Chapter1: Introduction, Aims and Objectives

1.1 Introduction

Recent advances in remote sensing technology have led to expanding applications in environmental monitoring, particularly in the near shore coastal zone. These advances include the use of High-Frequency (HF – generally includes frequencies between 3 and 30 MHz) radar in many areas of the remote sensing field. The HF radar technology can now be used for purposes as varied as homeland security to environmental coastal protection. The use of long range HF radar for defence purposes dates back to the Second World War however its role today is far more diverse. It is used to combat smuggling, drug trafficking, track illegal fishing vessels and to coordinate search and rescue operations, (Sevgi et al., 2001). When these systems are operational they encounter interference from various environmental and anthropogenic sources. The main environmental source is commonly termed ocean "clutter". For many applications this ocean clutter is discarded in search of a better signal to noise ratio, however, for oceanographers this ocean clutter can provide information on the state of the ocean surface. Current environmental applications of HF radar are mainly found in the areas of coastal management but occasionally find uses in the fisheries industry and tracing the progress of surface borne pollutants (Barrick, 1977). These kinds of functions are becoming more common as awareness and confidence in the technology increases. For a country like Australia which possesses the longest coastline of any country and has all of its major cities located on the coast, a tool such as HF radar can be very valuable.

An oceanographic interest in HF radar technology originated when Crombie, (1955), observed a structure to this background noise, or clutter, that he correctly related to ocean surface waves. He noticed the relationship between the transmitted electromagnetic wave and the ocean surface could be exploited to remotely provide information on sea state. HF radar systems have the capability of collecting data over a large area and therefore provide a much higher data density than can be achieved by using moored current meters and directional wave buoys. Since Crombie made his discovery, HF radar has been used to map short wavelength ocean waves and

amplitudes, with applications in coastal management and ship guidance. However, oceanographers are increasingly interested in long period ocean waves that have a greater impact on shipping and contribute to the impact of the ocean on the coastline. Long period ocean waves such as swell can increase the risks involved with the entry of large ocean going vessels into certain harbours and are also a concern when the ship is moored in port (van der Molen *et al.*, 2003). Possible links between swell waves and the generation of infra gravity waves which can prove devastating to ports and coastlines make their monitoring even more desirable (Oltman-Shay and Hathaway, 1989).

As radar technology developed the higher order interaction between the transmitted electromagnetic wave and the longer period ocean waves became accessible to analysis. Barrick (1971) derived a theorem to describe this interaction and proved that it is, in fact, produced by second order wave-wave interaction. Given this theory, oceanographers became enthusiastic about using HF radar to measure sea state. However, Hasselmann (1971) showed that although Barrick's theorem would provide estimates of dominant wave period and height, it would not yield any directional information from the second-order spectrum. This proved to be a complex problem and forced many oceanographers to resign themselves to the fact that the only directionality being extracted from an HF Doppler spectrum would be for shorter wavelengths. Lipa and Barrick (1977, 1986) examined the second-order spectrum closely and found a link between the position of the resonant swell peaks and the dominant direction of the swell waves. This model for the extraction of parameters from the long period wave spectrum remains unvalidated.

1.2 Aims and Objectives

This project is aimed primarily at developing a model for swell extraction using two large, independent data sets. The data was collected during February and March, 2001, from Tweed Heads and the Bass Strait during July, using the HF COSRAD system (Coastal Ocean Surface Radar) developed at James Cook University. Firstly an adaptation of the solutions for second-order extraction of swell waves from Lipa and Barrick (1977) will be developed for use with data collected by the COSRAD system.

Once a robust routine algorithm for the extraction of swell parameters has been developed, it will be integrated with COSRAD's current capabilities of measuring surface currents and significant wave heights (wind-wave heights). The system has the potential in the future to provide estimates of sediment resuspension and transport becoming an important tool for remotely sensing the ocean surface in the near-shore zone. Given an energetic environment and assuming a well-mixed water column, the surface currents can be extrapolated to the sea floor using a logarithmic function. This is where the main contribution for sediment resuspension occurs. Swell data and significant wave heights also contribute to benthic water velocities and can be extrapolated to the sea floor in a similar fashion. Given all these parameters and their interaction with sediment, estimates can be made as to the degree of resuspension occurring.

