

Modelling and Characterisation of Radar Sea Clutter

By

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This thesis is submitted to the University of London for the degree
of Doctor of Philosophy in Electronic Engineering

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University College London
October 2001

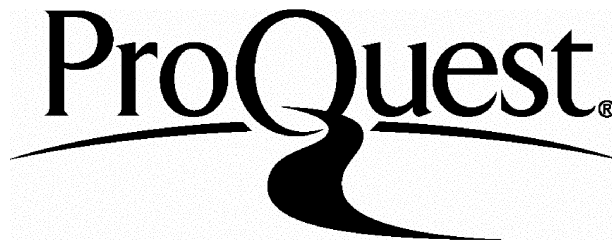
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Abstract

This thesis uses the analysis of radar data recorded in the controlled environment of a laboratory wave tank to develop ideas on the nature of the dominant mechanisms in microwave scattering from the sea surface. These ideas are then extended to the case of radar sea clutter recorded in coastal waters, and the individual mechanisms identified are investigated and reproduced using theoretical and numerical electromagnetic scattering calculations. In this way the stepping stone of the laboratory wave tank provides a link between the scattering calculations, necessarily performed for idealised surfaces, and radar clutter measurements made in operationally relevant and realistic environments.

Experimental observations made in the wave tank lead to the formulation of a Doppler model for radar backscatter from a water surface consisting of small scale ripples and larger, breaking waves. This model succinctly captures the polarisation and Doppler characteristics of the three scattering mechanisms found to be dominant, and can provide information on the relative strengths of two distinct types of scattering associated with steep and breaking waves. This ability to deconstruct the Doppler spectra into physically motivated basis components is shown to shed new light on the mechanisms which lead to the visibility in radar imagery of sea surface features caused by the modulation of surface waves by currents.

Using a powerful numerical scattering code running on a multi-processor computer, backscatter intensity and Doppler characteristics of the components which make up the model are reproduced. The results are found to compare well with both data recorded in the wave tank, and to established, perturbation model results.

To Claire

Acknowledgements

I would like to express my thanks to Professor Hugh Griffiths, of the Department of Electronic and Electrical Engineering, for his role as my supervisor at UCL. His help and encouragement throughout this piece of work have been very much appreciated. In addition, my sincere gratitude goes to Dr Keith Ward of TW Research, Malvern, for the time he has invested in critical review of this work at various stages of its development. His advice and guidance have been invaluable since the beginning of this course of study.

I owe thanks also to many people in the Maritime Radar and SAR groups at DERA (now QinetiQ) Malvern, in particular Shane Rouse, Bob Hill and Tim Lamont-Smith of the Ocean Imaging Group, not only for their support in the work which makes up this thesis, but for everything they have done to make the last four years so productive and enjoyable. A special thanks must go to Professor Marshall Tulin and his staff at the Ocean Engineering Laboratory, University of California, Santa Barbara, and to Andy Brownlow and the Full Scale Trials team at Thales Defence (formerly Racal), for all their assistance in the experimental aspects of this work. Also thanks to Val Ballard of QinetiQ Farnborough, for providing results from the laser slope meter experiments and to Zosia Huk, for her help in parts of the statistical analysis.

Contents

1	Introduction	20
1.1	Objectives	21
1.2	Thesis layout	22
1.3	Novel aspects	24
2	Overview of experimental and theoretical sea scattering	26
2.1	Background	26
2.2	Sea clutter prediction and measurement	28
2.2.1	Theoretical scattering predictions	28
2.2.2	Clutter measurement and empirical RCS modelling	34
2.2.3	Experimental Doppler measurements	37
2.2.4	Theoretical Doppler spectra and Doppler modelling	38
2.3	Statistical sea clutter models	41
2.4	Need for further research	44
3	Wave tank experiments and preliminary analysis	47
3.1	Introduction	47
3.2	Experimental facilities	47
3.2.1	The OEL wave tank	47
3.2.2	Radar systems	48
3.2.3	Surface truth measurements	50
3.3	Results from the MIDAS experiment	51

3.3.1	Calibration issues.....	51
3.3.2	Basic Doppler analysis.....	61
3.3.3	RCS measurements.....	73
3.3.4	Polarimetric phase statistics.....	76
3.4	Conclusions from preliminary analysis.....	85
4	A new Doppler model and application to wave tank data	87
4.1	Introduction.....	87
4.2	Synchronous radar and video data	88
4.3	Doppler modelling.....	95
4.3.1	Description of the model	95
4.3.2	Application to wave tank data.....	97
4.4	Discussion and conclusions.....	102
5	Analysis of cliff top radar data	104
5.1	Introduction.....	104
5.2	A comparison of cliff top and wave tank radar data.....	105
5.2.1	Cliff top radar set-up	105
5.2.2	Comparison of Doppler spectra.....	106
5.2.3	Further comparisons	110
5.3	Doppler modelling of cliff top data.....	115
5.3.1	Methodology	115
5.3.2	Confirmation of the scattering mechanisms.....	117
5.3.3	Application of the three component model	127
5.4	Scattering mechanisms in ship wake imagery	130
5.4.1	Aims.....	130
5.4.2	Imagery and Doppler spectra	131
5.4.3	Image enhancements	135
5.5	Conclusions.....	138

6	EM scattering calculations	140
6.1	Introduction.....	140
6.2	The need for numerical solutions.....	141
6.2.1	The failure of resonant models.....	141
6.2.2	Previous work	144
6.3	Bragg scattering with Forward-Back	146
6.3.1	RCS variation with grazing angle	146
6.3.2	Doppler spectra.....	148
6.4	Non-Bragg scattering.....	153
6.4.1	Forward-Back calculations from breaking waves.....	153
6.4.2	Radar data from breaking waves	157
6.5	Conclusions.....	165
7	Discussion.....	167
8	Conclusions and further work.....	174
8.1	Summary of conclusions.....	174
8.2	Further work	176
	References	178
	Appendix A : The Forward-Back method for EM scattering calculations..	185
	Appendix B : Polarimetric phase statistics	191
	Appendix C : The RSRE sea clutter model	194
	Appendix D : Application of the Central Limit Theorem and Chebyshev's	
	inequality	195

List of figures

2-1	Schematic of Bragg resonant scattering	31
2-2	Radar cross section and polarisation ratio as calculated from the composite Rice SPM for a number of underlying RMS tilt modulations	33
2-3	The empirical Georgia Institute of Technology (GIT) model for RCS for a number of mean wave heights	36
2-4	Examples of the basis functions used in Lee's lineshape analysis – the Gaussian (top), Lorentzian (centre), and a number of Voigtians (bottom) with the Voigt parameter varying from 0 towards ∞	40
3-1	A view down the large wave tank at the UCSB OEL (reproduced from Fuchs <i>et al</i> , 1997)	48
3-2	The MIDAS radar system with the F-band antennas mounted, at a low grazing angle	49
3-3	The MIDAS radar system with the F-band antennas mounted, at a moderate grazing angle	50
3-4	A schematic of the OEL wave tank and radar set-up	52
3-5	Simulated calibration curves at 3° and 6° grazing angles. The upper plots represent simulated returns from the water surface (solid line) and calibration sphere (triangles), and the lower plots are the recovered NRCS of the clutter	55
3-6	Simulated calibration curves at 12° and 24° grazing angles. The upper plots represent simulated returns from the water surface (solid line) and calibration sphere (triangles), and the lower plots are the recovered NRCS of the clutter	56
3-7	Recorded calibration curves at I-band, vertical polarisation, 6° and 12° grazing angles.....	57
3-8	Recorded calibration curves at J-band, vertical polarisation, 3° and 6° grazing angles.....	58

3-9	Calibrated range-time-intensity plots, I-band, 6° grazing angle, taken at 8 ms ⁻¹ wind speed (left) and 12 ms ⁻¹ wind speed (right).....	60
3-10	Calibrated RTI plots, I-band, 6° grazing angle, 1 m wavelength wavegroups with 6 ms ⁻¹ wind	61
3-11	Doppler spectra averaged over 30 seconds at F, I, J and K-bands, 6° grazing angle and 8 ms ⁻¹ wind speed. Red lines represent horizontal polarisation, black are vertical	62
3-12	J-band Doppler spectra at 6° grazing angle, with 12 ms ⁻¹ wind speed (top) and 8 ms ⁻¹ wind speed (bottom). The plots on the left are averaged over 30 seconds, those in the middle over one second in a period of low returns, and on the right over one second covering strong HH returns. Red lines are horizontal polarisation, black are vertical	64
3-13	Lineshape analysis of typical J-band data. Diamonds represent radar data. Top, vertical polarisation with best fit single Gaussian (left) and best fit combined Gaussian and Voigtian (right). Bottom, horizontal polarisation with best fit single Gaussian (left) and best fit combined Voigtian and Lorentzian (right)	66
3-14	Variation in spectral shape with wind speed. J-band, 6° grazing angle. Diamonds represent radar data, dotted lines are basis functions and solid lines are sum of basis functions	67
3-15	A clear example of a bimodal Doppler spectrum, with two Gaussian lineshapes fitted	68
3-16	Identification of the sources of the two Doppler components seen in figure 3-15. The time profile is shown along with the spectrum as averaged over the whole 30 seconds, and over just regions A and B.....	69
3-17	Unfiltered and filtered range-time-amplitude plots. The Doppler filtering technique removes the strong Bragg scattering returns to reveal a weak spike	70
3-18	Comparison of the predicted and measured Doppler shifts at 12 ms ⁻¹ and 8 ms ⁻¹	72
3-19	Calibrated RTI plot and Doppler spectra recorded at J-band, 6° grazing angle and 8 ms ⁻¹ wind speed. Dotted line in the Doppler plot represents HH, solid is VV	73
3-20	RTI plot after Doppler filtering at the Bragg resonant wave speed.....	75
3-21	Comparison of unfiltered and filtered data to the predictions of the composite Rice SPM.....	75
3-22	The phase difference distribution as derived assuming Gaussian statistics	76

3-23	One second data chunks plotted on Weibull paper. The dotted line represents a Rayleigh distribution, with a gradient of 2. The three lines on the left are all HH polarisation and cover a strong RCS feature.....	78
3-24	Third and fourth moments of data averaged over 250 ms compared to the expected value for a Gamma distribution	78
3-25	Phase difference distributions at F-band, covering 3-12 ms ⁻¹ wind speed and 6° to 24° grazing angle	80
3-26	Phase difference distributions at I-band, covering 3-12 ms ⁻¹ wind speed and 6° to 24° grazing angle	81
3-27	Phase difference distributions at J-band, covering 3-12 ms ⁻¹ wind speed and 6° to 24° grazing angle	81
3-28	Phase difference distributions at K and M-bands, 12 ms ⁻¹ wind speed, 24° grazing angle	82
3-29	Phase history of F, I, J and K-bands over approximately 0.25 seconds.....	82
3-30	Comparison of theoretical and best fit distributions to each frequency at 5 ms ⁻¹ wind speed and 24° grazing angle.....	83
3-31	Comparison of low (top) and high (bottom) wind speed data to theoretical and best fit distributions	85
4-1	Doppler spectra at J-band, 6° grazing angle, of 2.3 m wavelength breaking wave groups taken with the MIDAS radar	88
4-2	RTI plots from the UCSB C-band radar of 2.3 m breaking waves. Regions t ₁ , t ₂ and t ₃ cover different stages in the wave's breaking process	89
4-3	Doppler spectra averaged over the entire breaking process. The peak at 0 Hz is an artefact, not a clutter feature.....	90
4-4	Video frame, simultaneous range profile and Doppler spectra from t ₁ (top), t ₂ (middle) and t ₃ (bottom)	91
4-5	Breaking wave RTI plots from the MIDAS radar at J-band showing the same features as the UCSB C-band radar data	92
4-6	RTI plots of 12 ms ⁻¹ wind waves taken with the UCSB radar, and Doppler spectra averaged over range-time area A	93
4-7	Doppler spectra averaged over range-time areas B and C, covering a wind blown spike and whitecap respectively	94
4-8	Simultaneous video frame and range profiles of area C. The possible polarisation independent whitecap return is highlighted	94
4-9	Schematic of the Doppler model, showing all the main features seen in Doppler spectra.....	97

4-10	UCSB C-band radar data at 12 ms ⁻¹ wind speed, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH.....	99
4-11	MIDAS I-band data at 10 ms ⁻¹ wind speed, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH.....	100
4-12	MIDAS J-band data at 10 ms ⁻¹ wind speed, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH.....	100
4-13	MIDAS K-band data at 12 ms ⁻¹ wind speed, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH.....	101
4-14	MIDAS J-band data of 2.3 m breaking wave groups, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH.....	102
5-1	RTI plots of I-band cliff top radar data and wave tank data.....	106
5-2	Doppler spectra of cliff top and wave tank radar data taken at moderate wind speeds.....	107
5-3	Doppler spectra of cliff top and wave tank radar data taken at higher wind speeds.....	108
5-4	Lineshape analysis applied to cliff top data	109
5-5	Lineshape analysis applied to wave tank data.....	109
5-6	Comparison of RCS measured in the wave tank to GIT and RSRE models at various wind speeds	111
5-7	Comparison of RCS measured in the wave tank to GIT and RSRE models at various grazing angles.....	112
5-8	Amplitude distributions of cliff top and wave tank data plotted on Weibull paper	113
5-9	Cliff top radar polarimetric phase difference distributions with comparisons to theoretical and best fit curves.....	114
5-10	30 second average Doppler spectra, looking upwind, wind speed 10 ms ⁻¹ gusting to 15 ms ⁻¹	117
5-11	30 second average Doppler spectra, looking downwind, wind speed 7 ms ⁻¹ gusting to 10 ms ⁻¹	118
5-12	Time series, looking upwind, showing Bragg scattering	119
5-13	Doppler spectra of data in figure 5-12	120

5-14	Autocorrelation functions of data in figure 5-12	120
5-15	Time series, looking upwind, showing a whitecap	121
5-16	Doppler spectra of data in figure 5-15	122
5-17	Autocorrelation functions of data in figure 5-15	122
5-18	Time series, looking upwind, showing an HH spike	123
5-19	Doppler spectra of data in figure 5-18	123
5-20	Autocorrelation functions of data in figure 5-18	124
5-21	Time series, looking downwind, showing Bragg scattering	124
5-22	Doppler spectra of data in figure 5-21	125
5-23	Autocorrelation functions of data in figure 5-21	125
5-24	Time series, looking downwind, showing a whitecap.....	126
5-25	Doppler spectra of data in figure 5-24	126
5-26	Autocorrelation functions of data in figure 5-24	127
5-27	3 component Doppler model fitted to average upwind data	128
5-28	3 component Doppler model fitted to downwind data	128
5-29	Bragg scattering polarisation ratio as calculated from the composite Rice SPM at various grazing angles and RMS tilt angles	129
5-30	RTI plots of a ship generated internal wave wake. VV (top), HH (middle) and HH with wake peaks and troughs boxed (bottom)	132
5-31	Doppler spectra and three component fits for wake peaks (left) and wake troughs (right).....	133
5-32	Doppler spectra (top) and variance spectra (bottom) of vertical polarisation data from the Portland and Sognefjord experiments.....	134
5-33	Unprocessed (top left) and processed (top right) images, and cuts through the images at 60 m.....	136
5-34	Unprocessed (top left) and processed (top right) images, and cuts through the images at 540 m.....	137
6-1	A steepening wave approaching breaking point produced by the numerical code CHY	142
6-2	RCS scattering surface as calculated using Rice SMP with underlying tilt modulation given by the CHY waves in figure 6-1. The ridges along the top of the waves represent the breakdown of the resonant model owing to steepness and curvature beyond the model's region of validity	143

6-3	Examples of simplified whitecap surfaces (after Ward, 2001). Correlated random Gaussian noise is added to a Gaussian hump. The noise amplitude is increased from very small (left) to larger values (right)	145
6.4	Variation in VV (left) and HH (right) RCS with increasing amplitude of Gaussian noise roughness. Solid lines represent the Rice resonant value, crosses represent FB calculated results (after Ward, 2001).....	146
6-5	Simulated tilted rough surface for Bragg scattering calculations using the FB code. Correlated Gaussian noise is added to an underlying long sine wave, and the whole surface is Hanning weighted to give zero height and slope at the edges.....	147
6-6	FB calculated RCS variation with grazing angle. Each point is the mean of the calculation from 10 realisations of a surface such as the one in figure 6-5.....	148
6-7	J-band Doppler spectra from the MIDAS radar, 3 ms ⁻¹ wind speed, 24° grazing angle	149
6-8	Simulated resonant surface with no underlying tilt.....	150
6-9	Example of phase variation with time (left) and Doppler spectra (right) as calculated by the FB code for the 'sliding' rough surface.....	150
6-10	The 2-dimensional filtering process to produce a correlated range-time surface with characteristics defined by the capillary wave dispersion relation	151
6-11	Waterfall plot of the range-time scattering surface	152
6-12	Example of phase variation with time (left) and Doppler spectra (right) as calculated by the FB code for range-time surface	152
6-13	A steepening and breaking wave generated by the numerical code LONGTANK.....	153
6-14	Comparison of FB scattering calculations from the LONGTANK waves with an example of a breaking wave RCS profile as measured by the UCSB C-band radar	154
6-15	F-band RCS and polarisation ratio as calculated by the FB code.....	155
6-16	I-band RCS and polarisation ratio as calculated by the FB code	155
6-17	J-band RCS and polarisation ratio as calculated by the FB code	156
6-18	K-band RCS and polarisation ratio as calculated by the FB code.....	156
6-19	M-band RCS and polarisation ratio as calculated by the FB code	156
6-20	MIDAS radar F-band time profile (left) and RTI of a 2.3 m breaking wave..	157
6-21	MIDAS radar I-band time profile (left) and RTI of a 2.3 m breaking wave...	157

