ISPRS Journal of Photogrammetry and Remote Sensing 112 (2016) 37–49

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

The Costa Concordia last cruise: The first application of high frequency monitoring based on COSMO-SkyMed constellation for wreck removal

Andrea Ciampalini [a,*], Federico Raspini [a], Silvia Bianchini [a], Dario Tarchi [b], Michele Vespe [b], Sandro Moretti [a], Nicola Casagli [a]

[a] Department of Earth Sciences, University of Firenze, Firenze, Italy

[b] European Commission, Joint Research Centre (JRC), Institute for the Protection and Security of the Citizen (IPSC), Maritime Affairs Unit, Via Fermi 2749, 21027 Ispra, VA, Italy

A R T I C L E I N F O

Article history:
Received 18 May 2015
Received in revised form 28 October 2015
Accepted 1 December 2015

Keywords:
Costa Concordia
SAR
COSMO-SkyMed
Oil spill
Wreck

A B S T R A C T

The Italian vessel Costa Concordia wrecked on January 13th 2012 offshore the Giglio Island (Tuscany, Italy), with the loss of 32 lives. Salvage operation of the vessel started immediately after the wreck. This operation was the largest and most expensive maritime salvage ever attempted on a wrecked ship and it ended in July 2014 when the Costa Concordia was removed from the Giglio Island, and dragged in the port of Genoa where it was dismantled. The refloating and removal phases of the Costa Concordia were monitored, in the period between 14th and 27th of July, exploiting SAR (Synthetic Aperture Radar) images acquired by the X-band COSMO-SkyMed satellite constellation in crisis mode. The main targets of the monitoring system were: (i) the detection of possible spill of pollutant material from the vessel and (ii) to exclude that oil slicks, illegally produced by other vessels, could be improperly linked to the naval convoy during its transit along the route between the Giglio Island and the port of Genoa. Results point out that the adopted monitoring system, through the use of the COSMO-SkyMed constellation, can be profitably employed to monitor emergency phases related to single ship or naval convoy over wide areas and with a suitable temporal coverage. Furthermore, the refloating and removal phases of the Costa Concordia were a success because no pollution was produced during the operations.

1. Introduction

On January 13th 2012, during a cruise in the Mediterranean Sea, the Italian vessel Costa Concordia capsized and wrecked offshore the Giglio Island, along the coast of Tuscany (Italy), with the loss of 32 lives. In the late evening, after deviating the planned course to sail near the Giglio Island, the liner cruise struck on most seaward exposed rock of Le Scole, an underwater rock located a few hundred meters east of the coastline of the island (Schröder-Hinricks et al., 2012). The impact opened an irreparable 50-m gash in the ship's portside below the water line. After the impact the seawater entered in the engine room, submerging the generators and causing the power to fail. Without propulsive power, the ship started to drift and heel over only by means of inertia, finally grounding, after a starboard rotation, on the granitic seabed in front of Punta Gabbianara, where the Costa Concordia stood over the past two and a half years.

After the Parbuckling phase (the up-righting of the ship), in July 2014 the Costa Concordia was intended to be dragged away from the Giglio Island, to sail for its final cruise to be scrapped in the port of Genoa. In order to ensure the highest safety condition during refloating and transportation across the Tyrrhenian Sea, the selected time window fell in the period of the year characterized by the best meteo-marine conditions.

The implementation of a comprehensive environmental monitoring plan was deemed essential also during this phase in order to take preventive actions to face possible leakage of pollutants, i.e. remaining oil and/or oily mixtures, caused by the works on the vessel, with the adoption, if required, of corrective measures.

Space-borne SAR sensors represent effective tools in detection and monitoring of marine oil pollution related to illegal ship discharges. Reports on marine oil pollution (Fingas, 2001; REMPEC, 2002; Huijer, 2005; ITOPF) highlight that about 45% of the total oil pollution is due to illegal discharges from ships. On the contrary, accidents that involve tankers or platforms represent only to 5% and 2%, respectively, of the global oil pollution. This illegal practice has become frequent and it happens prevalently along maritime traffic routes. Several major oil routes of transportation

* Corresponding author at: Via La Pira 4, University of Firenze, Italy. Tel.: +39 055 2757548.

E-mail address: andrea.ciampalini@unifi.it (A. Ciampalini).

http://dx.doi.org/10.1016/j.isprsjprs.2015.12.001
0924-2716/

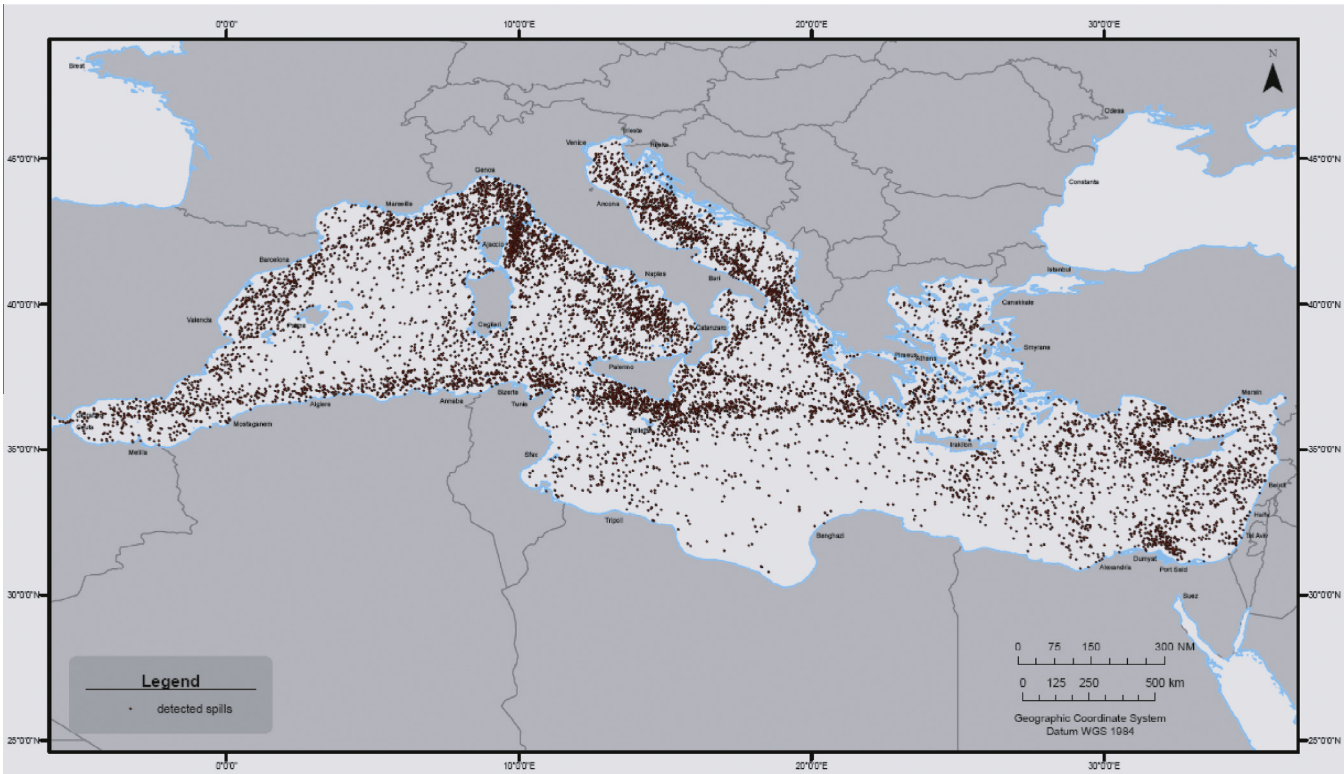

Fig. 1. Oil spill in the Mediterranean sea. Possible oil spills detected in the Mediterranean sea between the 1999 and the 2004. (Courtesy of European Commission, Joint Research Centre).

are located within the Mediterranean Sea because of its strategic position. The 25% of the global oil traffic transits the Mediterranean by means of tankers. This percentage corresponds to about 360–370 million tons annually (REMPEC, 2002). The Regional Marine Pollution Emergency Response Center for the Mediterranean Sea (REMPEC) estimated that the magnitude of the oil spill generated by this traffic, in the Mediterranean Sea, is between 100,000–150,000 tons of oil every year (REMPEC, 2002). Marine pollution surveillance systems usually employ naval and/or aerial platforms equipped with optical or radar sensors in monitoring activities. These platforms are limited by the high costs, by their capability to cover restricted areas and, moreover, are limited by weather conditions. For these reasons they can be used "on-demand" and not routinely, whereas a complete and very useful system should acquire continuously over wide areas and independently from weather conditions. A very useful monitoring system is represented by satellites that can be used in exclusive way or as a complement to the aircraft and naval platforms. Since the launch (1992) of the first ESA ERS-1 SAR satellite, space-borne SAR remote sensing techniques have been commonly used in detecting oil spill events (Singha et al., 2014) as also demonstrated by the European Maritime Safety Agency CleanSeaNet operational service.

The area supposed to be crossed by the Concordia convoy to Genova harbor is ecologically sensitive and it has been extensively analyzed to estimate the extent of operational oil pollution.

