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HF radar for wind waves measurements in the Malta-Sicily Channel

Arianna Orasi[a,*], Marco Picone[a], Aldo Drago[b], Fulvio Capodici[c], Adam Gauci[b], Gabriele Nardone[a], Roberto Inghilesi[a], Joel Azzopardi[b], Anthony Galea[b], Giuseppe Ciraolo[c], Jorge Sánchez Musulin[d], Andres Alonso-Martirena[d]

[a] *ISPRA, CN-COS, via Vitaliano Brancati 60, Rome 00144, Italy*
[b] *University of Malta, Physical Oceanography Research Group, Dept. of Geosciences, Msida MSD 2080, Malta*
[c] *University of Palermo, DICAM, Viale delle Scienze Ed. 8, Palermo 90128, Italy*
[d] *QUALITAS Remos, C. Toronga 31, Madrid 28.043, Spain*

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ABSTRACT

The CALYPSO HF radar network is a permanent and fully operational observing system currently composed of four CODAR SeaSonde stations. The system is providing real-time hourly maps of sea surface currents and waves data in the Malta-Sicily Channel. The present work aims to compare significant wave height measurements by HF Radar to wave data from numerical models and satellite altimeter. 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 the 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.

1. Introduction

Wave buoys are considered to be the most used and reliable observation platforms for in situ measurements of the offshore and coastal wave climate. They provide wave measurements at only a few selected single fixed points, but offer a solution for long term assessments with high temporal resolution at each mooring. However, the setting up of wave buoy stations comprises problems because of the time effort, the costs and the permissions needed for their installation. An exhaustive overview of the advantages and limits of this waves observation technique is given in [1]. On the other hand the radar altimeter and the Synthetic Aperture Radar (SAR) borne by remote satellite platforms can span data over large marine domains and offer unmatched synoptic scales; however satellite products are limited by the comparatively much larger temporal gaps between successive passes and can therefore only partially describe the evolution of the wave field [2].

All of these illustrated wave measurements do not allow singularly a detailed and continuous monitoring of the wave field. Significant advances in numerical wave modelling over the past years have rendered such models to become a very powerful tool in ocean wave forecasting. However, the lack of good-quality boundary conditions, and of wind forcing fields and bathymetric data remain a principal bottleneck leading to discrepancies in model results [3]. The good quality of the short term wave forecasts, in particular for the Mediterranean Sea, is still a difficult task due to the large spatial and temporal variability of the surface wind field over this basin. Wind-wave models are very sensitive to wind field variations which result in one of the main source of errors in wave predictions. The sensitivity of wave model prediction to variations in wind forcing fields has been studied by several authors [4–6]. This is particularly true for the Mediterranean where the limited contribution of swell to the wave spectrum makes the regional wind conditions the most important factor in determining the local wave state.Finally It is argued that for sea state forecasting in the coastal zone, an area of important economic significance, knowledge of the current and the mean sea level is very important. Actually, in coastal areas where the physical processes caused by the interaction of waves, currents and the sea bottom become important, the spatial wave properties are strongly variable, and model uncertainty increases.

In such dynamic environment, HF radar measurements can play an essential role to considerably increase the knowledge of these complex physical processes and their interactions [7]. Ground based remote sensing instruments (high frequency-HF and microwave X-band radars) provide directional wave spectra at a high temporal resolution. Results are provided in quasi real time with a spatial resolution that depends on

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[*] Corresponding author.
E-mail address: arianna.orasi@isprambiente.it (A. Orasi).

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the allocated bandwidth and antenna design, varying from 250 m up to 15 km [8]. The system characteristics also control the area covered by these instruments which spans between few to hundred kilometres.

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 [9], for coastal zone planning, protection, and management including wave energy resources [10] and safety at sea. In particular in places where strong currents are opposed to winds and waves, sea currents can affect the wave state both on small and large scales. For example large-scale oceanic currents can cause extreme sea states that are a hazard to navigation [11]; whereas small scales current variations can produce an enhancement of wave breaking and dissipation [12]. Some recent works investigated the assimilation of HF radar data in numerical wave models, such as Wavewacth III [13] and the SWAN model [14], providing satisfactory improvements particularly for significant wave height estimations during high sea states.

An integrated HF radar network providing real-time and quality controlled information is operative in the United States [15] and in Australia [16], while in Europe although some countries have implemented national HF radar systems [17,18], it is not yet developed a unified network. In particular, in the Mediterranean Sea, HF radar systems, mainly set up in the framework of EU funded project [19,18,20], have been deployed in relatively few coastal areas, even though the number is rapidly increasing.

