WERA HF radar measurements of wind direction in the South Atlantic Bight

Matthew Archer

10089949

Academic Year 2008/9

Project Advisor: Dr Daniel Conley, School of Earth, Ocean & Environmental Science, University of Plymouth, Drake Circus, Plymouth, PL4 8AA

Stage 3 Project Submitted in Partial Fulfilment for the Degree of B.Sc Ocean Science
Copyright Statement

This copy of the thesis has been supplied on condition that anyone who consults it is understood to recognise that its copyright rests with the author and that no quotation from the thesis and no information derived from it may be published without the author’s prior written consent.
WERA HF radar measurements of wind direction in the South Atlantic Bight

Abstract

Wind direction measurements collected at 4 in-situ anemometers were compared with the WERA HF radar over a 20 month period to assess the accuracy of the radar system. The radar data was interpolated onto the less frequent in-situ time series. An unexpectedly large RMS error of 58.9° was calculated over all stations. A complex correlation coefficient of 0.65 was obtained. An improved correlation was exhibited at all stations with increasing wind speed, which is explained by an increase in radar accuracy. The radar operates at 8.35 mHz, and using this frequency the phase speed of the shortest wave sensed by the radar was calculated to be 5.3 ms⁻¹; therefore in wind speeds under this threshold the radar estimates were discarded. Shallow water conditions were shown to affect all 4 locations when the dominant wave period exceeded a threshold limit for each station. Correlation improved when using only measurements made during deep water conditions. The results suggest that limited fetch affected all stations when the winds were blowing over the land. This is most evident at the Grays Reef station closest to the coast, where correlation actually declined in higher wind speeds that require longer fetch. Correlation of anemometers at different stations, and the radar between its grid cells, found that the in-situ measurements were more closely related to one another, suggesting the anemometers are in general more reliable. It was concluded that the WERA radar wind direction measurements are more accurate under a fully arisen sea state, specifically in high wind speeds for wind blowing over the open sea when deep water conditions apply. This was demonstrated when the radar data was corrected for these parameters; the grid cells at the 4 stations exhibited no significant difference in correlation with the in-situ measurements.
Contents

1. Introduction ................................................................................................................................. - 1 -
   1.1 High Frequency Radar ........................................................................................................... - 1 -
   1.2 Aims and Objectives ............................................................................................................. - 2 -
2. Background ................................................................................................................................. - 2 -
   2.1 How HF radar works ............................................................................................................. - 2 -
   2.2 Wind Measurement .............................................................................................................. - 3 -
      2.2.1 Wind-Wave Directional Distribution Models ............................................................... - 4 -
      2.2.2 Radar – Anemometer Comparisons ............................................................................. - 6 -
3. Methods ..................................................................................................................................... - 8 -
   3.1 Instrument Set Up ................................................................................................................... - 8 -
      3.1.1 WERA Radar ................................................................................................................. - 8 -
      3.1.2 In-Situ Anemometer ..................................................................................................... - 9 -
   3.2 Autocorrelation ...................................................................................................................... - 10 -
   3.3 Data Standardization ............................................................................................................. - 12 -
      3.3.1 Wind Direction Convention ............................................................................................ - 12 -
      3.3.2 Interpolation ................................................................................................................... - 12 -
      3.3.3 Wind Speed Correction .................................................................................................. - 13 -
   3.4 Measurement Differences ...................................................................................................... - 14 -
   3.5 Complex Correlation ............................................................................................................ - 14 -
4. Results ....................................................................................................................................... - 15 -
   4.1 Measurement Differences ...................................................................................................... - 15 -
   4.2 Complex Correlation ............................................................................................................ - 16 -
5. Discussion .................................................................................................................................. - 20 -
   5.1 Measurement Differences ..................................................................................................... - 20 -
   5.2 Complex Correlation ............................................................................................................ - 20 -
   5.3 Effect of Landmass ................................................................................................................. - 21 -
   5.4 Buoy Measurements .............................................................................................................. - 23 -
   5.4 Sources of Error ..................................................................................................................... - 26 -
6. Conclusions ............................................................................................................................... - 26 -
References ..................................................................................................................................... - 29 -
List of Figures

1. Introduction
   1. HF radar Doppler spectrum [Source: Gurgel et al., 1999] ..............................- 3 -

2. Background

3. Methods
   2. Map of the South Atlantic Bight; study site [Source: SKIO, 2009] .................- 10 -
   3. Autocorrelation plot for (a) Radar (b) Anemometer.....................................- 11 -
   4. Linear best fit (with residuals) for the raw versus interpolated radar data......- 13 -

4. Results
   5. Probability plot of difference between radar and in-situ.................................- 15 -
   6. RMS error versus wind speed at each in-situ station.................................- 16 -
   7. Complex correlation for data above wind speed cut-off.............................- 17 -
   8. Complex correlation for data below wind speed cut-off.............................- 18 -
   9. Measurement difference versus wind speed.............................................- 19 -

5. Discussion
   10. Map identifying angles for wind blowing over the land and wind blowing over
       the ocean [Modified from: SKIO, 2009].....................................................- 22 -
**List of Tables**

1. **Introduction**

2. **Background**

3. **Methods**
   1. R.M Young Anemometer specifications…………………………………….- 9 -

4. **Results**
   2. RMS errors for the four tested interpolation techniques…………………….- 12 -
   3. Mean differences between the radar and in-situ measurements……………….- 15 -
   4. Complex correlation magnitude at each station…………………………...- 16 -

5. **Discussion**
   5. Correlation magnitude for wind blowing over the land/sea sector………….- 22 -
   6. Radar grid cell correlation and anemometer station correlation……………….- 24 -
   7. Correlation magnitude with shallow water conditions removed……………….- 25 -
   8. Correlation magnitude with data corrected for wind speed, wind fetch and wave height……………………………………………………………………………….-25 -
List of Equations

1. Introduction
2. Background
   1. Empirical expression for the Bragg line ratio……………………………………..- 4 -
   2. Parametric spreading formula for single peaked directional spectrum……………- 5 -
   3. Cardioid angular distribution ………………………………………………………- 5 -
   4. Normalization constant, A…………………………………………………………- 5 -
   5. Bragg line ratio (using wind direction)……………………………………………- 5 -

3. Methods
   6. Autocorrelation…………………………………………………………………..- 10 -
   7. Root mean square error………………………………………………………….- 12 -
   8. Logarithmic wind profile……………………………………………………….- 13 -
   9. Complex correlation……………………………………………………………..- 14 -
  10. Complex correlation (north-east components) ……………………………- 14 -
  11. Complex phase angle……………………………………………………………..- 14 -

4. Results
5. Discussion
   12. Radio wave wavelength……………………………………………………………- 21 -
   13. Wave period (from deep water approximation of linear wave theory) .............- 21 -
   14. Wave phase speed (from deep water approximation of linear wave theory) ……- 21 -
   15. Wave period (from shallow water approximation of linear wave theory) ……..- 24 -
Acknowledgements