Between 1999 and 2004 the European Commission-Joint Research Center (JRC), analyzed 18,947 SAR images, to evaluate their usefulness in detecting possible spills in the Mediterranean sea (Pavlakis et al., 2001; Topouzelis et al., 2003; Bernardini et al., 2005; Ferraro et al., 2006; Tarchi et al., 2006). In the whole basin 9299 possible oil spill anomalies were detected (Fig. 1). According to this study, the general tendency for the density of the anomalies is to be higher in correspondence with the main shipping routes including the area of our interest located between Corsica and Tuscany. More recently, other studies detected and

Fig. 2. Costa Concordia vessel. (A) Soon after the wreck; (B) during the refloating phase (courtesy of Francesco Mugnai).

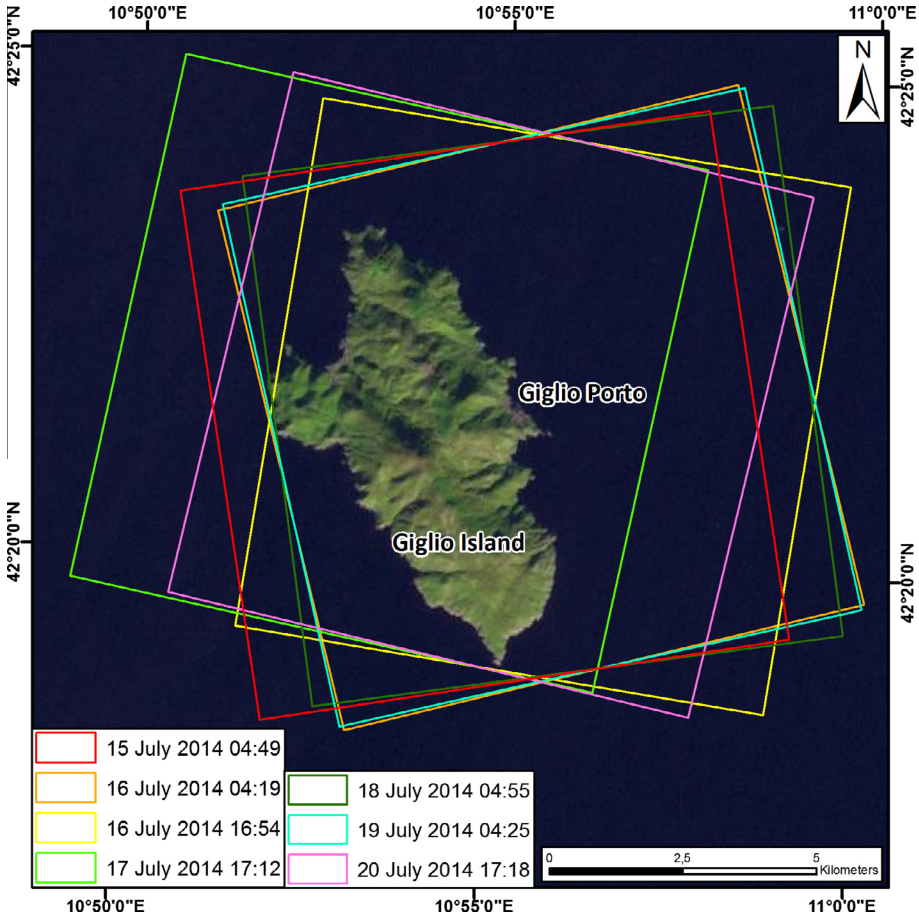

Fig. 3. Image localization. Location of the frames of the CSK images acquired over the Giglio Island. Base map: Landsat ETM +.

confirmed the presence of operational pollution in this area (e.g. OSCAR-MED coordinated surveillance operation (2009), CleanSea-Net first generation Report (2007–2011)), suggesting that the area is currently affected by the problem.

The main objective of the required activities was twofold: to detect any possible spill pollutant material from the Costa Concordia vessel and to exclude that oil slicks illegally produced by other vessels could be improperly linked to the convoy transit in the Tyrrhenian Sea. They represented a unique challenge since the convoy crossed quite a large sea area and each path segment had to be monitored in a specific time window (few hours before and after the time of passage of the wreck). This issue required the design of a tailored monitoring procedure based on satellite images able to ensure a timely and accurate spatio-temporal coverage of the area of interest. The use of the COSMO-SkyMed (CSK) satellite constellation in crisis mode had the pre-requisite to fulfill the requirements, as being particularly flexible and adaptable in terms of tasking and revisit time. In this paper we report about the implementation of the monitoring procedure and the achieved operational results.

2. Methodology

2.1. The operational phase

The refloating of the Costa Concordia vessel entered its final phase on 14th July 2014. Sufficient buoyancy for floatation was provided by pumping compressed air within the thirty sponsons, initially filled with water, installed to both sides of the vessel. As the sponsons were gradually emptied, the ship started to rise one deck at a time (Fig. 2). Once afloat, the hull emerged approximately 14 m on the sea level with respect to its starting position, with a maximum draft of 18.5 m. Salvage operators dragged the ship laterally a short distance away from the coast. Following the refloating, the vessel was towed to its final destination, i.e., the port of Genoa Voltri, for dismantling/recycling and scrapping.

The selected method of transport is traditional towage. Two heavy tugboats, namely Blizzard and Resolve Earl slowly towed the Concordia vessel from the bow from its position at the Giglio Island. Two more auxiliary tugs were positioned aft to stabilize the ship. Out to sea, the Costa Concordia was assisted by a massive environmental disaster response convoy. A 200-metric-ton crane traveled on a pontoon. A team of marine biologists preceded the convoy on a marine mammals-watching vessel. Four oil spill response vessels (equipped by off-shore and absorbent booms) and a debris recovery ship followed the Concordia. The other vessels carried personnel and equipment. A number of closed-circuit cameras (including a portable infrared sensor for the detection of oil on water at night) continuously monitored the stern of the Concordia to detect any debris releases, which could include chemical materials such as engine oil or cleaning products.

The convoy left the Giglio Island on 23rd July (11:30 am local time) and arrived to the port of Genoa four days later, on 27th July 2014 (05:00 am local time), after a journey of 191 nautical miles (about 353 km), at an average speed of 2.5 knots. The convoy passed north of the Giglio Island before heading west, traveling between the islands of Montecristo and Pianosa. After rounding

Table 1
Characteristics of the images acquired for the Costa Concordia monitoring in the Giglio Porto.

Date	Sensor	Mode	Pass	Look	Look angle (°)	Heading (°)	Status
14/07/2014 17:54	CSKS2	Spotlight-2	Descending	Left			Rejected
15/07/2014 04:49	CSKS2	Spotlight-2	Ascending	Right	22	78	Acquired
15/07/2014 18:12	CSKS2	Spotlight-2	Descending	Left			Rejected
16/07/2014 04:19	CSKS1	Spotlight-2	Ascending	Left	28	253	Acquired
16/07/2014 16:54	CSKS2	Spotlight-2	Descending	Right	50	276	Acquired
17/072014 17:12	CSKS2	Spotlight-2	Descending	Right	34	279	Acquired
18/07/2014 04:55	CSKS1	Spotlight-2	Ascending	Right	31	79	Acquired
18/07/2014 17:54	CSKS4	Spotlight-2	Ascending	Left			Rejected
19/07/2014 04:25	CSKS1	Spotlight-2	Ascending	Left	19	254	Acquired
19/07/2014 17:48	CSK2	Spotlight-2	Descending	Left			Rejected
20/07/2014 03:55	CSK1	Spotlight-2	Ascending	Left			Rejected
20/07/2014 17:18	CSK1	Spotlight-2	Descending	Right	26	280	Acquired