Contrary to HF radar surface currents which have been extensively proved to be reliable measurements for routine use in oceanographic studies and for operational services, the inversion of the second-order component 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. Two main methods are currently used to obtain wave information from the second-order radar spectrum: full integral inversion and fitting with a model of the ocean wave spectrum. 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. [21]). On the other hand the validity of the HF radar wave measurements is still not adequately supported by sufficient data assessments from radars configured for such tasks. Without this kind of data, and its 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. [22,8]. Another limitation of the theory supporting waves extraction and calculation by HF radar is related to the maximum wave height and saturation and convolution of first and second order spectra. With the 13.5 MHz frequency in application in the Malta Channel HF radars there is a theoretical cut-off value for wave period and for significant wave height [8,23] which is of approximately 7.5 m where the first and second order Bragg region merge in high sea-state and wave measurements by HF radar is not longer possible. There have been so far not enough studies describing how this theoretical limitation impacts fit-to-model waves calculation methods. Application studies have documented sea-states measured with 13.5 MHz SeaSonde HF radars with Hs data measured in between 7.5 and 8.5 m though no uncertainty assessment for this extreme data set is available. The Malta-Sicily data set and the comparison established between HF radar and altimetry data in the range in between 7.5 and 8.5 m as presented in section Results of this document is a first attempt to do this and will be the basis for future studies. The ocean community recognizes a high potential and importance to develop a standard capability to provide operational waves measurement by HF radar in a regular way from any site same as happens today for currents measurement. There is plenty of ongoing research around this topic structured in two main streams of work which are a) the development of algorithms which are specific and constrained to the HF radar observing technology applied in each case such as direction-finding SeaSonde in the Malta-Sicily case b) the analysis of the performance and limitations of an existing technology in a specific environment under a variety of met-ocean conditions [24–28]. The present work focuses on the study of the utility and performance of HF radar to measure waves in the Malta-Sicily Channel by comparing its output during a period with extreme wave conditions with satellite altimetry and wave models, not on the algorithms of the implemented HF radar which are established methods and described for SeaSonde HF radar thoroughly in the literature [29–32,23,25].

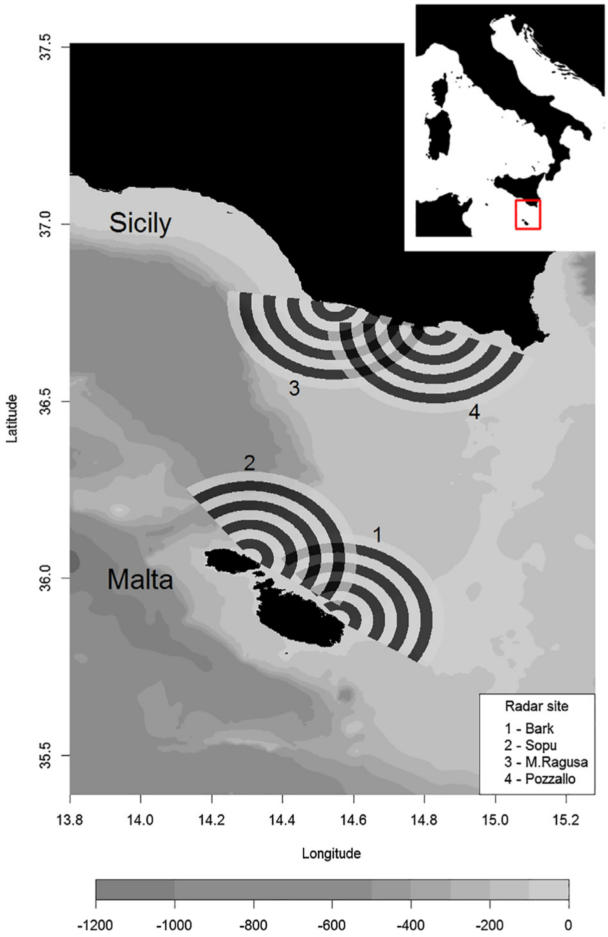

Fig. 1. HF radar locations and their annular range cells.

2. The CALYPSO HF radar monitoring system for wave measurements

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 [20]. The area of interest is shown in Fig. 1.

The first pair of HF Radars and a combine station were installed on the Maltese Islands in 2012. One radar is located at Ta' Barkat, limits of Xghajra, Malta (coord: $35^{\circ}52'56.7001''N$, $14^{\circ}33'22.0799''E$); the second radar is installed at Ta' Sopu, limits of Nadur, in Gozo (coord: $36^{\circ}3'22.9201''N$, $14^{\circ}18'30.24''E$); whereas the combine server is hosted by the University of Malta (UM). Similarly, two other radars were installed inside the harbours of Pozzallo (coord: $36^{\circ}42'37.9199''N$, $14^{\circ}49'47.5799''E$) (2013) and Marina di Ragusa(coord: $36^{\circ}46'40.1999''N$, $14^{\circ}32'53.5801''E$) (2016) respectively. In 2016, an additional combine server was installed at University of Palermo (UNIPA). All these HF stations are linked to two servers at UM and UNIPA respectively which combines all radials into two-dimensional sea surface current maps in real time. Sites were chosen such as to minimize the distance between the antenna and the waterfront to avoid signal attenuation by land. The radars were erected within line-of-sight of each other. In particular, the baseline between Ta' Barkat and Ta' Sopu is of 29.5 km. Pozzallo and Ragusa are separated by about 26.5 km. The closest Sicilian radar to Ta' Sopu is that installed at Ragusa which is 83 km away. On the other hand, Ta' Barkat is closest to the Pozzallo antenna which is 95 km away. With such a configuration, data covering the full Malta Channel is obtained.

