

On wave radar measurement

Kevin Ewans · Graham Feld · Philip Jonathan

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Abstract The SAAB REX WaveRadar sensor is widely used for platform-based wave measurement systems by the offshore oil and gas industry. It offers in situ surface elevation wave measurements at relatively low operational costs. Furthermore, there is adequate flexibility in sampling rates, allowing in principle sampling frequencies from 1 to 10 Hz, but with an angular microwave beam width of 10° and an implied ocean surface footprint in the order of metres, significant limitations on the spatial and temporal resolution might be expected. Indeed there are reports that the accuracy of the measurements from wave radars may not be as good as expected. We review the functionality of a WaveRadar using numerical simulations to better understand how WaveRadar estimates compare with known surface elevations. In addition, we review recent field measurements made with a WaveRadar set at the maximum sampling frequency, in the light of the expected functionality and the numerical simulations, and we include inter-comparisons between SAAB radars and buoy measurements for locations in the North Sea.

Keywords Wave measurement · Wave radar · Inter-comparison · Surface elevation · Wave spectra

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K. Ewans (✉)
Sarawak Shell Bhd, 50450 Kuala Lumpur, Malaysia
e-mail: kevin.ewans@shell.com

G. Feld
Shell Global Solutions, Aberdeen, UK

P. Jonathan
Shell Research Ltd, Chester CH1 3SH, UK

1 Introduction

Wave measurements are required for the operation of offshore oil and gas facilities, and wave measurement devices that can be mounted on the offshore platform itself are attractive to operators, because of their relatively low operational costs—they are easy to maintain and service and do not require expensive ship time needed for deployment and recovery of wave buoys. In addition, they offer the potential to measure absolute surface elevation, when mounted on a fixed platform, providing the opportunity to investigate more fundamental aspects of the wave field.

Among the instrument types that have been used are wave staffs, lasers and radars. A good description of these can be found in Tucker and Pitt (2001). Lasers and radars offer the additional advantage over devices such as wave staffs in that they are not in contact with the water and can more easily be deployed and maintained. Grønlie (2004) gives a high-level description of a number of different radar techniques suitable for wave and surface current measurements and a number of currently available commercial wave and current sensors that employ these techniques. Among these is the SAAB WaveRadar, which Grønlie (2004) categorises as a direct sensor, as it involves direct measurement of surface elevation. Indirect sensors are those that involve derivation of wave information from images associated with Bragg scattering at low grazing angles such as those based on ship navigation systems.

In a review of electromagnetic wave scattering theories, Valenzuela (1978) states that the backscatter of electromagnetic waves from the ocean is specular near normal incidence; and away from normal incidence, the scattering is diffuse, being produced by the smaller scale roughness characteristics. Accordingly, as the WaveRadar is mounted on a platform in a vertically downward-looking orientation, the tangent plane approximation, in which the surface fields may be

approximated by those that would correspond to a flat tangent plane existing at each point on the surface, is valid. In such cases, the scattered fields may be obtained using the physical optics or Kirchhoff method, but (Valenzuela 1978) cautions that an effective reflection coefficient should be used, and notes that the mean-square ocean wave slope influences the scatter, and small-scale roughness associated with spray and foam modify the reflection. In this respect, breaking waves will also have an effect on the scattering (e.g. Donelan and Pierson 1987). In addition to the effect on scattering, spray and foam may introduce errors in measurement; Grønlie (2004) notes that lasers may lock onto water spray and fog, and will be frequently be unable to track the sea surface, but that microwave radars are less susceptible to this, due their much lower frequency of operation.

While there is an extensive literature on the performance of wave radars based on low grazing angle measurements (e.g. Story et al., 2011), there are few publications on the performance of surface elevation measuring radars. Mai and Zimmermann (2000) found two “comparatively cheap” radar level sensors—Vegapuls 1, Vega and Kalesto, Ott – did not perform in a wave flume, but these were units specifically set up for tank level measurements. In the WACSIS project (Barstow et al. 2002), wave measurements from five platform-based wave sensors—a Vlissingen step gauge, a Baylor wave staff, a Thorn laser, a SAAB radar and a MAREX SO5 radar—were compared. The significant wave heights from the sensors were in agreement to within 3 %. The SAAB radar was found to produce higher crests and surface elevation skewness compared to the other instruments, but it was located separately on a different part of the platform, and it was concluded that real spatial features in the wave field could have caused the differences. They also concluded that there was only circumstantial evidence of elevated crests caused by spray effects, and it was possible that dispersive and/or short-crested effects may have caused the differences between the instruments in many cases. In addition, they identified a number of events for which there was a lot of spray present, but where the different instruments measured more or less the same crest heights, suggesting that ordinary spray was not being picked up by any of the instruments.

The SAAB WaveRadar is widely used by the offshore oil and gas industry. Shell alone has 12 facilities in the North Sea instrumented with REX WaveRadars and 10 in the South China Sea. These data provided the vast majority of the platform-based wave data analysed as a part of the CresT JIP project (Christou and Ewans 2011). The WaveRadar can be set to sample continuously at frequencies up to 10 Hz, apparently providing excellent temporal resolution for the study of wave processes; but with a specified angular microwave beam width of 10° and an implied ocean surface footprint in the order of metres, significant limitations in the spatial resolution and consequently the effective temporal

resolution might be expected. Noreika et al. (2011) report an inter-comparison between measurements made with a Datawell Directional Waverider buoy (DWR) and a SAAB Rex WaveRadar off the Australian Northwest Shelf. The WaveRadar was mounted at an elevation of 26 m above the water surface on Woodside Energy Limited's North Rankin A (NRA) platform, 135 km north-northwest of Dampier, and the DWR was deployed 3 km away in 125 m of water.

Data were compared from parallel measurements made over a 2-year period, covering a wide range of conditions. The WaveRadar sea states were found to produce significant wave heights 4 to 10 % lower than the DWR, with the biggest departure occurring during tropical cyclone conditions. At storm peak sea states, the WaveRadar significant wave heights were 16 % less than those from the DWR. However, the significant wave height calculated from the spectrum corresponding to wave periods longer than 9 s and wave periods were in good agreement. We present results in this paper that do not show such a bias between wave buoy measurements and WaveRadar measurements in the North Sea.

Nevertheless, the uncertainty of the effect of the resolution of the wave radar on the measurements remains, and it was the objective of the work reported in this paper to gain an understanding of this. Accordingly, we review the functionality of a WaveRadar using numerical simulations, based on theoretical considerations, to better understand how the radar estimates compare with known surface elevation. In addition, we review recent field measurements made with a Rex WaveRadar set at the maximum sampling frequency in the light of the expected functionality and the numerical simulations, and we present comparisons between WaveRadars and Datawell wave buoys at several locations in the North Sea.

A description of the WaveRadar is given in Section 2; the numerical simulations undertaken to assess the functionality of the radar are presented in Sections 3 and 4; the field measurements are given in Section 5; and conclusions are given in Section 6.

2 The waveRadar

The WaveRadar REX is now manufactured by Rosemount Tank Radar AB, Gothenburg, Sweden and is a derivative of their TankRadar system, (The company was SAAB until 2001 when it was bought by Emerson, and the radar unit is now part of the Rosemount group within Emerson). The first WaveRadar was a land-based TRL unit installed in the early 1990s by Rijkswaterstaat in The Netherlands. The first TRL/2 unit was installed in May 1993, and the first WaveRadar Rex was tested at the Shell Cormorant Alpha platform late in 1999. There are more than 500 WaveRadars installed worldwide, most of which are WaveRadar Rex gauges.

The WaveRadar consists of a transmitter head housing the electronics and a 0.44-m-diameter parabolic dish antenna (Plate 1). It employs the frequency-modulated continuous-wave (FMCW) method for determining the range to the target. The signal is a low power (<0.5 mW) frequency modulated 9.7 to 10.3 GHz (linear sweep) continuous microwave signal. Each measurement cycle consists of a linearly increasing frequency sweep, followed by a linearly decreasing frequency sweep—producing a triangular frequency modulation signal. The transmitted signal changes frequency during the time taken for the reflected signal to return. The received signal reflected from the water surface is mixed with the signal that is being transmitted at that moment, and the result is a signal with a beat frequency proportional to the distance to the surface. Various processing of the mixed signal is performed, including digital filtering, spectral analysis and “peak picking,” to convert the beat frequency to a distance. During the measurement cycle of 10.3 Hz, a number of measurements are produced and an average distance recorded. The measurement cycle includes both an increasing frequency sweep, followed by a decreasing frequency sweep, allowing Doppler shifts to be averaged out.

The manufacturer specifications (Aqua Ltd 2009) quote an accuracy: range <50 m ± 6 mm, range >50 m ± 12 mm; maximum deviation: range <50 m ± 1 mm; Clear downward view of the sea surface within at least a 10 angle conical beam; Range 3 to 65 m from the adaptor (the measurement datum or origin). The manufacturer calibrates every WaveRadar REX in a special calibration facility; and due to the design and construction of the electronic and microwave unit, the WaveRadar REX calibration is extremely stable and periodic re-calibration is not required.



Plate 1 WaveRadar REX mounted on a South China Sea platform

Details on the theoretical relationships for the signals of frequency-modulated radars and scattering can be found in Axelsson (1978) and Axelsson (1987).

3 Simulations

3.1 Method

3.1.1 Surface wave simulations

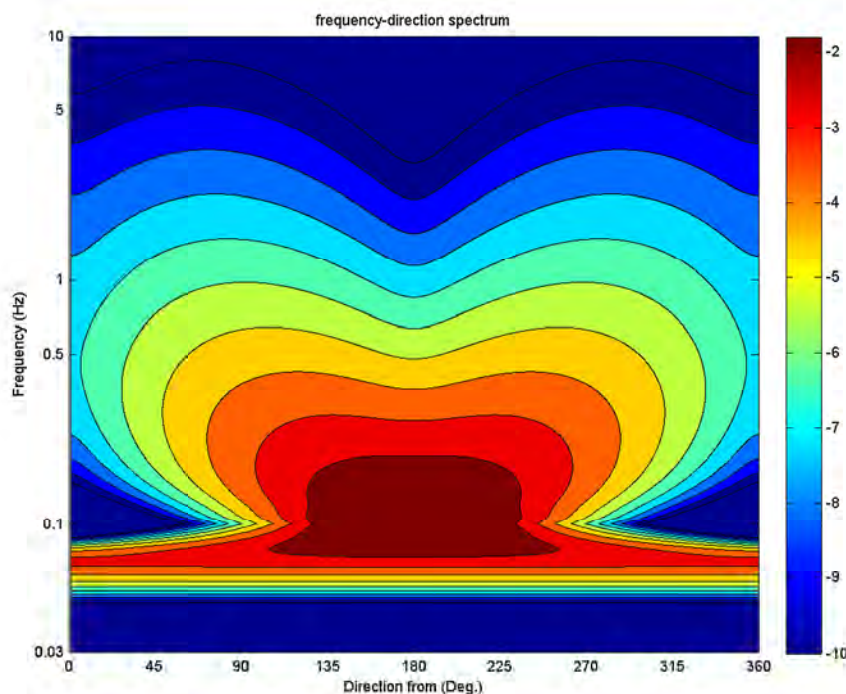
A simple plane sinusoidal wave of frequency 0.2 Hz, long-crested in one horizontal direction, was simulated first, to build some understanding of the radar simulations with this simple case before examining the irregular wave case. The amplitude of this sinusoid was set to 1 m.

Then, a linear simulation of the ocean surface was employed to provide a more realistic surface for the radar simulations. The simulations were produced with a JONSWAP frequency spectrum, with a peak frequency of 0.10 Hz, and a bimodal directional distribution (Ewans 1998). The frequency spectrum was defined with a resolution of 6.3×10^{-4} Hz, over the range 0 to 10 Hz. The resolution and range was chosen to provide a time series of 32,768 points with a time step of 0.0485 s. The directional resolution was 1° . A contour plot of the frequency-direction spectrum is given in Fig. 1. The units of the colour contours are dB re. $1 \text{ m}^2 \text{ Hz}^{-1} \text{ deg}^{-1}$.

At each time step, the surface was generated over a 5-m square at a resolution of 0.01 m, to provide spatial resolution for surface waves with frequencies up to 10 Hz.

This particular simulation is discussed in detail in Sections 4.2.1 and 4.2.2, but additional simulations were undertaken for different sea state conditions for comparison and are described in Section 4.2.3. The additional simulations were performed for JONSWAP frequency spectra, with spectral peak periods of 0.060 and 0.25 Hz, and also for a representation of the measured sea state at the St. Joseph platform that is discussed in Section 5.1. The sea states represented by a JONSWAP spectrum with spectral peak periods of 0.060 Hz and 0.25 Hz result in significant wave heights of 13.0 and 0.72 m, respectively, providing comparative results for a relatively extreme and a relatively mild sea state. The additional JONSWAP simulations were performed in accordance with the method described above. The St. Joseph platform sea state simulation was produced from a frequency-direction spectrum that consisted of the sum of a JONSWAP frequency spectrum, with spectral peak period of 0.20 Hz, with Ewans (1998) spreading, and the measured frequency spectrum between 0.05 and 0.19 Hz, together with the directional spreading specified by Ewans (2001).

Fig. 1 JONSWAP-bimodal frequency-direction spectrum. Colour scale in dB re. $1 \text{ m}^2 \text{ Hz}^{-1} \text{ deg}^{-1}$



3.1.2 WaveRadar simulations

The simulation of the WaveRadar essentially follows the physical optics method and involves a number of modelling steps—specification of the radar antenna pattern, determining the range to many points on the sea surface at an instant of time, modelling the attenuation as a function of range, modelling the reflection from the sea surface at each point, accumulation of the echoes from all of the points, and performing analysis of the accumulated signal strength from all of the echoes to determine the range corresponding to the measured surface elevation.

