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Directional spectra comparisons between HF radar and a wave model

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***Abstract*- Directional spectra measurements using HF radar are compared with model data to confirm limitations of the currently available theory that underpins these measurements. In high seas, waveheight is overestimated but it is demonstrated that there is no clear impact on the shape of the spectrum which is in reasonable agreement with the model. The need for increased averaging before inversion is discussed.**

I. INTRODUCTION

HF radar systems located on the coast have been used to 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 1 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. Wave measurement is a more complex process and has not yet gained the same level of acceptance. A higher signal to noise is required and the measurement, although numerically complex, is much more straightforward with phased array systems which are only recently gaining acceptance for operational, as opposed to experimental, applications. 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) with three different radar systems: OSCR (no longer available), WERA (developed at the University of Hamburg [1], Germany and available from Helzel GmbH) and Pisces [2] (developed from a University of Birmingham, UK, prototype and available from Neptune Radar Ltd). See www.seaviewsensing.com and follow ocean data links for more information and access to data from some of these deployments.

To date all our comparisons with wave buoy data have been at locations at close enough range to ensure good quality radar data under most conditions. Agreement between these two very different measurement technologies, particularly for significant waveheight, has generally been good. Two limitations have been identified. In low sea conditions at low radio frequencies signal to noise is often too low for reliable measurement and the approximations used in the inversion begin to lose validity. In high seas at high radio frequencies again the approximations become invalid and in extreme conditions the wave and current parts of the radar signal cannot be separated. It is this limitation that will be addressed in this paper. Towards the edges of the radar coverage region, away from the buoy, the radar wave measurement are sometimes noisier and larger in amplitude but without additional information it has been difficult to separate possible real spatial variation in the wave field from errors in the radar measurement. Wave model data will be used here to get some insight into the accuracy of wave measurements at long range.

II. THE DIRECTIONAL SPECTRUM

The mathematical formulation of and solution to the problem of the scattering of electromagnetic waves at HF frequencies from a moving ocean surface was developed in [3], [4], [5] and this forms the basis of the measurement process discussed here. The solution is in the form of a non-linear integral equation that has to be inverted numerically to provide a measurement of the directional wave spectrum. The numerical methods used for the work described here are discussed in [6], [7]. Other methods have been developed, [8], [9], [10], [11], but to date the Sheffield method has probably been through the most rigorous and extensive validation.

The inversion requires radar Doppler spectra from two radars observing the sea from two different directions. The software can provide simultaneous directional spectra measurements at hundreds of locations in near real-time. Wave parameters such as significant waveheight, peak direction and period can be determined from the directional spectrum using standard wave analysis techniques. Barrick's theory is based on a perturbation analysis with respect to the product of the radio wavenumber and ocean wave amplitude which has to be small. This approaches one in the high sea-state, high radio frequency case at which point the theory should no longer be used. Figure 1 shows this parameter as a function of radio operating frequency and significant waveheight. The impact on significant waveheight accuracy of a large value of this parameter has been shown in previous work to begin at 27MHz at less than 2m and at 6MHz above

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6m. The effect is to overestimate waveheight. The impact at high radio frequency was observed during the EuroROSE experiment on the Norwegian coast at Fedje [12]. For this case it was clear that the main impact was on the higher frequency part of the wave spectrum which was overestimated (see lower graph in Figure 2). In addition above about 6m significant waveheight (On 6-7 March 2000) it was not possible to make the measurements because the first and second order parts of this signal could not be separated. Measurements with the Pisces radar at low radio frequencies (6-10MHz) have only indicated a small impact in high sea-states although there was very little buoy data for comparison in the very highest seas.