I would like to thank my advisor Dr Daniel Conley for all the help and advice he has given me over this past academic year with regards to the analysis of the data. This project is a continuation of the research that I conducted during my summer internship at the Skidaway Institute of Oceanography. I was supervised by Dr Dana Savidge, who made this project possible, and I am extremely grateful for the help she has continued to provide. I would also like to thank Julie Amft and Trent Moore for answering my questions regarding radar and anemometer data acquisition and Professor Lucy Wyatt at Seaview Sensing for answering my questions regarding the wave angular distribution models.
1. Introduction

1.1 High Frequency Radar

High frequency (HF) radar is a shore based electronic system which transmits electromagnetic waves to remotely observe surface currents, waves and wind direction. It operates in the radio band between frequencies of 3-30 MHz with wavelengths of 10-100m. Transmitted electromagnetic waves are backscattered by the rough sea surface, which acts like a large diffractive grating, and are recorded by the receiving antennae. The conductive sea surface guides the radio wave propagation which allows measurements beyond the horizon with ranges of up to 200km [Gurgel et al., 2006].

The number of HF radar installations has increased substantially in the last decade and within the US the development of a national HF radar network has recently been implemented [CORDC, 2009]. The ability to provide non invasive near real-time measurements of coastal circulation is unique and therefore HF radar has received considerable attention in oceanographic research. This research has been predominantly focussed on the theory and application of radar to surface current velocity and wave height measurement. The information obtained is valuable to users other than scientists, specifically for coastal engineering, military operations, search and rescue, monitoring navigational seaways and port operations as well as the tracking of marine wildlife and pollution.

The inference of wind direction from surface waves is another useful application of the radar that can provide information to mariners, weather forecasters and offshore personnel. Wind direction data can supply near real-time observations of approaching fronts and storms, and along with current velocity and wave data, can be assimilated into coastal circulation models to provide a more accurate understanding of the nearshore processes. Early work on wind measurements by Long & Trizna [1973] used sky wave radars and focussed on development of a suitable semi-empirical algorithm to define the directional wave spreading. Further work into wind direction measurement has been conducted using both sky wave [Barnum et al., 1977; Georges et al., 1993] and ground wave HF radar [e.g. Heron et al., 1985; Heron & Rose, 1986; Wyatt, 1988].
Comparisons between radar and in situ anemometer data have been conducted with different radar systems [e.g. Harlan & Georges, 1994; Vesecky et al., 2005]; however there has been no in depth comparison of ground wave HF radar wind direction with multiple in-situ stations over a sufficient time scale. Furthermore, there is no published work focussed on the accuracy of wind direction measurements made by Wellen Radar (WERA), the HF radar used in this project. Knowledge of the accuracy is vital if the data is to be used in numerical models. Conversely, a comparison with in situ data could reveal inaccuracies with the measurements obtained from anemometers.

1.2 Aims and Objectives

The aim of this study is to assess the accuracy of the WERA HF radar wind direction measurements. The main objectives are to:

1. Compare radar data with in situ data at four locations within the radar area of coverage.
2. Analyse the source of the differences between the two instruments.
3. Investigate the effect of different physical parameters on the measurements including: wind speed and fetch, wave height and period.

The following section will review the theory of HF radar and explain how wind direction is inferred from ocean gravity waves. It will also summarise the main findings of the previous research on comparisons between radar and anemometer. Section 3 will explain how the data was processed and then describe the data analysis methods utilised in this study. The results are displayed in section 4 and then interpreted and discussed in section 5. Specifically, the effect of wind speed on the correlation between the instruments, and the physical parameters which affect the radar’s measurements. Finally, section 6 will summarise and conclude the main findings of the report.

2. Background

2.1 How HF radar works

The basic physics of backscattering of the electromagnetic waves from the sea surface was identified by Crombie [1955], who observed that the sea echo spectra showed a slight Doppler shift from the transmitted signal. The original model for ocean backscatter
proposed by Crombie [1955] however, is logically incorrect and this report refers the reader to Naylor & Robson [1986] who correctly explain the physical process. The Doppler shift is the change in frequency (and wavelength) emitted/reflected by an object due to motion. Surface waves with exactly one half of the incident wavelength produce an enhanced backscatter phenomenon known as Bragg scattering; this theory is described mathematically by Barrick [1972]. The energy reflected along the entire surface of the one wave is precisely in phase with another that travelled half a wavelength down and reflected half a wavelength back from the successive wave; this is resonance and amplifies the signal at the receiver [Teague et al., 1997]. Figure 1 displays a Doppler spectrum with two discrete peaks; the frequencies of the ‘Bragg waves’ travelling directly towards and away from the radar. The observed Doppler shift is attributed to the known deep water phase speed of the surface waves and to the unknown radial current which is thus inferred [Stewart & Joy, 1974]. The surrounding continuous sidebands are generated by multiple scattering and nonlinear hydrodynamic effects. Ocean wave spectra can be obtained from these sidebands by applying inversion techniques.

![Figure 1. HF radar Doppler spectrum normalised to the strongest signal, showing prominent Bragg peaks due to waves advancing toward and receding from the radar. The Doppler shift (Δf) is due to the underlying ocean currents. [Source: Gurgel et al. 1999]](image)

2.2 Wind Measurement

Wind is not directly measured by HF radar; instead it is inferred from the Bragg resonant gravity waves, which are assumed to be locally generated by the wind field. The functional relationship between the wind and wave directions has been a central research issue. If the seas are fully developed, the wave field is in equilibrium with the wind and
is not limited by fetch or duration and the relationship can be modelled relating the wave distribution to the wind direction.

Wave direction is estimated from the relative amplitudes of the two first-order Bragg peaks, known as the Bragg line ratio. Waves travelling towards or away from the radar will produce a large Bragg line ratio (due to predominantly approaching waves and almost no receding waves or vice versa) and waves travelling across the radar look direction will produce a small ratio. Long & Trizna [1973] noted that the universal existence of the weaker of the two Bragg peaks indicates that there is a non-zero component of sea roughness at angles greater than ±90° to the wind direction which is responsible for the scatter. If the form of the waves’ directional spreading function is known, the angle of the wind from a radar radial can be determined [Harlan & Georges, 1994]. With a single HF radar measurement there is a directional ambiguity as the radar cannot distinguish between left and right and this must be solved with additional information; using either independent observations or a second radar site viewing the ocean from a different angle.

Wind speed measurements by HF radar are still under investigation. With increasing wind speed the energy of the Bragg scattering waves increases less and less and will eventually reach saturation [Barale & Gade, 2008]. Instead of a further increase in wave height, the energy is transferred into longer ocean waves by nonlinear wave-wave interaction. Thus using the relative amplitude of the first order Bragg peaks is insufficient and the complete ocean wave spectrum must be utilised.

