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Discussions

X-Band Radar for the Monitoring of Sea Waves and Currents: A Comparison between Medium and Short Radar Pulses

Giovanni Ludeno[1], Francesco Raffa[2], Francesco Soldovieri[1], Francesco Serafino[3]

1. Institute for Electromagnetic Sensing of the Environment, National Research Council, Napoli I-80124, Italy (e-mail: ludeno.g@irea.cnr.it; soldovieri.f@irea.cnr.it).
2. Institute for Coastal Marine Environment, National Research Council, 98122 Messina, Italy (e-mail: raffa.francesco@iamc.cnr.it).
3. Institute of Biometeorology of the National Research Council , Florence, Italy (email: serafino.f@irea.cnr.it)

***Abstract*— This letter presents the monitoring results of the sea waves and the surface currents obtained by analyzing data acquired by a X-band marine radar in two different operative conditions, namely the short and medium pulse modes. In particular, we investigated the feasibility to use a medium radar pulse for sea state monitoring by comparing the performance in both the radar modes. The comparison was carried out by means of an experimental campaign and we observed a good agreement for surface current and sea state parameters estimation.**

1. INTRODUCTION

Marine radars are usually used by ships for surveillance purposes, i.e. for the detection and tracking of the targets during the shipping route. This entails surveillance coverages with range scale larger than 6 or 12 nautical miles, which is possible when the radar works in a medium pulse mode. On the other hand, in the last years, X-band marine radar has been also employed as a remote sensing tool for the sea state monitoring both on ships [1-4] and in coastal areas [5-10]. In this "remote sensing" configuration, X-band marine radars radiate short radar pulses with typical time duration of about 60 ns. This allows at carrying out the sea state monitoring at a short range (up to 3 nautical miles) with a high spatial resolution of orders of meters (for a 60 ns short pulse, a spatial resolution of about 9 m is achieved). Therefore, the use of a short pulse is suitable for an accurate estimation of the sea state parameters and allows at detecting sea waves with short wavelength (about 25-30 m).

Differently, for a medium radar pulse, with time duration of about 250 ns, the spatial resolution (of about 35 m) permits the detection of sea waves, whose minimum theoretical wavelength is about 70-75 m.

According to the previous considerations, the choice of the short or medium pulse results as the trade-off between the counteracting aims of surveillance and sea state monitoring; this limits the use of the X-band radar as sea wave monitoring tool during navigation routes.

The main contribution of this work is to provide a first proof of the feasibility about the use of a medium radar pulse for sea state monitoring; this is carried out by comparing the performance of the medium pulse and the short pulse modes.

The comparison has been carried out by means of a measurement campaign at Capo Granitola harbour (Sicily, Southern Italy). During the campaign, 21 radar datasets were collected, 11 in short pulse mode and 10 in medium pulse mode. These datasets were processed by means of the same inversion procedure [11]. In particular, due to the fact that the radar datasets were acquired in coastal area, they were processed with the "Local Method" inversion procedure [5-8]. This inversion scheme has already been tested for the short pulse mode in order to estimate bathymetry and surface current [5-8]. The "Local Method" is based on the normalized scalar product (NSP) procedure [12] for the surface current and bathymetry estimation. The NSP method has been compared with other surface current estimation

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approaches such as Least-Square (LS) [13], Iterative Least Square (ILS) [14], and has provided more reliable results [15].

Therefore, the paper is organized as follows. In Section II, we describe the test site and a brief presentation of the data processing is provided. Section III is devoted to the presentation of the results provided by the same marine radar working in medium and short pulse modes. Finally, conclusions end the paper.

2. TEST SITE DESCRIPTION AND DATA PROCESSING

The data was collected by a radar system (Remocean system) located at Cape Granitola harbour (LAT=37°34'19,70"N; LON=12°39'33,45"E), in Sicily (Italy) (see Fig. 1). The system was installed on an ancient water tank (see inset of Fig. 1) at the Istituto per l'Ambiente Marino Costiero (IAMC) of the Italian National Research Council (CNR), at a height of 15 m above sea level.

The radar system is equipped with a 9 feet (2.74 m) long Consilium Selesmar antenna able to transmit electromagnetic pulses in the X-band with a peak power of 25 kW. Table 1 summarizes the operating parameters of the radar.

