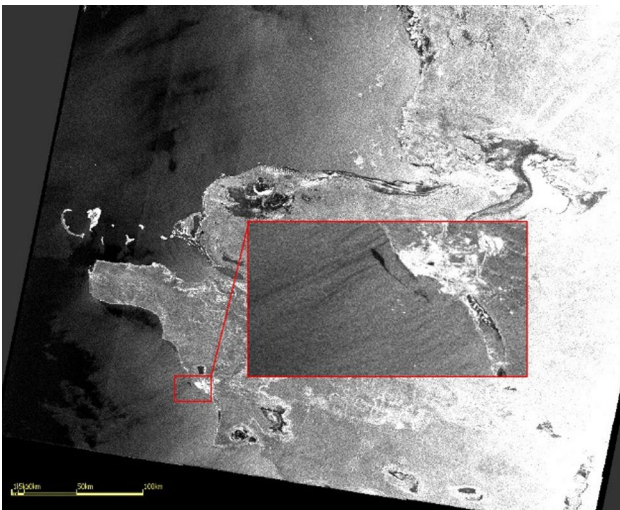


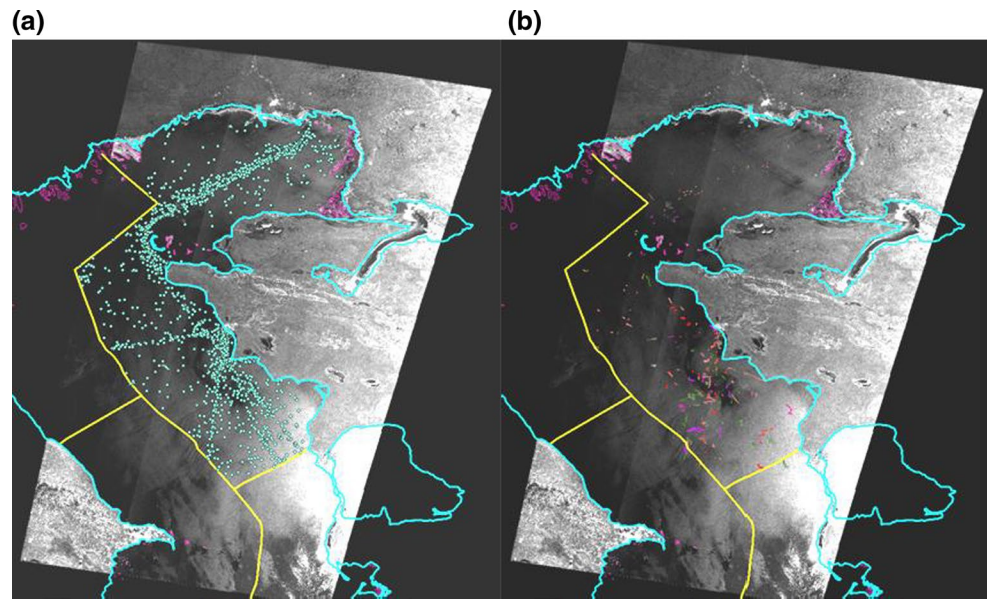
Fig. 10 An oil spill with the surface of 5.3 km² near the port of Aktau. Radar images reveal court (bright spots), while anchorage. Fragment of WSM ENVISAT radar images from May 18, 2008

Aktau, where the anchorage is located. Form slicks near the port of Aktau (slicks are rounded) indicate discharges of ship at anchor. Some numbers of slicks were detected in the northern part of the port Aktau in the Caspian Sea, in the direction of Astrakhan (Russia), Atyrau (Kazakhstan), and the Kashagan oil field. In the northeastern part, the intensity of shipping is related mainly to fishing and activity on Kashagan oil field.

Conclusion and Discussion

The monitoring of oil spills over the Kazakhstan sector of the Caspian Sea could show that it is possible to state with certainty that the main source of oil pollution is shipping (confirmed by analysis of slicks form and clusters along shipping routes) and the most contaminated area is its southern part, where there is more intensive navigation in the direction of Aktau–Baku, Aktau–Turkmenbashi, and Aktau–Neka. A significant number of spills were observed near the port of Aktau, where the shapes of the spills were specific to ship discharges of oily substances during anchorage and port activities. In the northern part of the Caspian Sea, it was determined that a low number of spills could have been caused by fishing and marine activities in the development area of the Kashagan oil field. Illegal discharges—which include ballast and bilge water, oily waste, tank washing, or fish processing waste—are very common and part of the daily technical operations of shipping. A large cluster of patches in certain areas could also indicate a constant discharge of ballast water or waste. The main concentration of the slicks is directly away from the shore in the open sea, where there is a high probability of ship discharges. This conclusion is based on comparing the contamination map and the map of navigation, as well as through an analysis of the geometry of the slicks. Monitoring results largely coincided with the results of work carried out in the region, and at different times for some of its sites. The findings based on the radar data showed advantages of ASAR ENVISAT satellite monitoring for the control of oil pollution on the sea surface.

