OCEAN SURFACE RADAR CURRENT MEASUREMENTS IN THE SURF BREAK ZONE AT COFFS HARBOUR

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Abstract: Ocean surface radars are being used routinely to map surface currents over tens of kilometres at resolutions typically around 3 km. At higher frequencies, in the VHF band, the Bragg wavelength for backscatter is reduced so that at 152.2 MHz the dominant scatter is from a wave with a wavelength just shorter than 1 m, compared with 5 m at 30 MHz. At this wavelength, the Bragg waves are heavily modulated by underlying wind waves and swell which produce significant broadening of the first-order Bragg peaks. The broadening of the peaks does not significantly impair our ability to locate the frequency of the peak and hence to derive surface current measurements. An upward-looking acoustic current profiler was used for inter-comparison with the surface currents measured by the radar. The deployment at Coffs Harbour was relatively short, but included calm conditions as well as a period of strong winds where the breaker zone extended well out from the shore. Although both the acoustic current meter measurements and the radar surface current data were affected by the presence of swell, it is clear that the VHF radar has potential to monitor rip currents and coastal vortices under surf break conditions when conventional techniques become limited.

Keywords: Ocean surface radar; surface currents; surf; rip currents; swell.

INTRODUCTION

The VHF coastal ocean surface radar (COSRAD) system has been developed at James Cook University in North Queensland and has been deployed on many occasions to map features in the surface current field on a spatial resolution grid of 100 m and over a spatial range of up to 1.5 km. This is a useful scale for evaluating the effects of coastal engineering works, and identifying rip currents and small scale eddies around obstacles like headlands and breakwaters.

Because the range cells are about 100 m long it is conceivable that whole pixels might be in the turbulent surf zone. The traditional theoretical basis for extracting surface currents from ocean surface radars rests on the principle of Bragg scatter of radar electromagnetic waves of wavelength λ from the surface gravity waves with wavelength $\lambda/2$ which are propagating radially away from and towards the radar station. The whole concept of Bragg scatter depends on a coherent spatial organisation of the scatterers, in this case successive wavelengths of the scattering wave. The question in focus in this work is about the coherence of the Bragg wavetrain in the surf zone. Also, one might expect incoherent scattering from sharp features and facets in the breaker line. The information from the VHF radar is obtained from the Doppler frequency spectra for the backscattered radar wave. A typical spectrum is shown in Figure 1.

Experiment set up at Coffs Harbour

The primary purpose of the deployment of the VHF COSRAD radar at Coffs Harbour was to provide planning data for a proposed new sewage outfall for the Coffs Harbour City Council off Boambee Beach. Two radar stations are required to get triangulation for direction as well as speed of the surface current in each pixel being examined on the sea surface. It is optimum to have the two radar beams orthogonal at the key point of interest on the sea surface because that is the condition for best accuracy in deriving the full vector from the two components. In this deployment we were able to put one station part way out on Corambirra Point and the second one at the back of the beach as shown in Figure 2. The lines indicate the sectors of ocean surface which are sequentially monitored by the radar beams, and the dots are points at which independent measurements of surface current can be made. The reference point for all maps shown here is the Corambirra radar station at 30^{O} 18' 50.8" S, 153^{O} 08' 36.5" E. The radar system was deployed between 04 Nov 1999 and 10 Nov 1999, and ADCP1 was deployed between 05 Nov 1999 and 05 Dec 1999.

ADCP1 on Figure 2 is the position of an upward-looking Nortek Acoustic Doppler Current Profiler which operated during the radar deployment. ADCP2 was occupied later and is not used in this paper.

THE VHF COSRAD SYSTEM

COSRAD uses very high-frequency (VHF: 152.2 MHz) ocean backscatter technology to map ocean surface currents and to infer sea-state and wind directions. This technology works by determining the Doppler shift of the backscattered radar wave. The incident radar wave is resonantly backscattered from ocean surface gravity waves whose wavelength is 1 m. This scattering produces two strong first-order peaks in the Doppler spectrum, which we call Bragg peaks, as shown in Figure 1. The first-order features of this spectrum are explained in terms of wave phase velocity of the Bragg wave, and bulk movement of surface water, which is the current. The total Doppler shift f_D can be written in terms of a component due to the wave phase velocity, f_B, of the Bragg wave, and a component, Δf (Heron et al., 1984).

