A Method of Swell-Wave Parameter Extraction From HF Ocean Surface Radar Spectra

Jonathan S. Bathgate, Malcolm L. Heron, and Arnstein Prytz

***Abstract*—A new method for the extraction of swell-wave parameters from high-frequency (HF) radar spectra is presented. The method of extraction of the parameters, period, direction, and height, relies on a frequency-modulation approach that describes the hydrodynamic interaction of the swell waves with the resonant, shorter, Bragg waves. The analysis process minimizes the electromagnetic second-order interaction and a simulation model was used to validate the approach. This simplified method provides a fast means of examining swell conditions over large areas of the ocean surface. Data are acquired using a pair of coastal ocean surface radar (COSRAD) systems deployed at Tweed Heads, Qld., Australia. The radar covers a sweep (approximately 60°) every 30 min with spatial resolution of the order of 3 km. A sample set of data from this deployment is used in a case study to show the extraction of swell direction and amplitude using these methods. The results support the use of the COSRAD HF radar for mapping swell in the near-shore zone.**

***Index Terms*—HF radar, remote sensing, swell, waves.**

I. Introduction

MONITORING sea state has long been a desirable addition to the capabilities of HF radar systems which are routinely used to measure and map surface currents with great accuracy. Crombie [2] discovered that waves which are half the length of the incident radar wavelength are represented by strong peaks in the first-order Doppler spectrum. This led to the extraction and mapping of surface current parameters. It was later suggested that higher order scatter could produce information on longer ocean waves through wave–wave interactions. Barrick [1] calculated the second-order spectrum for high-frequency (HF) spectra, which confirmed the continuum surrounding the first-order Bragg peaks as ocean wave scattering. Derivation of electromagnetic contributions and hydrodynamic effects were presented to fully describe the second-order backscatter and ultimately led to solutions for the extraction of long-period ocean wave parameters [5], [6]. These solutions relied on variations in frequency and amplitude of sidebands in the second order with wave direction. However, small differences in the position of these peaks are often difficult to resolve in the second-order spectrum as it is closer to the noise and, therefore, more susceptible to broadening or peak bifurcations. In cases such as this, small variations in peak position are not a reliable parameter to extract. It is for this reason alternate methods for the extraction of swell information from HF radar spectra were pursued.

The new method for the extraction of swell direction, height, and period presented here is based on the frequency modulation imposed upon the Bragg waves by the longer, faster moving swell. This technique is a sound hydrodynamic explanation for the expression and behavior of the swell peaks in the second-order spectrum. The electromagnetic contribution which adds the variations in sideband position and amplitude are minimized by taking the average swell-peak amplitude and assuming an equal frequency displacement from the Bragg line to attain the symmetry in sidebands as stipulated by the theory of frequency modulation. The changing amplitude of the peaks with the incident angle of the radar beam then provides directional and height information on the swell waves. A simulation was carried out to generate spectra with no electromagnetic contributions. The simulation shows this technique of taking the mean sideband amplitude, which provides a good representation of the hydrodynamic situation being modeled.

The final section of this paper describes the extraction method for swell parameters, direction and amplitude, by means of a case study. The sample set of data was taken from a deployment of the coastal ocean surface radar (COSRAD) system in which its main purpose was the mapping of surface currents [3]. COSRAD operates at a frequency of 30 MHz which is ideal for the measurement of surface currents. COSRAD is a coherent pulsed radar which uses a single phased array for transmit and receive functions through a transmit/receive (T/R) switch. The antenna beam steering is done electronically by introducing phase shifts in the antenna elements. The case study shows that simultaneous measurement of swell parameters and surface currents is possible without changes to radar configuration.

