Hindawi Publishing Corporation
Journal of Sensors
Volume 2016, Article ID 6236925, 9 pages
http://dx.doi.org/10.1155/2016/6236925

Research Article

Application of X-Band Wave Radar for Coastal Dynamic Analysis: Case Test of Bagnara Calabra (South Tyrrhenian Sea, Italy)

Michele Punzo,[1] Chiara Lanciano,[2] Daniela Tarallo,[1] Francesco Bianco,[2] Giuseppe Cavuoto,[1] Rosanna De Rosa,[2] Vincenzo Di Fiore,[1] Giuseppe Cianflone,[2] Rocco Dominici,[2] Michele Iavarone,[1] Fabrizio Lirer,[1] Nicola Pelosi,[1] Laura Giordano,[1] Giovanni Ludeno,[3] Antonio Natale,[3] and Ennio Marsella[1]

[1] *Institute for Coastal Marine Environment (IAMC), Italian National Research Council (CNR), Calata Porta di Massa, Porto di Napoli, 80133 Naples, Italy*
[2] *Earth Science Department, University of Calabria, Via P. Bucci, Arcavacata di Rende, 87036 Cosenza, Italy*
[3] *Institute for Electromagnetic Sensing of the Environment (IREA), Italian National Research Council (CNR), Via Diocleziano 328, 80124 Naples, Italy*

Correspondence should be addressed to Michele Punzo; michele.punzo@iamc.cnr.it

Received 17 July 2015; Revised 5 October 2015; Accepted 11 October 2015

Academic Editor: Jose C. Nieto-Borge

Sea state knowledge has a key role in evaluation of coastal erosion, the assessment of vulnerability and potential in coastal zone utilization, and development of numerical models to predict its evolution. X-band radar measurements were conducted to observe the spatial and temporal variation of the sea-state parameters along a 3 km long sandy-gravelly pocket beaches forming a littoral cell on Bagnara Calabra. We produced a sequence of 1000 images of the sea state extending offshore up to 1 mile. The survey has allowed monitoring the coastline, the directional wave spectra, the sea surface current fields, and the significant wave heights and detecting strong rip currents which cause scours around the open inlets and affect the stability of the submerged reef-type breakwaters. The possibility to validate the data acquired with other datasets (e.g., LaMMA Consortium) demonstrates the potential of the X-band radar technology as a monitoring tool to advance the understanding of the linkages between sea conditions, nearshore sediment dynamics, and coastal change. This work proves the possibility to obtain relevant information (e.g., wave number, period, and direction) for evaluation of local erosion phenomena and of morphological changes in the nearshore and surf zone.

1. Introduction

Coastal areas are dynamic and changing environments, extremely sensitive to sea-land interactions and to hydrodynamic and sedimentary processes which both act on different temporal scale: short-times (tides, waves, currents, and winds) and larger temporary scales (sea level fluctuating during glacial and interglacial phases).

The sediment movement induced by wave motion, currents, tides, and meteomarine events produces deep and incisive changes in these zones. Seasonally, these areas are subject to extreme morphological changes as continuous settlements of the shoreline and natural beach nourishment/retreat. Therefore, the study of the evolution trends of the coastal marine areas has become an indispensable tool to evaluate the quality and the degradation of these environments through the analysis of the marine currents, the effects of high-impact meteomarine events, and the consequent morphological variations.

In the last two decades, the use of remote sensing (e.g., satellite and SAR) allowed examining in real time the coastal morphodynamic and the morphological variations after storms to obtain a complete knowledge of the coastal system that allows an optimized management [1, 2].

Among the remote sensing techniques, the X-Band Wave Radars provide an alternative to the standard detection systems of the sea state (e.g., buoys and others) with some important advantages. It has a good operating flexibility resulting in a "plug and play" system situated on a mobile platform. If compared to traditional sea state systems monitoring, the X-Band Wave Radar is easier to install, manage, and maintain; the system returns real-time motion waves, wind field data, and near-surface current, usually underestimated by the traditional systems. The X-Band Wave Radar acquires sea state parameters such as wavelength, period and direction of the waves and the values of the significant wave heights, sea surface current fields, and the maps of the distribution of the wind on the sea surface. These data are useful for the reconstruction of the meteomarine climatology of the coastal sector but also for acquiring the bathymetric features and the morphologies of the seabed [3].

In general, the X-Band Radar system analyzes phenomena that occur on different scales of space and time: small-scale phenomena (transient phenomena as wave breaking interactions over the shallows morphology or structures, or rip currents observation linked to the sharp contrast dominant wave and superficial currents, bar movements during storms, and submerged structure interactions) and long scale phenomena (e.g., developing predictive models of coastal erosion and planning/monitoring the coastal defense works). Therefore, the system allows performing the accurate characterization of the meteomarine climatology of particular coastal sector without having to carry out the transposition of the data that, acquired through buoys, are almost always recorded in locations very distant from the site of study.

In many cases, it has been shown that the radar system is useful in assessing the effectiveness of the coastal defense works and in validating the level of exposure of the coast [4, 5].

In the radar images, in fact, the phenomena of interaction between the wave motion and the anthropogenic infrastructures (reflection and diffraction of the waves and rip currents) and between waves and seabed (refraction, shoaling, and wave breaking) are immediately visible. This latter aspect is particularly important because the system allows inferring valuable information for reproducing the beach morphology and for bathymetric reconstruction [4].

This paper presents an example of application of the X-Band Wave Radar under the actions of "Coastal Monitoring" provided in the SIGIEC PON Project (Integrated Management System for Coastal Erosion) [6], realized by the University of Calabria in partnership with some companies and with the National Research Council (IAMC and ISAC).

In general, the project studies causes and effects of erosion phenomena affecting beaches located in sample areas in the Italian regions of Calabria and Puglia, testing measures for its containment and developing quantitative methods for producing, evaluating, and implementing a correct coastal management policy.