The measurement of wind fields are another area that lends itself to monitoring by HF radar. Short period waves, which are measured as first-order interaction using HF radar, quickly align themselves with the wind direction. Measurement of wind direction has also been theoretically established by Heron and Rose (1986). The method used in that study relies on the analysis of the first-order peaks for calculating the wind direction and the wind-wave peaks for the calculation of the wind speed. The development of a routine algorithm for its extraction would provide a valuable extension to the COSRAD Radar system.

To summarize the aims of this thesis:

- Collect two independent sets of data from deployments of James Cook University's HF radar system COSRAD. The deployments are to be conducted at Tweed Heads, and Bass Straight,
- 2. Develop a spectral processing routine specifically to aid in the extraction of swell wave parameters,
- Attempt to adapt mathematical solutions proposed by Barrick (1972b) and Lipa and Barrick (1980) for the calculation of swell direction, height and period from HF radar spectra,

- 4. If necessary, develop an alternative method for the extraction of swell wave parameters,
- 5. Present swell wave parameters as measured by the algorithm during the Tweed Heads and Bass Strait deployments and validate using data from directional wave buoys present at each location.
- 6. Other improvements to the COSRAD system such as resolving wind field measurements.

On completion of this project the COSRAD system will be able to extract surface currents, significant wave heights, wind direction, as well as swell period, direction and amplitude. Such a complete set of data on such a large scale would be extremely valuable for use in a variety of coastal situations. Engineering projects, environmental monitoring and marine biological studies are just a few examples of possible applications.

Chapter 2: Radio Oceanography – Theory and Previous Work

This thesis is concerned with remote monitoring of the sea surface with particular interest in advancements in measuring sea state. It is important to define sea state and a variety of oceanographic nomenclature prior to further discussion. Firstly, it is best to determine what portion of the ocean wave spectrum with which we are concerned. Ocean surface waves are classified in to numerous categories, most commonly, by the frequency (the inverse of a wave's period) of the wave. The largest category is that of wind generated gravity waves which spans wave periods between 1 and 30 seconds (Kinsman, 1965). Gravity waves are a group containing all waves that are measurable using HF radio techniques. HF is commonly defined as transmitted wavelengths between 10 and 100 m which targets ocean surface waves between 5 and 50 m in length. This relationship will be described later. As defined by Phillips (1977), the term gravity wave refers to all waves whose chief restoring force is that of gravity. This is the case for all waves with a wavelength greater than 1.7 cm; below this the main restoring force is that of surface tension and these waves are classified as capillary waves. The most important of these, for the measurement of sea state, are swell waves. Kinsman divides gravity waves in to two groups, sea and swell. Sea, describes waves that are being worked on by the wind that raised them and swell describes waves that have escaped the influence of the generating wind. Separating the sea and swell by their period results in some overlap. Importantly all wave conditions discussed throughout this are assumed to be deep-water waves. This infers that the ocean floor has no effect on the propagation of the wave. This is considered to be true when the water depth is greater than half the length of the observed wave. Therefore, all waves discussed here to describe sea state are deep-water gravity waves.

2.1 Evolution of HF Radar

Advancements in radio technology during the Second World War provided the instrumentation necessary to discover an interaction of radio waves, at high-frequency

(HF), with the ocean surface. The radar system was being used at the time as an early warning for approaching enemy aircraft and was most commonly positioned on the coastline looking out to sea. Before long it was noticed that the ocean surface was scattering the incident radio signal often masking the target being tracked. The importance of the system as a defensive tool was greatly appreciated and therefore this decreased functionality was a considerable concern. However, the relationship between the ocean surface and the scattered electromagnetic waves was not sufficiently understood until well after the war had ended. Crombie (1955) made the discovery that began the new field of radio oceanography. In the ensuing decades, radio oceanography developed rapidly to a point where today certain aspects of the sea surface are monitored routinely by HF radar systems worldwide.

