IMEKO International Conference on
Metrology for The Sea
Naples, Italy, October 11-13, 2017

Application of X-Band Wave Radar for coastal dynamic analysis: case test of Bagnara Calabra (south Tyrrhenian Sea, Italy)

Michele Punzo[1], Giuseppe Cavuoto[1], Vincenzo Di Fiore[1], Daniela Tarallo[1], Giovanni Ludeno[3], Rosanna De Rosa[2], Giuseppe Cianflone[2], Rocco Dominici[2], Michele Iavarone[1], Fabrizio Lirer[1], Nicola Pelosi[1], Laura Giordano[1], 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] University of Calabria, Earth Science Department – Via P. Bucci, 87036 Arcavacata di Rende - Cosenza, Italy.
[3] Institute for Electromagnetic Sensing of the Environment (IREA), Italian National Research Council (CNR) – Via Diocleziano 328, 80124 – Naples, Italy.

***Abstract* – Sea state knowledge has a key role in evaluation of coastal erosion, in 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 the 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 to monitor the coastline, the directional wave spectra, the sea surface current fields and to detect strong rip currents.
The possibility to validate the data acquired with other dataset demonstrate 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 for evaluation of local erosion phenomena and of morphological changes.

I. INTRODUCTION

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 for 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 (eg: satellite, SAR) allowed to examine 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].

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]. The system allows to perform 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 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.

We present 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), 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 geo-morphologic and weather-marine dataset taking into account the landscape and structural restrictions, was preliminarily performed; this has allowed to identify some macro-areas which are subdivided into sedimentary cells.

Inside one of the sedimentary cells, some experimental sites have been selected to run tests of potential anti-erosion 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.

II. 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).

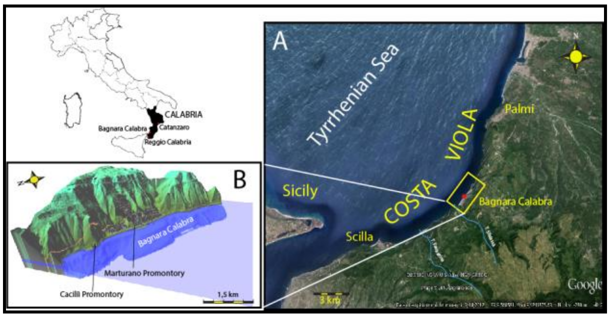

Fig. 1. Bagnara Calabra village is located in the Italian region of Calabria at about 100 kilometers southwest of Catanzaro and about 25 kilometers northeast of Reggio Calabria. (a) Costa Viola geographical position; the red dot indicates the position of X-Band Radar antenna. (b) DEM of Bagnara Calabra.

Cliffs surround 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 3), 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) suggesting very recent erosion [4]. 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 [5]. 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, that are characterized by fetches with remarkable extension (over one thousand kilometers, along certain directions) [6].

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.

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 introduced by the radar acquisition process [7], 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 [8]. 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, 9, 10]. 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 [11, 12].

The radar used during the Bagnara Calabra survey is a Bridge Master (25KW antenna with a 2.4 m antenna). The analyzed data radar consisted of 32 individual images with an interval of 1.97 s between successive images.

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.

III. OBSERVATION AND DATA PROCESSING

The radar dataset has been collected in the period 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" [6]. 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 coordinates: latitude=38°17’12.80"N and longitude=15°48’8.23"E. Radar data represents an area of 2km x 2km centered on the test area.

Figure 2 is an example of radar image that provides information about the coastal area. The coastal sector analyzed has a length of about 3 Km.

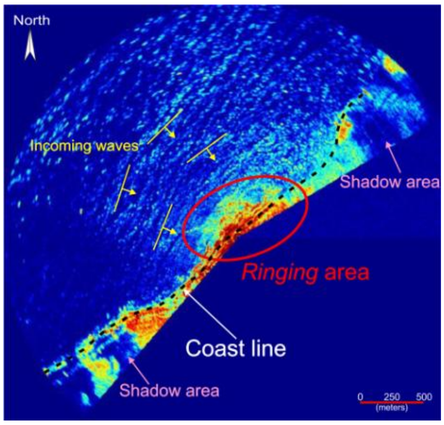

Fig. 2. Bagnara Calabra instant radar image: the black dashed line underlines the coastline. The along shore bands with very strong signals are related to wave breaking and suggesting the presence of reef-type breakwaters.

The radar images interpretation allows us to characterize the test area coastal dynamics. The main wave motion detected by the radar (visible through the clutter in Figure 2) comes from the northwest, in according to dominant wave motion listed in previous study performed by Calabria Region [6]. The incoming waves approaching the coast with different angles of incidence 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 2) correspond to regions that is experiencing the greatest wave breaking from the front face of the waves with respect to the radar. Unbalanced wave height distribution around breakwaters induce 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 2). 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 2). 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, high grounds) is the one characterized by the greater amplitude of the radar signal.