A complete simulation of the WaveRadar functionality would involve duplicating the FMCW method, entailing modelling the FMCW signal over its triangular sweep through one cycle and gathering the returned signal at a specific time, associated with the echoes from all the ocean surface grid points. The frequency sweep process during the increasing frequency stage is depicted in Fig. 2. The figure shows the radar signal sweep beginning at frequency f_0 , at time t_0 , and linearly increasing to frequency f_e , at time t_e , over an elapsed time of around 50 ms. At time t_e , the signal frequency starts to decrease returning to f_0 , over the ensuing 50 ms; this is not shown in the figure. The parallelogram with the thick borders depicts the frequencies of the received signal from the ocean surface echoes. The time delay between the radar transmission and the first return at each frequency is very small, corresponding to the point on the ocean surface closest to radar. The last return at the given frequency occurs a short time later, corresponding to the most distant point on the ocean surface. The diagram is relevant for a surface wave field that is stationary in time,

At an instant of time, the received signal from all the echoes corresponds to frequencies defined by a vertical slice through the parallelogram, as for example that given at t_e . For a random surface, we make the assumption that each frequency (corresponding to a given range to a surface point) is unique and the phase of the echo can be ignored. Taking the example of Fig. 2, at t_e , the ranges are determined from the difference in the frequencies between f_1 and f_2 and f_e . At any given time, the Fourier transform of the received signal mixed with the emitted signal is calculated to determine signal power as a function of Δf . In practice, this is done over the 50-ms sweep. The Fourier transform provides estimates of the amplitudes of each frequency difference component, and it has a peak

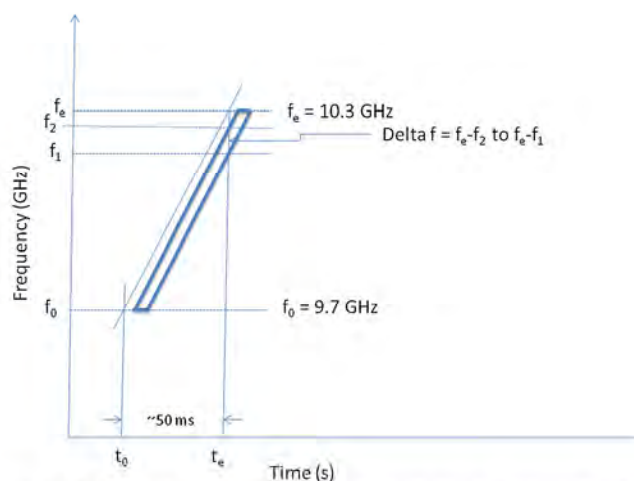


Fig. 2 Schematic of the FMCW transmission and reflected signal frequencies over the increasing frequency stage

corresponding to a particular frequency difference or range of interest.

Our approach to the simulations is based on the assumption that the signal processing to convert the frequency differences to ranges is done perfectly by the WaveRadar, to keep simulation times to a manageable level, and also because the actual processing performed is proprietary and unknown. Accordingly, we jump directly to what would be the output of the FMCW frequency analysis—the reflected signal intensity (or gain) as a function of range, which is available directly from the simulations.

Similarly, we minimise simulation times by treating the radar as a point source (located at the origin of a rectangular Cartesian coordinate system with z positive upwards). This was considered justified, due to the relatively small size of the antenna, and comparison of results from randomly choosing a point on the surface of the radar antenna as the source confirmed this.

Accordingly, it has been assumed that our signal is the summation of all the reflected signals from the surface of the water at an instant of time. The ray diagram given in Fig. 3 outlines the scenario for a specific point, j , on the surface.

The signal strength, $E_j(x_j, y_j, z_j)$, of the received echo from point, j with vector location \mathbf{x}_j and coordinates x_j, y_j, z_j on the ocean surface can then be expressed as:

$$E_j(x_j, y_j, z_j) = E(\theta_{j0}) A(2r_j) R(\theta_{jr})$$

where $E(\theta_{j0})$ is the antenna signal strength at the angle θ_{j0} subtended by the point x_j, y_j, z_j to the downward vertical at the antenna location of $(0, 0, 0)$, where $z_j = \eta(x_j, y_j)$ is the surface elevation, and θ_{j0} is also a function of x_j, y_j, z_j .

$A(2r_j)$ is the attenuation associated with path loss over the range, $r_j = \sqrt{x_j^2 + y_j^2 + z_j^2}$, and

$R(\theta_{jr})$ is the reflection coefficient corresponding to the radar signal reflection angle θ_{jr} at location j , where θ_{jr} is also a function of x_j, y_j, z_j and equal to the angle between the incoming ray from the radar and the local surface normal \mathbf{n}_j at x_j, y_j, z_j .

The total received signal at our instant of time is then simply the sum, $\sum_j E_j(x_j, y_j, z_j)$.

The signal strength, $E(\theta)$, was obtained from the antenna beam pattern provided by RS-Aqua, the suppliers of the Rosemount WaveRadar systems, and is given in Fig. 4, with Swedish labelling.

We have used the Friis expression for the attenuation associated with propagation of the radar signal, $A(r)$, given (in dB) by

$$A_{\text{dB}}(r) = -20 \log \left(\frac{4\pi 2r}{\lambda} \right)$$

where λ is the wavelength of the radar signal.

The backscatter from the ocean surface, which can range from specular to diffuse, is known to depend on the mean-square slope of the surface (e.g. Liu et al. 2000), which can take on a wide range of values, depending on the sea state and wind forcing. We investigate the backscatter effect on the simulated radar surface elevation estimates for three diffuse reflector forms:

1. An ideal diffuse reflector, in which the intensity of reflection is the same for all reflection angles. This type of reflectance is known as Lambertian, and we refer to it as “Lambertian” in this paper.
2. A combined diffuse-specular reflector, defined by

$$R(\theta_r) = \cos^{50} \theta_r$$

The reflection in this case is symmetric about the reflected angle, but reduces (relatively slowly) with increasing angle. We refer to this as “diffuse” in this paper.

3. A combined diffuse-specular reflector, which is more specular than diffuse, defined by

$$R(\theta_r) = \cos^{1000} \theta_r$$

We refer to this as “specular” in this paper.

The three reflection models are plotted in Fig. 5. A gain of one signifies 100 % reflection or a perfect reflector. In our

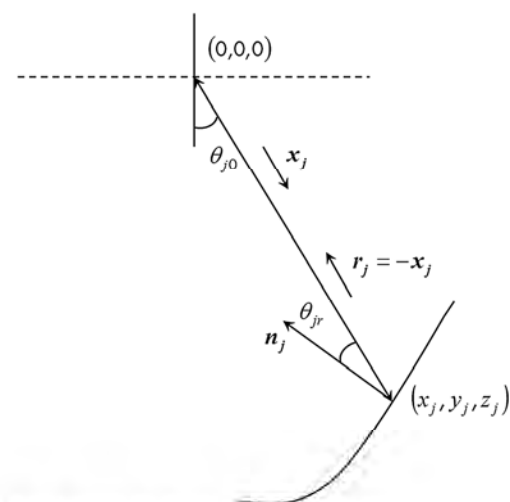
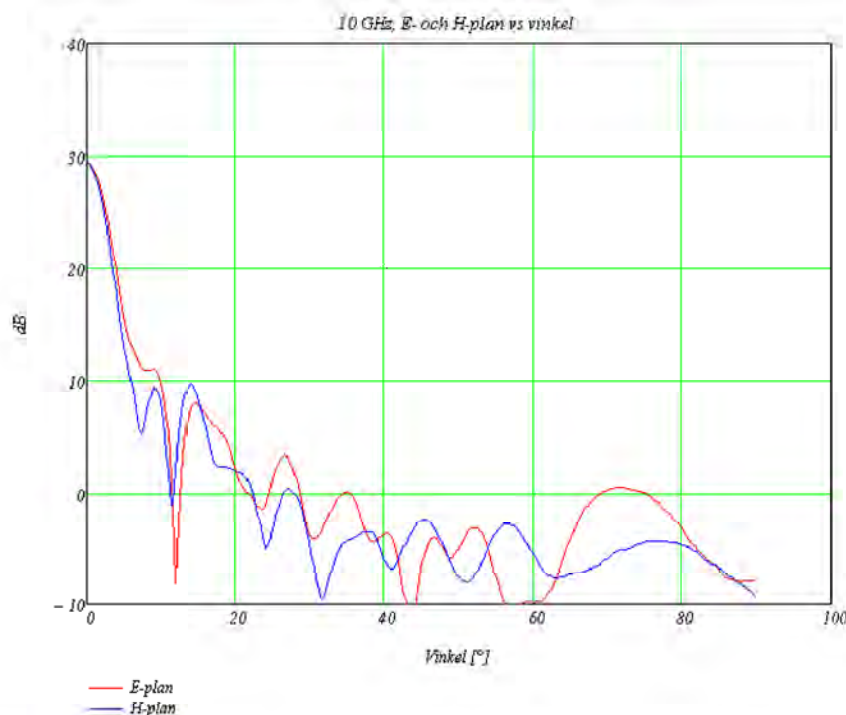


Fig. 3 Ray diagram for the point j on the surface

Fig. 4 WaveRadar antenna beam pattern



modelling, the Lambertian reflector is a perfect reflector for all angles, and the diffuse and specular reflectors are perfect reflectors at the specular reflection angle. A more physically realistic approach would be to turn these reflection forms into densities to better reflect the scattering, but this would involve multiplying each by a constant, and the result would simply be a change in the received signal gain, with the reflection gain from each point on the surface changed by the same amount. As it is only the relative gain that is important, we chose to keep the reflection forms simple.

With reference to Fig. 3, the ray from the radar source, at point $(0,0,0)$, to each surface point must be determined. This ray then defines the range to the surface point, allowing the attenuation associated with path loss to be determined, and the angle that the surface point subtends to the vertical at $(0,0,0)$, allowing the appropriate attenuation antenna transmitter gain to be selected.

Accordingly, the position vector, \mathbf{x}_j , of the surface point, j , relative to $(0,0,0)$, is simply given by $\mathbf{x}_j = (x_j, y_j, z_j)$, noting that $z_j = \eta(x_j, y_j) < 0$. The set of all position vectors defines the surface elevation $\eta(x_j, y_j)$.

The magnitude of \mathbf{x}_j is the range to the surface point, and the angle that the surface point subtends the vertical, θ_{j0} at the source can be derived from the z component, z_j , of the direction cosines of \mathbf{x}_j , as

$$\theta_{j0} = \cos^{-1} \frac{\mathbf{x}_j \cdot (0, 0, z_j)}{x_j |z_j|}$$

The diffuse-specular reflection component, back toward the radar at point j , is the reflection vector, $\mathbf{r}_j = -\mathbf{x}_j$, from which the reflection angle, θ_{jr} , is determined from

$$\theta_{jr} = \cos^{-1} \frac{\mathbf{r}_j \cdot \mathbf{n}_j}{r_j n_j}$$

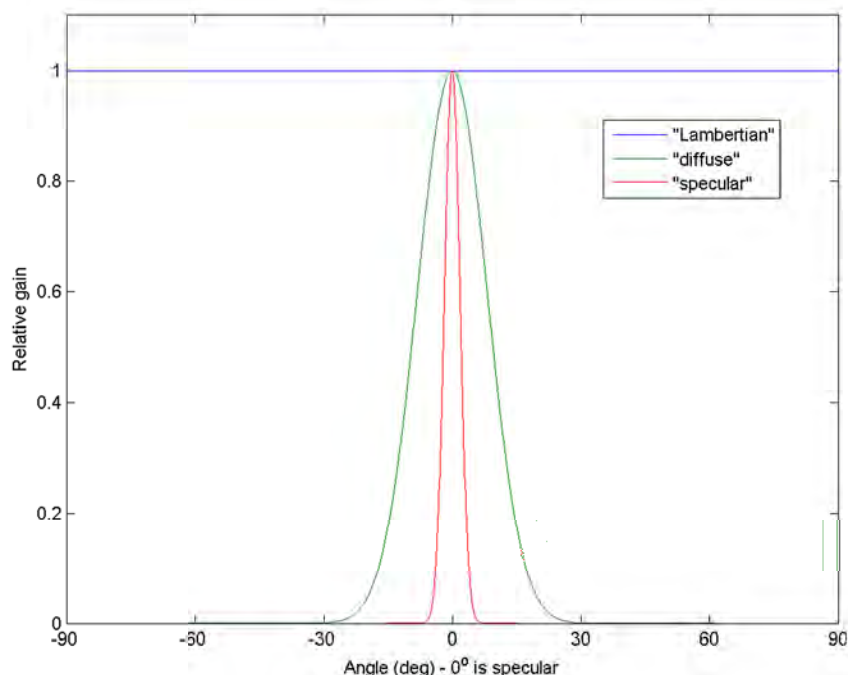
where \mathbf{n}_j is the vector normal to the surface at \mathbf{x}_j , and \mathbf{n}_j is calculated from the cross product of the gradient of the surface defined by the position vectors, \mathbf{x} , of all the surface points, as

$$\mathbf{n}_j = -(1, 0, \nabla \mathbf{x}_x) \times (0, 1, \nabla \mathbf{x}_y)$$

where $\nabla \mathbf{x}_x = \frac{\partial \eta}{\partial x}$ and $\nabla \mathbf{x}_y = \frac{\partial \eta}{\partial y}$

At each time step of 0.0485 s, the estimated surface elevation from the simulations involves accumulating the reflected signals from all of the surface points—some 251,000 points—each signal consisting of a gain and range. For practical purposes, we express our signal intensities in dB and refer to them as gain. The reflected signals are ordered in terms of range, and a cumulative sum of the gains calculated. The cumulative sum is smoothed, converted into a distribution and the density function derived. The estimated surface elevation is then taken as the maximum of the density function. Figure 6 is an example. The green curve is the smoothed distribution, and the blue line is the density. The vertical dashed line is the actual range from the radar to the point on the ocean surface directly beneath the radar, with coordinates

Fig. 5 Diffuse reflection models



$(0,0,\eta(0,0))$, which we abbreviate to surface location $(0,0)$ henceforth. In this example, the estimated range from the simulation is equal to the actual range.