II. Frequency Modulation of the Radar Echo

As mentioned previously, the main scattering mechanism for ocean radar backscatter is Bragg scattering from the surface wave which is propagating either towards or away from the radar with a wavelength half that of the radar wavelength. For the HF COSRAD system, the operating frequency is 30 MHz and the Bragg wavelength is 5 m. When there is an underlying swell, the smaller Bragg waves are thrust to and from by the faster moving, longer wavelength swell waves. Therefore, at any given point on the ocean surface, the velocity of the Bragg wave is determined by the propagation of that wave itself and the surge velocity im-

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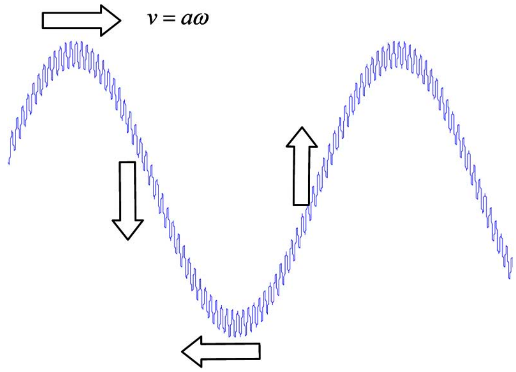

Fig. 1. Schematic of a two-scale system with a short wavelength Bragg wave riding on swell. The arrows show the instantaneous velocity of the surface water particles in response to the swell wave. The surge velocity of the swell wave modulates the instantaneous speed of the Bragg wave and when the radar wave backscatters, the echo is frequency-modulated.

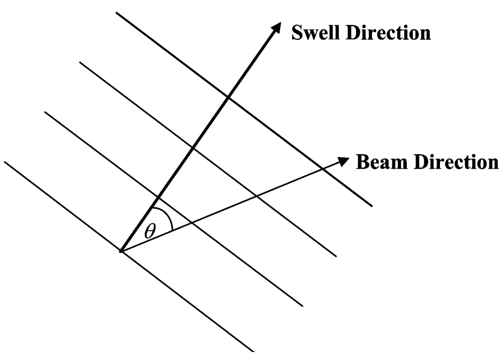

Fig. 2. Parallel lines represent the swell crests, with the wave propagating perpendicular to these. The radar beam can be directed at any angle θ to the swell and the surge velocities are projected through θ.

posed by the swell. (Note that we remove the Doppler shift due to surface currents before the wave analysis.) We assume that these velocities are linearly superposed as illustrated in Fig. 1.

The instantaneous surge velocity of a portion of water at the surface, illustrated in Fig. 1, is

$$v_s = a_s \omega_s \tag{1}$$

where a_s is the amplitude of the swell wave and ω_S is the frequency. The trajectory of the surface particle of water is a circle in the vertical plane. The horizontal component of the surge velocity is

$$v_{SH} = a_s \omega_s \cos(\omega_s t). \tag{2}$$

If we consider the projection of the swell-surge velocity in a direction θ from the direction of propagation of the swell, as shown in Fig. 2, then the horizontal component is expressed as

$$v_{SH} = a_s \omega_s \cos\theta \cos(\omega_s t). \tag{3}$$

The propagation speed of the Bragg wave is

$$v_B = \sqrt{\frac{gc}{4\pi f_0}} \tag{4}$$

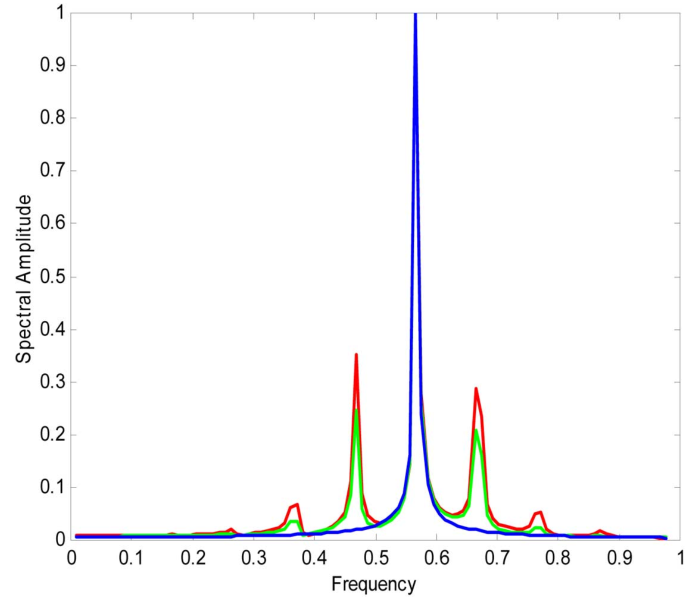

Fig. 3. Spectra from the two-scale model. $\theta = 0°$ gives the highest sidebands. The other sidebands are for $\theta = 45°$ and $90°$. The amplitude for $\theta = 0°$ fits the case study on March 5, 2001.

