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Article

The COSMO-SkyMed Constellation Monitors the Costa Concordia Wreck

Federico Raspini [1,*], Sandro Moretti [1], Alfio Fumagalli [2], Alessio Rucci [2], Fabrizio Novali [2], Alessandro Ferretti [2], Claudio Prati [3] and Nicola Casagli [1]

1 Earth Sciences Department, University of Firenze, Via La Pira, 4, I-50121 Firenze, Italy; E-Mails: sandro.moretti@unifi.it (S.M.); nicola.casagli@unifi.it (N.C.)
2 Tele-Rilevamento Europa T.R.E. s.r.l., Ripa di Porta Ticinese 79, I-21149 Milan, Italy; E-Mails: alfio.fumagalli@treuropa.com (A.F.); alessio.rucci@treuropa.com (A.R.); fabrizio.novali@treuropa.com (F.N.); alessandro.ferretti@treuropa.com (A.F.)
3 Dipartimento di Elettronica, Informazione e Bioingegneria, Polytechnic University of Milan, Milan 20133, Italy; E-Mail: prati@elet.polimi.it

* Author to whom correspondence should be addressed; E-Mail: federico.raspini@unifi.it; Tel.: +39-55-275-7548; Fax: +39-55-275-6323.

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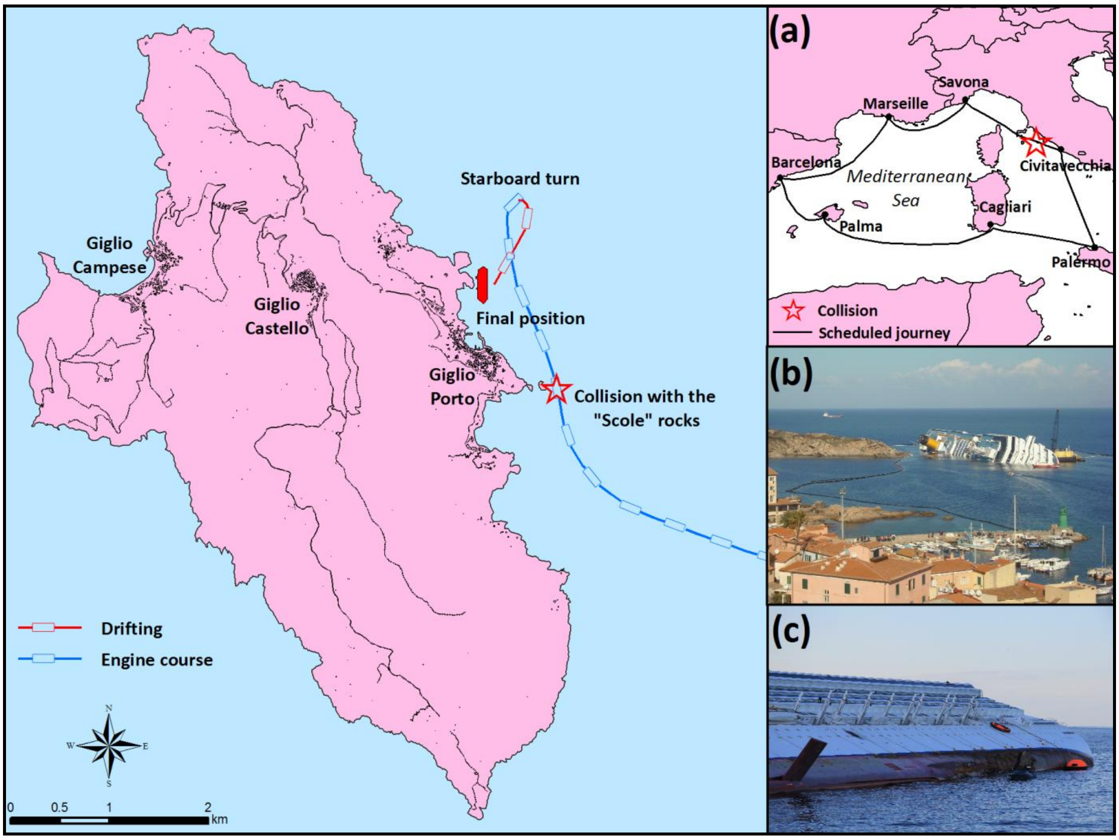
Abstract: On 13 January 2012, the Italian vessel, Costa Concordia, wrecked offshore Giglio Island, along the coast of Tuscany (Italy). The ship partially sunk, lying on the starboard side on a 22° steep rocky seabed, making the stability conditions of the ship critically in danger of sliding, shifting and settling. The tilted position of the ship created also pernicious conditions for the divers involved in the search and rescue operations. It became immediately clear that a continuous monitoring of the position and movements of the ship was of paramount importance to guarantee the security of the people working around and within the wreck. Starting from January 19, the Italian constellation of synthetic aperture radar (SAR) satellites, COSMO-SkyMed (CSK), was tasked to acquire high resolution images of the wreck. Thanks to CSK's short response and revisiting time and its capability to acquire high resolution images in Spotlight mode, satellite data were integrated within the real time, ground-based monitoring system implemented to provide the civil protection authorities with a regular update on the ship stability. Exploitation of both the phase (satellite radar interferometry, InSAR) and amplitude (speckle tracking) information from CSK images, taken along the acquisition orbit, Enhanced Spotlight (ES)-29, revealed a general movement of the translation of the vessel, consistent with sliding toward the east of the hull on the seabed. A total displacement, with respect to the coastline, of 1666 mm and 345 mm of the bow and stern, respectively, was recorded, over the time period of 19 January–23 March 2012.

