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Wave power measurements in the Celtic Sea using HF radar

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***Abstract*—It is well established that HF radar systems located on the coast can measure surface currents from close to the coast to more than 100km offshore. They can also be used to simultaneously measure the ocean wave directional spectrum. Thus current and wave power and other parameters relevant to the development of marine renewables can be measured. Wave measurements in the Celtic Sea using a Pisces HF radar system in 2003-2005 are presented. Good agreement with buoy data is demonstrated. The data are used to show that the wave power resource is variable in season, location and in direction with higher powers observed in Autumn but more directional variability in Winter.**

I. Introduction

HF radar systems located on the coast measure surface currents and waves simultaneously from close to the coast to more than 100km offshore [1]. Measurements can be made from every 10 minutes to every hour and with spatial resolutions of 300m to 15km as needed. HF radar current measurement is now a well accepted technology and there are many systems of different types in operation around the world. Wave measurement is more complicated and less common. The radar measures the full directional wave spectrum up to a maximum frequency which depends on radar operating frequency being about 0.2Hz at the lower end of the HF radar band and 0.35Hz at the upper. Wave parameters are calculated from the spectrum using standard techniques. The wave and current measurements, using methods originally developed at the University of Sheffield, have been validated in numerous short and long-term deployments at many different locations (e.g. UK, Norway, Spain, USA, Australia).

This paper focusses on the estimation of wave power from the radar data, together with its directional characteristics and their spatial and temporal variability. Wave power, its directional distribution and energy period are calculated from the radar measured directional spectra at all locations in the field of view of the radar that pass required quality control conditions. An HF radar system is currently being deployed by the University of Plymouth on the North Cornwall coast to provide wave measurements for the Wavehub project [2]. The paper will present data obtained from further north in the Celtic Sea using the Pisces HF radar system which had one radar site near Pembroke and one on the North coast of Devon (two sites are required for these measurements) for the period Dec 2003 to June 2005 [3]. This covers an area off the S Wales coast currently being considered for wave power exploitation.

One big advantage of HF radar is its siting on land so if there are any problems with the system these can be dealt with without any need to wait for weather windows, shiptime etc as would be required for offshore measurement systems. Furthermore all the data can be delivered in near real time (within ten minutes of the radar data collection) over broadband links. A big advantage of HF radar over buoys is the ability to provide spatial coverage and in this paper spatial variation of the wave power resource in coastal waters will be demonstrated. The aim is to demonstrate that HF radar has a role to play in both measuring the wave power resource and providing monitoring data during power extraction, device installation, testing and operations.

II. Measurements

The ocean wave directional spectrum is obtained from the radar signal using an inverse method [4], [5]. The ocean wave frequency range of the measurement depends on the radio frequency used [6]. Results have been validated in [7], [3] and elsewhere. Two examples of comparisons of Pisces radar measured directional spectra with those obtained from a directional waverider are shown in Fig 1. Note that the buoy does not measure the full directional wave spectrum, only the first five Fourier coefficients thereof. In this example the buoy spectra are obtained from the Fourier coefficients using a maximum likelihood method (MLM) [8]. The examples show two different types of spectra. Fig 1a is an example showing both frequency and directional bimodality. The radar spectrum also includes a low frequency/high period component between 15 and 20s and 250° not seen in the buoy spectrum. Spurious low frequency features are fairly common in the radar measured spectra and are due to ship signals, current shears and/or antenna sidelobes. Methods to reduce the impact of these sources of noise are being developed. In this example the mean direction plot does show that there is some energy in the buoy data over the same frequency range but at a much lower amplitude than is seen in the radar data. The second example, Fig 1b, shows a spectrum bimodal in frequency but with little variation in direction. In general radar-measured spectra tend to be more spread in both frequency and direction with lower peaks than those seen in the MLM buoy spectra. Apart from the obvious high period issue, in both cases the spectra are in good agreement