6-22	MIDAS radar J-band time profile (left) and RTI of a 2.3 m breaking wave ..	158
6-23	MIDAS radar K-band time profile (left) and RTI of a 2.3 m breaking wave..	158
6-24	MIDAS radar M-band time profile (left) and RTI of a 2.3 m breaking wave .	159
6-25	2.3 m and 3 m wave RCS values at various frequencies recorded over 4 minutes	160
6-26	1.5 m, 2 m, 3.5 m and 4 m RCS values at various frequencies recorded over 4 minutes	161
6-27	Two close to identical breaking wave profiles (left) and an expanded view of the tip (right) produced by the CHY numerical code	163
6-28	Mean RCS value plotted against the ratio of the water wavelength to the radar wavelength	164
6-29	Mean rise rate plotted against radar frequency for 2.3 m (left) and 3 m (right) breaking waves.....	165
A-1	Schematic scattering surface	185

List of tables

3-1	Comparison of theoretical and best fit parameters at each frequency, and the VV and HH normalised variance.....	84
3-2	Comparison of theoretical and best fit parameters at different wind speeds and grazing angles, and the VV and HH normalised variance	84
4-1	Three component model parameters used in the fits to the data in figures 4-10 to 4-14	98
5-1	Peak shift and Doppler width (full width at half maximum) for cliff top and wave tank data.....	108
5-2	Comparison of vertical polarisation RCS values as measured in the wave tank, and predicted by the GIT and RSRE models	111
5-3	Three component model parameters used in the fits to the up and downwind data	129
5-4	RCS ratios calculated using the three component model for an ambient clutter area, and areas covering wake peaks and troughs.....	131
6-1	Number of waves imaged in 4 minutes, mean RCS (m^2) and standard deviation for each radar band.....	162
6-2	Comparison of scattered field intensity for two close to identical breaking waves.....	162
C-1	Parameters for use in the RSRE sea clutter model	194

Symbols and abbreviations

a	Voigt parameter
A	Amplitude of radar backscatter
B	Magnetic flux density
B	Antenna beamshape function
B, W, S	Amplitude coefficients of Bragg, whitecap and spike components of Doppler spectrum
c_B	Overall Bragg scatterer speed
c_{BP}	Bragg wave phase speed
c_d	Stokes drift velocity
CFAR	Constant False Alarm Rate
CLT	Central Limit Theorem
d	Water depth
DERA	Defence Evaluation and Research Agency
E	Electric field
EM	Electro-Magnetic
FB	Forward-Backward
f_d	Doppler frequency
FM	Frequency Modulation
g	Acceleration of free fall
g_{HH}, g_{VV}	Reflection coefficients for horizontal and vertical polarisation
GIT	Georgia Institute of Technology

H	Magnetic field
h	Antenna height
H	Gravity wave trough to crest height
HH	Horizontal polarisation transmit-receive
I	In-phase component of radar backscatter
j	Current
k	Wavenumber = $2\pi/\text{wavelength}$
<i>k</i>	Wavevector
K	Gravity wave wavenumber
k_0	Magnitude of the complex correlation co-efficient
$K_v(x)$	Modified Bessel function of order v
LGA	Low Grazing Angle
LRP	Lorentz Reciprocity Principle
MCR	Maritime Cliff-top Radar
MFIE	Magnetic Field Integral Equatiion
MIDAS	Mobile Instrumented Data Acquisition System
M_n	Normalised n^{th} moment of intensity
MOMI	Method of Ordered Multiple Interactions
NRCS	Normalised Radar Cross Section
OEL	Ocean Engineering Laboratory
P	Power
$P(\alpha)$	Probability distribution of tilt angles
PRF	Pulse Repetition Frequency
Q	Quadrature component of radar backscatter
R	Range
R_0	Slant range at beam centre
RADAR	RAdio Detection And Ranging

RCS	Radar Cross Section
R_{G0}	Ground range to beam centre
RMS	Root Mean Square
RSRE	Royal Signals and Radar Establishment (forerunner of DERA Malvern)
RTI	Range-Time-Intensity
SAR	Synthetic Aperture Radar
SPM	Small Perturbation Model
UCSB	University of California, Santa Barbara
v	Scatterer velocity
VV	Vertical polarisation transmit-receive
$W(\Delta)$	Probability distribution of the phase difference of co-polar radar backscatter
w_B, w_W, w_S	Width parameters of Bragg, whitecap and spike components of Doppler spectrum
Δ	Phase difference of co-polar channels in a polarimetric radar
Γ	Characteristic width of Lorentzian
Ω	Gravity wave angular velocity
$\Psi_G(v)$	Gaussian spectral lineshape
$\Psi_L(v)$	Lorentzian spectral lineshape
$\Psi_V(v)$	Voigtian spectral lineshape
$\Psi(k_x, k_y)$	Two dimensional wavenumber spectrum
α	Composite surface local tilt angle
χ^2	Chi-squared goodness of fit parameter
ε	Relative permittivity (Dielectric constant)
ϕ	Angle from beam centre
ϕ_0	Phase of the complex correlation co-efficient
$\phi_{1/2}$	Beam half angle width

γ	Water surface tension divided by bulk density
$\gamma(\tau)$	Autocorrelation function at time lag τ
$\eta(\mathbf{x})$	Surface height at position $\mathbf{x}$
λ	Wavelength
μ	Relative permeability
μ_A	Mean amplitude
μ_P	Mean power
ν	Frequency
ν	Order parameter in K and Gamma distributions
ν_0	Centre frequency
ν_e	Half width at 1/e folding of Gaussian
θ, θ_g	Radar grazing angle
$\rho(\mathbf{x})$	Autocorrelation function of surface height
σ	Radar cross section
σ	Standard deviation
σ^o	Normalised radar cross section
ω	Angular frequency
$\psi_B(\nu), \psi_w(\nu), \psi_s(\nu)$	Bragg, whitecap and spike components of Doppler spectrum

Chapter 1 Introduction

Since its inception as a military tool during the Second World War, radar has been used extensively in maritime environments from cliff top, shipborne and airborne platforms. For radar operation in such environments to be successful a complete understanding of the unwanted background returns from the sea – the clutter – is necessary, principally to be able to discriminate between the clutter and a target of interest. This can be accomplished in one of two ways. First, in a purely statistical manner, by experimentally determining a good fit to the distribution of the amplitude returns from sea clutter. These distribution models can then be incorporated into detection algorithms to improve, and hopefully optimise, their performance. The alternative approach is to consider the physics of the scattering of electromagnetic (EM) waves from the sea surface and determine the expected characteristics of radar backscatter, principally in terms of radar cross section (RCS) and form of the Doppler spectrum. This is the more fundamental method of attacking the problem, being based purely on Maxwell's equations and the properties of the scattering surface, but is also by far the more expensive in terms of computational power and time. A perfect knowledge of both the scattering mechanisms and the water surface would lead directly to the statistics of the amplitude returns. It is precisely because neither the hydrodynamics of the sea surface nor the scattering of EM waves from it are completely understood that the statistical models are tackled separately. Both of these approaches have been areas of active research for many years now, and

complement each other in leading towards a more complete understanding of radar sea clutter.

1.1 Objectives

The aim of the work described in this thesis is to use a combination of the experimental and theoretical approaches to gain a more complete understanding of the scattering mechanisms and physical processes which are important in the clutter observed in maritime radar. In particular, by use of controlled laboratory wave tank experiments, the backscatter from breaking waves is investigated in some detail. Scattering from such features has been considered key in the understanding of sea clutter for many years, but has received little attention in terms of fully instrumented and reproducible experiments. By concentrating initially on this controlled though somewhat artificial laboratory environment, ideas can be easily and clearly developed and validated. If successful, the extension of these ideas to the more operationally relevant case of coastal cliff top radar is found to be straightforward, far more so than any attempt at this type of analysis without the stepping stone provided by the wave tank.

The tank also provides a unique opportunity for comparison of the predictions of theoretical electromagnetic scattering calculations with actual radar data. Attempts to perform such a comparison using open water sea clutter are very rarely carried out – an ill defined and unrecorded water surface together with uncontrolled environmental conditions mean that defining a suitable input surface for a scattering calculation is exceptionally difficult. Such comparisons are possible in the wave tank, however, demonstrating once again how the laboratory can provide a vital bridge between theoretical work and radar operation in realistic scenarios.

Throughout this work, particular emphasis is placed on the information which can be extracted from the Doppler spectrum of sea clutter. Several recent pieces of work (discussed in the next chapter) have demonstrated that simply recording one or two of the parameters of the spectrum, such as the position of the Doppler peak or the spectral width, does not fully characterise the spectrum and discards much of the information contained in the data. The extraction of as much information as possible from the spectrum is considered here by detailed investigation of the Doppler signatures of individual scattering processes, and the extent to which they contribute to the overall spectrum. This analysis is applied to theoretical scattering calculations, wave tank data and cliff top radar data.

1.2 Thesis layout

Chapter 2 of this thesis gives an overview of the current understanding of radar sea clutter and EM scattering from ocean like surfaces, together with important historical background references. This review concentrates on the experimental and theoretical characterisation and modelling of RCS and Doppler spectra of sea clutter, highlighting the work which is of particular relevance to that presented here. The chapter concludes with a summing up of the work which is needed to be done to further the understanding of this topic, and outlines how this piece of work attempts to address some of these needs.

Chapter 3 describes the planning, execution and analysis of two experiments conducted at the large wind wave tank of the Ocean Engineering Laboratory (OEL), University of California, Santa Barbara (UCSB). These experiments form an extensive data set covering a variety of radar operating modes and wind-wave conditions and, when coupled with surface truth measurements recorded in a variety of ways, characterise radar scattering from controlled water waves to a far higher fidelity than is possible in open water environments. Calibrated RCS measurements,

average Doppler spectra, amplitude statistics and phase statistics are presented over a wide matrix of radar and environmental parameters.

The work presented in chapter 4 uses high resolution radar data recorded in synchronisation with high speed video images to identify and isolate precise phases in the evolution of a breaking wave which give rise to different and readily identifiable scattering processes. These mechanisms are identified in terms of their Doppler signature and polarisation characteristics, and it is demonstrated that average Doppler spectra are very well modelled by a linear sum of these components. The model is applied to radar data from mechanically generated breaking waves and wind blown waves at a number of different radar frequencies.

Chapter 5 considers the application of the Doppler model developed using wave tank data to coastal, cliff top radar data. This first requires consideration as to how well the laboratory set-up actually reproduces scattering from the sea surface. In answering this question it is demonstrated that the same scattering mechanisms found to be dominant in the wave tank are also present in coastal sea clutter. The lack of surface truth measurements in the cliff top experiment requires a method of analysis based solely on the radar data to identify the scattering processes and hence justify the application of the Doppler model. The chapter concludes with an example of how the Doppler model can be used to extract information about the scattering processes which give rise to weak signatures in clutter.

Chapter 6 details the use of a numerical scattering code based on the Forward-Backward method [Holliday, 1996] for RCS predictions of scattering from a deterministic surface. Papers in the open literature have shown that this method can reproduce some of the more prominent scattering features seen in sea clutter, and this chapter concentrates on using the code to reproduce each of the scattering

processes identified in the wave tank and cliff top experiments, including the well understood resonant scattering phenomenon. As the code produces the complex scattered field, access to the phase information allows for the calculation of Doppler spectra and comparison with data recorded in the wave tank.

Chapter 7 draws together the results and conclusions from the previous chapters to give a general discussion and critical overview of what has been achieved as measured against the initial objectives of the work.

Chapter 8 presents the final conclusions and suggests ways in which this work could be taken further in the future, both in terms of continuation of the fundamental underpinning research and possible applications.

1.3 Novel aspects

The work in chapter 3 on the polarimetric phase statistics of clutter in the wave tank, and the trends in the distribution with wind speed, grazing angle and frequency is, to the best of the author's knowledge, the only work of its kind carried out in controlled laboratory conditions and covering such a wide matrix of measurements.

The identification of the precise Doppler and polarisation characteristics of individual features on the water surface, and the use of this knowledge to model the overall Doppler spectrum, is original work and has been published by the author individually [Walker 2000]. The application of this modelling technique to coastal radar sea clutter is also new and has again been published individually by the author [Walker 2001]. The novel use of the Doppler model to extract information on the scattering processes giving rise to weak modulations is original, though currently unpublished.

The accurate reproduction of resonant scattering RCS values and Doppler spectra using a dielectric surface in a numerical scattering code, and the successful comparison of these results to radar data is believed to go further than any published work in using this scattering code to simulate realistic sea clutter returns.

Chapter 2 Overview of experimental and theoretical sea scattering

2.1 Background

The modelling and understanding of radar sea clutter is a continually evolving problem, owing principally to the ever improving technology which drives a radar's design and capabilities. Early maritime surveillance radars were typically low range resolution, incoherent, fixed frequency and fixed polarisation instruments, with low transmit power limiting the stand off ranges achievable. The sea clutter models developed for use with such radars gradually became redundant, with each additional technical improvement requiring further levels of complexity and flexibility to be incorporated. This need for more complex and accurate clutter models has, in turn, driven forward research in the fundamental physics of electromagnetic scattering from the sea surface. With the continuing development of the capabilities of surveillance radars, such as high resolution long range synthetic aperture radars and imaging using inverse synthetic aperture systems, it is unlikely that the models used today will suffice for the future, necessitating continuing research in this area.

The problem of understanding and modelling sea clutter can be approached in two ways. The first, more fundamental of these is to consider the pure physics of the problem of electromagnetic scattering from a rough, dielectric surface and seek solutions to Maxwell's equations to predict the backscatter characteristics of a given geometry and environment. Owing to the complexity of the sea surface, in particular

its roughness on length scales ranging from swell waves hundreds of metres long to foam and spray on the millimetre scale, such an approach necessarily involves a vast amount of simplification and approximation before being realistically tractable. Even when considering scattering from stylised individual features, such calculations can often be extremely costly in terms of computing time and power. Greatly increased processor speeds available over recent years have made this a more practical option than previously. In the past, however, a more pragmatic solution was required. This second approach involves taking large numbers of sea clutter measurements and developing empirical or semi-empirical models which describe the data well. If measurements are made over a large enough variety of radar and environmental parameters, such models can predict clutter characteristics to an acceptable accuracy. This method is of particular use in statistical modelling of sea clutter. Large amounts of radar data suitable for statistical analysis are relatively easy to collect, whilst the limitations given above mean that it is impractical to attempt to generate such data from theoretical scattering calculations.

Both the theoretical and experimental analysis of sea clutter have been affected by two significant developments to maritime surveillance radar: the move to ever higher range resolutions, and the drive for increased stand – off ranges requiring lower grazing angles. With low range resolutions, that is, range cells of the order of tens to hundreds of metres, the backscattered power in each range bin comes from very many individual scatterers. Statistically, this means that the Central Limit Theorem (CLT) will apply, resulting in Gaussian statistics overall. From a scattering point of view, over such a large sea surface area, no one feature is likely to dominate the backscattered power and calculations of the RCS can be based on some assumed roughness or height distribution for the surface. Increased range resolution to modern day standards of well under one metre lead to the breakdown of the CLT and strong non-Gaussianity of the resulting statistics. The smaller range cell also means

that one single feature can easily dominate the backscattered power, requiring a different approach to the scattering problem.

Low grazing angle geometries are found to exacerbate these problems. Shadowing, specular scattering from steep waves and other effects associated with shallow look angles add to the non-Gaussian nature of the clutter and further complicate any attempt at scattering calculations.

In the next section, developments along both the theoretical and experimental lines are presented, with the measurement and modelling of sea clutter Doppler spectra considered separately owing to its particular relevance to this piece of work. The statistical modelling of sea clutter is also discussed.

2.2 Sea clutter prediction and measurement

2.2.1 Theoretical scattering predictions

One of the standard approaches to the problem of EM scattering from rough surfaces, and one which is in some circumstances applicable to radar sea scattering, is the physical optics or Kirchhoff approximation [see for example Beckman & Spizzichino, 1987],

$$\mathbf{B}_{scat}(r') = \frac{i \exp(ikr')}{2\pi r'} \frac{k^2}{k_z} \mathbf{B}_0 \int dx dy \exp(-i2\mathbf{k}_H \cdot \mathbf{x}) \exp(i2k_z \eta(\mathbf{x})) \quad [2-1]$$

where $\mathbf{B}_{scat}$ is the scattered magnetic field, $\mathbf{x}$ is a vector defining the position in the surface plane, at which the surface height is $\eta(\mathbf{x})$, k is the modulus of the incident wave vector with components $\mathbf{k}_H$ in the surface plane and k_z normal to the plane, and $\mathbf{B}_0$ is the incident magnetic field. This can be converted to a scattering cross section by

$$\sigma = \lim \left\{ \frac{4\pi r'^2}{A} \frac{\langle |\mathbf{B}_{scat}(\mathbf{r}')|^2 \rangle}{\mathbf{B}_0^2} \right\} ; r' \rightarrow \infty \quad [2-2]$$

giving the final form for the Kirchhoff RCS

$$\sigma = \frac{k^4}{\pi k_z^2} \int d^2 \mathbf{x} \exp(-2i\mathbf{k}_H \cdot \mathbf{x}) \exp(-4k_z^2 \langle \eta^2 \rangle (1 - \rho(\mathbf{x}))) \quad [2-3]$$

where ρ is the autocorrelation function of the surface height η . Equation 2-3 shows that the Kirchhoff approximation has no polarisation dependence, and is found to be a very poor description of radar sea clutter in the low grazing angle regime. The early 1950s saw the appearance of two new methods which proved particularly applicable to such geometries. In the first, known as the small perturbation model (SPM), Rice [Rice, 1951] derives the scattered fields in both horizontal and vertical polarisations from a surface which is considered to be, in Rice's words, 'almost, but not quite, flat'. Scattered fields from a perfectly conducting surface are derived to second order, and for a dielectric to first order, with an indication of how second order terms could be obtained. This paper is heavily referenced by later authors and contains much of the fundamental physics of LGA rough surface scattering, but does not provide an easily accessible formula for a radar scattering model which makes clear the trends with grazing angle, polarisation, radar frequency etc. It was also believed for some time that the SPM and Kirchhoff approximation were incompatible, leading some to question the validity of the SPM. This controversy was finally resolved by Holliday [Holliday, 1987] who demonstrated that the Kirchhoff result did indeed reduce to the SPM in the limit of small surface height and slope.