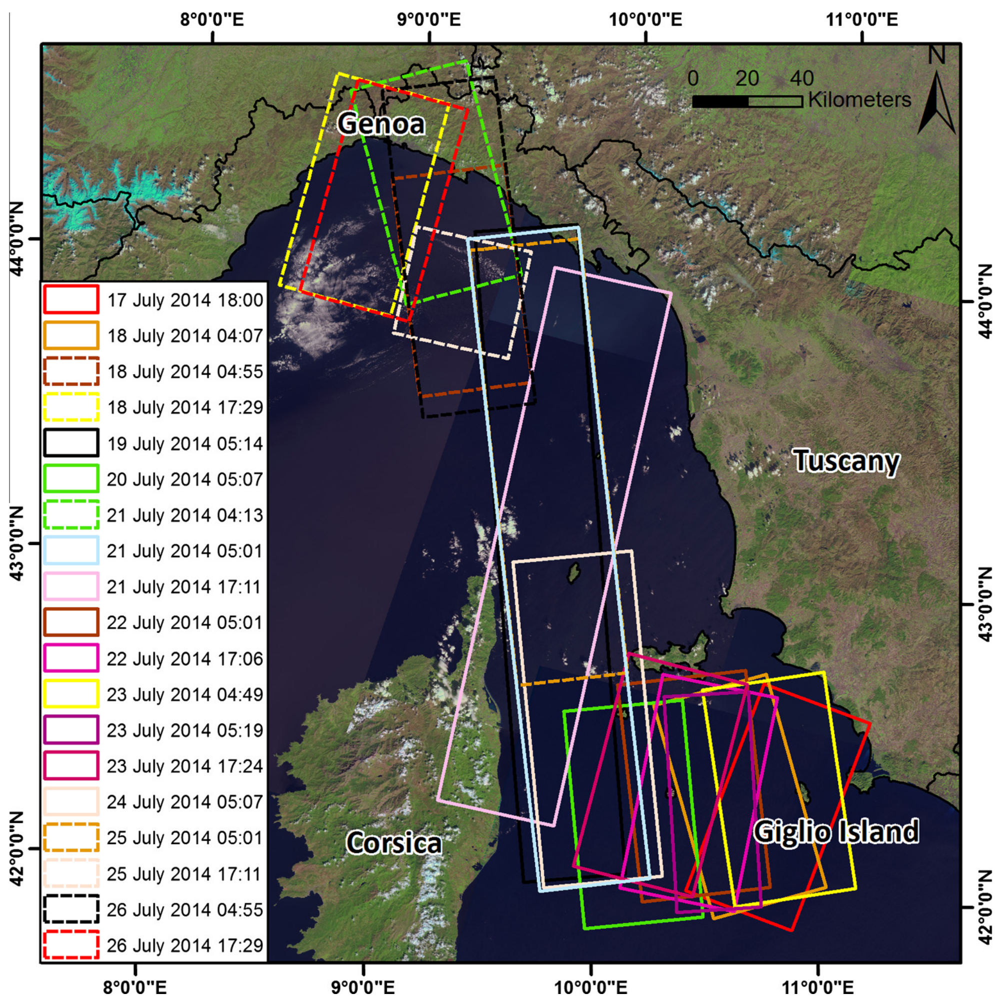

Fig. 4. Image localization. Location of the frames of the CSK images acquired along the Costa Concordia route. Base map: Landsat ETM +.

the south coast of Pianosa, the convoy headed northwest. From here the convoy sailed continuously northwards parallel to the east coast of Corsica, leaving the Elba and Pianosa islands to the east. In the final part of the route the convoy sailed in the Ligurian Sea, proceeding northwest toward the Port of Genoa Voltri.

2.2. End-user requirements

Since the beginning of salvage operations, a comprehensive environmental monitoring plan was defined, allowing the implementation of preventive actions to face any possible emergency and the identification of any potential environmental effects caused by the works on the vessel, with the adoption, if required, of corrective measures. The priority of this monitoring activity was to protect the marine environment of the Giglio Island (Broussolle et al., 2014; Raspini et al., 2014; Regoli et al., 2014). This commitment was not quitted with the removal of the Costa Concordia.

On the contrary, an environmental monitoring plan was implemented during the refloating operation, the towing of the

Table 2
Characteristics of the images acquired for the Costa Concordia monitoring between Giglio Porto and Genova harbor.

Date	Sensor	Mode	Pass	Look	Look angle (°)	Heading (°)	Status
17/07/2014 18:00	CSKS1	Stripmap	Descending	Left	38	107	Acquired
18/07/2014 04:07	CSKS2	Stripmap	Ascending	Left	42	251	Acquired
18/07/2014 04:55	CSKS1	Stripmap	Ascending	Right	24	78	Acquired
18/07/2014 17:29	CSKS2	Stripmap	Decending	Right	24	281	Acquired
19/07/2014 05:14	CSKS1	Stripmap	Ascending	Right	45	82	Acquired
20/07/2014 05:07	CSKS4	Stripmap	Ascending	Right	41	81	Acquired
21/07/2014 04:13	CSKS1	Stripmap	Ascending	Left	39	251	Acquired
21/07/2014 05:01	CSKS2	Stripmap	Ascending	Right	33	80	Acquired
21/07/2014 17:11	CSKS4	Stripmap	Descending	Right	41	278	Acquired
22/07/2014 05:01	CSKS3	Stripmap	Ascending	Right	36	80	Acquired
22/07/2014 05:19	CSKS2	Stripmap	Ascending	Right			Rejected
22/07/2014 17:06	CSKS2	Stripmap	Descending	Right	42	278	Acquired
23/07/2014 04:49	CSK1	Stripmap	Ascending	Right	21	78	Acquired
23/07/2014 05:19	CSK3	Stripmap	Ascending	Right	51	83	Acquired
23/07/2014 17:06	CSKS3	Stripmap	Descending	Right			Rejected
23/07/2014 17:24	CSKS2	Stripmap	Descending	Right	22	281	Acquired
24/07/2014 05:07	CSKS1	Stripmap	Ascending	Right	41	81	Acquired
25/07/2014 05:01	CSKS4	Stripmap	Ascending	Right	33	80	Acquired
25/07/2014 17:11	CSKS1	Stripmap	Descending	Right	42	278	Acquired
26/07/2014 04:55	CSKS2	Stripmap	Ascending	Right	23	78	Acquired
25/07/2014 05:20	CSKS4	Stripmap	Ascending	Right			Rejected
26/07/2014 17:29	CSKS1	Stripmap	Descending	Right	24	281	Acquired

Fig. 5. Image localization. Location of the frames of the CSK image acquired over the port of Genoa. Base map: Landsat ETM +.

Table 3
Characteristics of the images acquired for the Costa Concordia monitoring in the Genova harbor.

Date	Sensor	Mode	Pass	Look	Look angle (°)	Heading (°)	Status
20140727-0514	CSKS2	Spotlight-2	Ascending	Right	43	82	Acquired
20140727-1723	CSKS4	Spotlight-2	Descending	Right			Rejected

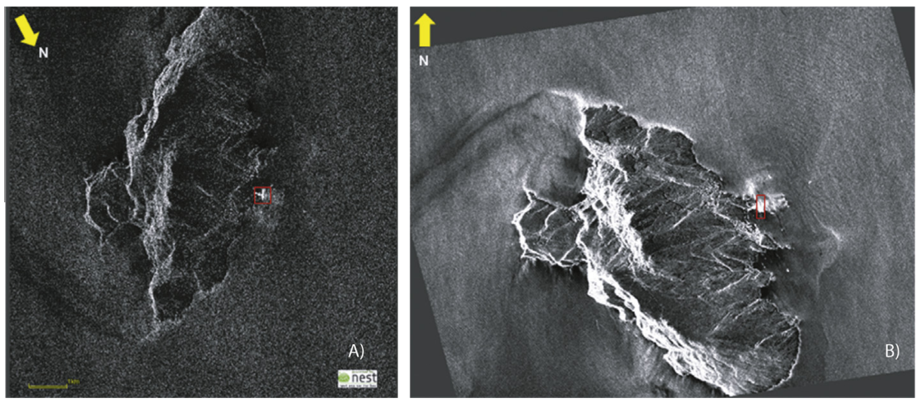

Fig. 6. Example of Spotlight image acquired on the Giglio Island. (A) Raw image; (B) multi-looked and reprojected image. The red rectangle represents the location of the wreck. No oil spill were detected. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Concordia away from the Giglio Island and the transportation of the vessel to the Genoa Voltri port. This monitoring was carried out not only by means of traditional techniques (e.g., sampling of the quality of the water and of physical properties such as temperature, salinity and turbidity), but also by using more sophisticated methods, such as remote sensed information.

The main risk during these last phases of the works on the Costa Concordia was related to the possible spill of remnant pollutant fluids, and to the sea water contamination after more than 2 years by the contact with the internal materials of the ship. It was first feared that spill of pollutants fluids and/or oil could occur, causing enormous damage to the Giglio Island, which is a much-beloved tourist location and part of a marine protected area.

These complex operations also led to international concerns because of the route of the vessel, between the Giglio Island and the Genova port, although being in the Italian territorial waters, passed very close to the French ones. There was a real concern for possible oil spill from the shipwrecked Costa Concordia that could contaminate the seawater and the coastlines along the convoy route.

In this framework the Civil Protection Department (the Italian authority in charge for the marine environmental protection) needed for a monitoring system with the following characteristics: (i) a proper recurrence time in data acquisition and (ii) reliable and fast outcomes for the detection of oil spill and illegal oil discharges from platforms and vessels according to the marine legislation and to the end-user (coast guards, meteorological centers, military organizations, weather services, environmental agencies) requirements. Thus the adopted methodology must deliver timely response to the environmental protection agencies and it must be standardized and fast.

To fulfill the end-user requirements the purpose of this monitoring system was twofold: (i) to perform a continuous monitoring of the Costa Concordia position both at the Giglio Porto harbor and during the travel route; (ii) to exclude that oil slicks illegally produced by other vessels could be attributed to the Costa Concordia transit. For this task the Civil protection Department requested the delivery of the results (bulletin) as soon as possible (no more than 6 h from the image acquisition) in order to prosecute illegal oil slicks.

2.3. Satellite Synthetic Aperture Radar for oil spill response

Remote sensing technologies are currently used for early detection, monitoring, and tracking of oil spills, and successful results have been largely documented (Sipelgas and Uiboupin, 2007; Topouzelis et al., 2008, 2009a; Ferraro et al., 2010, 2012; Shu et al., 2010; Singha et al., 2012, 2014; Fingas and Brown, 2014).