Keywords: Costa Concordia wreck; COSMO-SkyMed; InSAR; speckle tracking; displacement monitoring; risk management; data downstream service

1. Introduction

The Costa Concordia cruise ship, with 3206 passengers and 1023 crew members on board, was sailing off Giglio Island on the night of 13 January 2012, having begun a planned seven-day cruise from Civitavecchia to Savona and five other ports in the Mediterranean Sea. At around 21:45 local time, after having changed the scheduled course to pass near Giglio Island, the ship struck its portside on a reef. The reef is charted as an area known as Le Scole, about 800 meters south of the entrance to the harbor of Giglio Porto, on the island's east coast (Figure 1). The initial impact was at a point eight meters below the water at "Scola piccola", the most seaward exposed rock of Le Scole, which tore a 50-meter gash in the ship's portside below the water line. The impact sheared from the ship's hull two long strips of steel, later found on the seabed 92 to 96 m from the main island. The ship has a large boulder embedded in the hull at the aft end of the impact gash.

Figure 1. Collision path of Costa Concordia. Planned course in the Mediterranean Sea (**a**). Vessel view from Giglio Porto (**b**). View of the port side of the vessel (**c**).



As the water flowed through the gash, the ship started to drift and heel over, partially sinking in the shallow water in front of Punta Gabbianara, north of the harbor of Giglio Island, lying on the starboard side with an inclination of almost 65° on a 22° steep seabed. Within few hours of the evacuation order, most of the passengers on board were rescued. Search and rescue (SaR) operations of missing people, including salvage at sea and the search for persons trapped in the submerged and emerged parts of the wreck, became of vital importance and began immediately after the disaster under the guidance of the Italian Fire Brigade and Coast Guard.

Sunlight revealed the critical stability conditions of the ship, in danger of sliding, shifting and settling. An underwater survey confirmed the unstable position of the wreck, resting precariously on two granite teeth, creating also pernicious conditions, especially for the divers involved in the SaR operations in the interstices between the rocky bottom and the hull of the wreck. Moreover, the increasing depth of the granite slope below the Concordia exacerbated the instability conditions of the wreck and was expected to cause the complete sliding and sinking of the ship in the case of adverse sea and weather conditions.

On 20 January 2012, the Italian Council of Ministers officially declared a National State of emergency on Giglio Island and the Head of the Civil Protection Department (DPC) was appointed Delegate Commissioner by an ordinance of the Prime Minister.

Following the official request of the DPC, the Italian Synthetic Aperture Radar (SAR) constellation, COSMO-SkyMed (CSK), was tasked to acquire Spotlight high resolution images in "very urgent mode" [1], in order to guarantee a very short response time, allowing the monitoring of Giglio Island and the wreck.

Starting from this date, T.R.E. (Tele-Rilevamento Europa, a spin-off company of the Polytechnic University of Milano) and the Polytechnic University of Milano, in collaboration with the Center of Competence of the Earth Sciences Department of the University of Firenze (UNIFI-DST), started the monitoring of the movement of the Costa Concordia vessel by generating SAR-based products to support the emergency management. Radar satellite information was integrated into a sophisticated ground-based real-time warning system, coordinated by UNIFI-DST and fully operational a few hours after the request of the DPC. In the first phase of the emergency, nine different technologies were used to measure different components of the ship movements, namely: two onboard accelerometers, two robotic total stations, a ground-based SAR interferometer [2], satellite SAR sensors, a terrestrial laser scanner, three microseismic stations, GPS antenna and receivers, an underwater extensometer and underwater markers.

This innovative monitoring system was designed and implemented to provide robust, reliable and up-to-date data on any ship movements to the crisis unit of the DPC. This information was of vital importance to guarantee safety during maritime and defueling operations and to mitigate risks during the on-board SaR activities, providing alerts in case of the anomalous acceleration of the wreck, leading, at different times, to the emergency evacuation of the SaR operators.

This paper is aimed at presenting an exploitation of Earth observation data in an operational scenario, describing a product tailored for a specific situation and for a specific end user. In emergency situations, dealing with space-borne sensors, the main limiting factor to be overcome is the time to "refresh" a single image. The best refreshing time (which corresponds to the revisit time of satellite) is in the order of hours in the case of the COSMO-SkyMed (CSK) constellation. The main idea behind the exploitation of CSK images for monitoring the movements of the Concordia vessel was to test the time performances of the emergency mode of the CSK constellation (in terms of the capacity of acquisition, revisiting and latency time) and the feasibility of daily processing in an operational scenario. The activities carried out during the operations in Giglio Island have provided the perfect opportunity to extensively test these capabilities in a real and high-demanding operational situation. In other words, the main purpose of the presented application was to take a step beyond in the current state-of-the-art in the exploitation of SAR products, mainly relying on the use of the pre-existing SAR archive to analyze geo-hazard-related ground motions that had already occurred.

2. SAR Data and Processing Methods

The COSMO-SkyMed (Constellation of small Satellites for Mediterranean basin Observation (CSK)) [1,3] mission is a dual-use system [4] (*i.e.*, intended for both civil and military purposes), funded and developed by the Italian Ministry of Defense and the Italian Space Agency (ASI). The system is a constellation of four sun-synchronous satellites, each carrying an X-band high-resolution SAR sensor, with the capability to acquire images in both left and right looking mode, with off-nadir angles ranging from 16° to 51° at near range.

The CSK system has basically three types of imaging modes: Spotlight, Stripmap and ScanSAR. Each mode is specifically designed to acquire a target area with different swaths and resolutions, to fit the specific needs requested in different application fields, ranging from basin-scale mapping to localized emergency situations. In particular, the Spotlight-2 (Enhanced Spotlight, ES) mode provides a resolution of about 40 cm in slant range and 70 cm in azimuth, focusing on a scene only a few square kilometers wide (10 km^2).