The estimation of the surface current and the sea-state reconstruction was achieved by means of the inversion scheme in [5-8]. The core of this retrieval strategy is the use of the Normalized Scalar Product approach [12] for the surface current estimation.

Figure 1 Test site and location of the radar system

Table 1 Parameters of the radar survey

System parameter	Value
Antenna rotation period (Δt)	2.39s
Spatial image spacing (Δx and Δy)	5.0 m

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Minimum range	250 m
Maximum range	2574 m
Processed images number for a sequence (N)	64
Antenna height above sea level	15 m
View angular sector	110 deg

The accurate estimation of sea surface current represents a key step in order to extract the energy of the sea signal from the background noise and estimate the characteristic parameters of sea wave as: the wave period and wavelength; the wave direction of the dominant waves; the significant wave height. In [5-8] authors proposed an improvement of the original version of the NSP method [12], with the aim to reconstruct spatially inhomogeneous bathymetry and sea surface fields. Such a method relies on the spatial partitioning of the investigated region into partially overlapping patches, within which the local estimate of the surface current is obtained. The sea-wave spectrum is after obtained from this filtered radar spectrum through the equalization step based on the radar Modulation Transfer Function (MTF) [11]; this allows us to mitigate the distortions introduced in the radar imaging process [15-16 17-18]. Herein, we adopt the MTF already used for the sea state monitoring in the coastal area in front of Giglio Island [6]. Starting from the reconstructed 3D sea wave spectrum, afterwards we have computed the (2D) directional spectrum and derived parameters, such as the peak wavelength (λp), the peak direction (θp) and the peak period (Tp) of the dominant wave, the significant wave height H_s. Finally, the spatial-temporal sea wave sequence can be reconstructed from the 3D sea-wave spectrum by exploiting the IFFT (Inverse Fast Fourier Transform) technique.

3. EXPERIMENTAL RESULTS

This section presents the estimation results obtained from the analysis of 21 datasets collected by the radar with two different radar settings, i.e. with the short and medium pulse modes. The radar datasets have been acquired with a time delay of about 5 minutes from each other, and each dataset includes 64 consecutive radar images. Figure 2 depicts two sample radar images for the short and medium pulse mode. From these images, we can observe the different spatial resolution; in particular, the data acquired with the short pulse mode (pulse duration equal to 60 ns) exhibit a range resolution of about 9 m, which increases to 35 m if the medium pulse of 250 ns is used. As well known, the interaction of sea wave with the bottom is more significant close to the coast. In particular, as long as the water depth decreases, the wave height increases and the wavelength decreases. For this reason, when the wave radar system is used in medium pulse mode, there is not adequate resolution to discriminate the sea waves in the areas closer to the coast (as shown in bottom panel of Fig. 2). Therefore, we decided to carry out the analysis presented below for the area beyond the minimum range of 500 m till to the maximum range of 2574 m.