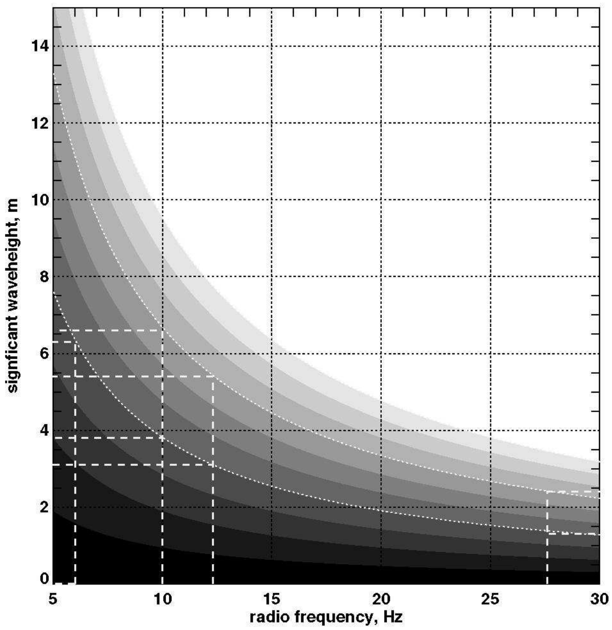

Figure 1 Perturbation parameter increasing from 0.1 (black) to 1 and above (white). White dotted line marks range between 0.4-0.7. White dashed lines indicate frequency ranges referred to in the text.

III. VIGICOTE DATA

A WERA deployment on the Brittany coast of France, for the SHOM Vigicote project, has been providing data at 12MHz over the last couple of years in a very wide range of sea-states. According to Figure 1 there is likely to be a growing impact on waveheight for values above 3m. In this paper we consider data for the period 17-25 January 2007 during which a number of strong storms passed through the region. There is no in-situ buoy data for this period but SHOM have provided three-hourly spectral data from the Wavewatch III wave model [13]. In addition we have data from the Brittany buoy located at at 47.5N,-8.4W well to the west of the radar coverage. The locations of the wave model data available for comparison are shown in Figure 3. The additional buoys shown on the figure were not operational during the period of these measurements. The radar measurement locations used in the comparisons to be discussed here are also shown in the figure. At the longer ranges there are less data for comparison because the signal to noise requirement is met less often. Figure 4 shows a waveheight comparison using the radar measurements about two-thirds of the way along the east-west line from the coast compared with the model and the Brittany buoy. The upper graph in this case shows the full waveheight which is then broken down into the peak and the same frequency bands as were used in Figure 2. It can be seen that although there is good agreement near the spectral peak there is overestimation across the rest of the spectrum in the higher seas.

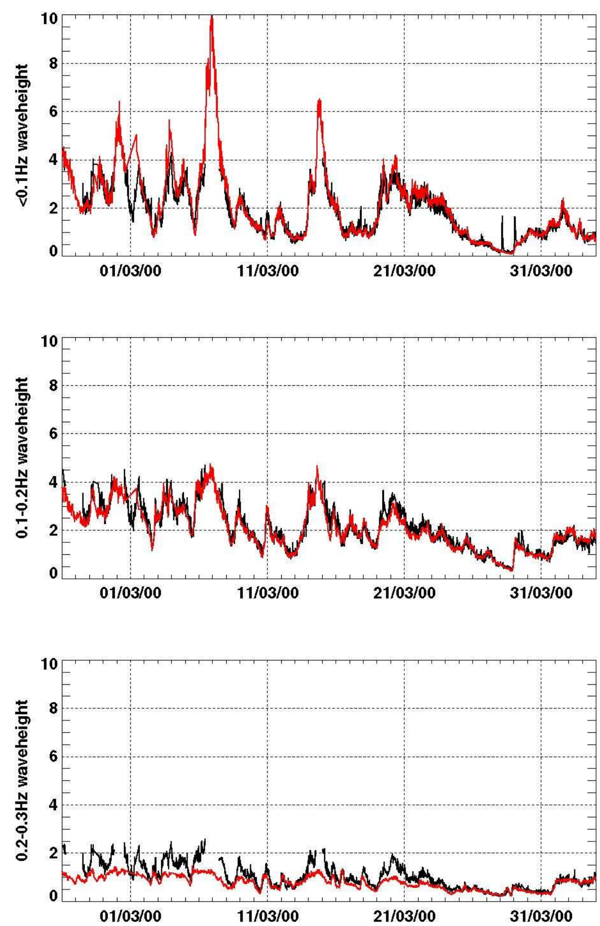

Figure 2 Waveheight (radar –black, buoy – red) measured at Fedje, Norway broken down into three frequency bands: top less than 0.1Hz; middle 0.1-0.2Hz; bottom 0.2-0.3Hz..