Fig. 12 **a** (left) The annual ship traffic in the waters of the Kazakhstan sector of the Caspian Sea according to the satellite ENVISAT. The blue color shows the court. **b** (right) A map of all oil spills detected by ASAR ENVISAT (ESA) in the Kazakhstan sector of the Caspian Sea for the period 2005–2012 (April–October)



Based on the construction of a general map of oil pollution, the most contaminated subject areas were identified:

- along the southern shipping routes from Aktau direction (the southern part of Kazakhstan sector of the Caspian Sea),
- in the port of Aktau, as well as near it (anchorage), and
- in the shipping lane north of Aktau direction (Astrakhan, Atyrau, and Kashagan oil field).

Advanced synthetic aperture radar (ASAR) is the most efficient and reliable satellite sensor for oil spill detections on the sea surface. The coverage 400×400 km ASAR WSM products with a geometrical resolution 150 m were sufficient to determine spot sizes of less than 1 km^2 . A large area of coating allowed virtually daily observations around the Caspian Sea. In addition, the use of other radar data (RADARSAT, TerraSAR-X, etc.), infrared (IR), optical (AVHRR NOAA, MODIS Terra and Aqua) and ultraviolet (UV) images, as well as the meteorological and satellite information on wind speed (QuickSCAT) and sea waves height (JASON) can significantly increase the reliability of detection.

The situation of oil pollution in the Caspian Sea, due to the increase in oil production, oil transportation, and shipping, is worsened by the Caspian countries' inadequate resource policy, a lack of environmental monitoring, and the depreciation of equipment and transport.

In the future, new SAR sensors such as Radarsat-2 (TerraSAR-X) might deliver additional oil spill parameters. In general, an evolving availability of SAR imagery from different sensors is needed to build up a coordinated database

of monitoring results, coverages, and oil spills frequencies over the Caspian Sea.

The results were determined by a visual analysis. It examined the direct characteristics of oil spills. Direct analysis means, according to Espedal et al. (1998) form, size, length, position, alignment, contrast, texture, and edge shape of a stain. Because the oil spills were recorded visually and subjective, no absolute accuracy is made.

In some cases, the detection of oil slicks on the radar screens is difficult or impossible. This is because several natural processes on the water surface or deep atmospheric on the radar images can appear as “dark spots” which can be confused with oil slicks (Lavrova et al. 2011). These phenomena are “look-alike” called effects. To distinguish this, also contextual characteristics can be analyzed apart from the direct features that were used in the present work. Weather conditions (wind, streams) were understood as contextual characteristics (Espedal et al. 1998).

The wind conditions that directly affect the process of radar recording are particularly important. The detection of oil slicks at sea is only at a wind speed of 2 m/s up to 12 m/s (depending on the oil properties) possible. The use of GIS, which spatially can collect all available information about the study area, is the best prerequisites for a detailed analysis.

The use of GIS, which spatially can collect all available information about the study area, is the best prerequisites for a detailed analysis. The joint application of radar data and GIS tools allows the detection of oil slicks on the sea surface (Morovic and Ivanov 2011) with very high probability (90–95%). Radar sensors remain the most effective instruments for the monitoring and detection of oil slicks

at sea. Therefore, more studies are based on radar data (Bern et al. 1993; Espedal et al. 1998; Gade and Alpers 1999; Lu et al. 1999; Ivanov et al. 2000, 2004a, b, 2007); Fiscella et al. 2000; Alpers and Espedal 2004; Ivanov and Ermoshkin 2004; Lavrova et al. 2011; Morovic and Ivanov 2011). Apart from the results of this work, which show that in the Kazakhstan part of the Caspian Sea, the main source of pollution in the period from 2005 to 2012 was the operation of the ship, there is a high risk for the ecosystems of the lake from the oil platforms that are no longer in operation.