The high resolution and unprecedented response and revisit time (two hours in the best situation [1]) provided by the full constellation are key features that make the CSK constellation ideally suited to support emergency management in the unique context generated by the Costa Concordia wreck.

During the Costa Concordia monitoring activities in the early phase of the emergency, different datasets were acquired by the CSK system on Giglio Island along different tracks, with different geometries and incidence angles. In total, thirty-six synthetic aperture radar images, acquired from 19 January 2012 to 24 March 2012, in Enhanced Spotlight imaging mode, have been collected and processed (Table 1).

The ES imaging mode includes 39 different acquisition beams (ES-0, ES-1, *etc.*). These beams are available for both right-and left-looking mode. The difference between ES-29 and other beams is basically the off-nadir angle at near and far range, which gradually increases (e.g., the off nadir angle is *ca*. 18.5° and 51.5° for ES-0 and ES-35, respectively).

SAR data analysis was mainly focused on two objectives:

(1) Detect any movement of the ship with respect to the Giglio Island coastline;
(2) Detect any deformation of the ship that could represent a risk for the structural integrity of the vessel.

To achieve these targets, both amplitude and phase values of the available SAR images were processed, through the use of speckle tracking [5] and Differential Interferometry (DInSAR) [6].

Amplitude information was exploited through the approach usually referred to as speckle tracking, a method used to estimate the slant range and azimuth offset fields of two SAR images. The slant range direction corresponds to the satellite line of sight (LOS), while the azimuth direction is parallel to the satellite orbit. Usually, the offset fields are obtained from a normalized cross-correlation of small patches of two SAR amplitude images.

Table 1. List of COSMO-SkyMed images acquired for the monitoring activity. In bold is the geometry acquisition Enhanced Spotlight (ES)-29.

Date and (Time) of Acquisition	Satellite	Track	Acquisition Mode	Geometry	Look
19 January 2012 (18:18)	**SAR4**	**158**	**ES-29**	**D**	**Left**
20 January 2012 (05:13)	SAR4	165	ES-22	A	Right
22 January 2012 (05:07)	SAR3	2	ES-16	A	Right
23 January 2012 (18:18)	**SAR1**	**158**	**ES-29**	**D**	**Left**
24 January 2012 (05:13)	SAR4	165	ES-22	A	Right
25 January 2012 (05:07)	SAR3	2	ES-16	A	Right
30 January 2012 (18:00)	SAR2	143	ES-09	D	Left
31 January 2012 (18:00)	SAR3	143	ES-09	D	Left
31 January 2012 (18:18)	**SAR2**	**158**	**ES-29**	**D**	**Left**
1 February 2012 (05:13)	SAR2	165	ES-22	A	Right
1 February 2012 (18:18)	**SAR3**	**158**	**ES-29**	**D**	**Left**
2 February 2012 (05:13)	SAR3	165	ES-22	A	Right
3 February 2012 (18:00)	SAR4	143	ES-09	D	Left
4 February 2012 (18:18)	**SAR4**	**158**	**ES-29**	**D**	**Left**
5 February 2012 (05:13)	SAR4	165	ES-22	A	Right
8 February 2012 (18:18)	**SAR1**	**158**	**ES-29**	**D**	**Left**
9 February 2012 (05:13)	SAR1	165	ES-22	A	Right
16 February 2012 (18:18)	**SAR2**	**158**	**ES-29**	**D**	**Left**
17 February 2012 (05:13)	SAR2	165	ES-22	A	Right
17 February 2012 (18:18)	**SAR3**	**158**	**ES-29**	**D**	**Left**
18 February 2012 (05:13)	SAR3	165	ES-22	A	Right
20 February 2012 (18:18)	**SAR4**	**158**	**ES_29**	**D**	**Left**
21 February 2012 (05:13)	SAR4	165	ES-22	A	Right
24 February 2012 (18:18)	**SAR1**	**158**	**ES_29**	**D**	**Left**
3 March 2012 (18:18)	**SAR2**	**158**	**ES_29**	**D**	**Left**
5 March 2012 (05:13)	SAR3	165	ES-22	A	Right
7 March 2012 (18:18)	**SAR4**	**158**	**ES_29**	**D**	**Left**
8 March 2012 (05:13)	SAR4	165	ES-22	A	Right
11 March 2012 (18:18)	**SAR1**	**158**	**ES_29**	**D**	**Left**
12 March 2012 (05:13)	SAR1	165	ES-22	A	Right
19 March 2012 (18:18)	**SAR2**	**158**	**ES-29**	**D**	**Left**
20 March 2012 (18:18)	**SAR3**	**158**	**ES-29**	**D**	**Left**
20 March 2012 (05:13)	SAR2	165	ES-22	A	Right
21 March 2012 (05:13)	SAR3	165	ES-22	A	Right
23 March 2012 (18:18)	**SAR4**	**158**	**ES-29**	**D**	**Left**
24 March 2012 (05:13)	SAR3	165	ES-22	A	Right

The local image offsets can be successfully estimated depending on the presence of nearly identical features in the two SAR images at the scale of the patches used in the cross-correlation analysis. The position of the maximum of the cross-correlation function yields the local image offset, *i.e.*, the motion of the patch in the temporal interval between the acquisitions of the two images used. The value of the ratio between the absolute maximum of the cross-correlation function is coupled with the ratio between this value and the values of the other local maxima to provide a proxy for the reliability of the estimation. The combination of these two indexes provides a more robust selection of reliable estimates, since it allows removing patches with an absolute maximum above the selection threshold, but too close to other local maxima, which indicates an ambiguous solution. A 32 × 32 single-look pixel patch (corresponding to around 13 m in the slant range direction and 22 m in the azimuth direction) was used for this analysis. The patch size fixes the theoretical limits achievable [7], which, in this case, correspond to about 1 cm. However, the theoretical precision does not account for the possible inaccuracy in the image co-registration process, due, in this case, to the challenging area analyzed (a lot of vegetation). Taking into account these errors, the overall precision of the estimates can be considered in the order of a few centimeters.