### 2.2.1 Wind-Wave Directional Distribution Models

Long & Trizna [1973] first suggested the use of the relative spectral densities of the two first order peaks to obtain at first wave direction then wind direction. They used the US Navy OTH-B sky-wave radars to map North Atlantic winds. They derived an empirical expression for the Bragg line ratio \( \gamma \) (in dB), defined:

\[
\gamma = 10 \log \left( \frac{B_+}{B_-} \right)
\]

where \( B_\pm \) are the approaching/receding first order Bragg peaks. The ‘height’ of these peaks is directly related to the energy within the approaching and receding wave
components. They noted that attenuation will reduce the strengths of the peaks, but that both peaks will suffer the same perturbation for a given range-azimuth cell and hence the ratio is not affected.

To relate the wave direction to wind direction, the directional spectrum describing the wave response to wind stress is required. The basic premise of parametric spreading functions is that the single-peaked directional spectrum is described in frequency $\omega$ (in Hz), and direction $\theta$ (in radians):

$$S(\omega, \theta) = F(\omega) \cdot G(\theta) \quad \text{[2]}$$

where $S(\omega, \theta)$= directional spectrum, $F(\omega)$= one-dimension energy spectral density function and $G(\theta)$= directional spreading function. The formulation of $G(\theta)$ requires that the total energy in the directional spectrum must be the same as the total energy in the corresponding one-dimensional spectrum [US Army Engineers, 1985]; hence the angle of wave to wind direction is determined entirely by $G(\theta)$. This parameterisation can represent the directional nature of a wave field in the absence of complicating influences such as a large change in wind direction or the propagation of swell into the generation area, which would result in a bimodal spectrum. The $F(\omega)$ term is modelled by the JONSWAP model [Hasselman et al., 1976] or the Pierson-Moskowitz model [Pierson & Moskowitz, 1964], although the technique for obtaining wind directions is not sensitive to $F(\omega)$ while equation 2 is valid. The form of the angular distribution $G(\theta)$ modelled as a cardioid distribution was suggested by Longuet-Higgins et al. [1963] to be:

$$G(\theta) = A \cos^s(0.5 \cdot \theta) \quad \text{[3]}$$

where $\theta$ is the angle from the direction of maximum wave energy (i.e. angle from the wind), $s$ describes the azimuthal spreading and $A$ is a normalisation constant:

$$A = 1/ \int_0^{2\pi} \cos^s(0.5 \cdot \theta) d\theta \quad \text{[4]}$$

Using equations 1 and 3 the Bragg ratio can be related to the wind direction:

$$\gamma = 10 \log \frac{\cos^s[0.5(\phi+\pi-\theta)]}{\cos^s[0.5(\phi-\theta)]} \quad \text{[5]}$$

where $\phi$= the radar beam direction. Equation 5 can be inverted for $\theta$, and assuming a value for the spreading parameter $s$ the wind direction can thus be calculated. Heron &
Rose [1986] tested the consistency of this model and confirmed the accuracy of it for wind directions. However, they agreed with US Army Engineers [1985], observing that the model cannot be used in the case of shallow water, where swell waves are behaving non-linearly (breaking) or during a large change in wind direction.

Wyatt et al. [1997] tested the parameters for the cardioid model and a sech$^2$(βθ) model [refer to: Donelan et al., 1985]. The sech$^2$(βθ) model was found to provide better agreement. This is because the cardioid model assumes there is no energy propagating in a direction opposite to the wind although it is always possible to observe both approaching and receding first order peaks. The Donelan model however does contain an explicit non-zero counter-wind component.

2.2.2 Radar – Anemometer Comparisons

Harlan & Georges [1994] used an entirely empirical relationship to obtain the wind direction over the North Atlantic and North Pacific with OTH-B radars and compared the results with in-situ reports from ships, buoys and model grid points. This is inconsistent because the empirical relationship was derived by fitting the radar measurements to the in-situ and model data in the first place, but they make a good argument for their reasoning; by observing how closely the data clusters about the law, the usefulness of it can be attained. They restricted comparisons to space-time windows of 100km and ±1.5 hours of in situ measurements or grid points to permit a valid comparison. After studying spatial differences between buoys, Gilhousen [1987] provides a contrary opinion that remotely sensed winds should only be compared to buoy winds when the spatial difference between the buoy and the centre of the footprint is ‘considerably less’ than 100km. RMS differences of ~30° were observed, but without dense and reliable in situ data, it is impossible to identify what was the cause of the difference. Gilhousen [1987] studied errors in winds measured at buoys and stated that the short temporal averaging time of the data can introduce a component of mesoscale wind to their values which does not represent the synoptic scale wind field. He also noted that when spatial averages (HF radar) are compared with point measurements, obvious errors will occur if point measurements decorrelate for space-time separations smaller than a radar cell. He compared pairs of NOAA buoys and found RMS differences of 22°. Stewart & Barnum [1975] note that the spreading parameter $s$ decreases with increasing wind speed, which
describes a narrowing of the directional spread of the wave field and improved measurements. By filtering the data to remove measurements under a speed threshold, the less accurate data may be removed. Harlan & Georges [1994] chose a wind speed cut off of 3 ms$^{-1}$. It was shown that for the small percent less than 3 ms$^{-1}$ the RMS error was 48.6°, compared with 31.3° for the data greater than 3 ms$^{-1}$.

Fernandez et al. [1997] examined measurements over a 2 day period with a ground wave Ocean Surface Current Radar (OSCR) off Duck, South Carolina, which included the passage of a front. They found that the estimates agree very well with a nearby mooring. They used only one radar (the other was unavailable) and so resolved the directional ambiguity by minimising the differences with the mooring data. This means that the radar measurements are not independent of the mooring data and so explains the good correlation. Even so, this does still imply a correlation between the two datasets.

Huang et al. [2002] applied newly developed HF radar from Wuhan University, OSMAR2000, to measure wave and wind fields over the Eastern China Sea. It was a preliminary trial and they analysed only 3 days’ data. They used only one radar site, requiring an algorithm suggested by Heron & Rose [1986] to resolve directional ambiguities, which is not the most accurate method. They compare the radar measurements with ship data, which as Pierson [1990] points out, are not the primary standard with which to compare wind measurements since the averaging times are short and the variance in the records are ‘unacceptably large’. They recorded the mean difference (measurement bias) between radar-deduced and ship-measured wind direction to be 20° which under the circumstances is good.

