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A Method for Approximating Surface Elevation from a Shore Mounted X-Band Radar with a Low Grazing Angle

Charles E. Greenwood, James Morrison Angus Murray, Arne Vogler
Lews Castle College, University of the Highlands and Islands.
Isle of Lewis, Scotland

ABSTRACT

X-band radar provides a spatial backscatter results over a large area. This shows wave features to be clearly visible over a large area providing an advantage over standard in situ measurements. This paper suggests a new method of quantifying surface elevation in an almost real-time method by applying a second order Stokes waves in shadow regions (troughs). The initial results show the artificial wave trough method having an improvement in phase and magnitude when compared to independent in situ measurements. This method provides a better representation of the surface elevation. Once refined, the real time surface elevation can be used as boundary conditions for a short-term wave-forecasting model.

KEY WORDS: Surface Elevation; Radar; Wave Measurements; Real-time; Wave Buoy; AWAC

INTRODUCTION

The use of X-band radar as a method of wave and current measurements has been around for a number of years (Alpers & Hasselmann, 1982; Young, Rosenthal, & Ziemer, 1985). This is due to the interaction between the sea’s surface and electromagnetic wave that allows wave images to be collected over an area of several kilometers in all directions. Previously, these images were referred to as sea clutter as they are a byproduct of a ships navigation radar. A high-resolution spatial and temporal map of wave condition and surface currents can be created when an X-band radar is optimized to receive this clutter information.

The applications of X band radar to measure waves and currents is common, however, in a few cases this has been extended measure bathymetry. (Ludeno et al., 2015; Tenthof van Noorden, 2015; Trizna, 2001) and uses a dispersion relation filter to track the change in wave profiles as then interact with the seabed.

A large number of studies had originally focused on the analysis of radar data to extract wave spectra (Borge, Hessner, Jarabo-Amores, & de la Mata-Moya, 2008; Gangeskar, 2000; J. C. Nieto Borge, Reichert, & Dittmer, 1999; Seemann, Ziemer, & Senet, 1997). This normally uses the Signal to Noise Ratio (SNR) and a three dimensional dispersion relation filter with additional measurement coming from in situ wave sensors i.e. wave buoy or a ship’s inertial measurement unit (IMU). This provides a good agreement when compared against standard wave measuring sensors. The calculated spectra however, is only capable to produce an output over a given period of time and for a given area. This provides good phase-averaged wave quantification but omits phase-resolving feature that are important for short-term wave predictions. In terms of resource assessment, the radar-derived spectra provides a low spatial and temporal resolution map, this remains a substantial advantage when compared to traditional 1-dimensional wave recordings from fixed locations.

The accurate measurement of the surface elevation within the radar domain would have vast scientific and commercial applications. This data could be used to provide short-term wave predictions that would be of considerable use for wave-by-wave tuning a wave energy devices and marine operations for the deployment and retrieval of operations crafts and helicopters.

One such study states uses X-band radar to provide surface elevation as inputs for a short-term wave forecast model (Belmont et al., 2014). This provides a reasonable attempt but more work is required to achieve a better spatial map of surface elevation. The calculation of the surface elevation in (Dankert & Rosenthal, 2004) implies an empirical inversion method to extract the surface elevation. This provided a reasonable description of surface elevation. A similar approach is applied in (J. Nieto Borge, Rodríguez, Hessner, & González, 2004) that uses a an inverse discrete Fourier transform based on an amplitude and phase spectra. A scaling factor applied based on data from an in situ sensor. The results of these studies show a similar method for calculating reconstructed surface elevation; this is a representation of the surface elevation and the direct measured surface. It is thought that these method require considerable computational resource and may not be suitable for a real-time calculation of surface elevation over a spatial domain. It is therefore not possible to apply to short-term wave prediction.
models. An alternative method for extracting surface elevation from synthetic radar data is presented in (Naaijen & Wijaya, 2014). This presents a linear method that uses tilt angle and a beam wise spectral integration, where a 1-dimensional FFT along each pulse is calculated. This was implemented on synthetic radar data and no actual radar measured dataset sets were used. This study presents a simplified Modulation Transfer Function (MTF) for the conversion of radar backscatter to surface elevation. With particular focus is on the analysis of radar data with a low antenna height and therefore low grazing angle, where wave shadowing is prevalent. This proposes the addition of artificial wave troughs in shadow regions, where a 2nd order stokes wave is applied with a wave-by-wave approximated magnitude and period. This provides an almost real time method with low computational requirement that can be performed over a large area. This was developed to provide a fast algorithm to measure spatial wave profiles to be used as boundary conditions for a short-term wave prediction model.