The WaveRadar takes many samples over each 0.0971-s cycle and averages the result. This cycle includes both the increasing and decreasing sweeps. For practical reasons, we simply take the average of pairs of consecutive 0.0485-s samples.

In the simulations, the vertical distance from the mean water level to the radar is 20 m. The WaveRadar simulations were repeated for sensor heights of 13 and 30 m above mean sea level, to assess the effect of the antenna gain spread, but no significant change in the results occurred.

4 Results

4.1 Long-crested regular wave

The time series and spectra of the actual and WaveRadar simulated surface elevation of the long-crested regular wave are plotted Fig. 7. The agreement is excellent and provides confirmation that the simulations are accurate. No discernible difference is apparent in the time series plot—Fig. 7a, while the spectral plot indicates minor deviation of the spectra from the simulations from the surface elevation spectrum at high and low frequencies—Fig. 7b, but this occurs at more than 10 orders of magnitude below the spectral peak. The side lobes of the spectrum of the actual surface are associated with the Blackman-Harris window used in the spectral analysis.

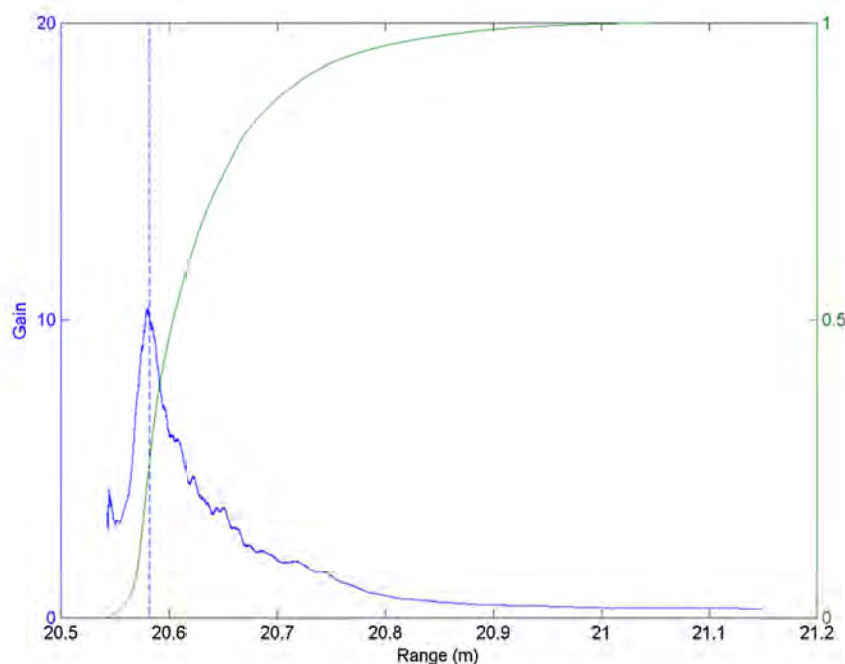
4.2 Random linear surface elevation

The results of the random linear surface elevations are presented in this section. Comparisons between the actual simulated surface elevations and the radar simulations for the JONSWAP spectrum with a spectral peak frequency of 0.10 Hz are given in Section 4.2.1, while in Section 4.2.2, we review results for specific times in the time series, comparing and interpreting the results from each of the surface reflection types, and providing some insight into the comparisons presented in Section 4.2.1. We present the results of the additional simulations in Section 4.2.3, and we conclude Section 4.2 with a general discussion of the results in Section 4.2.4.

4.2.1 Actual surface elevation and radar simulation comparisons

The surface elevation of the first 100 s of the simulated time series is presented in the left plot of Fig. 8. The discrepancies between the actual surface and the radar simulations are barely discernible in the time series plot, but this is more apparent from the scatter plot of the data in Fig. 8 (right), which shows some spread in the simulations but virtually no overall bias. The scatter is largest for the small elevations, which tend to be biased a little high. This is apparently due to situations at times when the surface is elevated close to but not at the location $(0,0)$, which produces a larger gain at a shorter range in the simulations. It is interesting to note from the scatter plot that there is less scatter in the peaks and troughs of the time series, indicating the radar estimates are closer to the actual values at

Fig. 6 An example of the received signal from the ocean surface at an instant of time. The *green line* is the distribution of gain, the *blue line* is the density and the *vertical dashed line* is the actual range from the radar to the point (0,0) directly below the radar



those times. This is important for studying the individual crest and heights in the time series.

Figure 9 shows scatter plots of the crest and trough elevations for this time series, for the three reflector types. Clearly there is some scatter in the radar estimates of the crests and troughs. There is a small but discernible bias in the crests but not in the troughs. The bias in the crests is likely due to cases where a local maximum in the crest occurs at a point close to (0,0) that produces a larger gain and shorter range in the simulations. However, there is generally better agreement between the actual and estimated values for the largest crest and troughs. It is also interesting to note the difference between the number of crests and troughs, given near the top of

each plot. The radar estimates have more zero-crossing crests and troughs than in the actual time series, and the number for each reflector is different. This is almost certainly due to an increased number of occurrences of small crests and troughs that are introduced by the three reflection models corresponding to the noise associated with the range estimation algorithm.

The spectra are given in Fig. 10. The blue curve is the spectrum of the actual surface, and the coloured are the radar spectra, for the three different reflector types, plotted on linear scales on the left and log scales on the right. As for the plane wave results, there is no discernible difference apparent in the linear plot, but the log plot shows increased levels in the radar

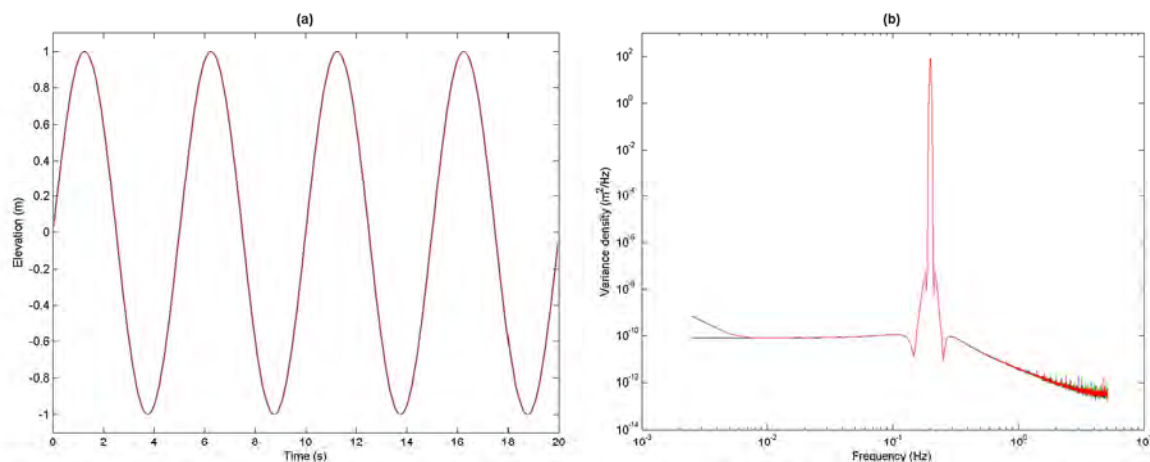


Fig. 7 **a** The first 20 s of the time series of the surface elevation (directly beneath the radar at the point (0,0)) and radar simulations of a simple plane wave with frequency 0.2 Hz and amplitude of 1 m. **b** Spectra of the

time series plotted in **a**. In the plots, the surface elevation signal is in *black*, the Lambertian signal is in *blue*, the diffuse signal is *green* and the specular signal is in *red*

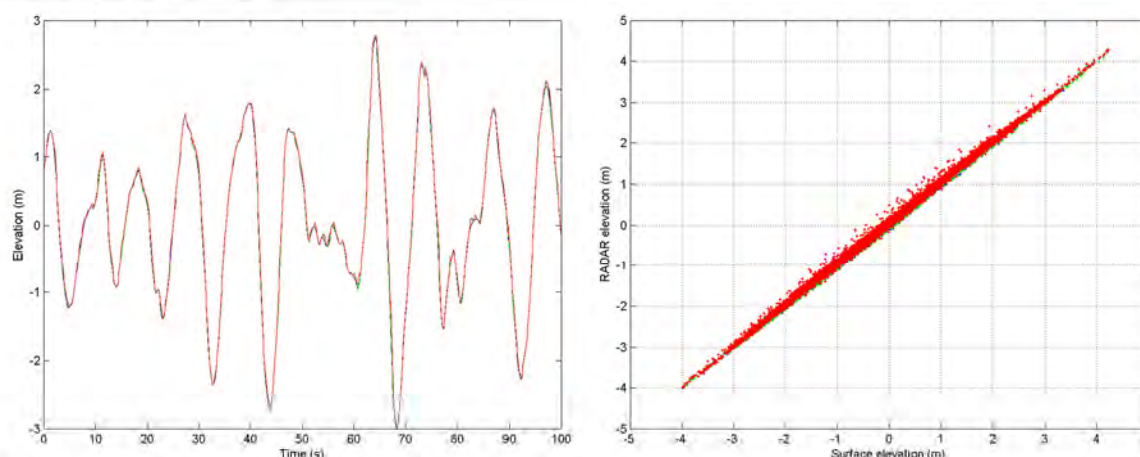


Fig. 8 Plots of the time series (*left*) and scatter plot (*right*) of actual and simulations of the surface elevation for the three reflector types. In the plots, the surface elevation signal (time series plot only) is in *black*, the Lambertian signal is in *blue*, the diffuse signal is *green* and the specular signal is in *red*

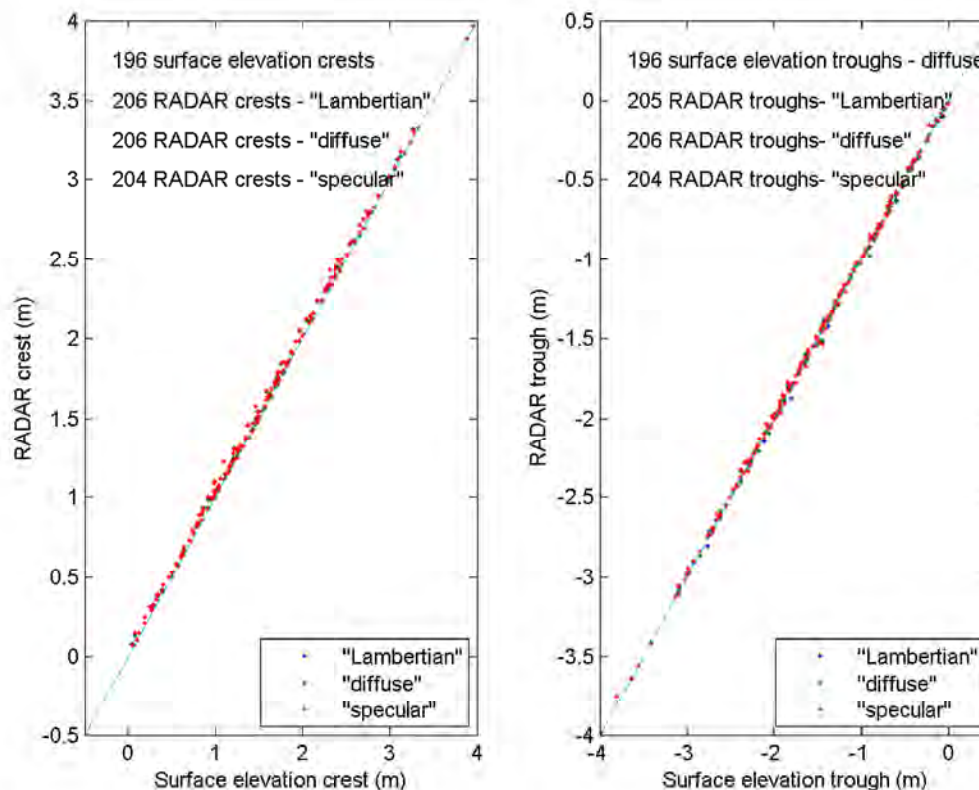
spectrum at high and low frequencies, with departures becoming apparent for frequencies below 0.06 Hz for all reflector types and above 0.8 Hz for the specular reflector type and above 1.0 Hz for the Lambertian and diffuse reflector types. The spectral parameters, which were calculated over the frequency range 0 to 5.15 Hz, are given in the left plot and also in Table 1. The significant wave heights are identical to three significant figures, the radar first moment periods, T1, are biased up to 1 % short, and the second moment periods, T2, biased 4–9 % short. The departures of the parameters T1 and

T2 from the simulations to those of the original surface elevations is solely due to the increased high-frequency spectral levels of the radar simulations that occurs above 0.8 Hz.