Acknowledgements We like to thank the European Space Agency (ESA) for providing the data inside the framework of the project “Screening of oil pollutions in the North-Eastern part of the Caspian Sea (Kazakhstan sector) using remote sensing and GIS analysis” ID: 14333. We remember our colleague PD Dr. Pavel Propastin from Kazakhstan who passed away on January 24, 2016. He gave us a lot of support and he was always a good friend.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- AIRBUS DEFENCE & SPACE (2012) ASAR deckte mehr als 400 km ab. <http://www.space-airbusds.com/de/nachrichten/envisat-instrumentasar.html>. Accessed on 11 Oct 2014
- Albertz J (2001) Einführung in die Fernerkundung. Grundlagen der Interpretationen von Luft- und Satellitenbildern, pp 58–62
- Alpers W (2002) Remote sensing of oil spills. Institute of Oceanography, University of Hamburg. Germany. In: Proceedings of the symposium “Maritime Disaster Management”. King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, pp 57–68
- Alpers W, Espedal H (2004) Synthetic aperture radar marine user’s manual. Chapter 11. Oils and surfactants. U.S. Department of Commerce, Washington, pp 263–276. http://www.sarusersmanual.com/ManualPDF/NOAASARManual_CH11_pg263276.pdf. Accessed on 10 Dec 2014
- Baldenhofer KG (2015) Lexikon der Fernerkundung. <http://www.felixikon.info/lexikon-o.htm>. Accessed on 23 June 2015
- Baschek B (2010) Vernetzung und Ausblick—Ein kombiniertes System zur Ölüberwachung. Referat: M4 Geoinformation und Fernerkundungsverfahren, GRDC Bundesanstalt für Gewässerkunde (BfG), Koblenz. www.bafg.de Öl im Meer. Risiken, Vorsorge und Bekämpfung. Tagungsband. Symposium vom 17. Bis 19. November 2010, Hamburg, pp 83–89. http://www.bsh.de/de/Produkte/Buecher/Berichte_/Bericht48/Bericht48.pdf. Accessed on 25 June 2015
- Bern TI, Wahl T, Andersen T, Olsen R (1993) Oil spill detection using satellite based SAR: experience from a field experiment. In: Proceedings of 1st ERS-1 symposium, Cannes, France, 4–6 November, pp 829–834
- Bernem C van, Lübke T (1997) Öl im Meer. Darmstadt, Katastrophen und langfristige Belastungen, p 104
- Brekke C, Solberg AHS (2005) Oil spill detection by satellite remote sensing. *Remote Sens Environ* 95:1–13. <https://doi.org/10.1016/j.rse.2004.11.015>. http://optics.marine.usf.edu/~hu/scratch/gower/pdf/Oil_spill_review_RSE2005.pdf. Accessed on 10 May 2015
- Brockhaus Enzyklopädie (2006) Kaspisches Meer, Mannheim, p 560
- CIA—Central Intelligence Agency Washington, DC (2001) Oil and gas infrastructure in the Caspian Sea region: March 2001. <https://www.loc.gov/item/2001621372/>. Accessed on 13 June 2015
- EOLi-SA (Earth Observation Link) ESA Earth Online. <https://earth.esa.int/web/guest/eoli>. Accessed on 19 June 2015
- Espedal HA (1998) Oil spills and its look-alikes in ERS SAR imagery. *Earth Observ Rem Sens Russ Acad Sci* 5:94–102
- Espedal HA, Johannessen OM, Johannessen JA, Dano E, Lyzenga DR, Knulst JC (1998) COSWATCH’95 ERS 1/2 SAR detection of natural film on the ocean surface. *J Geophys Res* 92, 24,969–24,982. <https://doi.org/10.1029/98jc01660>. <http://www.esacci.nersc.no/sites/default/files/98JC01660.pdf>. Accessed on 02 Apr 2015
- European Space Agency (1998a) Envisat ASAR science and applications, pp 1–59. https://earth.esa.int/c/document_library/get_file?folderId=13019&name=DLFE-615.pdf. Accessed on 22 Aug 2015
- European Space Agency (1998b) Oil pollution Monitoring. ESA brochure, pp 1–64. http://www.esa.int/esapub/br/br128/br128_1.pdf. Accessed on 11 May 2016
- European Space Agency (2000a) ASAR—Envisat’s advanced synthetic aperture radar. *Bulletin* 102:91–96
- European Space Agency (2000b) Oil pollution monitoring. p 2. http://www.esa.int/esapub/br/br128/br128_1.pdf. Accessed on 15 June 2015
- European Space Agency (2002) ENVISAT post-launch products. ASAR, p 2
- European Space Agency (2005) ENVISAT achievements, pp 220–229
- European Space Agency (2007) ASAR product handbook, pp 17–30, 31, 33. https://earth.esa.int/pub/ESA_DOC/ENVISAT/ASAR/ProductHandbook.2_2.pdf. Accessed on 27 June 2015
- European Space Agency (2014) SAR—synthetic aperture radar
- Fingas MF, Brown CE (1997) Review of oil spill remote sensing. *Spill Sci Technol Bull* 4(4):199–208
- Fiscella B, Giancaspro A, Nirchio F, Pavese P, Trivero P (2000) Oil spill monitoring in the Mediterranean Sea using ERS SAR data. Italy, pp 1–9. http://www.researchgate.net/publication/228957069_Oil_spill_monitoring_in_the_Mediterranean_Sea_using_ERS_SAR_data P. Accessed on 15 Apr 2015
- Gade M, Alpers W (1999) Using ERS-2 SAR images for routine observation of marine pollution in European coastal waters. *The science of the total environment* 237/238. Elsevier Science B.V, London, pp 441–448
- Global International Water Assessment (2006) Regional Assessment 23—Caspian Sea, pp 1–10. http://staging.unep.org/dewa/giwa/areas/reports/r23/regional_definition_giwa_r23.pdf. Accessed on 12 Sept 2016
- Hagemeister A (2001) Informationsgehalt von ERS-1/-2 SAR-Daten zur Erfassung der Arteninventare und des Zustandes landwirtschaftlich genutzter Böden und Vegetation. Dissertation am Fachbereich Geowissenschaften der Johannes Gutenberg-Universität in Mainz. p 214
- Ivanov AY (2000) Oil pollution of the sea on Kosmos-1870 and Almaz-1 radar imagery. *Earth Obs Rem Sens* 15(6):949–966
- Ivanov AY, Ermoshkin IS (2004) Mapping oil spills in the Caspian sea using ERS-1/ERS-2 SAR image Quick-Look and GIS, pp 1–10. <http://dx.doi.org/10.4067/S0717-65382004000200054>
- Ivanov AY, Zatyagalova VV (2007) Kartografirovanie plenochnyh zagraznenij morja s ispol’zovaniem kosmicheskoy radiolokacii i geograficheskikh informacionnyh sistem. Institut okeanologii im. P.P. Shirshova RAN. Inzhenerno-tehnologicheskij centr « Skan-Jeks ». Moscow, p 46