Among space-borne sensors, SAR is widely used in oil spill detection (Brekke and Solberg, 2005). The usefulness of SAR sensors, with respect to optical ones, is assured by their all-weather and all-day capability because they acquire independent of sun illumination and cloud cover conditions. The detection of oil slicks is possible thanks to the contrast between areas characterized by normal reflection of the radar pulse at capillary waves (known as sea clutter, which is usually "bright"), and areas occupied by oil which appear "dark" (reduction of sea clutter). If the quality of the acquired images, which depends on the calibration process (Vespe and Greidanus, 2012), is sufficient, and if acquisition parameters, such as the look angle, are appropriate and a wind field exists over the area of interest, then the contrast between sea clutter and reduced backscatter areas is often very clear. The limitations of these sensors depend on the fact that other phenomena may reduce surface backscattering producing a similar response in the SAR images (false positives). Such are, for instance, fresh water slicks, no wind areas, biogenic oils, algae (Tello et al., 2007; Topouzelis et al., 2007, 2009b; Mishra et al., 2011; Chaudhuri et al., 2012; Singha et al., 2012; Liu et al., 2013). An important parameter of the space-borne SAR data is represented by the revisit time, which corresponds to the time to repeat an image acquisition over a specific area, typically ranging from few to several days. This may often turn out to be too slow for an effective routinely use of oil spill monitoring. In fact, oil slicks are dynamic objects strongly affected by physical and

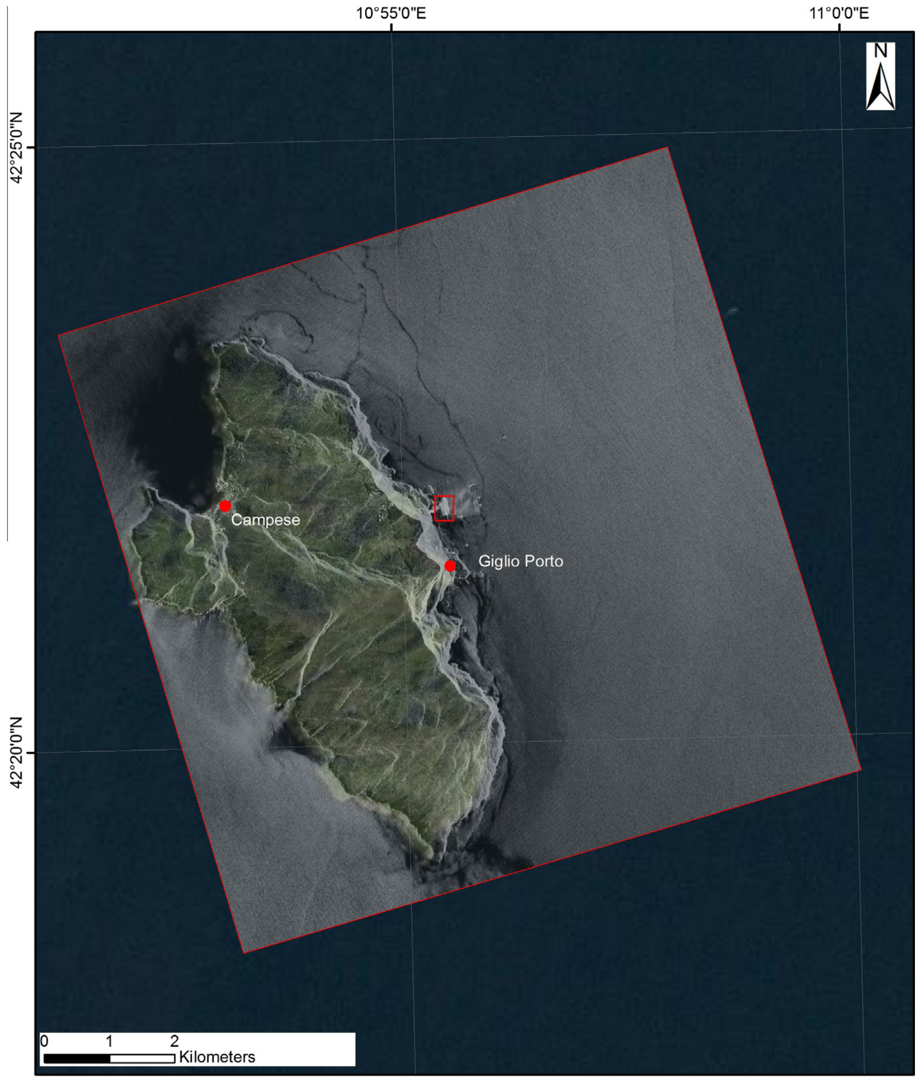

Fig. 7. Anomaly detection. Anomaly detected close to the Costa Concordia wreck in the CSKS1 image acquired in spotlight mode on the 19/07/2014 04:55 am. The red rectangle represents the location of the Costa Concordia. Base map: Landsat ETM +. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

environmental conditions (advection, spreading, evaporation, natural dispersion, emulsification, oil properties, wind speed and direction) (Wolfe, 1994; Nordvik, 1995; Reed et al., 1999; Brown and Fingas, 2003; Leifer et al., 2012). They typically evolve on an hourly to daily time-scale. The longer the revisit time the less effective is the spaceborne SAR approach. The maximum time during which useful data can be collected has been estimated to be 12 h to map oil on water and 6 h for legal and prosecution (Brown and Fingas, 2003). In addition, the intrinsic configuration of satellites may not be set for prompt modifications of the mission planning according to specific user requests as often required in risk management applications. On the other hand, the ability of the newest sensors to look right or left with respect to the satellite orbit may help to shorten the revisit time over a selected area.

Another important factor to consider in using SAR images for oil spill detection and mapping is the image spatial resolution. The minimum resolution required for the detection and mapping of large oil spill on water varies between 6 and 10 m, whereas 2 m resolution is required for small oil spill (Brown and Fingas, 2003).

The latest generation of space-based SAR has the ability to change the polarimetric mode of acquisition. In particular the VV antenna polarization (vertical for transmission and vertical for reception) is the best configuration for oil spill detection and mapping. The use of polarimetric SAR data may be also useful in discriminating oil slicks and false targets (Brown and Fingas, 2003; Leifer et al., 2012).

2.4. The monitoring system

With respect to the general context summarized in the previous section, the use of the CSK constellation of SAR satellites may bring a number of advantages. Time performances of the CSK constellation (in terms of the capacity of acquisition, revisiting and latency time) (Covello et al., 2008) and the feasibility of a continuous processing in an operational scenario were exploited during the different phases of the Concordia removal project to monitor potential spill of pollutant fluids and/or oil.

Moreover, the capability of the CSK system to timely convert the acquired raw data into the requested product (level 1_B, i.e. magnitude detected and map projected (ASI, 2007)) represents a main advantage in high-demanding operational situation. The flexibility of configuration, the capability of commanding the satellite to image a specific target area at a scheduled time are key features that make the CSK constellation ideally suited to support the