At each site, a SeaSonde compact HF radar system is operating with a trasmission frequency of 13.5 MHz. A thorough HF radar quality assurance and quality control plan following established methods was carried out at the time of system implementation and is continued as part of the system maintenance and operation over the years. QA started with the scanning of the assigned ITU band using a SDR-IQ radio and the analysis of a three month period of ocean backscatter gathered by the currently installed HF radar stations in order to find sub-bands with consistently lower interference levels. After selection of the optimal frequency sub-band a three month data set was collected and the respective spectra were analyzed in search of various ocean conditions in order to better adjust the first and second order settings of each station and, through this, ensure an optimal quality of the measured data.

As part of the initial QA/QC works, antenna pattern measurements (APMs) were performed to ensure data quality by inserting the specific antenna calibration into the real-time ocean variables calculation methods. APMs are performed since then periodically every two years to ensure the antenna and receiver channel properties haven't changed or if they did to adapt the pattern. Once the system was optimized, it was then released for its operational use. Since then a dedicated specialist team takes care of its maintenance following state of art methods which include staff time and automatic tasks such as the monitoring of critical system values like forward/reflected power, voltages and temperatures of several hardware components as well as variables related to the data such as variations in SNR, noise floors, phases and amplitudes. On top of this, periodic validation exercises of the HF radar measured data with other kinds of instrumentation like ADCPs an lagrangian drifters are performed [33–35].

Each station provides robust radial measurements of ocean surface currents which are obtained from the dominant first order peak in the radar echo spectrum. Methods to derive directional information about wind waves from a narrow radar beam started with the formulation of the theoretical expression of the HF sea-echo Doppler spectrum in terms of the ocean wave height directional spectrum and the surface current velocity by [36,37]. Subsequent studies [23,38,39] describe the extension of the narrow beam method to apply to broad-beam SeaSonde data. Wave parameters such as significant wave height, wave period and wave direction are measured with SeaSonde HF radars from the second-order portion of the echo spectrum and extracted along the annular rings centred in each of the radar stations. The detailed theory and mathematical formulation for the extraction of sea state applied to crossed-loop/monopole SeaSonde system from the narrow-beam derivation follows established methods [29–32,23]. SeaSonde Radial suite release 7 which is the one in application in the Malta Channel system uses ideal beam patterns for the calculation of waves data. In Ta' Barkat, Ta' Sopu and Marina di Ragusa the antenna environment fulfils technology requirements to provide accurate wave measurements with no relevant antenna radioelectric distortion in any of these sites.

The main wave parameters are obtained by performing a least squares fitting technique between the second-order radar spectrum and a Pierson-Moskovitz with cardioid directional function model.The Pierson-Moskowitz fit-to-spectrum model integrated into the Malta-Sicily HF radar stations has proven to be useful in wind dominated seas and also in swell dominated seas [28,24,26,27] while there is scientific evidence this can be different under some combination of bi-modal sea-states or when winds blow from land. Analysis of HF radar capability to measure waves under these particular conditions shall be the purpose of future work which will aim at defining how uncertainty of measurement can vary in relation to some relevant variables that define specific complex met-ocean conditions.

Analysis methods presently in use are based on the assumption of infinite water depth, and may therefore be inadequate close to shore where the radar echo is strongest [40]. Algorithms applied to HF radar spectrum for the calculation of wave parameters have therefore an important limitation which is the presence of shallow water. In the case of the Malta Channel HF radars limiting shallow water conditions are of 20 m. By looking at Fig. 1 which has a representation of the annular crowns used for the waves extraction on top of the bathymetry, we can conclude that all range cells or annular crowns starting with the second one have deep water conditions in its full domain. Variability of the sea-state inside the first five annular crowns, being those range cells almost completely inside the shadow area of the island where the antenna is installed, is low as expected. For range cells beyond that this stays the same during the main storm event analyzed in this paper.

Another limitation of the theory supporting waves extraction and calculation by HF radar is related to the maximum wave height and saturation and convolution of first and second order spectra. With the 13.5 MHz frequency in application in the Malta Channel HF radars there is a theoretical cut-off value for wave period and for significant wave height [8,23] which is of approximately 7.5 m where the first and second order Bragg region merge in high sea-state and wave measurements by HF radar is not longer possible. There have been so far not enough studies describing how this theoretical limitation impacts fit-to-model waves calculation methods. Application studies have documented sea-states measured with 13.5 MHz SeaSonde HF radars with Hs data measured in between 7.5 and 8.5 m though no uncertainty assessment for this extreme data set is available. The Malta-Sicily data set and the comparison established between HF radar and altimetry data in the range in between 7.5 and 8.5 m is a first attempt to do this and will be the basis for future studies.

The availability of CALYPSO data is allowing new insights on the hydrodynamical signals in the area especially on the mesoscale and sub-mesoscale variability [41]. 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 operations, security, safer navigation and improved meteo-marine forecasting. CALYPSO data can also support the operational monitoring of sea conditions in critical areas like the proximity to ports.

Under 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 for wave monitoring and assessments.