For the choice of the test sites, a qualitative analysis integrating geomorphologic and weather-marine dataset taking into account the landscape and structural restrictions was preliminarily performed; this has allowed identifying some macroareas which are subdivided into sedimentary cells.

Inside one of the sedimentary cells, some experimental sites have been selected to run tests of potential antierosion systems: among these sites, there is the coastal area of Bagnara Calabra (RC).

Four days of X-Band Wave Radar data, 24–27 February 2015, have been analyzed using the Remocean system developed at IREA-CNR.

A sequence of 1000 images of the sea state within one mile from the coast were produced. These images contain information regarding the wave field and its variation in time on a local scale.

2. Observation and Data Processing

2.1. Study Area and X-Band Radar REMOCEAN System. The study area of this research focuses on Bagnara Calabra village located in the western part of Calabria coast, southern Italy, facing Tyrrhenian Sea.

The study area is located in a sector of the "Costa Viola" mountain ridge, between Bagnara Calabra and Scilla (Figure 1).

From a morphological point of view, steep and uneven slopes, cut by deep canyons, characterize the test area in emerged sector [7]. Cliffs surrounding pocket gravel-sandy beaches are nourished by short high gradient torrents (the longest thereof are Favazzina and Sfalassà) which drain the western slope of the ridge. In the submerged sector, a discontinuous littoral wedge (LW in Figure 6), extending from coastline to 200 m offshore, characterizes the central part of site. Three channels indenting the LW as result of several coalescing landslide scars (up to 50–100 m wide) suggest very recent erosion [8]. In particular, the test area is connotated by coast-parallel erosion probably related to long shore currents and rip currents, which have formed shelf sand waves and small slope ward erosional channels, respectively [9]. Moreover, present day shoreline erosion is probably related to breakwaters structural defects.

There is a high percentage of high coast, with significant values of the wave energy flow concentrated around the sectors from the northwest, which are characterized by fetches with remarkable extension (over one thousand kilometers, along certain directions) [10].

Coastal erosion has been a serious problem for the entire coast of Calabria region, especially for its southwestern part. This area has been hit several times by coastal storms of high magnitude (e.g., 1928, 1980, 1984, 1985, 1986, 1987, 2008, and 2012), reef-type breakwaters have been built to protect the town center between the mouth of the Sfalassà Torrent and Promontory of Marturano (Figure 2). Regarding coastal erosion, the critical points are all areas, also with breakwaters and especially the beach situated at the south of Sfalassà Torrent, Promontory of Marturano, and Promontory of Cacilì [10].

2.2. X-Band Radar Method. Retrieving information on the wave motion through X-Band Radar devices requires the processing of a temporal sequence of marine radar images. Such a processing is aimed at compensating the distortions

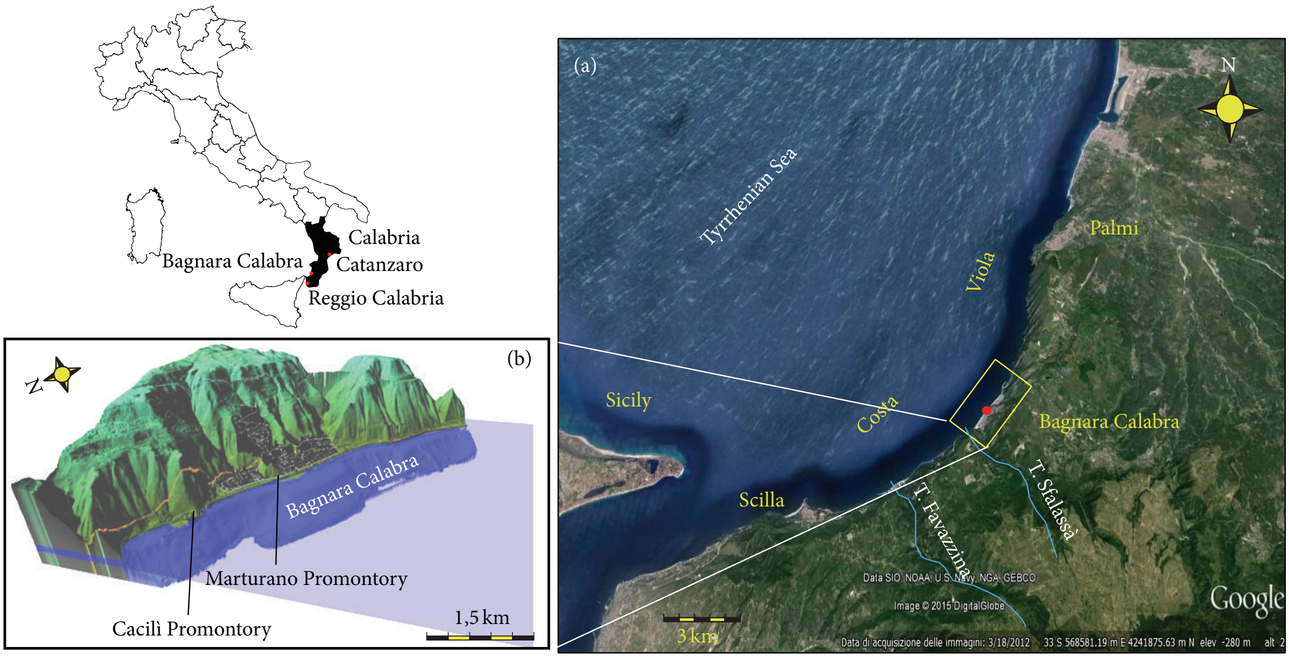

Figure 1: Bagnara Calabra village is located in the Italian region of Calabria at about 100 kilometers southwest of Catanzaro and about 25 kilometers northeast of Reggio Calabria. (a) Costa Viola geographical position; the red dot indicates the position of X-Band Radar antenna. (b) DEM of Bagnara Calabra.