$$f_D = f_B + \Delta f$$

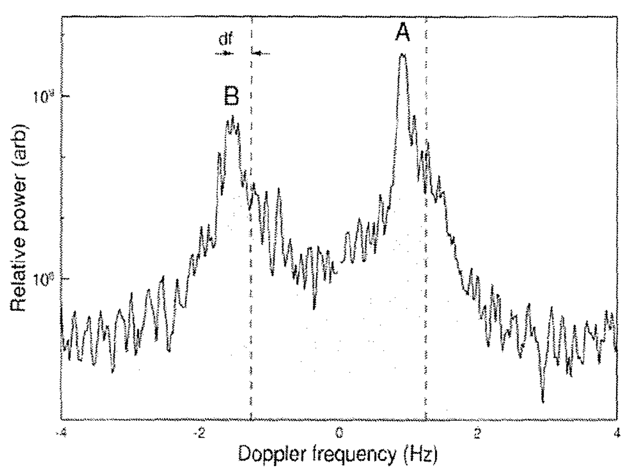


Figure 1. Typical spectrum for the VHF COSRAD radar.

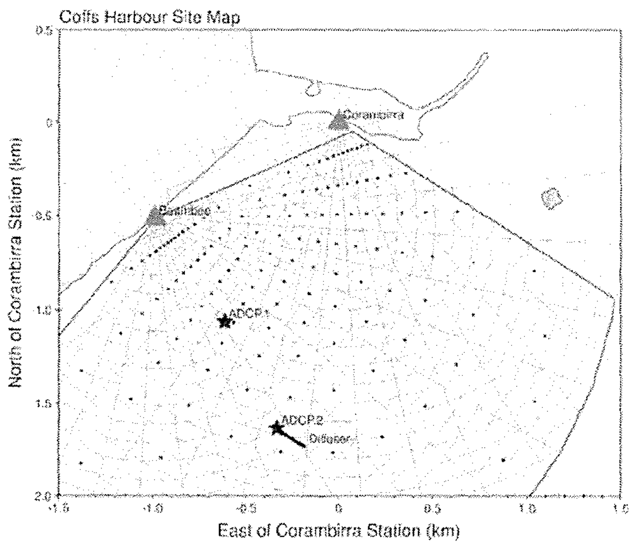


Figure 2. Configuration of the site at Boambee Beach.

$$f_D = \sqrt{\frac{g f_0}{\pi c}} - 2 f_0 \frac{v}{c} \tag{1}$$

where g is the acceleration due to gravity, c is the speed of electromagnetic waves, v is the magnitude of the surface current component parallel to the direction of the radar beam, and f_0 is the frequency of the radar.

The first-order Bragg theory summarised above would produce two narrow spectral lines. There have been some attempts to understand the line broadening at HF frequencies in terms of structure in the surface current field beneath the scale of the spatial resolution (Heron, 1985). However in the VHF band illustrated in Figure 1, it is more likely that the broadening is a modulation effect, with the Bragg line acting as the carrier in the radio engineering terminology. Barrick (1972) calculated the second-order spectrum for HF spectra. This generally has a clear separation between the narrow first-order spectral lines and a continuum with some spectral lines in the second-order part surrounding the Bragg lines. Some assumptions in this approach (which limit it to the second-order) mean that it is not valid for higher HF frequencies or high sea states.

What we are seeing in Figure 1 is a broadening of the first-order spectral line due to frequency modulation of the Bragg signal. Pursuing this modulated first-order approach, we would revert to equation (1) and expand the term for the bulk movement of the surface water at scales longer than that of the Bragg wavelength, which is approximately 1 m for the VHF COSRAD system. This would include surface surge velocities of waves near the peak of the gravity wave spectrum as well as those for swell. In the surf zone we would expect transient bursts of scattered energy from the breaking line parallel to the beach. As a first approach to this, we consider a two-scale wave field where one scale is the Bragg wave (scale ~1 m), and the other scale is a feature like a gravity wave at the peak of the spectrum (scale~50 m). Without prejudicing the argument we will set $v = 0$ to remove the surface current term. As the long wavelength wave propagation velocity is greater than that of the Bragg wave, the instantaneous surge velocities of the underlying wave will modulate the horizontal velocities of the Bragg waves. The velocity of a surface particle driven by the long wave is

