To appear in Proceedings of Oceans07 Vancouver September 2007

Data quality and sampling requirements for reliable wave measurement with HF radar

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***Abstract*- HF radar systems located on the coast can provide measurements of surface currents and waves. The maximum range of these measurements depends on the signal to noise in the radar backscatter spectrum. Previous work, comparing radar with buoy wave measurements, has shown that a second order peak signal to noise of 15dB can provide reliable measurements of the directional wave spectrum. However recent evidence suggests that this is not sufficient and some ideas for a more robust measure are discussed. For radar and buoy measurements averaging is required in order to reduce the variance in wave parameter estimates. The work of Sova (1995) on the impact of temporal sampling variability in radar Doppler spectrum estimation on wave measurement is reviewed. The implications of this for various sampling strategies that have been used for radar wave measurements is discussed and compared with the corresponding sampling variability of wave buoy measurements. The impact of increased averaging will be demonstrated using WERA data from the Eurorose Fedje experiment**

I. Introduction

HF radar systems located on the coast have measured surface currents and the ocean wave directional spectrum simultaneously from close to the coast to more than 100km offshore. Measurements have been 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. 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, Germany [1] and available from Helzel GmbH) and Pisces (developed from a University of Birmingham, UK, prototype and available from Neptune Radar Ltd [2]). 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 [3], [4], [5], [2]. 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. This paper discusses some examples where it does appear that the longer range measurements are overestimating waveheight and some suggestions for providing more robust measurements in low signal-to-noise conditions are outlined. Other recent wave measurements have been made using radar systems configured primarily for surface current measurement. Averaging requirements for currents are less than those for waves and the noisiness of the wave measurements obtained have prompted a revisit of some work carried out several years ago on estimating and reducing sampling variability impacts on wave measurements.

II. Signal to noise issues

The radar coverage region is determined by the signal to noise in the radar backscatter spectrum and for our measurements we have required a 15dB peak signal to noise in the part of the spectrum used for wave measurement. Wave measurements can be made either through an integral inversion method [6], [7], which is referred to below as a full inversion, or using empirically derived relationships between the Doppler spectrum and integrals thereof and buoy measured waveheight [8], [9]. The empirical methods developed at Sheffield provide two single radar estimates at each location for each radar, one corresponds to the case when the waves are propagating roughly towards (or away from) the radar and one when they are roughly perpendicular. The non-perpendicular algorithm is more reliable and is used for all the single radar data shown here. The perpendicular algorithm gives larger estimates except in low seas ($Hs < k_0/2$ where k_0 is the radio waveneumber) when both estimates are similar. A 15dB signal to noise threshold is also used to ensure these estimates are of good quality. Where both radars satisfy the signal to noise requirement the full inversion can be carried out but also the two single radar estimates from each radar can be used to remove the directional ambiguity and create a combined Hs estimate.

Fig. 1a is one example of a waveheight and mean direction measurement using the full inversion. These data have been provided by Actimar who are operating a WERA HF radar system for the SHOM Vigicote project on the west Brittany coast of France. The radar has been in operation for about 1 year. The map shows waveheights measured at 01:45 GMT on 2nd December 2006 ranging from 2-6m over this region. However the Meteo France buoy (second from the left of the black dots on the maps) was measuring about 3.5m during this period indicating that the radar waveheight measurements at longer ranges are overestimated. Similar discrepancies were found at other times. Fig. 1b shows the single radar waveheight estimates from both sites overlaid with the combined waveheight where both radars have sufficient signal to noise. Both single radar estimates seem to be consistent (so perpendicularly propagating waves do not appear to be an issue in this case) and the long range waveheights are more consistent with the buoy data. Since the combined Hs estimate is available everywhere the full inverted Hs is determined, a simple solution to the overestimation is to use the ratio of the two to decide whether or not the inversion is acceptable. Fig. 1c shows the result of such an approach. Where the ratio exceeds 1.3 the fully inverted Hs has been replaced with the combined value and the mean direction has been discarded. A number of such cases have been explored and a figure of 1.3-1.4 seems to give the best qualitative results over a range of different waveheights.