Figure 3 depicts several morpho-hydro 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 [4]. 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 (<-15m), 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.

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° respect the dominant waves. Moving seaward, the rip currents lose energy gradually and interacts with small-scale near-surface current direction, which generate an 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.

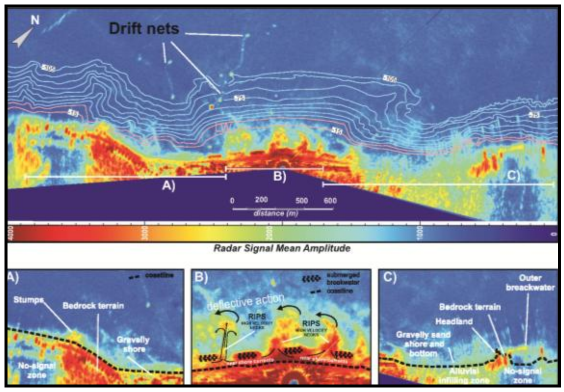

Fig. 3. Radar image with articulated bathymetry offshore Bagnara Calabra (redrawn from [4]), showing three channels deeply indenting the littoral wedge from -15 to over -200 with headwalls very close to the shore. Coastal area subdivision: (a) Southern sector, (b) Central sector, and (c) Northern sector.

In the enlargement C, the different signal intensity permits to discriminate 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 are an area with no radar signal.
Figure 4 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).

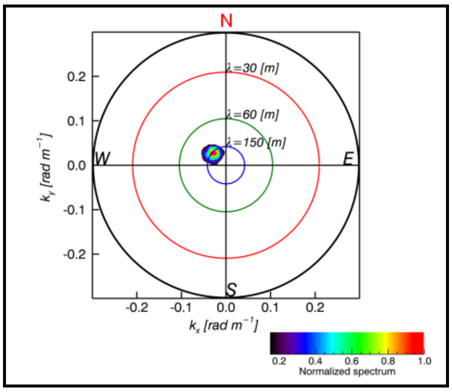

Fig. 4. Directional spectrum of Bagnara Calabra area.

The resolution of sea near-surface current was evaluated detecting drifting objects (as drift nets) on the sea surface (figure 5).
Figure 5 illustrates the synchronous combination of sea near-surface current intensity and direction and a black/white radar image retrieved by X-band radar.

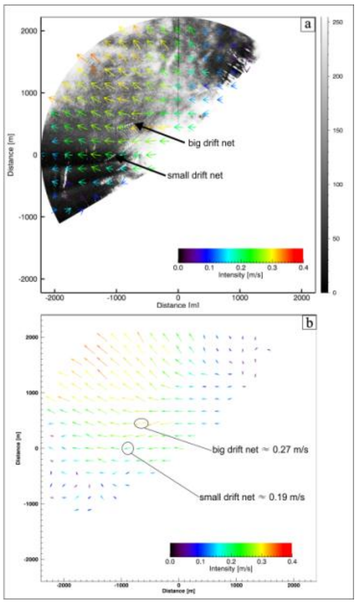

Fig. 5. (a) Comparison between radar image integrated over time and the corresponding relative sea near-surface current field. (b) Sea near-surface current map: the system best evidences the current vectors oriented in the drifting objects displacement.

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 are 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 5 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 6 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 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.

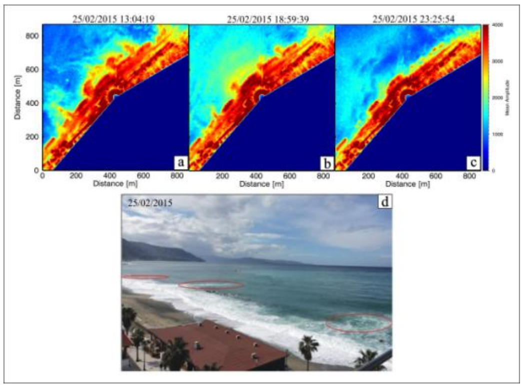

Fig. 6. Temporal variation of intensities rip current occurrence: a) very rough sea; b) moderate sea; c) smooth sea. d) The rip currents can be seen in the photograph (red circle), identified by the region without breaking waves and foam transported outside of the surf zone.