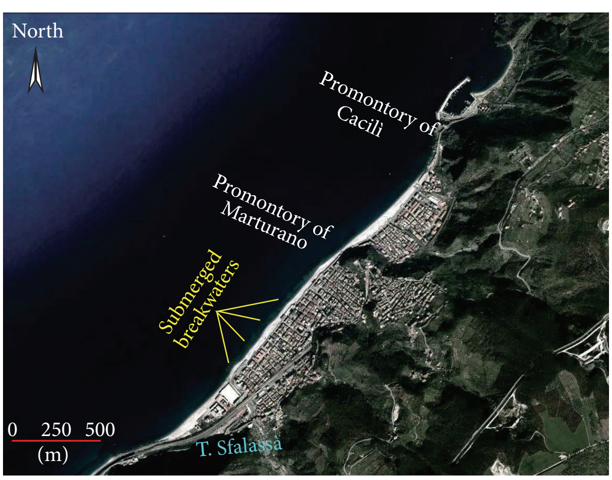

Figure 2: Google Earth image of Bagnara Calabra.

introduced by the radar acquisition process [11] and allows us to get the wave spectrum and the sea state parameters, as, for instance, the direction, the period, and the wavelength of the dominant waves, from the 3D spectrum of a raw radar sequence [12]. Based on the knowledge of the dispersion relation for the sea gravity waves, which rules the space-time behavior of a wave motion propagating over a given sea bottom with a prescribed sea surface currents field, it is indeed possible to extract the sea wave signal from the overall noisy data and reconstruct the bathymetry and currents fields [13–15]. However, achieving reliable estimates of the latter quantities from radar data is anything but a straightforward task, above all if the remote survey is carried out in a coastal zone, where a significant inhomogeneity in space can affect the considered parameters. Nevertheless, a number of inversion procedures to be applied on radar data acquired in nearshore areas have been developed in recent years [3, 4, 15, 16]. Among them, the one based on the Normalized Scalar Product (NSP) is the most accurate to get the sea surface current and bathymetry fields from a sequence of marine radar images [14, 17]. In particular, the main steps to deal with the surface current estimation in nearshore areas through the NSP method are summarized in the flow chart of Figure 3, while further details can be found in [3, 16, 18].

Table 1: Remocean coastal monitoring system configuration parameters.

Acquisition range	2222.4 m
Rotation time of the antenna	1.97 s
Spatial resolution	5 m
Antenna height (over sea level)	20 m
Angular sector	180°

The radar used during the Bagnara Calabra survey is a Bridge Master (25 KW antenna with a 2.4 m antenna). Remocean Coastal Monitoring Mobile version measures real-time sea state parameters as wave direction, wavelength, period, significant wave height, sea surface current intensity and direction, and temporal-spatial images of the sea surface elevation. The analyzed data radar consisted of 32 individual images with an interval of 1.97 s between successive images.

Table 1 presents the system configuration parameters.

Radar system was installed on a hotel panoramic rooftop, with view on the sea and on the coast at a height of approximately 20 m from the mean sea level (Figure 4). The radar

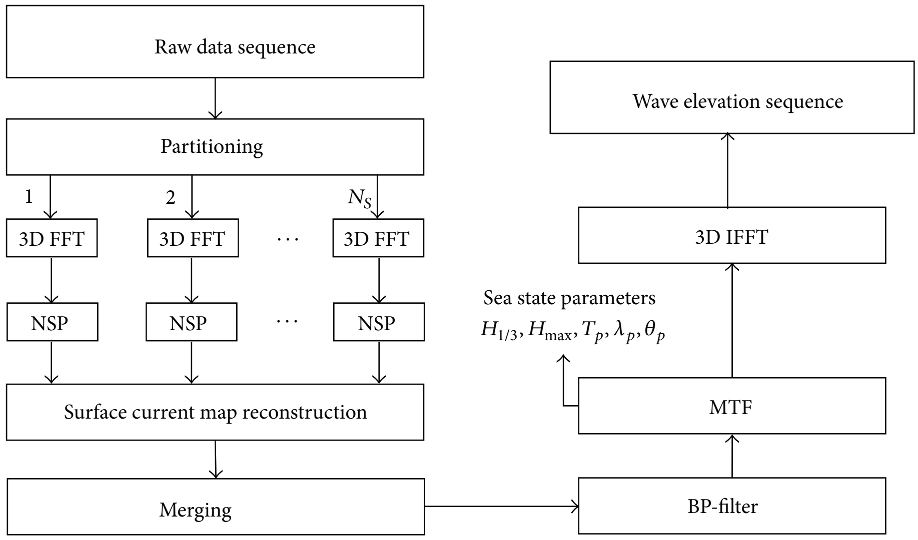

Figure 3: Block diagram of the inversion procedure.

Figure 4: Particular of Remocean "plug and play" system.

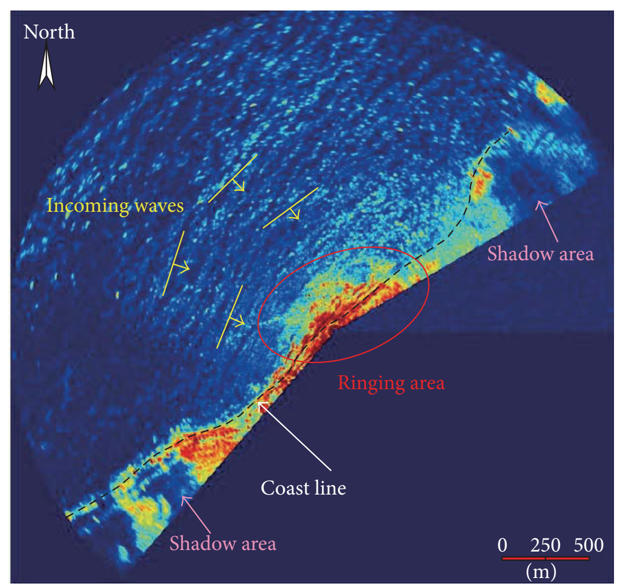

Figure 5: Bagnara Calabra instant radar image: the black dashed line underlines the coastline. The along shore bands with very strong signals are related to wave breaking and suggesting the presence of reef-type breakwaters.

configuration in "mobile data acquisition modality" allows having a great flexibility in the choice of the observation point and is readily installed and operated in mobile modality acquisition.