so the combined speed which modulates the radar backscatter is

$$v_M = v_B + v_{SH}. \tag{5}$$

The Doppler frequency imposed on the backscattered echo then becomes

$$f_D = \sqrt{\frac{gf_0}{\pi c}} + \frac{2f_0}{c} a_s \omega_s \cos\theta \cos(\omega_s t) \tag{6}$$

and the echo signal may be written

$$E(t) = a_B \cos\{\omega_B t[1 + m\cos(\omega_s t)]\} \tag{7}$$

where

$$m = \frac{\omega_B a_s \omega_s}{g} \cos\theta \tag{8}$$

a_B is the amplitude of the Bragg echo and ω_B is the Bragg frequency.

The expression for $E(t)$ represents frequency modulation and the corresponding spectrum is a series of Bessel functions when the modulating function is a sinusoid, as used here. For a small modulation index (m), the spectrum is dominated by the carrier, which in this case is the first-order Bragg line, and the first pair of side lobes with relatively minor contributions from the higher order sidebands. Spectral amplitudes corresponding to $E(t)$ can be calculated for any set of two-scale parameters.

A measurement of the ratio R_{swell} of first-order Bragg amplitude to the mean amplitude of the first sidebands is simple and would be a reliable and robust parameter to extract. R_{swell} is a minimum when the radar beam is in line with the direction of swell propagation $(\theta = 0°)$ and is infinite when the beam is orthogonal to the direction of swell-wave propagation $(\theta = 90°)$. No modulation from the swell-surge speed is observed in this direction. Fig. 3 shows this relationship with R_{swell} in terms of

