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Measuring high and low waves with HF radar

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***Abstract*-HF radar measurements are presented focussing in particular on the estimation of wave parameters in both high and low sea conditions. In high sea conditions theory suggests that low radio frequencies are needed in order to make wave measurements whereas in low sea conditions, higher radio frequencies are required. The theory is reviewed and measurements used to demonstrate the impact of these theoretical limitations. Work in progress aimed at improving the accuracy of wave measurement in both high and low seas is discussed.**

I. INTRODUCTION

HF radar systems located on the coast measure surface currents and the ocean wave directional spectrum simultaneously from close to the coast to more than 100km offshore. 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 many systems of different types in operation around the world. 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). See www.seaviewsensing.com and follow ocean data links for more information and access to data from some of these deployments.

In this paper we present some HF radar measurements focussing in particular on the estimation and accuracy of wave parameters in both high and low sea conditions. Fig. 1 shows examples of wave measurements off the coast of Brittany, France with the WERA [1] HF radar operated by Actimar on behalf of SHOM. The central region shows significant waveheight and mean direction obtained from the directional spectrum using data from both radars (two sites indicated on the maps). The outer regions show significant waveheight estimated from the individual radars. The colours are darkened in these regions to reflect increased uncertainty in these estimates because they are not accounting for wave directional influences on the radar signal [2]. These extend to longer range because they only require good signal-to-noise from one radar. High seas limit the maximum range over which waves can be measured as can be seen on the left map.

In the following sections theoretical limitations to wave measurement are reviewed and further measurements presented to illustrate these limitations.

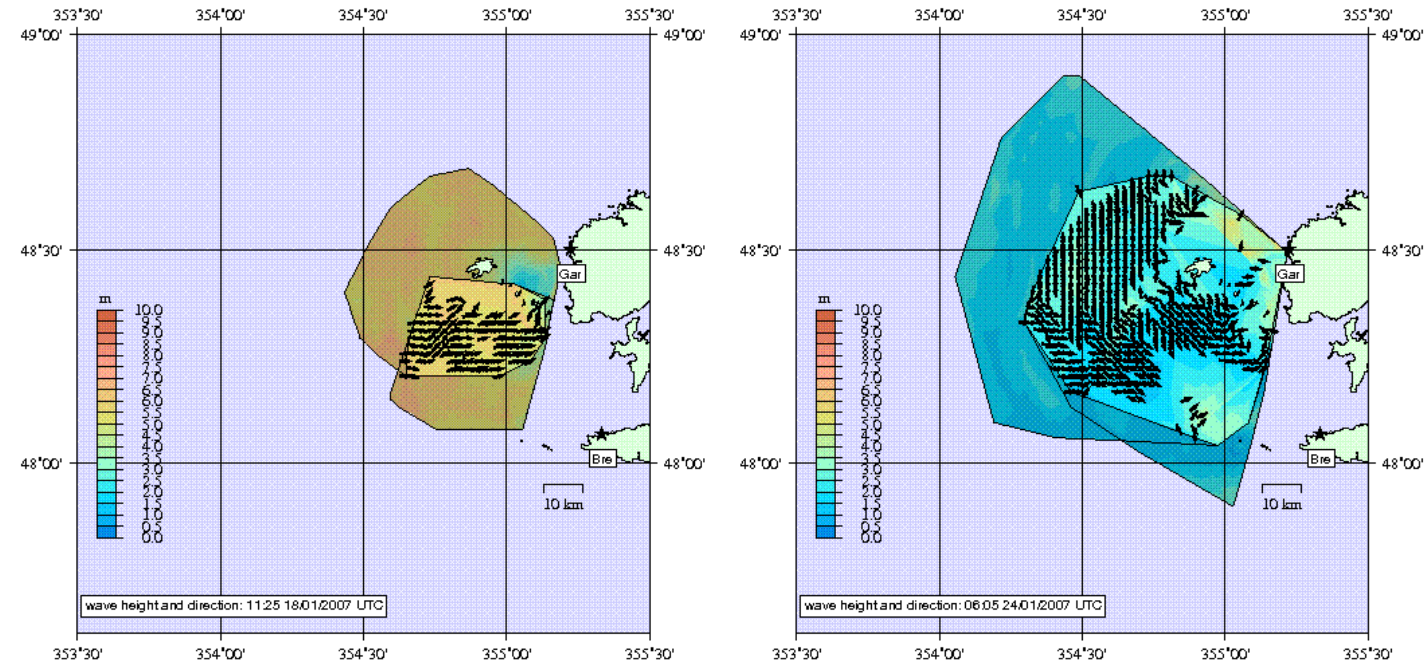

Figure 1. Maps of significant waveheight and mean direction during (left) storm and (right) calmer conditions.