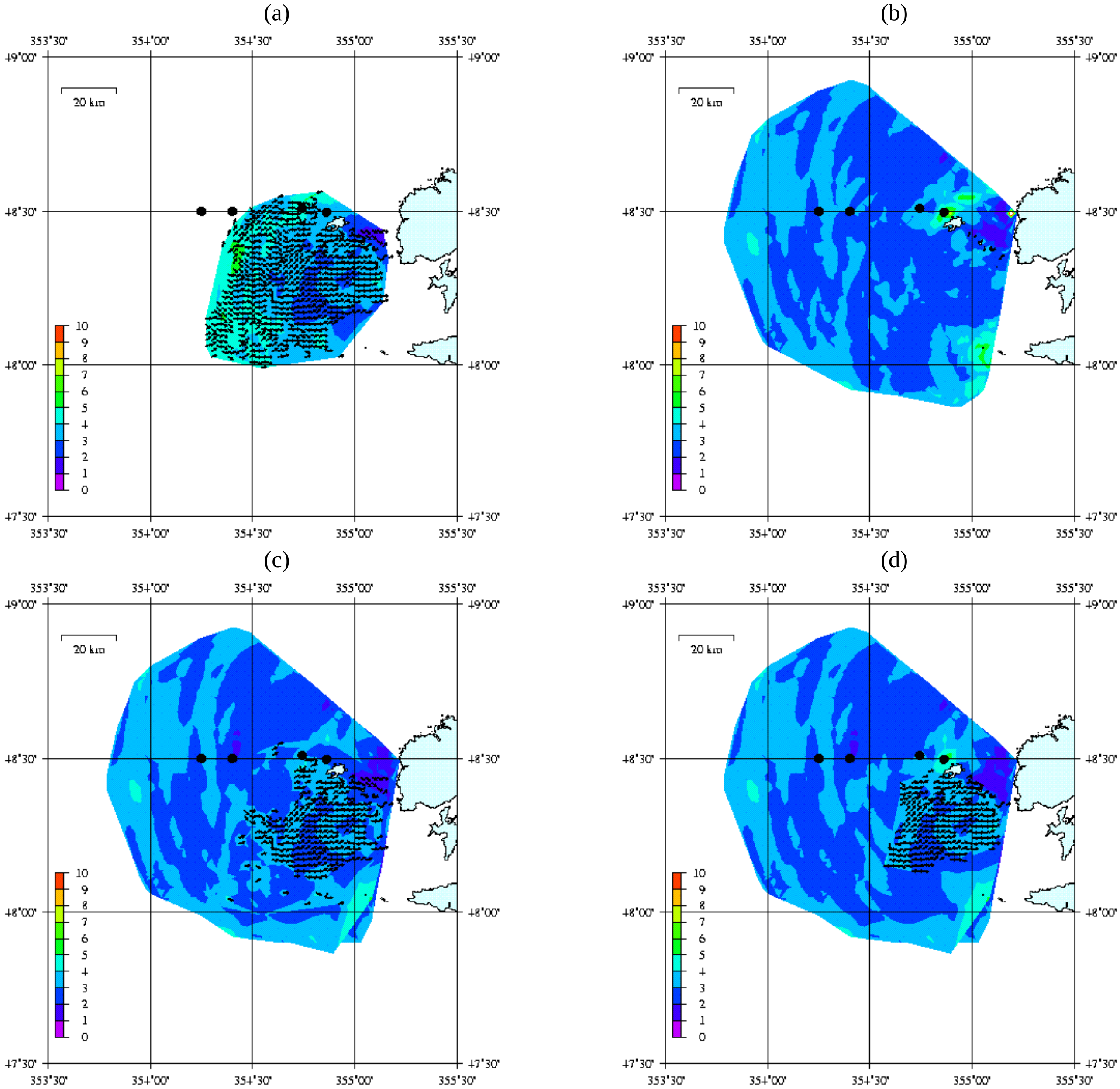

Fig 1. Wave maps (a) Hs and mean direction for full inversion with >15dB signal to noise; (b) single radar Hs overlaid with combined where both satisfy signal to noise criterion; (c) single radar Hs overlaid with full inversion and combined if Hs ratio criterion violated; (d) single radar Hs overlaid with full inversion where all Doppler bins have signal to noise > 10dB. Black dots mark buoy positions.