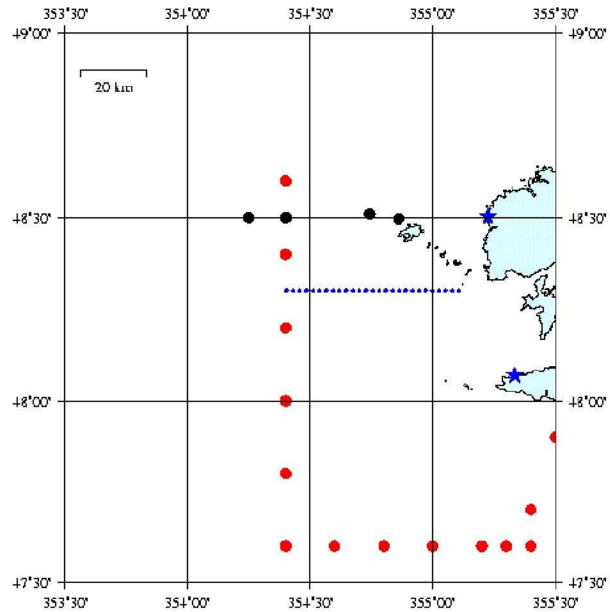

Figure 3 Map showing model (red), radar (blue) and buoy (black) locations for Vigicote project.

The Vigicote data is noisier than the Norwegian data shown in Figure 2. Increased averaging is needed [14]. Figure 5 shows the comparison of mean direction and peak period for the same period showing that impact of the perturbation parameter is primarily in waveheight and not in the shape of the spectrum. This is consistent with our current thinking about a modification to Barrick's theory that more correctly represents the scattering to second order. This work is in progess and will be reported at a later date. Direction and period parameters do get noisier in the lower sea-states in the later part of the data presented in Figure 5 and again the need for increased averaging is clear.

As can be seen in Figure 5 there is a large change in mean direction of the waves on 22 Jan 2007. This is associated with a wind direction change as can be seen in Figure 6 which shows directional spectra, in each case normalised to its peak, every three hours (the times when the model spectra are available) during this period. At the beginning of the period the radar spectrum is similar in shape but broader than that of the model. This is also characteristic of radar buoy comparisons although in those cases such comparisons have to be made with caution since a buoy spectrum is not measured but derived using a statistical model e.g. maximum entropy [15]. As the wind direction changes the radar measurement shows more complexity than that of the model. Some of this may be associated with the need for extra averaging already referred to but some of it may also be real since some of the features persist in the radar data in between the three hourly measurements shown here.