Regarding the radar functionality, it must specify that, in rough sea conditions, the system can detect dominant wave motions and sea near-surface currents, while, in calm sea conditions, the system allows identifying exclusively the coastline. In fact, intense meteomarine events cause high wave reverberation that hides the shoreline, contrary to what happens in calm sea conditions.

Thanks to the ability to detect the coastline, the radar is a useful tool for comparing subsequent images in time and making both short-term and long-term comparisons and, consequently, to study coast erosion phenomena.

3. Results and Observations

The radar dataset has been collected in the period of 24–27 February 2015. The survey was planned during a period of very rough sea state to be taken as evidence for the near-shore and surf-zone morphological variations on Bagnara Calabra "sedimentary cell" [10]. This approach is normally used for standout wave propagation, wave run-up, and wave interaction with submerged or emerged structures at stormy conditions.

The radar antenna was located just on centre of cell, on a mobile platform installed at the following coordinates: latitude = 38°17′12.80″N and longitude = 15°48′8.23″E. Radar data represents an area of 2 km × 2 km centered on the test area.

Figure 5 is an example of radar image that provides information about the coastal area. The coastal sector analyzed has a length of about 3 Km.

The radar images interpretation allows us to characterize the test area coastal dynamics. The main wave motion

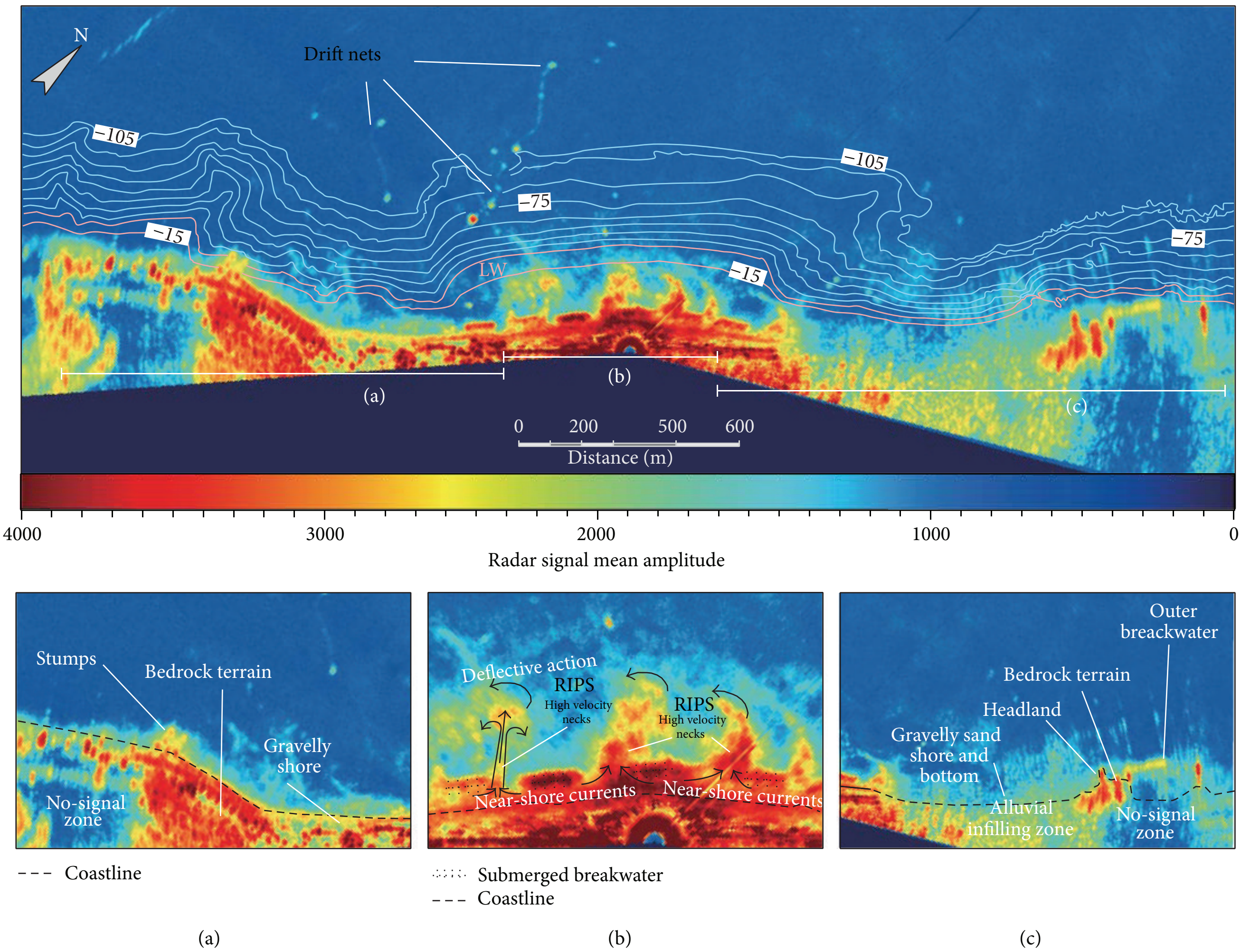

Figure 6: Radar image with articulated bathymetry offshore Bagnara Calabra (redrawn from [8]), showing three channels deeply indenting the littoral wedge from −15 to over −200 with headwalls very close to the shore. Coastal area subdivision: (a) southern sector, (b) central sector, and (c) northern sector.

detected by the radar (visible through the clutter in Figure 5) comes from the northwest, according to dominant wave motion listed in previous study performed by Calabria region [10]. The incoming waves approaching the coast with different angles of incidence are produced by their refraction. In fact, if the waves approach the coast obliquely, they will begin to feel the effects of the slowdown in their propagation only in part and the result is a wave fronts rotation that will tend to align the waves parallel to the coast. The red, high-intensity areas in the snapshot image (Figure 5) correspond to regions that are experiencing the greatest wave breaking from the front face of the waves with respect to the radar. Unbalanced wave height distribution around breakwaters induces rip currents and the submerged barriers become a trap for the wave energy content. Consequently, intense waves ringing runs in the stretch between the reef-type breakwaters and the shoreline (Figure 5). In fact, the radar signal reflection is greater in this area than in the others, as well as in all the areas in which there are hard objects as cliffs, buildings, and morphological highs (Figure 5). In general, the radar image shows a different signal reflection related to the different coastal morphological elements (rocky coast and gravel sandy beach). This area, together with those in which there are “hard” objects (cliffs, buildings, and high grounds), is the one characterized by the greater amplitude of the radar signal.