The second method, due to Kerr [Kerr, 1951], is based on the Lorentz Reciprocity Principle (LRP). In a short appendix to the text book *The propagation of short radio*

waves' he outlines the reciprocity theorem and its application to scattering from large scale smoothly varying objects. The theorem itself comes from a quite simple manipulation of Maxwell's equations to relate incoming and scattered electric and magnetic fields in the presence and absence of a target. Assuming harmonic time variation, Maxwell's equations give

$$\nabla \wedge \mathbf{H} = (\mathbf{j} + i\omega\epsilon)\mathbf{E} \quad [2-4]$$

$$\nabla \wedge \mathbf{E} = -i\omega\mu\mathbf{H} \quad [2-5]$$

where $\mathbf{j}$ is the current, ω is the angular frequency, ϵ is the relative permittivity and μ the relative permeability. If $\mathbf{E}_1$ and $\mathbf{H}_1$ are the electric and magnetic fields in the absence of a target, and $\mathbf{E}_2$ and $\mathbf{H}_2$ are those with a target in place, then, by forming four scalar products one can show that

$$\mathbf{H}_2 \cdot \nabla \wedge \mathbf{E}_1 - \mathbf{E}_1 \cdot \nabla \wedge \mathbf{H}_2 - (\mathbf{H}_1 \cdot \nabla \wedge \mathbf{E}_2 - \mathbf{E}_2 \cdot \nabla \wedge \mathbf{H}_1) = 0 \quad [2-6]$$

and, by recognising a vector identity and using the divergence theorem

$$\int_S \mathbf{n} \cdot (\mathbf{E}_1 \wedge \mathbf{H}_2 - \mathbf{E}_2 \wedge \mathbf{H}_1) dS = 0 \quad [2-7]$$

where $\mathbf{n}$ is the outward normal to the surface S enclosing the region of interest. Equation 2-7 represents the Lorentz Reciprocity Principle and from this, the RCS of the object can be calculated as

$$\sigma = \frac{k^2}{4\pi E_0 B_0} \left| \int_T (\mathbf{E}_1 \wedge \mathbf{B}_2 - \mathbf{E}_2 \wedge \mathbf{B}_1) \right|^2 dS \quad [2-8]$$

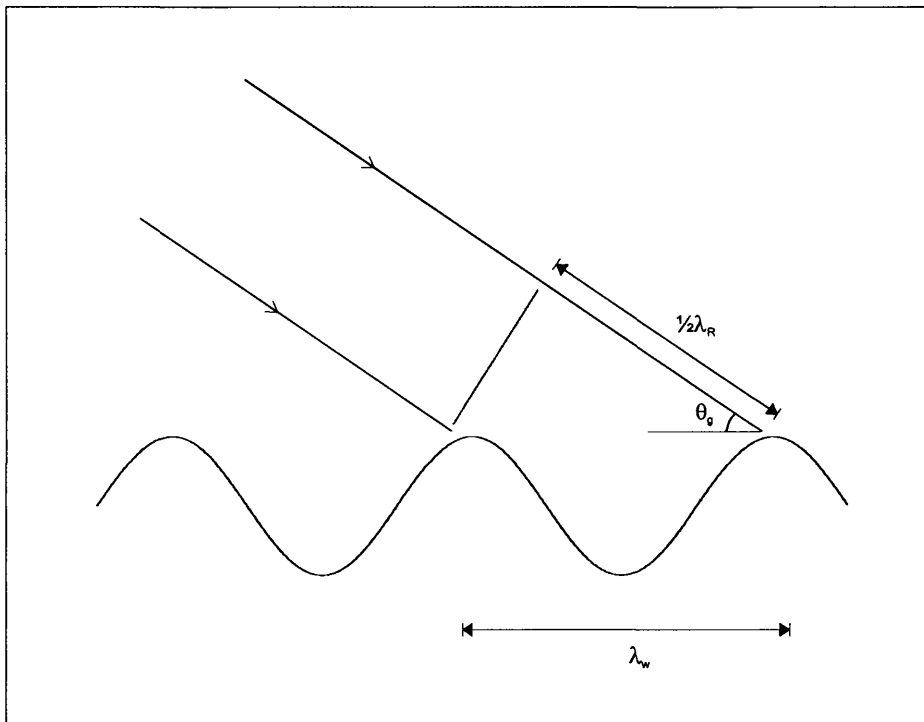
where σ is the RCS, k is the incident wavenumber, E_0 and B_0 are the magnitudes of the incident fields and T is the surface of the target. Kerr considers only perfectly conducting targets, and by use of certain approximations, recovers the Kirchhoff RCS result

Although this section is concerned with the development of theoretical scattering calculations, an important experimental result must be mentioned at this point. In a

1955 paper, Crombie [Crombie, 1955] reported on a set of experimental data and gave 'a tentative explanation' for the features seen. The data was a Doppler spectrum of 13.56 MHz radio waves backscattered from the sea surface. The tentative explanation was that the sea waves were acting in a manner analogous to a diffraction grating, giving constructive interference when the path difference of two rays is an integer number of radar wavelengths, as shown schematically in figure 2-1. This model quickly gained wide support, and was termed 'Bragg scattering' because of the similarity to the well established Bragg resonant scattering phenomenon seen in x-ray crystallography. The first order resonant relationship between water wavelength and radar wavelength is easily calculated as

$$k_w = 2k_R \cos \theta_g \quad [2-9]$$

where k_w is the water wavenumber ($k=2\pi/\lambda$), k_R is the radar wavenumber, and θ_g is the radar grazing angle.



2-1 : Schematic of Bragg resonant scattering

This form of resonant scattering is readily incorporated into rough surface scattering via a Fourier description of the surface heights. Starting from the Rice SPM, and including the Bragg resonance formula by defining the scattering surface in terms of a wavenumber spectrum $\Psi(k_x, k_y)$, a relatively simple form for the radar cross section's dependence on transmit frequency, polarisation and grazing angle can be obtained [Valenzuela, 1967]

$$\sigma_{ij}(\theta_g) = 4\pi k_R^4 \sin^4 \theta_g \left| g_{ij}(\theta_g) \right|^2 \Psi(2k_R \cos \theta_g, 0) \quad [2-10]$$

$$g_{HH}(\theta) = \frac{\epsilon - 1}{\left[\sin \theta + (\epsilon - \cos^2 \theta)^{1/2} \right]^2} \quad [2-11]$$

$$g_{VV}(\theta) = \frac{(\epsilon - 1)[\epsilon(\cos^2 \theta - 1) - \cos^2 \theta]}{\left[\epsilon \sin \theta + (\epsilon - \cos^2 \theta)^{1/2} \right]^2} \quad [2-12]$$

$$g_{HV} = g_{VH} = 0 \text{ (to first order)}$$

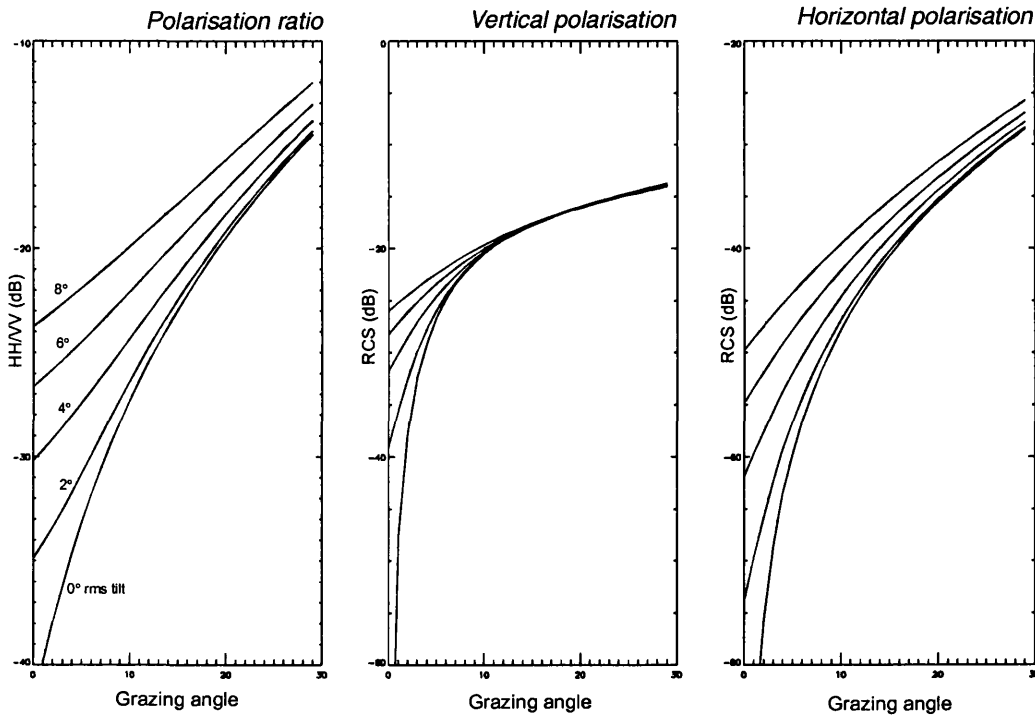
where HH refers to horizontal polarisation transmit and receive, VV to vertical transmit-receive, and HV and VH to the cross polar terms. Analogous results to these can be obtained starting from the LRP [Wright, 1966]. These formulae give the exact result for Bragg resonant scattering from a slightly rough, flat surface and in some situations (moderate grazing angles, low wind speed and no swell) provide accurate values for both horizontal and vertical polarisation RCS, assuming the form of the sea surface wavenumber spectrum is known. In cases in which it is not known, standard models such as the Phillips, Pierson-Moskowitz, or Donelan-Banner-J  nhe spectra may be used, [Phillips, 1958], [Pierson & Moskowitz, 1964], [Apel, 1994]. To add further realism, however, and make the model more widely applicable, it is necessary to include the effect of large swell waves. This can be done by assuming that the effect of such a wave is to tilt a small patch of the surface towards or away from the radar by an angle α , altering the local grazing angle. Assuming such tilts

have a Gaussian distribution (following work on sun glint from the sea surface [Cox & Munk, 1954]), the modified, composite RCS can be found by integrating equation 2-10 over all such tilt angles [Wright, 1968, Valenzuela, 1968].

$$\sigma_{ij}^{comp} = \int d\alpha \cdot \sigma_{ij}(\theta_g + \alpha) P(\alpha) \quad [2-13]$$

$$P(\alpha) = \frac{1}{\alpha_{rms} \sqrt{2\pi}} \exp\left(-\frac{\alpha^2}{2\alpha_{rms}^2}\right) \quad [2-14]$$

This description of composite surface resonant scattering model is presented in its most accessible form in Valenzuela's review paper [Valenzuela, 1977] and is still often used to describe phenomena observed with lower resolution radars operating at moderate grazing angles, such as satellite imagery of ship wakes [Hennings et al, 1999]. Figure 2-2 shows the predicted variation in RCS and polarisation ratio with grazing angle and underlying root mean square tilt angle (α_{rms}), assuming 3 cm wavelength radiation and a Phillips wavenumber spectrum.



2-2 : Radar cross section and polarisation ratio as calculated from the composite Rice SMP for a number of underlying RMS tilt modulations

The composite model includes only scattering from small scale ripples with wavelengths of the same order as the incident radiation. No consideration is given to breaking waves or other individual scattering features which may become important at high resolution and low grazing angle. Over recent years, several new techniques for the numerical calculation of solutions to Maxwell's equations to give the backscattered field from a deterministic surface have been developed, among the most successful being the Method of Ordered Multiple Interactions (MOMI). One such MOMI technique, the Forward-Backward method, has been used in particular for the study of backscatter from breaking waves at low grazing angles [Holliday et al, 1996, 1998], and has also been shown to be robust in the calculation of scattering from random rough surfaces [Kapp & Brown, 1996]. The method, outlined in more detail in appendix A, takes its name from the manner in which iterations are performed to calculate the backscattered magnetic field, separating the contributions from the forward and backward propagating surface currents. This technique is used in scattering calculations presented in chapter 6.

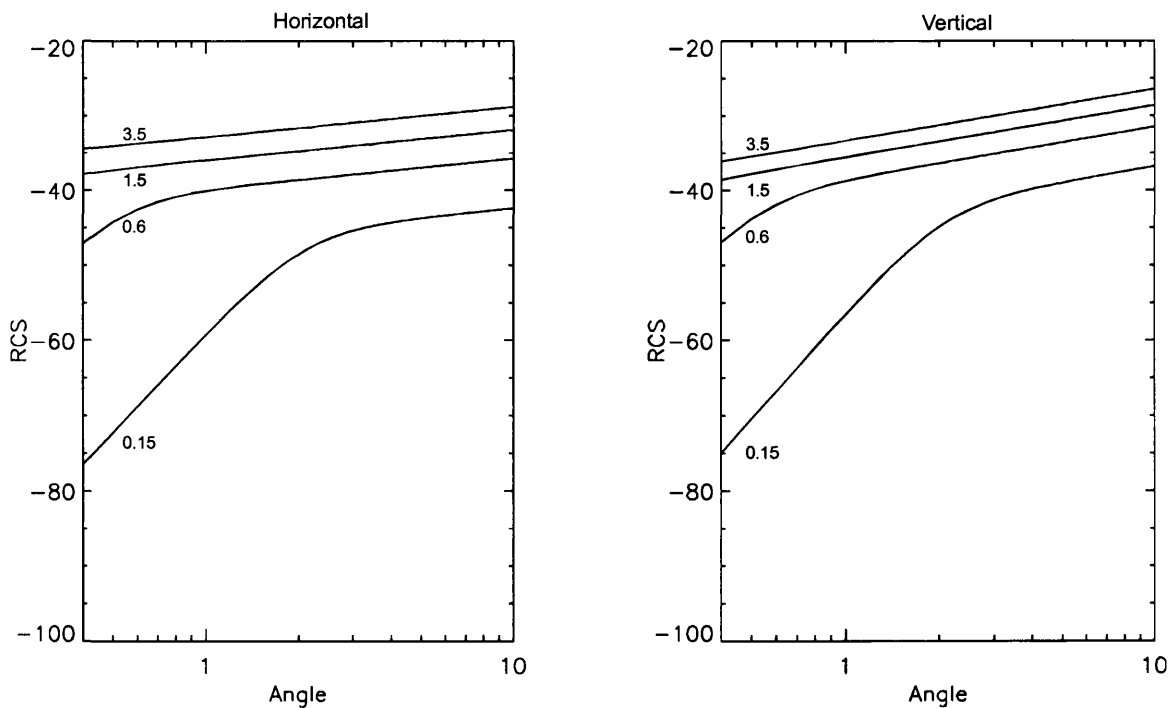
2.2.2 Clutter measurements and empirical RCS modelling

For some time after the popularisation of Bragg resonant scattering by Crombie's experimental results and the Bragg based scattering theories of Valenzuela and Wright, it was considered that such models were sufficient to describe low grazing angle sea clutter backscatter. However, a string of experimental results began to show that this was not the case. Airborne radar data collected by the US Naval Research Laboratory in the late 1960s showed average radar cross section values in horizontal polarisation at low grazing angles far higher than predicted by the Rice SPM [Guinard & Daley, 1970]. In later wave tank experiments [Duncan et al, 1974], polarisation ratios of unity ($HH=VV$) were observed at high wind speeds, suggesting that such deviations from Bragg theory are associated with individual energetic breaking waves. Using a shipborne radar with boresight mounted telescope, Long

[Long, 1974] confirmed that these high RCS HH events, or 'spikes', were associated with sharply crested or breaking waves, and can in fact have cross sections greater than that seen in VV, in direct contradiction to Bragg theory in which HH can never exceed VV. Many subsequent authors have confirmed the presence of HH spikes in LGA sea clutter (for example, [Lewis & Olin, 1980], [Trizna et al, 1991], [Rosenberg et al, 1995, 1996]) and each has attributed the phenomenon in some way to steep or breaking waves. The term spike has come to mean any discrete HH backscatter event which is clearly non-Bragg, whilst the term 'superevent' has been coined to refer to instances in which the HH RCS becomes greater than VV. It has been the regular observation of such features in LGA, high resolution radar data which has motivated much of the recent work on EM scattering calculations from breaking waves, such as Holliday's work with Forward-Back.