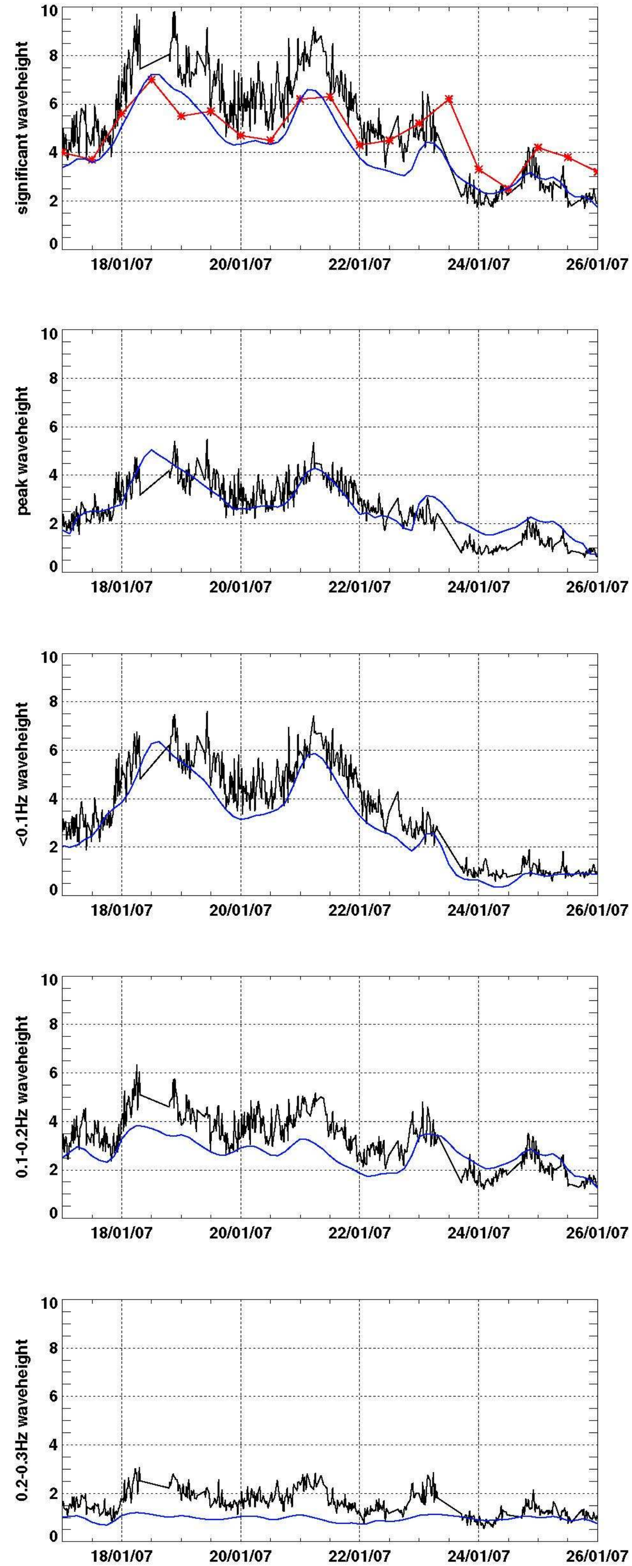

Figure 4 Vigicote significant waveheight (top) and contributions to it from the peak, <0.1Hz, 0.1-0.2Hz, 0.2-0.3Hz. Radar – black, model –blue, buoy-red.

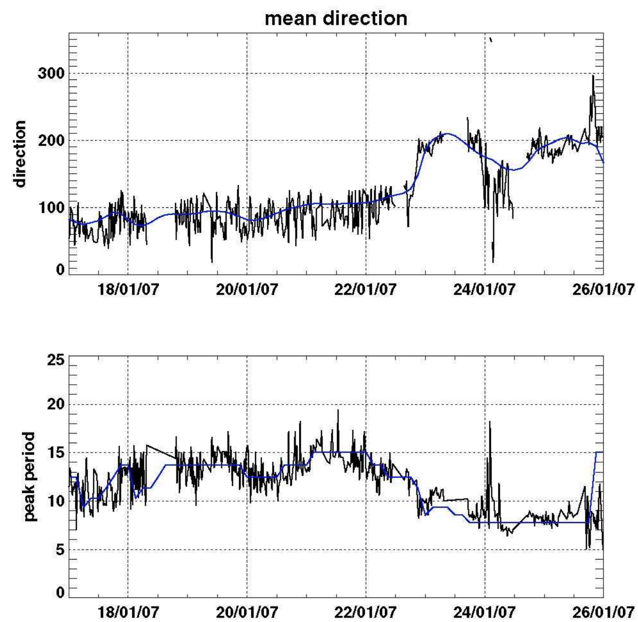

Figure 5 Vigicote mean direction and peak period. Radar – black, model – blue.