Figure 6 depicts several morphohydro dynamic characteristics evidenced by the radar system and other important features, as the detection of drifting objects (fishing nets) on the sea surface.

The radar image was compared to the multibeam bathymetry acquired by [8]. This comparison illustrates a close link between the radar images and the bathymetric survey, since the waves, at local scale, are driven by water depth and currents. For example, the increase of the reflected signal intensity (due to the waves breaking) identifies an area characterized by lower depth (< −15 m), which coincides with the external boundary of LW.

Taking into account the different signal amplitude related to the dissimilar coastal morphological elements, we considered three sectors.

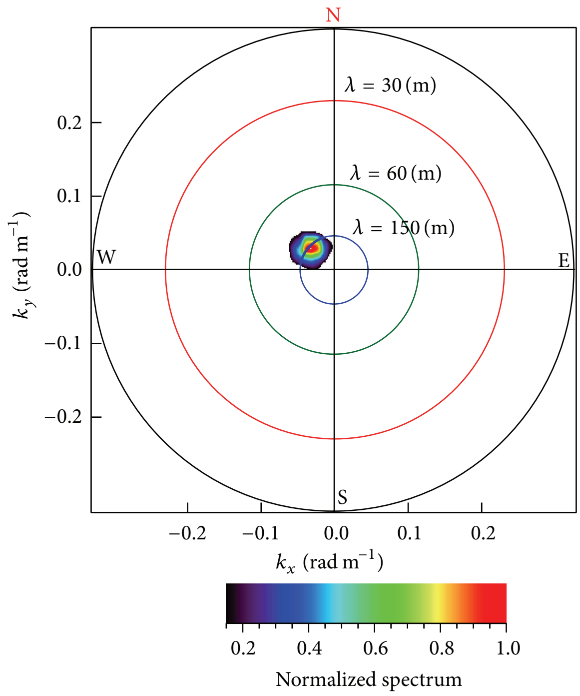

Figure 7: Directional spectrum of Bagnara Calabra area.

In the enlargement A, the main signal amplitude is related to the outcrop of the bedrock terrain; conversely "no-signal zone" is due to the shielding of the radar signal by the promontories. The gravelly shore and some stumps are also identified.

In the enlargement B, the image contains a long shore oriented feature of increased backscatter intensity that is connected to incident waves and submerged breakwaters. Consequently, intense rip currents take place (forced currents that move towards sea) at the gaps between the submerged breakwaters. Rip currents appear elongated northwestward with high velocity neck at about 40° with respect to the dominant waves. Moving seaward, the rip currents lose energy gradually and interact with small-scale near-surface current direction, which generate high radar returns as rip heads deflection represented by a plume. Near-shore currents are also well identified between the submerged breakwater and the coastline.

In the enlargement C, the different signal intensity permits discriminating the main principal morphological evidences as the gravelly sand shore, the alluvial infilling from the rocky headland, and the areas with submerged bedrock. There is an additional evidence, of high reflectivity located in proximity of outer breakwater of the harbour area. As the high grounds shield the reflected signal, there is an area with no radar signal.

Figure 7 depicts the directional spectrum obtained by the dataset collected on 25 February 2015 at about 13:00 am (UTC). The directional spectrum has one dominant spectral wave direction from about 300° (northwest).

The resolution of sea near-surface current was evaluated detecting drifting objects (as drift nets) on the sea surface (Figure 8).

Figure 8 illustrates the synchronous combination of sea near-surface current intensity and direction and a black/white radar image retrieved by X-Band Radar. In particular, we analyzed in detail a set of 527 images collected over a period of approximately 17 min starting at 11:14:37 to 11:31:56 for the day 25/02/2015. During this period, the presence of boats that release fishing nets is clearly identifiable; the nets, then, drift mainly towards SW. Subsequently, considering an acquisition time of 1.97 sec, we calculated the displacement of two drift nets. The big one in 1039 seconds shifted 278 m southwest, with a speed of 0.27 m/s; the smaller drift net in 1039 seconds shifted 201 m southwest, with a speed of 0.19 m/s. The map of the sea near-surface current (considering the same period analyzed for the displacement of the drift net) was superimposed on radar image. The sea near-surface current map (Figure 8(b)) shows a current intensity of about 0.3 m/s and about 0.18 m/s in the area of the big and of the small drift nets, respectively. Therefore, the differences between calculated and measured values of current intensity are comparable.

Figure 9 shows temporal variation of intensities rip current occurrence compared with sea conditions. The set of three mean images collected, depicts an example of variation of the rip patterns with identified rip intensities, which indicates that the rip patterns vary rapidly in a short time with the sea conditions. The intensities of rip were estimated by image analyses evaluating long shore pixel brightness distribution.

Radar system provides not only images but also real-time sea state information as the significant wave height (H_s), defined as the mean wave height (trough to crest) of the highest third of the waves ($H_{1/3}$). During the three acquisition days, the system measured H_s values ranging from about 0.5 to 4.5 meters (Figure 10(d)), with the maximum value reached on 25th February. The H_s value estimated by wave radar is a calibrated value. The calibration depends on a number of factors such as acquisition geometry and radar setting. With wave buoy measures not being available, in this case a measure provided by web forecast systems is used. The significant wave height recorded by the Consortium LaMMA (Figures 10(a), 10(b), and 10(c)) is in agreement with the recorded data. The main wave direction detected by LaMMA (Figure 10(a)) is not in agreement with radar measurement (Figure 8(b)): this is probably due to the different scales of measurement.