There are several factors that could be influencing the full inversion estimates in low signal to noise conditions: interference, shipping, the ionosphere; but all of these will also impact on the single radar estimates to a certain extent. More likely the problem with the data shown above lies in the fact that the signal to noise estimate is of the peak in the 2nd order spectrum and when this is near 15dB much of the spectrum may be at a significantly lower level. We could be inverting parts of the spectrum with signal to noise less than 10dB which will inevitably be very susceptible to noise. If the inversion then gets the direction wrong at wavenumbers associated with these low amplitude Doppler bins, the amplitude is likely to be wrong because of the ambiguities inherent in the backscatter process. Smoothing within the inversion will spread these errors across, at least part of, the spectrum. Imposing a requirement that all the data used in the inversion has single to noise greater than 10dB does indeed get rid of most of the anomalous waveheight measurements for the cases explored here (see Fig. 1d). The next step is to examine the signal to noise at each Doppler bin before the inversion is carried out and only use the range of bins around the peak that are above 10dB. This may provide better quality inversions at a few more locations.

During trials with the Pisces HF radar [2] problems were identified in low waveheights with directional parameters in particular. Again a 15dB threshold was imposed but we anticipate that these too will benefit from the more detailed signal to noise assessment and thresholding and thus potentially provide increased data return and robustness at low radio frequencies in low sea states.

III. Sampling and Averaging

The sampling variability in HF radar wave measurements can be inferred from the temporal sampling variability in the radar Doppler spectra used to obtain those measurements The implications of various sampling strategies that have been used for radar wave measurements are discussed here and compared with the corresponding sampling variability of wave buoy measurements. The relative impact of sampling variability and other factors that influence the comparison between radar and buoy measurements will be discussed. The impact of increased averaging is demonstrated using WERA data from the Eurorose Fedje experiment [5].

A. Sampling Variability

This analysis will focus on the sampling variability associated with the single radar waveheight estimates. Sova [10] looked at the sampling statistics associated with empirical methods to extract significant waveheight from the HF radar Doppler spectrum. Barrick [11] also considered this problem. The statistics of the full inversion estimates were also investigated by Sova [10] using Monte-Carlo simulations. However the estimates were found to depend on radio frequency, sample rate and Doppler averaging and estimating the degrees of freedom for a new set of such parameters, for example for a new radar system, requires additional simulations. It is also not yet clear that the range of conditions used in the simulations is sufficient to get reliable estimates of the statistics hence the analysis here is limited to the single radar estimates. The Doppler spectrum is obtained with an averaged periodogram and, on the assumption of approximate normality of HF radar backscatter (discussed by Barrick and Snider [12] and also demonstrated by Vizinho [13]), each spectral estimate is a χ^2-distributed variable with ν degrees of freedom, i.e. statistically similar to a buoy-measured wave spectrum. The number of degrees of freedom depends on the number of individual spectra that are averaged and on the degree of overlap of their respective timeseries (see [14], [15], [10] for details). All the analysis here will assume that the time series of length M is subdivided into N-point sequences for which a periodogram is obtained using FFT methods and they are overlapped by 75% with a Blackman Harris 4-point window to minimise the correlation between successive time sequences. M and N may be different for the different experimental data sets included in this analysis.

The empirical methods for waveheight estimation are of the form $\mathrm{Hs} = F\left(\sum_{\eta_r}\sigma_2(\eta)\right)$ where F is an empirically determined function of $\sigma_2(\eta)$, the normalised (by the integral of the first order peak region) second order part of the averaged Doppler spectrum, summed over a range η_r of normalised Doppler frequencies, η. Because the normalised spectrum is involved, the Hs estimates involve ratios of sums of χ^2-distributed variables and these ratios are therefore F_{ν_2,ν_1}-distributed with degrees of freedom ν_2 for the sum over the second order spectrum and ν_1 over the first order peak.