The radar data are available every 20 minutes. Certainly the radar spectrum at the end of the period shown is not showing a dominant wind-wave peak unlike the model spectrum. The bimodality seen in the radar data at 21:00 and 23:00 and in the model data at 21:00 persists in the radar data, with a strengthening in the wind-wave component throughout the following morning whereas the model remains similar to the 23:00 case. There is evidence of bimodality in the model data but the swell component is much weaker than the wind-wave component and doesn't show clearly in these plots.

However the comparisons in Figure 6 are not co-located. The radar measurement site is east of the model point and there may be some island or coastal influence since the wind is from the north-east. Figure 7 shows the radar measured spectrum at locations going westwards from the data shown in Figure 6 and the influence of the wind does increase with the final spectrum looking similar to the buoy spectrum. This spatial variability in the wave field is also seen in Figures 8 – 10. These are maps of significant waveheight and mean direction at 18:00, 21:00 on 22/01/07 and 00:00 on 23/01/07. Included in these Figures are estimates of significant waveheight from the individual radars [16]. These assume that the wave energy is propagating roughly towards the radars and do not account for depth variations but because they only require one radar to have sufficient signal to noise they extend the coverage range.

IV CONCLUDING REMARKS

The data presented here demonstrate that although the amplitude of radar-measured directional spectra is overestimated in high sea-states, the shape of the spectrum remains in reasonable agreement with a (roughly) co-located WAVEWATCH III wave model spectrum. The waveheight overestimation is related to the perturbation parameter in Barrick's theory which underpins all the radar measurements presented here. The onset of overestimation as this parameter increases is consistent with earlier data sets collected with different radio frequencies. This is the subject of current research and we expect to demonstrate improved waveheight and spectral amplitude estimates soon. Together with data from other recent WERA deployments, the Vigicote data has confimed the need for additional averaging of the radar Doppler spectra before inversion. Recommendations for this are being developed.

ACKNOWLEDGMENT

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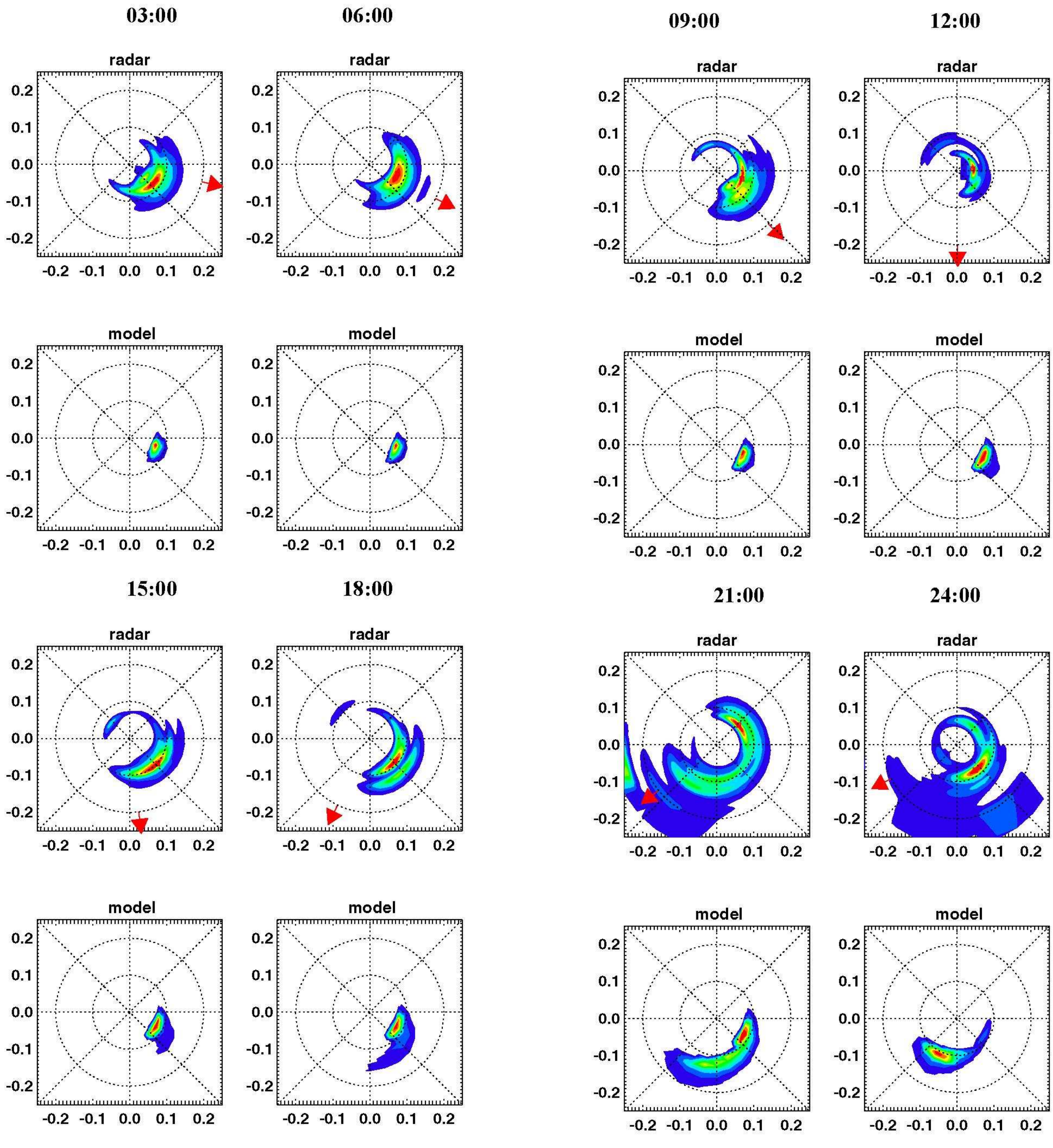