4. Conclusions

The paper presents the results carried out with the Remocean X-Band Radar system in the Project SIGIEC test site of Bagnara Calabra. From a technology perspective, the main interest lies in the "coastal" configuration of the system. This feature is important since it offers a good flexibility in the choice of the spatial and temporal observation modalities considering also the paucity of data related to hydrodynamics in the nearshore area.

The system, during the acquisition period, provides sea state images useful to characterize the Bagnara Calabra coastal area, such as dominant waves length, period and

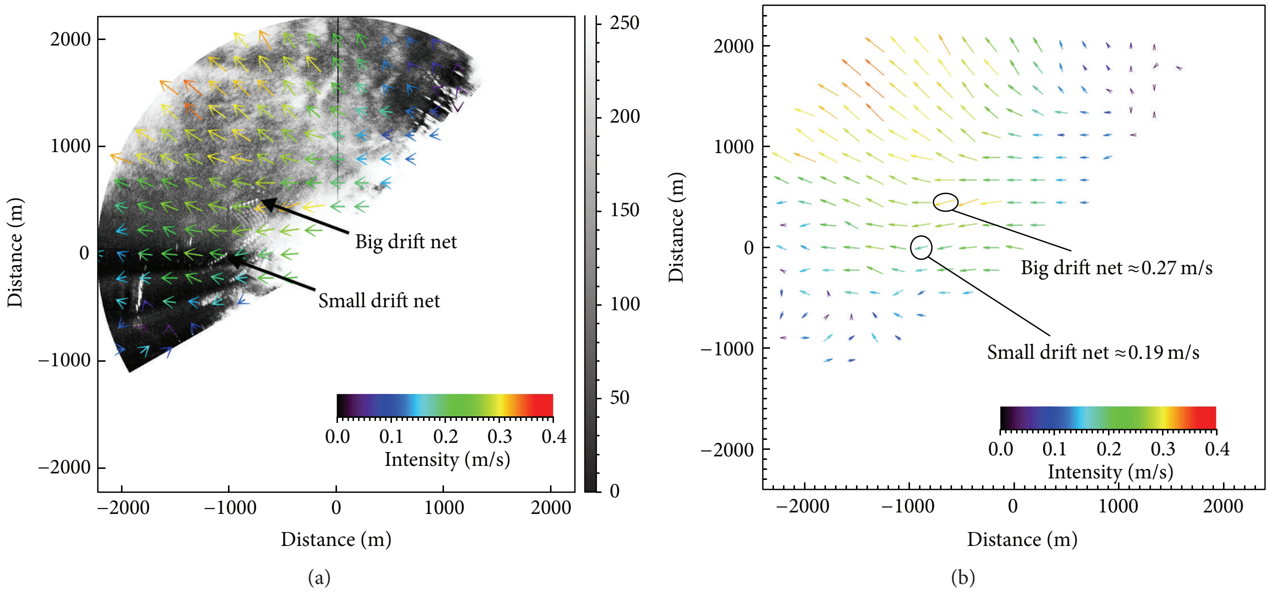

Figure 8: (a) Comparison between radar image integrated over time and the corresponding relative sea near-surface current field. (b) Sea near-surface current map: the system best evidences the current vectors oriented in the drifting objects displacement.