$$v_p = a_p \omega_p \cos \omega_p t'$$

and following (1), the frequency of the echo is

$$f_D = \sqrt{\frac{g f_0}{\pi c}} - \frac{2 f_0}{c} v_p .$$

Then the echo signal becomes

$$\begin{aligned} E(t) &= a_B \cos 2\pi f_D t \\ &= a_B \cos \omega_B t \left\{ 1 + \sqrt{\frac{4\pi f_0}{gc}} a_P \omega_P \cos \omega_P t \right\} \\ &= a_B \cos \omega_B t \left(1 + m \cos \omega_P t \right). \end{aligned} \tag{2}$$

Where a_B is the amplitude of the echo from the Bragg wave, and m is a modulation index for the normal communications formulation given in equation (2).

For each modulating component ω_P the time domain expression in (2) corresponds to a set of Bessel functions in the frequency domain. For weak modulation (m small), the J_1 first side-band spectral lines dominate the frequency modulation spectrum, and the carrier remains strong. As m increases, the carrier (which is the Bragg line here) decreases and energy is increasingly passed out into the outer sidebands.

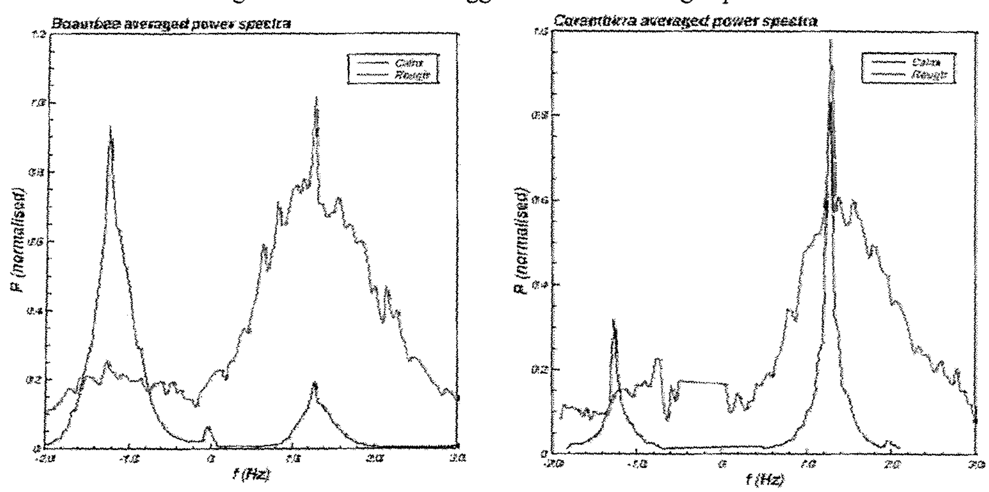
When there is a spectral continuum of ω_P values, the sidebands merge into a continuum and the result is a broadened first-order peak. The ω_P continuum under normal conditions for the VHF COSRAD system will relate to the peak of the wind-wave spectrum of gravity waves, and swell. In the surf zone $E(t)$ may be augmented by transient bursts of energy due to non-Bragg scatter from the line of breakers. This scattered radar signal will have Doppler shifts proportional to the forward velocity of the breaking wave fronts. Thus, the broadening of the first-order Bragg lines in the VHF radar spectrum is likely to be broadened by wind waves under normal (non-breaking) conditions, and may be enhanced by breakers.

In this project we are concerned with the line broadening, not so much for the broadening effect *per se*, but to evaluate any effect the line broadening may have on the location of the frequency of the centre of the first-order Bragg lines. We want to know whether we can extract surface current measurements when these wind wave and surf breaking conditions prevail.

LINE BROADENING

During the radar deployment the sea state off Boambee Beach varied from calm, when the surf zone was a narrow strip along the coast, to rough conditions when there were serious breaking waves with associated white water extending to about half a kilometre form the beach, and white caps beyond the breakers. The calm conditions prevailed with a southwards set on the current (the East Australian Current) and winds dominated by the sea breeze cycle. During rough conditions there was a strong southerly wind which produced a northwards set on the current near to the shore.