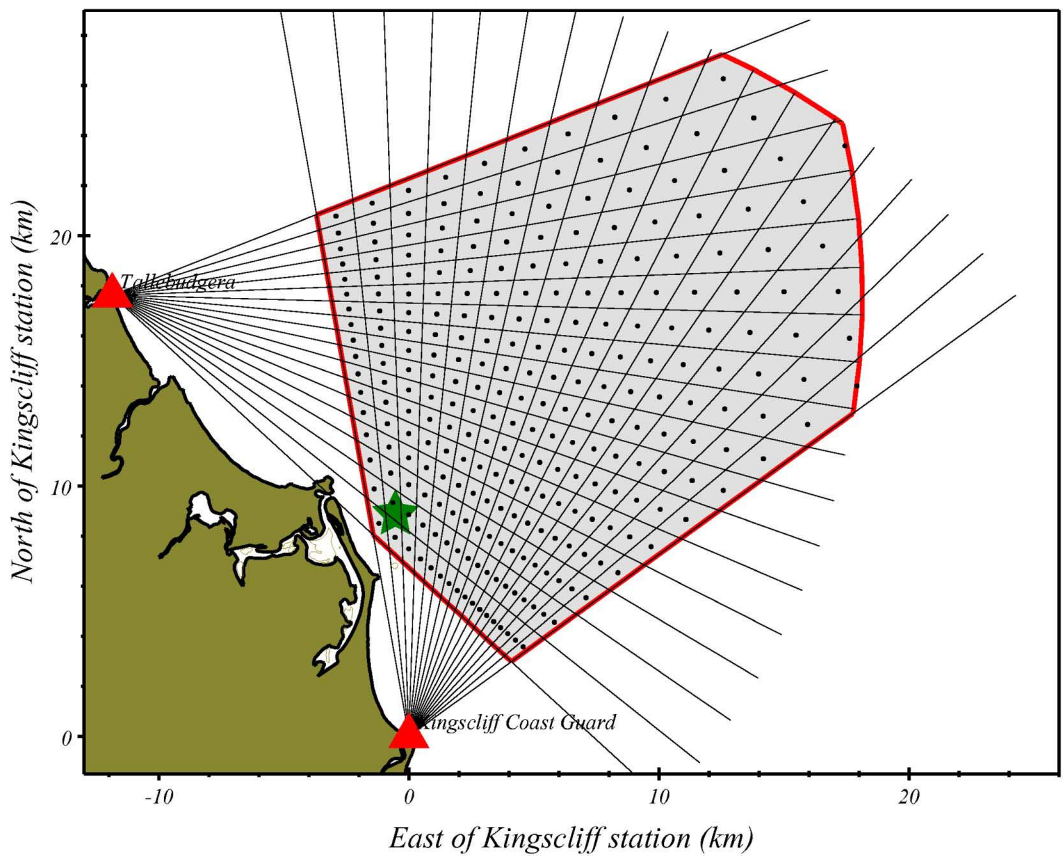

Fig. 4. Coverage map of two COSRAD stations deployed at Tweed Heads. The boresights of the stations at Tallebudgera (99°) and Kingscliff (21°) intersect almost orthogonally. The star marks the location of a directional wave buoy.

sideband amplitudes as calculated using the preceding equations for $E(t)$. A typical swell-wave period of 12 s was used in this case. The maximum sideband amplitudes here were calculated to match the minimum $R_{\rm swell}$ value for a sample data set collected on March 5, 2001 during a deployment of the COSRAD system at Tweed Heads, Qld., Australia (Fig. 4). However, before the sample data are used as a case study for the extraction of swell parameters, we need to clarify the extraction of the parameter and its role in terms of minimizing the electromagnetic effect on the sidebands.

III. Hydrodynamic and Electromagnetic Simulation

The method of swell-parameter extraction discussed here is a good hydrodynamic representation of the interactions between the Bragg waves and the swell. However, in complete second-order solutions for swell-parameter extraction [5], there is an electromagnetic component that alters the position of the second-order peaks in frequency and amplitude. The total coupling coefficient is the summation of both the electromagnetic and hydrodynamic components

$$\Gamma_T = \Gamma_{EM} + \Gamma_H. \tag{9}$$

A simulation model was developed to assess the relative contributions of two effects. The $R_{\rm swell}$ value was taken as the ratio of the first-order Bragg peak and the mean amplitude of the sidebands to reduce the contribution of asymmetry to the sidebands from the electromagnetic interaction. By taking the mean sideband amplitude, we remove the variations in sideband amplitude, and the extracted $R_{\rm swell}$ parameter from the spectrum conforms approximately to the hydrodynamic theory presented previously. The simulation allows for the definition of Pierson and Moskowitz [7] wind spectrum and added swell-wave parameters to produce the sidebands according to the solutions for the second-order spectrum. Fig. 5 shows the resulting simulated spectrum and the asymmetry present in the sidebands when the electromagnetic component is included in the calibration. The dashed line shows the reduction in asymmetry between the peaks when the spectrum is calculated with the electromagnetic component removed.

The simulation was carried out for a range of swell directional values between $\theta = 0°$ and 90° to show the changing sideband amplitudes with direction. The wind parameters in this simulation were fixed at a direction of 90°, wind speed of 5 m/s, and a spread of 40°. Fig. 6 shows the amplitudes for a pair of sidebands about the positive first-order Bragg line. The sideband amplitudes display the asymmetry and decrease to zero as θ approaches 90°, as predicted. The mean peak amplitude is shown by dots that separate the two peaks and these are equivalent to the values used to calculate the $R_{\rm swell}$ parameter above. The simulation was then run again, this time with the electromagnetic interaction removed and the asymmetry in the peak