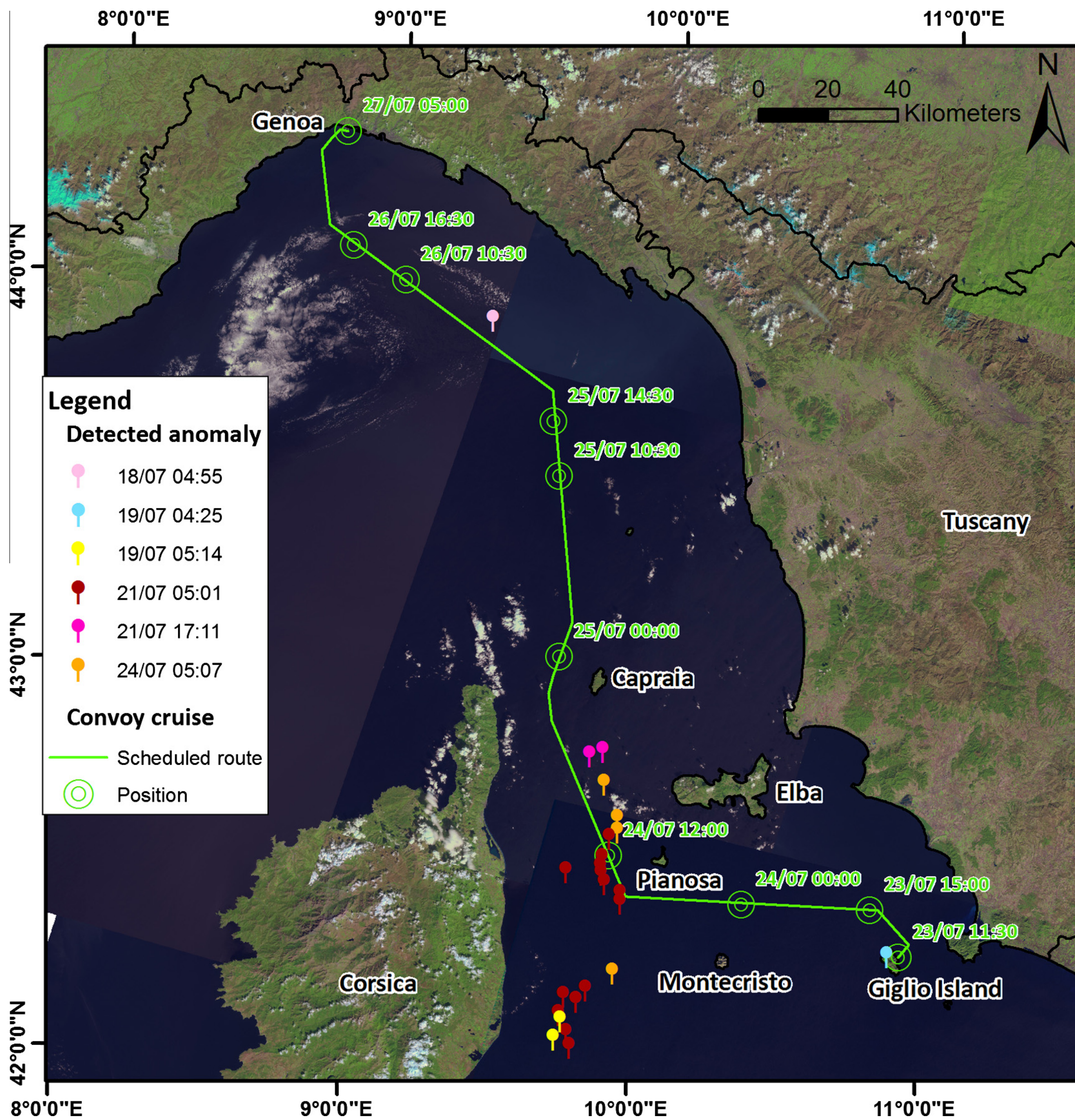

Fig. 8. Overview of the detected anomalies. The reported anomalies are probably related to the presence of oil slicks, during the monitoring of the removal operation, using CSK images acquired in stripmap mode. Base map: Landsat ETM +.

activities performed in the complex scenario generated by the Concordia refloating and removal project.

The CSK constellation is composed by four Low Earth Orbit mid-sized satellites equipped with a multi-mode high-resolution SAR operating at X-band. They can change their look mode acquiring both in left or right looking mode. CSK can acquire in different modalities: (i) ScanSAR which cover areas between $100 \times 100\ km^2$ and $200 \times 200\ km^2$ with a resolution of 30 m and 100 m, respectively; (ii) Stripmap characterized by $30 \times 30\ km^2$ or $40 \times 40\ km^2$ wide, with resolution of 3 m and 15 m, respectively; (iii) Spotlight acquires images $10 \times 10\ km^2$ wide with 1 m of resolution.

Following the official requests of the end-user (Italian Department of Civil Protection), the Italian Space Agency (ASI) switched the Italian Synthetic Aperture Radar (SAR) constellation CSK to "crisis" mode in order to acquire images of the Costa Concordia liner cruise and of the sector of the sea along the last voyage from Giglio Porto to Genoa. The images, made available by the CIMA Research Foundation (International Centre on Environmental Monitoring) 2 h after the acquisition, were processed and analyzed by the Earth Sciences Department of the University of Firenze (UNIFI-DST), in collaboration with the Joint Research Centre Institute for the Protection and Security of the Citizen (JRC-IPSC) of the European Commission. This task required about 3 h. The aim was to produce and interpret SAR-based products, delivered daily to the Italian Civil Protection after 1 h from the interpretation of the results. The complete procedure, from the image acquisition to the delivery of the bulletin, takes about 6 h.

The constellation was tasked to acquire images with the lowest look angle, more effective for oil spill detection. Nevertheless, all the available images were used in order to reduce the revisiting time, even those acquired with less steeper incident angle. The monitoring was performed using a set of VV polarized images acquired in Spotlight mode during the refloating phase of the vessel in the Giglio Island and the parking in the Genova port, and in Stripmap mode to cover the area of the route. The speckle effect was reduced by using a multi-looking algorithm at 10 looks (Migliaccio et al., 2007) which is useful for oil spill detection

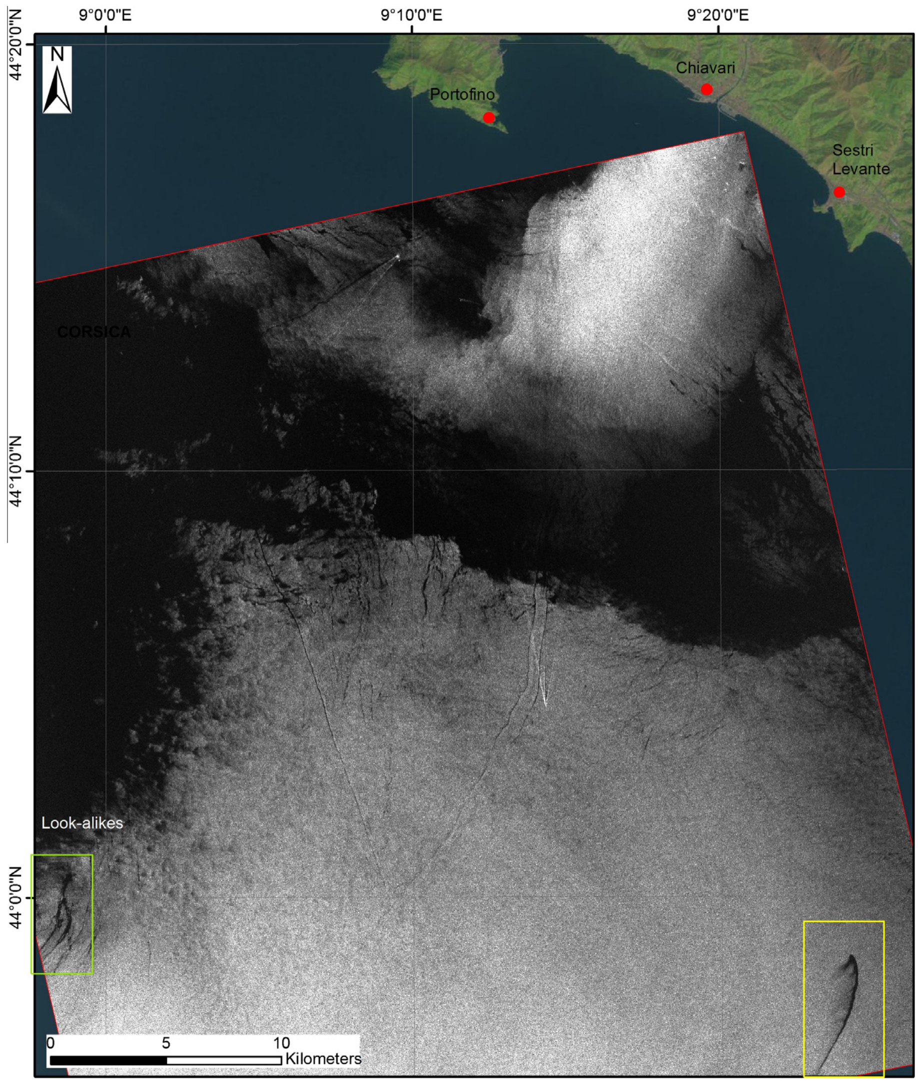

Fig. 9. Anomaly detection. Oil slick detected in the 18th of July off the Ligurain coast (yellow rectangle) and an example of look-alike (green rectangle). Base map: Landsat ETM +. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Vespe et al., 2011). The problems related to the false positives can be solved in many cases considering that oil has specific shapes and textures over look-alikes allowing to discriminating slicks (Mishra et al., 2011; Chaudhuri et al.,2012).

After multi-looking and land-masking, the SAR images are segmented on the basis of brightness and contrast parameters. This phase enables the isolation of dark spots in the image. This is followed by the feature extraction process (see e.g. Singha et al., 2013), that is the calculation of properties related the dark spot geometry (e.g. shape, area, perimeter, etc.), backscatter statistics (e.g. mean and standard deviation), and context within the image (e.g. low wind conditions, distance to ships, etc.). These features are then tested against predefined values that enable the automatic classification of dark formations into look-alike and potential oil spills. The full processing chain is described in Topouzelis et al. (2015).

The methodology was implemented to detect two different types of oil spills, one related to potential leakages from the Concordia, the other due to deliberate discharges from ships transiting the area. This distinction was necessary in order to unambiguously understand the origin of the detected spills. Oil spills from the Concordia were expected to appear as amorphously shaped fresh oil slicks. Conversely, deliberate discharges from ships sailing in the area were expected to appear as less fresh oil, released at higher speeds and therefore presenting elongated shape distorted by local currents and surface wind fields.

Given the complexity of the task in distinguishing between the above mentioned categories of spill, the automatic classification was always followed by a verification stage performed by expert operators.

The monitoring of the oil spill related to the refloating and removal of the Costa Concordia from the Giglio Island to the Genova port was performed planning 12 acquisitions on Giglio Island (Fig. 3 and Table 1), 22 acquisitions along the route (Fig. 4 and Table 2) and 2 acquisitions at Genova port (Fig. 5 and Table 3). Some of them were rejected, but a total of 27 images in 13 days were acquired and analyzed. The images were acquired by all four CSK satellites, either in ascending and descending pass and using spotlight and stripmap modes, respectively in harbor or open sea areas. Moreover, the images were formed from right or left looking sides and with angles ranging from 19° to 51°. This demonstrated the significant flexibility of the constellation showing the full potential of the system also for this specific monitoring operation.

