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HF Radar for Coastal Monitoring – a Comparison of Methods and Measurements

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Abstract - **HF radar systems and methods for wave, current and wind measurement are discussed. Comparisons between compact antenna systems and phased-array systems are made. Examples are presented illustrating the capabilities of the phased array systems WERA and Pisces.**

I. INTRODUCTION

Although the use of HF radar for coastal monitoring has been increasing in recent years, there are still many potential customers for this technology who are either unaware of its existence or unsure of the capabilities of and the differences between different systems. To date the market has been dominated by the CODAR Ocean Sensors' Seasonde system but the emergence into the market of the WERA radar, developed at the University of Hamburg, Germany [1] and with Helzel GmbH, and the operational use of the Pisces system (Neptune Radar Ltd) in the UK [2] means that it is timely to look at these systems and review their relative merits.

HF radars are usually located on the coast surveying an area of 40x40km to 150x150km or so depending on the radio frequency and system used. They provide measurements of surface currents, waves and winds through analysis of the power spectrum of the radar signal scattered from the sea surface. To provide spatial maps of surface current or wave measurements, HF radar signals have to be processed to separate them into contributions from different ranges and from different directions relative to each of the radar stations. Range measurement is achieved using time or frequency differences, depending on the radar signal modulation, between the transmitted and received signal. Direction measurement can be achieved by measuring the phase differences at each frequency in the backscattered signal at each antenna together with geometrical considerations. This is called direction-finding and can be achieved with three or more antennas. Alternatively phase differences can be added to the signal at each antenna and these modified signals are summed, such a system is termed a phased-array. These phase differences can be dealt with digitally, in which case the radar can effectively look in all directions at the same time, or using different cable lengths which have to be switched, in which case the radar has to scan in direction. For good angular resolution with a phased array system a large number (16 is often used) of individual antenna elements is required which means that the area of land required to site such a system can be large.

The SeaSonde radar is an example of a direction-finding system. CODAR have always focussed on compact designs for ease of installation and siting and has a long history of provision of coastal surface current measurement systems. More recently they have developed systems providing long range current measurements. The WERA radar can also function as a direction-finding radar although it has mostly been used to date in phased-array mode. The phased array approach for WERA was specifically developed to facilitate the measurement of ocean waves using techniques developed at the University of Sheffield. These were tested in two European projects, SCAWVEX [3] and EuroROSE [4] and the associated software, which now also includes current measurement, has been licensed by the University to Seaview Sensing Ltd. A WERA system with Seaview Sensing and Neptune Radar Ltd software is currently in operation in Liverpool Bay in the UK. Seaview Sensing software was also used with the Pisces radar system operated by Neptune Radar Ltd in a 15 month trial for potential inclusion in the UK Department for Environment Food and Rural Affairs (DEFRA) wave monitoring network, WAVENET [2]. Pisces operates at lower frequencies than WERA to obtain longer ranges. There are a number of other experimental HF radar systems developed for metocean applications in different parts of the world (e.g. COSRAD in Australia, OSMAR in China, and others).

In this paper we will discuss the relative merits of these systems illustrating them with some recent data obtained using Seaview Sensing software from the WERA and Pisces systems.

II. SURFACE CURRENT MEASUREMENT

Surface current measurements are obtained by measuring the Doppler frequency of the peaks in the power spectrum of the received signal. The measurement is actually that of the speed of ocean waves of half the radio wavelength travelling towards and away from the radar (in a backscatter system). To first order this speed is made up of the intrinsic wave speed (determined from the well-know dispersion relationship for ocean surface waves) plus the component of surface current in the direction of wave propagation.

With a phased array system this is a straightforward measurement since each backscattered power spectrum is from a single range-direction cell (the resolutions in range and direction begin determined by radar parameters). In the direction finding case there can be limitations if surface current patterns are such that there are more than two locations within one range where the components in the direction of the radar happen to be equal.