To make his discovery Crombie examined a Doppler spectrum of the backscattered sea echo with the intention of focussing on the background echo, or "clutter", rather than processing the spectrum with the aim of enhancing a particular target's intensity. By doing this Crombie observed that the received Doppler spectrum consisted of two discrete spectral peaks situated at an equal distance above and below the radar carrier frequency (Figure 1). He related this to two discrete targets that must be moving with a constant velocity, of which the radial component could be calculated using the Doppler equation,

$$v_r = \frac{I\Delta f}{2} \tag{1}$$

where λ is the radar wavelength. With this piece of information Crombie then inferred these two signals could be the result of ocean waves with components moving radially towards and away from the radar. It is known from the gravity-wave dispersion relation,

$$v = \sqrt{\frac{g}{2p}}L\tag{2}$$

This shows that sea waves of a given wavelength, L, will move at a certain velocity, v, where g is the acceleration due to gravity. Given this relationship, it was then possible to calculate the ocean wavelength, L, which was the target producing these two spikes in the spectrum. This calculation gave a value for L of exactly half that of the transmitted electromagnetic wavelength. Crombie considered that the sea waves act as a

diffraction grating, i.e. a large signal is received when radio waves, of wavelength I_o , reflect off sea waves with wavelength I_w , where

$$\boldsymbol{I}_{w} = \frac{\boldsymbol{I}_{o}}{2\cos(\boldsymbol{q})} \tag{3}$$

and q is the grazing angle of the incident beam on the sea surface. The angle, q, is usually considered to be zero as the radar is at or is very close to sea level. Hence, this simplifies to $I_w = I_o/2$. This resonance phenomenon is recognised in other physical situations as "Bragg scatter" and was discovered by W. L. Bragg in 1912. This theory relies on the fact that there are sea waves of this particular length present in the ocean spectrum at all times. However, this is not an issue because the Fourier decomposition of any random area of the sea surface will contain wave energy at or near the required wavelength to support Bragg scatter.

The first-order peaks, Bragg peaks, in the spectrum are easily identifiable, as shown in Figure 1, and provide the necessary connection between the ocean surface and the transmitted radio wave to form the basis for remotely sensing sea state. The spectrum in Figure 1 was recovered by the COSRAD system. The Bragg peaks are located at a frequency of ± 0.56 Hz determined by the operating frequency of the radar being at 30 MHz. This spectrum represents a single pixel in the sweep, not an average, and still the first-order peaks are clear.

Experimental evidence supporting Crombie's discovery appeared over following years, with the next breakthrough being made in 1966, (Wait, 1966) when it was shown that the intensity of the backscattered signal produced by the resonant ocean waves is related to the height of the wave-train. This discovery encouraged other oceanographers to dedicate time to this area of research, as it was now beginning to remotely provide valuable physical information on the sea surface and further advances in this area looked promising. At this stage it was only possible to examine the short wavelengths due to the radar transmission frequencies that were being used. At HF, between 3-30 MHz, the radar wavelengths interact with resonant Bragg waves of the order of 50 m to 5 m long. These waves are considered short in terms of measuring sea-state. In order to measure long wavelengths by first-order interaction, the radar would be required to

transmit at medium frequency (MF). Transmission at such frequencies requires long antennae arrays to generate such long wavelengths and also, frequencies in this range of the spectrum are widely used for other purposes and therefore anthropogenic interference is common.



Figure 1: Typical HF Doppler spectrum displaying the two discrete first-order Bragg peaks at ± 0.56 Hz. Spectral processing is required to distinguish the second-order features.

Therefore, at this time in the development of radio oceanography, scientists had to be content with the extraction of short wave information, such as surface currents (Stewart and Joy, 1974).

Calculating surface current velocities requires the calculation of the total Doppler shift f_D . The total Doppler shift is comprised of the Doppler shift due to the phase velocity

of the Bragg wave, f_{B} , and Δf which is the shift due to the bulk movement of surface water,

$$f_D = \pm f_B + \Delta f \tag{4}$$

Where

$$f_B = \pm \sqrt{\frac{gf_o}{pc}}$$
(5)

and

$$\Delta f = -2f_0 \frac{v}{c} \tag{6}$$

 f_0 being the radar frequency, c is the speed of light and v is the magnitude of the surface current component parallel to the direction of the radar beam. The Doppler shift due to surface currents, Δf , can be found from the departure of the Bragg peaks from the Bragg frequency, f_B . Δf can be positive or negative in a particular spectrum depending upon the direction of shift in relation to f_B , to the left or right. This in turn allows for positive or negative values of v, which represent waves moving towards or away from the radar. In equation 6 the negative sign shows that we label components moving away from the radar as being positive. To resolve directionality of the surface currents and their true velocity, two radar stations are required to operate simultaneously with approximately orthogonally intersecting beams.