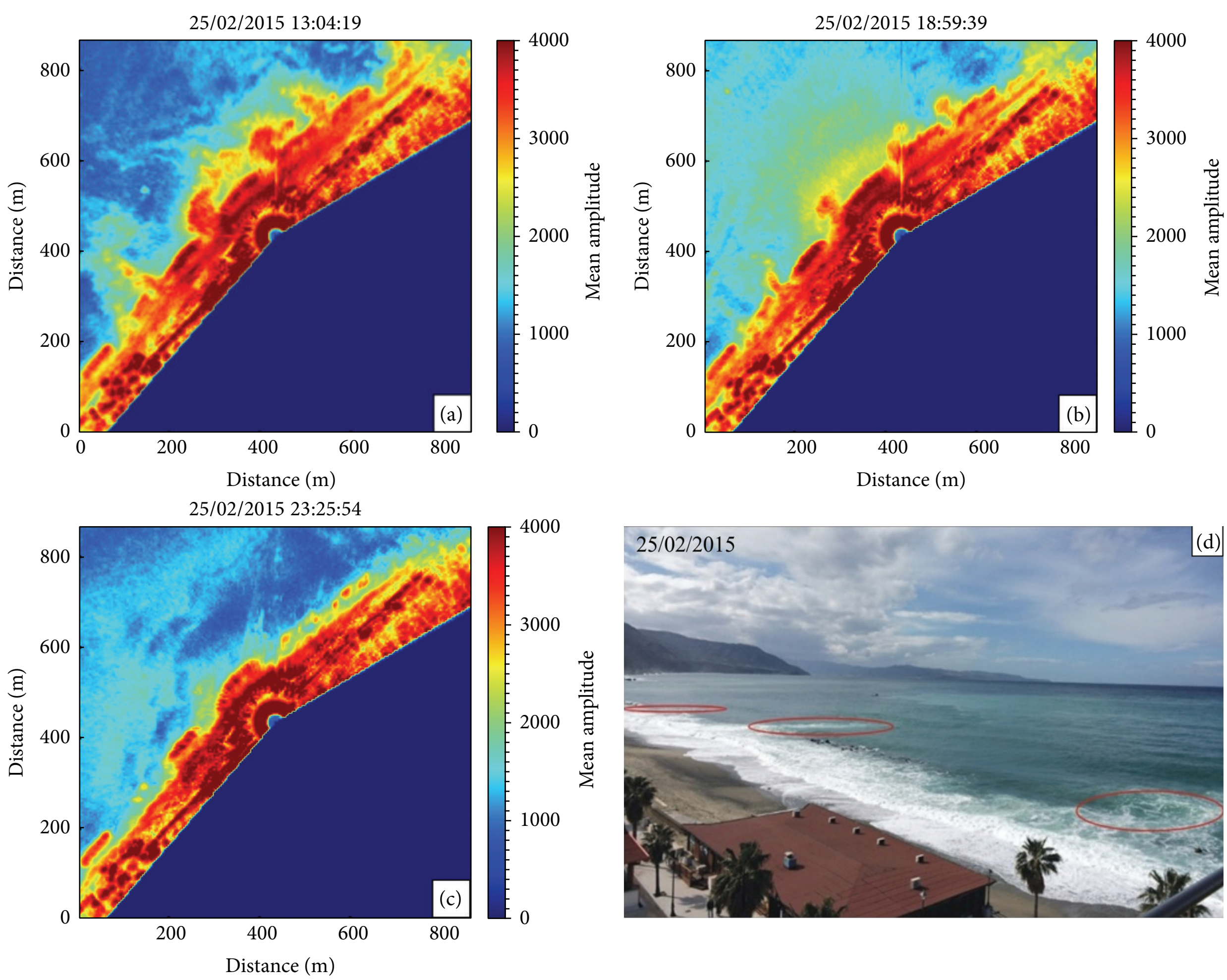

Figure 9: Temporal variation of intensities rip current occurrence: (a) very rough sea; (b) moderate sea; (c) smooth sea. (d) The rip currents can be seen in the photograph (red circle), identified by the region without breaking waves and foam transported outside of the surf zone.

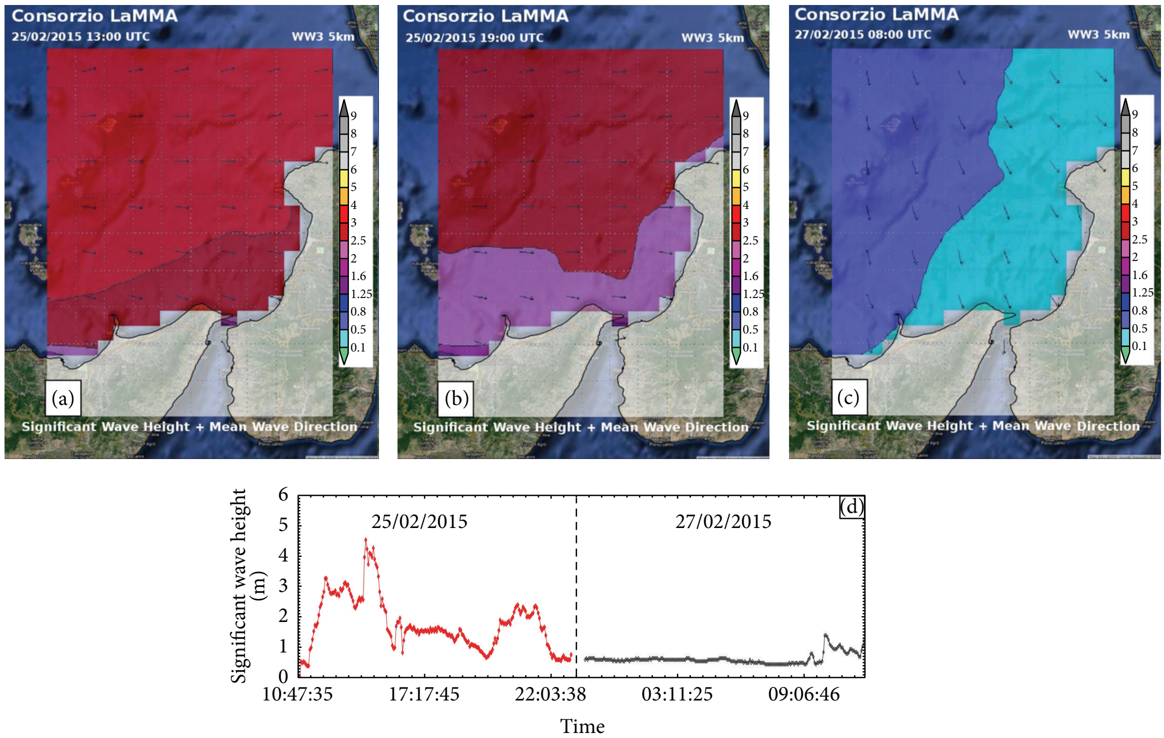

Figure 10: (a), (b), and (c) Maps of significant wave height recorded by the Consortium LaMMA in Bagnara Calabra (Data SIO, NOAA, US Navy, NGA, GEBCO ©2015 Google Image Landsat). (d) Significant wave heights measured by X-Band Radar system.

direction, significant wave height, surface current field intensity, and direction.

In particular, the system has allowed determining directional wave spectra, which show a dominant wave direction from the northwest, in agreement with the Master Plan of the Calabria region [10]. The sea surface current field has been validated calculating the speed of drifting objects (drift nets) located near the coast. Significant wave heights, for the acquisition period, are characterized by values ranging from about 0.5 m to 4.5 m.

In the test area, the X-Band Radar has detected anthropic elements as the harbour outer breakwater and the long shore reef-type breakwaters. The system has also permitted determining phenomena of interaction between waves and defense works as intense waves ringing concentration between reef-type breakwaters and coastline. These observations indicate that radar remote sensing can be an effective tool for detecting rip currents and provide a more synoptic picture of the rip current flow field outside the surf zone during high energy events.

Reef-type breakwaters, inducing strong wave breaking above the crown of the same structures, are able to reduce incoming wave energy to the shore. However, in Bagnara case study unbalanced wave height distribution around breakwaters induces intense rip currents and causes scars around the open inlets that affected breakwaters stability. Moreover, shoreline erosion is probably related to breakwaters structural defects.