The spectra for compact systems are from single range cells but contain information from all directions. The current measurements are resolved using direction-finding methods and fine directional resolution can be achieved. It usually takes longer (an hour or so) to gather current data covering the whole area of interest with these methods. This can be a problem in rapidly varying environments. At high radio frequencies and high waveheights the peaks used for current measurement are less easily separated from the part of the signal that provides wave measurements. This is likely to be a more serious problem with a direction-finding system although it can be solved by switching to lower frequency operation.

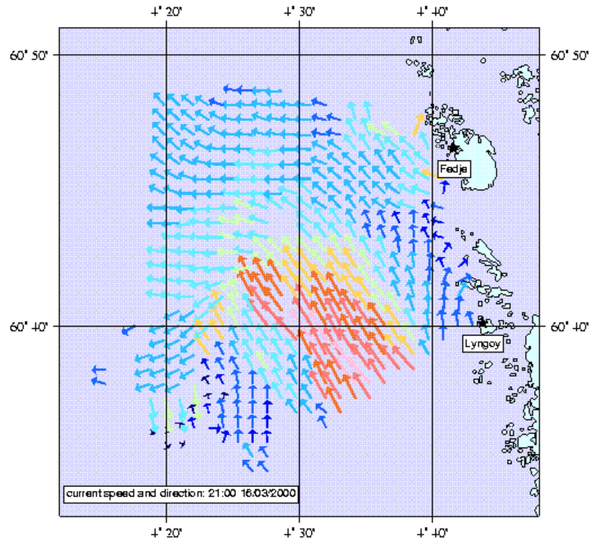

Fig 1. Map showing surface currents measured with WERA at Fedje, Norway on 16 March 2000 at 21:00.

Validation of these current measurements is not straightforward. They tend to be compared with measurements obtained using in situ instruments which do not measure the near surface current and which provide essentially a point measurement. The radar measurement is over a region determined by the range resolution (fixed by radar modulation parameters) and angular resolution (a few degrees for a phased-array system). These differences in location can be used at least partially to explain differences between the measurements. A study by Essen et al [5] compared currents measured with a direction-finding system and a phased-array system and suggested that the former are less robust to radio interference and ship signals. Detailed comparisons of phased-array current measurements with moored instruments are also discussed in [6].

Fig 1 is an example of a current field measured with the WERA HF radar at Fedje, Norway. The digital beam-forming used with this system provides high spatial resolution measurements to a maximum range of about 40km for these data. Maps like this are obtainable every 10 minutes if required. In contrast, fig. 2 shows a current field measured with Pisces in the Celtic Sea. Analog beam-forming and narrow bandwidth (required for operation at lower radio frequencies) provides coarser resolution but much longer range – to about 150km from the coast for these data. These maps can be updated every time a new beam is measured with the complete field changing every hour or more often with an increased number of receivers.

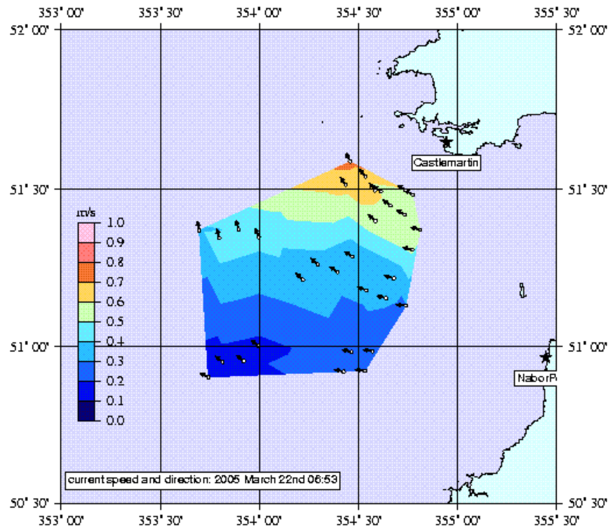

Fig 2. Map showing surface currents measured with Pisces in the Celtic Sea, UK on 22 March 2005 at 07:00.