Paduan et al. [1999] used 2 MCR radars located in Monterey Bay, California over 2 months during the summer of 1997 to map surface wind fields. They used a Georges et al. [1993] simple linear algorithm and compared results to an in situ buoy mooring. They filtered the data, using only Bragg ratios which exceeded the signal to noise ratio (SNR) by 3dB, which can significantly reduce the dataset but will improve on the accuracy. They found fairly good agreement, consistent with observations of the sea breeze in the area. The correlation between the radar and mooring observations was negligible. They discovered however that a much increased correlation was present for the subset of times when the wind speed at the mooring exceeded 5ms$^{-1}$. This corresponds to the findings of
Harlan & Georges [1994]. They concluded that when wind speeds, and hence wave heights and backscatter are low, the SNR is large and this reduces the correlation. They also noted that errors can de due to the lag between the change in the wind direction and the change in the wave direction.

A further study with the MCR radars was performed by the same research group Vesecky et al. [2005]. They used a yearlong dataset from 2001-2002 and performed greater statistical analysis. They used a nonlinear Partial Least Squares (PLS) regression on the data with the same mooring buoy as before. The standard error of prediction (SEP) is simply the difference between the observed direction and the radar estimated direction. When compared to the buoy, the SEP was 25.4° with a bias of 0.3° (with $R^2 = 0.89$ which indicates a good fit). They noted that for their transmit frequency of 21.8 mHz, the phase speed of the shortest waves they exploit is $3.2 \text{ms}^{-1}$. Therefore at wind speeds less than $3.2 \text{ms}^{-1}$ the waves that the radar observes cannot have been produced by the wind, so all measurements calculated at this set of times should be discarded.

The preliminary results of a WERA installation along the Atlantic coast near Brest, France are available from the manufacturer Helzel [2004]. An RMS difference of 32.5° ($22.2° > 6 \text{ms}^{-1}$) was calculated with a moored anemometer together with a very high correlation of 0.924.

3. Methods

3.1 Instrument Set Up

3.1.1 WERA Radar

The radars are installed on St Catherines Island, Georgia, USA and Pritchards Island, South Carolina, operated by Skidaway Institute of Oceanography and the University of South Carolina respectively. The WERA system installed here is long range, operating at a frequency of 8.35 mHz with a frequency modulated continuous wave mode (FMCW) bandwidth. This system runs the Helzel software, which uses a $\cos^s$ angular distribution model (where $s$ is the spreading parameter). It has a working range of up to 200km, spatial resolution of 3km and azimuth resolution of 2°. The two radar systems operate in ping-pong mode transmitting 1024 chirps over ~7.5 minutes; Pritchards radar acquires
1024 samples starting at :00 and :30, St Catherines samples at :15 and :45. The Prichards and St Catherines data is matched :00 with :15 and :30 with :45. This produces wind direction estimates every half hour, labelled at :15 and :45.

### 3.1.2 In-Situ Anemometer

In-situ data is obtained from the NOAA National Buoy Data Centre website [NBDC, 2009], which runs the Coastal Marine Automated Network providing oceanographic and meteorological data. The in-situ measurements used are:

1) NOAA Buoy 41008, located in the Grays Reef National Marine Sanctuary in 18m water depth. It is a 3m discus buoy with an ARES 4.4 payload, and an R.M Young wind monitor 05103 (specifications in table 1). Anemometer height is 5m elevation above sea level. Wind measurements are made every hour at :00, from true north, with a unit-vector averaging time of 10 minutes.

2) Three U.S Navy Platforms; R2, R6 and R8. Water depth is 27m (R2), ~30m (R6) and ~45m (R8). The anemometer model at all 4 locations is the R.M Young marine wind monitor 05106 (specifications in table 1). Anemometer elevation is 50m (R2 and R6) and 34m (R8). Wind measurements are made every hour at :00 from true north, with a unit-vector averaging time of 6 minutes.

<table>
<thead>
<tr>
<th>Table 1. Measurement specifications for the 05103 and 05106.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R.M Young wind monitor</strong></td>
</tr>
<tr>
<td><strong>05103 &amp; 05106</strong></td>
</tr>
<tr>
<td><strong>Wind Speed</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Accuracy</td>
</tr>
<tr>
<td>Resolution</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Wind Direction</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
</tr>
<tr>
<td>Resolution</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Map of the South Atlantic Bight (SAB), displaying the locations of Grays reef buoy and Navy Towers R2, (M2)R6 and R8. [Source: SKIO, 2009]

Figure 2 displays the locations of the four in-situ stations. This study uses data collected by the WERA and in-situ instruments from 07:00/11/04/06 to 23:00/31/12/07.

3.2 Autocorrelation

Autocorrelation is an important measure of the persistence within a time series, and can complicate the application of statistical tests by reducing the effective sample size. Autocorrelation measures the correlation between one time series and the same series lagged by one or more time units [Jenkins & Watts, 1968]. In first-order autocorrelation the lag is one time unit. Where \( N \) is the number of data points, first-order autocorrelation is the correlation coefficient of the first \( N-1 \) observations \( x_t \) at \( t=1,2,\ldots,N-1 \) and the next \( N-1 \) observations at \( t=2,3,\ldots,N \). The correlation between \( x_t \) and \( x_{t+1} \) is given as:

\[
\rho = \frac{\sum_{t=1}^{N-1} (x_t - \bar{x})(x_{t+1} - \bar{x})}{\sum_{t=1}^{N-1} (x_t - \bar{x})^2} \tag{6}
\]

where \( \bar{x} = \sum_{t=1}^{N} x_t \) is the overall mean.
This method allows the determination of the number of independent data points used in the analysis. Figure 3 illustrates the decorrelation time for the radar and in-situ data at the four locations. It shows the data sets take between approximately 60-80 hours to decorrelate fully to zero; however, the functional decorrelation time can be visually identified at approximately 35 hours (highlighted by the black bars). This is indicative of the large scale weather systems which influence the synoptic wind direction. Dividing the total number of data points by the decorrelation time will yield the number of independent measurements available for analysis.

(a)

(b)

Figure 3. Autocorrelation plots for the four stations for (a) WERA data (b) Anemometer data. The bold dark black line highlights the approximate decorrelation time for wind measurements using each instrument (~35 hours for both).
3.3 Data Standardization

3.3.1 Wind Direction Convention

To permit comparisons between the radar and in-situ anemometers the WERA data was adjusted. The radar uses the oceanographic convention for measuring winds (clockwise from north, winds blowing towards) and the anemometers use the meteorological convention (clockwise from north, winds blowing from). Because wind direction is a meteorological measurement the WERA data was converted.