II. THEORETICAL LIMITATIONS

The directional wave spectrum is measured by inverting an integral equation relating this spectrum to the power (Doppler) spectrum of the backscattered radar signal [3, 4]. The integral equation results from an analysis of first and second order (both electromagnetic and hydrodynamic) scattering of electromagnetic waves from the moving rough sea surface developed by Barrick [5,6,7]. A perturbation method was used and the subsequent linearisation means that there is a radar frequency dependent upper limit on waveheight for which the analysis is valid. Fig 2 shows the contoured perturbation parameter (proportional to the product of significant waveheight Hs and radio wavenumber, k_0) where darker colours are lower values (<1) and white is the region where the parameter is ≥ 1. At high radio frequencies this waveheight limit is much lower than at low radio frequencies. In low seas there are also radio frequency dependent limitations. These are shown with white curves in Fig. 2. At low radio frequencies the signal to noise requirements are higher for a given waveheight and thus low seas can be more difficult to detect (solid white line indicates where directional accuracy is a problem [8]). Also, the inversion has a radio frequency dependent upper ocean wave frequency for which the full directional spectrum can be determined. If this is lower than the ocean spectral peak frequency (white dashed line), the assumptions made in the inversion are no longer valid and again this is more likely to occur at low radio frequencies. An example of this can be seen in Fig 3 measured with a Pisces radar system [8]. Note that, unlike the radar, the buoy does not provide the full directional spectrum. The buoy directional spectra shown in this figure were obtained using the maximum likelihood method [9]. In the case shown on the right the buoy peak frequency is at the border of the invertible range in the radar data (in these figures the radar spectra have been extended to higher frequencies shown in red using a f^{-5} slope and the wind direction). So although the rest of the spectrum is measured with reasonable agreement the radar cannot find the wind-wave peak and thus will identify the swell component as the spectral peak giving significant differences in estimated peak frequency and direction. Mean directions and frequencies, if compared without taking the limited frequency range into account will also be very different. In contrast the spectra on the left in higher sea conditions show good agreement and the parameters will also compare well.

The dotted white line in Fig. 2 is a lower limit for any wave or wind measurement since below this the waves observed directly by the radar cannot be assumed to locally wind-driven.

One way of minimising these problems is to use a radar system that can operate over a range of radio frequencies with automatic switching controlled by the environmental conditions. An example of such a radar is the Pisces system [8] available from Neptune Radar Ltd. However many users have systems that currently only operate at fixed frequencies (an example being the WERA HF radar [1] available from Helzel GmbH). Also obtaining a sufficiently flexible radio frequency license may sometimes be difficult. Methods that improve accuracy for such systems and circumstances are needed .

III. MEASUREMENTS

The original work on wave measurement at Sheffield was carried out at radio frequencies mostly less than 10MHz since most wave measurement applications are more interested in higher seas [10,11]. This was then extended to wave frequencies at the upper end of the band: 25–30MHz since these were being used more extensively for current measurements and there was a growing interest in extending their measurement capabilities [12,13,14,15]. The results obtained over both these frequency ranges are consistent with the theoretical expectations. Below 10MHz waveheights up to 10m have been measured [8] whereas at 27MHz the upper limit is about 6m with overestimation of amplitude at the higher frequency end of the spectrum above waveheights of about 4m [15]. The lower limit has not proved to be a problem at 27MHz but below 10MHz wave measurements become noisy below about 2m for spectral features and 1m for waveheight [8]. These features can be seen in Fig. 4 which shows waveheight comparisons from the Celtic Sea using the Pisces radar in 2005 [8] and from the coast of Norway using the WERA radar in 2000 [15] . The low frequency cases in this figure include comparisons with both a wave model and with a buoy because the buoy was not operational during the higher storm events. The statistics are given in Table 1.