III. WAVE MEASUREMENT

Wave measurements are obtained by applying inverse methods to the power spectrum. This process, although numerically complex for the full directional spectrum, is again easier when the spectrum is from a single range-direction cell. For broad beam (few antenna elements) systems the range resolved spectrum is a convolution of narrow beam spectra from all directions with the antenna beam pattern [7]. To date solutions to this require that the wave spectrum is either homogeneous over the range of measurement (usually made at a range a few kilometres from the radar site) or homogeneous in deep offshore waters provided that there is no significant wave-current interaction or local wave generation so the only factor affecting the local wave spectrum in shallower water is refraction. Close to an offshore platform in deep water homogeneity can probably be assumed and accurate measurements have been demonstrated [8]. But such methods are probably inadequate in locations where there is significant wave-current interaction or in offshore wind conditions. Fig. 3 shows an example of fetch-limited wave generation associated with winds blowing from the north-east measured with a phased-array system (in this case Pisces). Development of this sort would be difficult to measure with a direction-finding system. Waveheights on this map are measured by a combination of inversion (where both radars provide sufficient signal to noise) and using a single radar algorithm [9]. With phased array systems homogeneity is not required and measurements showing wave refraction (not assuming it, as would be the case with a broad-beam measurement) have been published [10]. For such measurements information about depth variations across the region is needed for wave inversions. Where tidal ranges are large this also needs to be taken into account. This is being done with the WERA system deployed in Liverpool Bay, part of the Proudman Oceanographic Laboratory coastal observatory, although the results have yet to be validated.

However even phased array systems can produce data corrupted by signals received via antenna sidelobes and this can lead to errors in the inferred wave measurements [11]. This problem often manifests itself as a spurious long wave contribution to an otherwise good estimate of the directional spectrum an example of which is shown in fig.4 at ~ 0.6Hz although this could also be attributed to a ship.

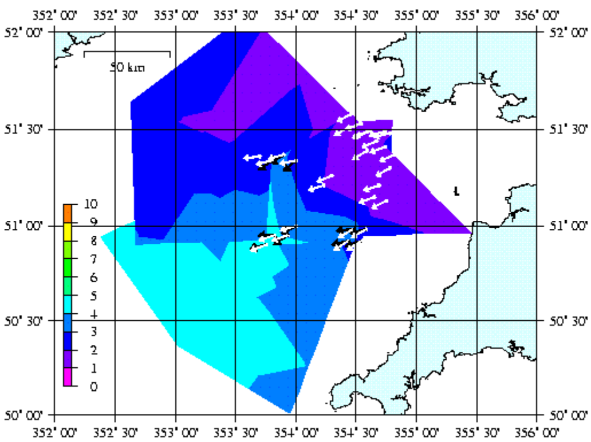

Fig. 3. Fetch-limited wave growth (waveheight colour-coded) measured with Pisces on Feb 25 2005 at 09:00. The white arrows show wind direction and black arrows wave peak direction both measured by the radar.

For both types of radar there are problems for wave measurement in high seas at high radio frequencies and in low seas at low radio frequencies. The accuracy of wave measurement using current methods and theories depends on the value of k_0Hs where k_0 is the radio wavenumber and Hs is significant waveheight. When this is high, the perturbation theory [12] used to describe the radar power spectrum in terms of the ocean wave directional spectrum becomes less accurate; when it is low the wave signal is more difficult to detect in the presence of noise.