Radar system provides not only images but also real-time sea state information as the significant wave height (Hs), defined as the mean wave height (trough to crest) of the highest third of the waves (H1/3). During the three acquisition days, the system measured Hs values ranging from about 0.5 to 4.5 meters (Figure 7 d), with the maximum value reached on 25th February. The Hs 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 7(a), 7(b) and 7(c)), is in agreement with the recorded data. The main wave direction detected by LaMMA (figure 7(a)) is not in agreement respect to radar measurement (figure 5(b)): this is probably due to the different scales of measurement.

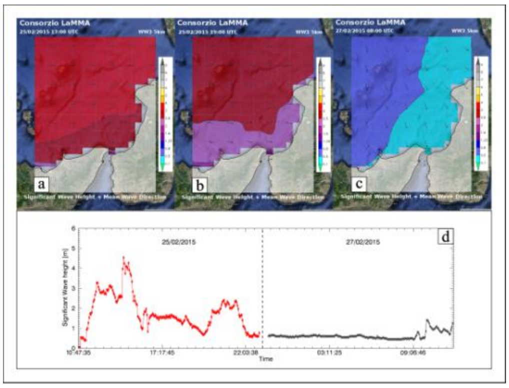

Fig. 7. (a), (b), and (c): maps of significant wave height recorded by the Consortium LaMMA in Bagnara Calabra (Data SIO, NOAA, U.S. Navy, NGA, GEBCO ©2015 Google Image Landsat). D)Significant wave heights measured by X-Band Radar system.

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

In particular, the system has allowed to determine directional wave spectra, which show a dominant wave direction from the northwest, in agreement with the Master Plan of the Regione Calabria [6]. 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 to determine 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 induce intense rip currents and cause 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.

REFERENCES

[1] A.Kroon, M.A.Davidson, S.G.J.Aarninkhof, R.Archetti, C.Armaroli, M.Gonzalez, S.Medri, A.Osorio, T.Aagaard, R.A.Holman, R.Spanhoff, "Application of remote sensing video systems to coastline management problems", Coastal Engineering, 54, 2007, pp. 493-505

[2] J.P.Dugan, C.C.Piotrowski, J.Z.Williams, "Water depth and surface current retrievals from airborne optical measurements of surface gravity wave dispersion", J. Geophys. Res., 106(C8), 2001, 16,903–16,915, doi:10.1029/2000JC000369.

[3] G.Ludeno, F.Reale, F.Dentale, E.Pugliese Carratelli, A.Natale, F.Soldovieri, F.Serafino, "An X-Band Radar System for Bathymetry and Wave Field Analysis in a Harbour Area", Sensors, 15(1), 2015, pp. 1691-1707; doi:10.3390/s150101691.

[4] D.Casalbore, A.Bosman, D.Ridente, F.L.Chiocci, "Coastal and Submarine Landslides in the Tectonically-Active Tyrrhenian Calabrian Margin (Southern Italy): Examples and Geohazard Implications". In: Krastel S. et al.(Eds.), Chapter 23, Submarine Mass Movements and their Consequences. Advances in Natural and Technological Hazard Research, 37, 2013, pp. 261-269.

[5] L.Ferranti, C.Monaco, D.Morelli, F.Antonioli, L.Maschio, "Holocene activity of the Scilla Fault, Southern Calabria: Insights from coastal morphological and structural investigations" Tectonophysics 453, 2008, pp. 74–93.

[6] Autorità di Bacino Regionale, Regione Calabria, "Masterplan degli interventi di mitigazione del rischio di erosione costiera in Calabria – Area 13", 2013.

[7] B.J.C.Nieto, R.G.Rodriguez, K.Hessner, I.P.Gonzales, "Inversion of marine radar images for surface wave analysis", J. Atmos. Ocean Technol. 21, 2004, pp. 1291–1300.

[8] R.Young, W.Rosenthal, F.Ziemer, "Three-dimensional analysis of marine radar images for the determination of ocean wave directionality and surface currents", J. Geophys. Res. 90, 1985, pp. 1049–1059.

[9] C.M.Senet, J.Seemann, S.Flampouris, 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", IEEE Trans. Geosci. Remote Sens. 46, 2007, pp. 2267–2279.

[10] G.Ludeno, C.Brandini, C.Lugni, D.Arturi, A.Natale, F.Soldovieri, B.Gozzini, F.Serafino, "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 7(7), 2014, pp. 1939–1404.

[11] F.Serafino, C.Lugni, F.Soldovieri, "A novel strategy for the surface current determination from marine X-band radar data", IEEE Geosci. Remote Sens. Lett. 7, 2010, pp. 231–235.

[12] F.Serafino, C.Lugni, B.J.C.Nieto, V.Zamparelli, F.Soldovieri, "Bathymetry Determination via X-Band Radar Data: A New Strategy and Numerical Results". Sensors 10(7), 2010, pp. 6522–6534.