3.3.2 Interpolation

The WERA measurements which are more frequent at half hour intervals, were interpolated onto the time series of the in-situ measurements, which are every hour at :00. Four different interpolation methods were tested in Matlab; linear, nearest neighbour, piecewise cubic hermite interpolating polynomial (pchip) and cubic spline. Data from each interpolation was compared with the raw radar data using the root mean square error (RMS):

\[ RMS = \sqrt{\frac{\sum_{i=1}^{N}(x_r-x_i)^2}{N}} \]  \[ 7 \]

where \( x_r \) is the raw wind direction data acquired from the radar and converted to the meteorological convention, \( x_i \) is the interpolated data and \( N \) is the number of data points. On the basis of this calculation, the pchip function was determined to be the best representation of the data on the in-situ time series, as shown in table 2. Figure 4 displays the residuals between the raw and interpolated data for the pchip method. Care was taken not to invent spurious data during the interpolation and so interpolated points which coincide with gaps in the original data were excluded.

<table>
<thead>
<tr>
<th>Interpolation Method</th>
<th>RMS Error ((x_r-x_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pchip</td>
<td>18.29</td>
</tr>
<tr>
<td>Nearest Neighbour</td>
<td>26.30</td>
</tr>
<tr>
<td>Linear</td>
<td>21.04</td>
</tr>
<tr>
<td>Spline</td>
<td>21.50</td>
</tr>
</tbody>
</table>

Table 2. Displays the root mean square difference between the raw and interpolated data for each interpolation method.
3.3.3 Wind Speed Correction

The wind measurements made by the in-situ anemometers are at heights of between 5-50m; this is in the surface layer of the atmospheric boundary layer, where the Ekman spiral is negligible and therefore wind direction does not need to be corrected [Gilhousen, 1987].

The surface layer does however exhibit a logarithmic profile of wind speeds, increasing from the surface. This study will investigate the effects of wind speed on comparisons between radar and in-situ data, and therefore the wind speed data must be corrected at all locations to the 10m height standard. This is done using a semi-empirical relationship that describes the logarithmic profile, as suggested by Tennekes [1973]:

$$u_z = \frac{u_*}{k} \ln \left( \frac{z-d}{z_0} \right) + \varphi(z, z_0, L)$$  \[8\]

where the wind speed $u_z$ at height $z$ (m) above the ground is given by $u_*$= friction velocity (m$^{-1}$), $k$= von Karmans constant (0.41), $d$= zero plane displacement (height of zero velocity due to obstacles (m)), $z_0$= surface roughness (0.0002 meters for open sea surface) and $\varphi$= stability term where $L$= Monin-Obukhov length (stability parameter). A neutral atmosphere was assumed, along with the absence of obstacles, which removes the zero plane displacement and stability terms.
3.4 Measurement Differences

Two measures of difference are calculated. The RMS error is defined by equation 7. It provides a good measure of the difference between two sets of data, and will be used to relate this project to the results of previous research. The measurement bias is the difference of the means between the two random vectors, and will show if there is a tendency for one instrument to measure clockwise or anticlockwise to the other.

3.5 Complex Correlation

A statistical measure of the correlation between two vector measurements was suggested by Kundu [1975]. It uses complex numbers, which are a mixture of real and imaginary numbers. Complex numbers are able to describe vectors in one equation, as opposed to real numbers which must use 2 equations, one for N-S and one for E-W. Complex correlation finds the phase angle between two vectors:

\[ w(t) = u(t) + iv(t) \]  

Where \( w \) is the complex representation of the two dimensional velocity vector at time \( t \) where \( i = \sqrt{-1} \). In terms of north-east components, equation 8 can be written as:

\[ \rho = \frac{\langle u_w u_a + v_w v_a \rangle + i \langle u_w v_a - v_w u_a \rangle}{\langle u_w^2 v_w^2 \rangle^{1/2} \langle u_a^2 v_a^2 \rangle^{1/2}} \]  

and the complex phase angle as:

\[ \phi = \tan^{-1} \left( \frac{\langle u_w u_a - v_w v_a \rangle}{\langle u_w u_a + v_w v_a \rangle} \right) \]

where \( \langle ... \rangle \) represents an arithmetic average in time (based upon the number of points) for the WERA wind measurements \( (w) \) and in-situ measurements \( (a) \). \( \rho \) is a complex number whose magnitude gives the overall measure of correlation \((0<1)\) and whose phase gives the average counter-clockwise angle of the second vector with respect to the first (the phase is only meaningful if the magnitude of the correlation is high). Note that this method estimates the mean veering at time \( t \), so weights the averaging process according to the magnitude of the instantaneous vectors.
4. Results

4.1 Measurement Differences

The mean measurement bias between the two instruments is presented in *table 3* and illustrated in *figure 5*. There is a clear negative skew to the data, indicating that there is a bias with radar wind measurements clockwise of the anemometers.

![Figure 5](image.png)

*Figure 5*. Difference between radar and in-situ data versus the probability at the 4 in-situ locations

*Figure 5* and *table 3* indicate that the bias increases with station distance offshore. *Table 3* shows that the bias at the platforms is an order of magnitude larger than at the buoy.

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean Difference (In-situ – radar (Deg))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR</td>
<td>-1.00</td>
</tr>
<tr>
<td>R2</td>
<td>-12.95</td>
</tr>
<tr>
<td>R6</td>
<td>-13.87</td>
</tr>
<tr>
<td>R8</td>
<td>-14.80</td>
</tr>
</tbody>
</table>

*Table 3*. Mean differences between radar and the 4 in-situ stations

The total RMS error at all four stations was calculated at 58.9°. *Figure 6* is a continuous plot of the RMS error for wind data restricted to values greater than an increasing threshold wind speed at all four locations. The broken green line indicates the number of data points used in the calculation, which decreases with increasing wind speed. The figure shows clearly that the difference between the measurements decreases with increasing wind speeds at all four locations. The largest RMS errors are exhibited at Grays Reef (mean RMS is 66.61°), followed by the three Navy towers (R2 is 56.7°, R6 is 52.9°, R8 is 53.6°). The pattern of the Grays Reef dataset differs slightly from the tower
data; the decreasing RMS error levels at ~8ms⁻¹ and even rises slightly before falling again. All three Navy tower datasets exhibit a similar downward trend.

Figure 6. The blue line is the RMS error for wind data restricted to values greater than an increasing threshold wind speed at (a) GR (b) R2 (c) R6 (d) R8. The broken green line displays the number of data points used in the calculation. Different stations recorded difference maximum wind speeds, as is evident from the plots.