EXPERIMENTAL SETUP

A SeaDarQ X-band radar system was deployed for 2 days along with additional wave sensors in the sound of Taransay on the Isle of Harris, Scotland from the 23rd -25th of March 2016. This used a 2.4m VV polarised antenna with a 360° azimuth with blanked sections from 20° to 230°. A pulse width of 50ns with a PFR (Pulse Return Frequency) of 1300 Hz was used. The rotational speed was 48 rpm, this resulted in a sample rate of 1.3 seconds for any cell in the radar domain. The antenna was installed at a height of approximately 12m above sea level. The radar backscatter was stored in individual rotation matrices of 4096 by 1024 cells. The range of the radar was set to 3.07km, providing outputs at a 3m resolution. The data from a single rotation is presented in Fig. 1. This shows the location and extent of the measured radar domain. Near the center of the radar image a small bay can be seen as well as the southern coastline of the island of Taransay towards the north-northwest outer reaches. In this Figure it is possible to identify individual wave crests by the lighter regions, this shows higher magnitude of returns as the wave approach the shore. Radar shadow regions can also be observed as the nearby headlands cast shadows where no radar returns are recorded.

Two in situ wave sensors were also deploy for this period. These were a seabed mounted Signature 1000 device that uses acoustic surface tracking and pressure as well as a moored Datawell 40cm Wave Buoy. The location of these sensors is shown in Fig. 1. The separation of the sensors varies but ranges from 35-150m. These sensors will be used as calibration and validation points for the direct comparison between the phased resolved and phased average datasets.

GENERATION OF ARTIFICIAL WAVE TROUGHS

When the Signature 1000 and the Wave buoy data are compared
to the radar data (see Fig. 3) results show that the radar is capable of capturing the wave peaks and seems incapable of measuring the full extent of the wave troughs. This is due to the wave shadowing and can be seen in Fig. 1, whereas the distance away from the radar increase the grazing angle lessens and the less wave information is recorded. In order to provide a better representation of the surface elevation a method is shown for generating artificial wave troughs to improve the comparison between radar and measured surface elevations.

The application of applying artificial wave troughs to a time series is implemented by separating the time series by waveforms, calculating a new wave trough elevation and merging the new waveform with the time series without losing information from the wave peak. A detailed description of this is shown below.

The raw backscatter signal obtained from SeaDarQ, the signal comprises of an matrixes of absolute values corresponding to location and time with the radar domain. In order to convert this to surface elevation the data is zeroed about the mean and multiplied by a surface scaling factor. The scaling factor is calculated from the linear regression of the measured dataset and the zeroed radar dataset. The radar data is then separated on a wave by wave basis defined from peak to peak. The definition of a peak is a peak value with a prominence greater than 0.7 of the standard deviation that is not within 4 s of each other. This identifies approximately the maximum 34% of waves which otherwise could be describes as H_{1/3}. Other methods of identifying wave peaks were tested, these include exceedance of signal aptitude and period and a zero up-crossing analysis, while these methods worked, they produced higher errors values when compared to the application of the peak prominence method. Additional quality control methods were applied that used wave steepness, wave height and period restrictors. The wave steepness parameter excludes waves from the time series if the steepness (H/L) exceeded 1/7, this value is based on the maximum wave steepness in deep water (Michell, 1893). Wave height and period limiters were applied to ensure that wave height and period remain within tangible values; it was noted that white capping caused increased magnitude radar returns that could be misrepresented during this method of processing.

The artificial wave trough amplitude is then calculated using the average of the values of the start and end peak by -1.7. This produces a wave trough adjustment parameter. The magnitude of the artificial wave is known a theoretical surface elevation (η) can then calculated using a 2nd order Stokes wave.

\[
\eta = \frac{H}{2} \cos \theta + \frac{1}{16} kH^2 (3 \coth^3 kh - \coth kh) \cos 2\theta
\]  

(1)

Where H is artificial wave height, θ is the wave phase, k is the wave number (based on the wavelength calculated from the dispersion relation) and h is the water depth. The use of a 2nd order wave was applied to help replicate the wave profile shape experienced in shallow waters, where wave profiles exhibit peakier crest and flatter troughs. This increases the validity of the surface approximation and allows the approximation to be used in much shallower waters when compared to a sinusoidal wave.

Once the theoretical waveform is calculated it must be merged with the radar time series. This uses a negative windowing function (w) that is applied to the radar waveform (see Fig. 2).

\[
w(n) = \frac{1}{2} \left( 1 + \cos \left( \frac{2\pi n}{N-1} \right) \right)
\]  

(2)

![Fig. 2 Windowing function used to merge radar and artificial wave forms.](image)

Where n is the number of a specific data point within the waveform and N is the total number of data points for each wave. The resultant surface elevation (\textit{Surf}) for a single point is then approximated by

\[
\textit{Surf}(n) = \eta + w(B_s - \eta)
\]  

(3)

Where η is the second order stokes wave, w is the windowing function and B_s is the backscatter intensity. This allows the crest of the wave to keep 100% of its shape from the backscatter measurements and allows the estimation of the wave troughs to be entirely 2nd order wave form with a smooth transition between the two.