4.2.2 Results at specific times

In this section, we investigate the simulated radar signal to help understand the effects observed in Section 4.2.1. We examine the signal at three instants in time—1.36, 53.48 and

Fig. 9 Scatter plots of the zero-crossing crest and trough elevations for the three reflector types



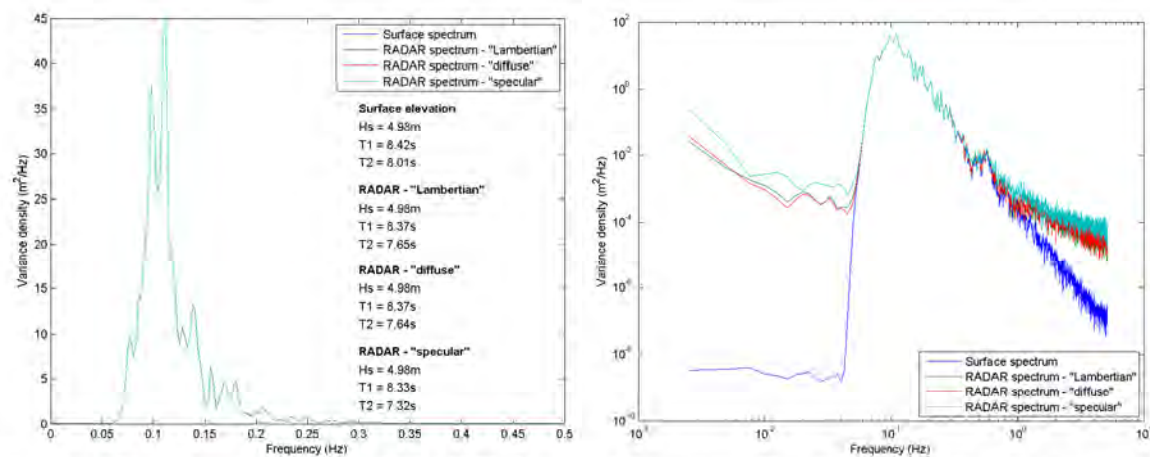


Fig. 10 The spectra of the time series—linear left and log right. The *blue* curve is the spectrum of the actual surface, and the *green*, *red* and *cyan* are radar spectra for the different reflection types

64.13 s after the start of the record. The signal at these times are of interest for the following reasons: the signal at 1.36 s is a typical wave crest height, and should represent a common result; the signal at 52.48 s is an example when the wave height is small and of short period and may provide some insight into the cause of the scatter that we observed for small elevations (Fig. 8, right hand plot); and the signal at 64.13 s after the start of the record corresponds to the large peak in the first 100 s of the time series (Fig. 8) and is of interest because lower scatter is seen in the larger peaks (Fig. 8, right hand plot). We shall also see later that these three times turn out to be interesting examples in terms of the reflected signal gain—the first has a very clear maximum corresponding exactly to the vertical range to surface; the second has a clear local maximum corresponding to the vertical range to the surface, but the maximum gain corresponds to a point on the surface that has a smaller range than the vertical to the sensor; while the third does not have a clear local maximum corresponding to the vertical range to the surface, and like the second, the

maximum gain corresponds to a point on the surface that has a smaller range than the vertical to the sensor.

An example of the results at an instant of time is given in Fig. 11. The figure shows results at the simulation time 1.36 s, which is the first crest to occur in the time series. Plot (a) is the time series plot of the first 100 s, with the time of interest, 1.36 s, indicated with a cross. Plots (b) through to (f) are contour plots over a 5-m square of the surface centred at the vertical through the centre of the radar dish—plot (b) is the surface elevation; plot (c) is the range from the dish origin in metres; and plots (d) to (e) are plot of the received signal gain for the Lambertian, diffuse and specular surface reflection cases, respectively. Plots (g) to (f) are plots of the gain-range distribution and density for the Lambertian, diffuse and specular surface reflector case, respectively; the vertical dashed line is the estimated distance to the surface for each example. The contours show respective values at points on the surface given by the x and y coordinates, with the point (0,0) marked with a cross. The units of the surface elevation are given in z

Table 1 Spectral parameter values calculated over the bandwidth 0–5.15 and 0.06–0.60 Hz in parentheses

| Simulation | Parameter | Signal | Lambertian | Diffuse | Specular |
|------------------------|-----------|---------------|---------------|---------------|---------------|
| JONSWAP $T_p=0.10$ Hz | Hs (m) | 4.98 (4.98) | 4.98 (4.98) | 4.98 (4.98) | 4.98 (4.98) |
| | T1 (s) | 8.42 (8.45) | 8.37 (8.44) | 8.37 (8.44) | 8.33 (8.44) |
| | T2 (s) | 8.01 (8.10) | 7.65 (8.09) | 7.64 (8.09) | 7.32 (8.08) |
| JONSWAP $T_p=0.060$ Hz | Hs (m) | 13.00 (10.17) | 13.01 (10.17) | 13.00 (10.17) | 12.99 (10.16) |
| | T1 (s) | 13.72 (11.74) | 13.69 (11.73) | 13.69 (11.73) | 13.68 (11.73) |
| | T2 (s) | 12.83 (11.17) | 12.59 (11.16) | 12.58 (11.16) | 12.37 (11.15) |
| JONSWAP $T_p=0.25$ Hz | Hs (m) | 0.72 (0.71) | 0.74 (0.72) | 0.74 (0.72) | 0.74 (0.72) |
| | T1 (s) | 3.53 (3.70) | 3.34 (3.67) | 3.34 (3.65) | 3.36 (3.68) |
| | T2 (s) | 3.35 (3.63) | 2.69 (3.60) | 2.69 (3.60) | 2.60 (3.61) |
| St. Joseph | Hs (m) | 2.63 (2.62) | 2.64 (2.63) | 2.64 (2.63) | 2.64 (2.63) |
| | T1 (s) | 6.55 (6.60) | 6.44 (6.58) | 6.44 (6.58) | 6.41 (6.58) |
| | T2 (s) | 6.20 (6.34) | 5.65 (6.31) | 5.63 (6.31) | 5.38 (6.31) |

coordinate metres (where the WaveRadar is at position $(0,0,0)$), the units of the gain are in dB and are negative, and the units of the ranges (absolute distance from the WaveRadar to the point on the surface) is in metres.

The surface elevation contour plot (Fig. 11b) shows that the distance to the surface at the radar source $(0,0,0)$ is around 18.6 m. This can also be read from the range contour plot (Fig. 11c) at the point $(0,0)$. The actual value of 18.62 m is plotted as the vertical dashed line on the gain-range plots (g) to (e). The contour plots of the reflected signal gain (Fig. 12d–f) show that the most intense signals are those that are reflected directly beneath the radar source, even though the range (Fig. 11c) is less to locations at grid points around $(-0.6,-1)$. The diffuse gain contour plot (Fig. 11e) is noisier than that for the Lambertian case (Fig. 11d), and in turn, the specular gain contour plot (Fig. 11f) is noisier than the diffuse plot. Thus, the degree of noise in the received signal pattern increases with increasing specularity, but, the characteristics of the patterns remain consistent, with maximum gain occurring in the vicinity of the point $(0,0)$.

The combined effect of reflected signal gain and range, from accumulating the gain across the range by combining the gain and range in the contour plots, are presented in Fig. 12g–i. The plots show that most of the reflected signal intensity falls within a narrow range, and that the maximum of each density curve which is taken as the radar estimate is, in each case, very close to the actual range (dashed line). This result is clearly a consequence of the narrow antenna beam width of the WaveRadar, but the maximum of the gain-range plot can be expected to vary, depending on the wave field at a given time, and we have indeed observed less accurate and more accurate examples. Examples of less accurate cases are given below.

The next example is the wave field at 52.48 s after the start (see Fig. 12), for a case when the wave height is small and of short period. At this time, the actual range to the point $(0,0)$ corresponds to a local maximum in each of the gain-range plots (Fig. 13g–i). However, in each case, the maximum in the gain-range plot is at a shorter range, approximately 0.1 m shorter, corresponding to a point on the surface nearby but at a higher point on the wave, which is receding from the point $(0,0)$. Otherwise, the gain contour plots and gain-range plots are qualitatively the same, and also similar to those in Fig. 11.

The inaccuracy in the measured range here is a direct consequence of the method of choosing the peak in the gain-range plot—simply taking the maximum of the data was sufficient to provide an accurate estimate, for the results at 1.36 s, but this approach introduces an error, for the results at 52.48 s. Nevertheless, it is clear that due to the narrowness of the gain-range density function, it is not possible to get a grossly inaccurate result, irrespective of the method to pick the peaks, and this is primarily due to the narrowness of the radar antenna beam pattern. However, as we shall see later, this error introduces bias at the high frequencies.

Figure 13 gives the results for the wave field at 64.13 s after the start of the record. This corresponds to the largest peak in the first 100 s of the time series. The surface elevation contour plot (Fig. 13b), shows a crest directly below the radar, but there is a more elevated local peak at $(0.5,0)$, near to $(0,0)$, the point of interest. The local peak is closer to the radar and provides a slightly more intense reflected signal. This is the maximum in the gain-range plots for all three reflector types (Fig. 14g–i). As for the previous case, the error is in the order of 0.1 m.

4.2.3 Additional simulations

The spectra derived from the additional simulations generally showed similar characteristics to those described in Section 4.2.1, showing good agreement within the frequency band 0.060 to 0.80 Hz but elevated spectral levels outside that frequency band, by comparison with the surface elevation signal. It was also noted that the elevated spectral levels have a larger effect on the overall differences between the surface elevation simulation and the wave radar estimates when the sea state is lower, as can be seen in the spectral parameters derived from the additional simulations, given in Table 1. In the table, two values are given for each parameter—one derived over the complete bandwidth 0–5.15 Hz and the other derived over the reduced bandwidth 0.06–0.60 Hz specified in parentheses in the table. The significant wave heights from the wave radar simulations for the lowest sea state are still less than 3 % different from the surface elevation signal, but the second moment period is up to 22 % shorter. The values associated with the three reflector types agree to better than 1 % with the original signal for the reduced bandwidth of 0.06–0.60 Hz.

4.2.4 Discussion

Overall, the simulations show that the radar measurements of the sea surface are excellent in the vicinity of the spectral peak. At frequencies well below and well above the spectral peak (approximately five times the spectral peak in the example presented here), the simulations are biased high, but as these are for elevations with spectral densities more than two orders of magnitude less than the spectral peak, they have little practical consequence, on the wave spectrum and the significant wave height, and their effect is relatively small on estimates of the crests and troughs. Periods calculated from the moments of the spectra are biased short on account of the elevated spectral levels of the simulations at high frequencies, but the degree of bias will depend on upper frequency used to calculate the spectral moments—if this is constrained to 0.60 Hz, little bias will occur.

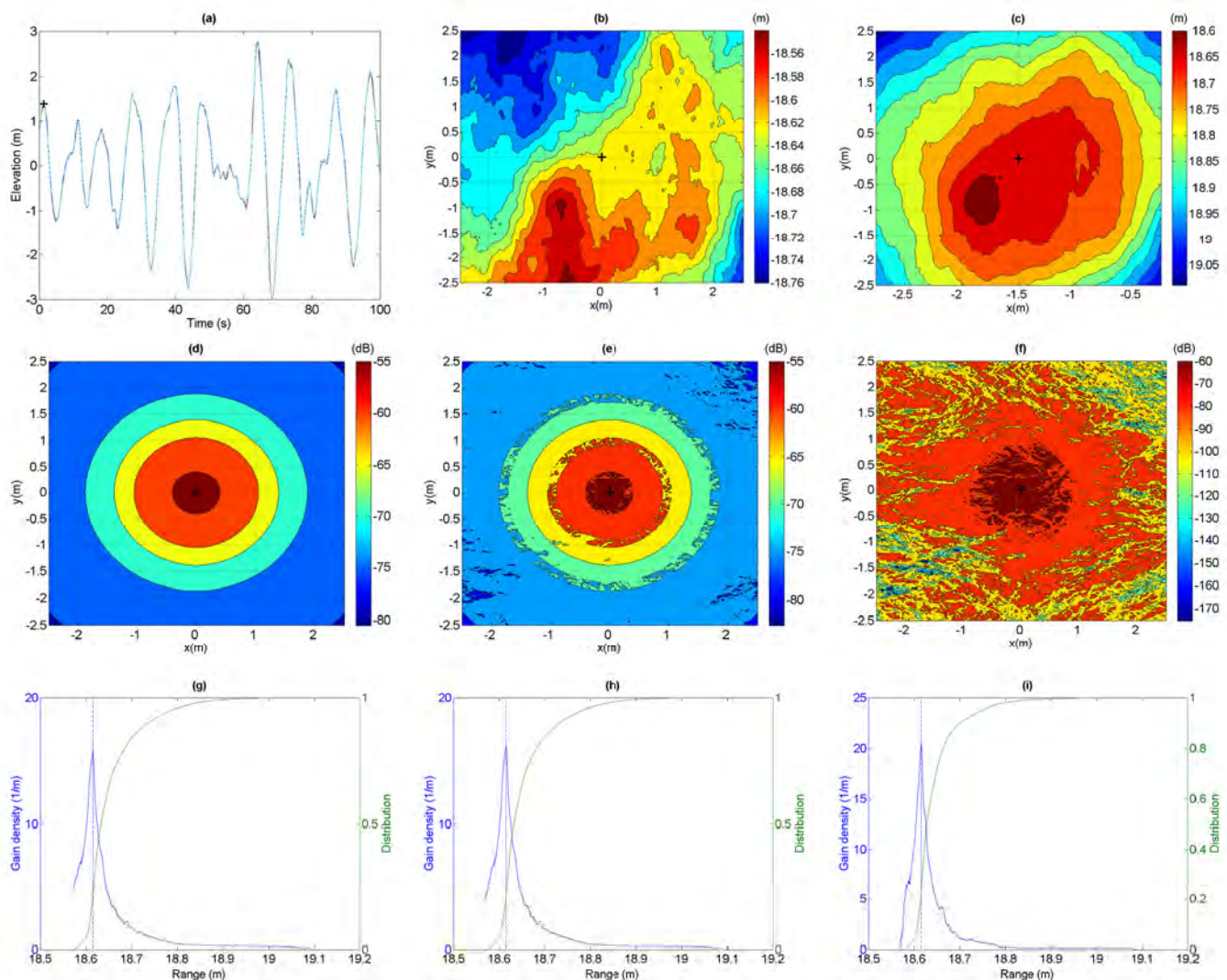


Fig. 11 Results at simulation time 1.36 s—**a** time series plot of first 100 s (the cross is at 1.36 s), **b** contour plot of surface elevation in metres over 5 m square, **c** contour plot of range in metres over 5 m square, **d** contour plot of received signal gain in decibels for the Lambertian surface reflection case over 5 m square, **e** contour plot of received signal gain in decibels for the diffuse surface reflection case over 5 m square, **f** contour plot of received signal gain in decibels for the specular surface reflection

case over 5 m square, **g** gain-range distribution and density in decibels for the Lambertian surface reflector case (vertical dashed line is the estimated distance to the surface), **h** gain-range distribution and density in decibels for the diffuse surface reflector case (vertical dashed line is the estimated distance to the surface), and **i** gain-range distribution and density in decibels for the specular surface reflector case (vertical dashed line is the estimated distance to the surface)

The inaccuracies in the simulations result from the approach to peak fitting the gain-range density. We have simply chosen to take the maximum of the density. This introduces error when there is a more elevated section of water close to the point directly below the radar at (0,0). We suspect that it may be possible to develop a better peak picking algorithm, which would yield improved accuracies.