Interferometric synthetic aperture radar (InSAR) was adopted to extract motion information from the phase of the available SAR images. InSAR is the measurement of signal phase change, or interference, over time. When a point on the ground moves, the distance between the radar and the point on the ground also changes and, so, the phase value recorded by the sensor. By comparing the phase values of two SAR images acquired at different times, it is possible to detect changes that reflect the motion of the target on the ground along the satellite LOS. This simple concept can be used successfully whenever radar targets on the ground do not change their "radar signature" over time, *i.e.*, the radar returns are expected to be identical in the two acquisitions. In real cases, this never happens, and the phase information is affected by a noise, known as temporal decorrelation: the larger the time separation between the two images, the stronger the decorrelation. These two approaches have different advantages and limitations.

The advantage of speckle tracking with respect to DInSAR is the possibility to analyze each patch independently of all the others, allowing the estimating of its "absolute" displacement. On the contrary, the InSAR interferometric phase is known only modulus 2π, and this requires the phase to be unwrapped in order to translate it into motion. Conventional 2D phase unwrapping algorithms require the gradient of the interferometric phase to be bounded within $\pm\pi$. Whenever coherent areas separated by low coherence regions are found in the image, there are no guarantees that this condition is met, *i.e.*, phase variations between coherent points can exceed 2π.

In the available images, the sea separated the Costa vessel from Giglio Island, and this prevented the possibility of correctly unwrapping the phase. On the contrary, speckle tracking, which does not require phase unwrapping, was successfully applied to estimate the motion of patches located on the ship and on the coast, allowing the retrieving of the differential ship-coast displacement.

While speckle tracking was the only solution to estimate the ship-coast motion, its centrimetric precision was considered not enough to obtain a reliable estimate of the differential deformation of the vessel, for which millimetric precision was required. Since the interferometric coherence on the Costa Concordia indicated the possibility to unwrap its phase, it was decided to use InSAR for this purpose.

This consideration led to the definition of the approach to combine speckle tracking and InSAR information to retrieve the motion of the ship.

As soon as a new image was available, it was co-registered with the previous acquisition using only patches located inland. Speckle tracking was then applied to all patches located on the ship, allowing the estimation of the motion with respect to Giglio Island to occur in the temporal interval between the two acquisitions.

The interferogram between the new image and the previous one was also generated, and the interferometric phase of the ship unwrapped (using a reference point located on the stern) and converted into motion. The displacement along a section connecting the stern with the bow was then used to quantify the differential motion of the ship.

In order to increase the precision of the ship-coast motion estimated with speckle tracking, the differential displacement of the ship obtained with interferometry was removed from the motion estimated for each patch and the residual (representing the desired signal) averaged.

3. Results

After an initial evaluation of all the available acquisition geometry, the two acquisition modes, ES-29 and ES-09, were identified among the others as the most suitable for the monitoring program. The combination between the orientation of the ship and the LOS of the ES-29 and ES-09 acquisition modes (which depend on the acquisition geometry and looking angle) allowed a good imaging of the vessel, in terms of resolution and visibility. On the contrary, the vessel image acquired by ES-16 and ES-22 appeared shortened and deformed. Unfortunately, only a very limited number of images could be acquired in ES-09 mode, so it was necessary to rely on ES-29 mode alone. Figure 2 shows how the vessel was imaged by all the available acquisition modes, in SAR coordinates.

Some examples of interferograms obtained for the Concordia ship are shown in Figure 3. Differential motion was estimated by unwrapping the interferometric phase with respect to a reference point located on the stern. Atmospheric contribution was neglected, since the relative distance is smaller than one km. Considering the orientation of the fringes, mainly perpendicular to the stern-bow direction, it was decided to characterize the ship deformation by plotting the displacement estimated along a stern-bow profile (Figure 2), as a function of the distance from the stern.

Examples of the cumulative displacement measured along the stern-bow profile for the temporal interval 11 January–20 March 2012, is presented in Figure 4. Each line represents the displacement measured in different time intervals defined by the available acquisitions, taking as reference the image acquired on 19 January 2012.

In addition to the stern-bow profile, providing information on the differential motion of the ship in the time interval between the new and the previous acquisition, the cumulative displacement of the bow, computed by simply integrating over time the information coming from all the images available on a specific date, was also retrieved. This graph, updated with the last available acquisition, is shown in Figure 5 and shows a cumulative displacement of the bow with respect to the stern of 1328 mm from 19 January to 23 March 2012.

Figure 2. Amplitude image for all the available acquisition modes. ES-29 and ES-09 represented the best viewing geometry. The horizontal and vertical axes correspond to azimuth and range coordinates, respectively. A-A' represents the stern-bow profile selected for the characterization of the ship deformation. Displacement along this profile obtained by unwrapping the interferometric phase was plotted *versus* the distance from the stern.