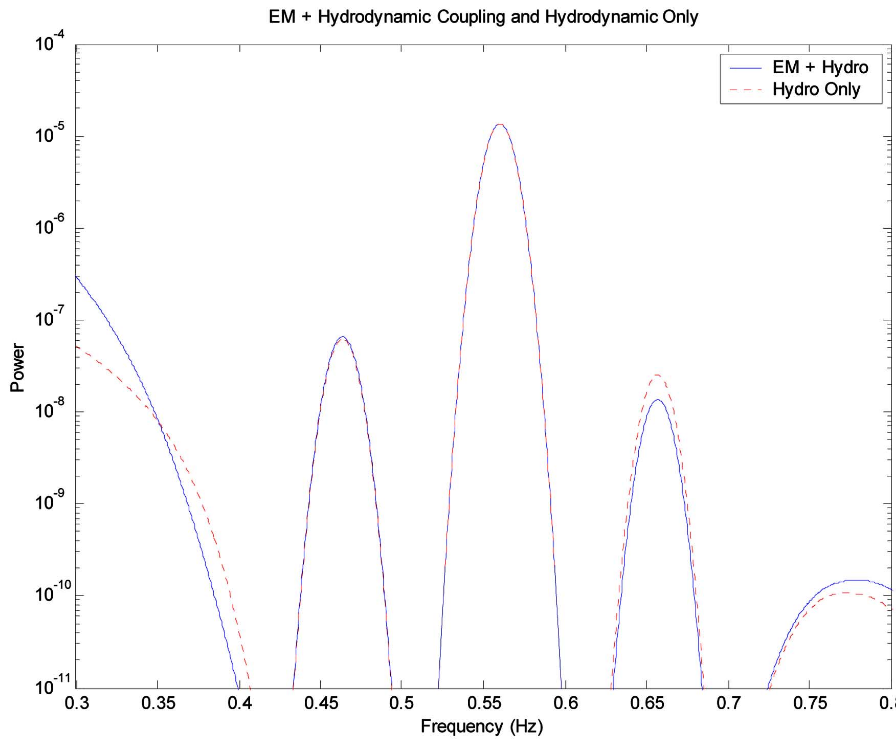

Fig. 5. Contribution of the electromagnetic component to sideband asymmetry. The dashed line shows the spectrum calculated using the hydrodynamic coupling only and there is a significant shift in the sideband powers to become more level. Wind wave parameters: wind speed = 5 m/s, spread = 40°, direction = 100°. Swell parameters: period = 12 s, direction = 70°, spread = 10°, and peak width =0.02 s.

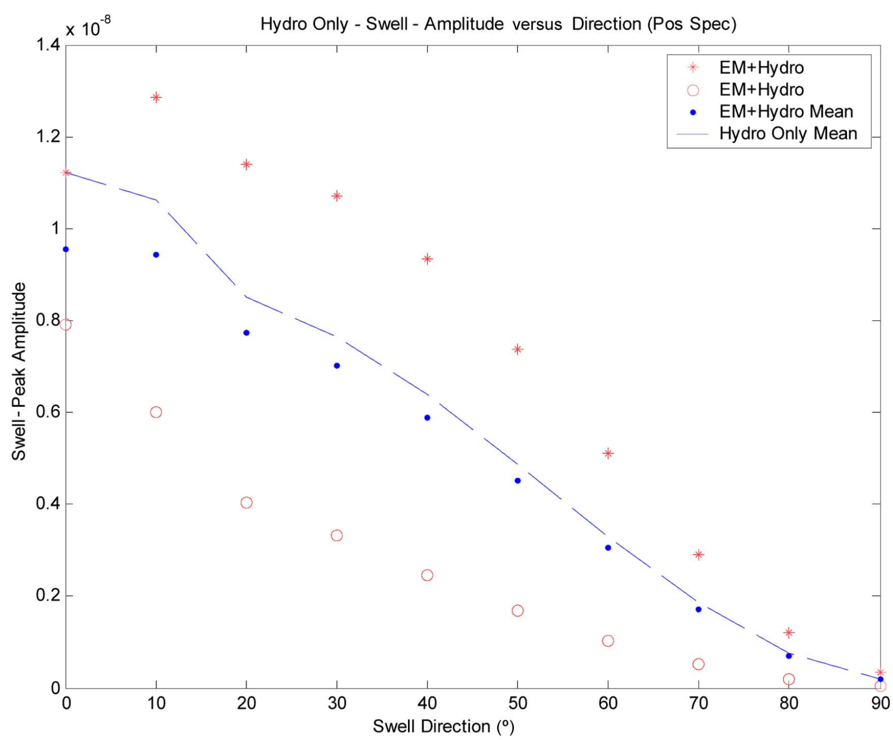

Fig. 6. Asymmetry due to the electromagnetic interaction is shown by the $*$ and $\circ$ which represent the two swell peaks surrounding the same Bragg peak. The mean swell peak is represented by the dots and the dashed line represents the swell-peak average without the electromagnetic component.