**RADAR PHASE COMPARISON FOR THREE WAVE SENSORS**

To assess the quality of the radar measured surface elevation the three additional sensors were deployed. The sensors used were a Nortek Signature 1000 device and a Datawell DWG G4 40cm wave buoy. The Signature 1000 sensor uses Acoustic Surface Tracking (AST) and an integrated pressure sensor to record surface elevation with a sample rate of 4Hz. The wave buoy uses a GPS sensor for measuring wave motion, this had a sample rate 1.28Hz. The position of buoy was recorded every 30mins. Surface elevation of the AST, wave buoy and pressure sensor are shown in Fig. 3. This shows a direct comparison of the artificial wave trough elevation and the radar scaled backscatter with the surface elevation from each sensor. It can be seen that there is generally a good phase agreement between the data sets. The scaled radar measurements provide a reasonable approximation of the peak values. However, they show an under prediction in the wave troughs elevations.
This is compensated for by the application of the artificial wave trough, where a better agreement in the wave troughs is achieved. The magnitude of the surface elevation for the buoy and AST results shows very similar wave heights, whereas the wave pressure sensor shows a much smaller magnitude with a very smooth surface profile. This is due to the depth of the sensor and does not represent the actual surface elevation. As the dynamic pressure of the surface elevation reduces with depth more higher frequency wave components are removed. The provides a smoothened reduced amplitude of the version of the surface elevation.

When the approximated surface elevation is plotted against the measured data for each sensor, the correlation between the surface elevations can be obtained. The method of least square was used to plot a line of best fit, this shows a positive gradient for all cases, where a steeper gradient (closer to 1) is shown in for the artificial wave trough analysis. The y intercept is shown for each surface approximation; this indicates that the mean value is close to zero. The scaled backscatter values show a poor uneven distribution of data points in the y-axis. This shows no values below -0.5m for the buoy and AST radar results and -0.2m value is close to zero. The scaled backscatter values show a poor uneven distribution of data points in the y-axis. This shows no values below -0.5m for the buoy and AST radar results and -0.2m for the pressures sensor radar results, whereas for the measured data, a maximum reading of up to -1.4m for the buoy and AST and -0.6 for the pressure sensor. This discrepancy a result of wave shadowing, the addition of the artificial wave troughs minimises this effect and provides a better distributed approximation of the surface elevation.

When basic statistical analysis is applied the agreement between the radar and in situ sensor data can be quantified. The Pearson correlation (r) and the range based Normalised Root Mean Squared Error (NRMSE) are used to determine the relation between the datasets, these can be described as:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

And

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{N(y_{max} - y_{min})}}$$

Where x is the measured surface elevation from the wave sensors, y is the radar approximated surface elevation calculated from the backscatter and N is the number of samples.
The Pearson correlation provides a phase agreement quantification parameter while the NRMSE quantifies the wave amplitude agreement. Table 1 shows the $r$ and NRMSE values for the 30min test example shown above. This suggests that the inclusion of the artificial wave troughs has an increase performance in all cases for phase and wave amplitude. The best phase agreement achieved by the pressure sensor when the artificial wave troughs are included. This produces a correlation coefficient of 0.725. The pressure sensor also provides the minimum NRMSE with a value of 0.11. While the agreement between the radar surface approximation and the pressure based surface elevation provide the most promising agreement, the approximated surface is likely to be non-representative of the actual surface. When the other sensors are considered, the artificial wave trough analysis provides a phase correlation of 0.666 and 0.652 with a NRMSE of 0.118 and 0.131 for the wave buoy and AST respectively. These results show an improvement for the application of 2nd or stokes wave troughs of 6.1% for the wave buoys phase measurement and 3.5% for the AST radar measurement. The NRMSE shows an improvement of 7.3% for the wave buoy and 6.9% for the AST results.

Table 1 Statistical comparison of 30min surface elevation

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Artificial Wave Trough</th>
<th>Scaled Backscatter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Buoy</td>
<td>$r=0.666$</td>
<td>NRMSE = 0.118</td>
</tr>
<tr>
<td>AST</td>
<td>$r=0.652$</td>
<td>NRMSE = 0.131</td>
</tr>
<tr>
<td>Pressure</td>
<td>$r=0.725$</td>
<td>NRMSE = 0.110</td>
</tr>
</tbody>
</table>
Spectral analysis of the times series allows a frequency based analysis of the distribution of energy with frequency (see Fig. 5). In order to achieve this a Welch’s FFT was applied with a 50% overlap and Hanning window of 45 seconds. This shows a peak period of around 0.095 Hz (10.5 s) for all sensors, where the scaled backscatter pressure sensor results indicate a slightly higher peak period. The magnitude of the Buoy and AST sensor measurements are similar. However, the pressure sensor experiences a much lower peak value. The artificial wave trough method shows a similar peak energy value combined with a slight overestimation in the energy content for very low frequencies. The scaled backscatter results show a large underestimation of energy, with the high and low frequency regions experiencing a proportionally higher energy contents.