This alone was a great discovery and asset to the field of oceanographic remote sensing however, being constrained to the analysis of short ocean waves saw a brief lull in development in the field. The analysis of long ocean waves is crucial if the purpose of the radar system is to measure sea-state. The shipping industry requires a reliable description of the sea-state in order to regulate the safety of its vessels, particularly in a coastal environment. Barnum (1971) sparked another flurry of developments when he realised that the noise floor in the spectrum surrounding the first-order was much higher than expected from atmospheric interference or system-generated noise (Barrick 1972b). He confirmed this by simply examining the system noise spectrum independently of the ocean scatter and also comparing the ocean spectrum to scatter from the land. This idea was taken further by Hasselmann (1971) who suggested that this continuum surrounding the first-order spectrum was due to a second-order interaction with the ocean and a possible measure of sea-state. However, it was Barrick (1972a, b) that discovered the continuum surrounding the first-order spectrum varies in shape and amplitude with sea-state and radar frequency. Therefore by examining the second-order peaks in the spectrum, their strength and relative positions, information on sea-state can be extracted. The explanation for this higher-order interaction lies in the extrapolation of electromagnetic and hydrodynamic equations to reveal second-order terms. The second-order term resulting from the electromagnetic interaction is shown below:

$$\Gamma_{EM} = \frac{1}{2} \left[\frac{\left(\tilde{k} \cdot \tilde{k}_o \right) \left(\tilde{k}' \cdot \tilde{k}_o \right) / k_o^2 - 2\tilde{k} \cdot \tilde{k}'}{\left(\tilde{k} \cdot \tilde{k}' \right)^{1/2} + k_o \Delta} \right]$$
(7)

where k_0 is the radar wave number, k' is the short wavelength wind wave number and k is the swell wave number. These wave numbers adhere to the relationship: $k + k' = -2k_0$. Δ is the normalised impedance of the sea surface (Barrick, 1971). The hydrodynamic contribution to the second order spectrum is:

$$\Gamma_{H} = -\frac{i}{2} \left[k + k' - \frac{\left(kk' - \tilde{k} \cdot \tilde{k}'\right)}{mm' \left(kk'\right)^{1/2}} \left(\frac{\mathbf{w}^{2} + \mathbf{w}_{B}^{2}}{\mathbf{w}^{2} - \mathbf{w}_{B}^{2}}\right) \right]$$
(8)

where $i = \sqrt{-1}$, $m, m' = \pm 1$ represents the four combinations of second-order peaks surrounding the first-order Bragg lines. **w** is the second-order peak frequency and $\omega_{\rm B}$ is the Bragg frequency. The summation of the contributions due to electromagnetic and hydrodynamic effects forms a coupling coefficient

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

that is sensitive to second-order wave directionality.

Even though Barrick (1972b) was able to derive this relationship and support Hasselmann's theory that sea state could be deduced from HF sea scatter by the strength and position of second-order peaks, he could not provide confirmation due to the lack of quality measurements available at the time. This would quickly change as technology was soon able to provide high quality sea-echo backscatter spectra and this relationship was proven experimentally.

Since it had been shown that longer waves could indeed be identified by HF radar, it was necessary to develop ways to extract the parameters of these waves, such as, wave height, period and direction of propagation. Hasselmann (1971) provided the means to extract period and wave height but also concluded that it would render the spectrum insensitive to directional information. This remained the case for several years until Lipa (1978) was able to extract wind wave directions from the second-order echo. It was shown that the second-order peaks vary in position and in amplitude with changing direction. The amplitudes are dependant on the coupling coefficient which is known to vary with direction. With this solution to the directional problem now in hand, it was possible to develop a series of expressions to describe sea state from HF radar sea echoes.

HF radar as a reliable remote monitoring tool is gaining acceptance throughout the oceanographic community as repeated validation with conventional measurement devices occurs (Prandle and Wyatt, 1999). HF surface current measurements have reached the level of acceptance that many in the field are trying to achieve with wave measurements.