5 Field measurements

This section involves analysis of wave data measured with WaveRadars in the field. In Section 5.1, we present a wave

spectrum for measurements acquired on a platform in the South China Sea at the maximum sampling rate of 10 Hz, and in Section 5.2, we present comparisons between measurements made with a WaveRadar and a nearby wave buoy at several locations in the North Sea.

5.1 10-Hz sample measurements

The 10-Hz data were recorded with a Rex WaveRadar mounted at 13 m above mean sea level on the St. Joseph Platform offshore Sabah in Malaysia. The water depth at the St. Joseph Platform is 94 m.

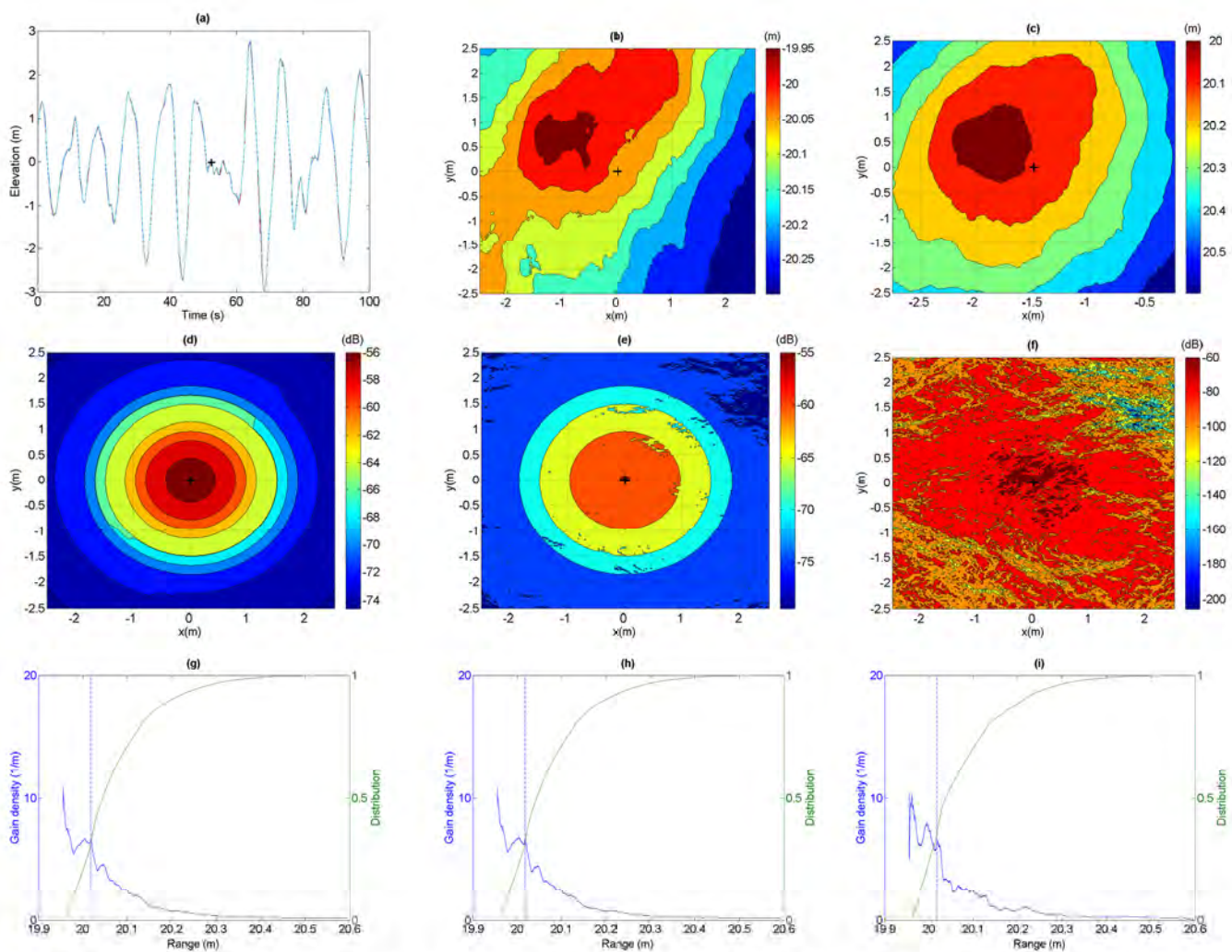


Fig. 12 Results at simulation time 52.48 s—**a** time series plot of first 100 s (the cross is at 52.48 s), **b** contour plot of surface elevation in metres over 5 m square, **c** contour plot of range in metres over 5 m square, **d** contour plot of received signal gain in decibels for the Lambertian surface reflection case over 5 m square, **e** contour plot of received signal gain in decibels for the diffuse surface reflection case over 5 m square, **f** contour plot of received signal gain in decibels for the specular surface reflection

case over 5 m square, **g** gain-range distribution and density in decibels for the Lambertian surface reflector case (vertical dashed line is the estimated distance to the surface), **h** gain-range distribution and density in decibels for the diffuse surface reflector case (vertical dashed line is the estimated distance to the surface), and **i** gain-range distribution and density in decibels for the specular surface reflector case (vertical dashed line is the estimated distance to the surface)

On 10th of June, 2012, the WaveRadar was set to record at the maximum sampling rate of 10 Hz. The variance density spectrum was computed for 1 h of data, starting at 16:00 h, at which time a local wind-sea was active in the region, responding to a local wind of around 15 m/s. The spectrum is plotted on log axes in Fig. 14.

The main features of this spectrum are the well-defined spectral peak and the rapid fall off in spectral level at frequencies below the spectral peak and above the spectral peak. Below the spectral peak, the spectral levels plateau to levels some three orders of magnitude below that of the spectral peak. Above the spectral peak, the spectral levels fall to levels nearly six orders of magnitude below the spectral peak. Over the frequency range 0.2 to 0.8 Hz ($\approx 1.6f_p$ to $6.6f_p$), the spectral

levels fall off with $f^{-4.7}$, which is consistent with observations that typically fall between f^{-4} and f^{-5} (Babanin 2010). Accordingly, these appear to be reasonable measurements of the equilibrium range of the spectrum of wind waves. Above 0.8 Hz, the spectrum continues to roll off at a steady rate of $f^{-2.9}$, until 4 Hz ($\approx 33f_p$), when the spectral levels “kick up” to the Nyquist frequency of 5 Hz. The “kick up” is symptomatic of aliasing, but for frequencies below 4 Hz, there is little to suspect the spectral levels are erroneous. This being the case, the WaveRadar appears to be resolving signals at high frequency that are nearly six orders magnitude smaller than those at the spectral peak. This is substantially better than achieved with the simulations described in Section 4.2, suggesting the WaveRadar performs better in practice than modelled in the

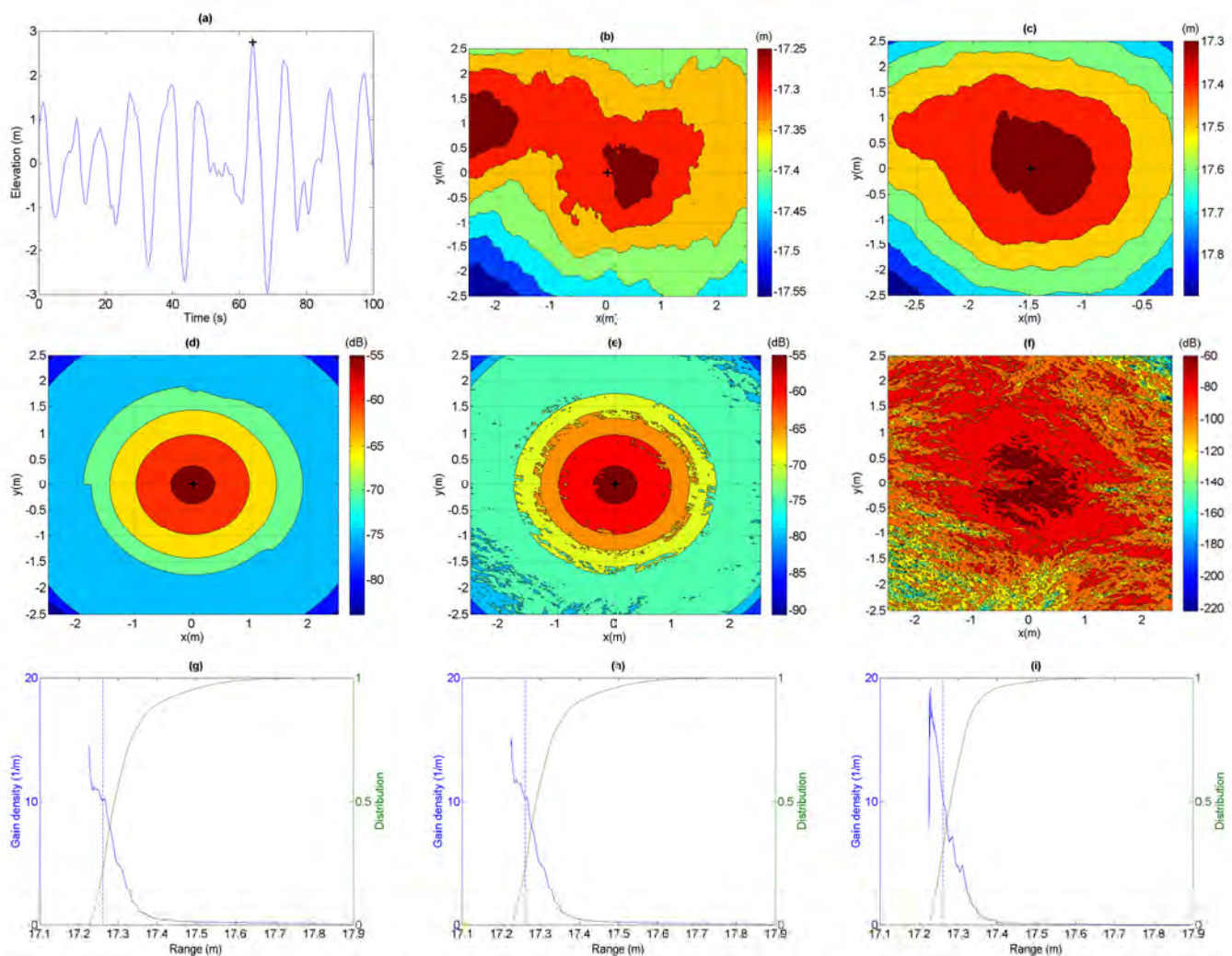


Fig. 13 Results at simulation time 64.13 s—**a** time series plot of first 100 s (the cross is at 64.13 s), **b** contour plot of surface elevation in metres over 5 m square, **c** contour plot of range in metres over 5 m square, **d** contour plot of received signal gain in decibels for the Lambertian surface reflection case over 5 m square, **e** contour plot of received signal gain in decibels for the diffuse surface reflection case over 5 m square, **f** contour plot of received signal gain in decibels for the specular surface reflection

case over 5 m square, **g** gain-range distribution and density in decibels for the Lambertian surface reflector case (vertical dashed line is the estimated distance to the surface), **h** gain-range distribution and density in decibels for the diffuse surface reflector case (vertical dashed line is the estimated distance to the surface), and **i** gain-range distribution and density in decibels for the specular surface reflector case (vertical dashed line is the estimated distance to the surface)

work reported in this paper. This observation must however be tempered by the absence of corroborating evidence of a $f^{2.9}$ high-frequency tail (to the authors' knowledge); if one assumes that the $f^{2.9}$ range is not reliable, we might conclude that the WaveRadar is producing reliable results out to 0.80 Hz, which is similar to that achieved in the simulations.

5.2 Comparisons with other sensors

The WaveRadar measurements used for the inter-comparisons presented here were made on the North Cormorant, Gannet and Auk platforms, at elevations of 28.7, 22.5 and 24.3 m, respectively. Plan views and photographs of these are given in Fig. 15. The location of the WaveRadar on each platform is

indicated with a green dot on the plan view of each. The North Cormorant WaveRadar location might be expected to result in measurements that have interference from the platform, for sea states with predominant directions from the north to east sector. In the case of the Gannet and Auk platforms, these sectors would be southwest to north and east to south, respectively.

The wave buoy used for the comparisons at North Cormorant was located approximately 7 km north-northeast of the platform, and that for Auk was located about 4 km west of the platform; but as there was no buoy located at the Gannet platform, the data from a wave buoy located at the Anasuria site, some 15 km to the northwest, were used for comparison with the Gannet platform WaveRadar measurements. The

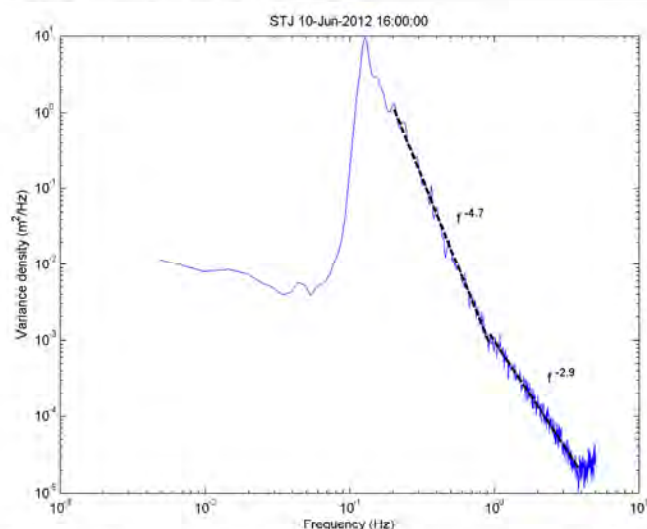


Fig. 14 The wave spectrum for wave measurements at St. Joseph Platform at 16:00 h on 10th June, 2012 local time, derived from a record of 1 h in length and a sampling frequency of 10 Hz

locations are given in Fig. 16, and details on the data used in the comparisons are given in Table 2.