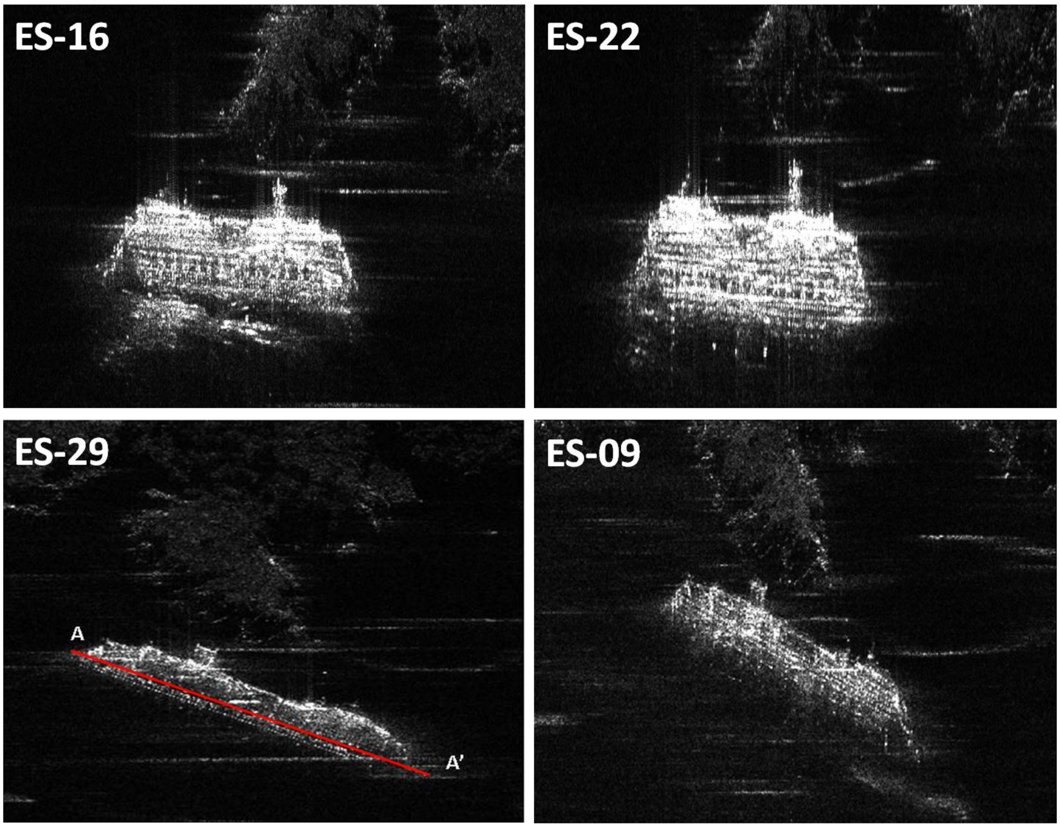


Figure 3. Example of interferograms obtained for the Costa Concordia interferometric analysis. It is possible to notice how interferometric fringes change over time when considering a similar temporal interval.