3. Materials and methods

3.1. The study area

The study area is shown in Fig. 2 where the locations of the four HF radars and the circular concentric ranges (annular rings) of their wave measurements are indicated. The Maltese islands are located in the Central Mediterranean Sea, 93 km south of Sicily. The archipelago consists of the Islands of Malta, Gozo and Comino. The Malta-Sicily Channel, the strip of sea dividing the Maltese Islands from the southern Sicilian coast, is located inside the southeastern continental shelf of Sicily presenting a complex bathymetry in the form of a large, roughly square bank with the Maltese Islands, residing on its southernmost extremity. A plateau with an average depth of 150 m characterizes the

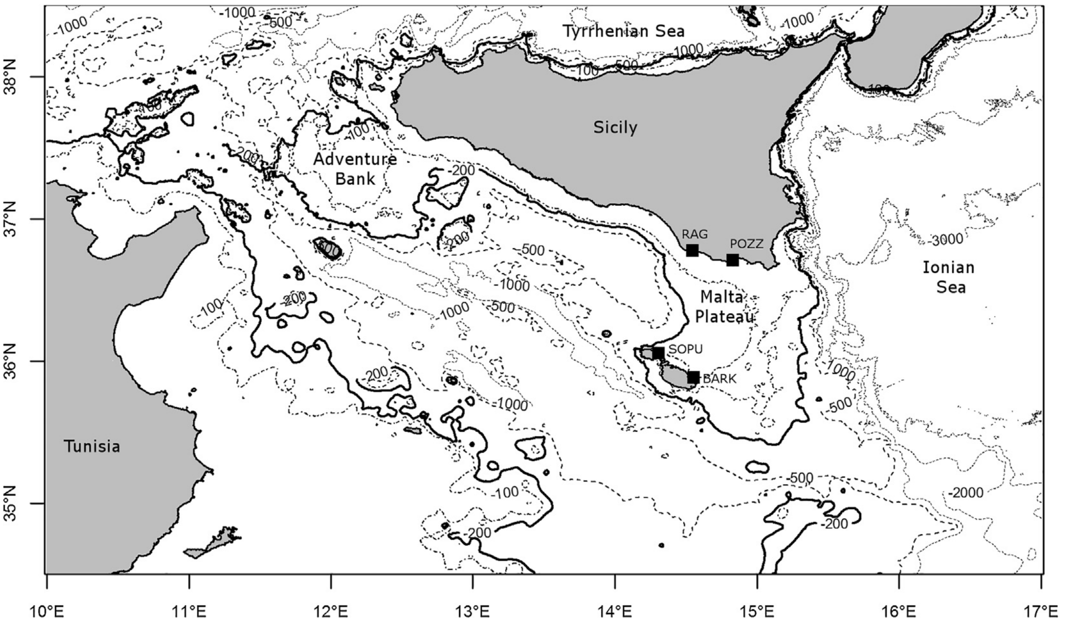

Fig. 2. The study area (Malta-Sicily Channel), with the locations of the four radar stations and the main topographical structures in the region. Black squared denote the SeaSonde installations in the Maltese archipelago (SOPU, BARK), and along the Sicilian coast (RAG, POZZ).

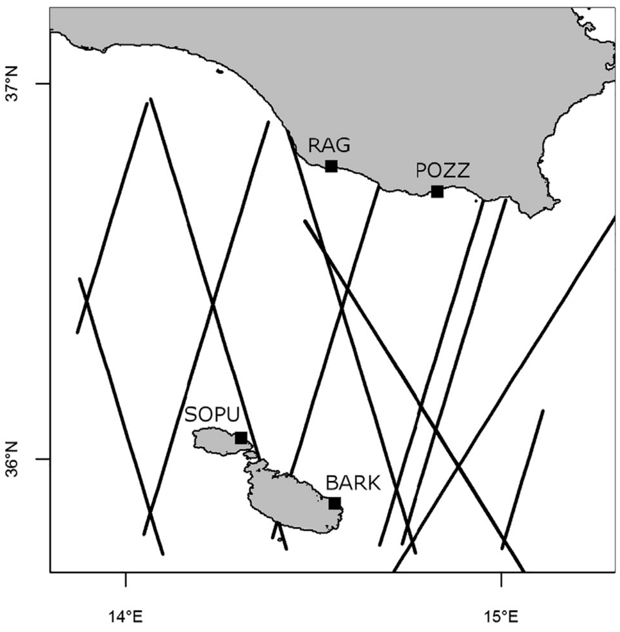

Fig. 3. Altimeter tracks over the study area.

shelf in this area. The Maltese Islands are very close to the shelf break and flanked by a very steep bathymetry in the south [42].

The topography and bathymetry of the Maltese Islands influences the flow of water in the central area of the Strait of Sicily [43]. The currents in the Malta-Sicily Channel are mainly driven by the slow Mediterranean thermoaline basin scale circulation which has two-layer flow consisting of a fresh Modified Atlantic Water (MAW) eastward surface flow, and a deeper saltier westward Levantine water flow. In particular the energetic and meandering Atlantic Ionian Stream (AIS) [44] characterizes the surface circulation throughout the year. This swift current proceeds south-eastwards and loop back northward around Malta and as it reaches the sharp shelf break to the east of Malta it gains positive vorticity and tends to deflect with an intense looping northward meander, forming the characteristic Ionian shelf break vortex.

In the Malta-Sicily Channel and in particular the Maltese Plateau, the generally weak Mediterranean tidal signal is intensified [45] and mostly concentrated in semidiurnal and diurnal bands [41].