It has not been possible to retrieve all the measurement details of the buoys, but we believe the moorings were standard, as recommended by Datawell, and all the

processing, including spectral analysis and derivation of the wave spectral parameters, was performed on-board by Datawell firmware.

Two versions of the SAAB radar were involved in the measurements. Recent measurements were made with the SAAB Rex WaveRadar, and the earlier measurements were with the predecessor to the Rex, which we refer to simply as the SAAB WaveRadar in this paper when distinguishing it from the Rex but both are referred to as WaveRadars. The SAAB WaveRadar had a different processor to the SAAB Rex WaveRadar, providing a 5.12-Hz digital output rather than a variable output of 2 to 10 Hz in the case of the Rex. The spectral analysis of the WaveRadar signals followed the Welch (1967) method, with sampling frequencies of 2.0 Hz for the earlier data and 4.0 Hz for the later data, record lengths of around 30 min, and spectral moments calculated over frequencies out to 0.60 Hz.

Table 2 provides statistical details of the comparisons of the significant wave heights between the WaveRadar and buoys. The median is given for the WaveRadar and buoy data sets separately, and the bias, standard error and RMS difference between the WaveRadar and buoy data sets is given. In addition, statistics are given for data sets stratified by the mean wave direction measured by the directional buoys for each sea state. These statistics include the slope

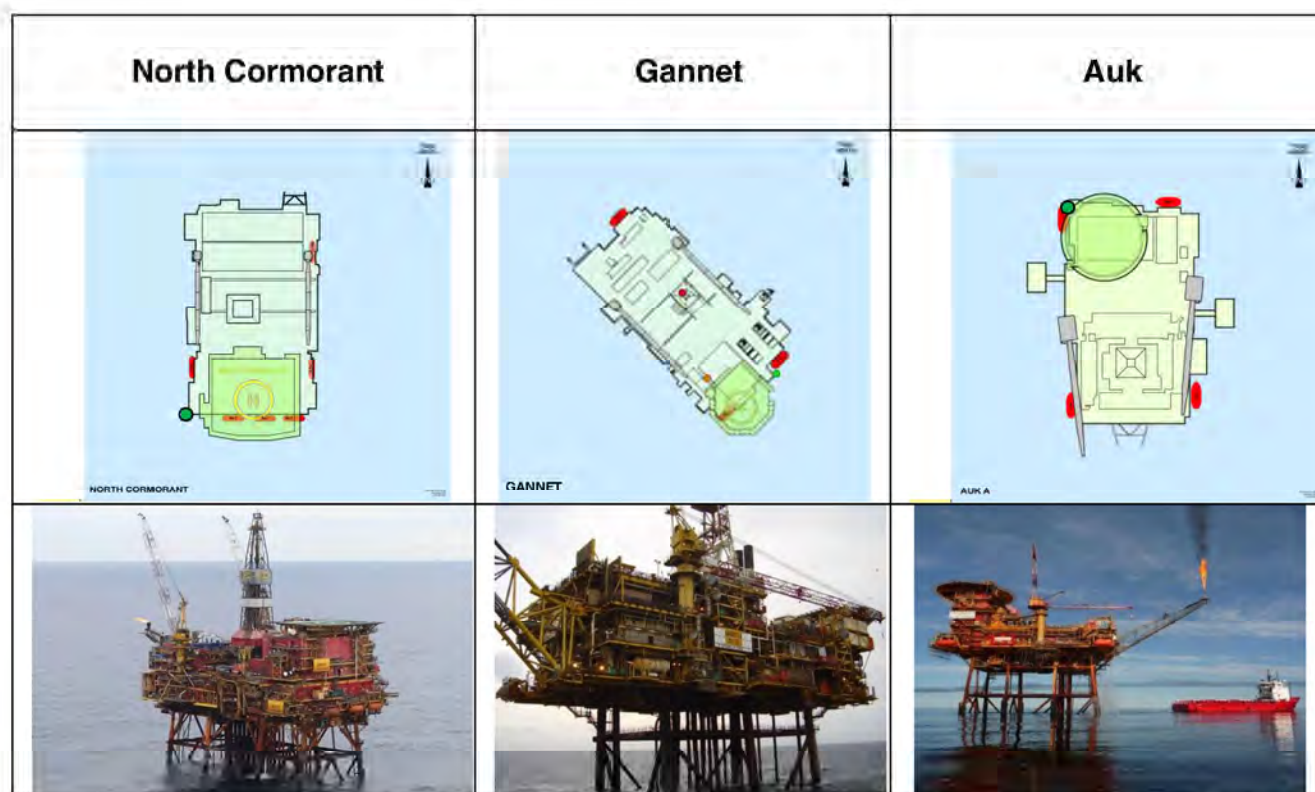


Fig. 15 Plan views of the three North Sea platforms, with the locations of the WaveRadar marked by a green dot. The photograph of each platform (below the plan view in each case) provides some indication of the amount of wave shielding that the platform might provide

and offset of the linear regression parameters and the mean ratio of the WaveRadar significant wave height to the buoy significant wave height. This ratio provides an estimate of the overall relative level of the significant wave heights for each direction.

A measure of the effect of the platform shielding is given by the row in Table 2 labelled *platform-induced attenuation*. This is obtained by taking an average of the ratio values for all the data in the sectors from which wave blockage might be expected and another average ratio for those sectors from which waves are not expected to be blocked by the platform (labelled

clear in Table 2) and then taking the ratio, A_t , of these two average ratios, expressed by the following equation.

$$A_t = \frac{1}{n} \sum_{i=1}^n H_{S_{r_i}} / H_{S_{b_i}} \bigg/ \frac{1}{m} \sum_{j=1}^m H_{S_{r_j}} / H_{S_{b_j}}$$

where $H_{S_{r_i}}$ and $H_{S_{b_i}}$ are, respectively, the observed WaveRadar and buoy significant wave heights for the sectors from which wave blocking is expected; $H_{S_{r_j}}$ and $H_{S_{b_j}}$ are those for the sectors from which wave blocking is not expected (labelled *clear* in Table 2).

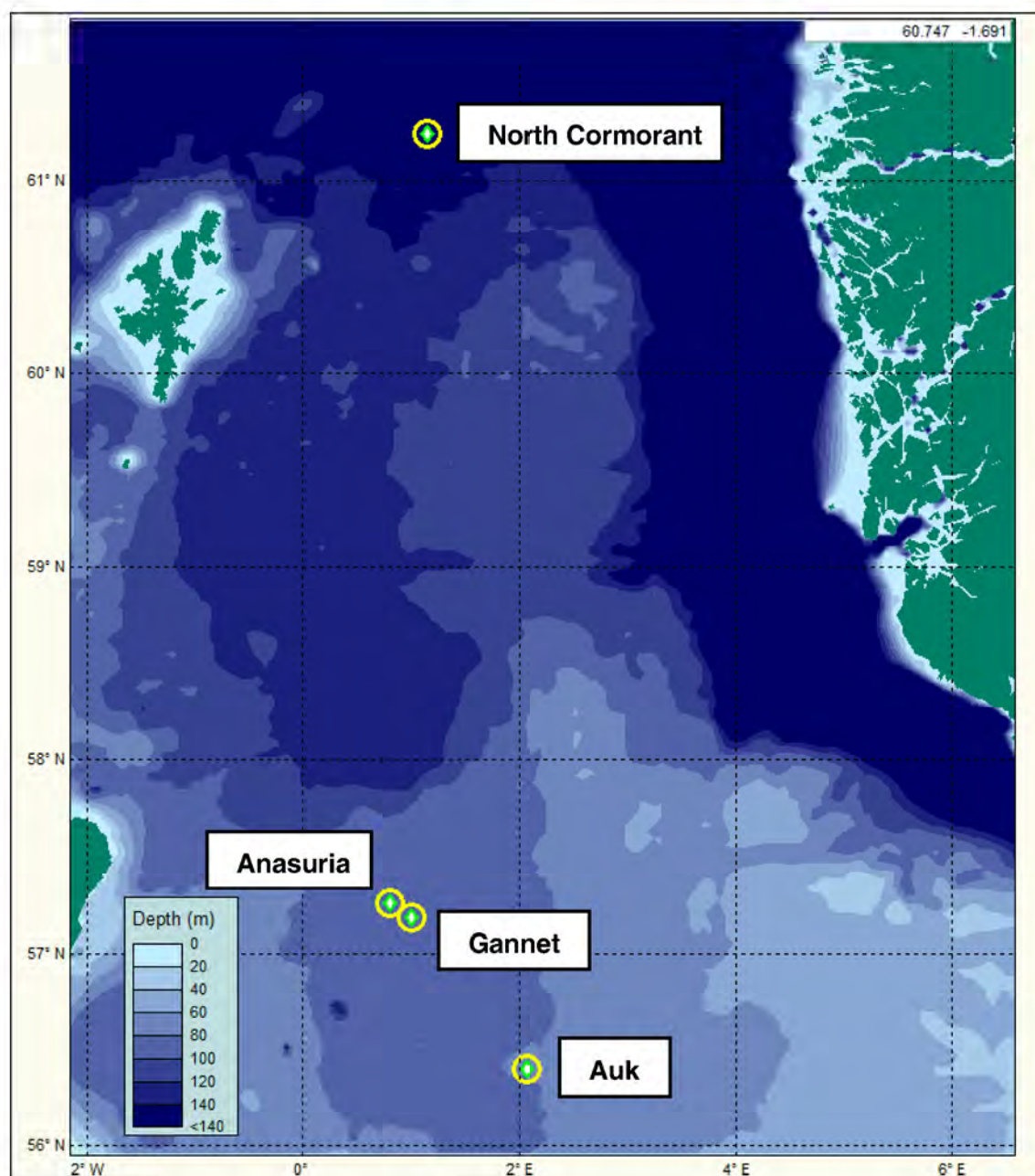


Fig. 16 The locations of the wave measurements

Table 2 Measurement time series details

| | North Cormorant–Saab | | | | North Cormorant–Saab Rex | | | | Auk Saab | | | | Gannet–Saab Rex | | | |
|------------------------------|----------------------------|----------|--------|-------|----------------------------|----------|--------|-------|----------------------------|----------|--------|-------|----------------------------|----------|--------|-------|
| WaveRadar | Saab | | | | Saab Rex | | | | Saab | | | | Saab Rex | | | |
| Elevation | 28.7 m | | | | 28.7 m | | | | 24.3 m | | | | 22.5 m | | | |
| Buoy | Wavec | | | | Wavec | | | | Wavec | | | | Directional Waverider | | | |
| Distance | 7 km | | | | 7 km | | | | 4 km | | | | 15 km (Anasuria) | | | |
| Period | 05 Nov 1995 to 02 Sep 2002 | | | | 21 May 2003 to 01 Jan 2004 | | | | 26 Jan 1987 to 29 Jan 2003 | | | | 17 Feb 2012 to 31 Aug 2013 | | | |
| No. data | 44,656 | | | | 8,649 | | | | 74,926 | | | | 23,781 | | | |
| No. years | 6.8 | | | | 0.6 | | | | 16.0 | | | | 1.5 | | | |
| Radar Hs median | 2.40 m | | | | 1.90 m | | | | 1.70 m | | | | 1.47 m | | | |
| Buoy Hs median | 2.40 m | | | | 1.80 m | | | | 1.61 m | | | | 1.58 m | | | |
| Bias (buoy – Radar) | 0.04 m | | | | –0.12 m | | | | –0.03 m | | | | 0.12 m | | | |
| Std (buoy v radar) | 0.21 m | | | | 0.24 m | | | | 0.20 m | | | | 0.16 m | | | |
| RMS Diff (buoy v radar) | 0.22 m | | | | 0.27 m | | | | 0.20 m | | | | 0.20 m | | | |
| | | All Data | | | | All Data | | | | All Data | | | | All Data | | |
| | Exposure | Slope | Offset | Ratio | Exposure | Slope | Offset | Ratio | Exposure | Slope | Offset | Ratio | Exposure | Slope | Offset | Ratio |
| N | | 0.95 | 0.06 | 0.98 | | 1.07 | –0.04 | 1.05 | clear | 1.00 | 0.06 | 1.04 | | 0.95 | –0.01 | 0.94 |
| NE | | 0.94 | 0.05 | 0.97 | | 1.10 | –0.11 | 1.02 | clear | 0.99 | 0.04 | 1.03 | Clear | 0.94 | –0.01 | 0.93 |
| E | | 0.93 | 0.08 | 0.97 | | 1.08 | –0.08 | 1.02 | | 0.98 | 0.05 | 1.02 | Clear | 0.95 | –0.01 | 0.95 |
| SE | clear | 0.94 | 0.08 | 0.97 | clear | 1.12 | –0.15 | 1.03 | | 0.98 | 0.04 | 1.01 | Clear | 0.95 | –0.02 | 0.93 |
| S | clear | 0.96 | 0.08 | 0.99 | clear | 1.10 | –0.10 | 1.04 | | 0.96 | 0.06 | 1.00 | Clear | 0.94 | –0.03 | 0.93 |
| SW | clear | 0.98 | 0.07 | 1.01 | clear | 1.08 | –0.04 | 1.05 | clear | 0.98 | 0.07 | 1.02 | | 0.93 | –0.02 | 0.92 |
| W | clear | 0.99 | 0.04 | 1.01 | clear | 1.09 | –0.04 | 1.06 | clear | 1.00 | 0.07 | 1.04 | | 0.93 | –0.02 | 0.94 |
| NW | clear | 0.97 | 0.04 | 1.00 | clear | 1.07 | –0.03 | 1.06 | clear | 0.99 | 0.09 | 1.05 | | 0.94 | 0.00 | 0.94 |
| Omni | | 0.97 | 0.05 | 0.99 | | 1.08 | –0.06 | 1.05 | | 0.99 | 0.06 | 1.03 | | 0.95 | –0.02 | 0.93 |
| Platform-induced Attenuation | | | | 0.98 | | | | 0.99 | | | | 0.97 | | | | 1.00 |
| | | Top 10 % | | | | Top 10 % | | | | Top 10 % | | | | Top 10 % | | |
| | Exposure | Slope | Offset | Ratio | Exposure | Slope | Offset | Ratio | Exposure | Slope | Offset | Ratio | Exposure | Slope | Offset | Ratio |
| N | | 0.88 | 0.50 | 0.97 | | 0.93 | 0.84 | 1.07 | clear | 0.91 | 0.46 | 1.03 | | 0.88 | 0.27 | 0.95 |
| NE | | 0.88 | 0.35 | 0.96 | | 0.98 | 0.47 | 1.10 | clear | 0.95 | 0.18 | 1.01 | Clear | 0.94 | 0.01 | 0.95 |
| E | | 0.78 | 0.70 | 0.95 | | 0.92 | 0.61 | 1.09 | | 0.76 | 1.00 | 1.01 | Clear | 0.90 | 0.35 | 0.96 |
| SE | clear | 0.82 | 0.88 | 0.97 | clear | 0.97 | 0.66 | 1.12 | | 0.80 | 0.88 | 1.01 | Clear | 0.88 | 0.30 | 0.95 |
| S | clear | 0.79 | 1.17 | 0.98 | clear | 1.05 | 0.22 | 1.09 | | 0.82 | 0.65 | 0.98 | Clear | 0.89 | 0.24 | 0.95 |
| SW | clear | 0.85 | 1.00 | 1.00 | clear | 0.75 | 1.38 | 1.09 | clear | 0.84 | 0.69 | 1.01 | | 0.85 | 0.29 | 0.93 |
| W | clear | 0.88 | 0.71 | 1.01 | clear | 0.87 | 0.87 | 1.09 | clear | 0.87 | 0.72 | 1.03 | | 0.92 | 0.16 | 0.96 |
| NW | clear | 0.88 | 0.62 | 0.99 | clear | 1.05 | 0.15 | 1.08 | clear | 0.88 | 0.71 | 1.03 | | 0.89 | 0.20 | 0.95 |
| Omni | | 0.86 | 0.71 | 0.99 | | 1.00 | 0.46 | 1.08 | | 0.88 | 0.55 | 1.02 | | 0.92 | 0.12 | 0.95 |
| Platform-induced Attenuation | | | | 0.98 | | | | 0.99 | | | | 0.98 | | | | 1.00 |