amplitudes was greatly reduced. The dashed line in Fig. 6 represents the mean peak amplitudes when only the hydrodynamic interaction is considered. The result shows a close agreement between the hydrodynamic case and the mean amplitudes taken with the electromagnetic interaction present. This tells us that we have effectively reduced the electromagnetic interaction to the extent that it is contributing very little to the extracted ratio, so that we are effectively measuring the hydrodynamic compo-

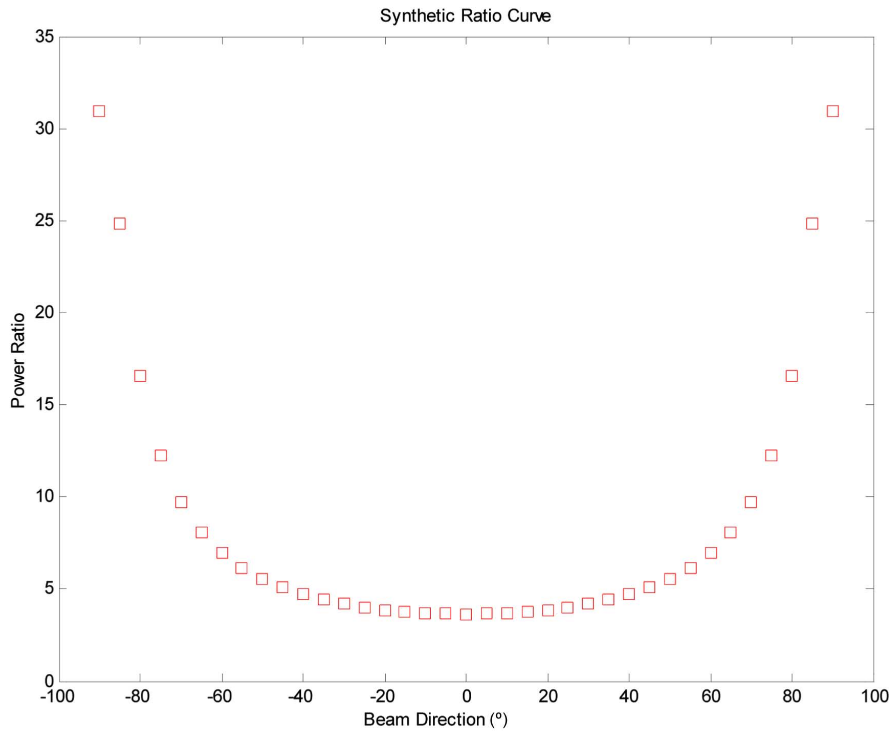

Fig. 7. R_{swell} values calculated between 0°–90° and mirrored about zero to produce an entire curve at an arbitrary amplitude.

nent that governs the behavior of the sidebands in the manner described by frequency modulation theory.

IV. Case Study

A sample set of data from a deployment of the COSRAD system at Tweed Heads, in 2001 is used here to show the method of swell-parameter extraction. Specifically, swell direction and amplitude are extracted from spectra averaged over a 2-h period on March, 5, 2001, as collected by the Tallebudgera COSRAD station. The directional wave buoy in the coverage zone measures the swell during this time as approximately 1 m in height. The Tallebudgera station has a boresight of 99° east. The COSRAD sweep extends 30° either side of this boresight and is divided into 17 sectors. Numerous spectra are incoherently averaged in space and time to improve the signal-to-noise ratio (SNR) in the second-order and this ultimately provides us with 16 R_{swell} values in a 2-h period to match the curve produced by modulation theory and shown in Fig. 7.