For what meteo conditions concerns, light to moderate winds prevail in the study area for most of the year with some case of strong winds although their frequency is much less during summer when pressure gradients are usually less. Prevailing wind, especially in the winter month, is Mistral (N-W), which typically blows in period of three days. During summer, the northerly and north-easterly winds become equally dominant to wind blowing from northwest. Gregale wind (N-E) is not frequent but generally rises their force during the period between December and February. Scirocco winds (S-E) of continental tropical origin usually occur towards late winter or in the April/May transition.

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 [46]. 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.

A more recent study using a high resolution numerical wave model [47] provides a detailed characterization of the wave climate and an estimation of the wave energy potential in the coastal and offshore areas of the Maltese Islands. The study reveals that the western approaches to the islands are amongst the most energetic as a result of the prevailing North-Westerly winds. In this marine area, maximum significant wave heights exceed 7 m in winter, with a seasonal mean of 1.92 m as determined from direct measurements. The mean wave power transport during the winter season is estimated at 15 kW m^{-1}; the wave resource is more than halved in spring and even weaker in autumn; it is under 2 kW m^{-1} during summer.

3.2. Data set

Two twin combine servers (in Malta and Sicily respectively) elaborate and publish data to users through a dedicated quick-view and data access interface [48]. The data used in the study spans over three months, from December 2016 to February 2017, and comprises several climatologically relevant storms. This selected period is representative

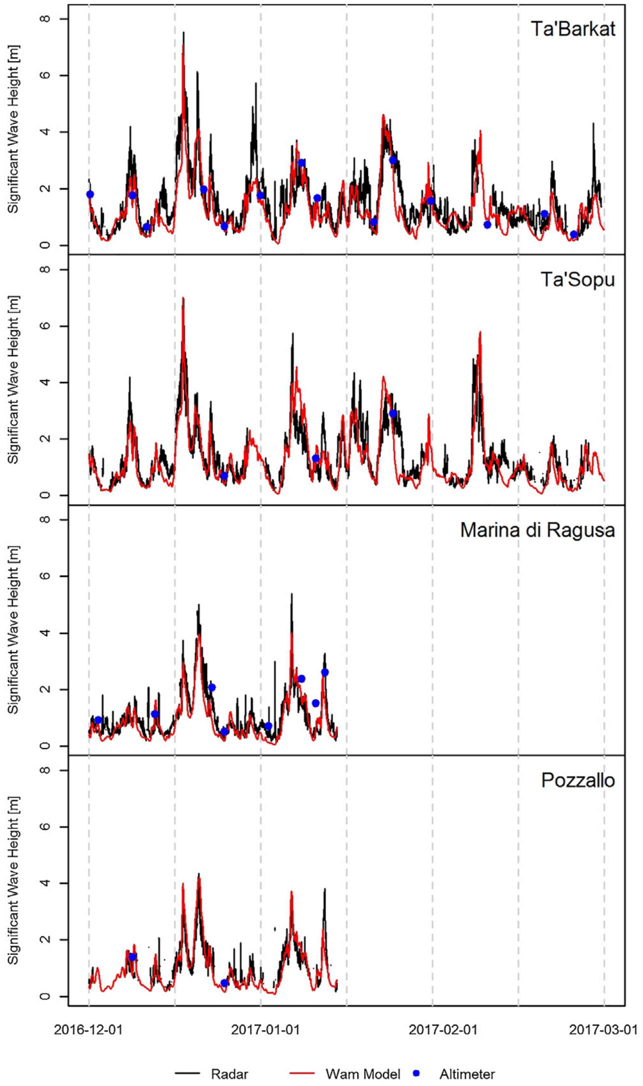

Fig. 4. Time series of SWH from HF radar (black line), WAM model (red line) and altimeter data (blue dots) at Ta' Barkat site, third annular rings. December 2016-February 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