Given that average sea clutter RCS measurements almost invariably display polarisation ratios incompatible with either the Rice SPM or composite model, owing to the contribution of spikes, and that the exact nature of these spikes and their relation to environmental parameters such as wind speed are as yet unknown, a possible way forward is to empirically model the clutter RCS variation using a large database of measurements. Several organisations have independently produced such models, one of the most widely used being the Georgia Institute of Technology (GIT) model [Horst et al, 1978]. This model takes inputs of radar wavelength, grazing angle and azimuth look direction relative to the wind. As with many of these empirical models, problems arise in the description of the sea surface roughness. Traditionally, the 'sea state' index (a single number running from 0 being a flat calm up to 7 or 8 representing storm like conditions) has been used. Others choose to use the wind speed alone, or the significant wave height (mean peak to trough height of the highest third of the waves). Example tables and plots of the relationships between each of these measures of roughness can be found in [Skolnik, 1970]. The GIT

model takes wind speed as the parameter, and presents a suggested relationship between this and significant wave height. The resulting HH and VV RCS values for a number of wave heights are given in figure 2-3. Note the differences between these plots and those in figure 2-2. Whilst empirical models such as the GIT clearly offer a more complete and realistic description of sea clutter RCS than pure Bragg scattering models, the fact that their predictions are so sensitive to the ill defined sea state or wind speed parameter is disconcerting. The choice of exactly how wind speed, wave height and sea state are related can affect the GIT RCS predictions by around ± 3 dB, which can have a significant effect on radar performance calculations, for which empirical clutter models are often used. Also, the GIT model is somewhat at variance with certain other clutter models in its treatment of propagation and ducting effects. This can lead to significant differences between the GIT predictions and those of, for example, Sittrop or RSRE models [Sittrop, 1977], [Potter, 1975] at long ranges, again with significant effect on performance predictions.



2-3 : The empirical Georgia Institute of Technology (GIT) model for RCS for a number of mean wave heights

2.2.3 Experimental Doppler measurements

In tandem with the early experimental evidence for the non-Bragg nature of sea clutter RCS described in the previous section, Doppler measurements were increasingly shedding light on the precise behaviour of these non-Bragg events. As early as 1960, experimental Doppler spectra from a low range resolution radar [Hicks, 1960] showed that, whilst at low wind speeds the spectra were symmetrical, at higher wind speeds they were clearly skewed to the high frequency side. Given the increased number of breaking waves at high wind speeds, and the fact that these waves travel significantly faster than the small Bragg resonant ripples, it was concluded that these must be the source of the fast scatterers. Differences in the spectra of the two polarisations were also soon noted [Pidgeon, 1968, Mel'nichuck & Chirikov, 1970], the peak shift in horizontal polarisation being found to exceed that in vertical by a factor of 2 to 4. Possible explanations for this polarisation dependence included suggestions that vertical polarisation, having a greater penetrating power than horizontal, was exhibiting some type of volume scattering effect, whilst horizontal backscatter was purely a surface mechanism, or that both polarisations were undergoing Bragg scattering but of a different order, such that the waves from which they were scattering were of different wavelengths and so moving at different speeds, according to their dispersion relation. However, steep or breaking waves remained the most probable source of the fast scatterers, a view strengthened further by wave tank experiments [Duncan et al, 1974].

The polarisation characteristics of the Bragg and non-Bragg contributions to Doppler spectra were highlighted by Lee et al [Lee, 1995, 1996]. By filtering data in the Fourier domain, the fast and slow components of the spectra could be isolated and the RCS and polarisation ratios of each studied individually. The slow component's RCS was found to be well described by the Rice SPM at grazing angles of 20° and over, whilst the model was found to underpredict the data below this angle. It is likely

that the use of a tilted composite model would rectify this disparity. The fast scatterers, however, showed a polarisation ratio far from the Rice value, with horizontal polarisation greater than or equal to VV. When viewed as a whole, experimental evidence in the open literature (of which the references presented here are only a small sample) clearly points to the conclusion that non-Bragg, fast scattering is associated in some way with breaking waves and can give rise to instances of horizontal polarisation being equal to or exceeding vertical.

2.2.4 Theoretical Doppler spectra and Doppler modelling

Initial attempts at purely theoretical calculation of the Doppler spectra of sea clutter were based on Bragg scattering alone, and hence could not reproduce the observed polarisation dependence of the fast scatterers [Valenzuela & Laing, 1970]. More recent work, still based just on resonant scattering, has attempted to introduce slow and fast components as free and bound capillary waves, the bound variety being parasitic capillaries on the front of crested gravity waves [Zavoritny & Voronovich, 1998]. Full numerical scattering calculations on time varying surfaces have in some cases been performed with encouraging results, particularly in the observed polarisation differences of the resulting spectra [Toporkov & Brown, 2000]. A semi-empirical model, which calculates the backscatter from a time evolving surface using the well understood SPM for Bragg scatter and experimentally derived values for the fast non-Bragg RCS, has been shown to produce realistic looking spectra [Caponi et al, 1999], but has certain critical shortcomings such as a lack of any polarisation dependence of the fast scatterers, which is at odds with many experimental results.

A different approach to Doppler analysis, due to Lee et al [1995b, 1998] sacrifices somewhat any attempt to theoretically predict the form of the spectrum, and instead uses a set of physically motivated basis functions to model it and, from the combinations giving the best fit, infer which scattering mechanisms are dominant.

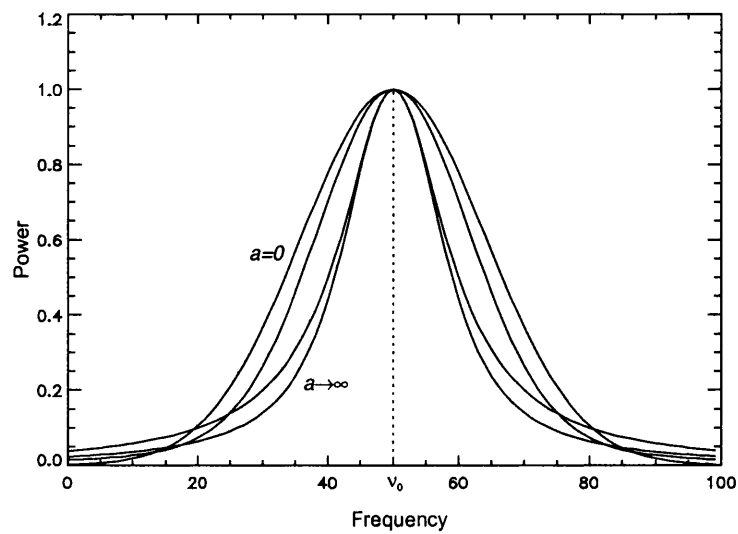
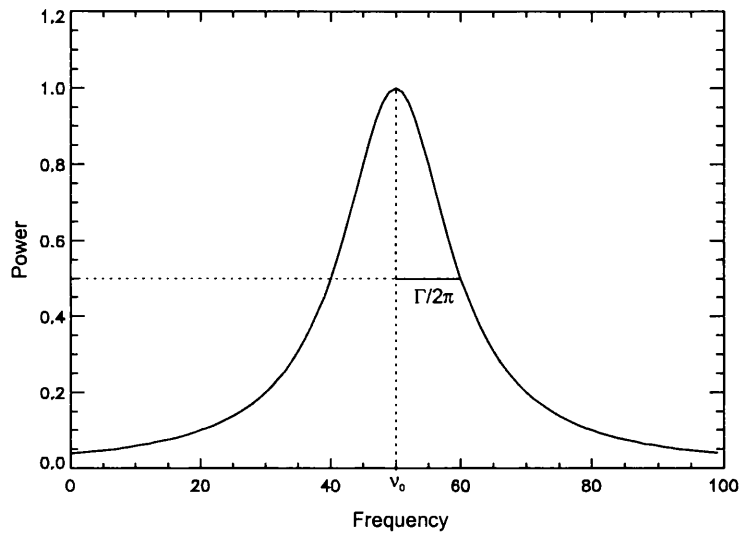
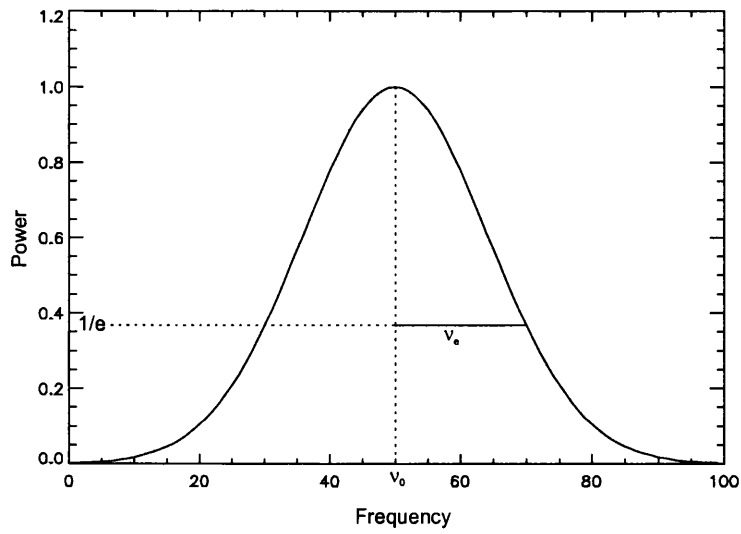
The three functions used are the Gaussian, Lorentzian and Voigtian. It is argued that the scatterers contributing to the Bragg component in the spectrum will have a Gaussian spread of speeds, giving rise to a Gaussian power spectrum. Non-Bragg scattering from facet-like scatterers at the tips of steep waves would be a lifetime dominated process. Such a process, if all the scatterers are assumed to be moving at the same speed, would result in a Lorentzian power spectrum. The convolution of these two, a Voigtian, would come about from lifetime dominated scatterers with a Gaussian spread of speeds. Figure 2-4 shows these three functions, which are given explicitly in equations 2-15, 2-16 and 2-17.

$$\Psi_G(\nu) = \frac{1}{\nu_e \sqrt{\pi}} \exp\left(-\frac{(\nu - \nu_0)^2}{\nu_e^2}\right) \quad [2-15]$$

$$\Psi_L(\nu) = \frac{\Gamma / 2\pi^2}{(\nu - \nu_0)^2 + (\Gamma / 2\pi)^2} \quad [2-16]$$

$$\Psi_V(\nu) = \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{\exp(-y^2)}{\left(\frac{\nu - \nu_0}{\nu_e} - y\right)^2 + a^2} dy \quad [2-17]$$

where subscripts G, L and V refer to Gaussian, Lorentzian and Voigtian lineshapes, ν_0 is the centre frequency of each spectrum, ν_e is the half width at 1/e folding of the Gaussian, $\Gamma/2\pi$ is the half width at half maximum of the Lorentzian, and $a = \Gamma/2\pi\nu_e$ is the Voigt parameter, giving the ratio of the Lorentzian width to that of the Gaussian. A Voigt parameter of 0 gives a Gaussian, whilst $a \rightarrow \infty$ leads to the Voigtian tending towards a Lorentzian.



2-4 : Examples of the basis functions used in Lee's analysis - the Gaussian (top), Lorentzian (centre) and a number of Voigtians (bottom) with the Voigt parameter varying from 0 towards ∞

Application of these lineshapes to sea clutter spectra collected in a number of different experiments [Lee 1995b] shows the data well described by, in general, a combination of two out of the three lineshapes. Vertical polarisation usually takes the form of a large, dominant slow Gaussian and a small, faster Voigtian. This may be interpreted as vertical polarisation comprising of mainly Bragg scattering, with some fast non-Bragg scatterers at a variety of speeds. Horizontal polarisation is found to be best described by a combination of a narrow, fast Lorentzian defining the Doppler peak, and a low, wide Voigtian stretching out the skirts of the spectra. This indicates the dominance of non-Bragg scattering in horizontal polarisation, with an explicit Bragg term often entirely absent. This lineshape analysis can also be applied to data of large breaking waves, which show non-Bragg dominance in both polarisations, with a small Bragg contribution at low speeds seen in the vertical [Lee et al, 1998].

2.3 Statistical sea clutter models

The modelling of the amplitude statistics of sea clutter is motivated primarily by the need to incorporate such models into maritime surveillance radars' detection algorithms in clutter limited environments. Accurate clutter modelling can lead to substantial improvements in detection performance. Certain aspects of this work, in particular the development of statistical models which, rather than simply providing good fits to the data have some physical basis, have led to an increased understanding of the nature of sea clutter.

Early clutter models, given their intended application to low resolution radar data, were naturally based on the central limit theorem, giving Gaussian In-phase (I) and Quadrature (Q) returns, leading to a Rayleigh amplitude (A) distribution ($A^2 = I^2 + Q^2$).

$$P(I) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{\frac{-I^2}{2\sigma^2}\right\} \quad [2-18]$$

$$P(Q) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{\frac{-Q^2}{2\sigma^2}\right\} \quad [2-19]$$

$$P(A) = \frac{2A}{\mu_p} \exp\left\{\frac{-A^2}{\mu_p}\right\} \quad [2-20]$$

where σ is the standard deviation of the Gaussian process, and μ_p is the mean power of the clutter returns, this being related to the mean of the Rayleigh amplitude distribution μ_A by

$$\mu_p = \frac{4\mu_A^2}{\pi} \quad [2-21]$$

High range resolutions and low grazing angle geometries bring about the collapse of the CLT and increased spikiness of the clutter. A number of models may be used to describe the resulting long tailed distributions, such as the Log-Normal, Weibull and K-distributions. Of these, the K-distribution is in many ways the most satisfactory in that it not only models clutter very well in a variety of conditions, but owing to its possible representation in compound form, gives some physical insight into the clutter behaviour which can be used to improve detection performance [Ward, Baker, Watts, 1990], [Watts, Baker, Ward, 1990]

The K-distribution clutter model assumes the amplitude returns are made of two components: a rapidly fluctuation, Rayleigh distributed speckle component, modulated by a slowly varying Gamma distributed mean power. Following the treatment of Watts [Watts, 1987], if $P(x)$ represents the overall compound amplitude distribution, and $P(y)$ is the distribution giving the mean power fluctuation, then

$$P(x) = \int_0^{\infty} P(x|y)P(y)dy \quad [2-22]$$

where y , the mean of the Rayleigh speckle distribution, is given by

$$P(y) = \frac{2b^{2\nu} y^{2\nu-1}}{\Gamma(\nu)} \exp\{-b^2 y^2\} \quad [2-23]$$

where b is a shape parameter, and the speckle distribution itself is given by combining equations 2-20 and 2-21 and letting μ_A be the random variable y

$$P(x|y) = \frac{\pi x}{2y^2} \exp\left\{\frac{-\pi x^2}{4y^2}\right\} \quad [2-24]$$

The overall amplitude distribution can then be found by combining equations 2-23 and 2-24 in equation 2-22, and recognising the integral form of the modified Bessel function $K_\nu(x)$

$$P(x) = \frac{4c}{\Gamma(\nu)} (cx)^\nu K_{\nu-1}(2cx) \quad [2-25]$$

where $c=b\sqrt{(\pi/4)}$. This concise representation of the K-distribution belies the power of the compound description of sea clutter. Separation of the statistics into slow and fast varying components allows a cell averaging CFAR algorithm to take full advantage of pulse to pulse integration, which will reduce the quickly decorrelating speckle (particularly if frequency agility is used) whilst leaving the mean clutter level unchanged. This significant physical insight intrinsic to the model has been shown experimentally to lead to improved detection performance over other possible amplitude distributions, such as those mentioned above.

Whilst amplitude statistics clearly contain useful information about the clutter, the phase of the backscattered radiation in a coherent radar has a uniform distribution when examined over a reasonable length of time. However, the distribution of the phase difference between two channels of a multi-channel radar (such as a polarimetric or interferometric system) can be shown to be non-uniform. Assuming

Gaussian statistics, but also applicable to K-distributed clutter, the phase difference distribution can be shown to be

$$W(\Delta) = \frac{(1 - k_0^2)}{2\pi} \left[\frac{\beta \left(\frac{1}{2}\pi - \sin^{-1} \beta \right)}{(1 - \beta^2)^{3/2}} + \frac{1}{1 - \beta^2} \right] \quad [2-26]$$

where $\beta = k_0 \cos(\Delta - \phi_0)$, Δ is the phase difference between the two channels and ϕ_0 and k_0 are shape parameters (see appendix B). This distribution has been explored to some extent with regard to multi look SAR imagery of land [Lee et al, 1994], and interferometric systems [Barber, 1993], but little has been published on the polarimetric phase statistics of sea clutter. This area is explored further in chapter 4.

2.4 Need for further research

As mentioned several times in this chapter, the modelling and understanding of radar sea clutter evolves in parallel with the advances made in experimental and in service radar systems. So long as these advances continue, there is a need for continuing research into the nature of sea clutter backscatter in each new system. However, as processing methods become more sophisticated, the form of simple features in sea clutter can become somewhat convoluted. As an example, consider the form of a short lifetime sea spike in SAR imagery. A SAR system with a 2° beamwidth, operating at a range of 10 km on a platform with a speed of 100 ms^{-1} requires a target to be stationary in the beam for approximately 3.5 seconds for a fully focused point in the image to be formed. Quite apart from the fact that breaking waves which cause sea spikes are moving, they may only last for a fraction of that time, leading to unfocused streaks in the image instead of sharp spikes. Such a representation may make identification of the precise scattering event responsible for the feature in the image difficult. This simple example shows why, for a full understanding of clutter characteristics in complex imaging systems, a more fundamental approach can sometimes be necessary.

The most fundamental of approaches is that of theoretical and numerical EM scattering calculations. This has, however, remained thus far unable to satisfactorily explain the complete nature of non-Bragg scattering from breaking waves. The most useful results in this area have come from laboratory wave tank experiments or other experiments in which the scattering surface has been recorded or viewed simultaneously to the radar measurements. The importance of Doppler analysis to deduce the speeds of the different types of scatterers as well as their temporal variations is clear, and the information which can be extracted from the spectra above and beyond simply the peak shift and width is demonstrated in Lee's lineshape analysis.