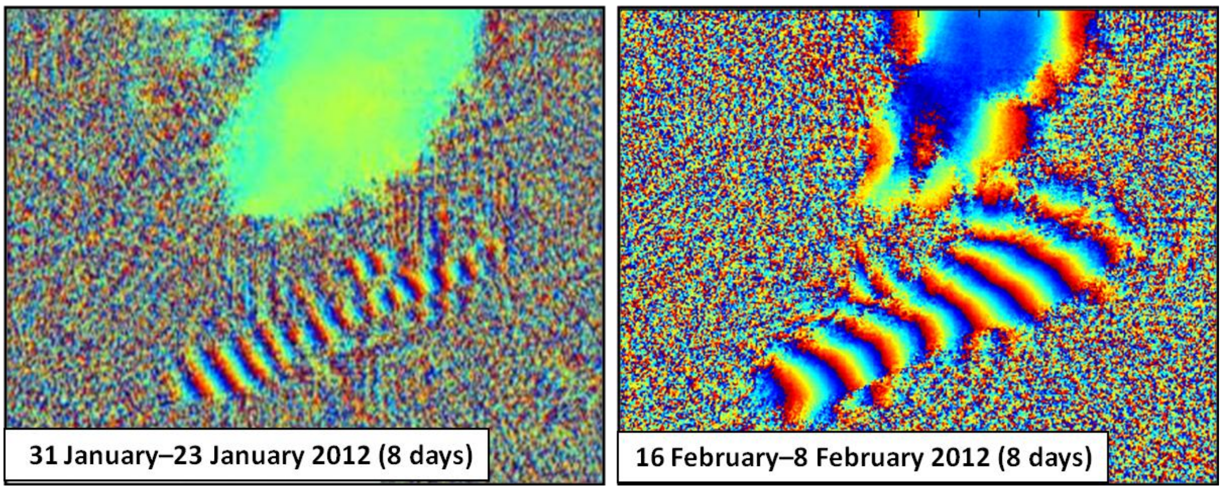


Figure 3. *Cont.*

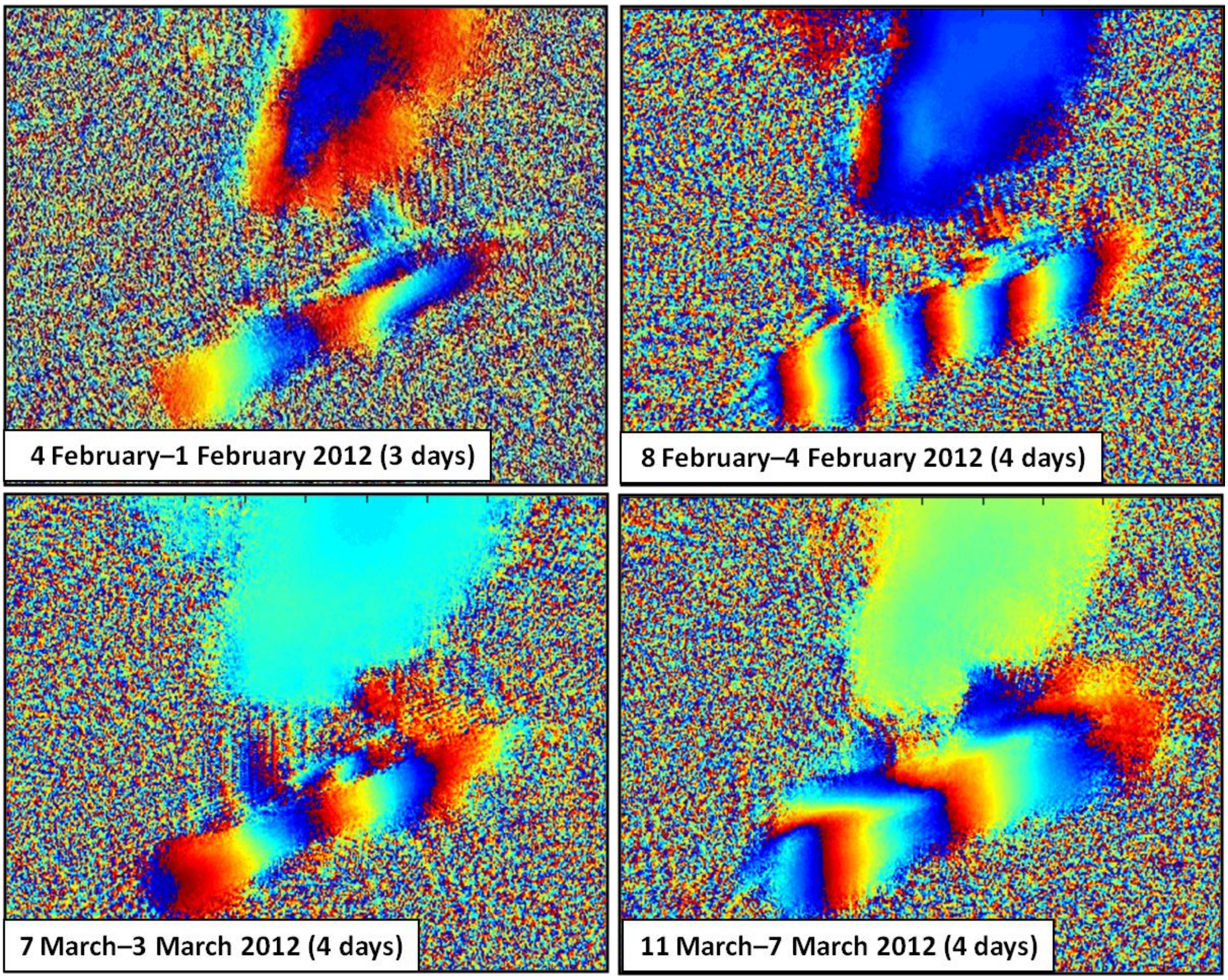


Figure 4. Stern-bow deformation profile for different temporal intervals from 19 January to 20 March 2012.

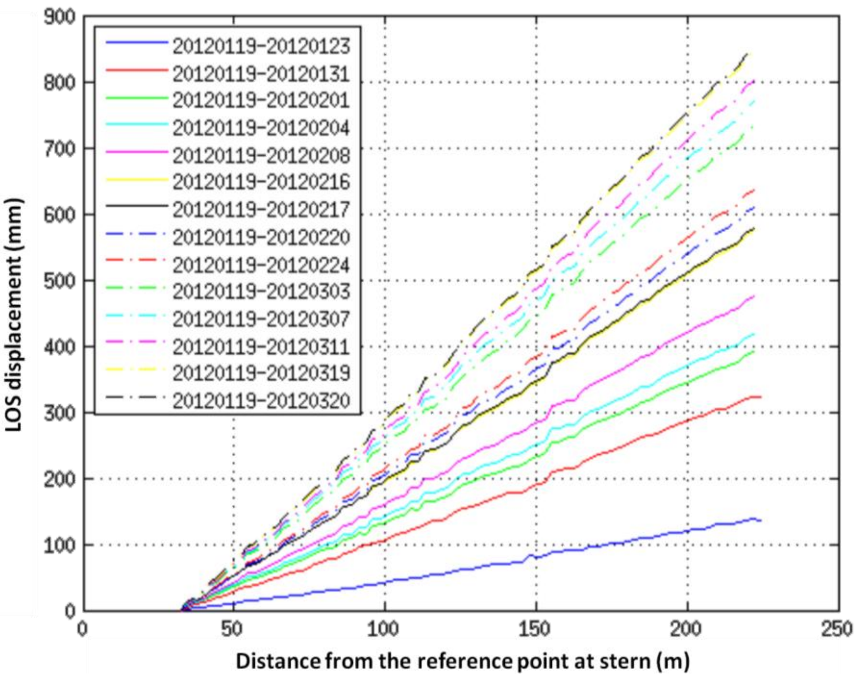
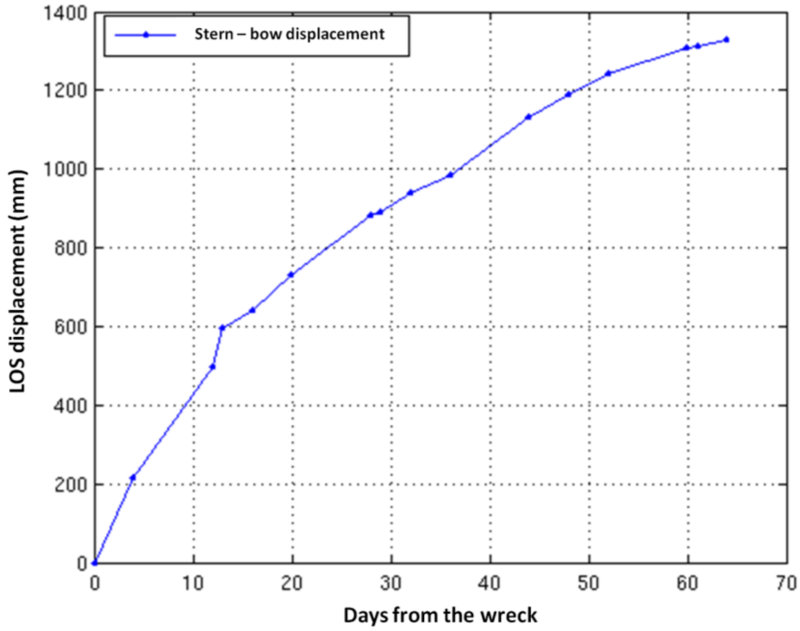
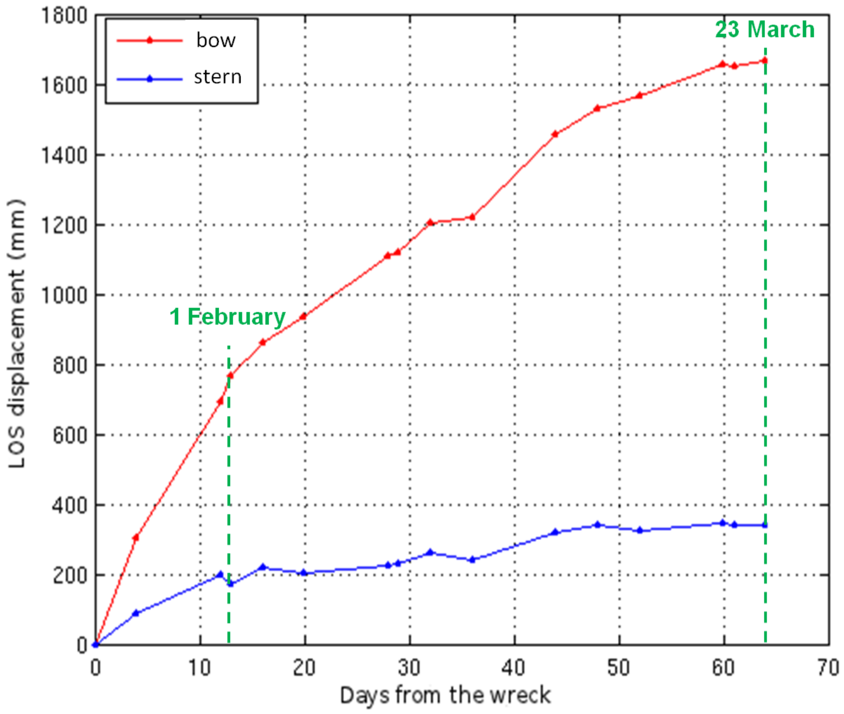