The formulae used at Sheffield [8], [9] take the following form:

$$\mathrm{Hs} = \frac{\beta}{k_0}\left(\frac{\sqrt{\sum_{L}\sigma_2(\eta)} + \sqrt{\sum_{U}\sigma_2(\eta)}}{2}\right)^{\alpha}$$

where k_0 is the radio wavenumber, α and β are engineering parameters and are different for the cases when waves are travelling perpendicular to the radar beam and otherwise. The integration ranges below, L, and above, U, the main Bragg peak are separated in this formula. Other empirical methods, e.g. [16], [17], add the two ranges together before applying a power and the same analysis (developed below) has been applied to such cases but is not discussed further here.

Using a Taylor series expansion the variance of H_s can be estimated from the above expression [10] as:

$$\mathrm{Var}(\hat{H}s)=\frac{\alpha^2\beta^2}{2^{2\alpha+2}k_0^{\ 2}}\left(\mathrm{Var}(F_{\nu_L\nu_1})E\left(\sum_L\sigma_2(\eta)\right)+\mathrm{Var}(F_{\nu_U\nu_1})E\left(\sum_U\sigma_2(\eta)\right)\right)\left(\sqrt{E\left(\sum_L\sigma_2(\eta)\right)}+\sqrt{E\left(\sum_U\sigma_2(\eta)\right)}\right)^{2\alpha-2}$$

where $\mathrm{Var}(F_{\nu_2,\nu_1})=\dfrac{2\nu_1^2(\nu_1+\nu_2-2)}{\nu_2(\nu_1-2)^2(\nu_1-4)}$ for $\nu_1>4$. This waveheight variance has to be estimated by replacing the expectations in the above formula by the calculated values for each spectrum. Similar expressions can be derived for other functional forms for the significant waveheight calculation.

To complete these calculations the degrees of freedom, ν_1,ν_2, for the first and second order parts of the spectrum respectively need to be estimated. Sova estimated these from the Doppler spectrum, D, using $\nu=\nu_R\dfrac{\mathrm{mean}^2}{\mathrm{variance}}$ where ν_R is the degrees of freedom for each Doppler spectral estimate (= 2 if no averaging has been done). When windowed, overlapped, averaged Doppler spectra are used, ν_R is determined using [14]:

$$\frac{2}{\nu_R}=\frac{1}{N}\left[1+2\rho^2(75\%)+2\rho^2(50\%)+2\rho^2(25\%)\right]-\frac{2}{N^2}\left[\rho^2(75\%)+2\rho^2(50\%)+3\rho^2(25\%)\right]$$

where *N* is the number of overlapped series, $\rho(\phi\%)$ is the $\phi\%$ overlap correlation. For the minimum 4-sample Blackman-Harris window ([14], [15]) used for all the data presented here, $\rho(75\%)=0.460$, $\rho(50\%)=0.038$ and $\rho(25\%)$ is effectively zero.

The mean and variance are determined over the Doppler spectral range being considered. The expression Sova derived (after a tortuous algebraic analysis) is:

$$\nu=\nu_R\frac{\left[\sum_{j=-\lambda}^{\lambda}a_j^{\ 2}\sum_{f=f_L}^{f_U}D(f-j)\right]^2}{\sum_{f=f_L}^{f_U}\sum_{g=f_L}^{f_U}\sum_{j=-\lambda}^{\lambda}\sum_{l=-\lambda}^{\lambda}a_ja_la_{g+j-f}a_{g+l-f}D(f-j)D(f-l)}$$

where a_i, $i=-\lambda,\lambda$ are the $2\lambda+1$ coefficients used in the window applied to the data during Doppler processing, $f_{L,U}$ are the Doppler spectral indices at the edges of the spectral range, $D(f)$ is the Doppler spectrum and is shorthand for $D(f\Delta)$ where Δ is the frequency sampling in the Doppler spectrum. This expression accounts for the loss of statistical independence of neighbouring Doppler bins due to the windowing.

