Remocean: A X-Band Radar System As Tool for Environmental Monitoring in Costa Concordia Ship Wreck Management

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REMOCEAN :A X-BAND RADAR SYSTEM AS TOOL FOR ENVIRONMENTAL MONITORING IN COSTA CONCORDIA SHIP WRECK MANAGEMENT

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ABSTRACT

This paper describes the new opportunities made possible by the X-band radar systems for monitoring and management of infrastructures in coastal areas as well as for offshore platforms. In particular, the paper presents the effectiveness and the reliability of the Remocean system, a X-band radar developed at IREA-CNR, as observational tool for the support of the Costa Concordia ship wreck removal and as a scientific opportunity to observe wave phenomena rarely observable in deep sea.

KEYWORDS : *Sea state monitoring, X-band radar, coastal and offshore monitoring and protection.*

INTRODUCTION

X-band radar systems enable a high spatial resolution sea state monitoring (of the order of meters) in a range of few kilometres from the observation platform. In particular, the low cost and easiness of installation, as well as the operational flexibility, make the X-band radars a relevant tool to scan the sea surface with high temporal rate, by using both fixed and moving observation platforms for ship navigation support and coastal areas monitoring purposes [1]. In this frame, recent research efforts have been aimed at developing novel data processing techniques for the estimation of the sea surface currents and bathymetry based on the maximization of the Normalized Scalar Product (NSP). This technique has been validated in several challenging cases, as for the Remocean system [2, 3]. In particular, by considering the sea state monitoring in coastal areas, the performance of the Remocean system has been already assessed in sea surface currents estimation and comparison with the measurements provided by a HF radar system [1]. In [2] Remocean has provided a bathymetry estimation of quality comparable with the direct measurements provided by the multi-beam echo-sounder.

In the present work, we present the results achieved by exploiting Remocean system for bathymetry estimation and sea wave height reconstruction at Giglio Island (Tuscany, Italy). It is worth noting that the X-band radar data processing is very challenging in coastal areas, due to the high variability of the sea surface current and bathymetry, which makes the assumption of spatial homogeneity of the data unfeasible. Under this hypothesis of non-homogeneity, it is not possible to use the data processing techniques usually adopted for deep water; thus, in order to overcome this drawback, here we present a novel technique based on an enhanced version of the NSP, which makes it possible a local analysis of the sea surface current and bathymetry.

In this paper, we analyzed the sea wave height in the Giglio Island port, where the Costa Concordia ship wreck is located. The Remocean system was installed at the Giglio Island by the LaMMA

Consortium as a supporting observational tool providing information about the sea state, which was an important for the removal operations of the Costa Concordia ship wreck. The operational environment at Giglio Island, is very challenging for the X-band radar system, due to the fact that we are very close to the coast and for the presence of the wreck, which arose sea state phenomena not easily predictable by the current provisional models. The presence of the wreck makes this area of high interest for scientific and applicative purposes, since the Remocean wave radar measurements allowed at optimizing the design of the infrastructure deployed for the wreck recover.

The radar data has been collected during the storm of the 27 November 2012 by the system installed at the Giglio Island.. The presence of the Costa Concordia allowed us to make a performance analysis of the X-band wave radar for the observation of phenomena rarely detectable in coastal zones. In particular, here we focus on the 3D (space-time) reconstruction of the sea surface in order to show the capability of the system to detect and characterize the waves reflected by the shipwreck. Furthermore, the reliability of the estimated sea state parameters, as the direction θ and the period T of the dominant wave, has been tested through a comparison with the direct measurements provided by a buoy located close to the ship wreck.

DATA PROCESSING APPROACH

Images of marine radar permit to recover important hydrodynamic sea parameters information. In fact, the sea surface can be observed and analyzed by X-band radar at grazing angles, thanks to the Bragg scattering of electro/magnetic waves by water waves with comparable wavelength.

X-band E/M wavelength is approximately 3 cm, so that it mostly interacts with the short capillary waves, which in turn ride over longer gravity waves, so that the backscattered signal is modulated by the local slope of the sea surface. In this way, longer waves can be thus observed in the radar image thanks to the tilt modulation and shadowing phenomena [1-5]. These phenomena were originally considered as just an undesirable clutter effect for the navigation purposes, but in the last two decades several approaches have been developed and validated to estimate sea state parameters, surface currents and bathymetry from X-Band radar data [6-8].

Remocean system has been developed at the Institute for Electromagnetic Sensing of the Environment (IREA) of the Italian National Research Council. The system is able to digitalize the backscattering signal received by the antenna radar, so to obtain a time series of sea clutter images. These images are after processed to determine the sea state parameters (such as wavelength, direction, period of the dominant waves, significant wave height, surface currents and bathymetry). The reconstruction approach is summarized in Figure 1.