Figure 5. Cumulated displacement of the bow with respect to the stern as a function of days from the wreck.



Last, but not the least, the absolute motion of the ship with respect to Giglio Island was calculated. Figure 6 shows the evolution over time of the Costa Concordia vessel stern and bow motion with respect to Giglio Island, obtained by combining speckle tracking and InSAR results from ES-29 data processing, as described in the previous section. The absolute movement of the bow and stern of the Costa Concordia wreck with respect to the Giglio coastline is 1666 mm and 345 mm, respectively.

Figure 6. Movement of stern and bow of the Concordia ship with respect to Giglio Island, obtained from the combination of speckle tracking and InSAR.



4. Discussions

The shipwreck of the Costa Concordia has generated a complex and unique scenario, and SAR remote sensing data are used for the first time to support emergency management. The peculiarity of the situation includes the size and the weight of the cruise ship (nearly 290 m, 13 decks, 114,000 gross tonnage and 2400 tons of fuel oil), its tilted position on the seabed with the starboard side lying at depths of 40 m and the necessity of ensuring safety conditions for SaR activities onboard immediately after the shipwreck. The novelty of this emergency and the lack of an *ad hoc* monitoring system, specifically implemented for this kind of situations, induced the DPC and the DST-UNIFI to assess the stability conditions of the ship by arranging a new monitoring system. The efficiency and adaptability of a system of different sensors, usually successfully employed to monitor geohazard-induced movements, was exploited to guarantee a constant (on a 24/7 basis, *i.e.*, available without interruption regardless of time or day) stream of information. The monitoring system, still active up to early 2014 after the parbuckling salvage operation (*i.e.*, the Concordia wreck removal project) was originally conceived to comprise nine different independent technologies, encompassing also SAR-based products for the first ten weeks, when SaR operations requested to increase the control and reliability of the data of the ship's movements.

Before the launch of the COSMO-SkyMed mission, the reduced revisit capacity of orbiting satellites was the most serious gap for the extensive use of satellite SAR information as an operational monitoring tool. A further critical issue for the operational employment of remotely sensed data in risk management applications was generally the limited capability of previous EO satellite systems to offer an efficient response to user's specific needs, in terms of image resolution and accuracy, reaction time, latency of data and delivery time.

The purpose of the presented application was to take a step beyond in the current state-of-the-art in the exploitation of SAR products. Several advances have been made, in the last decade, in the use of radar images to map and monitor ground deformations related to geo-hazards in the deferred time. InSAR-based techniques were mainly applied, thanks to the availability of huge historical SAR image archives [8], to measure and monitor ground deformation phenomena that had already occurred. Geoscientists have widely exploited SAR-based information to resolve the spatial distribution and temporal evolution of displacements in areas affected by slow or very slow moving landslides (e.g., [9–13]) or by land subsidence (e.g., [14–17]). On the contrary, few examples exist of the use of satellite InSAR in real and quasi-real time. The enhanced temporal repetitiveness of the CSK constellation, the unprecedented timeliness in terms of response time (quasi-real-time delivery of data within a few hours of acquisition) and the flexibility of mission configuration, now offer the opportunity to effectively employ radar imagery as a quasi-real-time monitoring tool in the emergency and post-emergency phases associated with natural phenomena (e.g. [18–20]).