B. Results

The implications of these results for various sampling strategies that have been adopted with metocean radars will now be discussed. Data from three different radars will be considered: OSCR, Pisces and WERA, operating at a range of frequencies. Table 1 shows the cases that have been considered and the relevant parameters. In addition to these, part of the Fedje data set has also been further averaged by factors of 2 and 3 (referred to as Fedje 2 and 3) and the Miami data by a factor of 3 (referred to as Miami 3) by averaging the appropriate number of consecutive incoherent data sets. The corresponding degrees of freedom for these longer averages can be obtained by multiplying the original figure by the additional averaging factor. For each deployment the values of single radar Hs have been determined and the variances have been estimated as discussed above. Other Hs and variance estimation methods have also been examined but are not discussed here.

The discussion will focus on the coefficient of variation, CoV = Std(Hs)/Hs, expressed as a percentage, where Std(Hs) is the standard deviation obtained from the square root of the variance estimated using the methods discussed above. The radar figures should be compared with a 4-6% CoV range for buoy data [18]. Some of the same data sets were considered in [9] where the directional characteristics of the waves were taken into account to show the need for the two relationships discussed here. The Fedje data set was found to be anomalous in that work in that the perpendicular cases fell above and the non-perpendicular cases below the two expressions that do describe reasonably well all the other data sets considered. That is also seen here and suggests that the Wyatt formulae may need to be modified for high k_0H_S cases. The higher k_0H_S cases are all from the Fedje data set and are predominantly perpendicular cases.

The results are plotted in Fig. 2. Here it can be seen that to reduce the sampling variability impacts on waveheight estimates to the level achieved by wave buoys it is necessary to have Doppler degrees of freedom of above about 35. Only the NURWEC2 deployment used this level of averaging. The Sova estimates of variance for waveheight estimated from radar-measured directional spectra for the Holderness data set gives a CoV of 3-5% [18]. However, as mentioned above, we do not have as much confidence in this estimate which was based on limited Monte-Carlo modelling. Certainly the scatter between radar and buoy waveheight estimates at Holderness was significantly greater than can be attributed to such a low CoV [18].

TABLE 1.
DATA SETS USED IN THE ANALYSIS.

deployment	radar	frequency	bandwidth	fft length	no of averaged Doppler spectra	doppler degrees of freedom
Nurwec2 [3]	Pisces	6-16	2.5	512	33	47
Holderness [4]	OSCR	25.4	3.05	512	12	18
Fedje [4]	WERA	27.65	3.84615	512	13	19
Showex [19]	OSCR	25.4	3.05	512	12	18
Miami [20]	WERA	16.04	3.84615	512	5	7
Wavenet [2]	Pisces	6-10	5.	1024	19	27