Figure 6 Peak-normalised Vigicote directional spectra during a wind direction (radar measurement shown with a red arrow) change on 22/01/2007.

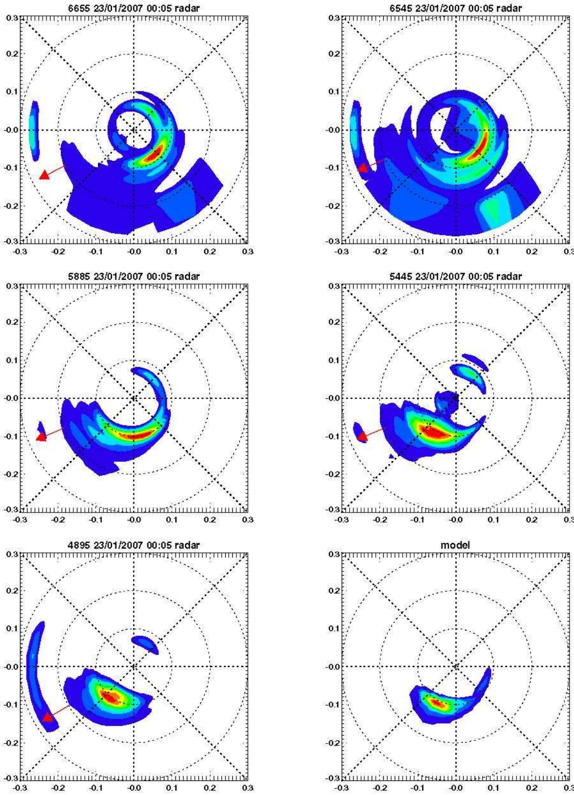

Figure 7 Peak-normalised Vigicote directional spectra at 00:00 23/1/07 going westwards (left to right, top to bottom) from measurement in Figure 6 with model spectrum on lower right.