The calculation of the R_{swell} value relies on consistent identification of the sidebands. The algorithm examines the swell-wave portion of the Doppler spectrum in predefined frequency windows to identify the swell peaks. This window was determined by the upper and lower wave periods which define the swell-wave band, and it separated swell from sea. Kinsman [4] defines 10 s as an approximate boundary between sea and swell with considerable overlap. Therefore, to allow for short-period swell, a lower boundary of 8 s was chosen. Barrick [1] used an upper limit for swell period as 16 s. Again, a conservative upper limit of 18 s was used. At this stage, the algorithm identifies only the dominant swell peak present in the frequency window at any given time. There is potential to measure multiple swells with different wavelengths so long as there is a separation in the spectral peaks. In practice, this has proven to be a complex task to automate with a high-level reliability and remains a goal for future revisions of the algorithm to address.

The curve in Fig. 7 can be manipulated to fit the radar ratios in direction and amplitude almost independently. A tenth-order polynomial was fitted to the curve to facilitate the automated fitting process to the radar data. The directional fit to the radar data is done by first finding the gradient m_r, produced by the 16 R_{swell} values. The stylized curve is then differentiated and the position on the curve closest to m_r is found. The curve can then be moved so that the radar values are centered at this point. The swell direction is then found at the minimum point of the curve (when the radar beam is looking in the direction of swell propagation). The next stage is to fit the curve in amplitude, which is simply a matter of minimizing the vertical differences. This amplitude requires a calibration at one point, provided for this deployment by a directional wave buoy in the coverage zone. The resulting fit of the stylized curve to the radar data is shown in Fig. 8, giving us the swell direction and amplitude. The swell-amplitude and swell-direction adjustments are highly independent and can be fitted sequentially as described. In principle, we can iterate once more through the fitting procedure, but in practice we found this to be unnecessary.

Swell period is calculated independently from swell direction and amplitude by simply finding the frequency displacement of the second-order swell peaks from the Bragg peak they are associated with. The peaks surrounding the more dominant Bragg peak are considered more reliable due to the increase in separation from the noise floor. When both peaks surrounding the dominant Bragg line are available, the average frequency displacement is found to calculate the swell period. This method has proven to be extremely robust and accurate.

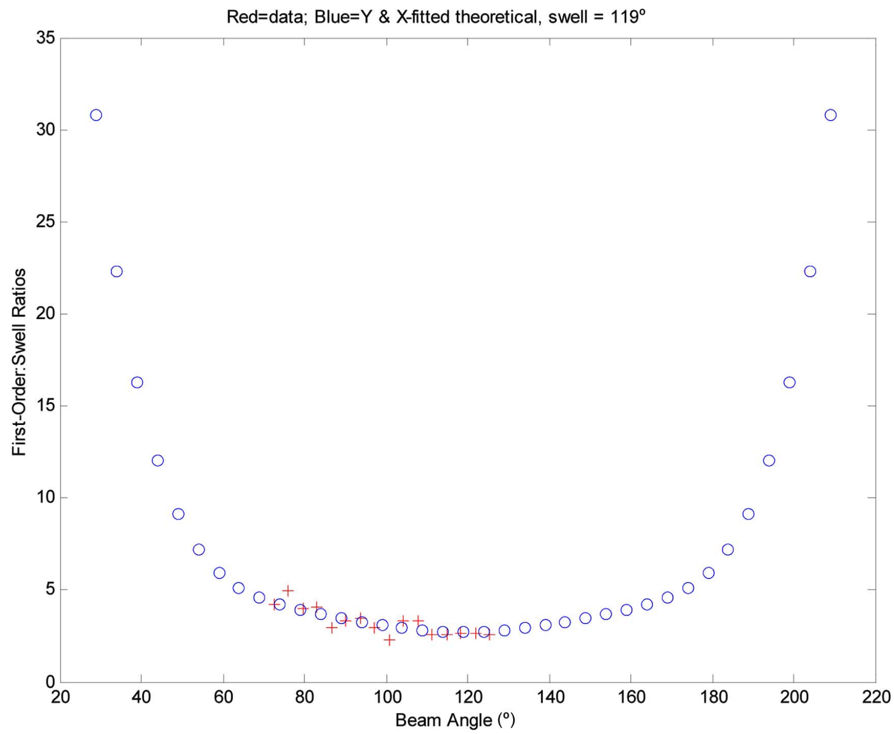

Fig. 8. Sample of fitted radar data (+) from Tallebudgera station, Tweed Heads, on March 5, 2001. The resulting swell direction is given by the position of the minimum of the theoretical curve. In this case, it is 120°.