4.2 Complex Correlation

Table 4 displays the overall complex correlation coefficient for all stations and at each station separately. The magnitudes of the coefficients show that there is a clear correlation between the radar and anemometer measurements. There is a monotonic increase in correlation magnitude with increasing distance from the coastline. The Grays Reef dataset displays a disproportionately lower correlation that the three Navy towers, with a magnitude of ~0.1 smaller. These results show the same pattern as the RMS calculations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Correlation Magnitude (0-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>0.65</td>
</tr>
<tr>
<td>GR</td>
<td>0.56</td>
</tr>
<tr>
<td>R2</td>
<td>0.68</td>
</tr>
<tr>
<td>R6</td>
<td>0.71</td>
</tr>
<tr>
<td>R8</td>
<td>0.72</td>
</tr>
</tbody>
</table>
Figure 7 illustrates the effect of increasing wind speed on the correlation, where the blue line represents the correlation coefficient and the broken green line is the number of data points used in the calculation. Grays Reef exhibits a smaller correlation and in addition varies independently to the pattern of the three Navy towers, where there is a steady increase with increasing wind speed. The correlation at Grays Reef increases with wind speed up to 8ms\(^{-1}\), after which it fluctuates; decreasing until 12ms\(^{-1}\), increasing thereafter. Note the number of data points used at the highest wind speeds is low and may not be a reliable indication of the physical processes.
Figure 7. The blue line displays the correlation magnitude for wind data restricted to values greater than an increasing threshold wind speed at (a) GR (b) R2 (c) R6 (d) R8. The broken green line represents the number of data points used in the calculation. Different stations recorded different maximum wind speeds, as is evident from the plots. Note all plots have the same axis to aid comparison.

Figure 8 illustrates the correlation between radar and in-situ wind direction data restricted to values less than an increasing threshold wind speed at each location. This plot provides good visual evidence that at low wind speeds there is little correlation between the data. The same pattern is displayed at each station. With increasing wind speed there is increasing correlation up to 8-10ms⁻¹, at which point the rate of change reduces to
almost zero. The gradual increase in correlation at the lower wind speeds is indicative of the effect of the lower correlated measurements in the first few calculations.

Figure 8. Correlation between radar and in-situ wind direction data restricted to values less than a threshold wind speed at R2 Navy Tower. This is representative of the pattern exhibited at all stations.

To visualize the divergence between the measurements for different wind speeds, figure 9 was plotted, which displays the difference between each data point with increasing wind speed. Below 5-6ms\(^{-1}\) there is no visual correlation between the data; the differences are almost evenly spread over the 360° range. Above this threshold, the difference decreases with wind speed up to the maximum speed. This plot shows the negative bias inherent in the measurements; the centre of mass of the data points is located not at zero, but just below zero.

Figure 9. Wind difference versus wind speed at Grays Reef. This is representative of the pattern exhibited at all stations.
5. Discussion

5.1 Measurement Differences

The mean differences displayed in table 3 reveal that at the Navy towers, there is a bias for the radar to measure winds clockwise of the anemometers. At the Grays Reef buoy however the mean difference is an order of magnitude smaller (at -1°). This result suggests that the structure of the Navy towers could be constantly deflecting the flow of air to the anemometer, and at the buoy the same process may occur on a much smaller scale. The effect of surface friction on wind direction (Ekman spiral) was investigated as a possible explanation of why this bias was strongly present at the towers, however after research into literature [Gilhousen et al., 1987; Holton, 2004] it was found that any Ekman correction would increase the bias magnitude; nonetheless Ekman veering in the surface layer is negligible.

Unfortunately, due to the irregularity of statistical tests in the literature, it is complicated to compare the results reliably with the existing research. The RMS error results (overall 58.9°) are surprisingly high compared to the RMS errors of 30° and 32.5° calculated by Harlan & Georges [1994] and Helzel [2004]. However, the mean difference of 20° found by Huang et al. [2002] implies that the results obtained in this study are to some extent comparable to the literature. Figure 6 displays the effect of increasing wind speed on the RMS errors, and it is clear that at higher wind speeds the RMS error is more akin to the results expected of around 30°. The Grays Reef buoy measurements exhibit the largest difference, in addition to a slightly different trend, with a slight increase in difference at the highest wind speeds. This will be discussed further in the following section.

5.2 Complex Correlation

The overall correlation magnitude of 0.65 confirms that there is a relationship between the wind direction measurements from the two instruments. Figure 7, displaying the effect of increasing wind speed on the correlation, supports the results of Harlan & Georges [1994], Paduan et al. [1999] and Vesecky et al. [2005]; correlation between the two instruments improves with increasing wind speed. The strongest hypothesis for this result is that at higher wind speeds the radar measurements are more accurate. There are two reasons for greater accuracy, the first is the relationship between wind speed and wave height; increasing wind speeds lead to increasing wave heights (apparently
increasing the radar cross-section of the Bragg wave), this improves the backscatter to the receiving antennae resulting in a better SNR and therefore the radar measurement accuracy is improved (along with the correlation). Secondly, in higher wind speeds the directional spectrum of the wave field narrows, which improves the output of the angular directional model and thus the accuracy of the measurements. Another hypothesis set forward by Gilhousen [1987], who found similar results when comparing anemometers, is that wind direction is more variable at lower wind speeds, so the instruments will be measuring a more variable flow and thus the correlations would decline.

*Figure 8*, which displays correlation at wind speeds *less* than an increasing threshold speed, shows evidence of little to no correlation at wind speeds <5-6ms\(^{-1}\). Using the method of Vesecky et al. [2005], the phase speed of the shortest Bragg wave (1/2 \(\lambda\) of incident wave) could be calculated using the transmit frequency of 8.35 mHz where:

\[
\lambda = \frac{c}{v}
\]  

where \(\lambda\) is the incident wavelength (m), \(v\) is the wave frequency (hz) and \(c\) is the speed, which is 3*10\(^8\)ms\(^{-1}\) (speed of light) for radio waves. Using the transmit wavelength (36m) and the deep water approximation of linear wave theory [Craik, 2004] the phase speed of the shortest Bragg wave could be calculated:

\[
T = \sqrt{\frac{2\pi L}{g}}
\]  

\[
c = \frac{gT}{2\pi}
\]

where \(T\)= wave period (3.3s) and \(L\)= wavelength (36/2=18m). The speed \(c\) of the Bragg wave was calculated to be 5.3ms\(^{-1}\); this implies that when wind speeds are less than 5.3ms\(^{-1}\), the Bragg waves that the radar measures cannot have been generated by the wind, and therefore the data for the set of times when wind speeds are below this threshold should be discarded. *Figure 9* shows that at wind speeds less than this threshold of 5.3ms\(^{-1}\) (highlighted in red), the differences are almost evenly spread over the 360° range.

### 5.3 Effect of Landmass

To examine the reason for increasing correlation at stations further from the coast, the correlation between the measurements was performed in two sectors; one sector in which
the wind is blowing over the land (220°-10°), and one sector in which the wind is blowing over the open ocean (10°-220°). Figure 10 illustrates the two sectors used in the correlation.

![Figure 10](image)

**Figure 10.** Map of the SAB highlighting the two sectors: wind blowing over land (220°-10°) and wind blowing over open ocean (10°-220°). [Modified from: SKIO, 2009]

**Table 5.** Correlation magnitude for winds blowing over the land sector and the sea sector, for all measurements and at low wind speeds ≤8ms⁻¹ and high wind speeds >8ms⁻¹.