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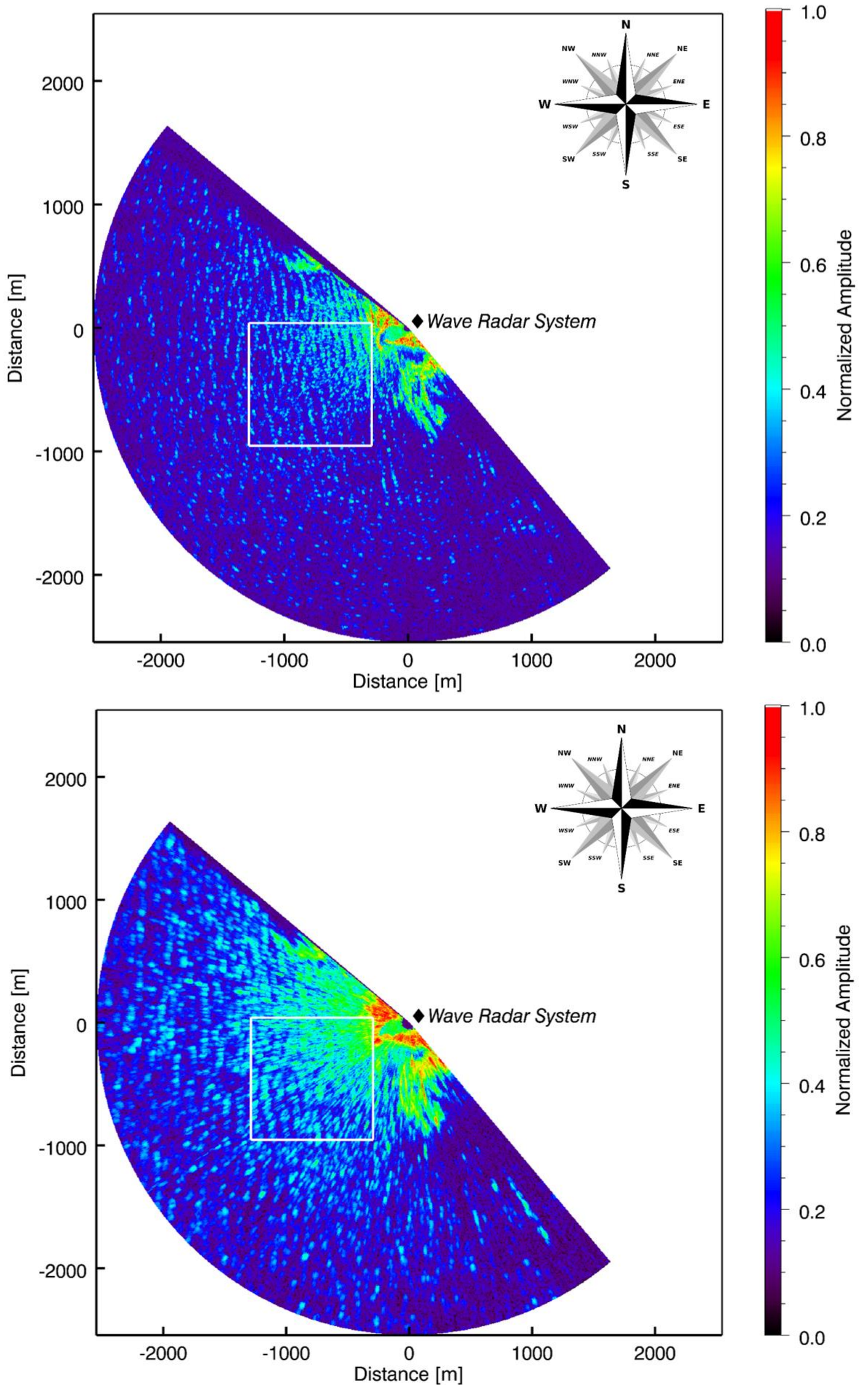

Figure 2 Radar images acquired at Cape Granitola with the short (Top) and medium (Bottom) pulse modes. The white square marked a sub-area, close to the coast, of the radar image.

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Figure 3 depicts the cuts of the 3D radar spectrum, along the direction of the wave propagation, obtained from the two datasets comprising the sample images shown in Figure 2. It is worth to note that the spectral energy relevant to the data acquired with the short pulse mode is spread in a wider wavenumber domain with respect to its counterpart obtained with the medium radar pulse. This result is easily expected due to the fact that short pulse is able to capture sea wave phenomena with higher spatial variability (better resolution). Conversely, the data, collected in the medium pulse mode, provide a spectral representation of the sea, which mostly concentrates at lower wavenumbers, i.e. at larger wavelengths.