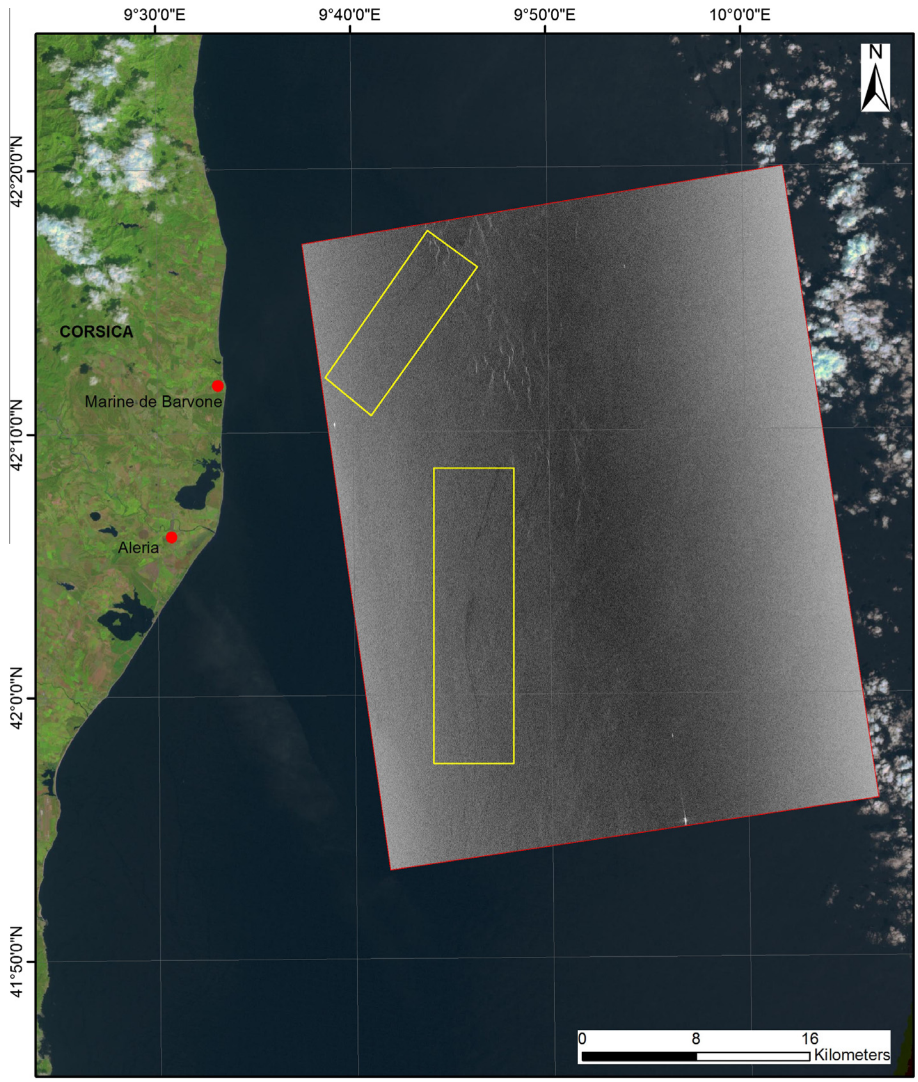

Fig. 10. Anomaly detection. The two anomalies detected along the Corsica east coast on the 19th July 2014. Base map: Landsat ETM +.

3. Results

The oil spill monitoring performed during the refloating phase started the 15th of July 2014. Seven Spotlight images acquired using the CSKS1 and CSKS2 sensors were used (Fig. 6) in order to evaluate the presence of possible spillage of pollutant materials from the ship, as consequence of the works. The monitoring of the refloating phase was performed both in the area where the vessel was located and in the neighboring areas. During this phase no relevant spillages of pollutant materials were detected. The last Spotlight image was acquired on 20th July of 2014 when the removal of the ship was expected. Actually the removal started 3 days later. This gap was due to the adverse weather conditions. Despite the gap, the monitoring continued using the Stripmap acquisition mode.

After the visual inspection of the processed CSKS1 image acquired in spotlight mode on Giglio Island on 19th of July 04:25 am, an anomaly, characterized by a filamentous pattern, was detected in correspondence with the Costa Concordia wreck and the neighborhood (Fig. 7). This anomaly was not related to an oil spill. The pattern suggests a natural origin. Following the delivery of the bulletin a suggested inspection of the area by a vessel definitely excluded the presence of oil on the sea surface.

Starting from the 17th of July 2014 the oil spill monitoring was extended to the route between the Giglio Island and the Genova port (Fig. 8), before the ship convoy transit, to detect the presence of oil slicks that could have been incorrectly charged to the Costa Concordia. The monitoring along the route ended the 27th of July 2014. During this period 25 anomalies in the analyzed SAR images, potentially related to oil slicks, were recognized and reported in the daily bulletin. In some cases the slick was associated to a specific vessel in its proximity, potentially originating the spill.

The first detection of an oil slick located along the route of the Costa Concordia wreck occurred in the CSKS1 image acquired on the 18th July 04:55 am off the Ligurian coast (Fig. 9). The detected slick is obviously not related to the refloating and removal activities since at the moment of the acquisition the Costa Concordia was still in Giglio Porto. The slick is 6.5 $\times$ 1 km wide and its shape is typical of an oil spill action, shaped by the currents and spread by action of local surface wind waves and water turbulence. After the oil slick identification the Coast Guard was promptly activated by the Civil Protection Department and tasked to identify the vessel responsible of the oil spill.

During the monitoring of the future route of the Costa Concordia convoy the area most affected by illegal oil spill action was

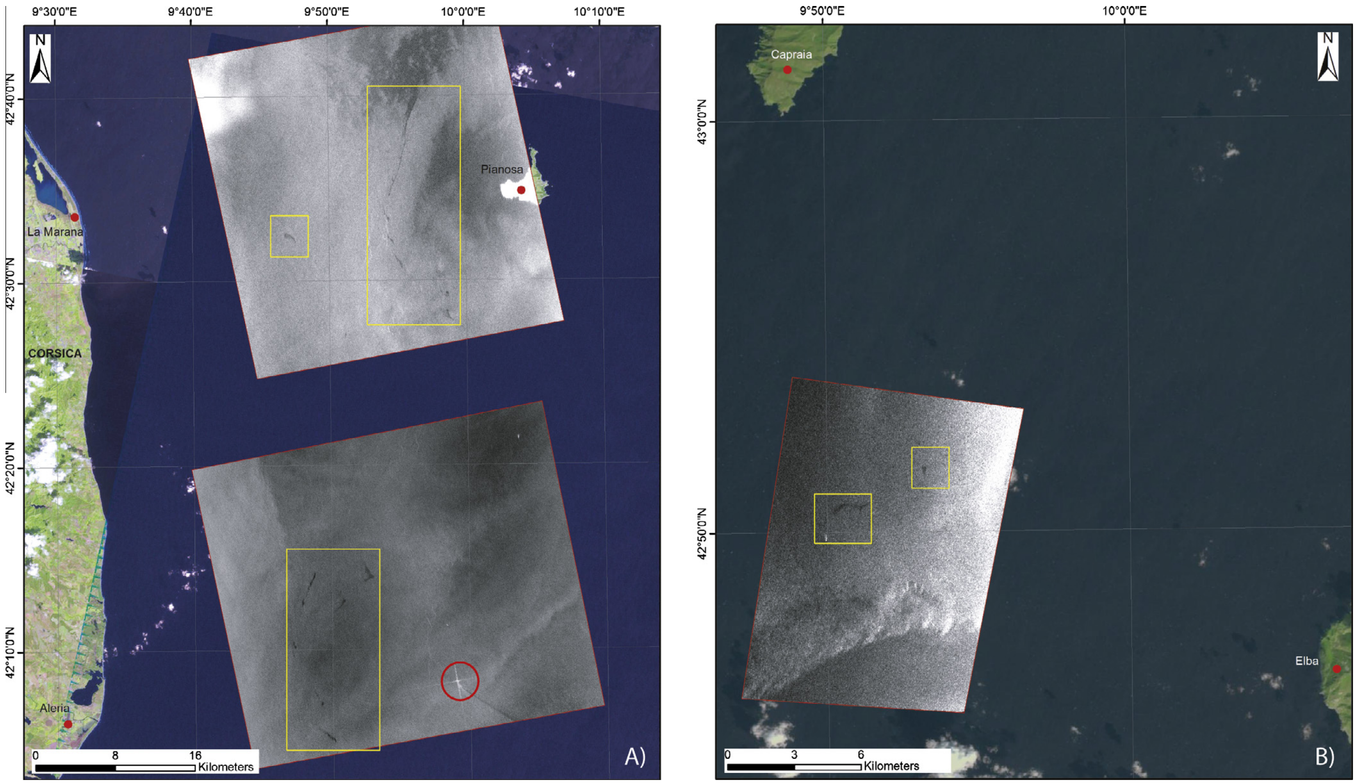

Fig. 11. Anomaly detection. Some subset of the CSKS acquired in stripmap mode on the 21st of July where several anomalies are clearly detectable. The figure (A) shows some of the recognized oil slicks and the position of the Costa Concordia convoy (in the red circle). In the figure (B) is the presence of the vessel directly linked to the slick is evident. Base map: Landsat ETM +. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

located between the east coast of Corsica Island and the Tuscan archipelago.