The work presented in this thesis attempts to link together laboratory experimentation, cliff top sea clutter experiments and numerical scattering calculations. This is done starting from a series of wave tank experiments which aim to characterise the clutter over a number of different radar modes and wind/wave conditions. The use of words such as spike, fast non-Bragg scatterer and super event in the literature can sometimes vary from author to author and a clear definition of exactly what a spike is, what its temporal, Doppler and polarisation characteristics are and the form of the wave which causes it does not appear to exist. Using controlled laboratory experiments, concentrating on strong individual features in the data, these questions can be answered. The next question must then be whether this characterisation of non-Bragg scattering holds true in environments outside of the laboratory. This too is considered here, with the foundation provided by the laboratory work allowing for a detailed investigation of prominent features in a different light to that possible before. Finally, the scattering mechanisms identified can be investigated using numerical methods, with the possibility of direct comparison to laboratory data, thus bridging the gap between the theoretical and experimental methods of attacking the sea clutter problem.

By considering sea scattering on three different levels – numerical codes, laboratory experiment and full scale cliff top trials – it is hoped that this piece of work will give a more complete picture of the nature and characteristics of sea clutter than those given before, linking together what have previously been separate approaches.

Chapter 3 Wave tank experiments and preliminary analysis

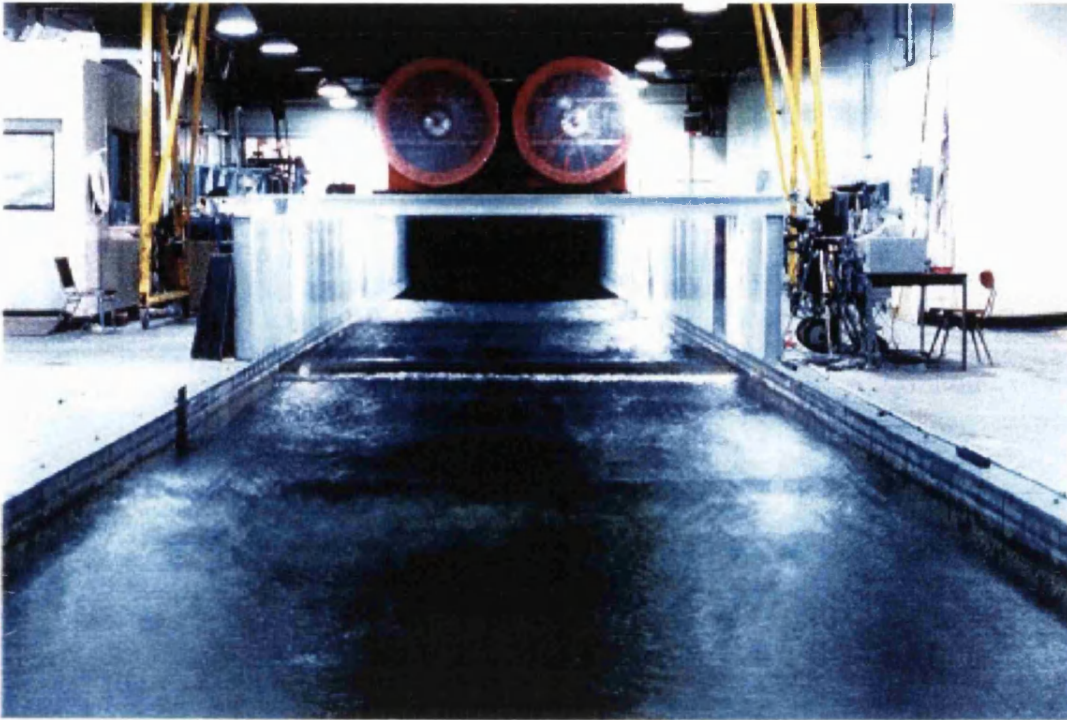
3.1 Introduction

During 1998 and 1999, several collaborative experiments were conducted by the Radar Ocean Imaging group at DERA Malvern and the Ocean Engineering Laboratory of the University of California, Santa Barbara, at the OEL's large wind wave tank facility. Two experiments in particular will be described in this and the following chapters. The first was a three week data collection trial using a multi frequency polarimetric radar capable of imaging at various grazing angles. The aim of this trial was to set up a large database of radar measurements in a controlled environment covering as many combinations as possible of radar modes, grazing angles, wind speeds and wave types. Including calibration measurements, over two terabytes of data were collected. The second experiment was shorter and more focused, concentrating explicitly on high resolution measurements of breaking waves at 6° grazing angle with synchronous high speed video imaging.

3.2 Experimental facilities

3.2.1 The OEL wave tank

The UCSB OEL large wind-wave tank is 53.34 m long, 4.27 m wide and 2.13 m deep. A wind tunnel extends 30.48 m down the tank, leaving an open test section of just over 23 m. A wooden beach at the test end of the tank reduces wave reflections. Wind turbines can produce windspeeds of up to 12 ms⁻¹, and a computer controlled



3-1 : A view down the large wave tank at the UCSB OEL (taken from Fuchs et al, 1997)

plunging wavemaker can produce wave groups of wavelength 0.6 m – 10 m, the breaking of which can be controlled via the sideband (Benjamin-Feir) instability. In this way it can be ensured that waves break in the test section of the tank, and so in the radar footprint. A view down the wavetank is shown in figure 3-1 (taken from [Fuchs et al, 1997]). The mechanically generated breaking waves and the wind wave fields produced by the turbines are considered repeatable enough (once an equilibrium has been reached) for results from separate days or even separate experiments to be fully comparable.

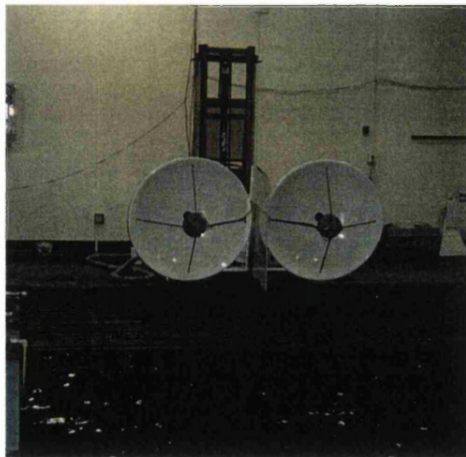
3.2.2 Radar systems

Two different radar systems were used for the two experiments. For the three week data collection trial, the Thales Defence (formerly Racal Thorn Wells) Mobile Instrumented Data Acquisition System, MIDAS, was used. This system operates with a linear FM chirped pulse of 500 MHz bandwidth, with possible centre frequencies of

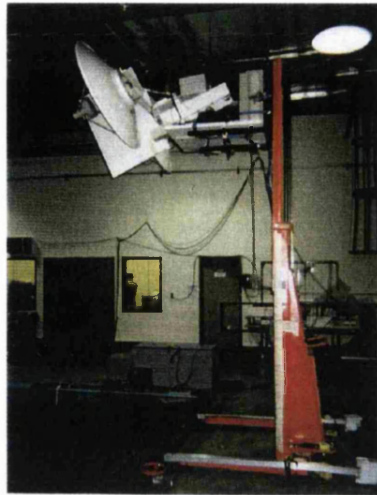
3 GHz, 9.75 GHz, 15.75 GHz, 35 GHz and 94 GHz, which will be referred to as F, I, J, K and M bands respectively. Each of these bands requires a different antenna head, precluding pulse to pulse frequency agility. Pulse to pulse polarisation agility, however, is possible and the typical pulse repetition frequency (PRF) of 2 kHz gives an unambiguous Doppler bandwidth of ± 500 Hz per polarisation.

In order to vary the grazing angle of the radar, MIDAS was mounted on a fork lift, as shown in figures 3-2 and 3-3, here with the F-band antennas attached. In this way, grazing angles from 3° to 24° were possible for all bands except F, in which case the physical size of the antennas allowed a minimum of 6° grazing.

The second experiment, in which synchronous radar and video measurements were made, utilised the UCSB C-band radar, which operates with a 4 GHz bandwidth centred on 6 GHz, giving a 3.75 cm range resolution. Polarisation agility with a PRF of 1 kHz gives an unambiguous Doppler bandwidth of ± 250 Hz. The radar is fixed at 6° grazing angle.



3-2 : MIDAS radar system with the F-band antennas mounted, at a low grazing angle



3-3 : MIDAS radar system with the F-band antennas mounted, at a moderate grazing angle

The physical size and shape of the laboratory meant that in both experiments the radars were required to be mounted looking directly down the tank, allowing for no variation in radar look direction relative to wind and wave direction.

3.2.3 Surface truth measurements

As already mentioned, in the second radar experiment surface truth was provided by a side looking high speed digital video camera. Operating at 250 frames per second, this provided a visual of the scattering surface for every other pulse in each polarisation. The field of view of the camera was relatively limited, covering about 1 m in range. However, the controllability of the breaking wave groups made it possible to ensure that a breaking event was captured in the area imaged.

In a separate experiment to the two outlined above, a laser slope meter was used to characterise the water surface in terms of along tank and across tank slopes for each wind speed and wave group [Taylor, 1999]. The slope meter was mounted in the tank covering the area around the centre of the test section, making simultaneous radar measurements impossible. Although these measurements were not made at the same time as the radar experiments, the reproducibility of the waves in the tank

means that the results on average wave period, slope and height are applicable to data gathered at other times, and will be referred to in this and later chapters.

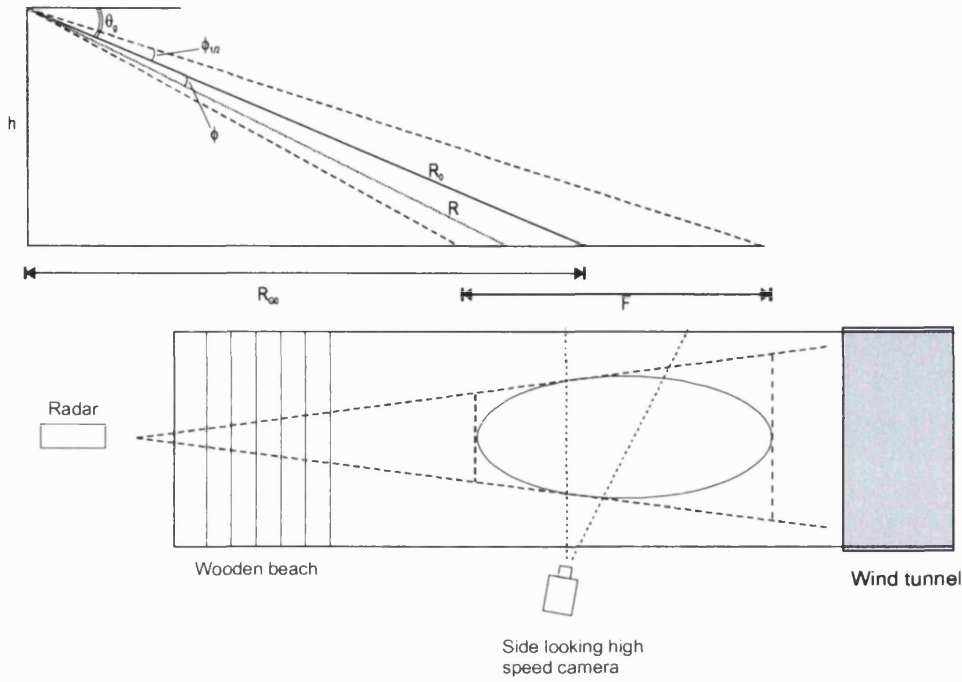
3.3 Results from the MIDAS experiment

3.3.1 Calibration issues

In order to produce normalised RCS values from the power backscattered to the radar, it was necessary to calibrate the radar by measurement of a known target. Also, operating at such a close range, the elevation beamshape of the radar would be expected to have a larger effect than range fall off, requiring calibration measurements in each rangecell to provide a full mapping of the beam. This was done by moving a 12" metal sphere hung from a kevlar thread through the radar beam in the range direction. This results in a curve giving the returned power in each rangecell from a target of known RCS, which can be used to calculate the RCS of the clutter simply as

$$\sigma = \frac{P}{P_{sp}} \sigma_{sp} \quad [3-1]$$

where σ is the clutter RCS and P the power returned by the clutter, with subscript sp referring to the same quantities for the calibration sphere. This quantity can then be divided by the area of a single range gate to give the normalised RCS of the clutter. However, for a more complete understanding of the calibration and measurement process, it is instructive to look at the full calibration calculation. Figure 3-4 shows a schematic of the set up for the experiments, giving side on and plan views.



3-4 : A schematic of the OEL wave tank and radar set-up

The parameters in the figure are:

- R Slant range
- R_0 Slant range at beam centre
- R_{G0} Ground range to beam centre
- h Antenna height
- θ_g Grazing angle (depression angle from horizontal to beam centre)
- ϕ Angle as measured from beam centre
- $\phi_{1/2}$ Half the beamwidth (the angle from beam centre to the half power point)
- F The footprint of the radar (to the half power points)

The power backscattered from a scatterer at range R is given by the radar range equation

$$P_R = \frac{P_T C B \sigma}{R^4} \quad [3-2]$$

where P_T and P_R are the transmit and receive powers respectively, B gives the antenna beamshape (2 way gain), σ is the RCS of the scatterer and C encapsulates other constants of the radar such as compression gain, wavelength etc.

The Gaussian beamshape is given by

$$B = \exp\left\{\frac{-(\phi - \theta_g)^2}{2\sigma^2}\right\} \quad [3-3]$$

where the standard deviation of the Gaussian can be found in terms of the half power points by setting $B=1/2$

$$\frac{1}{2} = \exp\left\{\frac{-(\phi_{1/2} - \theta_g)^2}{2\sigma^2}\right\} \quad [3-4]$$

$$\Rightarrow 2\sigma^2 = \frac{(\phi_{1/2} - \theta_g)^2}{\ln 2} \quad [3-5]$$

using simple trigonometry ϕ can be found in terms of R by

$$h = R_{G0} \tan \theta_g \quad [3-6]$$

$$\sin(\theta_g + \phi) = \frac{h}{R} = \frac{R_{G0} \tan \theta_g}{R} \quad [3-7]$$

$$\phi = \sin^{-1}\left(\frac{R_{G0} \tan \theta_g}{R}\right) - \theta_g \quad [3-8]$$

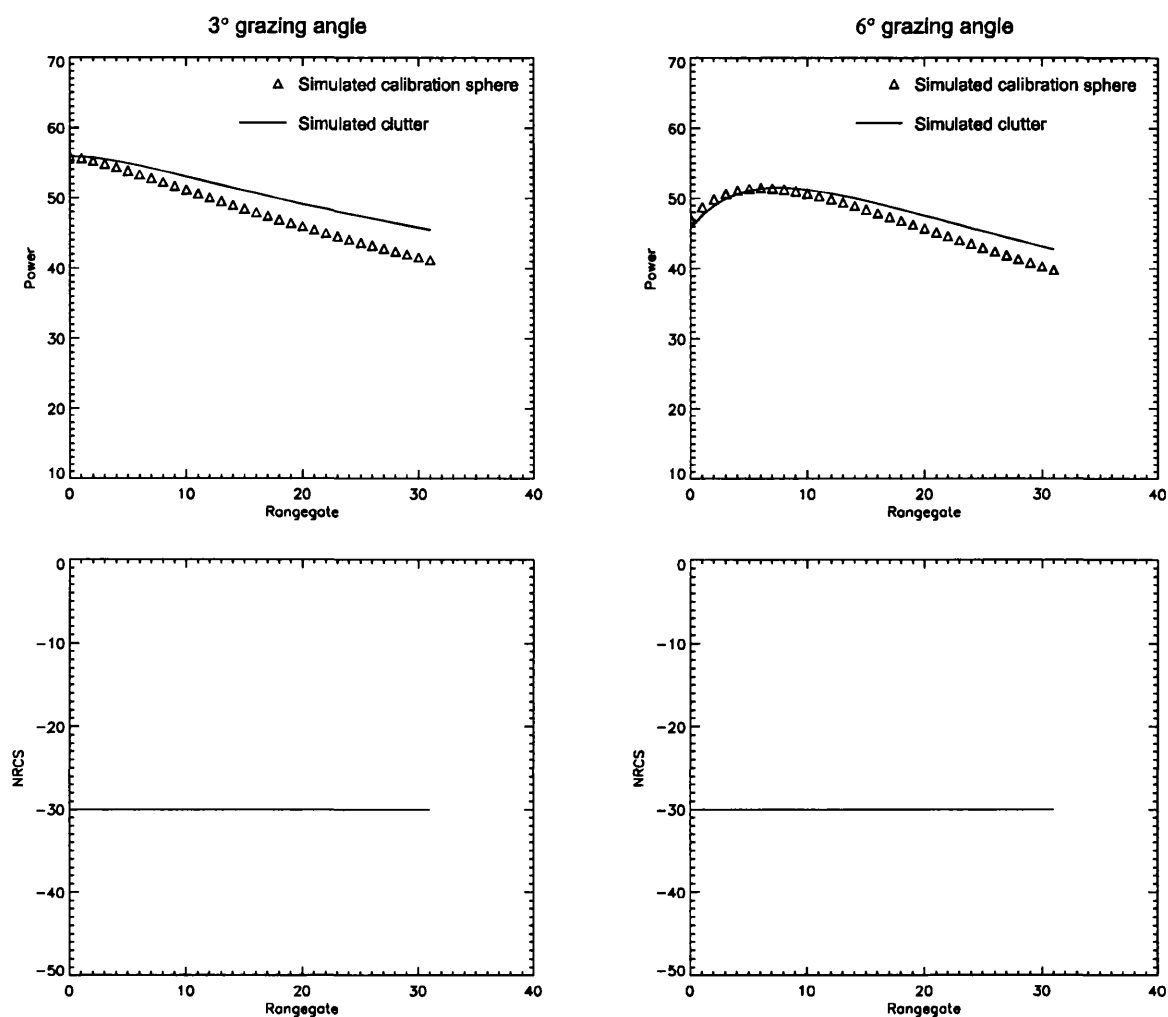
Substitution of 3-5 and 3-8 into 3-3 gives the antenna beamshape in terms of R , which can then be combined with 3-2 to give the backscattered power in terms of R and the RCS of the scattering object. For the cases of a calibration sphere and clutter, we have