Wave power, P in kW/m, is obtained from the radar-measured spectrum using

$$P = \rho g \int c_g(f) E(f) df)/1000,$$

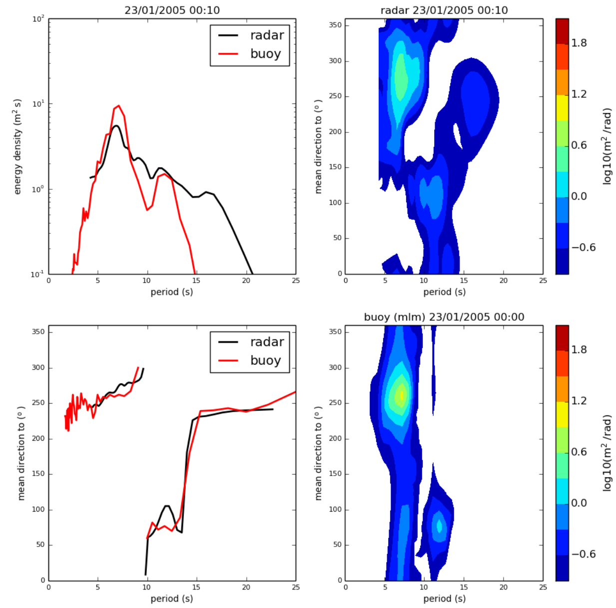
where ρ is the density of sea water $= 1027$ kg/m^3, g acceleration due to gravity $= 9.80665$ ms^{-2}, $c_g(f)$ is the finite depth group velocity in m/s, $E(f)$, energy spectrum in m^2/Hz, f frequency in Hz. The integral is over all measured frequencies. Another important parameter in wave power applications is energy period, T_E in seconds, which is also calculated from the spectrum as follows.

$$T_E = \frac{m_{-1}}{m_0} = \frac{\int f^{-1} E(f) df}{\int E(f) df.}$$

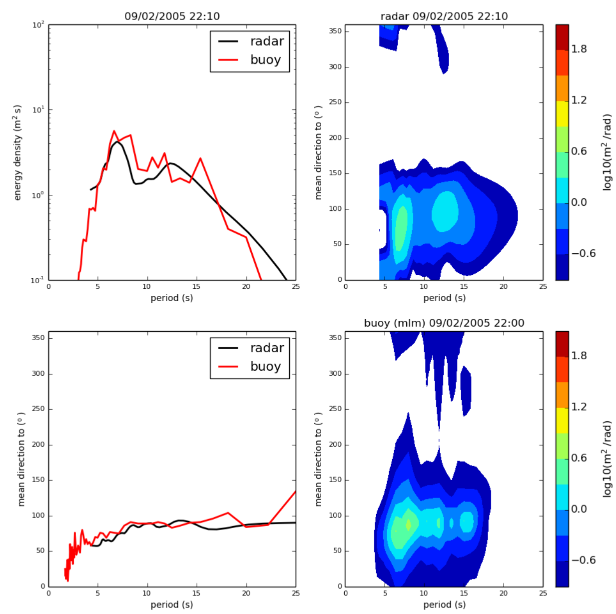
In this paper the directional characteristics of the wave power are characterised with the power-weighted mean direction [9].

Significant waveheight and wave power measured by the radar during the first four months of 2005 are compared with those from a directional waverider in Fig 2. Fig 3 shows the same data presented as histograms together with the statistics of the comparisons. It is clear in Fig 3b that most of the time available power is less than 20kW/m. Also shown, Fig 3c, is the comparison of T_E. The radar measured T_E data are affected by the high period noise referred to above leading to overestimation of T_E particularly when waveheight is low. In addition the radar has a lower high frequency cut-off than the buoy and this has not been accounted for in the calculation of T_E so when the buoy is measuring a low value of T_E, the radar estimates tend to be higher. As previously mentioned the first issue is the subject of ongoing research. The second matter needs to be borne in mind when interpreting the radar data.

Fig 4 shows polar histograms of wave power for the Pisces Celtic Sea deployment [3] separated by season. Note that, for this deployment, the spatial density of observations often seen in HF radar measurements was not a requirement so a very coarse spatial grid was used. The figure shows variations both in space and time. In spring to autumn a north-eastward direction dominates in the northern part of the region whereas in winter directions are more towards the north as is the case in spring and summer in the south-east part of the region. Power was found to be highest in the autumn and lowest in the summer but with a lot of temporal variability as is also evident in Fig 2b. The distributions in the western part of the region seem to be more variable both in direction and strength. Measurement at these locations are more vulnerable to noise (signal strength drops off with range) which may be influencing these results. Unfortunately only one buoy was available for the validation. This was located at about $5°20'$W $51°10'$N and radar data at that location was used in the comparisons in Figs 1 - 3.