Designing reef-type breakwaters to reduce the water surface elevation difference between front and rear sides of the barriers (which determines rip current intensity), it is possible to obtain a reduction of rip currents. For existing reef-type breakwaters, three technologies can be used to limit rip currents: putting gravels on the bottom of the open inlet, installing a small-submerged structure on the onshore side of the open inlet, or installing a drainage channel inside the submerged breakwater to reduce water surface elevation at the rear side of the reef-type breakwater.

The results emphasize the potential of the X-Band Radar for cost-effective monitoring systems in coastal regions. The system, providing real-time wave parameters measures and detecting phenomena due to coastal hydrodynamics, as rip currents, represents a very important tool for coastal areas studies, sea state, and coastal defense works monitoring. It can be very useful especially when it is necessary to estimate coastal erosion phenomena evolution and to project eventual coastal defense works, as in the case of SIGIEC Project.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors wish to thank Dr. Rodolfo Baculo, IAMC Naples, for technical support during the field data acquisition. Thanks are due to Dr. Francesco Raffa, IAMC-Messina, who provided great supports in the data analysis. Thanks are due to LaMMA

Consortium which provided evolution and swell of the sea. Finally, they want to thank the anonymous reviewers for their useful comments and suggestions. X-Band Radar has been hosted by Grand Hotel Victoria whose hospitality is gratefully acknowledged. The research activity has been financially supported by PON (Operational National Plan) 2007–2013 from MIUR (Italian Research Ministry of Research) Project SIGIEC (Integrated Management System for Coastal Erosion) ID: PON01_02651 (http://www.sigiec.sister.it/).

References

[1] A. Kroon, M. A. Davidson, S. G. J. Aarninkhof et al., "Application of remote sensing video systems to coastline management problems," *Coastal Engineering*, vol. 54, no. 6-7, pp. 493–505, 2007.

[2] J. P. Dugan, C. C. Piotrowski, and J. Z. Williams, "Water depth and surface current retrievals from airborne optical measurements of surface gravity wave dispersion," *Journal of Geophysical Research C: Oceans*, vol. 106, no. 8, pp. 16903–16915, 2001.

[3] G. Ludeno, F. Reale, F. Dentale et al., "An X-band radar system for bathymetry and wave field analysis in a harbour area," *Sensors*, vol. 15, no. 1, pp. 1691–1707, 2015.

[4] K. Hessner, K. Reichert, J. C. N. Borge, C. L. Stevens, and M. J. Smith, "High-resolution X-band radar measurements of currents, bathymetry and sea state in highly inhomogeneous coastal areas," *Ocean Dynamics*, vol. 64, no. 7, pp. 989–998, 2014.

[5] L. H. Holthuijsen, *Waves in Oceanic and Coastal Waters*, Cambridge University Press, 2007.

[6] http://www.sigiec.sister.it/.

[7] G. G. R. Iovine, R. Greco, S. L. Gariano, P. Iaquinta, A. Pellegrino, and O. G. Terranova, "Shallow-landslide susceptibility in the Costa Viola Mountain Ridge (Italia)," in *Proceedings of the 2nd World Landslide Forum (WLF '11)*, pp. 81–87, Rome, Italy, October 2011.

[8] D. Casalbore, A. Bosman, D. Ridente, and F. L. Chiocci, "Coastal and submarine landslides in the tectonically-active tyrrhenian calabrian margin (Southern Italy): examples and geohazard implications," in *Submarine Mass Movements and Their Consequences*, S. Krastel, J.-H. Behrmann, D. Völker et al., Eds., vol. 37 of *Advances in Natural and Technological Hazards Research*, chapter 23, pp. 261–269, Springer, 2013.

[9] L. Ferranti, C. Monaco, D. Morelli, F. Antonioli, and L. Maschio, "Holocene activity of the Scilla Fault, Southern Calabria: insights from coastal morphological and structural investigations," *Tectonophysics*, vol. 453, no. 1–4, pp. 74–93, 2008.

[10] Autorità di Bacino Regionale and Regione Calabria, *Masterplan degli interventi di mitigazione del rischio di erosione costiera in Calabria—Area 13*, Autorità di Bacino Regionale, Regione Calabria, 2013.

[11] J. C. N. Borge, G. R. Rodríguez, K. Hessner, and P. I. González, "Inversion of marine radar images for surface wave analysis," *Journal of Atmospheric and Oceanic Technology*, vol. 21, no. 8, pp. 1291–1300, 2004.

[12] I. R. Young, W. Rosenthal, and F. Ziemer, "Three-dimensional analysis of marine radar images for the determination of ocean wave directionality and surface currents," *Journal of Geophysical Research*, vol. 90, no. 1, pp. 1049–1059, 1985.

[13] P. S. Bell, "Shallow water bathymetry derived from an analysis of X-band marine radar images of waves," *Coastal Engineering*, vol. 37, no. 3-4, pp. 513–527, 1999.

[14] F. Serafino, C. Lugni, and F. Soldovieri, "A novel strategy for the surface current determination from marine X-Band radar data," *IEEE Geoscience and Remote Sensing Letters*, vol. 7, no. 2, pp. 231–235, 2010.

[15] C. M. Senet, J. Seemann, S. Flampouris, and F. Ziemer, "Determination of bathymetric and current maps by the method DiSC based on the analysis of nautical X-band radar image sequences of the sea surface (November 2007)," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 46, no. 8, pp. 2267–2279, 2008.

[16] G. Ludeno, C. Brandini, C. Lugni et al., "Remocean system for the detection of the reflected waves from the costa concordia ship wreck," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 7, no. 7, pp. 3011–3018, 2014.

[17] F. Serafino, C. Lugni, J. C. N. Borge, V. Zamparelli, and F. Soldovieri, "Bathymetry determination via X-band radar data: a new strategy and numerical results," *Sensors*, vol. 10, no. 7, pp. 6522–6534, 2010.

[18] G. Ludeno, S. Flampouris, C. Lugni, F. Soldovieri, and F. Serafino, "A novel approach based on marine radar data analysis for high-resolution bathymetry map generation," *IEEE Geoscience and Remote Sensing Letters*, vol. 11, no. 1, pp. 234–238, 2014.