$$\sigma_{sp} = \text{constant} \quad [3-9]$$

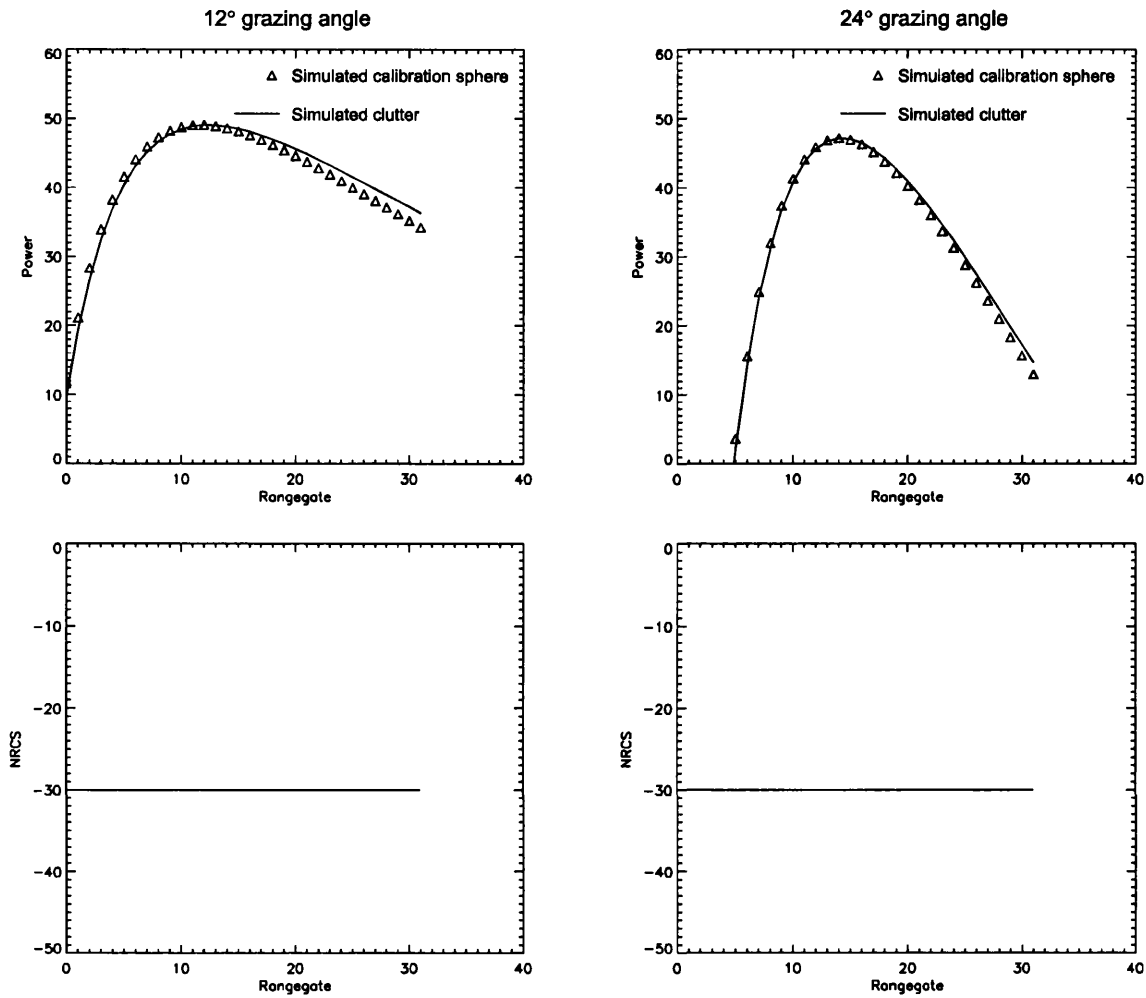
$$\sigma_{cl} = A\sigma_{cl}^o = R dR d\phi_{az} \sigma_{cl}^o \quad [3-10]$$

where dR is the range extent of one range gate, and $d\phi_{az}$ is the azimuth beamwidth. To calculate σ_{cl} precisely, one should integrate over the full range and azimuth sidelobe pattern, however simply using the area of the primary range cell is sufficiently accurate here. It is now possible to simulate both calibration and clutter returns, taking arbitrary values for the radar power and constants. In line with the MIDAS setup for the UCSB experiment, the ground range is set to 10m, azimuth and elevation beamwidth to 5° and range resolution to 30 cm. The normalised clutter RCS is set to -30dB , and the sphere RCS to its optical cross section of 0.706 m^2 (-11.5 dBm^2) as at all wavelengths except F-band the sphere is well outside the Mie resonance region, and even at F-band the resonance is very small and deviation from the optical value is negligible.

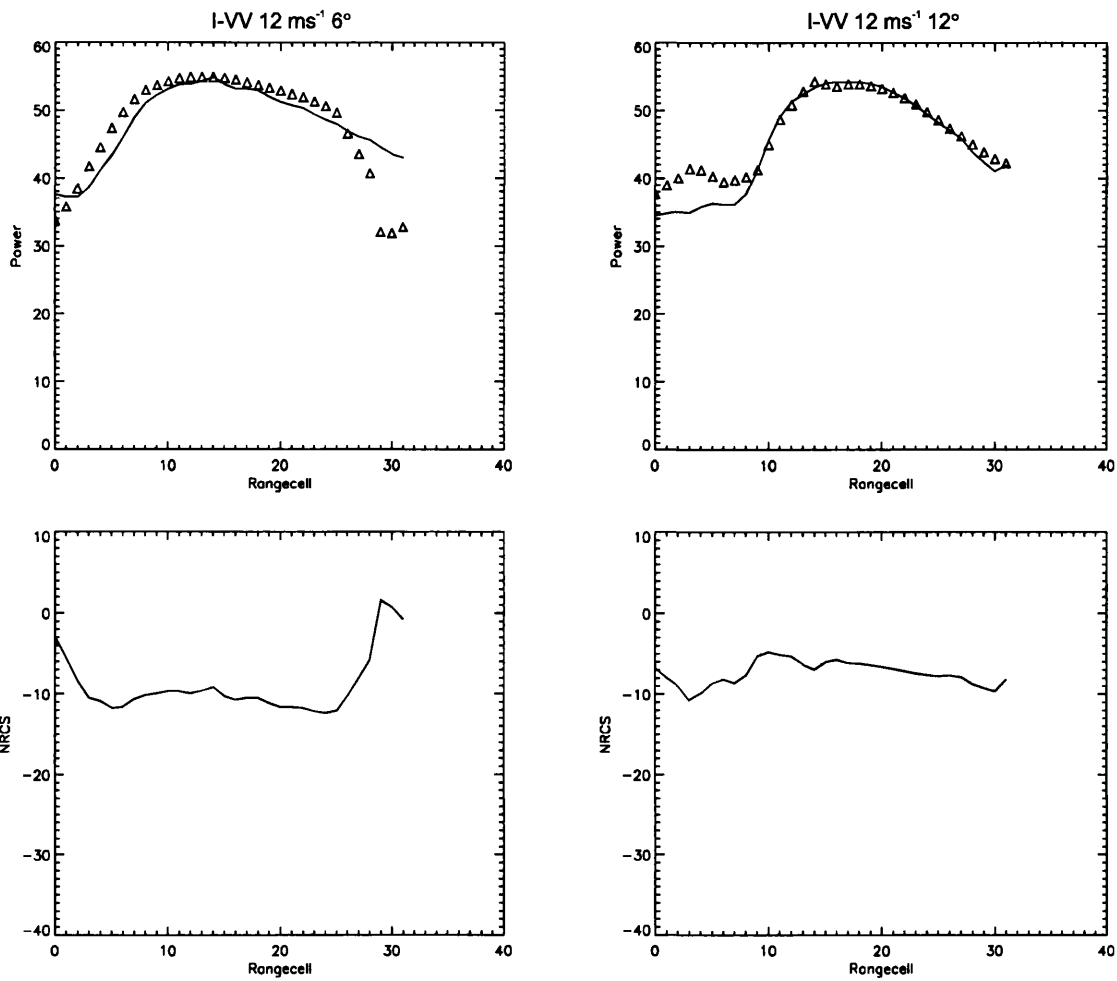
Figures 3-5 and 3-6 show simulations of the backscattered power from a calibration sphere and a roughened water surface, with the normalised RCS as calculated from this plot using equation 3-1. A constant offset has been added to the curve for the clutter power has been shifted to enable it to be shown on the same plot as the calibration sphere data. As expected, the simulated calibration curve removes the beamshape from the clutter measurements, recovering the correct, constant RCS at all ranges. Figures 3-7 and 3-8 show examples of actual calibration sphere and clutter measurements, together with the calibrated normalised RCS range profile, for measurements made at I and J-bands. Here, a certain amount of shifting of the calibration curve in range to line up with the clutter data was sometimes necessary, meaning that deviations from the true calibrated RCS levels can sometimes be seen at the edges of the range profile. The data is vertical polarisation, and the clutter range profile has been averaged over 30 seconds to give a smooth curve. The removal of the beamshape to give a region of constant normalised RCS away from these edge errors shows the calibration has been successful.



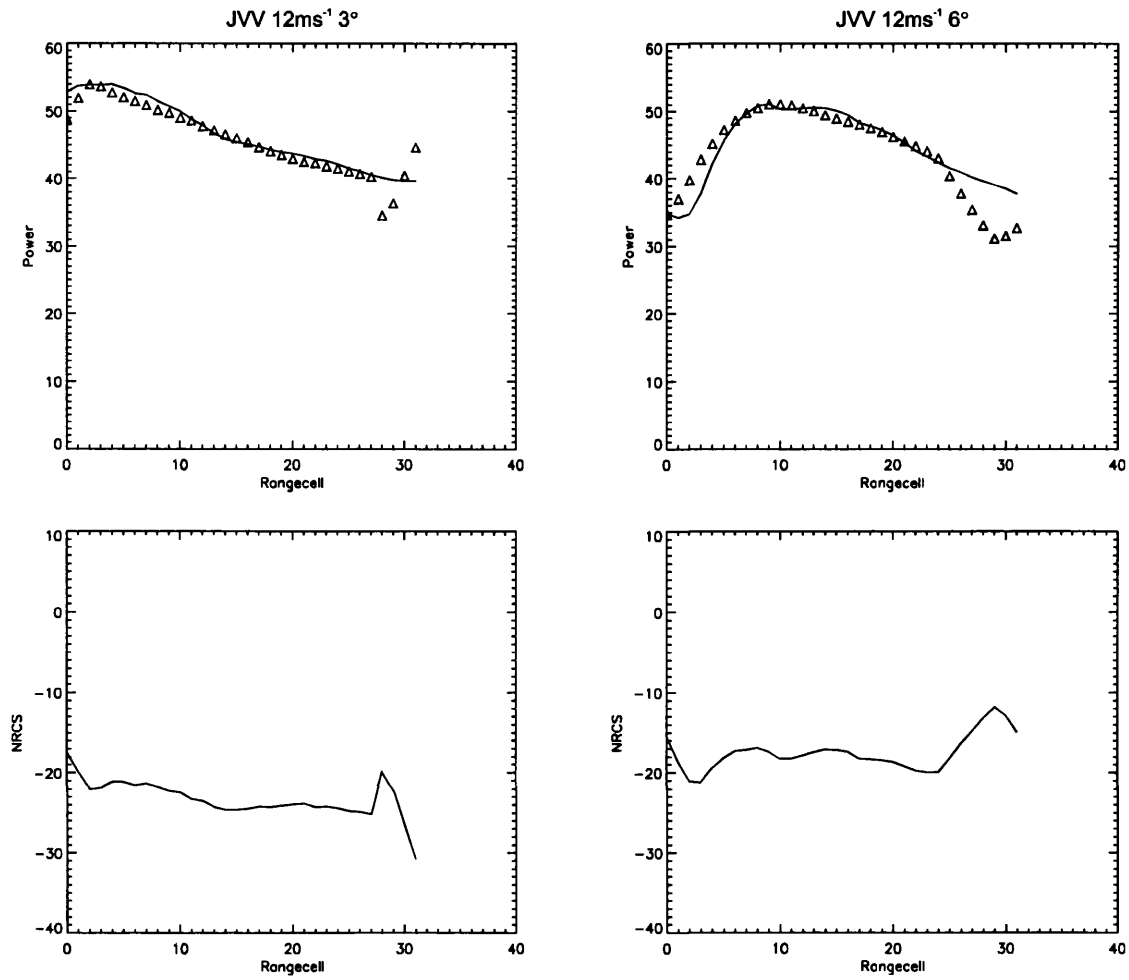
3-5 : Simulated calibration curves at 3° and 6° grazing angles. The upper plots represent simulated returns from the water surface (solid line) and calibration sphere (triangles), and the lower plots are the recovered NRCS of the clutter



3-6 : Simulated calibration curves at 12° and 24° grazing angles. The upper plots represent simulated returns from the water surface (solid line) and calibration sphere (triangles), and the lower plots are the recovered NRCS of the clutter

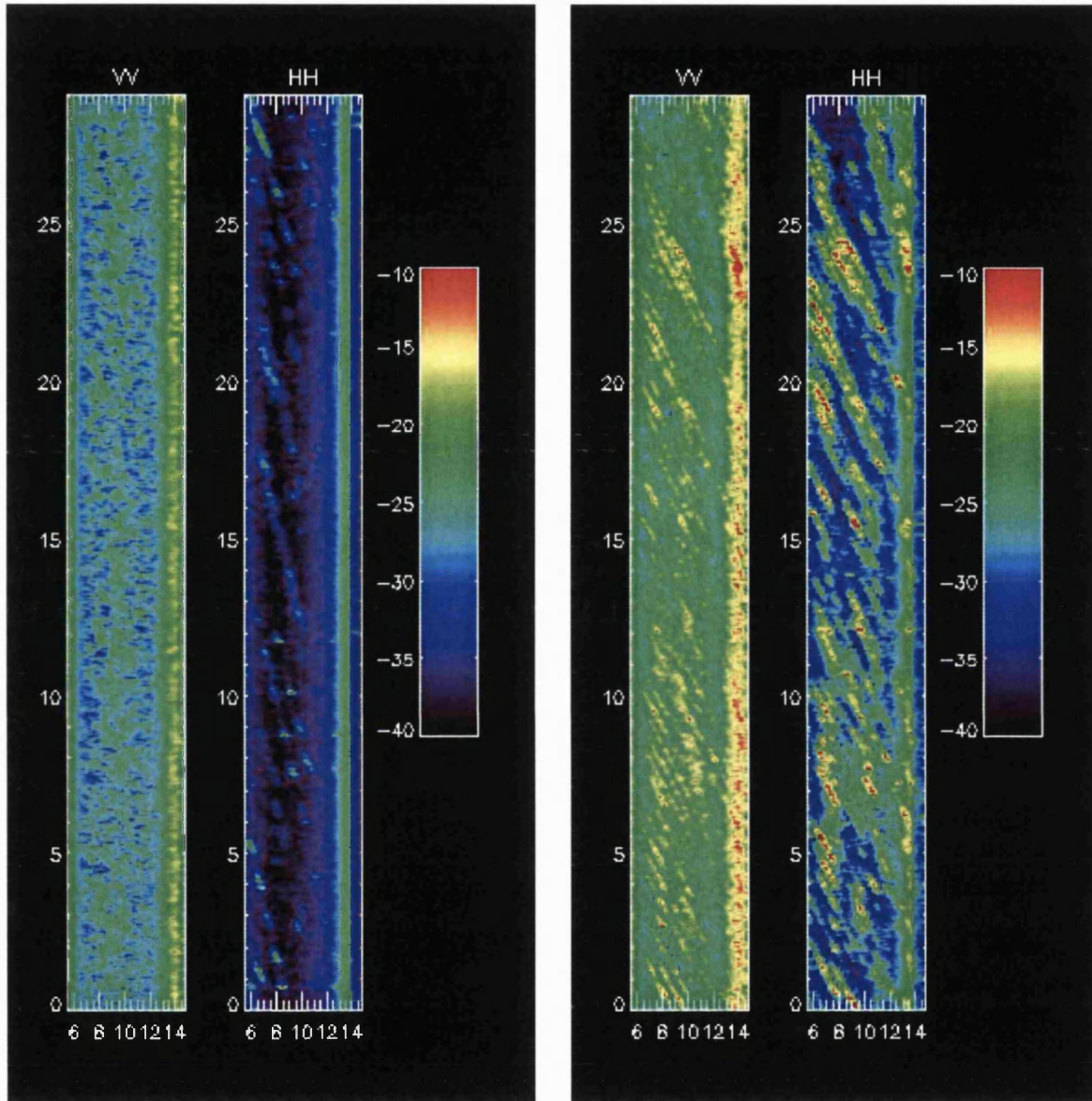


3-7 : Recorded calibration curves at I-band, vertical polarisation, 6° and 12° grazing angles