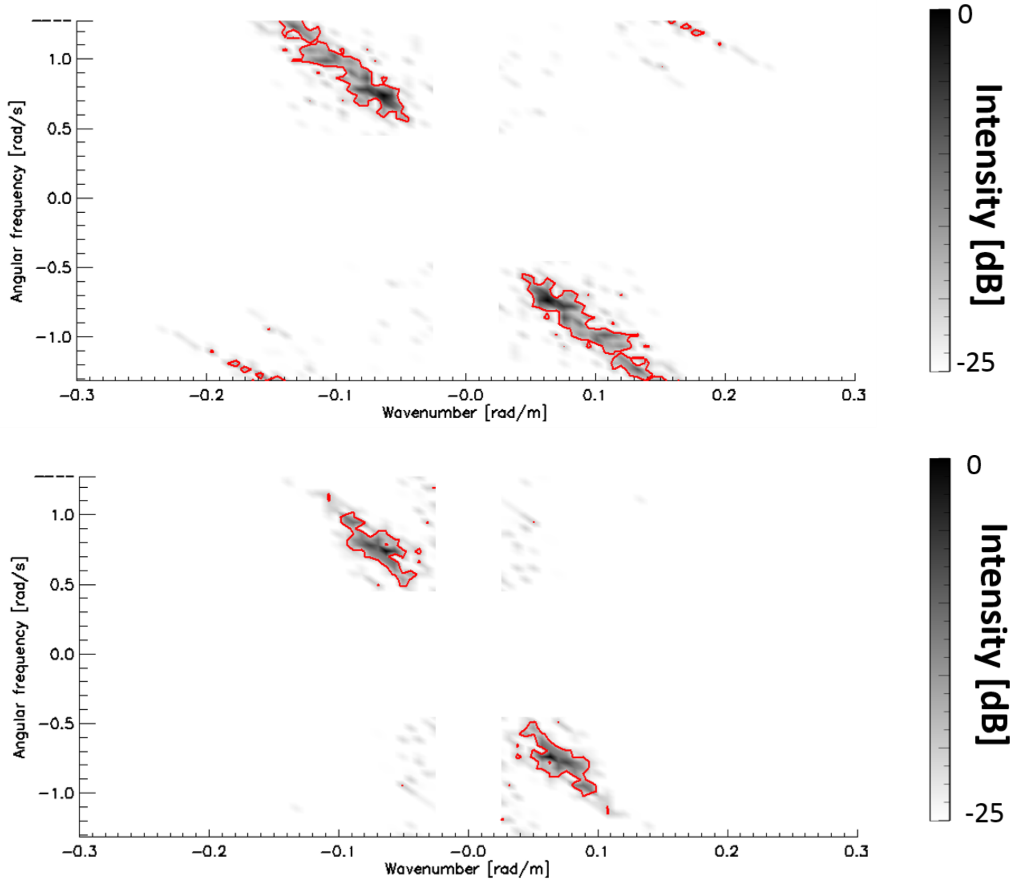

Figure 3 Cuts of the radar spectra relevant to the short (Top) and medium (Bottom) pulse mode configurations. Red edge indicates the region where the radar spectrum intensity is greater than -20dB of the maximum value.

All 21 datasets have been processed through the "Local Method" so to estimate the surface current field. Figure 4 depicts the average values of the intensity and direction of the surface current fields. Figure 4 shows an overall good agreement between the surface current estimation results obtained with the two radar acquisition modes. In particular, the absolute mean error, between the results of the two acquisition modes, is about 0.12 m/s and 22.5° for the average values of the intensity and direction of the sea surface current, respectively. It should be noted that the absolute mean error values are comparable with the sensitivity of the wave radar system for the surface current estimation [19].

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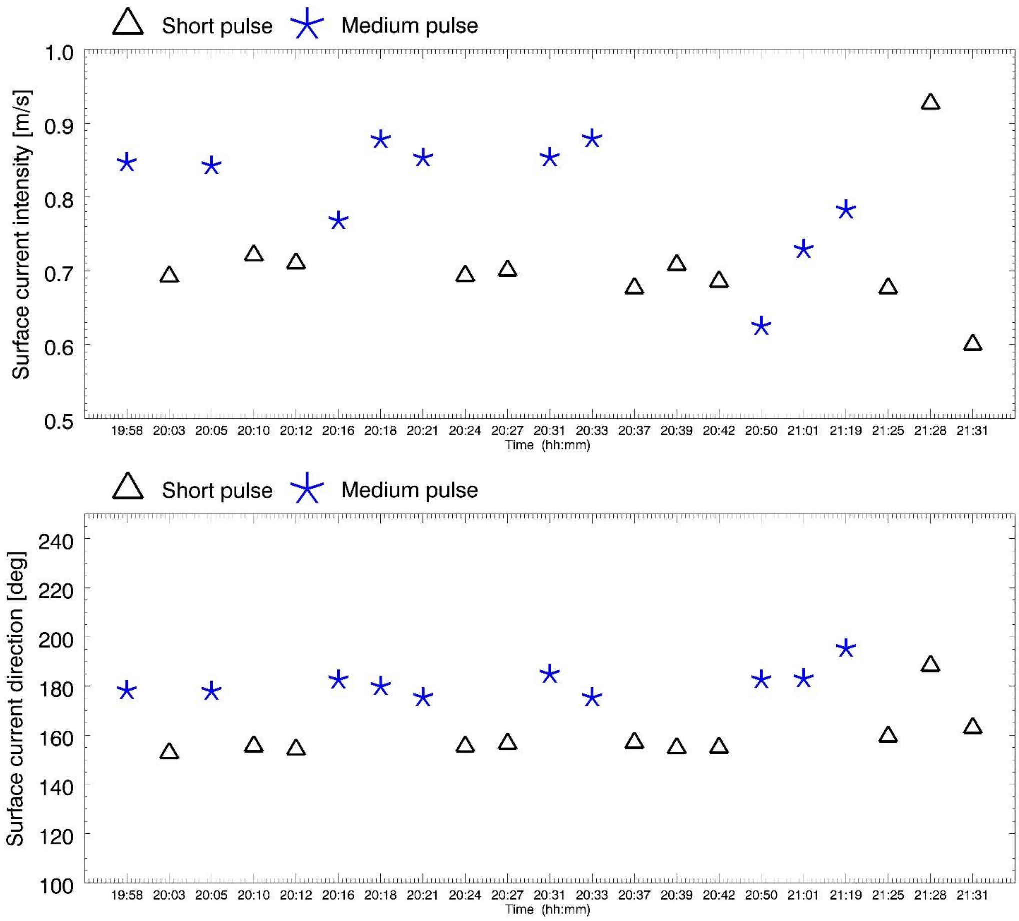