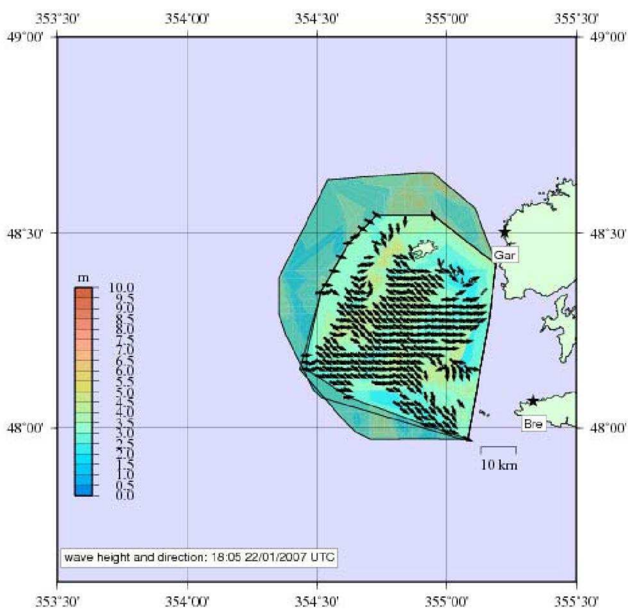

Figure 8. Map of significant waveheight and mean direction measured at 18:00 on 22/01/08. Darker shades show single radar significant waveheight estimates. Radar sites indicated with *.

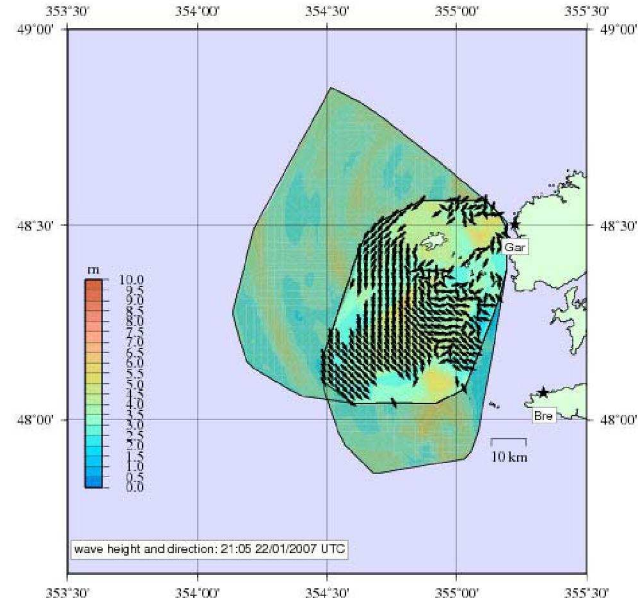

Figure 9. Map of significant waveheight and mean direction measured at 21:00 on 22/01/08.

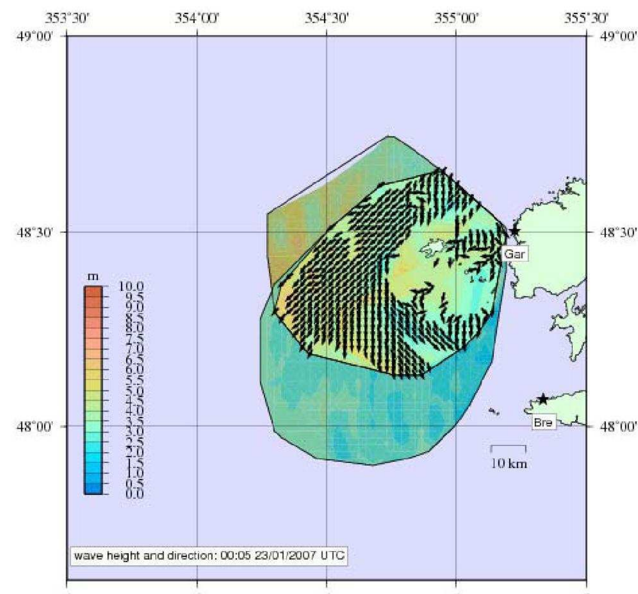

Figure 10. Map of significant waveheight and mean direction measured at 00:00 on 23/01/08.