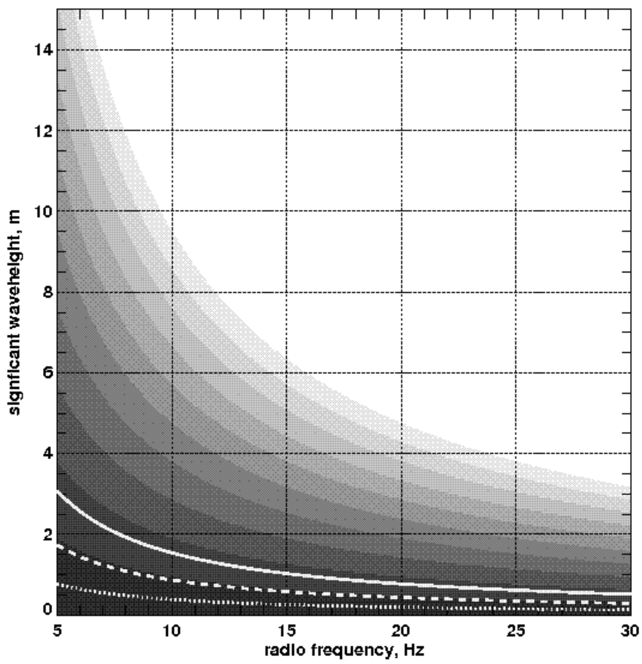

Figure 2. Contoured perturbation parameter.

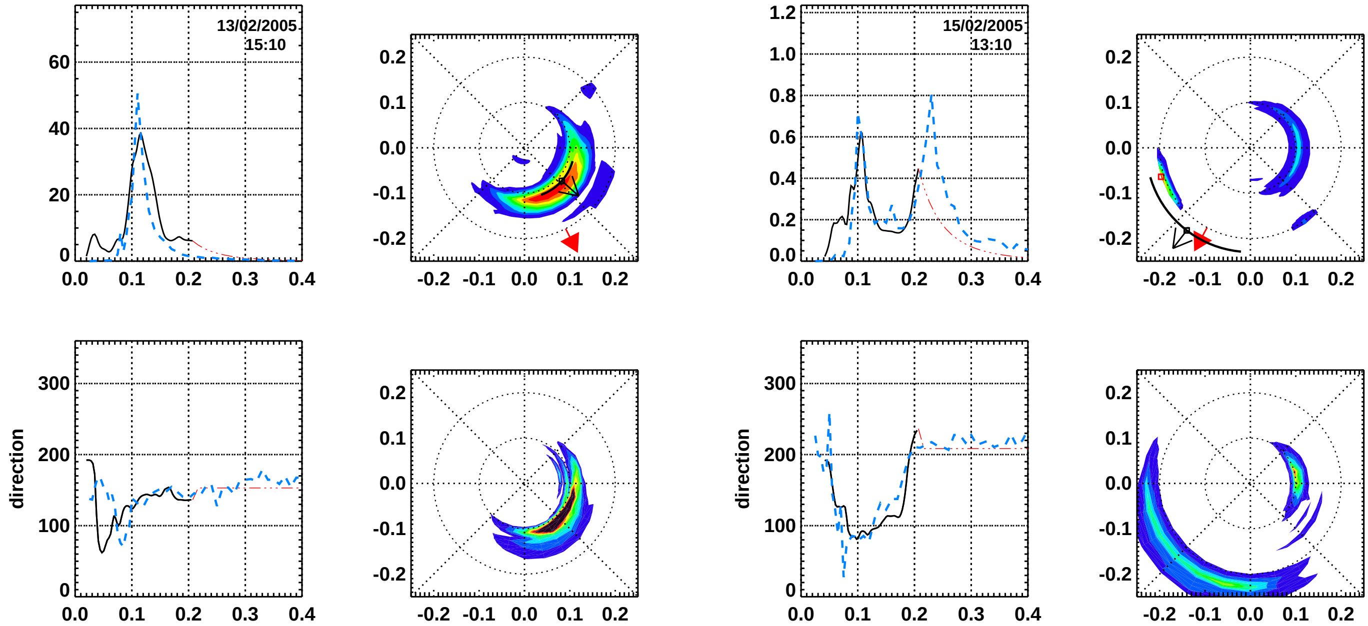

Figure 3. Comparisons of (top left) frequency spectrum (m^2/Hz), (bottom left) direction spectrum, radar black, buoy blue dashed; (right) directional spectra, radar above, buoy below. The colour coding is a linear scale in 10% increments relative to the peak in the radar spectrum from dark blue at 10%. On the radar spectrum the radar measured wind direction is shown with a red arrow and the buoy peak direction and spread with a balck arrow and curve. The figure on the left is a high sea case, that on the right a low sea case.