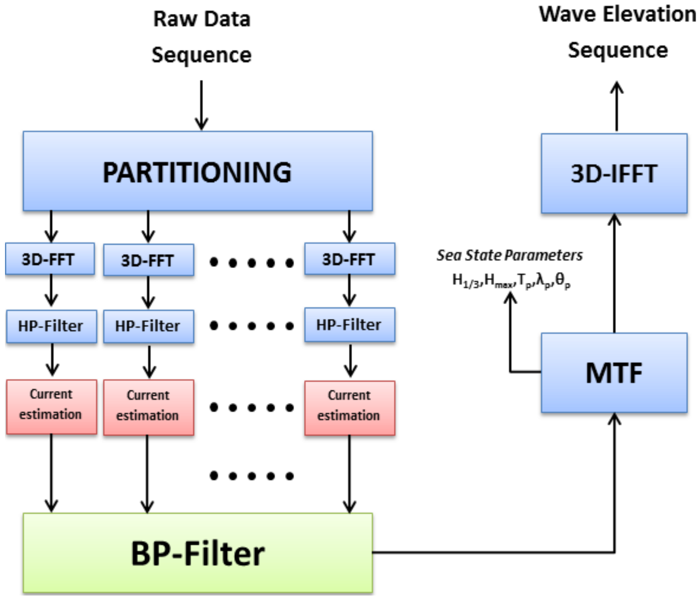

Figure 1 Block diagram of the inversion procedure

As a first step, the raw X-band radar images sequence is subdivided in subareas, whose extent is dictated by a tradeoff between the necessity to assume the sea surface current and bathymetry constant in such subareas (pushing to a narrowing of the subarea) and the necessity to achieve a reliable spectral analysis (pushing to the enlargement of the subarea).

As a second step, the sub area radar images sequence is transformed into 3D image spectrum by means of a 3D-Fast Fourier Transform (3D-FFT); after, the effect of the received signal power decay along the range direction is filtered by applying a high-pass (HP) filter; the resulting signal is the image spectrum $F_I(k_x, k_{y,}\omega)$ [9, 10].

The third step aims at extracting the linear gravity wave components from the image spectrum $F_I(k_x, k_{y,}\omega)$. This filtering stage exploits the dispersion relation relating the wavenumber $\bar{k}$ to the angular frequency $\omega(\bar{k})$ through the sea surface current $\bar{U} = (U_x, U_y)$ and the water depth h. The dispersion relation is given by:

$$\omega(\bar{k}) = \sqrt{g|\bar{k}|tanh(|\bar{k}|h)} + \bar{k}\bar{U} \qquad (1)$$

where g is the acceleration due to the gravity at the earth's surface and $k = |\bar{k}| = \sqrt{k_x^2 + k_y^2}$.

Note that the estimation of the current vector $\bar{U} = (U_x, U_y)$ and water depth h are needed before applying the dispersion relation in the filtering step [11]. In this frame, here we exploit a recently proposed approach for the surface current and depth estimation, which is based on the maximization of the Normal Scalar Product [8]:

$$V(\bar{U}, h) = \frac{\langle |F_I(k_x, k_y, \omega)|, G(k_x, k_y, \bar{U}, h, \omega) \rangle}{\sqrt{P_F \cdot P_G}} \quad (2)$$

where $|F_I(k_x, k_{y,}\omega)|$ is the amplitude of the image spectrum, $G(k_x, k_y, \omega, U_x, U_y, h)$ is a characteristic function accounting for the support of the dispersion relation (1) and $P_F \cdot P_G$ are the power associated to the image spectrum *F(·)* and *G(·),* respectively. This technique has been shown to have better performance compared to the Least Square approach presented [12,13] as regards the accuracy of the estimation.

Once the current $\bar{U} = (U_x, U_y)$ and bathymetry h have been estimated, **the forth step** consists in reassembling the spectra in order to obtain a spectrum able to account for the sea surface current contributions estimated for each subarea. The Band-Pass (BP) filter is built on the basis of the dispersion relation defined in (1) and then applied to the image spectrum $F_I(k_x, k_{y,}\omega)$; the result of the filtering is the function $\widetilde{F}_I(k_x, k_{y,}\omega)$.

The fifth step aims at turning from the filtered radar image spectrum $\widetilde{F}_I(k_x, k_{y,}\omega)$ to the desired sea-wave spectrum $F_W(k_x, k_{y,}\omega)$. This step requires the knowledge of the radar modulation transfer function (MTF), which specifically accounts for the specific modalities of the electromagnetic sensing phenomenon. It is worth to stress that in this study case we employed a MTF different from the one commonly adopted in literature [10]. More details on the MTF here employed are presented in Section 4.
Finally, the knowledge of the wave spectrum $F_W(k_x, k_{y,}\omega)$ permits to determine the main sea state parameters; this is carried out by generating the wave number directional spectrum $F(k_x, k_{y,})$, whose maximum provides the wavelength, the direction and period $[\lambda, \theta, T]$ of the dominant wave.