Figure 17 presents scatter plots of the significant wave height derived from measurements made at the North Cormorant facility with a Datawell Wavec buoy and SAAB WaveRadar, and Fig. 18 presents scatter plots for the significant wave height from the Wavec buoy and a SAAB Rex WaveRadar. The scatter plots are stratified by the mean wave direction derived from the Wavec buoy, and the result of a linear regression for each data set is given at the top of each plot and also in Table 2.

The plots in Fig. 17 show the scatter between the significant wave height estimates, with some quite large differences

for specific sea states, but the significant wave height ratios given in Table 2 show that the WaveRadar and Wavec buoy significant wave heights agree on average to within 3 % for any particular direction and to within 1 % for all directions overall, with the WaveRadar values biased low by 0.04 m (Table 2) by comparison with the buoy values. The average ratios in Table 2 are generally higher and close to one when the waves are from the West, the side of the platform where the radar was installed and the side most likely to be least affected by the presence of the platform. Accordingly, these measurements suggest virtually no difference between the significant

wave heights derived from the Wavec and WaveRadar when platform interference of the wave field is expected to be small.

Remarkably, the comparison between the SAAB Rex WaveRadar and the Wavec (Fig. 18 and Table 2) show the WaveRadar to be producing significant wave heights up to 6 % higher on average than those from the Wavec, although the trend with wave direction is less notable than observed in Fig. 17. We do not have an explanation for this result. It is our understanding that the only difference between the installations associated with the data sets presented in Figs. 17 and 18 is the different WaveRadar types, which we would not expect to account for the differences in the results. Nevertheless, the differences between the two sets of comparisons does appear to be due to the specific set up of the system rather than anything related to the actual ability of the sensor to measure the wave heights.

The results for the Auk platform are given in Fig. 19. These results substantiate those observed in Fig. 17—that the SAAB WaveRadar and Wavec significant wave heights are essentially the same for wave directions not expected to result in significant platform interference with the wave field.

The comparisons between the Gannet SAAB Rex WaveRadar and the Anasuria Directional Waverider buoy are given in Fig. 20. Interestingly, the results show the significant wave heights to be lower than the Directional Waverider buoy values, fairly consistently for all directions, but by as much as 8 % for the southwest sector (Table 2). This may be due to actual differences between the wave fields at Gannet and Anasuria but probably not as a consequence of water depth, which is around 90 m at each location.

Overall, the WaveRadar significant wave heights differ from the wave buoys by −1 and +5 % at the North

NC SAAB versus NC WAVEC Hs 05-Nov-1995 to 02-Sep-2002

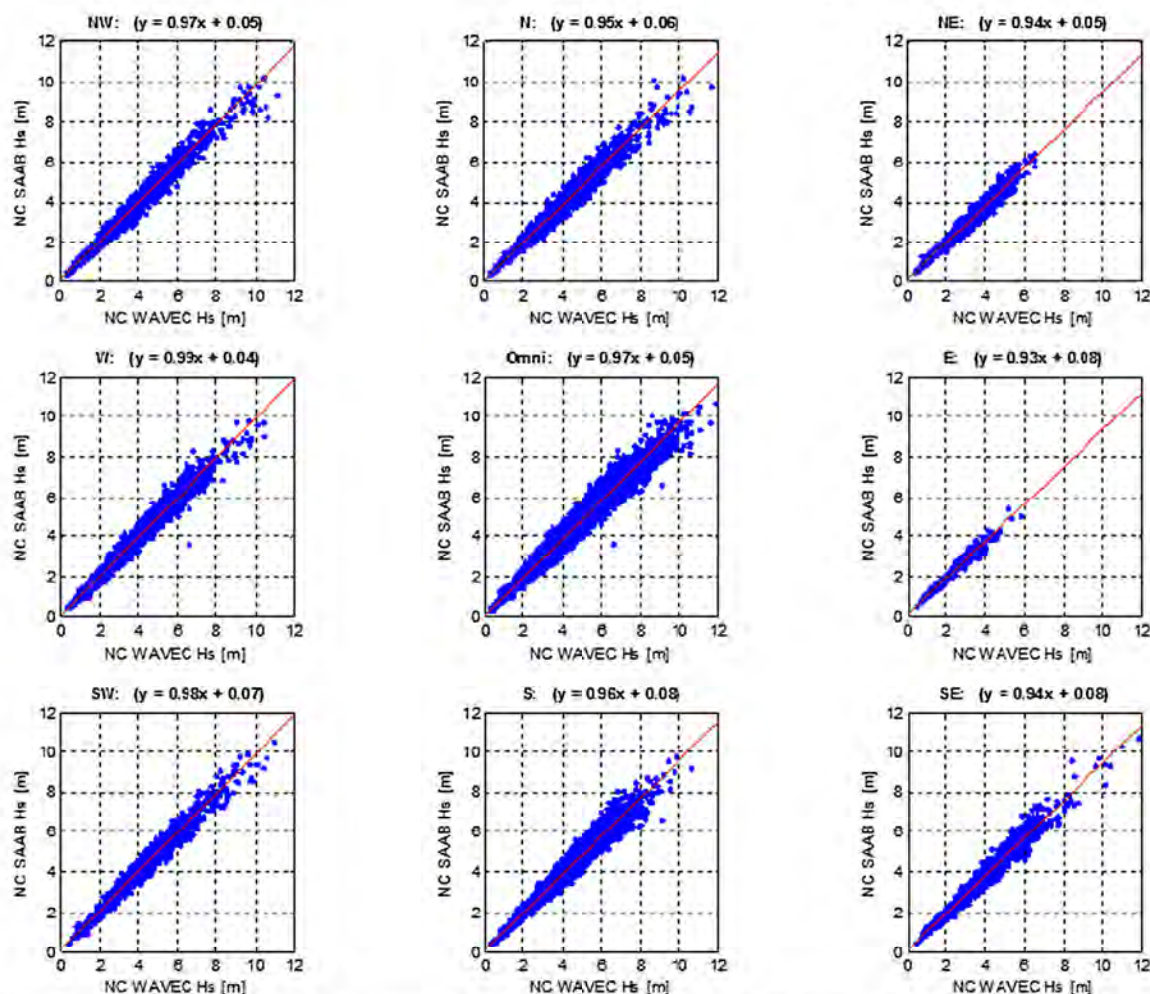


Fig. 17 Scatter plots of the significant wave height measured by a Datawell Wavec buoy and a SAAB WaveRadar, at the North Cormorant platform, stratified by mean direction of the waves at the Wavec buoy

NC SAAB REX versus NC WAVEC Hs 21-May-2003 to 01-Jan-2004

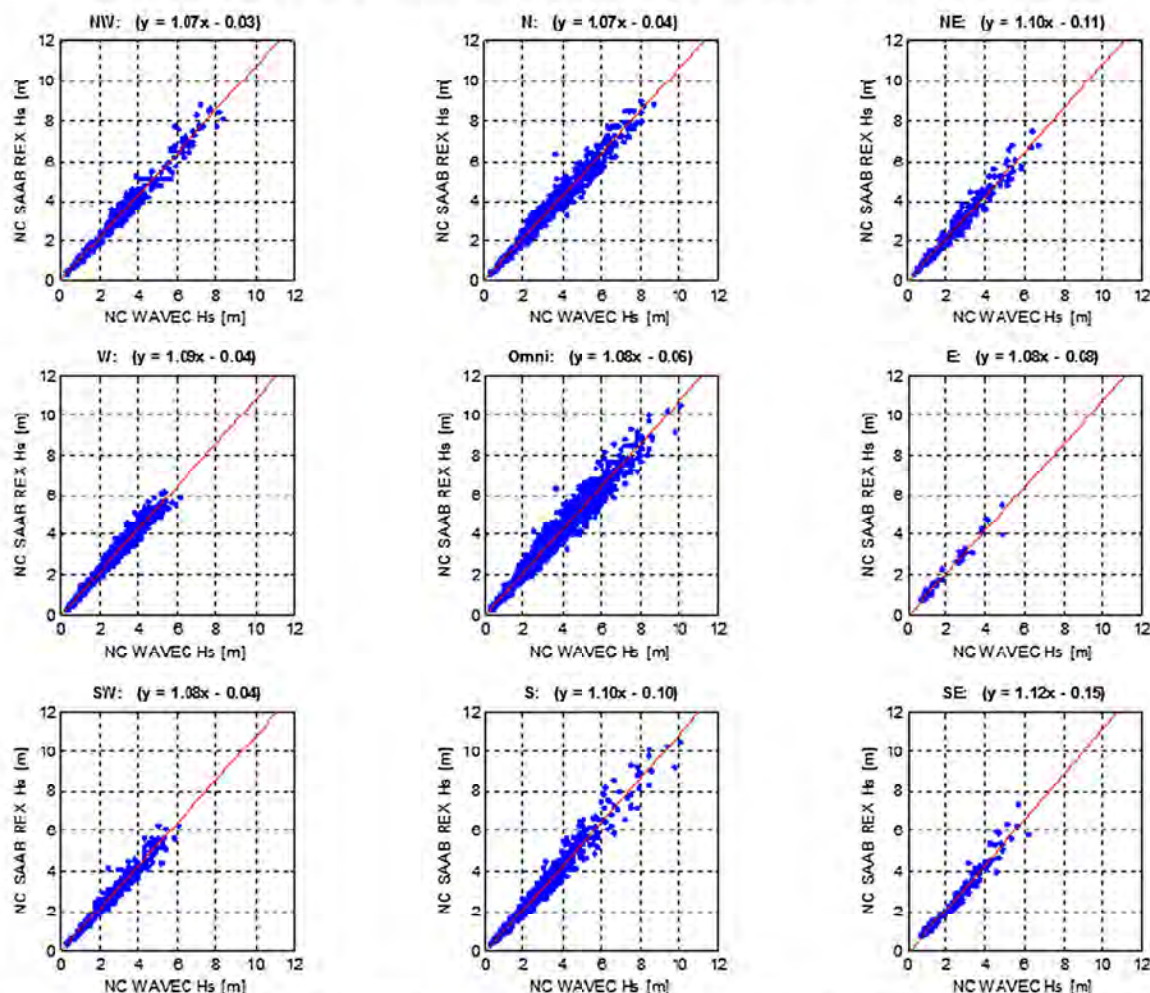


Fig. 18 Scatter plots of the significant wave height measured by a Datawell Wavec buoy and a SAAB Rex WaveRadar, at the North Cormorant platform, stratified by mean direction of the waves at the Wavec buoy

Cormorant location, +3 % at the Auk location and −7 % at the Gannet location. These differences cannot be explained by the platform shielding. A measure of that is given by the ratios in the column labelled platform-induced attenuation in Table 2. These values indicate the blockage effect appears to result in 1–3 % reduction in significant wave height, with apparently slightly less reduction for the larger sea states on average (refer *Top 10%* values in Table 2). The photographs in Fig. 15 give some idea on the amount of shielding that might be expected from each of platforms. While the North Cormorant platform appears to be more congested with tubulars than the other two, closer inspection reveals that this impression is an artefact of the perspective of the camera, and in fact all have eight legs with similar K-bracing and an array of vertical conductors.