<table>
<thead>
<tr>
<th></th>
<th>LAND Sector</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector</td>
<td>Overall</td>
<td>0.46</td>
<td>0.61</td>
<td>0.73</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>≤8ms⁻¹</td>
<td>0.49</td>
<td>0.59</td>
<td>0.69</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>&gt;8ms⁻¹</td>
<td><strong>0.42</strong></td>
<td>0.66</td>
<td>0.85</td>
<td>0.87</td>
</tr>
<tr>
<td>SEA</td>
<td>Overall</td>
<td>0.47</td>
<td>0.60</td>
<td>0.63</td>
<td>0.62</td>
</tr>
<tr>
<td>Sector</td>
<td>≤8ms⁻¹</td>
<td>0.38</td>
<td>0.52</td>
<td>0.57</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>&gt;8ms⁻¹</td>
<td>0.77</td>
<td>0.86</td>
<td>0.89</td>
<td>0.91</td>
</tr>
</tbody>
</table>

**Table 5** reveals some interesting results. For winds blowing over the land, the correlation increases monotonically with station distance from the coastline. This is not observed with winds blowing over the open sea; the difference in correlation at the three Navy towers is negligible. This indicates that land affects the magnitude of the correlation. The radar requires a fully arisen sea state in which the wave field is in equilibrium with the wind; this requires sufficient wind speed, duration and fetch [US Army Engineers, 1984]. A possible explanation for the decline in correlation for the stations nearest the coast is that there is an insufficient length of sea for the wind fetch to fully develop. Under these circumstances, the wave field is not in complete equilibrium with the wind; this will decrease the accuracy of the radar measurements, since the angular directional model will not correctly estimate the direction of the waves from the wind. As the station
distance from shore increases, the fetch will increase, leading to more uniform conditions and an increase in radar accuracy and thus measurement correlation.

As expected, the correlation for both sectors at all the Navy towers (R2, R6, R8) is greater for wind speeds $>8\text{ms}^{-1}$ than at $\leq 8\text{ms}^{-1}$. This is not exhibited at Grays Reef however, where there is a marked decrease in correlation at the higher wind speeds. This again suggests limited fetch; higher wind speeds require longer fetch for a fully developed sea [US Army Engineers, 1984]. In the case of Grays Reef, the station closest to the coast, the fetch is so limited that the wave field is far less aligned with the wind than it is at lower wind speeds which require shorter fetch. This results in inferior wind measurements in higher wind speeds at this station, even accounting for the poorer accuracy at lower wind speeds. This is shown to some extent at the R2 tower, the second nearest to land, where the correlation at $>8\text{ms}^{-1}$ is only slightly improved than at $\leq 8\text{ms}^{-1}$.

During low speed wind conditions, the correlation between the instruments is greater at each location when the wind blows over the land than when it blows over the sea. This is most probably due to the inaccuracy of the radar. The wave field will have a narrower bandwidth for winds blowing over the land because the majority of the waves will be locally generated by the wind. This relates to a purer, more uniform wave field which will produce a good SNR and improve measurements. When the wind blows from offshore, the wave field will be diverse, comprising both locally generated and swell waves, which will exacerbate the SNR and lead to less accurate measurements. The reason that this pattern is not observed at higher wind speeds is because, as explained previously, at higher speeds a longer fetch is required to produce a fully arisen sea. This suggests that all the stations are to some extent affected by limited fetch for winds blowing over the land, since the correlation is worse than for the sea sector.

5.4 Buoy Measurements

It has been evident throughout the results that differences between wind direction measurements by radar and anemometer at the Grays Reef buoy is greater than the Navy towers. A hypothesis for this is that because the buoy is floating on the sea surface, it is affected by the sea state, unlike at the Navy towers. To test this hypothesis a complex correlation was performed on wind measurements made by the radar at different in-situ stations, and then with the anemometers at the different stations. By correlating the radar
and in-situ measurements against themselves, a measure of the precision of each instrument can be attained. The results are displayed in table 6.

<table>
<thead>
<tr>
<th></th>
<th>Radar Correlation</th>
<th>Anemometer Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR - R2</td>
<td>0.87</td>
<td>0.92</td>
</tr>
<tr>
<td>R2 - R6</td>
<td>0.91</td>
<td>0.98</td>
</tr>
<tr>
<td>R6 - R8</td>
<td>0.91</td>
<td>0.98</td>
</tr>
<tr>
<td>GR - R8</td>
<td>0.72</td>
<td>0.89</td>
</tr>
</tbody>
</table>

This table demonstrates two points; the in-situ instruments are better correlated than the radar cells and the Grays Reef buoy is less correlated with the tower stations for both instruments. This suggests that anemometers are more reliable at measuring wind direction than the WERA HF radar. The difference between the Grays Reef buoy measurements and the towers could support the theory that the anemometer on the buoy is affected by the wave field, although this contradicts the findings of Gilhousen [1987], who noted there was no significant error from the pitch and roll experienced by buoys. Another explanation is that Grays Reef uses a different anemometer type, which employs a longer averaging time of 10 minutes, compared with 6 minutes at the Navy towers. Further data is required to identify the source of this difference.

The radar correlations also exhibit smaller magnitudes at the Grays Reef location. A possible explanation is that radar measurements at Grays Reef, which is in 18m deep water, could be affected by the seabed. The Bragg wavelength was calculated (equation 11) as 18m which implies that it is not governed by shallow water equations in 18m deep water. However, the wave field it propagates in consists of a spectrum of wavelengths, some of which may be affected by the seabed and thus disturb the Bragg scattering. The shortest wavelength that is affected in 18m deep water is \( \lambda = 18 \times 4 = 72m \). Using the shallow water approximation of linear wave theory, the period of a wave with this wavelength was determined:

\[
T = \frac{L}{\sqrt{gh}}
\]

A wave period \( T \) of 5.4 seconds was calculated for the wavelength \( L \) (72m) in water depth \( h \) (18m) where \( g \) is acceleration due to gravity (9.81ms\(^{-2}\)). Next, using the dominant wave period measurements made at the Grays Reef buoy, a complex correlation was performed on data for the subset of times when the dominant wave period was less than 5.4 seconds;
this effectively removes data which may be affected by shallow water conditions. This improved the correlation at Grays Reef by 0.06, which indicates that at this location shallow water conditions can apply at times and lead to reduced radar accuracy. This same method was applied to the R2, R6 and R8 locations as well, which may also be affected by shallow water conditions at certain wavelengths. Note that Grays Reef was the only station which supplied wave period data, so this data was used at all four stations. Table 7 illustrates that all four stations exhibited improved correlation in the subset of times when the wave field was not governed by shallow water conditions.

Table 7. Calculated shallow water wave period for each station, along with correlations using all data, and using a subset of data when the dominant wave period was less than the threshold for shallow water conditions (using dominant wave period data at Grays Reef).