The spectra presented in Fig. 5 is used to calculate the $H_{m0}$, where $H_{m0} = 4 \sqrt{m_0}$. This allows the energy equivalent wave heights can be compared. Table 2 shows the measured spectral wave height of the different sensors. The results indicate that for the wave buoy and AST sensors an under prediction occurs. The results of the scaled backscatter results show a very large disagreement in wave height. When sensor locations are compared there is considerable variation in the measured $H_{m0}$ for the wave buoy and AST given their separation distance. This variation in $H_{m0}$ is consistent when the results of the radar is analysed. This highlights the importance of identifying the exact location of the sensors within the radar domain to maintain a meaningful comparison.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>$H_{m0}$ [m]</th>
<th>Measured</th>
<th>Artificial Wave Trough</th>
<th>Scaled Backscatter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Buoy</td>
<td>1.19</td>
<td>1.07</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>AST</td>
<td>1.12</td>
<td>1.03</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>0.57</td>
<td>0.55</td>
<td>0.34</td>
<td></td>
</tr>
</tbody>
</table>

The results presented above show that the application of the artificial wave trough method increases the performance in terms of phase and amplitude when reconstructing the surface elevation. The current results also suggest the comparison between radar surface elevation and pressure are meaningless as this is not a portrayal of the seas surface as it excludes higher frequency waveforms.

**APPLICATION TO TIME SERIES**

When the method described above is applied to the two-day X-Band radar deployment radar the agreement between methods of calculating surface elevation can be assessed. This shows a time series of the Pearson correlation and NRMSE of the surface elevation for the artificial wave trough for the wave buoy and AST sensor (see Fig. 6). The pressure sensor results are no longer presented as this sensor shows a misrepresentation of the surface elevation. The Pearson correlations shows that the AST comparison experiences, in general, a better correlation than the wave buoy. This shows an agreement of around 0.6 for the AST and 0.49 for the wave buoy. The NRMSE yields a similar result to the Pearson correlation where the AST results in a generally much lower and more stable relative error. This results in an average NRMSE of 0.15 for the AST results and 0.20 for the wave buoy. This dataset shows small regions where there are gaps in the data, these regions were excluded as segments of radar or measurement data were missing and caused increased error values.
Statistical analysis of surface elevation between the measured and artificial wave trough analysis for the two-day deployment. The $H_{m0}$ is calculated for the wave buoy and the AST sensor and presented in Fig. 7. This shows that the artificial wave trough analysis calculates the energy equivalent wave height well for both sensors, where a slightly better agreement is achieved for the AST location. Similar to the statistical results the wave buoy experiences a greater level of variance when compared to the AST.

The calculation of the peak period ($T_p$) is shown in Fig. 8. $T_p$ is identified as the frequency with the largest spectral energy content. The comparison between radar and measured peak period shows a good correlation. The wave buoy calculated period shows brief regions where a large increase in period is observed, these can be excluded as they are likely a processing error. The AST results show a poor agreement towards the beginning of the time series but after 03:00 on the 24/03/2016 this agreement becomes very good. It is thought that this initial disagreement is caused by alterations in the data collection method that were not included in the post processing of the data.

CONCLUSIONS

The results of this initial data analysis have shown that the calculation of surface elevation using artificial wave troughs provides an increase in the magnitude and phase agreement when compared to scaled radar backscatter. In the condition tested it was possible to replicate the surface elevation with a minimum error of 10.9% and a maximum phase agreement of 0.7. The post processing applied to approximate the surface elevation strongly depends on the method used to identify individual waveforms. When this method breaks down the larger wave period can be created, this is what may have caused the increase $T_p$ values in Fig. 8 for the wave buoy. It is though that these regions may be caused by poor radar backscatter. This maybe a result of low radar grazing angle or transverse travelling waves.

When the AST and wave buoy sensors are considered it is expected that given their close proximity that the results would be similar. While this was the case for some temporal regions not all cases reflected this, this highlighted the importance of identifying exact sensor location. The use of a wave buoy increases complications due to its “free floating” nature. While the buoy location is reported via GPS, it is only recorded every 30min. Therefore, the cell from which the radar backscatter data is retrieved may vary to the buoys actual position which leads to a difference in surface elevation. This can be corrected for by increasing the recording sample rate of the buoy. The AST sensor also experienced minor difficulties in tracking the surface, although this only resulted in peaks in the signal magnitude that were able to be filtered out.

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