2.2 HF Radar – Technical Information

HF radars have now been used for many decades to monitor the ocean surface and with continuing technological advancements in design and computational processing they are becoming even more popular. There are two forms of radar transmission that are commonly employed for oceanographic purposes. These are known as skywave or ground-wave propagation. Skywave systems reflect the transmitted beam off the ionosphere in order to achieve large propagation ranges. Ground-wave propagation on the other hand is closely coupled to the sea surface in an attempt to minimise complicated ionospheric effects on the sea surface echo. Ground-wave propagation is maintained by polarising the electromagnetic wave in the vertical direction so that it follows the contours of the air-sea interface however, this mode of propagation severely reduces the working range of the radar (Heron *et al.*, 1985). This outline will

concentrate on ground-wave propagation properties; however, many of them are still applicable to some degree to skywave systems.

2.2.1 Ground-Wave Attenuation

The working range of a radar system is dependant on various aspects, both environmental and anthropogenic. The transmitted electromagnetic wave is attenuated in its advancement to the target and again during its return to the receiver. An increase in the range from the radar to the target results in a decrease in the signal-to-noise ratio. The strength of the returned signal is dependant upon the scattering strength of the target, atmospheric noise and noise due to radio interference in the working frequency band (Gurgel *et al.*, 1999). With ground-wave propagation, sea surface conditions are as important a factor as atmospheric conditions. Attenuation over the sea surface is reliant upon the transmitted frequency and conductivity of the sea, where conductivity is a function of water temperature and salinity. High salinity levels allow greater ranges to be achieved at lower power levels.

Scattering strength is an important factor in the attenuation of the ground-wave but is not as straight forward a relationship as first thought. It sounds reasonable to assume that higher sea states would provide higher scattering strengths and this is the case at relatively close range. Stronger signals are received during times of large wave heights, however, it does not continue at intermediate ranges due to the higher losses incurred by the high level of scattering, out to the long ranges and back again (Barrick. 1971, Gurgel *et al.*, 1999).

2.2.2 Spatial Resolution

Spatial resolution consists of two dimensions, range and azimuth. Range resolution is dependant upon the transmit frequency and the method of transmission. The two main methods of transmission are by short pulses or by frequency modulated chirps (FMCW). Of course range resolution at VHF is very high but this also decreases the working range of the radar and thus a compromise must be reached. Towards the high end of the HF band working range is reasonable and radio interference can be overcome

by using a very narrow bandwidth for transmission. This, however, will decrease the range resolution of the system. The main advantage of using a pulse system is the simplified design required to run it. The FMCW method allows more flexibility in the alteration of transmission frequency and range resolution (Gurgel *et al.*, 1999).

Direction finding and beam forming are the main methods used for azimuthal resolution. The design of an array of antennas works by each antenna collecting the scattered sea echo from differing azimuthal directions. Each of these received traces is then superimposed to provide one complete signal with embedded directional information. The main advantage for systems employing direction finding is the small array sizes required. It compares the amplitudes and phases of the received signals from each antenna in order to determine the direction they were arriving from on a polar grid relative to the antenna. However, this method can only be used for first-order signals as the second-order is masked by these higher power returns. This method also is susceptible to problems if the assumption that the current field is homogeneous does not apply. The direction finding method will fail to recognise when the same Doppler shift has sources in different directions. The beam forming method doesn't rely on assumptions such as this but does require large antenna arrays in order to provide directional information. Beam forming employs the formation of a narrow beam that can be electronically steered over the required area of the sea surface. They generally can be steered up to a maximum of 45 degrees on either side of the bore sight. The antenna array is normally up to 8λ in length, where λ is the electromagnetic wavelength. Optimal spacing between each antenna is $\lambda/2$. This system is also sensitive to secondorder sea echo directional information (Heron, 2005).

2.3 Data Collection and COSRAD Specifications

The James Cook University developed Coastal Ocean Surface Radar (COSRAD) was deployed on two occasions throughout 2001 as part of this project. On both occasions the radar was in situ for a period of one month, collecting data 24 hours a day. The first deployment began in late February with two COSRAD stations covering a portion of the sea surface off the coast of Tweed Heads. The second deployment of the system was during July, recording data of sea surface conditions at the entrance to Port Phillip Bay in Victoria. The setup of the radar at both stations during a single deployment is exactly the same apart from the look directions. Positioning of the radar is constrained by availability of suitable space to accommodate the antenna array with an uninterrupted view of the ocean. Other settings can be assigned to the system to suit the intended aims of the project. A typical set up of a COSRAD station transmits at a frequency of 30 MHz, (f), that essentially determines the length of the transmitted electromagnetic wave by $\mathbf{l} = c/f$ and therefore the length of the resonant ocean wave, which is defined as $\lambda/2$ by Crombie (1955), where λ is the transmitted wavelength and c is the speed of light. Therefore for this COSRAD setup the transmitted wavelength is 10 m and the resonant ocean wavelength is 5 m. The antenna array consists of 8 elements, spaced half a transmitted wavelength apart. Therefore the complete array occupies an area of approximately 45 x 2.5 m². The 8 elements form a beam of width,