<table>
<thead>
<tr>
<th>Station</th>
<th>Shallow Water Period (sec)</th>
<th>Overall Correlation</th>
<th>Correlation (Tdwpd&lt;Td)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR</td>
<td>5.4</td>
<td>0.56</td>
<td>0.62</td>
</tr>
<tr>
<td>R2</td>
<td>6.6</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
<td>R6</td>
<td>6.9</td>
<td>0.71</td>
<td>0.74</td>
</tr>
<tr>
<td>R8</td>
<td>8.6</td>
<td>0.72</td>
<td>0.73</td>
</tr>
</tbody>
</table>

The greatest improvement is at Grays Reef where the shallow water period is smallest, indicating that the data was affected more often by non-linear affects in the wave field. The table still shows however, even after the correction, that Grays Reef exhibits the smallest correlation; this is because the data is affected by limited fetch in high wind speed conditions. Therefore, the correlation was performed again, but this time using only data at wind speeds greater than 5.3ms⁻¹, and for winds blowing over the open ocean with fully developed fetch (10°< & > 220°). Table 8 gives the correlation magnitude calculated with the original interpolated data, and then the correlation using the aforementioned constraints. Using data corrected for wind speed, fetch and wave period, it is shown that there is no significant difference between the correlations at the four locations.

Table 8. Correlation magnitude between the radar and anemometer. The first column displays the original correlation magnitudes, the second column displays the correlation for each station when wind speed >5.3ms⁻¹, dominant wave period > threshold values (GR-5.4s, R2-6.6s, R6-6.9s, R8-8.6s), and when winds are blowing across open sea, unlimited by fetch (10°< & <220°).

<table>
<thead>
<tr>
<th>Station</th>
<th>Correlation (before)</th>
<th>Correlation (after)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>0.65</td>
<td>0.71</td>
</tr>
<tr>
<td>GR</td>
<td>0.56</td>
<td>0.71</td>
</tr>
<tr>
<td>R2</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
<td>R6</td>
<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
<td>R8</td>
<td>0.72</td>
<td>0.69</td>
</tr>
</tbody>
</table>
With this knowledge, the radar measurements were corrected for wind speed, fetch and wave period and again correlated against one another. As expected, the results showed insignificant variation between stations; however the magnitudes were still less than the in-situ values, confirming the earlier finding that in-situ anemometers are more reliable than the radar.

5.4 Sources of Error

The WERA radar obtains time averaged measurements integrated over a finite space, whereas the anemometers obtain temporally averaged measurements at a fixed point. These two distinctly different methodologies will inevitably provide different results. Graber et al. [1997] studied the accuracy of HF radar on current measurements, they note that “…even if both the HF radar system and (in-situ) instruments provided perfect, noise-free estimates of the ocean vector current, comparison between their estimates would still exhibit differences”. This is because the instruments record different aspects of the spatially and temporally varying flow as well as using different averaging techniques (the radar averages over 7.5 min, whereas the anemometers average over 6 min (Navy towers) and 10 min (buoy)). Chapman & Graber [1997], in a paper validating current measurements by HF radar, divide observed errors into three categories: instrument errors, differing methodologies and physical processes (e.g. Ekman spiral, baroclinicity etc.). This leads to the question of accuracy of the WERA radar, and this report is unable to quantitatively isolate the radar errors from the other sources of observed difference. What this report has demonstrated is that the radar is sensitive to physical parameters; specifically wind speed, wind fetch and shallow water conditions which can affect the accuracy of the measurements.

6. Conclusions

There is a clear correlation between the measurements made by the WERA HF radar and the in-situ anemometers. This correlation increases with increasing wind speed, as the radar measurement accuracy improves due to an enhanced signal-to-noise ratio and a narrowing of the wave directional spreading which reduces the error in the model. It was found that the radar is unable to accurately measure wind direction at wind speeds less than 5.3ms⁻¹, as the Bragg waves could not have been locally generated by the wind. An examination of the winds blowing over the land illustrated that all the locations were
affected to some extent by limited fetch when wind speeds exceeded $8\text{ms}^{-1}$. Conversely, at low wind speeds, the correlation is greater for winds blowing over the land; the hypothesis is that the wave field comprises a narrower bandwidth of waves which improves the Bragg backscattering and the accuracy of the radar measurement.

It has been identified that at times when the dominant wave period exceeded a threshold value for each station, shallow water conditions applied, resulting in non-linear interaction and a diminished correlation with the in-situ measurements. After correcting the radar data by removing measurements affected by wind speed, fetch and wave period the correlation at each location showed no significant difference.

Correlation of anemometers at different stations, and the radar between its grid cells, found that the in-situ measurements were more closely related to one another, suggesting the anemometers are in general more reliable. However, the in-situ correlation highlighted that there is a difference between the buoy and tower, although with the data available it is not possible to determine whether this was a function of buoy inaccuracy or the difference in averaging times between the anemometers.

Disappointingly, RMS errors were high when compared with the few results published in literature, although the mean difference compared favourably to the higher value obtained by Huang et al. [2002]. The mean difference results indicate that the in-situ measurements are biased towards measuring winds counter-clockwise to the radar; it was suggested that this is an aerodynamic effect of the fixed structures the anemometers are attached to, although this is currently just speculation.

An interesting find is an apparent fault in coastal radar systems observing wind direction; at locations with proximity to the coast, when the wind is blowing over the land at wind speeds $>8\text{ms}^{-1}$ the measurements are inevitably inaccurate, possibly because the sea is not fully developed and therefore the observed waves are not in equilibrium with the wind direction.

This study has identified several sources of error inherent in the radar system measuring wind direction. The results indicate that the WERA radar wind direction measurements are more accurate under a fully arisen sea state when deep water conditions apply for the
entire wave spectrum. Under these circumstances, the WERA radar system performs well and is an exceptionally valuable technology that surpasses in-situ instruments by providing a rare view of near real-time mesoscale wind directions over the coastal ocean.

Further work needs to be done to identify and quantify the different sources of error between the instruments. Algorithms to further clean the radar data reliably should improve the comparisons. Using a longer dataset would be beneficial, in addition to more statistical analysis into the confidence of the results. Recently an algorithm has been developed and incorporated into the WERA system that uses the second order spectrum to estimate wind speed. The ability to map a true vector wind field using the WERA radar is extremely valuable and therefore validation and comparison of the measurements should be undertaken as soon as possible. The programs and scripts written to analyse the data in this study could be easily corrected for wind speed, allowing a quick determination of the accuracy of the measurements.
References


US Army Engineer Waterways Experiment Station, 1985. Coastal Engineering Research Center. Directional Wave Spectra Using Normal Distribution Model of Spreading Functions. CETN-I-6, Vicksburg, US.

