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Inter-comparison of HF radar wave measurements in the Malta-Sicily Channel

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Abstract – **The CALYPSO HF radar network is a permanent and fully operational observing system currently composed of four CODAR HF stations. The system is providing real-time hourly maps of sea surface currents and wave data in the Malta-Sicily Channel since 2012.**

The present work aims to compare significant wave height from HF Radar, numerical models and satellite altimeter data.

This is the first time that this set of wave data are analysed since the four HF radars were installed between 2012 and 2015.

Results suggest that CODAR HF Radar wave data are a reliable source of wave information even in case of extreme events, providing an avenue to improve and complete the offer of services deriving from the CALYPSO system.

Comparisons of HF radar data with both numerical sea wave model and satellite altimeter data confirm agreement, in particular for radar measurements in the annular sectors within the central range-cells which are also characterized by a more reliable and homogeneous temporal behaviour.

Keywords: wave parameters, HF radar, wave models, satellite altimeter, Malta-Sicily Channel

I. INTRODUCTION

Wave buoys are among the most reliable instruments for in situ measurements of the offshore and coastal wave climate. These observation platforms are probably still the most used and trusted method for wave measurement, providing information at a single fixed point; on the other hand the setting up of wave buoys comprises problems because of the time effort, the costs and the permissions needed for their installation.

Although the radar altimeter and the Synthetic Aperture Radar (SAR) suffer the large temporal resolution of the satellite products, these data can partially fill the spatial gap in describing the time and spatial evolution of the wave field [1]. Ground based remote sensing instruments (high frequency-HF and microwave X-band radars) provide directional wave spectra at a high temporal resolution, but the area covered by these instruments is restricted. Results are provided in *quasi* real time with a spatial resolution that depends on the allocated bandwidth and antenna design, and varies from 250 m up to 15 km [2].

All of the illustrated wave measurements do not allow singularly a detailed and continuous monitoring of the wave field.

Significant improvements of numerical wave models over the past years have been made and they have become a very powerful tool in ocean wave forecasting. However the lack of good-quality boundary conditions, and of wind forcing fields and bathymetry data results in the discrepancies of model results [3]. Moreover, in coastal areas where the physical processes caused by the interaction between waves, currents and the bottom become important, the spatial wave properties are strongly variable, and model uncertainty increases.

In such a dynamic environment, HF radar measurements can play an essential role to considerably increase the knowledge of these complex physical processes and their interactions [4]. Some recent works investigated the assimilation of HF radar data in numerical wave models, such as Wavewacth III [5] and the SWAN model [6], providing satisfactory improvements particularly for significant wave height estimations during high sea states.

The near-real time data provided by HF radar can be of assistance to many operational activities and the synoptic measurements of both currents and wave heights would allow the characterization of wave-current interactions, which have been found to play an important role in wave resource estimates [7].

However, while HF radar surface currents are considered reliable measurements, which are routinely used for oceanographic studies and for operational services, the inversion of the second-order part of the Doppler spectrum into meaningful wave data is an area of active research, and the validity of the HF radar wave products is still under study.

The measurement of surface sea currents is therefore the primary activity of the majority of HF radars installed worldwide, which have accordingly been optimized for this purpose as reported by several studies on coastal processes using HF radar-derived surface currents [*eg.* 8].

The credibility of HF radar wave measurements is therefore still not supported by enough data assessments from radars adequately configured for such task. Without these data, and their validation against well established wave measuring techniques, it is not possible to identify the appropriate error bounds for the HF radar wave measurements and to advance their operational use as summarized in *e.g.* [9] and [2].

In the Mediterranean Sea, HF radar systems have been deployed in relatively few coastal areas, even though the number is rapidly increasing.

With the partial financing by the EU under the Operational Programme Italia-Malta 2007-2013, the CALYPSO project and its follow-on activity has delivered a permanent and fully operational HF radar observing network capable of recording (in *quasi* real-time with hourly updates) surface currents and wave data in the Malta-Sicily Channel [10]. The area of interest is shown in Fig.1.

The availability of CALYPSO data is allowing new insights on the hydro-dynamical signals in the area especially on the mesoscale and sub-mesoscale variability [11]. The combination of HF radar data to numerical models supports applications to optimise intervention in case of oil spill response as well as for search and rescue, security, safer navigation and improved meteo-marine forecasts. CALYPSO data can also support the operational monitoring of sea conditions in critical areas like the proximity to ports. In this framework, as a first attempt, the comparison between significant wave height data from the four CALYPSO HF radars, an operational WAM model and three altimeter satellites has been performed to evaluate and independently corroborate the reliability and accuracy of using HF radar measurements.