$$\Delta \boldsymbol{q} \approx \arcsin\left[1/(2N_A)\right] \tag{10}$$

where N_A is the number of elements in the array. This gives a beam width of about 7 degrees which is electronically steered to 17 different angular positions about the bore sight. It is important to note here that the 8 element antenna array used for both transmit and receive produces an effective beam width comparable to that of a wide angle transmit antenna and a 16 element receive antenna array which has the advantage of reducing the installation space requirements. However, with this configuration it is no possible to measure the backscatter spectra from all directions simultaneously. The azimuthal extent of coverage of each COSRAD station is approximately ±30 degrees about the bore sight. Data is usually collected from 12 different ranges in each of the 17 sectors completing an entire sweep within 30 minutes. To meet these specifications the integration time for each pixel is set at 102.4 seconds. Noise levels are too high to retain workable spectra beyond this. The range resolution is determined by the width

of the transmitted radio-frequency pulse. A common antenna array is used to transmit and receive the frequency signal and therefore the width of the transmitted pulse becomes important. The signal is received by switching the array to receive during the quiet time to detect any scattered signals from the ocean surface. The range resolution for COSRAD during both deployments was set to 3 km using

$$\Delta r = \frac{1}{2}c\Delta t \tag{11}$$

to determine the pulse width, Δt . The maximum range of the system, R_{max} , is a function of the time between pulses, T_p , and the pulse width, Δt , related by

$$R_{\rm max} = \Delta r T_P / \Delta t \tag{12}$$

This maximum theoretical range is effectively shortened in practice by numerous factors including interference from land, the sensitivity of the receiver and the resulting signal to noise ratio.

2.3.1 The Tweed Heads Deployment

As mentioned above the first deployment was to monitor coastal ocean surface conditions off the coast of Tweed Heads for a period of one month. The deployment commenced on the 12th of February and concluded on the 15th of March. During this period the radar was in continuous operation, observing a variety of weather conditions including some storm activity and heavy rain. Figure 2 shows the two COSRAD stations located at Kingscliff (28°15.526' S, 153°34.923' E), to the south of the entrance to the Tweed River, and Tallebudgera (28°06.007' S, 153°27.661' E) to the north. The sites were selected for their coverage of a directional wave buoy run by the Queensland Beach Protection Authority (QBPA), the probability of observing strong swell conditions in the area during this time of year and interest in sediment transportation by means of surface currents and wave action in the vicinity of the Tweed River.



Figure 2: Map showing the main features of the study area. Relative locations of the radar sites at Kingscliff and Tallebudgera are shown. The directional wave buoy is also marked (star). The rectangle encloses the Tweed River Entrance Sand Bypassing Project shown in more detail in Figure 3. The dashed line shows a portion of the radar coverage zone.

The selection of the Tweed Heads region as an area of interest was not only due to the likelihood of strong swell conditions at this time but also to a recent agreement between New South Wales and Queensland state governments to undertake a joint project to employ and maintain a permanent sand bypass system at the entrance to the Tweed River. The aims for the project included an improved navigable entrance to the Tweed River and to supply a continuous volume of sand to beaches on the northern side of the river (Dyson et al., 2001). The entrance bar has historically been troublesome for ocean going craft to navigate due to a net northerly littoral flow of sand that fills the entrance. To combat this occurrence breakwaters were installed in the 1960s with considerable success. However in recent years the build up of sand on the southern wall became extreme and the entrance bar reformed. The sand trapped along this southern breakwater would have naturally supplied the beaches to the north

however with this in place these beaches experienced considerable depletion and erosion. It is these beaches that will be supplied by the bypass system along with initial mass dumps to restore them to their original condition. These mass movements will be supplied by sand collected from preparatory dredging of the river entrance. Figure 3 shows the location of the beaches supplied by the bypass project.