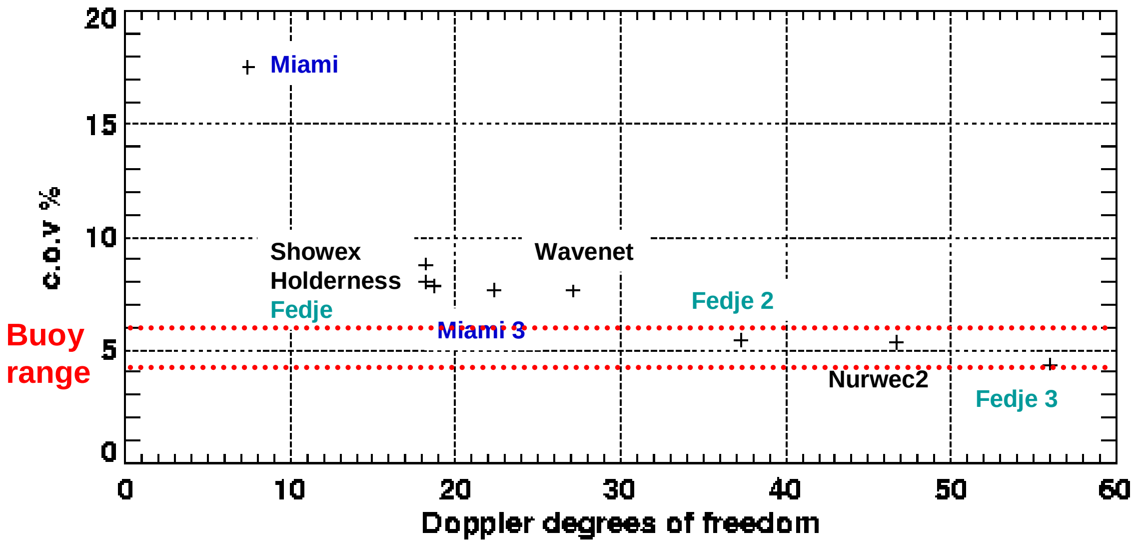

Fig 2. Percentage coefficient of variation as a function of Doppler degrees of freedom.

Fig. 2 implies that the NURWEC2 averaging and the buoy CoV range could be achieved by averaging consecutive radar Doppler spectra from the Fedje experiment. Any improvement can then be assessed by comparison with the buoy deployed for that experiment. Increasing the averaging to three consecutive spectra does not appear to provide a significant advantage and is more likely to involve stationarity issues. Fig. 3 shows scatter plots of significant waveheight and mean direction comparisons for the standard and double averaged cases. Differences are small but they can be seen. They are also evident in the statistics of the comparisons shown in table 2. Notice that the increase in averaging provides ~ 9% more data suitable for inversion. The scatter index is the standard deviation of the difference between the radar and buoy measurement divided by the mean of the buoy measurement. Making the assumption that the true means of the buoy and radar Hs estimates are the same, that the buoy and radar measurements are uncorrelated and that the CoV for the buoy data is 5% (see above) and for the radar data is the value shown in Fig. 2 (i.e. the CoV for the full inversion is assumed to be the same as that for the empirical method), an expected scatter index for the comparisons can be estimated and this is shown in the table. The change in its magnitude between the two averages is similar to the measured change but the measured values are larger indicating that there is more than sampling variability in the difference between the two measurements. One contribution to this is the radar overestimation of waveheight in the higher seas. This radar was operating at 27MHz for which 6m is a very high waveheight, much higher than the threshold that would be advised for the linearization used in the inversion analysis [15].

C. Alternatives to temporal averaging.

There are limitations to temporal averaging. Stationarity in oceanographic and/or interference conditions is required. The Miami 3 case gave improved performance during the morning with significantly more, and less noisy, wave measurements but in late morning and afternoon when the ionosphere was beginning to influence the radar backscatter in an intermittent manner, the averaging tended to smear out the ionospheric contamination in time resulting in significantly less data. This radar was operating at 16MHz, a lower frequency system would have a similar problem at a different time of day.

Reductions in variance are also possible in principle using Doppler and/or spatial averaging. Barrick [22] analysed the impact of both of these and referred to the need to normalise (using a logarithmic method) each Doppler spectrum before spatial averaging to remove path loss effects. To analyse the impact of Doppler averaging (smoothing) the correlation between neighbouring bins due to the windowing in the spectral analysis must be accounted for. The impact of spatial averaging needs to account for correlations associated with range correlation due to windowing in the spectral analysis that is required for FMCW systems and to any interpolation that might be applied in gridding the radar data. Azimuthal correlation may also be an issue when gridding since grid spacing is not usually matched to beamwidth. These issues are all being explored but it is too early to report on their impact at the time of writing.

TABLE 2
STATISTICS OF FEDJE COMPARISONS

		Standard average	Double average
	Number of pairs	1186	1294
Hs	Correlation coefficient	0.96	0.97
	Rms difference	46cm	41cm
	Scatter index	15.7%	13.3%
	Scatter index using CoV	9.3%	7.4%
Mean direction	Correlation coefficient	0.83	0.87
	Mean difference	24.3º	21.1º