We separated the calm conditions from the rough conditions and established an intermediate category. For all calm conditions we removed the frequency offset due to surface currents from the spectra and superposed them to produce an average spectrum in order to look at the overall line broadening of the first-order Bragg lines. The average spectrum for calm



(a) **(b)**

Figure 3. Average spectrum for (a) Boambee Beach and (b) Corambirra Point stations under calm conditions (narrow peaks) and rough conditions (broad peaks).

conditions is shown in Figure 3 as the narrower of the two in each case (a) and (b). The corresponding average spectrum for rough conditions is shown with the broader peak.

It is clear from Figure 3 that the broadening of the first-order Bragg line expected under frequency modulation considerations is a significant effect for the VHF radar. It is also clear that the location of the peak may be degraded by the line-broadening, but it is certainly not removed. If the frequency modulation approach is valid then we might expect some limitation because ultimately, as the operating frequency increases above 152.2 MHz, or the modulating velocities are greater, the modulation index may increase to a point where the carrier energy (which is the first-order Bragg line) is reduce below that of the sidebands. This case is discussed by Heron (2002) in the context of microwave backscatter from the ocean.

The fact that the frequencies of the peaks in Figure 3 can be determined indicates that the Bragg wavetrain is sufficiently coherent to act as a tracer for the surface current measurements. The effects of the modulating longer waves are all pushed into the sidebands in the modulation process. Any transient bursts of energy are no doubt increasing the added wideband noise in the spectra. In spite of these effects which reduce the energy in the Bragg lines (by moving it into sidebands) and raise the noise floor (by transient incoherent pulses in the time domain), the data in Figure 3 indicate that surface current measurements retain integrity.

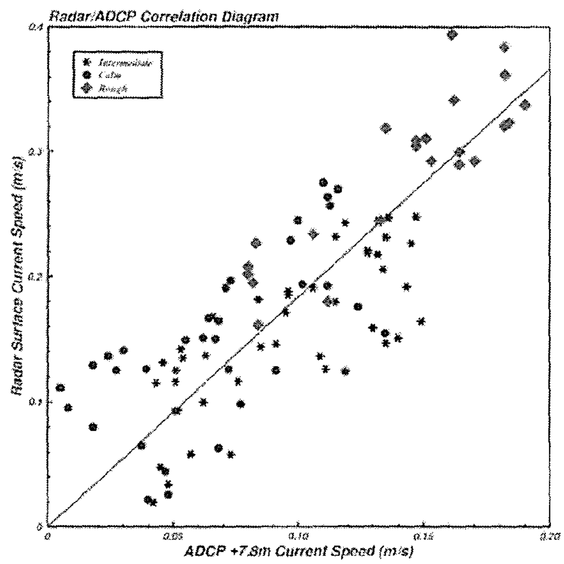
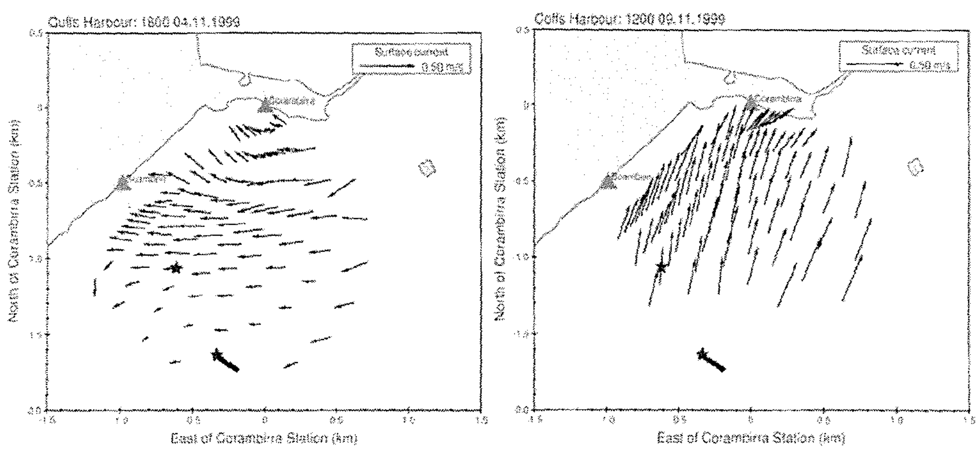


Figure 4. Regression between VHF radar surface currents and ADCP currents 7.8 m above the sea floor.