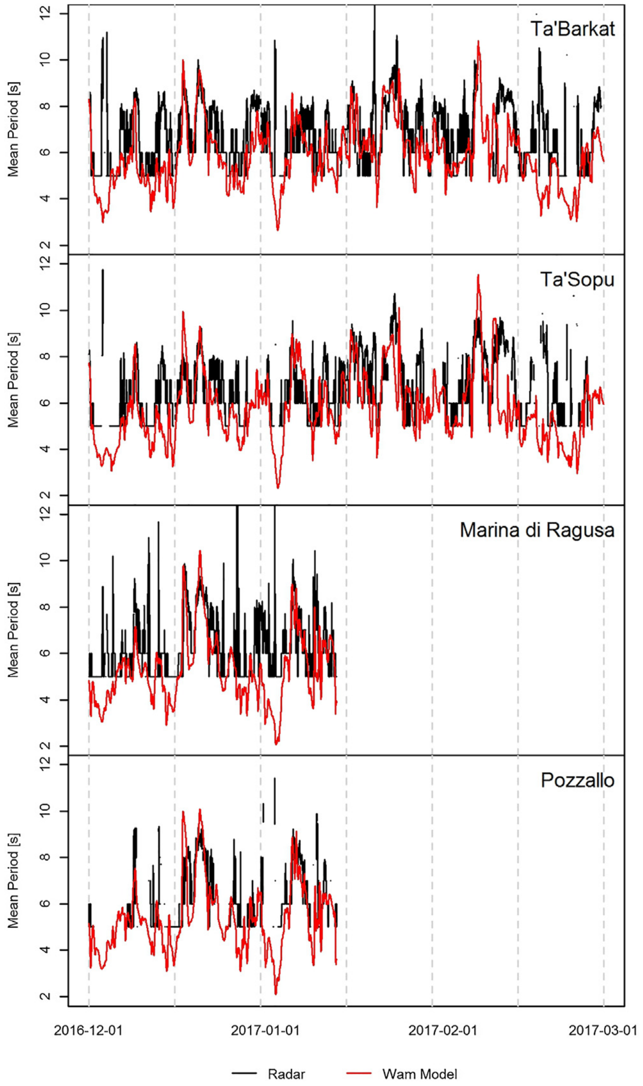

Fig. 5. Time series of mean period from HF radar (black line), WAM model (red line) for the third annular rings. December 2016-February 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the standard HF radar operation as it includes homogenous time series as well as missing values and outliers due to noise signals and interferences. This time frame choice is the approach and layout of some of the most recent research going on around HF radar and waves [49,25,50].

The significant wave height (SWH), mean period and wave direction at half-hour intervals are obtained by the radars from close-in radar range sectors, each sector being approximately 1.6 km distant. Data used in the study were processed to discard erroneous measurements before applied in the comparison with numerical model and altimeter data. In this study, we used the tripled standard difference method to screen outliers: individual data points for which the difference between the neighbour observations were outside the range of $m \pm 3\sigma$ were selected as outliers, where m is the mean value and σ is the standard deviation of differences of SWH observations from pairs of consecutive points for each radar. As result, the selected outliers were mostly registered on Ta' Sopu.

The McWaf system, operating in ISPRA since 2012, provides sea state forecasts over the Mediterranean Sea and over selected Italian regional and coastal areas. The regional WAM model is the part of the Mcwaf system which produces 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 at regional scale [51]. For this dataset the SWH, mean period and mean wave direction at one hour intervals, are averaged within each annular sector obtaining a unique value for each annular sector.

Satellite altimeter wave measurements are obtained by analysing the shape and intensity of the altimeter radar beam reflected from the sea surface, and hence give only the SWH. Passes over the Malta-Sicily Channel from the Jason 2, Jason 3 and Saral Altika missions have been selected 3. To create a compatible set of near-simultaneous SWH data from satellite altimeter and HF radar, satellite data at 30 km from the radar origin every 30 min intervals were averaged.

3.3. Data analysis

Time series plots of SWH from radar, model and altimeter data are produced and biases, root-mean-squared errors, and the linear correlation between two datasets were calculated as:

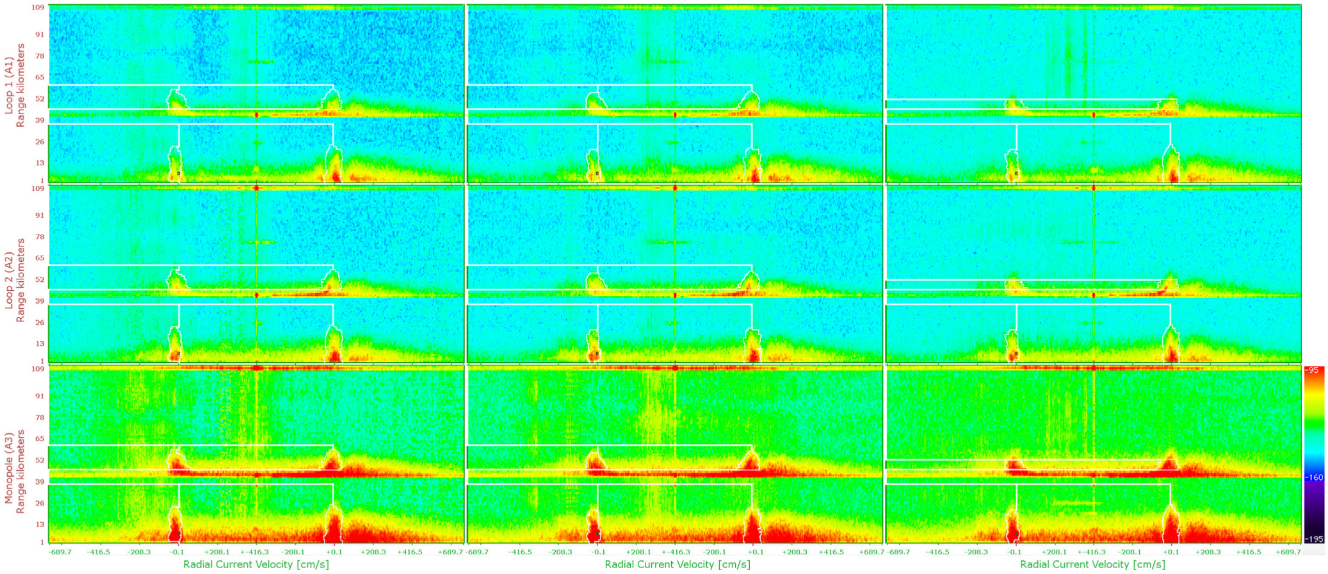

Fig. 6. Three of the hourly spectral images centered in the peak of the storm registered at 17th December 2016 15 p.m. at Ta' Barkat.

Table 1
Main statistical parameters for SWH radar and SWH WAM model agreement evaluation. Number of pairs in the last column.