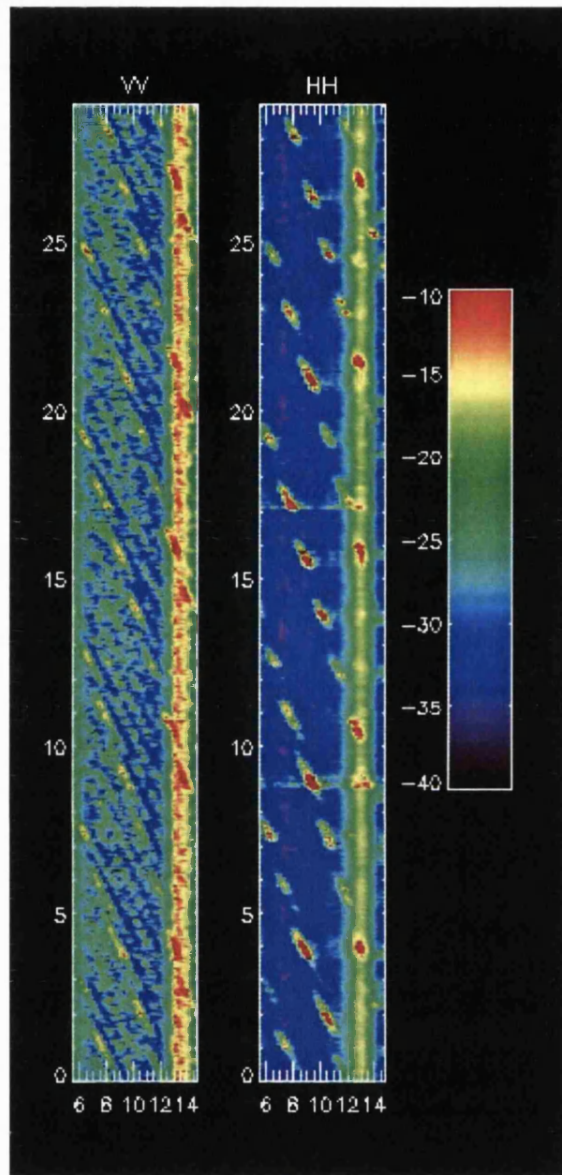


3-8 : Recorded calibration curves at J-band, vertical polarisation, 3° and 6° grazing angles

If this process is now applied to each profile individually (as opposed to the integrated range profiles shown in the previous figures) calibrated range-time-NRCS images can be produced. Figure 3-9 shows HH and VV NRCS images taken at J-band, 6° grazing angle, and windspeeds of 8 and 12 ms^{-1} . These images cover 30 seconds in time running up the page, and approximately 9.5 m in range with near range on the left. Note the line down the right hand side of each image, which is an artefact of the error in the calibration curve mentioned above. The difference between the two polarisations is clear, as is the change with windspeed. At 8 ms^{-1} horizontal polarisation shows very low RCS punctured by several strong, distinct spikes whilst vertical shows a relatively even pattern. Both show more high RCS structure as the wind speed is increased. The differences between the two polarisations are highlighted in figure 3-10, which shows data of 1m wavelength mechanically generated waves in a 6 ms^{-1} wind field. The high RCS breaking wave groups are clear in the HH image, whilst VV is dominated by the returns from the wind waves. These basic RCS images alone demonstrate the dominance of Bragg scattering from small ripples in vertical polarisation, and the importance of non-Bragg scattering from breaking waves in horizontal.



3-9 : Calibrated range-time-intensity plots, I-band, 6° grazing angle, taken at 8 ms^{-1} wind speed (left) and 12 ms^{-1} wind speed (right)



3-10 : Calibrated RTI plots, I-band, 6° grazing angle, 1 m wavelength wavegroups with 6 ms^{-1} wind

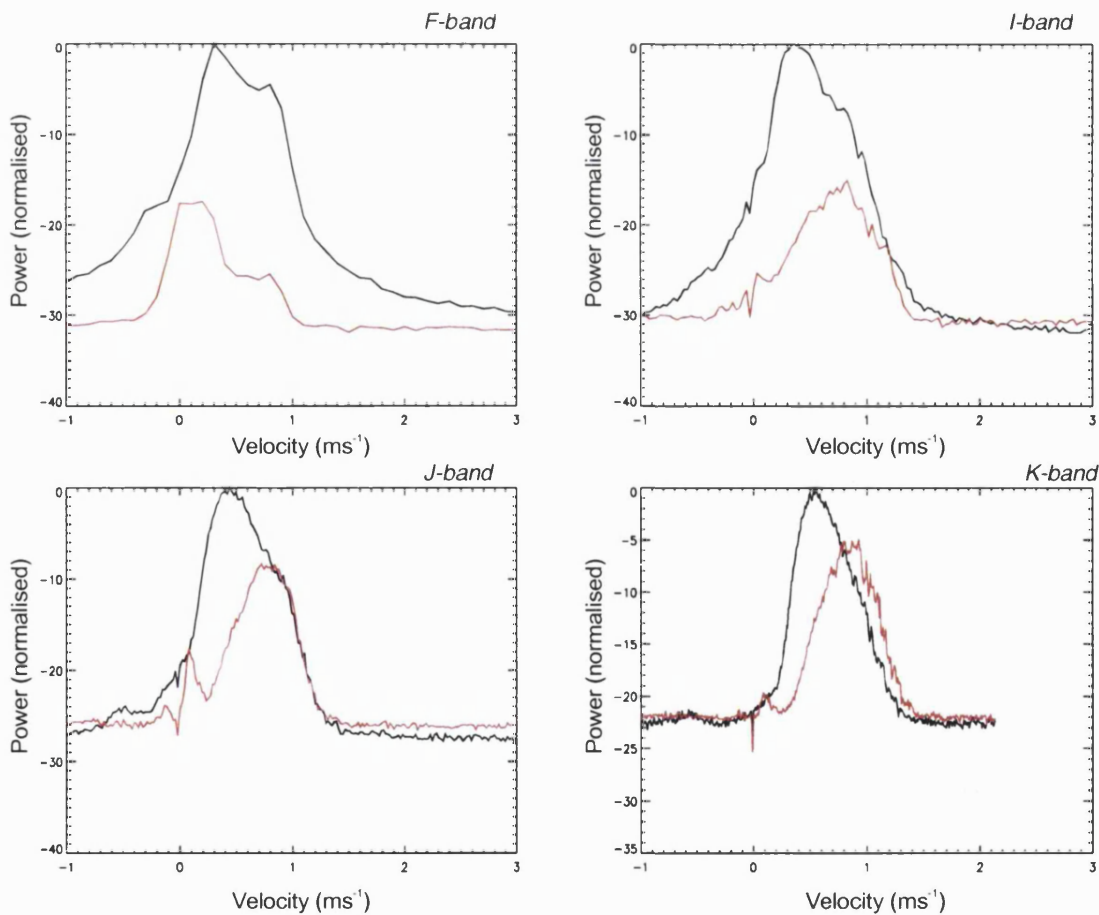
3.3.2 Basic Doppler analysis

In order to investigate the precise nature of the differences between the two polarisations such as those seen in figures 3-9 and 3-10, the Doppler spectra can be examined to ascertain the velocities of the different scatterers. Doppler spectra were formed by Fourier transform of the coherent pulse to pulse data in half second blocks, averaged over 30 seconds in time and the centre 5 cells in range. As

mentioned previously, the PRF of 1 kHz per polarisation gives a Doppler bandwidth of ± 500 Hz. In the case of M-band, with a 3 mm wavelength, the Doppler shift formula of

$$f_d = \frac{2v}{\lambda} \quad [3-11]$$

shows that the return from any scatterer moving faster than about 80 cm s^{-1} will be aliased, making the spectra difficult to interpret. Aliasing was not found to be a problem at the other frequencies, and example spectra are shown in figure 3-11 plotted on a dB scale, with horizontal polarisation shown in red and vertical in black. The spectra were taken at 6° grazing angle with an 8 ms^{-1} wind speed.

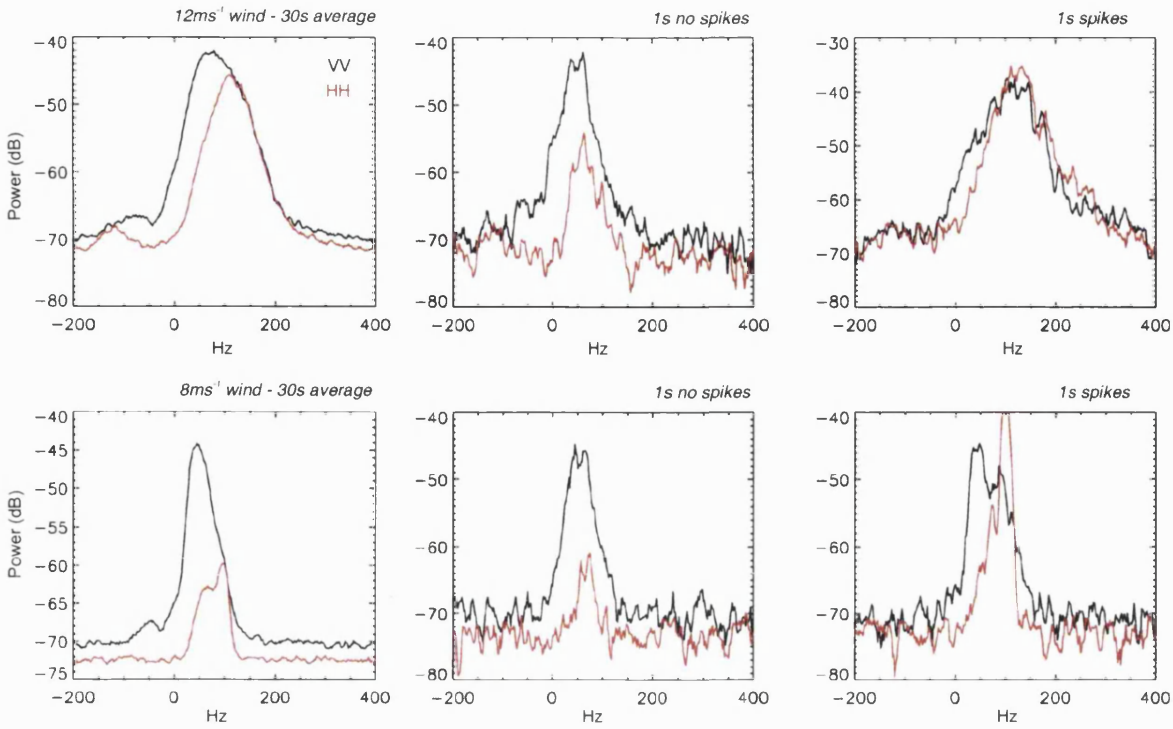


3-11 : Doppler spectra averaged over 30 seconds at F, I, J and K-bands, 6° grazing angle and 8 ms^{-1} wind speed. Red lines represent horizontal polarisation, black are vertical

The data was uncalibrated and the spectra have been normalised to the maximum in vertical polarisation. In each case, the VV peak is at a low speed, and is far stronger

than the horizontal spectrum at this point. In all cases except F-band, the horizontal spectrum is seen to become equal to or greater than vertical at higher speeds, and even in the case of F-band both polarisations appear to show a fast secondary peak. All these observations are qualitatively suggestive of slow Bragg scattering with VV greater than HH in accordance with the Rice result, and some form of fast, non-Bragg scattering which, from figure 3-10, would appear to be associated with breaking waves.

In order to pinpoint more accurately the exact Doppler characteristics of non-Bragg spikes, one can isolate the Doppler signatures of just the strong HH features. Figure 3-12 shows J-band spectra taken at 6° grazing angle, 12 ms^{-1} (top three plots) and 8 ms^{-1} (bottom three plots). The data shown in the spectra on the left has been averaged over 30 seconds, whilst that in the centre and right hand plots has been averaged over just 1 second covering either a clear spike, or areas of low, uniform return as indicated in the plot title. Considering first the 30 second average spectra at 12 ms^{-1} , the plot shows that although the two polarisations have peaks at different magnitudes and shifts, the fast, high shift sides of the two are exactly coincident, strongly suggesting a fast moving, polarisation independent scattering mechanism which is the dominant mechanism in HH. On the slower side of the spectra, VV is far stronger than HH, as would be expected from Bragg scattering. The “1 s, spike” spectra show the two polarisation matching almost exactly, with both polarisations peaking at 120 Hz (1.2 ms^{-1}) and VV possibly showing some Bragg scattering lifting it slightly above HH at low frequencies. The “1s, no spike” spectra again both peak at the same shift, this time 55 Hz (0.55 ms^{-1}), with VV now far stronger than HH everywhere. All this appears to confirm that, at this wind speed, spikes are fast and polarisation independent, whilst areas away from spikes see Bragg scattering at lower speeds.



3-12 : J-band Doppler spectra at 6° grazing angle, with 12 ms^{-1} wind speed (top) and 8 ms^{-1} wind speed (bottom). The plots on the left are averaged over 30 seconds, those in the middle over 1 second in a period of low returns, and on the right over 1 second covering a strong HH return. Red lines are horizontal polarisation, black are vertical

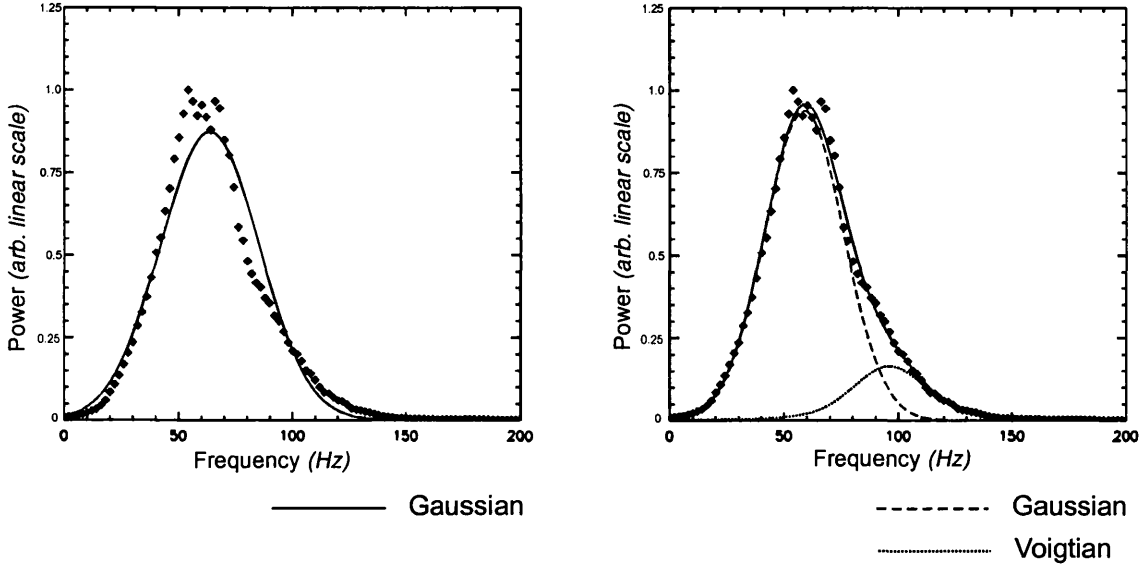
At the lower wind speed of 8 ms^{-1} , the behaviour appears somewhat different. Whilst the “1s, no spikes” spectra are very similar to those taken at 12 ms^{-1} , indicating that Bragg scattering is still present, the “1s, spikes” spectra show clear differences between the two polarisations, with a narrow, fast HH peak many dBs above VV. This peak can still be seen in the 30 second spectra, although averaging over the longer time has dramatically reduced the effect. This result would suggest, however, that at the lower wind speeds, spikes can be seen to have a highly polarisation sensitive nature, being far greater in HH than in VV.

As no simultaneous surface truth data was recorded in the MIDAS experiment, it is impossible to confirm directly what it is that causes this observed difference in fast scatterers at these two wind speeds. One possible explanation is that at higher wind

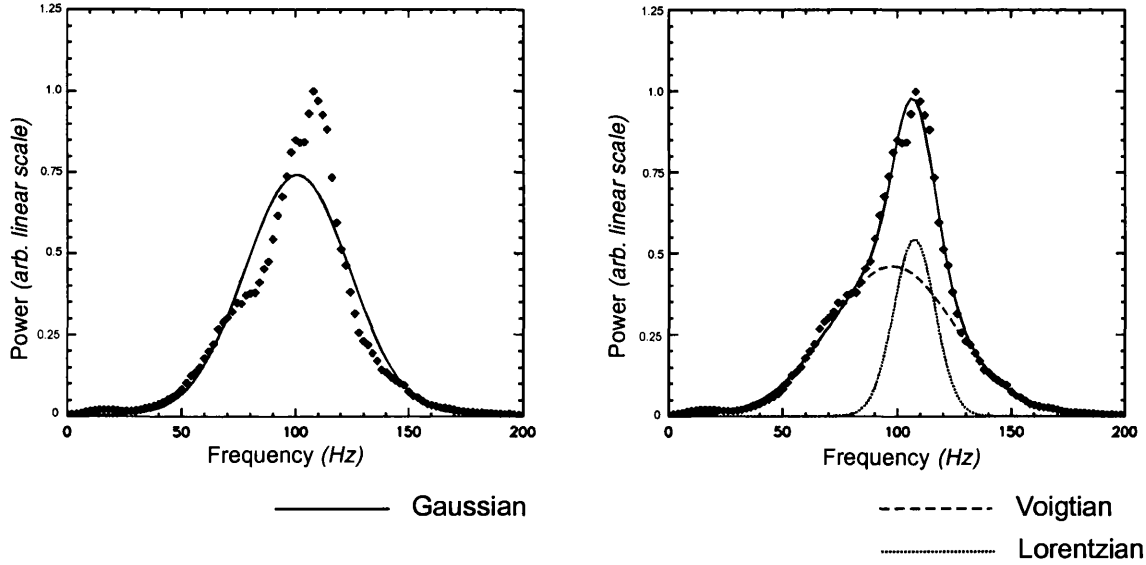
speeds, the waves are physically bigger and break more energetically, with splashing and white water, whilst at low wind speeds there may be a more small scale, spilling breakers [Duncan et al, 1994]. It is highly likely that these two types of breaking wave would have different polarisation characteristics.