In assessing whether a radar Doppler spectrum is suitable for wave measurement we require that the second order signal to noise (measured at the second order peak) be greater than 15dB. We then use a measure of the convergence of the inversion procedure to further filter poor quality data [3]. Increased robustness is also obtained if we filter frequencies below 0.05Hz and cases where the change in waveheight from a previous measurement within one hour is greater than 1m. These conditions seem to be sufficient for waveheight measurement (provided there has been sufficient averaging [16]) and it may even be possible to relax the15dB requirement to 10dB. Mean and peak directions and periods are much more sensitive to non-sea signals – interference or ships – in the radar backscatter and also to the frequency range limitations referred to above [8]. The best comparisons with buoy data for these parameters are obtained in high signal to noise conditions >35dB. However most of the errors in the directional spectrum (from which all parameters are derived) occur at low ocean wave frequencies (<0.1Hz – as mentioned above, we can filter frequencies below 0.05Hz but many waves of interest will have frequencies between 0.05 and 0.1Hz). These are generally associated with lower signal to noise than the part of the radio power spectrum that provides the higher ocean wave frequencies and more detailed signal to noise assessments may be necessary to ensure robust directional and period parameter estimates. The other approach we are investigating is to filter the directional spectra using partitioning methods to remove contributions that cannot be attributed to ocean waves through continuity in space and/or time arguments.

Many operational systems are now using radio frequencies in the range 12–16MHz giving the opportunity to explore the waveheight limits at these radio frequencies on different wave spectral parameters. One such system has been deployed by the Proudman Oceanographic Laboratory on the coast of Liverpool Bay in NW England as part of their Coastal Observatory [17]. These are WERA radars operating in the 12-13MHz band and have been providing data nearly continuously since mid 2005. Figs 5 and. 6 shows the waveheight comparison for this system for a four month period in the winter of 2005-6. Liverpool Bay is a sheltered shallow bay with very little swell propagating into the region and with generally low waveheights, as can be seen here. The radar measurements are from a site a few km to the SW of the buoy. Radar measurements at the buoy position are rather noisy perhaps due to depth limitations or to shipping since this is closer to the main shipping lane into Liverpool. This is under investigation. The standard 15dB signal to noise criterion has been used with the result that waveheights below about 0.5m are not measured by the radar. The statistics of the waveheight comparison are similar to those for the other frequency ranges (see Table 1). The correlation coefficient is lower but this is probably due to the limited range of waveheights. The wave directions and period comparisons also have similar characteristics to the others with again a high signal-to-noise giving better agreement. The inversion is limited to frequencies less than about 0.27Hz corresponding to a period of 3.7s. Since the average mean period measured by the buoy for these four months is only 4.1s the limited frequency range is a particular problem in this case.

Some approaches for improving the robustness of data, at the expense of reducing quantity, have been referred to above. Work is also in progress aimed at improving the accuracy of wave measurement in high seas. This is a limit associated with the perturbation analysis used to derive the equations used in the inversion. Strictly speaking one should operate well within the non-white regions in Fig. 2 although it should be noted that the larger waveheight in the lower scatter plot in Fig. 4. are well above this threshold. Extending beyond the formal limits of the perturbation analysis appears to lead to an overestimation in waveheight [18] and eventually to an upper limit beyond which waves cannot be measured due to first and second order parts of the Doppler spectrum no longer being separable [15]. This is a hard, radio-frequency,dependent upper limit being about 6m at the 25MHz frequency of this case but, assuming this limit is proportional to the perturbation parameter, it is well over 14m at the lower radio frequencies (we have not had experimental data to test this yet). The work underway is looking at the range of values of the perturbation parameter where overestimation in waveheight begins up to this hard upper limit. At the time of writing results are not yet ready to report but preliminary results should be available soon.

IV. CONCLUDING REMARKS

This paper has reviewed existing work on the high and low seastate limitations at high and low HF radio frequencies on wave measurement and extended these to measurements obtained over midrange radio frequencies. Results are consistent with theoretical expectations. Ongoing work will establish clear signal to noise and post-processing filter recommendations to improve the robustness of the direction and period estimates. We hope to report on work aimed at improving accuracy at high seas in the near future.