	Annular rings	MSE	BIAS	Correlation	N
Ta' Barkat	1	0.642	0.654	0.823	1969
	2	0.437	0.784	0.815	2001
	3	0.435	0.827	0.803	1983
	4	0.491	0.803	0.796	2012
	5	0.577	0.779	0.786	2006
	6	0.668	0.758	0.776	2013
	7	0.681	0.758	0.776	2012
Ta' Sopu	1	0.382	0.805	0.83	1667
	2	0.324	0.889	0.836	1758
	3	0.389	0.919	0.818	1772
	4	0.562	0.879	0.751	1328
	5	0.811	0.827	0.71	1151
	6	0.927	0.809	0.691	1101
	7	1.354	0.987	0.594	212
Marina di Ragusa	1	0.161	0.784	0.898	1042
	2	0.153	0.853	0.886	1059
	3	0.177	0.848	0.883	1066
	4	0.161	0.865	0.903	1053
	5	0.203	0.854	0.896	1049
	6	0.264	0.84	0.888	1038
	7	0.316	0.819	0.883	1019
Pozzallo	1	0.535	0.853	0.67	419
	2	0.543	0.931	0.655	556
	3	0.535	0.998	0.666	605
	4	0.296	0.997	0.809	606
	5	0.464	0.965	0.745	604
	6	0.429	0.924	0.777	606
	7	0.662	0.863	0.707	605

Table 2
Main statistical parameters for SWH radar and SWH Altimeter agreement evaluation. Number of pairs in the last column.

	Annular rings	MSE	BIAS	Correlation	N
Ta' Barkat	1	0.255	0.878	0.875	12
	2	0.158	1.021	0.863	12
	3	0.066	1.035	0.943	12
	4	0.104	1.029	0.909	12
	5	0.149	1.018	0.88	12
	6	0.088	1.019	0.92	12
	7	0.133	0.987	0.875	12
Marina di Ragusa	1	0.125	1.271	0.981	7
	2	0.255	1.336	0.916	8
	3	0.292	1.288	0.878	8
	4	0.161	1.269	0.943	8
	5	0.069	1.154	0.984	8
	6	0.04	1.046	0.971	8
	7	0.125	1.028	0.897	8

$$BIAS = \frac{\sum_{i=1}^{n} x_i}{\sum_{i=1}^{n} y_i}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_i - y_i)^2}$$

$$R = \frac{\sum_{i=1}^{n} (y_i - \bar{y})(x_i - \bar{x})}{\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})(x_i - \bar{x})}}$$

to evaluate the agreement between the different sources. In all the equations, x corresponds to the reference value and y is the radar measurement. The variables with an over-bar indicate mean values.

Given that the radar data are available over different annular rings, it was important to investigate how the correlation between model, altimeter and HF radar SWH varies with distance from the radar origin.

The Pearson correlation coefficients, the RMSE and its square MSE have been thus computed comprising the three sources of data at each available annular sector.

Moreover time series plots of mean period from radar and numerical model have been produced to study the agreement and to analyse the limits related to the HF radar measurements of this parameter. Some problems relating to wave radar direction have not been resolved as yet and more investigations have to be made regarding this task.

4. Results

Fig. 4 displays the time series plot of SWH from radar, model and

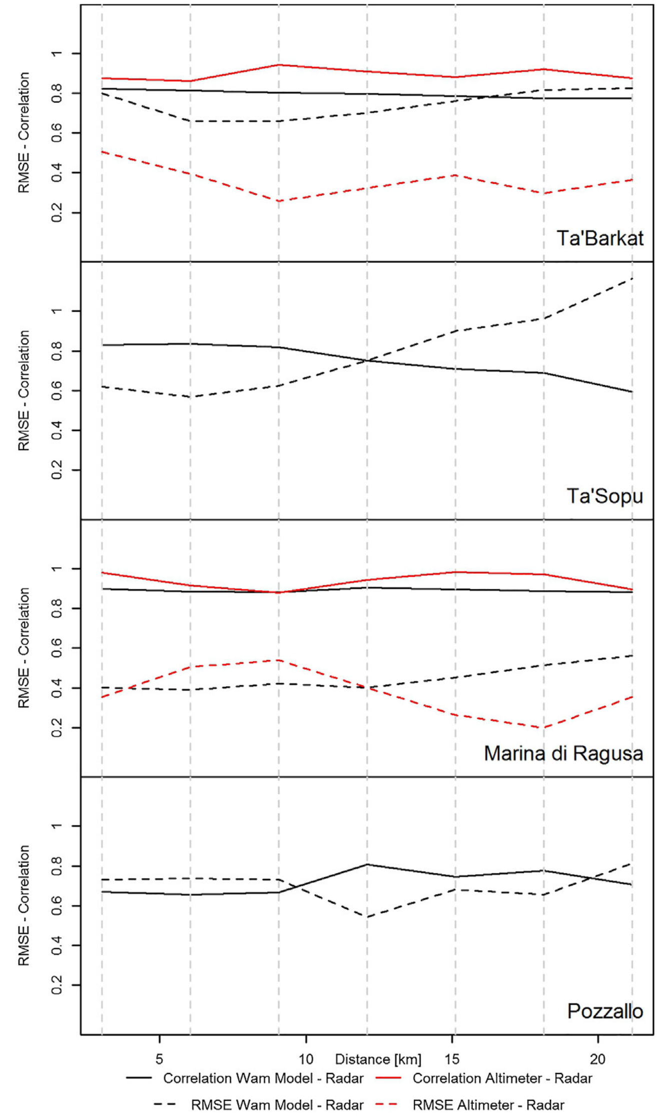

Fig. 7. Correlation (solid line) and RMSE (dashed line) values, between WAM model and HF radar data (black line), altimeter and HF radar data (black line). X-axis represents the distance from the radar origin.

altimeter data in correspondence of the third annular ring at the four sites.