- Ivanov AY, Zatyagalova VV (2008) Geoinformacionnyj podhod k probleme kartografirovanija plenochnyh zagrjaznenij morja. Institut okeanologii im. P.P. Shirshova RAN. Moskva. pp 1–10. <http://www.scanex.ru/ru/publications/pdf/publication17.pdf>. Accessed on 10 June 2015
- Ivanov AY, Fang M, He M-X, Ermoschkin IS (2004a) An experience of using ERS-1/2, Envisat and Radarsat SAR images for oil spills mapping in the waters of the Caspian, Yellow and East China Sea. Envisat Symposium Programme and Abstract Book. Envisat and ERS Symposium, 6–10 September 2004, Salzburg, Austria, pp 1–10, 2005ESASP.572E.250I. <http://adsbit.harvard.edu/full/2005ESASP.572E.250I/0000250.001.html>. Accessed 22 July 2015
- Ivanov AY, Vostokov SV, Ermoschkin IS (2004b) Kartografirovanie plenochnyh zagrjaznenij morskoy poverhnosti po dannym kosmicheskoy radiolokacii (Na primere Kaspijskogo morja). Institut okeanologii im. P.P. Shirshova, Moskva, p 82
- Kamagate SA (2011) Radar monitoring of oil pollution gulf of Guinea. Ecological faculty of People's friendship university of Russia. Moscow, Russia, pp 9–10
- Kostianoy AG, Lobkovskij LI (2004) Sputnikovyy monitoring Kaspijskogo morja. Institut okeanologii im. P.P. Shirshova, pp 1–14. http://www.caspinfo.org/ru/library/bulletin/caspvk/ZIPS/2003/6-44_03.pdf. Accessed on 15 June 2015
- Kostianoy AG, Litovchenko KS, Lavrova OY, Mityagina MI, Bocharova TY, Stanichnyiy SV, Solovlev DM, Lebedev SA, Sirota AM (2007) Operativnyiy sputnikovyy monitoring neftyanogo zagryazneniya yugo—vostochnoy chasti Baltijskogo morya. Institut okeanologii im. P.P. Shirshova. pp 22–31. <http://www.iki.rssi.ru/earth/articles06/vol1-022-031.pdf>. Accessed on 10 Apr 2015
- Lavrova OY, Kostianoy AG, Lebedev SA, Mityagina VI, Ginzburg AI, Sheremet NA (2011) Complex satellite monitoring of the Russian Seas. Space Research Institute (Russian Academy of Sciences, Moscow), pp 26–30, 112, 138, 165–182, 262
- Lu J, Lim H, Liew S, Bao M, Knowoh L (1999) Ocean oil pollution mapping with ERS synthetic aperture radar imagery. In: International geoscience and remote sensing symposium (IGARSS 99), pp 212–214. <https://doi.org/10.1109/igarss.1999.773450>
- Lusch DP (1999) Introduction to microwave remote sensing. Center For Remote Sensing and Geographic Information Science Michigan State University, p 19. http://www.trfic.msu.edu/products/profcorner_products/Intro_Microwave.pdf. Accessed on 01 Mar 2015
- Mintranscom RK (Kazakh Ministry of Transport and Communications) (2013)
- Mityagina MI, Lavrova OY (2012) Long-term complex satellite monitoring of the surface oil pollution of the Baltic and Caspian seas. Space Research Institute, Russian Academy of Sciences. Moscow, Russia, pp 269–288. http://d33.infospace.ru/d33_conf/sb2012t5/269-288.pdf. Accessed on 09 June 2015