Figure 3: Detailed map of sand outlet points comprising the Tweed River entrance sand bypass project.

At the time of commission a coastal monitoring support system was also in place to provide information for management of the system in order to maintain both beach conditions to the north of the river and a safely navigable river entrance. The monitoring in place is of numerous forms including the Tweed directional wave buoy, a coastal image monitoring system (Anderson et al., 2003) and acoustic Doppler current profiles (ADCPs). This data has been used to produce morphological models of the river entrance to assist in determining how the entrance is reacting to this anthropogenic form of sediment transport (Callaghan and Nielson, 2003).

At the time of deployment this sand bypass project was not fully operational although initial dredging of the channel had occurred. This situation provided a good opportunity to display the ability of the COSRAD system to support such monitoring projects with valuable data including surface current and wave activity that impacts upon the natural sediment transport regime occurring in the area. Results acquired from the developed directional wave algorithm could be used to provide independent estimates of natural sediment movement due to wave and surface currents which has previously been the role of the moored wave buoy. The wave buoy however only provides data at a single location. The use of COSRAD to provide data over a wider area would assist in observing the components involved in a larger sediment transport system. A map of the operational ocean coverage of the COSRAD system at Tweed Heads is shown in Figure 4.



East of Kingscliff station (km)

Figure 4: Ocean coverage of the COSRAD system at Tweed Heads. Surface current and wave measurements can be made in the areas of overlap between the two stations. The star marks the location of the QBPA directional wave buoy.

2.3.2 The Bass Strait Deployment

Port Phillip Bay has multiple uses including major port facilities, a significant commercial fishery and it also supports numerous nature conservation areas (Harris and Crossland, 1999). The HF COSRAD system has already been employed in this area as a valuable part of the Port Phillip Bay Environmental Study (PPBES) commissioned by the Government of Victoria and carried out by the CSIRO (Commonwealth Scientific and Industrial Research Organisation), (Provis, 2004). This study was concerned with an evaluation of the environmental state of Port Phillip Bay in terms of nutrient and toxicity levels. The COSRAD system was used to provide information in the form of current maps to describe the physical processes involved in the transport of these chemicals (Prytz and Heron, 1999). The coverage area is shown in Figure 5 below.



Figure 5: Port Phillip Bay study site. The locations of the COSRAD stations at Ocean Grove and Portsea are shown. The wave rider buoy is also marked (star). The dashed line encloses the coverage area of the previous COSRAD study attached to the PPBES (1999).

The Bass Strait deployment was focussed more towards the extraction of swell data than the Tweed Heads deployment and configuration changes were made to the radar system to facilitate this. The focus on swell detection was the primary reason for the choice of location and the time of year. Bass Strait is known for the large sea states that often reach the shores of Victoria during the winter months (Spillane *et al.*, 1972). Safe passage through Port Phillip Heads for both commercial and recreational vessels is also of concern.

Monitoring of the ocean surface near the entrance to Port Phillip Bay by two COSRAD stations began on the 27th of June and ended on the 26th of July 2001. The coverage area, the portion where the two sweeps overlap, is shown in Figure 6. The locations of the stations at Ocean Grove (38°16.425'S, 144°30.943'E) and Portsea (38°20.15'S, 144°42.202'E) are shown and are clearly separated by the entrance to Port Phillip Bay. The area shown sufficiently covers all approaches into the Bay and therefore indications of swell wave activity in this region will be extremely valuable for shipping safety.

The operating changes made to the COSRAD system to assist in the extraction of swell parameters were to increase the dwell time at each position. Although this results in a lower temporal resolution it is again not of great concern when extraction of swell is the main objective. This increased dwell time enhances the backscattered ocean signal against the surrounding noise. This parameter was not set for the Tweed Heads deployment because the objects were slightly broader and therefore a compromise was reached. The temporal resolution is an important factor when trying to monitor surface currents and wind direction as they can change significantly within a short time period. As mentioned earlier an entire sweep of the area was produced every 30 minutes at Tweed Heads, this was increased to an hour for the Bass Strait deployment.



Figure 6: Coverage area of the COSRAD system monitoring the entrance to Port Phillip Bay. The directional wave buoy here (star) is maintained by the Port of Melbourne Corporation.