In emergency situations, one of the most important points is the timely delivery of updated products (*i.e.*, the time from image acquisition to the output of results has to be as short as possible). Considering the ES-29, the time of acquisition over Giglio Island is 6:18 pm. Once available, the new SAR image was immediately downloaded and processed. The related information of the vessel motion was therefore delivered in order to be useful in the framework of the emergency management procedures. In detail, output products of the processing of CSK images were released by

Tele-RilevamentoEuropa to DST-UNIFI at 6:00 pm the following day, in order to be included into the daily monitoring bulletin (delivered by DST-UNIFI to DPC at 8:00 pm), which encompassed the data collected by each sensor of the monitoring system.

Among the technologies installed within the ground-based measurement system on Giglio Island, the CSK InSAR was one of the least effective for performing continuous monitoring in real time. The main limiting factor was the time to "refresh" a single image (which corresponds to the satellite revisit time), typically ranging from one to a few days (Table 1). Despite this limitation, satellite InSAR was the only technology, with a terrestrial laser scanner, able to produce spatially continuous deformation maps. Unlike the other ground-based technologies (which record the displacement of targets, specific points or individual reflectors), satellite InSAR, through the generation of interferograms, can provide 2D maps of changes in the satellite-to-target path between the acquisition times of the two SAR scenes. Hence, CSK InSAR provided a significantly increased coverage of information, leading to a better overall understanding of movements of the Costa Concordia vessel.

The analysis of the data was primarily aimed at measuring any movements of the wreck with respect to the Giglio coastline. The movements (Figure 6), both at stern and bow, show a continuous (positive monotonic) trend over time (19 January to 23 March 2012).

Nevertheless, looking at the interferograms of Figure 3, it is possible to notice that the number and orientation of the interferometric fringes over the vessel vary over time, also when considering similar temporal intervals. For instance, considering the temporal intervals from 23 January to 31 January and from 8 February to 16 February (both of them covering eight days), the number of fringes varies remarkably: 13 fringes (corresponding to *ca*. 20.2 cm) can be identified in the first interval, and eight fringes (corresponding to 12.4 cm) can be counted in the second interval. This is clearly evidence of a change in the velocity of the movements and a non-linear evolution of the stern-bow deformation dynamics. The graphs of the movements reported in Figures 5 and 6 show that the time series can be roughly divided into two intervals: during the first interval, from 19 January to 1 February (fourth available image in the graphs), velocity values of about 2.5 mm/h and 0.60 mm/h have been recorded at the bow and stern, respectively. The second interval, from 1 February to the end of the monitoring period (23 March), shows lower values, with an almost constant velocity of movement of about 0.8 mm/h at the bow and 0.3 mm/h at the stern.

More precisely, the time series of displacements show, within these two major intervals, some events characterized by higher values: between 31 January and 1 February, the ship's bow accelerated up to 3.8 mm/h, and from 20 to 24 February, a speed of 1.4 mm/h has been recorded. In the whole analyzed period, the hull has undergone a differential rate of movement, with higher values at the bow and lower ones at the stern.

At the same time, the interpretation of processed CSK data was also aimed at distinguishing the absolute movement of the Concordia wreck along the granitic slope from the components of the internal deformation of the hull. This distinction could be performed by identifying any evident deformation of the monitored structure by the analysis of displacements along the longitudinal direction of the hull. In the graphs of Figure 5 is shown the LOS displacement, cumulated acquisition by acquisition, of points located along the stern-bow profile. Assuming the stern as a reference point, displacement increases almost linearly along this direction in each temporal interval.

The analysis and interpretation of data acquired by CSK SAR sensors indicate a remarkable variation in the position of the Costa Concordia, consistent with the general movement of the ship, from its original position taken immediately after the wreckage towards the lower sector of the slope. Internal deformations of the whole structure of the wreck are, in general, negligible compared to the movements recorded with respect to the coastline, exhibiting a predominant linearity along the longitudinal direction of the hull, over the analyzed period. As the internal deformation, for the investigated period, is of lower magnitude compared to the ship-coast displacement, movements of the Costa Concordia could be assumed as a roto-translation of an (almost) rigid body along the granitic slope, with a rotation of the portside towards the sea.

An increase of internal deformation was expected to be recorded over time, with the Concordia lying on its flank for months after the shipwreck, with the two rocky teeth wedged in the hull of the ship. That was confirmed by the image of the flank of the Costa Concordia after the parbuckling salvage operation.

5. Conclusions

This paper presented a successful exploitation of high-resolution SAR data in an operational scenario, describing an application tailored for a specific situation, during disaster management for civil protection purposes.

The high spatial resolution and very short revisit and response time of the CSK constellation has been successfully exploited to measure the movement of the Costa Concordia vessel, the cruise liner that struck granitic rocks jutting up from the shoreline of Giglio Island (Italy) and ran aground north of Giglio Porto on 13 January 2012. Special attention was directed to the use of Spotlight-2 SAR images taken along descending acquisition geometry ES-29, from 19 January to 23 March 2012.

The movement of the Concordia wreck with respect to the coastline and the information of differential displacements along the stern-bow profile were retrieved by combining the information obtained from both amplitude and phase values of the available SAR images, through the use of speckle tracking and conventional DInSAR techniques.

The pattern of measurements indicates a general movement of the roto-translation of the vessel, consistent with sliding toward the east of the hull on the seabed, more remarkable at the bow, as well as a negligible internal deformation.

The results presented in this paper show the effectiveness of the CSK constellation as a monitoring tool in emergency situations. Despite the novelty of the scenario and although the monitoring methodology was never tested anywhere else before this emergency, SAR-based information was successfully integrated within the 24/7 monitoring system arranged by DST-UNIFI and other scientific entities.

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Author Contributions

All authors contributed extensively to the various phases of the work presented in this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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