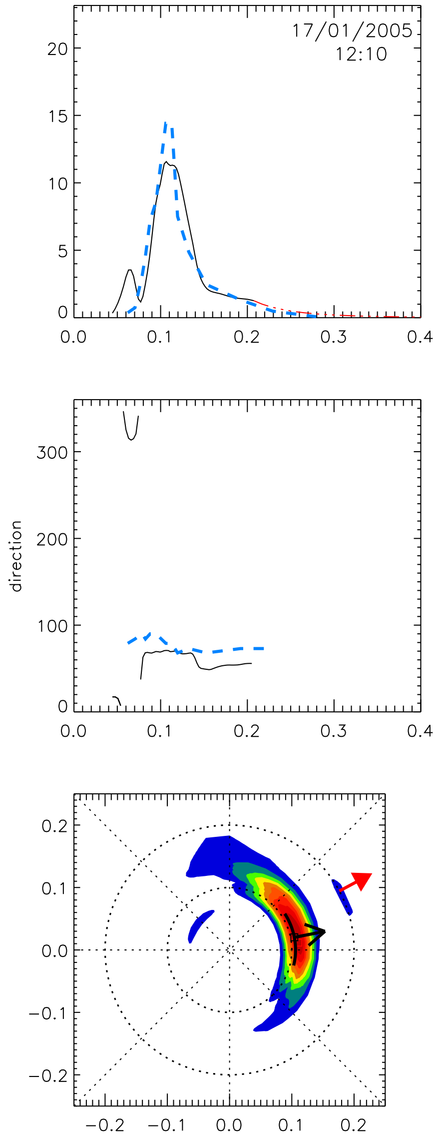

Fig. 4. Wave spectra (top: frequency spectrum, middle: direction spectrum, Pisces – black (red where f^5 tail has been added), buoy – blue dashed, bottom: directional spectrum colour-coded in 10 10% levels relative to the peak (red). Black arrow indicates buoy peak direction, black arc indicates buoy directional spreading, red arrow is radar-measured wind direction).

Fig.5 shows a timeseries of significant waveheight measurements at a frequency of about 27MHz using WERA at Fedje, Norway [4]. There is a cut-off of about 6m above which the inversion has not been carried out as a result of automatic quality checks on the radar Doppler spectrum. An increase in the maximum value of the waveheight that can be measured is possible by adjustment to the quality checks but an overestimation in these high waveheight estimates is found [4]. The corresponding scatter plot in fig.6 shows that low waveheights are in good agreement with the buoy. In contrast the scatter plot for Pisces measurements, using lower frequencies and hence smaller k_0, also seen in fig.6, shows more scatter at low waveheights. Low radio frequencies are needed to get measurements at longer ranges, fig shows waveheights to well over 100km. The ocean wave frequency range is more limited with measurements to about 0.2Hz at 6MHz compared with 0.35Hz at 27MHz. as can be seen comparing fig.4 with fig.7.

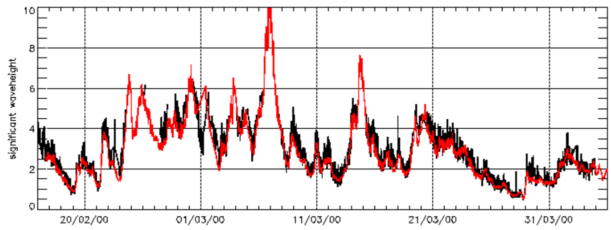

Fig. 5. Significant waveheight measurements (radar – black, buoy –red) using WERA at Fedje, Norway.

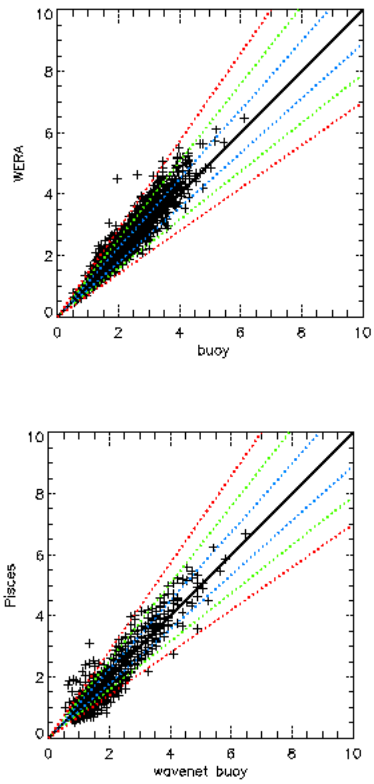

Fig 6. Scatter plots of significant waveheight. Upper is for WERA at Fedje 10km offshore, lower for Pisces in the Celtic Sea 60km offshore. The dashed lines indicate scatter within 5, 10 and 15%.