The image CSKS1 acquired on 19th July 05:14 shows the presence of two anomalies located along the east coast of Corsica Island between Ghisonaccia and Cervione. In this case the quality of the acquired image was not optimal for oil spill detection. The contrast between the sea and the slicks is not sharp and well defined leaving doubt regarding the origin of the recognized anomalies (Fig. 10). This is mainly due to the high incidence angle for this acquisition.

The most critical situation occurred on 21st of July when two different images were acquired. The first one at 05:00 a.m., whereas the second one was observed at 05:11 p.m. Both images clearly show several anomalies that can be related to the presence of oil slicks (Fig. 11). One of the recognized oil spills is about 22 km long. The confidence level (see e.g. (Ferraro et al., 2010)) is assured considering the contrast between "bright" and "dark" areas, the shape of the slicks and, in one case, the presence of a vessel directly connected to the slick.

All the slicks recognized till now are undoubtedly not linked to the refloating of the Costa Concordia because of the distance from Giglio Porto and to the removal phase because they were acquired before the wreck leaving the Giglio Island.

The last interesting image was acquired on 24th of July, during the passage of the convoy close to Pianosa Island (Fig. 12). Also on this date three well defined anomalies were detected. The southern one is most likely an oil slick with the potential offender directly linked. It is worth noting that the vessel can be identified using self-reporting tracking systems such as Automatic Identification System data. Other two possible oil slicks were recognized northwest of Pianosa (Fig. 12). Also in these cases considering the shape and the contrast between the slick and the gray surroundings the detected anomalies can be considered as oil slick. All the reported slicks were not connected to the Costa Concordia convoy, which is visible in the image (the red circle) as it is located far from the slicks.

4. Discussion and conclusion

The refloating and removal operation of the Costa Concordia ship represents an unprecedented scenario considering the tonnage (114,137 gross registered tonnage) and the dimension (290 m and 13 decks) of the ship. At the moment of the wreckage there were 2400 tons of fuel oil stored inside the tanks and other several different pollutant fluids (e.g. engine oil, alimentary oil, soap). Most of these fluids, potentially dangerous for the marine environment, were removed before the par buckling phase, after the sealing of the leaks that occurred when the ship struck a rock (the Scola Piccola).

SAR satellite data are commonly used in order to detect illegal oil spillage actions over the sea. Images acquired by SAR satellites can cover wide areas under all-weather conditions. The main problem related to a routine use of space-borne SAR images, in order to prepare a monitoring system of a naval convoy, is represented by the revisit time of the satellite. In addition also the necessary time for the removal operation had to be considered, which was estimated to 5 days. For example the minimum revisit time of the X-band sensor TerraSAR-X is 2.5 days. The use of the CSK constellation allowed shortening the revisit time to less than 12 h over the same area making possible the effective use of radar satellite images for the monitoring of wide areas in support to the ongoing operation.

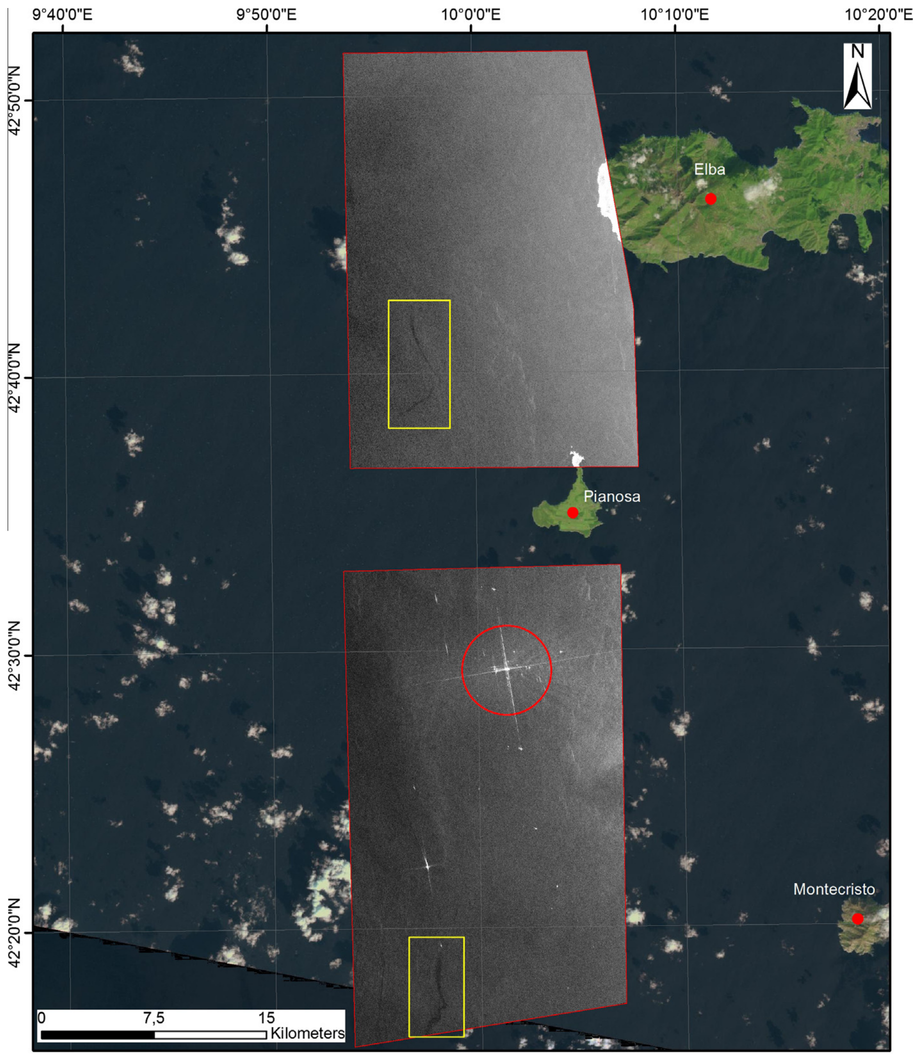

Fig. 12. Anomaly detection. Detected oil slicks in the image acquired on the 24th of July. The red circle represents the location of the Costa Concordia convoy at the moment of the acquisition. Base map: Landsat ETM +. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A near real time product generation by means of satellite SAR sensors to support and help end users activity is today a challenging task. The near real time, as requested by the end-user, was assured by using the COSMO-SkyMed constellation which acquired an average of two images per day. An average of 6 h was necessary between the image acquisitions and the delivering of the results to the end-users. For the first time the flexibility of use and time performance (in terms of revisiting time and timeliness of delivery) of the CSK constellation have been exploited as monitoring tool in a real operational scenario. The reliability of the adopted methodology relies on the literature on remote sensing with specific focus on SAR based oil spill detection. In doing this, we have applied scientifically sound and robust well known methodologies to guarantee a correct image interpretation and a reliable oil spill detection and standardized products.

Considering the limitations in the detection of oil pollution using radar images, such as the possible presence of look-likes, the CSK shows performance in line with other sensors currently available. The available techniques to solve or mitigate the problem, namely considering the typical signature of oil spills from ship discharge and, in some cases, the presence of the vessel potentially linked to the slicks, can be also effectively implemented.

In conclusion the reported activities achieve two important results. First, the designed oil spill detection monitoring system, using the CSK constellation, represents a robust methodology which can be profitably used to monitor single ship or naval convoy in case of emergency over wide areas and with a suitable temporal coverage. The adopted and described procedure can be used as guideline for future similar events. For example it can be used to monitor the evolution of ship or platform accidents, causing oil spill, that need a near real time response and a reduced temporal revisit time. The near real time response, in case of disasters, can be limited to 30 min from the SAR image acquisition.

The second important result produced by the designed monitoring system is the demonstration that the refloating and removal phases of the Costa Concordia were a success. No pollution was produced during these phases. Several anomalies were recognized during the monitoring period but none of these can be related to the transit of the ship convoy. Results also confirm that the northern Tyrrhenian and the Ligurian Seas are still potentially affected by frequent and consistent illegal discharge of oil even though the area is located inside of the whale sanctuary, a marine protected area since the 1991.

Acknowledgments

The authors are grateful to the Italian Space Agency (ASI), and in particular Laura Candela, for providing the COSMO-SkyMed data.

We are also grateful to the Italian Civil Protection Department team (Silvano Meroi, Paola Pagliara, Chiara Proietti, Roberta Onori) that supported this work. We thank two anonymous reviewers for their suggestions which greatly improved this work.

References

ASI, Italian Space Agency, 2007. COSMO SkyMed SAR Products Handbook, 103 pp. <http://www.cosmo-skymed.it/docs/ASI-CSM-ENG-RS-092-A-CSKSARProductsHandbook.pdf>.

Bernardini, A., Ferraro, G., Meyer-Roux, S., Sieber, A., Tarchi, D., 2005. Atlante dell'inquinamento da idrocarburi nel Mare Adriatico. European Commission, EUR 21767 IT, 2005.

Brekke, C., Solberg, A.H.S., 2005. Oil spill detection by remote sensing. Remote Sens. Environ. 95, 1–13.