Although the two Sicilian series have missing values in the second half of the data series, the plots reveal the very good agreement of SWH amongst the different data sources, even in the case of extreme wave conditions. Indeed, the detection of extreme events is well performed both in terms of forecasting and observations; this demonstrates that HF radar and WAM model data could be both useful to provide alert services for marine operators (not always verified for the altimeter, due to the coarse temporal resolution). 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, forecasted by WAM model 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.

It is important to analyze how the theoretical cut-off value for significant wave height which is of approximately 7.5 m works during the event of the 17th to 20th of December. The focal point is in understanding if the first and second orders Bragg region merge during the storm and for this reason wave measurements by HF radar is not longer possible. Fig. 6 displays the three spectral maps captured at Ta' Barkat the 17th of December at 14:00:00, 15:00:00 and 16:00:00 h which correspond exactly to the highest peak which was registered at 15:00:00 h with a significant wave height of 7.54 m (8.11 in the first annular ring). If currents (the first order echo) and waves (the second order echo) get smeared then the two cannot be separated and waves are not possible to extract. In Fig. 6 it is clearly shown that there is not overlapping between echoes in any of the spectral samples of the Ta' Barkat site at the highest of the peak of the storm. First order and second order have been clearly identified at all times as the white alignment lines show. As a result, the algorithm has had no trouble in analysing the second order region and plausible waves data have been calculated. This confirms that at 13.5 MHz the 7.5 m limit is not a "hard" boundary, meaning cross above the limit unreliable data are obtained. The Malta-Sicily system has been able to capture a case where the radar wave height is measured in the range in between 7 and 8 meters properly.

Fig. 5 displays the time series plot of the mean period from radar and WAM model in correspondence of the third annular ring, at the four radar sites. It is to be noticed that the wave periods observed by HF radar are constrained by a lower limit of resolution of 3 s, thus compromising the agreement with the numerical model in the range between 0 and 3 s. The agreement is not always consistent in particular in the last part of the series at the two Maltese sites, The presence of spikes and suspicious values indicate the need to apply a further quality control check on the whole dataset.

Tables 1 and 2 list the main metrics accounting for the agreement between SWH values taking radar HF as a reference. The last column reports the number of pairs used in the skill matrix computation. Regarding satellite altimeter data Ta' Barkat and Marina di Ragusa time series are considered due to the insufficient number of satellite passages in coincidence to the other two sites.

MSE (Mean Squared Error) values vary with the distance from the radar origin; errors are lower not too far neither too close to the radar origin, namely the better agreement is achieved in the intermediate rings from the radar origin.

BIAS values indicate the same spatial behaviour; moreover, respect to the optimal agreement equal to 1, 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 and with an opposite tendency of the HF radar to register lower values of SWH with respect to the altimeter.

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.

The correlation coefficient and the RMSE of the radar-WAM and the radar-altimeter pairs are computed and plotted in Fig. 7 as a function of distance from the radar origin at the Ta' Barkat site. The correlation between model, altimeter and HF radar SWH is always high, indicative of a strong linear relation between the different sources of data. The correlation between HF radar and WAM model slightly decreases as the distance from the radar origin increases. RMSE reveal that there is an optimal distance from the radar site for the relevance of the HF radar wave data, being most accurate at intermediate distances from the coast, and deteriorating both closer to coast as well as further offshore. These results are corroborated all the four radar stations even though it is noticed that the HF radar wave data are subject to differing interfering noise levels in the signal depending on the station.

5. Conclusions

The study confirms that CODAR HF radar data are a reliable source of information 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 to improve the model skill through data assimilation. In general, better correspondences are obtained at intermediate distances from the coast, and deteriorating both closer to coast as well as further offshore, this suggesting the use of wave radar values registered at intermediate rings.

Another important consideration comes from the analysis of the storm occurred in the selected period, because it could be helpful in defining how hard the theoretical threshold boundary based on the radius of convergence used in the perturbation series analysis derived by [29] should be considered.

Further analysis is needed to assess the more detailed performance of HF radar across different bands of sea wavelengths and different wave heights. The study also brings out the need to apply a quality control procedure on the whole dataset to highlight spikes and outliers, and to construct the most reliable dataset to users. A major aspect that needs to be investigated concerns the nature of the inconsistency in the spatial coverage of the radar data which varies from one time frame to another as a result of the changing sea states as well as due to interference from unknown sources that are sporadically competing with transmissions in the same frequency band. Other further investigations will focus on wave period and direction. It is also expected to extend the study by direct correlation to wave buoy measurements. Finally the analysis of particular met-ocean conditions such as the multimodal seastates and conditions when winds blow from earth are of and will be the object of future works.

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