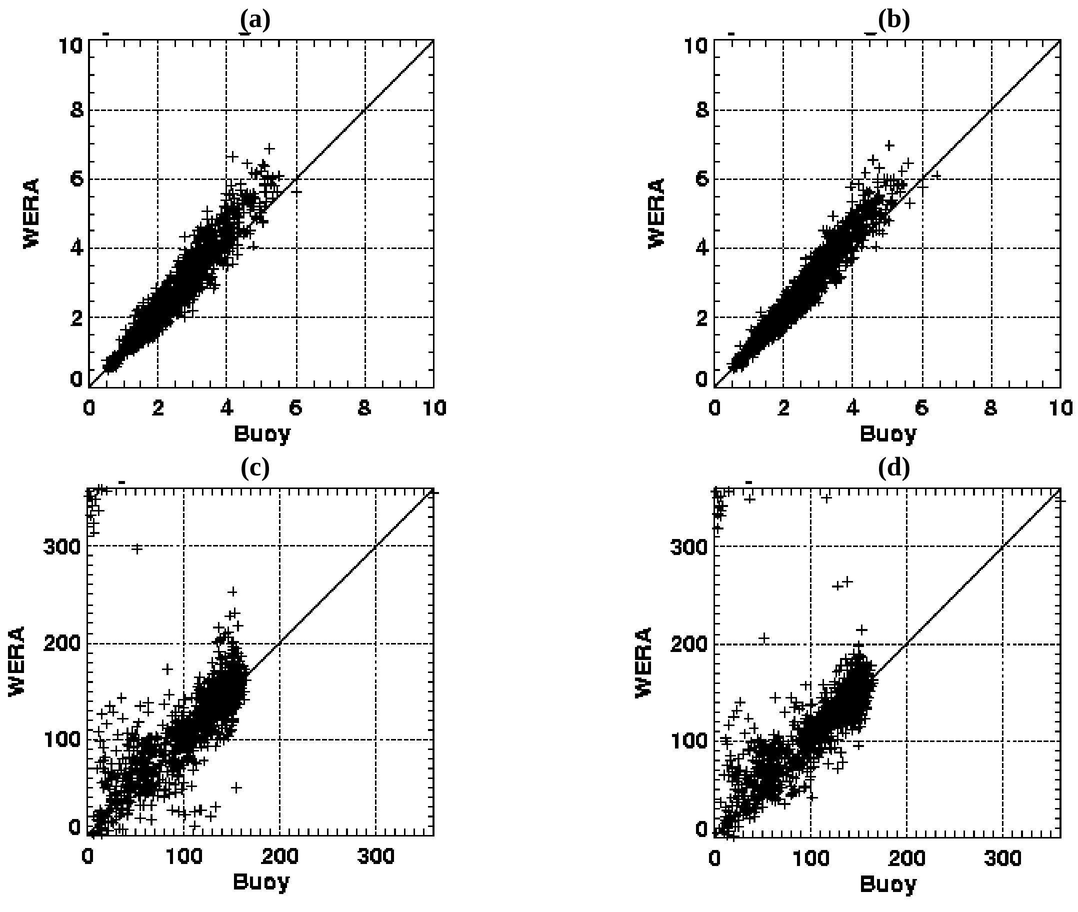

Fig 3. Scatter plots of Hs for the original averaging (a) and increased averaging (b), mean direction arranged similarly (c), (d).

DISCUSSION

This paper has reported on work in progress to identify some of the issues associated with the availability and quality of wave measurements using HF radar systems and to explore appropriate methods to improve their reliability and robustness. The simple peak signal to noise condition, used at Sheffield at least, to determine fitness for inversion has been shown to be inadequate and a more sensitive measure is under development. The simple measure does however appear to be adequate for empirical inversion algorithms the results of which can be used instead pending improvements to the full inversion method.

Wave measurements require longer averaging than current measurements and this can be achieved either by extending the observation period (which could be subdivided for more frequent current measurements if required) or by temporal, spatial or frequency averaging or some combination of all of these. The analysis of temporal averaging for an empirical significant waveheight estimate has been summarised here and shown to provide a rough estimate of the observed difference between the WERA radar and buoy data from the Fedje experiment with two different averaging periods. The analysis for spatial and frequency averaging is being developed, using [10], [22] as a basis.

ACKNOWLEDGMENTS

The Vigicote data were kindly supplied by Actimar and SHOM. The Fedje data were obtained during the EU-funded EuroROSE project and we thank Klaus-Werner Gurgel and all the EuroROSE team for their contributions.

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