The last step aims at providing the time-spatial evolution of the wave height $\eta(x, y, t)$ by performing an Inverse Fast Fourier Transform (3D-IFFT) of the spectrum function $F_W(k_x, k_{y,}\omega)$.

MEASUREMENT CAMPAIGN

This section is devoted at describing the instrumentation and the measurement campaign carried during the storm on 27 November 2012.
A CONSILIUM X-band radar radiating a maximum power of 25 KW and equipped with an 9 feet (2.74 m) long antenna was deployed. The radar antenna is located at the coordinates: LAT=42°21'39.66"N; LON=10°55'16.31"E. The antenna is installed on a lighting pylon at a height of 15 m above sea level (see Figure 2).

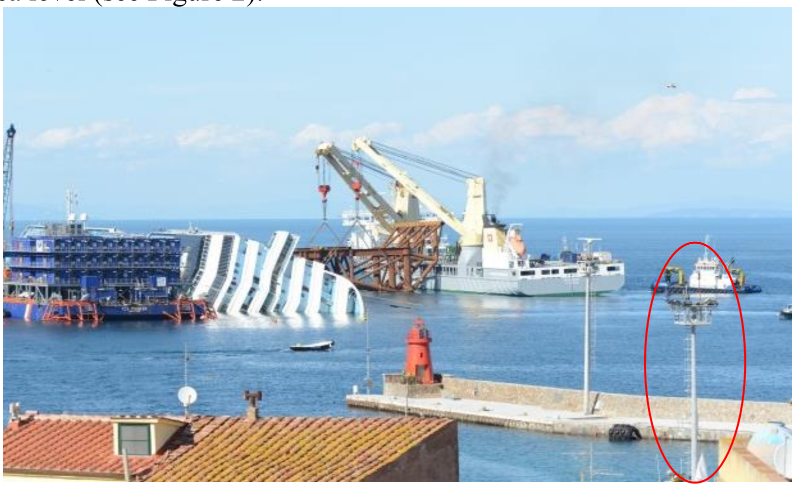

Figure 2 Installation site of the Remocean system indicated by the red circle.

The details of the acquisition parameters are given in Table I.

Radar parameters	*Value*
Antenna rotation period (Δt)	2.41 s
Spatial image spacing (Δx and Δy)	2.42 m
Minimum range	250 m
Maximum range	1150 m
Processed images number for a sequence (N)	32

Antenna height over sea level	15 m
View angular sector	110 deg

Table I Measurement parameters of the Remocean system during the storm

Figure 3 depicts a X-band radar image collected during the storm, where it is possible to observe the sea-wave pattern, the location of the radar indicated by the red triangle and the position of the Costa Concordia ship wreck as indicated by the red arrow.

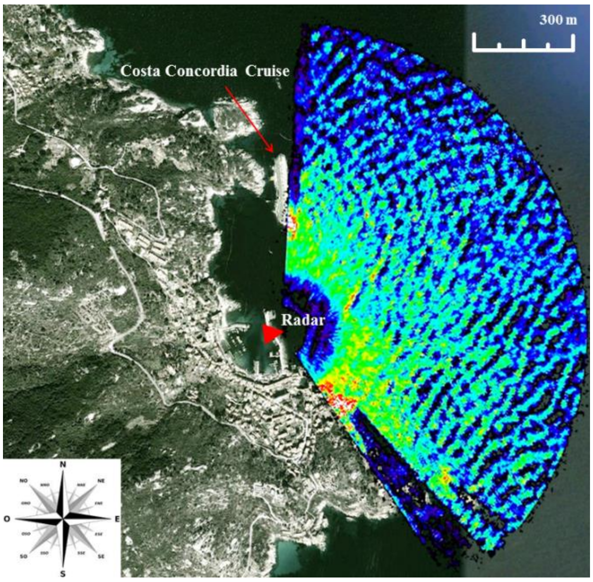

Figure 3 A radar image collected during the storm. The position of the radar and the ship wreck is indicated by the red triangle and the red arrow, respectively.

COMPARISON AND RESULTS

This section is devoted at presenting and comparing the results provided by Remocean system in terms of sea state parameters estimation, thanks to the inverse scheme described in Section "Data Processing Approach".

The 2D wavenumber spectrum $F(k_x, k_y)$ permits to determine the characteristic sea state parameters in terms of wavelength, wave direction, wave period of the dominant wave.