- Morovic M, Ivanov A (2011) Oil spill monitoring in the Croatian Adriatic waters: needs and possibilities. ACTAADRIAT, 52(1). Institute of Oceanography and Fisheries Šetalište I. Meštrovića 63, Split, 21000, Croatia, pp 45–56. <http://hrcak.srce.hr/89645>
- Nurushev MZH, Diarov MD (2010) Nauchnoe obosnovanie jeffektivnyh mer po preduprezhdeniju i likvidacii katastrof neftegazovyh vybrosov Kazahstanskogo sektora Kaspijskogo morja. Evrazijskij nacional'nyj universitet im. L.N.Gumeleva g. Astana, Institut nefti i gaza g. Atyrau. Kazakhstan, p 238
- Oil and Gas Journal (2013) <http://www.ogj.com/articles/2013/09/kashagan-oil-field-starts-production.html>. Accessed on 15 June 2015
- Patin S (2009) Environmental impact of the offshore oil and gas industry. Ecomonitor Publications, p 425
- Ports of Ukraine Nr. 02 (114) (2012) Marine industry of Kazakhstan. <http://portsukraine.com/node/2546>. Accessed on 22 June 2015
- Ramminger G (2004) Erfassung von Sturmschäden mit Hilfe von modernen Radar-Fernerkundungssystemen. Inaugural-Dissertation zur Erlangung der Doktorwürde der 131 Fakultät für Forst- und Umweltwissenschaften der Albert-Ludwigs-Universität Freiburg i. Brsg. p 174
- Reshetnjak EM, Monahov SK, Dzerzhinskaja IS (2000) Jekologicheskaja politika OAO « LUKOIL » na Kaspijskom more. Sostojanie okružhajushhej prirodnoj sredy pri provedenii izyskatel'skih i geologorazvedochnyh rabot na strukture « Hvalynskaja » v 1997–2000 gg. Glava 1.1 Fiziko-geograficheskie uslovija. Astrahan', pp 1–16. <http://caspijanmonitoring.ru/mono/mono3/1.1.pdf>. Accessed on 22 June 2015
- Santilli G, Marzioletti P, Laneve G (2011) A novel synergy between remote sensing and GIS for oil spill detection on satellite imagery. Italy, Argentina, pp 1–4. <http://www.isprs.org/proceedings/2011/ISRSE-34/211104015Final00093.pdf>. Accessed on 22 June 2015
- Soergel U (2006) Stand der Technik und Trends der Radarfernerkundung. IPI, Hannover. Vortrag, p 1. http://www.ipi.uni-hannover.de/uploads/tx_tkpublikationen/Soergel_125_Jahre_Geodäsie_Hannover.pdf. Accessed on 22 June 2015
- Walzog S (2013) Ausgewählte Kapitel der Theoretischen Geodäsie. SAR-Toolboxen. Material zu Seminar. Rheinische Friedrich-Wilhelms Universität Bonn, pp 3–5
- Zatyagalova VV, Ivanov AY, Golubov BN (2008) Application of ENVISAT SAR Imagery for mapping and estimation of natural oil seeps in the south Caspian Sea. R&D Center ScanEx (Moscow), P.P. Shirshov Institute of Oceanology, Russian Academy of Science (Moscow), Institute of Dynamics of Geospheres Russian Academy of Science (Moscow), pp 1–6. <https://earth.esa.int/envisatsymposium/proceedings/posters/3P14/456173Za.pdf>. Accessed on 05 June 2015
- Zhindarev LA, Ignatov EI, Badjukova EN, Luk'janova SA, Solov'eva GD, Shipilova LM (2013) Kaspijskoe more. TOM 6, pp 944, 962