II. MATERIAL AND METHODS

A. The study area

The topography and bathymetry of the Maltese Islands influences the flow of water in the central area of the Strait of Sicily [12]. This flow corresponds to the constrained passageway connecting the western and eastern Mediterranean sub-basins which is characterised by a complex bathymetry with wide continental shelves, deep and shallow channels as well as deep grabens.

The study area is shown in Fig. 1 where the locations of the four HF radars and the circular concentric ranges (annular rings) of their wave measurements are indicated.

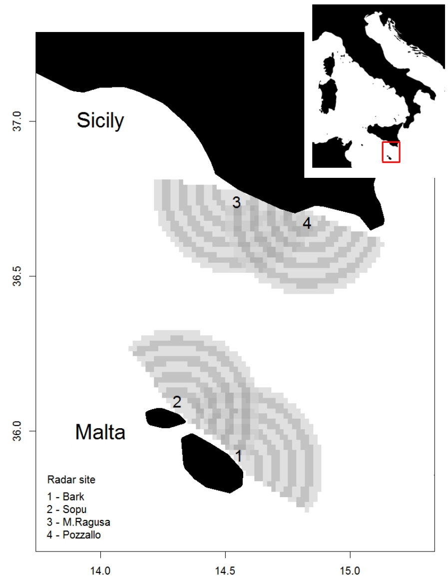

Fig. 1. HF radar locations and their annular range cells

In particular, the four HF radar stations are located at Ta' Barkat and Ta' Sopu on the northern Malta/Gozo coastline, and at Ragusa and Pozzallo harbours on the southern Sicilian shores.

The wave climatology in the study area has been investigated by other authors that applied UK Meteorological Office (UKMO) Wave Model data sets generated between 1988 and 2002 [13]. The results indicate that significant wave heights are milder for the summer period when compared to the annual period. The predominant wave direction is from the north-west; waves from the south-east are also relatively frequent, while waves with directions from the south-east and north-east occur less frequently.

B. Data set

Two twin combine servers (in Malta and in Sicily) elaborate and publish data to users through a dedicated quick-view and data access interface [14].

The data used in the study spans over three months, from December 2016 to February 2017, and comprises several climatologically relevant storms.

The significant wave height at half-hour intervals are obtained by HF from close-in radar range sectors, each sector being approximately 1.6 km distant.

The numerical WAM model data is derived from the ISPRA regional model which produces the main wave parameters over a grid having a spatial resolution of 1/60 degrees and a temporal resolution of one hour. The WAM model has been validated against Italian RON buoys and a very good agreement is found as well at regional scale [15]. For this dataset the significant wave height, at one hour intervals, are obtained at the radar range sectors

Satellite altimeter wave measurements are obtained by analysing the shape and intensity of the altimeter radar

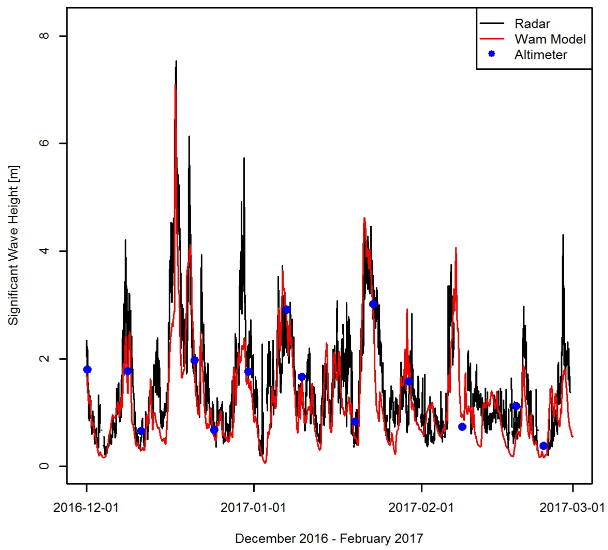

Fig. 2. Time series of SWH from HF radar (black line), WAM model (red line) and altimeter data (blue dots) at Ta' Barkat site, third annular rings. December 2016-February 2017.

beam reflected from the sea surface, and hence give only the significant wave height (SWH). Passes over the Malta-Sicily Channel from the Jason 2, Jason 3 and Saral Altika missions have been selected. To create a compatible set of near-simultaneous SWH data from satellite altimeter and HF radar data at 30km from the radar origin every 30-minute intervals were used.

C. Data Analysis

Time series plots of SWH from radar, model and altimeter data are produced and the main statistical diagnostics of MSE and BIAS are computed to evaluate the agreement between the different sources. Given that the radar data are available over different annular rings, each 1.6 km wide, it was important to investigate how the correlation between model, altimeter and HF radar SWH varies with distance from the radar origin. Thus, the Pearson correlation coefficients and RMS differences have been computed comprising the three sources of data at each available annular sector.