Figure 4 (Top) Surface current intensity estimated in short (black triangle) and medium (blue asterisk) pulse mode. (Bottom) Surface current direction estimated in short (black triangle) and medium (blue asterisk) pulse mode.

The retrieved surface current is after used to build the Pass-Band filter, which allows us to separate the energy of the sea signal from the background noise from the image radar spectrum. Afterwards, the sea-wave spectrum is obtained from this filtered radar spectrum through an equalization step based on the radar Modulation Transfer Function (MTF) [6]. Figure 5 permits to state the good agreement between the two directional spectra obtained from the reconstructed sea-wave spectra relative to the consecutive datasets acquired at 20:33 and 20:37 for the medium and short pulse mode, respectively. The characteristics sea state parameters in term of peak wavelength, peak wave direction and peak period of the dominant waves obtained from the processing of all the datasets are depicted in Fig. 6.

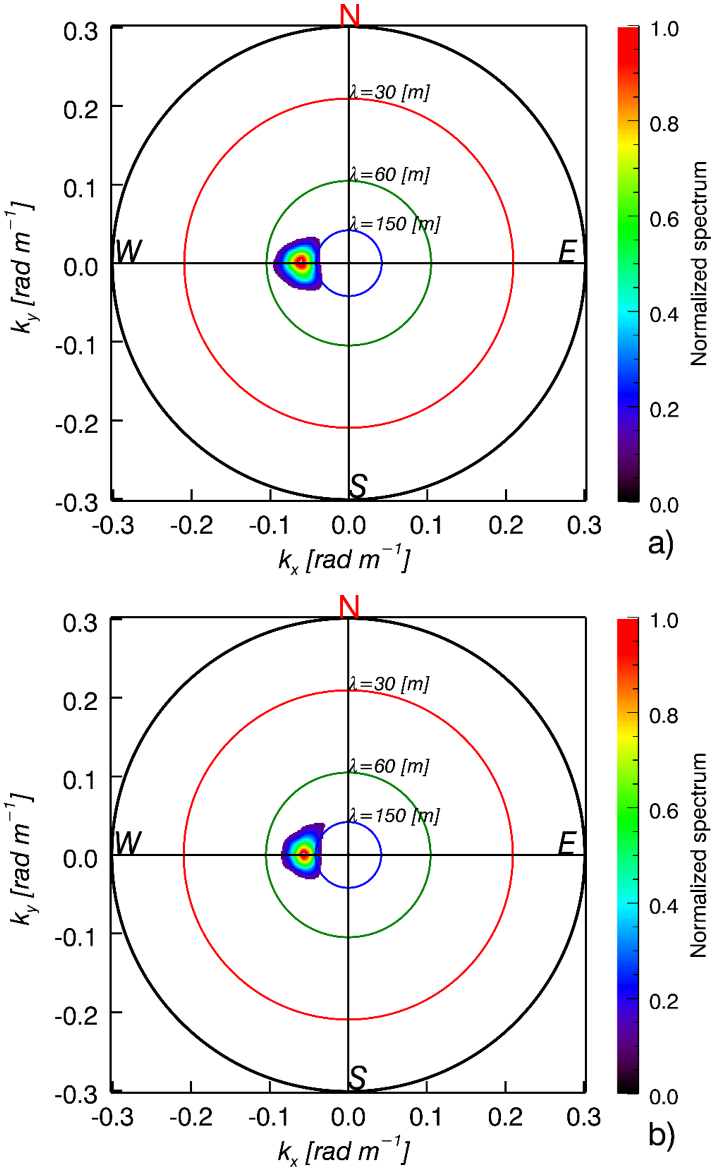

Figure 5 a) Directional spectrum obtained from the radar data acquired in short pulse mode at 20:37 ($\theta_p = 271\ deg$, $T_p = 8.9\ s$, $\lambda_p = 100\ m$) . b) Directional spectrum obtained from the radar data acquired in medium pulse mode at 20:33 ($\theta_p = 270\ deg$, $T_p = 9.2\ s$, $\lambda_p = 110\ m$).

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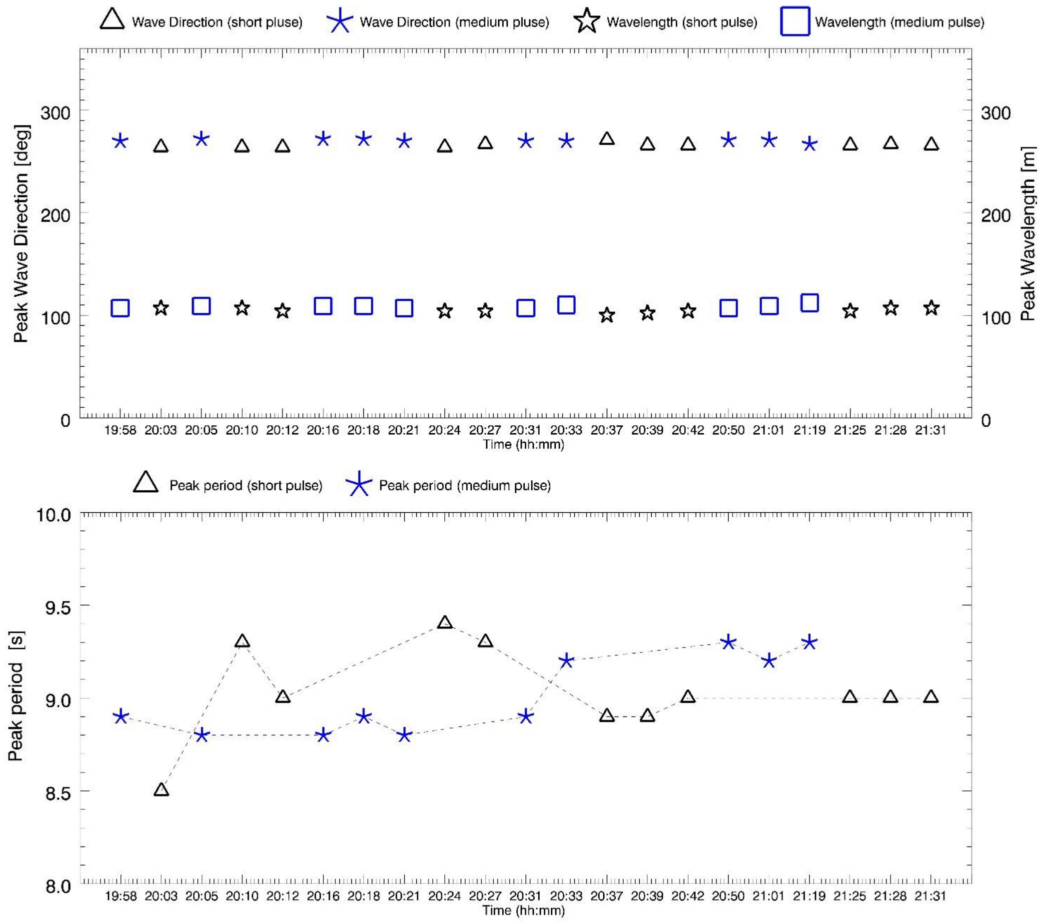

Figure 6 Characteristic sea state parameters obtained from the elaboration of the radar data acquired in short (black color) and medium (blue color) pulse mode, (Top) Peak wave direction and Peak wavelength. (Bottom) Peak wave period.