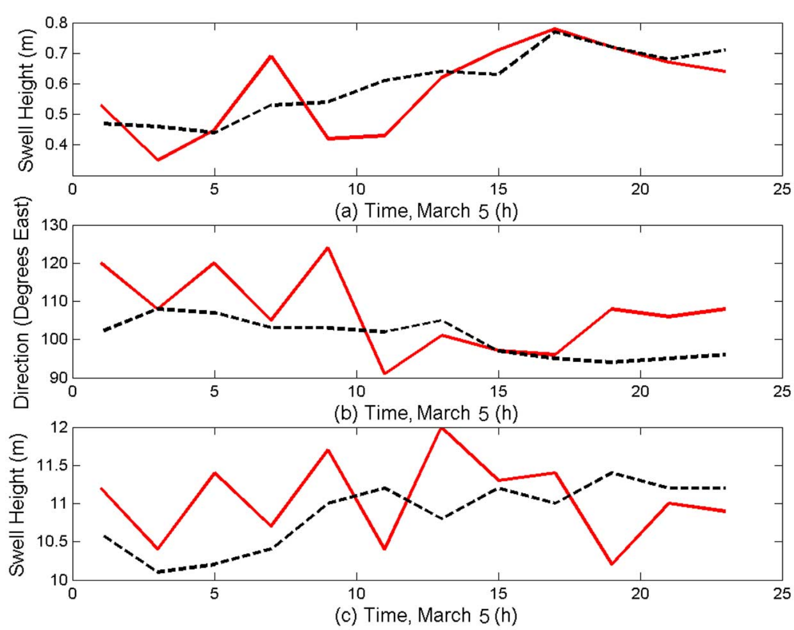

Fig. 9. Comparison of modulation results (solid line) and directional wave buoy measurements (dashed line) for March 5, 2001, at Tweed Heads. Comparison of (a) swell height, (b) swell direction, and (c) swell period.

The calculated swell direction, amplitude and period for March 5, 2001 are shown [Fig. 9(a)–(c), respectively] at 2-h intervals and validated by a directional waverider buoy located inside the coverage area. A distinct increase in swell amplitude during this period can be seen in the wave buoy measurements and this is also detected by the radar. Both measurements agree to within 0.1 m. Similarly, the gradually changing direction of the dominant swell at this time was detected by the algorithm and agrees with the wave buoy to within 10°.

V. Conclusion

The results of the case study presented using data collected during the deployment of the COSRAD system at Tweed Heads shows that dominant swell-wave direction, height, and period can be measured in the coastal waters using a method of frequency-modulated Bragg waves. This method is fast and capable of providing a reliable representation of swell-wave activity over a large area in near real-time. The swell information is provided in addition to surface current measurements and the radar configuration can remain unchanged. A system that is optimized for surface current measurement requires that the two radars are oriented orthogonally. The swell-extraction method presented here does not rely on simultaneous measurement from multiple radars to resolve directional parameters. Only one of the two stations is required to supply information that is collected at angles that are not perpendicular to the direction of swell propagation. When two radars are operating with this configuration, it is highly likely that at least one of them will be directed close to the direction of swell propagation. The particular station in the best position to provide swell information may vary as the swell direction varies.

This model provides a good approximation of the hydrodynamic interaction between swell and the resonant Bragg waves by minimizing the electromagnetic effect. In doing so, the small variations in the second-order sidebands are removed and information is extracted from theory relying on the hydrodynamic interaction only. In this manner, swell-wave parameters are measured in addition to COSRAD's present capabilities of routinely mapping surface currents, wind waves, and wind fields on the ocean surface.

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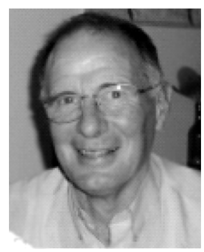

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