To further put these results into perspective, it is useful to compare the differences in WaveRadar and wave buoy significant wave heights with the results of the definitive wave sensor inter-comparison test carried

out in the Wave Direction Measurement Calibration Project (WADIC) project and reported by Allender et al. (1989). In that project, the significant wave heights measured with a number of sensors were compared against that from a laser array at the Edda field in the North Sea. They found 2.5–5 % discrepancy both positive and negative to be common. Some were in the range 10–15 %. It would appear therefore that our comparisons are more or less consistent with the WADIC inter-comparisons.

Finally, it is important point to note that while the differences between the relationships from the various comparison data sets remains to be explained, we do not observe a trend for the relationships between the significant wave heights from the WaveRadars and buoys to change with the value of the significant wave height. The results of regression analyses to the largest 10 % of the sea states for each direction are given in

Auk SAAB versus Auk WAVEC Hs 26-Jan-1987 to 29-Jan-2003

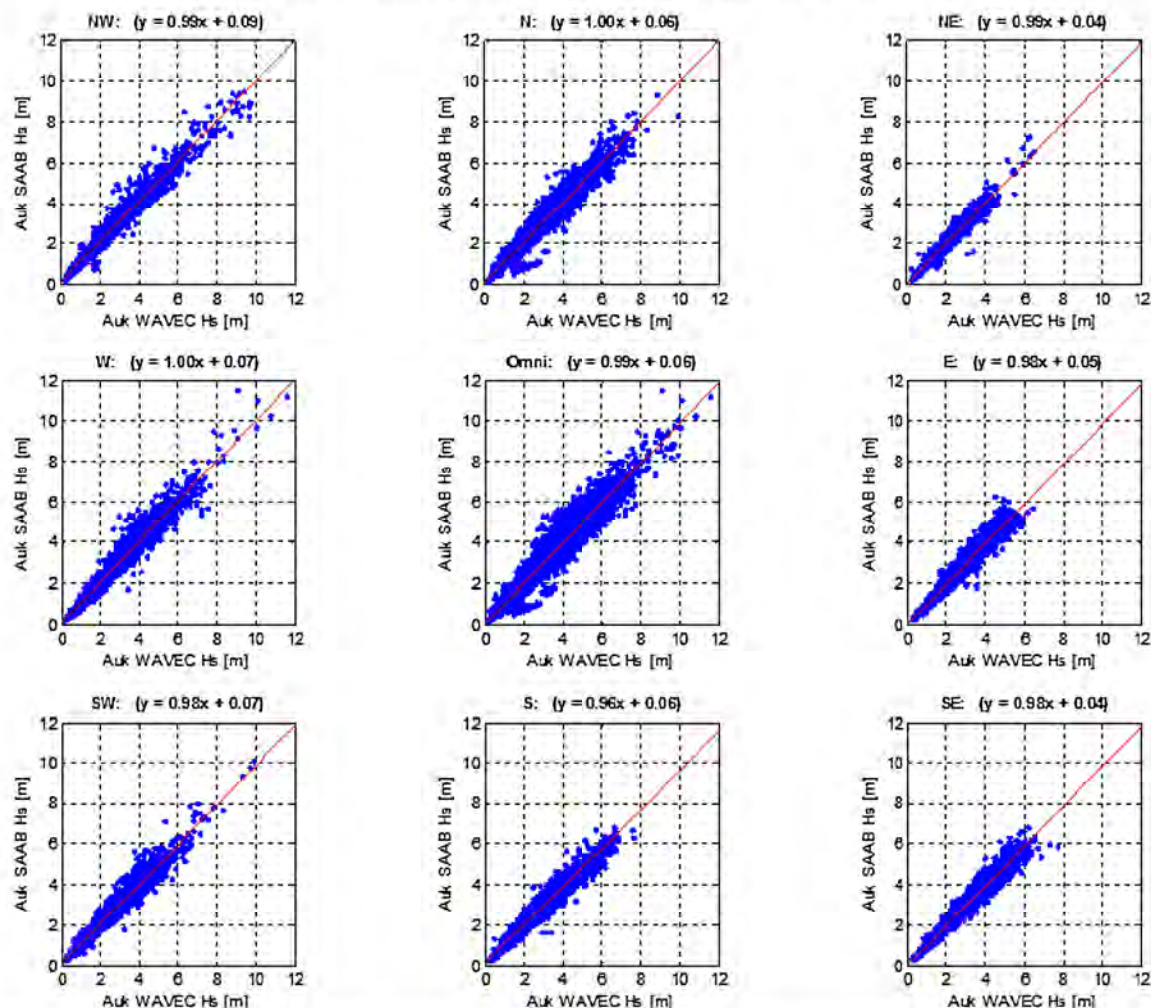


Fig. 19 Scatter plots of the significant wave height measured by a Datawell Wavec buoy and a SAAB WaveRadar, at the Auk platform, stratified by mean direction of the waves at the Wavec buoy

Table 2 (labelled Top 10 %). The regression coefficients are significantly different from those when all the data are utilised (labelled *All Data* in Table 2), with the regression slopes of the top 10 % lower and the offset higher than the corresponding top 10 % values. However, when the ratios of the WaveRadar to buoy significant wave height values are compared between the Top 10 % and the data sets of all data, they differ on average by ± 5 % at most.

To conclude this section, we present results of comparing estimates of the spectral second moment wave period, T_2 , from the WaveRadar and buoy for the four data sets. Averages of the ratio the WaveRadar values to the buoy values are given in Table 3, for the blocked directional sectors combined and for the clear directional sectors combined. The category referred to as top 10 % in the table consists of the top 10 % of the data with

respect to the significant wave height. The agreement between the WaveRadar and buoy T2 values is better than 7 % and mostly better than 5 %, with the WaveRadar values being the larger in most cases.

We have been somewhat selective in the Auk data for the T2 comparisons. When all the data were included for Auk, the scatter plot indicated more than one linear regression line would be needed to explain the observations. This is believed to be due to some of the SAAB Rex WaveRider values actually being zero-crossing periods from time-domain calculations rather than being estimates of T_2 . We have excluded those values from the analysis. Nevertheless, uncertainty remains with the T2 comparisons for the Auk data set, and this may explain why these comparisons show a reverse trend to those from the other three data sets.

The table also shows the ratios for the blocked sectors to be generally larger than for the clear sectors for all cases, except

Gannet SAAB Rex versus Anasuria Dir. WaveRider Hs 17-Feb-2012 to 31-Aug-2013

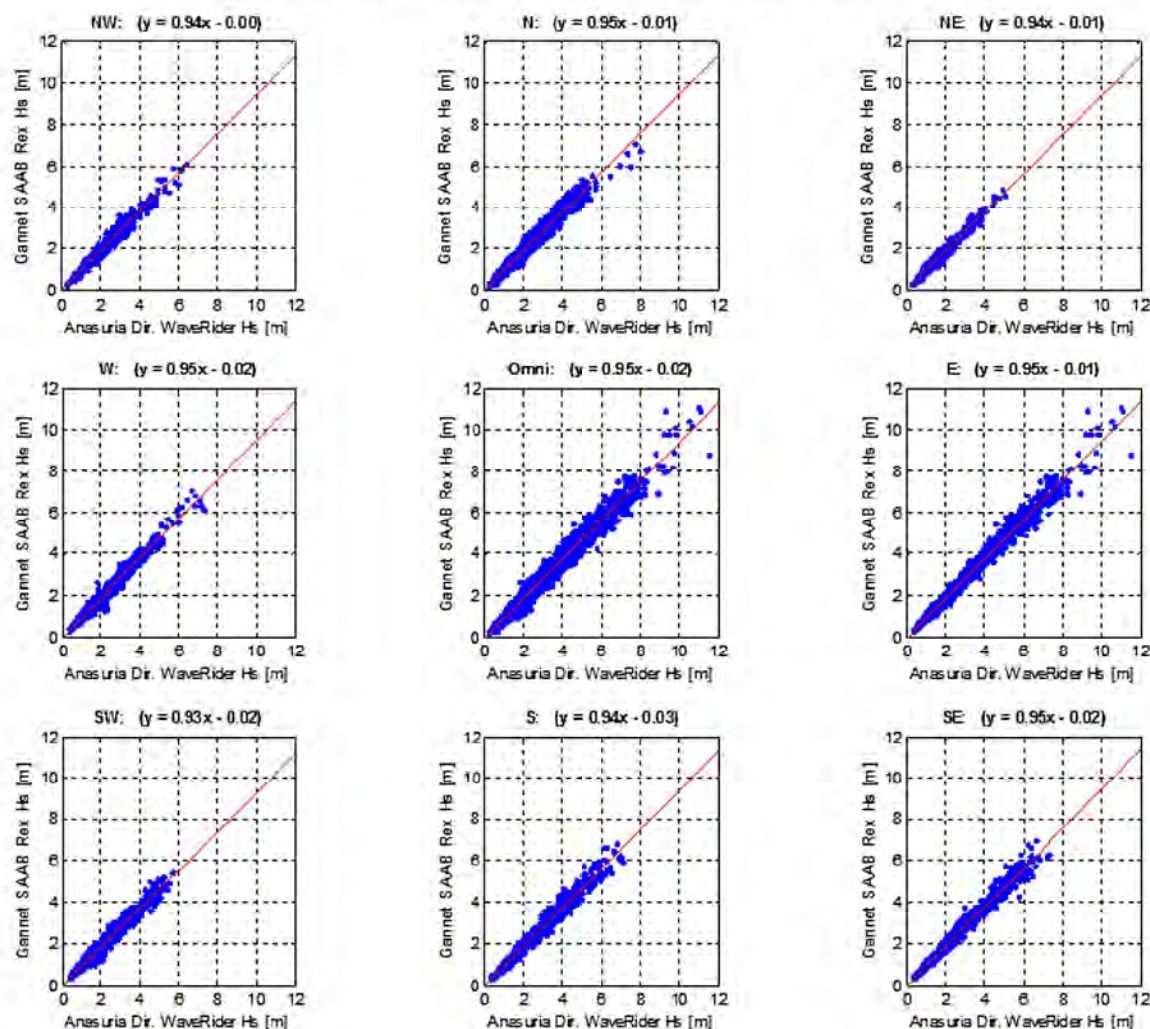


Fig. 20 Scatter plots of the significant wave height measured by a Datawell Directional Waverider buoy at the Anasuria location and a SAAB WaveRadar, at the Gannet platform, stratified by mean direction of the waves at the Directional Waverider buoy

for the Top 10 % Auk SAAB data set. This suggests the platform blockage may attenuate the higher frequency components in the wave field more than the lower frequency components, as the value of T2 will be reduced if the high-frequency spectral levels are decreased.

6 Conclusions

Our simulations of WaveRadar measurements of a random linear surface wave field indicate that the WaveRadar should faithfully follow the surface elevation at a point directly below

Table 3 Average values of the ratio of the WaveRadar T2 values to the buoy values

| | North Cormorant - Saab | North Cormorant - Saab Rex | Auk Saab | Gannet - Saab Rex |
|-----------------|------------------------|----------------------------|----------|-------------------|
| Platform Effect | All Data | All Data | All Data | All Data |
| Blocked | 1.04 | 1.04 | 1.00 | 1.04 |
| Clear | 1.03 | 1.03 | 0.99 | 1.02 |
| Platform Effect | Top 10 % | Top 10 % | Top 10 % | Top 10 % |
| Blocked | 1.05 | 1.05 | 0.98 | 1.07 |
| Clear | 1.04 | 1.04 | 0.99 | 1.03 |

the radar at frequencies between 0.06 and 0.6 Hz, and possibly out to 1.0 Hz. The main cause for the departures in the simulated measurements outside that frequency band is due to the particular method we have employed for processing the reflected radar signals, and especially the peak picking method. However, this has no effect on the significant wave height, but the elevated spectral levels above 0.6 Hz can bias the spectral moment periods high by a few percent, if the calculation of the spectral moments includes frequencies above 0.6 Hz.

Similarly, the departures in the simulated measurements outside that frequency band have no appreciable effect on the calculated zero-crossing crests and troughs, though a small spread is seen for small values of those parameters.

The field measurements made at a sampling frequency of 10 Hz indicate that the WaveRadar may perform better than our simulations suggest, with the expected roll-off in spectral density continuing to higher frequencies than the simulations, and the low-frequency plateau occurring an order of magnitude lower relative to the spectral peak.

The comparisons of the significant wave height of WaveRadar measurements against Datawell wave buoy measurements made in the North Sea generally show fairly good agreement and do not show any trend with increasing significant wave height. Comparisons between the earlier WaveRadar units and the Wavec buoy are in very good agreement for wave directions not expected to be affected by the platform and small reductions in the WaveRadar values compared with the buoy values for directions expected to be affected by the platform. Reduced significant wave heights due to platform interference on the wave field are expected, but these appear to be just a few percent.

Comparisons of the Rex WaveRadars against the wave buoys show systematic differences in the significant wave height in some cases. The differences are less than 8 % and generally less than 5 %, and therefore more or less consistent with wave sensor inter-comparisons performed in the WADIC experiment (Allender et al. 1989). Nevertheless, an explanation for these differences is desirable. The differences cannot be explained by platform interference but appear to be more related to the specific setup of the instrumentation, for which we currently do not have an explanation.

Accordingly, we acknowledge that further investigation of the field measurement setups is needed, to explain the differences between the results of the various inter-comparisons, and we note improvements in the WaveRadar “peak picking” algorithm might lead to improved fidelity of the simulations; but the results of this study support the conclusion that the WaveRadar provides good measurements of the surface wave elevation, not only for supporting offshore operational activities and engineering requirements but also for investigations into fundamental aspects of ocean surface waves.

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