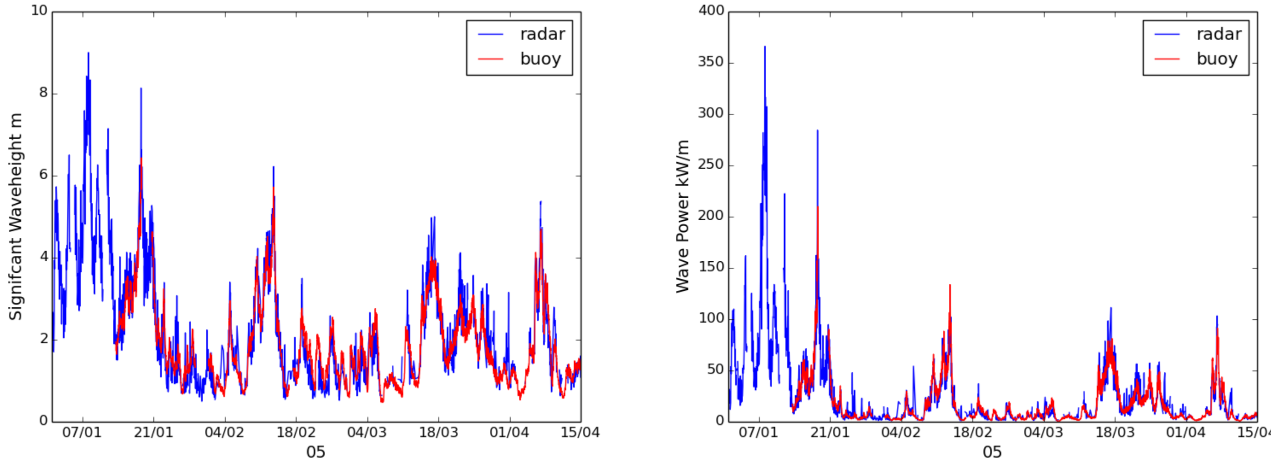


(a)



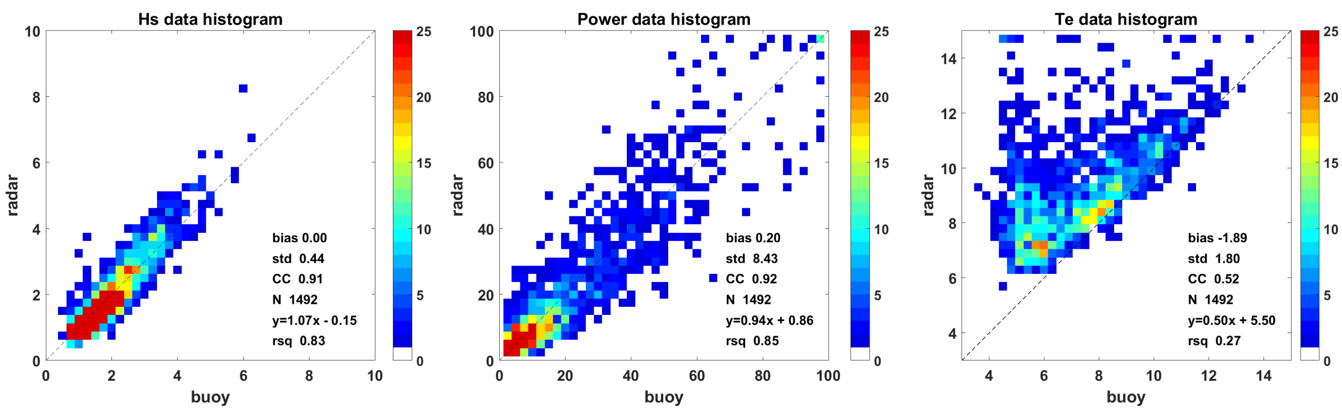
(b)

Fig. 1. Comparisons of radar and wavebuoy directional spectra. In each panel, top left is the energy spectrum, bottom left the mean direction, top right the radar directional spectrum and bottom right that of the buoy. The horizontal axis is period in each case. Log scales are used for the energy and directional spectra.



(a) (b)

Fig. 2. Comparisons of radar and wavebuoy (a) significant waveheight and (b) wave power.



(a) (b) (c)

Fig. 3. Comparisons of radar and wavebuoy (a) significant waveheight (m), (b) wave power (kW/m) and (c) energy period (s). Colour coding is number of observations in each bin.

III. Discussion and Conclusion

Examples of wave measurements with HF radar have been presented and compared with those from a directional waverider buoy. Good agreement has been demonstrated although period estimates are sometimes contaminated by spurious low frequency signals generated by ships, current shears and or antenna sidelobes. One way of dealing with this problem is to partition the directional spectrum and identify and remove these spurious features. Another is to identify them in the original radar data and remove them there. Both approaches are the subject of ongoing research. Partitioning has been applied to HF radar wave measurements in order to identify spurious components [10] and to assimilate the data into models [11]. A filtering method applied to the radar data has also shown some promise [12]. These are not yet implemented in the operational package that was used to make the measurements presented here. Developments along these lines will certainly increase the robustness of the wave measurements.