IV WIND MEASUREMENT

Wind directions are estimated from the difference in magnitude of the two first order peaks. Methods used assume a model of directional spreading of short ocean waves with one (wind direction) or two (with directional spreading) parameters to be determined by fitting the model to the data. One such method is [13]. Fig. 8 shows a time series of wind directions obtained with this method using Pisces compared with wind directions from the UK Met Office. Good agreement can be seen with a mean difference of 10º and rms of 20º. Limitations to this measurement are similar to those for currents in terms of a requirement to be robust to interference and ship signals and for operation in high seas.

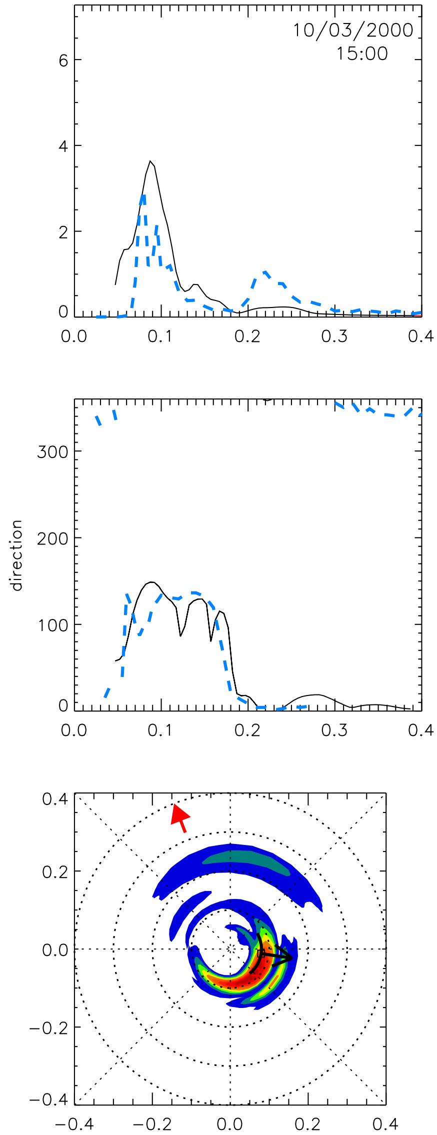

Fig. 7. As fig. 4 for WERA data at Fedje, Norway.

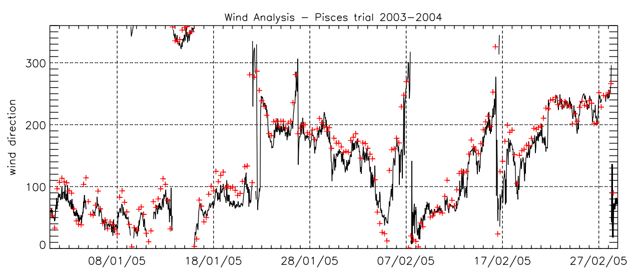

Fig 8. Wind directions measured with Pisces (black) compared with UK Met Office model (red).

Wind speed measurements have been made [14] but are not yet sufficiently reliable for operational use. In our work we are using an algorithm that assumes all wave energy is locally wind generated and can be described by a simple wind-wave model, the inversion of which provides a wind speed estimate [15]. This approach will fail in low wind speeds and would also be difficult to apply to a direction-finding system.

V. CONCLUSION

The aim of this paper ir to provide a short review of the types and capabilities of HF radar systems for coastal monitoring. It does not attempt to describe all such activity across the globe but is focussed particularly on developments with which the author has been involved. A comparison is made with the CODAR Seasonde system because that is the first system that most newcomers to this technology become aware of. It has the great advantage of compactness and hence ease of deployment and is also founded on a long and distinguished history of technological and theoretical contributions to this field. Examples have been presented here to show that phased array systems, such as the Helzel WERA and Neptune Radar Pisces, with similar historical credentials, have advantages in terms of the wider range of ocean surface parameters that can be measured more easily, more frequently and, for waves at least, more accurately.

Acknowledgments

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