III. RESULTS

For the sake of simplicity only results referring to Ta' Barkat site are reported because a similar behaviour has been found at the other three sites.

Fig. 2 displays the time series plot of SWH from radar, model and altimeter data in correspondence of the third annular ring. It reveals the very good agreement of SWH provided by the different data sources, even in case of extreme waves. Indeed, the detection of extreme events is well performed both in terms of forecasting and observations; this demonstrates that both HF radar and WAM model data could be useful to alert services for marine operators (not always verified for the altimeter, due to the less temporal resolution).

Table 1. Main statistical parameters for SWH radar and SWH wam model agreement evaluation. Ta Bark. site

Annular rings	MSE	BIAS	Correlation
1	0.643	0.654	0.824
2	0.444	0.784	0.813
3	0.437	0.827	0.801
4	0.496	0.803	0.794
5	0.581	0.779	0.784
6	0.674	0.758	0.773
7	0.686	0.758	0.774

Table 2. Main statistical parameters for SWH radar and SWH altimeter agreement evaluation. Ta Bark. site

Annular rings	MSE	BIAS	Correlation
1	0.255	0.677	0.875
2	0.158	0.787	0.863
3	0.066	0.798	0.943
4	0.104	0.793	0.909
5	0.149	0.785	0.88
6	0.088	0.786	0.92
7	0.133	0.761	0.875

It is worth noting, for instance, the event from 17th to 20th of December, when a storm occurred with a return period of 4 years, previewed by models and registered by the HF radar.

During this event both radar and WAM model registered a value of significant wave heights of ~ 8 m, with WAM slightly underestimating the SWH.

Table 1 and 2 list the main metrics accounting for the agreement between SWH values taking radar HF as reference one.

MSE values vary with the distance from the radar origin; errors are lower not too far neither too close to the radar origin, *i.e.* the better agreement is achieved in the intermediate rings respect to the radar origin.

BIAS values indicate the same spatial behaviour; moreover, BIAS values show a tendency of the HF radar to register higher values of SWH with respect to the WAM model, whereas the agreement with altimeter data seems to be higher.

Correlations show very high values; in particular the agreement of SWH from HF radar and altimeter data is higher even if this result could be influenced by the lower points used for the comparison. Again as an example, the correlation coefficient and RMS differences of the radar-WAM and the radar-altimeter pairs are computed and plotted in Fig. 3 as a function of distance from the radar

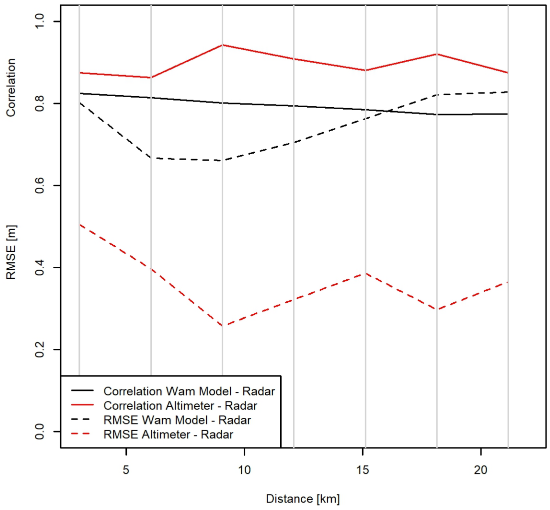

Fig. 3. Correlation (solid line) and RMSE (dashed line) values, between WAM model and HF radar data (black line), altimeter and HF radar data (black line). Y-axis represents the distance from the radar origin at the Ta' Barkat site.

origin at the Ta' Barkat site.

The correlation between model, altimeter and HF radar SWH, is always high indicating a linear relation between the different sources of data. In particular, the correlation between HF radar and WAM model slightly decreases as the distance from the radar origin increases.

RMS differences reveal that there is an optimal distance from the radar site for the relevance of the HF radar wave data, being most accurate at the intermediate distances from the coast and deteriorating both closer to coast as well as further offshore. These results can be similarly extended to the other radar stations even though it is noticed that the HF radar wave data are subject to differing interfering noise in the signal depending on the station.

IV. CONCLUSIONS

The study confirms that CODAR HF radar data are a reliable source to describe sea wave conditions in *quasi* real-time. This opens the way to the use of HF radar in the delivery of added value services that integrate sea conditions in support to safer navigation and operations at sea, as well as for more precise nowcasting services including conditions of adverse and extreme weather situations. In addition, the strong correspondence between the WAM model and the HF radar data, suggest that the latter could be used to specifically calibrate numerical wave models (or assimilate them). Further analysis will assess the more detailed performance of HF radar across different bands of sea wavelengths and different wave heights. Other further investigations will focused on other wave parameters, such as wave period and direction. It is also expected to extend the study by direct correlation to wave buoy measurements.

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