One of the limitations of wave measurement with HF radar systems is the requirement to have two radars (e.g. at NP and EB in Fig 4) to resolve directional and amplitude ambiguities associated with single radar measurements [13]. Two radars are also needed for surface current measurement but often deployments designed for that application do not have a suitable configuration for routine dual-radar wave measurement. They therefore tend to fall back on single radar measurements which are more limited in scope and in accuracy. A Pisces radar will be making further measurements from the north Devon site (NP on the figure) over the 2017-2018 winter to test some new ideas to improve the wave measurement performance with a single radar. The region covered by the northern measurements shown in Fig 4 is roughly the location of the proposed WAVEHUB Pembrokeshire wave energy test site (see https://www.wavehub.co.uk/pembrokeshire-wave-zone) and the deployment will be used to raise interest in that sector with a view to a longer term operation.

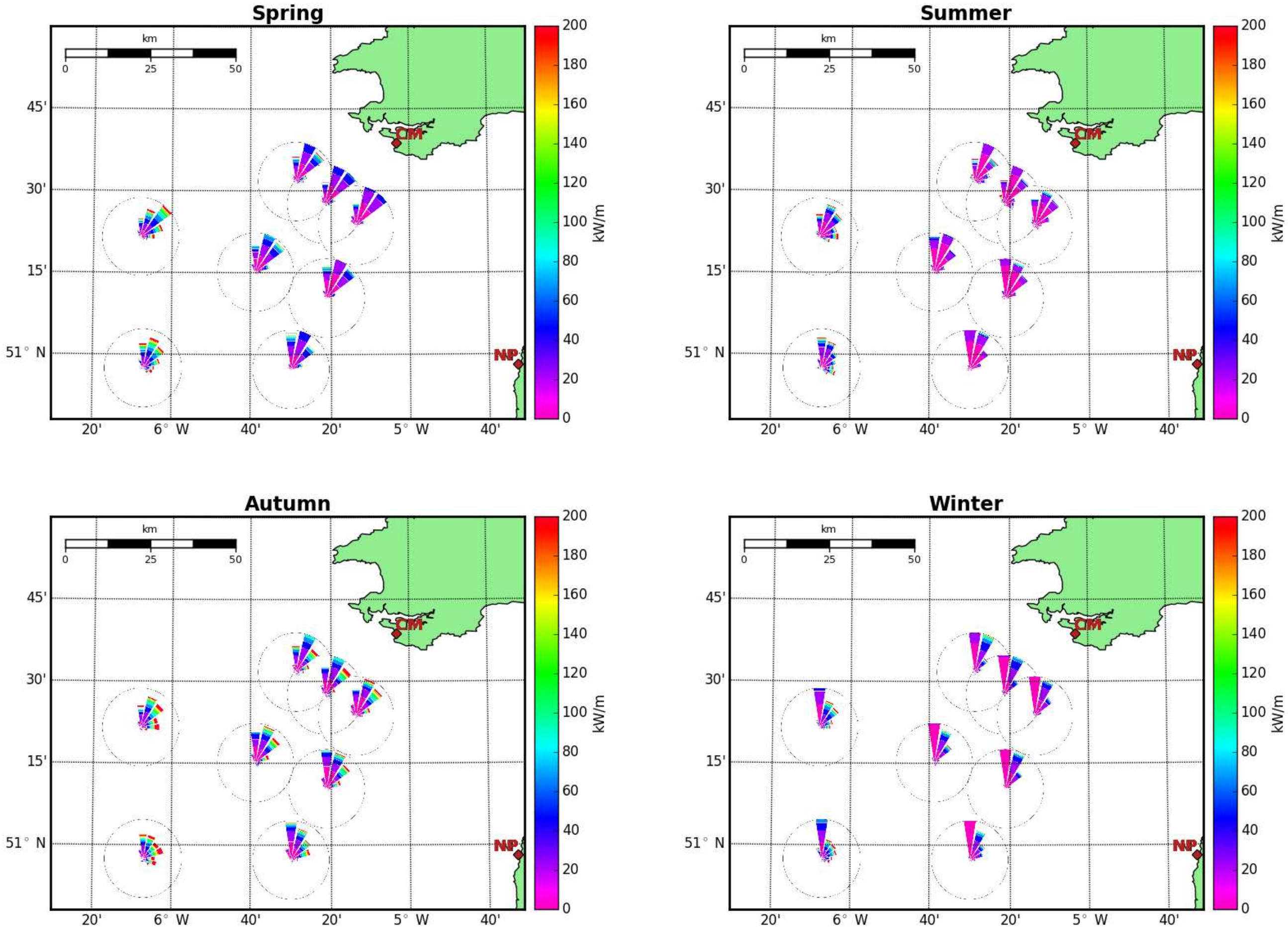


Fig. 4. Polar histograms of wave power in the Celtic Sea. Circles are at 25%.

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