Broussolle, J., Kyovtorov, V., Basso, M., Ferraro di Silvi, E., Castiglione, G., Figueiredo Morgado, J., Giuliani, R., Oliveri, F., Sammartino, P.F., Tarchi, D., 2014. MELISSA, a new class of ground based InSAR system. An example of application in support to the Costa Concordia emergency. ISPRS J. Photogram. Remote Sens. 91, 50–58.

Brown, C.E., Fingas, M.F., 2003. Synthetic Aperture Radar Sensors: Viable for Marine Oil Spill Response? 26th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, Environment Canada, Victoria, Canada.

Chaudhuri, D., Samal, A., Agrawal, A., Sanjay, A., Mishra, A., Gohri, V., Agarwal, R.C., 2012. A statistical approach for automatic detection of ocean disturbance features from SAR images. IEEE J. Select. Topics Appl. Earth Observ. Remote Sens. 5 (4), 1231–1242.

Covello, F., Battazza, F., Coletta, A., Lopinto, E., Fiorentino, C., Pietranera, L., Valentini, G., Zoffoli, S., 2008. COSMO-SkyMed an existing opportunity for observing the Earth. J. Geodin. 49 (3–4), 171–180.

Ferraro, G., Bernardini, A., Meyer-Roux, S., Tarchi, D., 2006. Satellite monitoring of illicit discharges from vessels in the French environmental protection zone (ZPE), 1999–2004. European Commission, EUR 22158 EN.

Ferraro, G., Baschek, B., de Montpellier, G., Njoten, O., Perkovic, M., Vespe, M., 2010. On the SAR derived alert in the detection of oil spills according to the analysis of the EGEMP. Mar. Pollut. Bull. 60 (1), 91–102.

Ferraro, G., Trieschmann, O., Perkovic, M., Tarchi, D., 2012. Confidence levels in the detection of oil spills from satellite imagery: from research to the operational use. Proc. SPIE – Int. Soc. Opt. Eng. 8536, 85360G.

Fingas, M., 2001. The Basics of Oil Spill Cleanup. Lewis Publishers, 286 p.

Fingas, M., Brown, C., 2014. Review of oil spill remote sensing. Mar. Pollut. Bull. 83, 9–23.

Huijer, K., 2005. Trends in Oil Spills from Tanker Ships 1995–2004. In: Proceedings of the Twenty-eighth Arctic and Marine Oilspill Program (AMOP) Technical Seminar, Calgary, Canada, 7–9 June 2005. pp. 319–332.

ITOPF (International Tanker Owners Pollution Federation). Statistical information available from <http://www.itopf.com/>.

Leifer, I., Lehr, W.J., Simecek-Beatty, D., Bradley, E., Clark, R., Dennison, P., Hu, Y., Matheson, S., Jones, C.E., Holt, B., Reif, M., Roberts, D.A., Svejkovsky, J., Swayze, G., Wozencraft, J., 2012. State of the art satellite and airborne marine oil spill remote sensing: application to the BP Deepwater Horizon oil spill. Remote Sens. Environ. 124, 185–209.

Liu, L., Cui, X., Chen, M., Sun, Y., 2013. Marine oil spill detection in SAR image based on mathematical morphology. Appl. Mech. Mater. 256–259, 2320–2323.

Migliaccio, M., Ferrara, G., Gambardella, A., Nunziata, F., Sorrentino, A., 2007. A physically consistent stochastic model to observe oil spills and strong scatterers on SLC SAR Images. Int. Geosci. Remote Sens. Sympos. (IGARSS) 4423049, 1322–1325.

Mishra, A., Chaudhuri, D., Bhattacharya, C., Rao, Y.S., 2011. Ocean disturbance feature detection from SAR images – an adaptive statistical approach. In: 3rd International Asia-Pacific Conference on Synthetic Aperture Radar, APSAR 2011 (6087017), pp. 163–166.

Nordvik, A.B., 1995. The technology windows-of-opportunity for marine oil spill response as related to oil weathering and operations. Spill Sci. Technol. Bull. 2, 17–46.

Pavlakis, P., Tarchi, D., Sieber, A., Ferraro, G., Vincent, G., 2001. On the monitoring of illicit discharges – a reconnaissance study in the Mediterranean Sea. European Commission, EUR 19906 EN.

Raspini, F., Moretti, S., Fumagalli, A., Rucci, A., Novali, F., Ferretti, A., Prati, C., Casagli, N., 2014. The COSMO-SkyMed Constellation monitors the Costa Concordia wreck. Remote Sens. 6, 3988–4002.

Reed, M., Johansen, Ø., Brandvik, P.J., Daling, P., Lewis, A., Fiocco, R., Mackay, D., Prentky, R., 1999. Oil spill modeling towards the close of the 20th century: overview of the state of the art. Spill Sci. Technol. Bull. 5, 3–16.

Regoli, F., Pellegrini, D., Cicero, A.M., Nigro, M., Benedetti, M., Gorbi, S., Fattorini, D., D'Errico, G., Di Carlo, M., Nardi, A., Gaion, A., Scuderi, A., Giuliani, S., Romanelli, G., Berto, D., Trabucco, B., Guidi, P., Bernardeschi, M., Scarcelli, V., Grenzilli, G., 2014. A multidisciplinary weight of evidence approach for environmental risk assessment at the Costa Concordia wreck: integrative indices from Mussel Watch. Mar. Environ. Res. 96, 92–104.

REMPEC, 2002. Protecting the Mediterranean against maritime accidents and illegal discharges from ships. Malta, 2002.

Schröder-Hinricks, J., Hollnagel, E., Baldauf, M., 2012. From Titanic to Costa Concordia – a century of lessons not learned. WMU J. Marit. Affairs 11, 151–167.

Shu, Y., Li, J., Yousef, H., Gomes, G., 2010. Dark-spot detection from SAR intensity imagery with spatial density thresholding for oil-spill monitoring. Remote Sens. Environ. 114 (9), 2026–2035.

Singha, S., Bellerby, T.J., Trieschmann, O., 2012. Detection and classification of oil spill and look-alike spots from SAR imagery using an artificial neural network. Int. Geosci. Remote Sens. Sympos. (IGARSS) 6352042, 5630–5633.

Singha, S., Vespe, M., Trieschmann, O., 2013. Automatic Synthetic Aperture Radar based oil spill detection and performance estimation via a semi-automatic operational service benchmark. Mar. Pollut. Bull. 73, 199–209.

Singha, S., Velotto, D., Lehner, S., 2014. Near real time monitoring of platform sourced pollution using TerraSAR-X over the North Sea. Mar. Pollut. Bull. 86 (1–2), 379–390.

Sipelgas, L., Uiboupin, R., 2007. Elimination of oil spill like structures from radar image using MODIS data. Int. Geosci. Remote Sens. Sympos. (IGARSS) 4422822, 429–431.

Tarchi, D., Bernardini, A., Ferraro, G., Meyer-Roux, S., Muellenhoff, O., Topouzelis, K., 2006. Satellite monitoring of illicit discharges from vessels in the seas around Italy 1999–2004. Eur. Commission, EUR 22190 EN.

Tello, M., Bonastre, R., Lopez-Martinez, C., Mallorqui, J.J., Danisi, A., 2007. Characterization of local regularity in SAR imagery by means of multiscale techniques: application to oil spill detection. Int. Geosci. Remote Sens. Sympos. (IGARSS), 5228.

Topouzelis, K., Karathanassi, V., Pavlakis, P., Rokos, D., 2003. Oil spill detection: SAR multi-scale segmentation and object features evaluation. In: 9th International Symposium on Remote Sensing (SPIE), pp. 77–87. doi: 10.1117/12.462518.

Topouzelis, K., Karanthanassi, V., Pavlakis, P., Rokos, D., 2007. Detection and discrimination between oil spills and look-alike phenomena through neural networks. ISPRS J. Photogram. Remote Sens. 62 (4), 264–270.

Topouzelis, K., Karanthanassi, V., Pavlakis, P., Rokos, D., 2008. Dark formation detection using neural networks. Int. J. Remote Sens. 29 (16), 4705–4720.

Topouzelis, K., Stathakis, D., Karanthanassi, V., 2009a. Investigation of genetic contribution to feature selection for oil spill detection. Int. J. Remote Sens. 30 (3), 611–625.

Topouzelis, K., Karanthanassi, V., Pavlakis, P., Rokos, D., 2009b. Potentiality of feedforward neural networks for classifying dark formation to oil spills and lookalikes. Geocarto Int. 24 (3), 179–191.

Topouzelis, K., Tarchi, D., Vespe, M., Posada, M., Muellenhoff, O., Ferraro, G., 2015. Detection, Tracking, and Remote Sensing: Satellites and Image Processing (Spaceborne Oil Spill Detection). Handbook of Oil Spill Science and Technology, 2015.

Vespe, M., Ferraro, G., Posada, M., Greidanus, H., Perkovic, M., 2011. Oil spill detection using COSMO-SkyMed over the adriatic sea: the operational potential. Int. Geosci. Remote Sens. Sympos. (IGARSS), 4403–4406.

Vespe, M., Greidanus, H., 2012. SAR image quality assessment and indicators for vessel and oil spill detection. IEEE Trans. Geosci. Remote Sens. 50, 4726–4734.

Wolfe, D.A., 1994. The fate of the oil spilled from the Exxon Valdez. Environ. Sci. Technol. 28 (13), 561–567.