Figure 4 depicts the directional spectrum obtained by the dataset collected on 27 November 2012 at about 12:00 am (UTC); the directional spectrum has two spectral modes: the dominant one and a secondary mode associated to the sea waves reflected by the Costa Concordia wreck (see the red arrow in Figure 3).

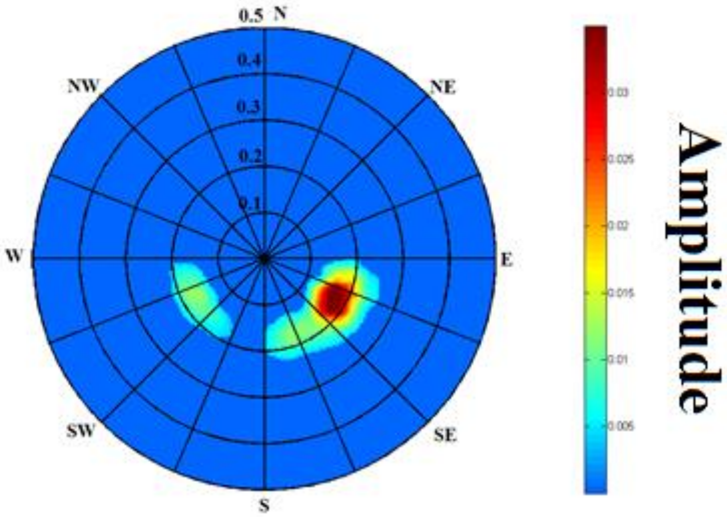

Figure 4 Directional Spectrum obtained by the Remocean system

The reliability of the results of the Remocean system has been tested by a comparison with independent measurements provided by a buoy located in the vicinity of the wreck.

Dominant Sea State parameters	***Buoy***	***Remocean system***
Period (s)	6.3	6.2
Wave direction (deg)	137	136

Table II Comparison between the buoy and Remocean results

As can be seen in Table II, the estimates of the period and direction obtained from the Remocean system are very similar to the direct measurement provided by the buoy, with the difference of only few degrees regarding the direction of the wave.

Figure 5 depicts a spatial map of the sea wave height collected during the storm, which is the final outcome of the inversion procedure. In particular, is possible to observe the presence of two different wave modes: the first one is the dominant mode, coming from South-East, indicated by the yellow arrow; a secondary wave mode, coming from South-West, is indicated by the green arrow.

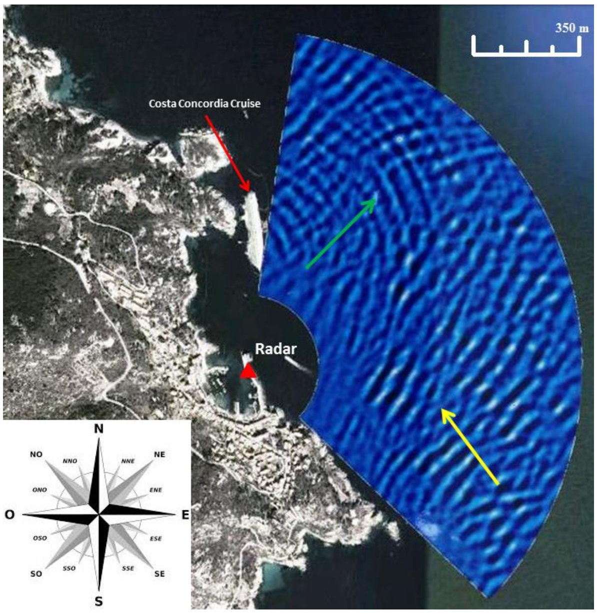

Figure 5 Sea wave height reconstruction provided by the Remocean system. The yellow arrow indicates the direction of the dominant wave mode; the green arrow indicates the direction of the secondary wave mode.

CONCLUSION

This paper has shown the effectiveness of the Remocean system for the sea state monitoring in coastal zones. In particular, we have presented X-band radar observations at Giglio Island, where Remocean system was deployed as an "observational" tool for a support to the Costa Concordia wreck removal operations.
The presence of the "artificial" obstacle of the Costa Concordia has permitted to show the reliability of the Remocean system in order to detect and characterize the phenomenon of the reflection of the sea waves (associated to the dominant mode) impinging on the wreck. The good performance of the Remocean system in the reconstruction/monitoring of the sea dominant mode has been assessed by the comparison with the ground truth measurements provided by a buoy.
Remocean system, has a significant potentiality in the filed of safety of the offshore platform as for the wind turbine platform offshore, where is possible to evaluate the impact of the wave on the structural status of the platform.

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