TABLE 1

WAVEHEIGHT COMPARISON STATISTICS

Frequency range		Buoy	Model
7–12MHz Pisces	Correlation	.91	.92
	Mean difference	1cm	10cm
	rms	45cm	57cm
25MHz WERA	Correlation	.97	
	Mean difference	22cm	
	rms	41cm	
12–13MHz WERA	Correlation	,83	
	Mean difference	12cm	
	rms	37cm	

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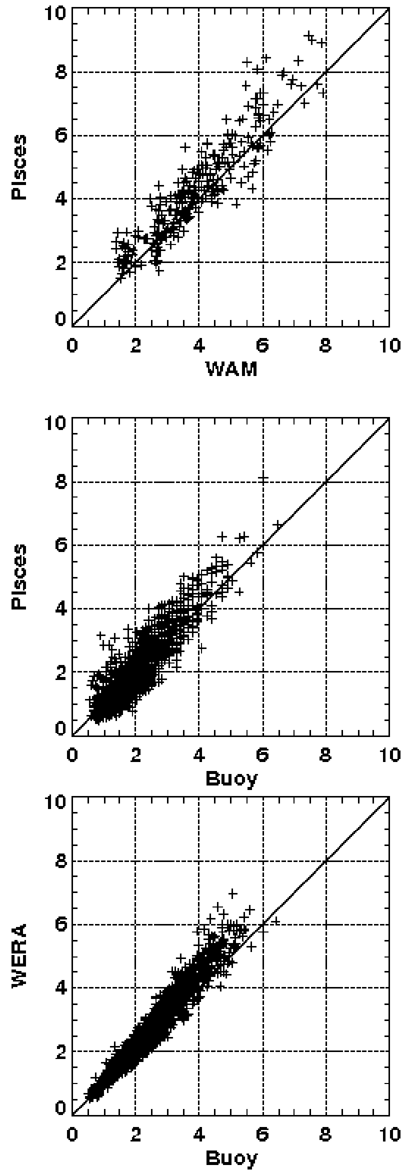

Figure 4. Svatter plots of significant waveheight comparisons. Upper two are at low radio frequencies and lower one at high radio frequency.

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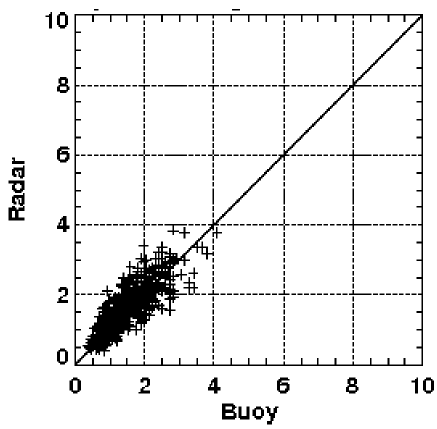

Fig 5. Liverpool Bay significant waveheight comparison

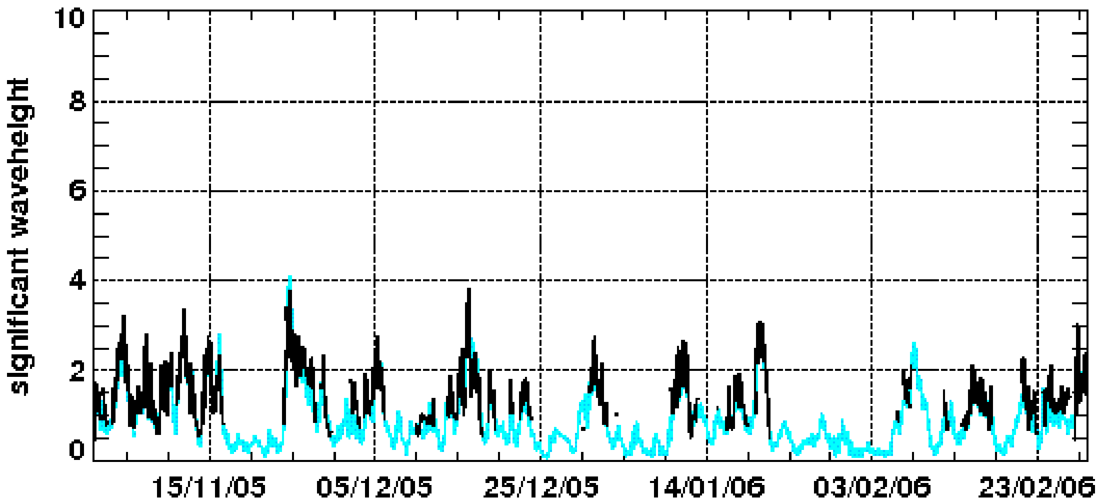

Fig 6. Time series of significant waveheight measurements with radar (black) and buoy (cyan) from Liverpool Bay.