SURFACE CURRENTS

An independent analysis of the ADCP data was carried out to evaluate the effects of the surf zone on those measurements. We investigated the standard deviations of the ADCP measurements at each 2 m height range in the 14 m column. The standard deviations increased gradually up to about 8 m above the bottom and then increased rapidly towards the surface. We chose the bin at 7.8 m (± 1 m) to carry out comparisons with the VHF radar current measurements at the surface. The comparison for the radar pixels around the site of ADCP1, and the ADCP currents from the 7.8 m bin are shown on a scatter plot in Figure 4. The regression line has a slope of 1.84 with a correlation of 0.82. At the ADCP bin centred on 5.8 m, the corresponding slope is 2.17, with a correlation of 0.82. This indicates a shear in the velocity across the water column. The data points are coded according to the conditions being calm, intermediate or rough. Most of the currents under calm conditions are at the low end of the scatter plot. Under rough conditions the currents are dominated by the wind-driven component and are at the high end of the scatter plot. Note that the spread of data points is about the same under calm and rough conditions. This suggests that the surface current measurements are not significantly degraded by the rough conditions.

During the deployment of the VHF radar, maps of surface currents were produced hourly so that we would have an archive for a range of conditions. Typical surface current maps are shown in Figure 5. Figure 5(a) was selected from times of calm conditions. There is a southwards set on the current offshore, driven by the East Australian Current, and modified by the bathymetry and shape of the coastline. In Figure 5(a) the recirculation on the south side of Corambirra Point is clear, with a point of separation in the flow about 100 – 200 m north of the Boambee Beach radar station. Vorticity is injected into the flow at the headland, but the return flow close to the beach is driven by wind and wave energy. Maps like this provided powerful planning data for the siting of the sewerage outfalls off Boambee Beach.



(a) **(b)**

Figure 5. Surface current maps under (a) calm, and (b) rough conditions.

The surf at 1800 AEST on 4 Nov 1999 (Figure 5(a)) was very flat with the white breaking zone extending about 200 m from the shore and consisting of disorganised short waves. The radar map shows the main linear feature extending perpendicular to the beach, and is consistent through the surf zone. There is no feature parallel to the beach which might suggest a systematic effect of the surf zone.

Figure 5(b) is a surface current map selected from the times of rough conditions. The wind here is northwards at about 15 knots, produced by a low pressure in the Tasman Sea to the south. The surf breaking zone extends to about 400 – 500 m offshore and beyond that there were extensive white caps from deep water breaking waves. It was an energetic coastal sea. The surface current map shows a strong northwards flow in the surface current. This is a wind driven flow, and the vertical mixing is sufficiently dominant that the whole vertical column at the location of ADCP1 is moving northwards. There is no sign of abatement in the northwards surface flow velocity even at the furthest extent of the measurements, even though the influence of the southwards East Australian Current still exists and must dominate at depth past the edge of the continental shelf.

Under these rough conditions we do not see the linear feature perpendicular to the beach. The map is remarkable for its uniformity. For the hypothesis of this study, it is pertinent to note that there are no linear features parallel to the beach at a distance of 300 – 400 m offshore in the surf breaking zone.

CONCLUSIONS

The deployment of the VHF COSRAD ocean surface radar at Coffs Harbour covered conditions from calm, with a small surf zone, to southerly buster conditions with an energetic surf zone. Comparison of the radar-produced surface currents with those from an acoustic current profiler Indicates a consistency between the techniques at that single point location. A self-consistency features, but there was no correspondence between features on the maps and the location of the (linear) surf breaking zone.

The VHF radar spectra show a broadening of the first-order lines unlike the second-order structure in the theoretical approach by Barrick (1972), because the conditions here are well outside the limits of the second-order assumptions. The approach which treats the line broadening as frequency modulation of the Bragg peaks may be a useful basis for understanding these line broadening effects for VHF ocean backscatter. The frequency modulation approach treats the transient pulse of any specular reflection from a surf breaker front as a wide band of noise spread across the whole spectrum. This is consistent with the result that we are able to identify the Bragg peak and determine its frequency even under these rough conditions.

The VHF COSRAD system for mapping sea surface currents retains its integrity under surf zone conditions. It is a powerful technique for mapping rip currents on beaches and storm currents in the coastal zone.

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