The main apparent discrepancy between the estimates obtained from the data acquired in the two acquisition modes concerns the significant wave height H_s, which is computed from the 3D sea-wave spectrum $F_w(k_x, k_y, \omega)$ through the following equation [11, 14]

$$H_s = 4\sqrt{\int_{\overline{k},\omega} F_w(k_x, k_y, \omega)\, dk_x dk_y d\omega} \qquad (1)$$

In this regard, it is worth emphasizing that the radar image is not the direct representation of sea surface due the distortions introduced in the electromagnetic scattering phenomenon. In particular, the intensity of the radar signal is mostly related to the electromagnetic backscattering of the sea surface rather than to the sea wave elevation [11,16]. Accordingly, the function $F_w(k_x, k_y, \omega)$ retrieved from the analysis of the radar data represents a scaled version of the actual sea wave spectrum.
In literature, there are two classes of algorithms that have been developed for the estimation of H_s. A first class is based on the calibration of the wave spectra and requires an external reference, such as the wave buoy [11,16, 20]. The second class of approaches does not require calibrations using additional reference sensors [20-23].

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A calibration stage has been carried out in campaigns previously carried out with the same radar working in the short pulse configuration [24,25] thanks to the use of buoy observations. Therefore, although no independent measurements of the significant wave height are available for this present campaign, we can consider the H_s estimations reliable for the short pulse mode.

Figure 7 shows a comparison between the H_s estimates obtained from the radar data collected with the two acquisition modes when the calibration factor is the one adopted for short pulse mode. Of course, the two estimations are different but this difference is mostly for a multiplicative factor, whereas the temporal behavior of the two estimates is almost the same. This suggests to adopt for the medium pulse a calibration factor that is equal to the calibration factor of the short pulse mode times the multiplicative factor. By adopting this strategy, we achieve a good agreement, as shown by Fig. 7, where red crows represent the estimates for medium pulse mode configuration.

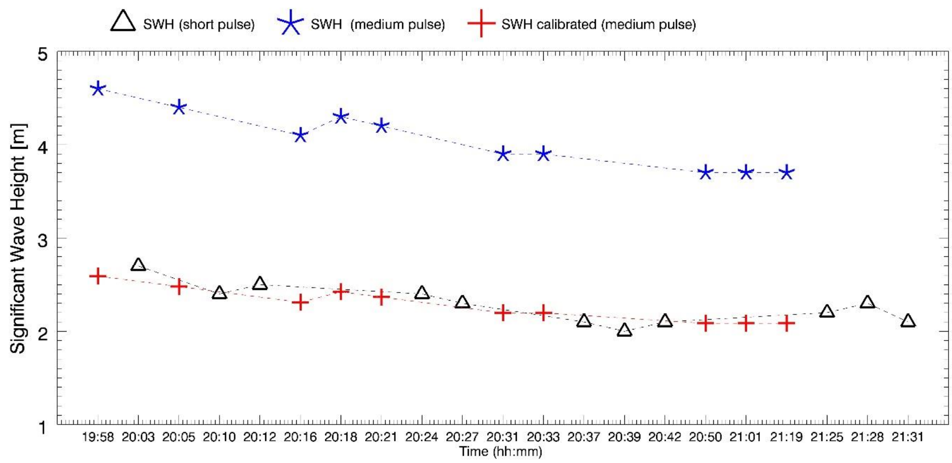

Figure 7 Significant wave height obtained from the processing of the radar data acquired in short (black color) and medium (blue color) without calibration factor. Red crows indicate significant wave height for calibrated medium pulse data.

4. CONCLUSIONS

This paper, presents a first proof of feasibility of the sea state monitoring from data collected in medium pulse mode by a wave radar system. In particular, the reliability of medium pulse mode has been evaluated by considering a comparison with the estimations retrieved from data collected in short pulse mode. Although we have processed a small temporal interval of the radar data, the preliminary analysis here presented makes us confident that a reliable sea state monitoring can be obtained also when the medium pulse configuration mode is adopted. In particular, for the surface current estimation, the discrepancies between the two modes are comparable with the sensitivity of the wave radar system and a good agreement has been observed for the sea state parameters. Specific attention has been paid to the significant wave height estimation, where a recalibration procedure was necessary for medium pulse in order to achieve good results.

As future developments, further study activity (already in course) has to be performed in order to analyze the performances in a more systematic way by considering long term observations in different sea state conditions.

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