The polarisation and Doppler characteristics of data can be investigated in a more quantitative way using the lineshape analysis method due to Lee and outlined in chapter 2. This method is readily applied to data such as that recorded in the wavetank which, as shown in figure 3-12, can be easily decomposed into slow and fast components. Figure 3-13 shows typical Doppler spectra from each polarisation, with fits to single and combined basis functions. The data is here plotted on a normalised, linear power scale, with the small diamonds showing the data, and the dotted and solid lines the individual components and the overall fit respectively. It is immediately clear from figures on the left that a single basis function is an inadequate description of the spectrum of either polarisation. In the cases shown a Gaussian has been used, though Lorentzians and Voigtians give similarly poor fits. The top right plot shows the same VV data, with a combination of a dominant Gaussian and unresolved high speed Voigtian overplotted. This combination was found to give the best fit in terms of a minimum χ^2 value and can, by eye, be seen to give a very good fit. This can be interpreted as indicating that the dominant scattering mechanism in this case is Bragg, with some power returned from faster scatterers which may be bound Bragg waves or lifetime dominated scatterers with a spread of speeds. The bottom right plot shows the HH spectrum to be well represented by a combination of a broad Voigtian envelope and a narrow Lorentzian which defines the peak. This suggests that scattering from free Bragg waves is not a major contributor to the backscattered power in horizontal polarisation, with lifetime mechanisms being dominant. These results are all in good agreement with those of Lee [Lee 1995b] in which open water data is analysed in this way.

Vertical polarisation, 6° grazing angle, 8ms^{-1} windspeed

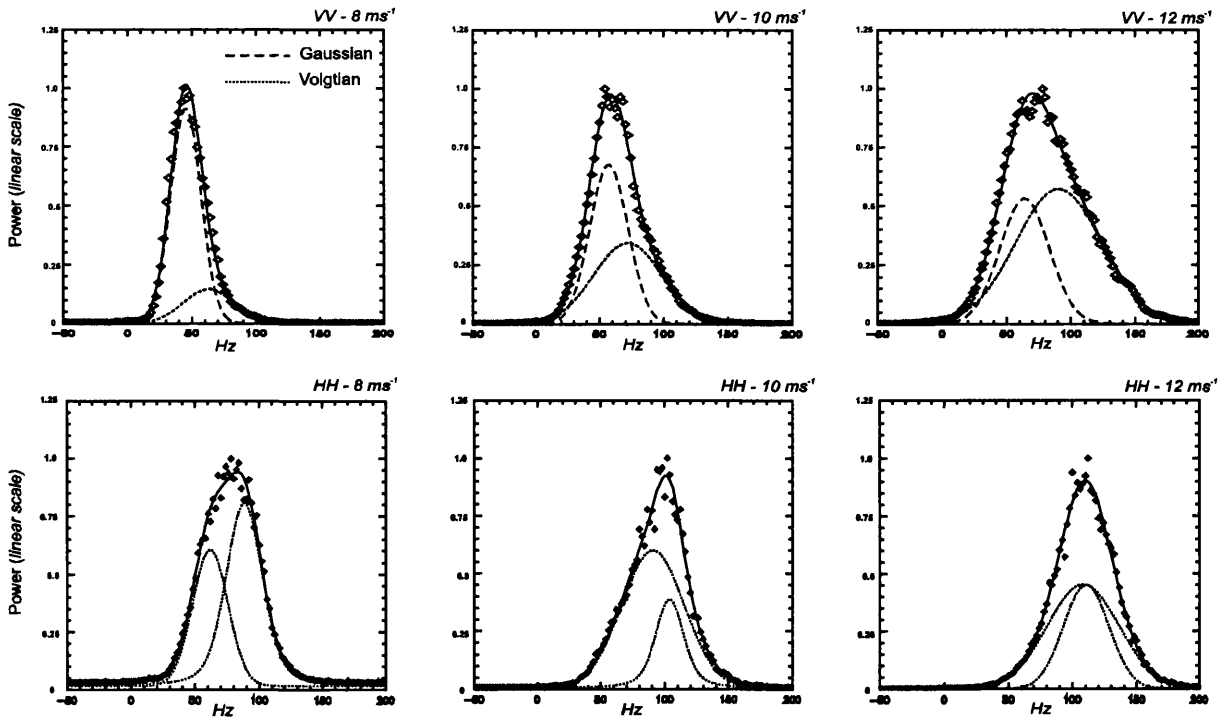


Horizontal polarisation, 6° grazing angle, 12ms^{-1} windspeed



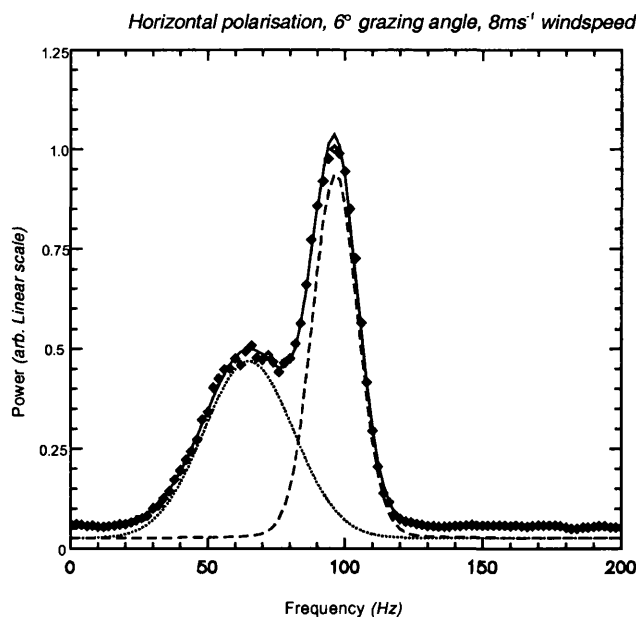
3-13 : Lineshape analysis of typical J-band data. Diamonds represent radar data. Top, vertical polarisation with best fit single Gaussian (left) and best fit combined Gaussian and Voigtian (right). Bottom, horizontal polarisation with best fit Gaussian (left) and best fit combined Voigtian and Lorentzian (right)

The variation of spectra with wind speed is shown in figure 3-14. Doppler spectra are shown at 6° grazing angle and speeds from 8 to 12 ms⁻¹, integrated over 240 seconds. The top three spectra are vertical polarisation, the bottom horizontal. The overall trend in the VV data is clear – the spectrum changing from a relatively narrow single Gaussian with a subsidiary fast Voigtian to the point where, at 12 ms⁻¹, the Voigtian outgrows the Gaussian. This suggests that the non-Bragg returns in vertical polarisation have an RCS which increases with wind speed faster than the Bragg. In horizontal polarisation, the low wind speed spectrum is well modelled by two narrow, unresolved Voigtians, whilst at the higher wind speeds the best fit is given by a broad Voigtian envelope with a narrower Voigtian defining the peak. It should be noted that in some cases, the spectrum from high wind speed HH returns is best modelled with a Lorentzian as the narrow component. In the main, however, the combination of two Voigtians gives a lower χ^2 value than the combination of Voigtian and Lorentzian. Very little power appears to be returned at the Bragg speed in HH, particularly at high wind speeds.



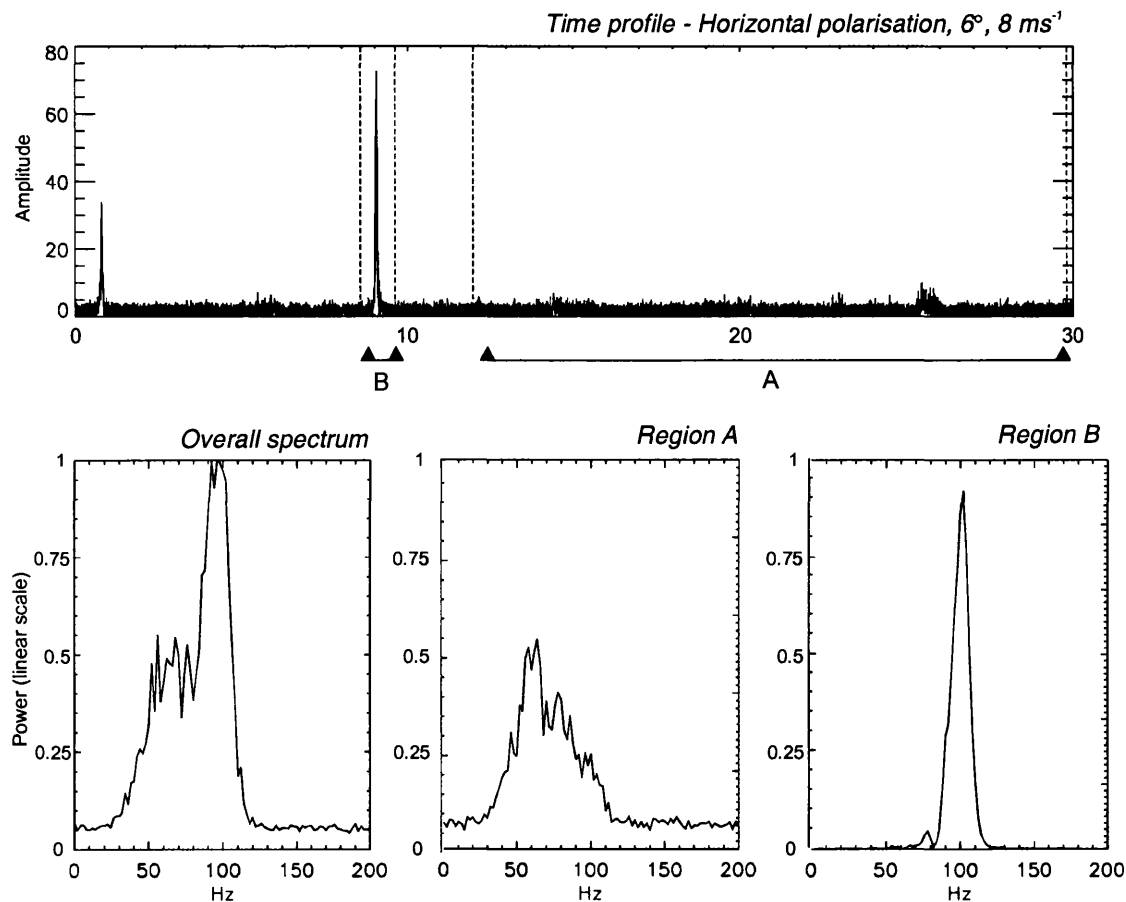
3-14 : Variation in spectral shape with wind speed. J-band, 6° grazing angle. Diamonds represent radar data, dotted lines are basis functions and solid lines are sum of basis functions

Whilst there can be no doubt that the above combinations of the three basis functions give good fits to the data considered here, and that they can be helpful in identifying trends in the spectral shape, there are certain important shortcomings to the technique. First, no attempt is made to link together the descriptions of the two polarisations. Bragg scattering, for which the theoretical polarisation ratio is easily calculable, is often absent from the fit to the HH spectrum, and there is much experimental evidence, including that presented earlier in this chapter, that returns from some of the fast scatterers are polarisation independent, leading to coincident fast sides of the spectra. In ignoring these facts and simply treating the two spectra separately, physical insights into the scattering processes in action are lost. Also, whilst a scattering mechanism is ascribed to each of the basis functions, the statistics of which lead to the characteristic shape, it can often be more instructive to simply look at the time series from which the spectra were formed and identify exactly which features in the time domain correspond to which in the frequency domain. Figure 3-15 shows a clearly bimodal spectrum well described by two basis functions. The data is HH, 6° grazing angle at 8 ms⁻¹ wind speed. Whilst the two lineshapes give a very good fit, they tell us little about the data which could not already be seen.

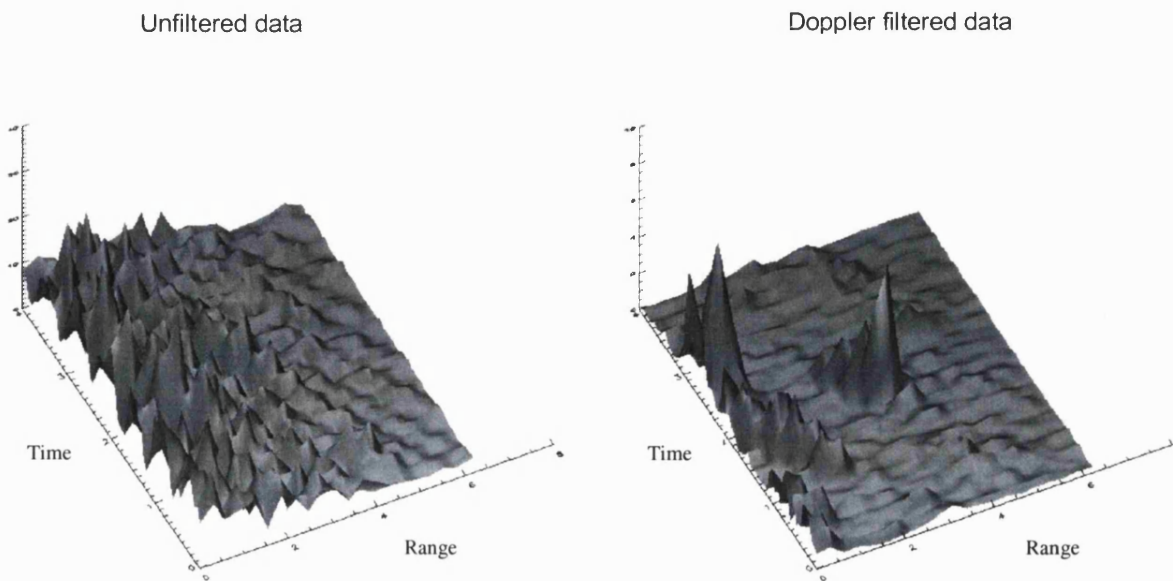


3-15 : A clear example of a bimodal Doppler spectrum, with two Gaussian lineshapes fitted

The time series from which the spectrum came is shown in figure 3-16. Also shown are the overall spectrum from the whole 30 seconds (here with no smoothing applied), and spectra formed from two subregions of the data. Region A covers a low, uniform period, whilst region B covers the extremely strong, sharp spike seen at around 9 seconds. The differences in the spectra from these two regions, and the way they combine simply to give the overall spectrum is clear. The uniform, low region has a slow, broad and noisy spectrum whilst the spike has a sharp spectrum at a single well defined frequency. Region A is evidently a region of Bragg scattering, whilst B is very probably a return from a small, spilling microbreaker. Exploring the data in both time and frequency domains, and isolating individual features in this way, gives more understanding of the physical processes involved than applying lineshapes alone.



3-16 : Identification of the sources of the two Doppler components seen in figure 3-15. The time profile is shown along with the spectrum as averaged over the whole 30 seconds, and over just regions A and B



3-17 : Unfiltered and filtered range-time-amplitude plots. The Doppler filtering technique removes the strong Bragg returns to reveal a weak spike

A simple application of this type of understanding is in the technique of Doppler filtering. With an understanding of which features in the time domain will appear where in frequency, this type of processing can suppress or enhance specific types of backscatter. For example, figure 3-17 shows a three dimensional range-time-amplitude representation of VV data taken at 6° grazing angle and 8 ms^{-1} windspeed. The plot on the left shows the unprocessed data, and that on the right shows data after filtering in the frequency domain at 100 Hz (1 ms^{-1}). Filtering at this speed brings out a very clear spike which cannot be seen at all in the original data. The spike is weak (the amplitude scale goes up to 40 on the unfiltered data, compared to 10 on the filtered) and is utterly drowned out by the strong Bragg scattering in the unprocessed data. However, the fact that the scatterers travel at different speeds allows for the recovery of the weak feature.

The precise speeds of the Bragg and non-Bragg scatterers, which should give the centre frequencies of the components used in lineshape analysis, is something not explicitly considered in Lee's original work. Components were loosely termed Bragg

or fast, non-Bragg without exact specification of the velocities. These are, however, values which are calculable in the wavetank. As the VV data is Bragg dominated, with only a small faster component, the peak will be given by the speed of the Bragg scatterers, that is, capillary waves of the Bragg resonant wavelength. The Bragg resonant relationship (equation 2-9) gives a resonant water wavelength for a given radar wavelength and grazing angle. This is converted to a velocity via the capillary wave dispersion relation

$$c_{BP} = \sqrt{\frac{g}{k_w} + \gamma k_w} \quad [3-12]$$

where c_{BP} is the Bragg wave phase speed, g is the acceleration of free fall and γ is the surface tension divided by the bulk density. This velocity is then modulated by the orbital motion and drift velocity of the underlying gravity waves, c_d . A form for this modulation by the large waves is given by

$$c_d = \Omega K \left(\frac{H}{2} \right)^2 \frac{\cosh 2Kd}{2 \sinh^2 Kd} - \left(\frac{H}{2} \right)^2 \frac{\Omega \coth Kd}{2d} \quad [3-13]$$

where Ω and K are the angular velocity and wavenumber of the underlying gravity waves, H is their trough to crest height and d is the depth of the water [Trizna, 1985]. It should be noted that this is the solution for a closed system, as in the wave tank. For open waters, the second term of equation 3-13 should be omitted. The overall speed of the Bragg scatterers is thus given by

$$c_B = c_{BP} + c_d \quad [3-14]$$

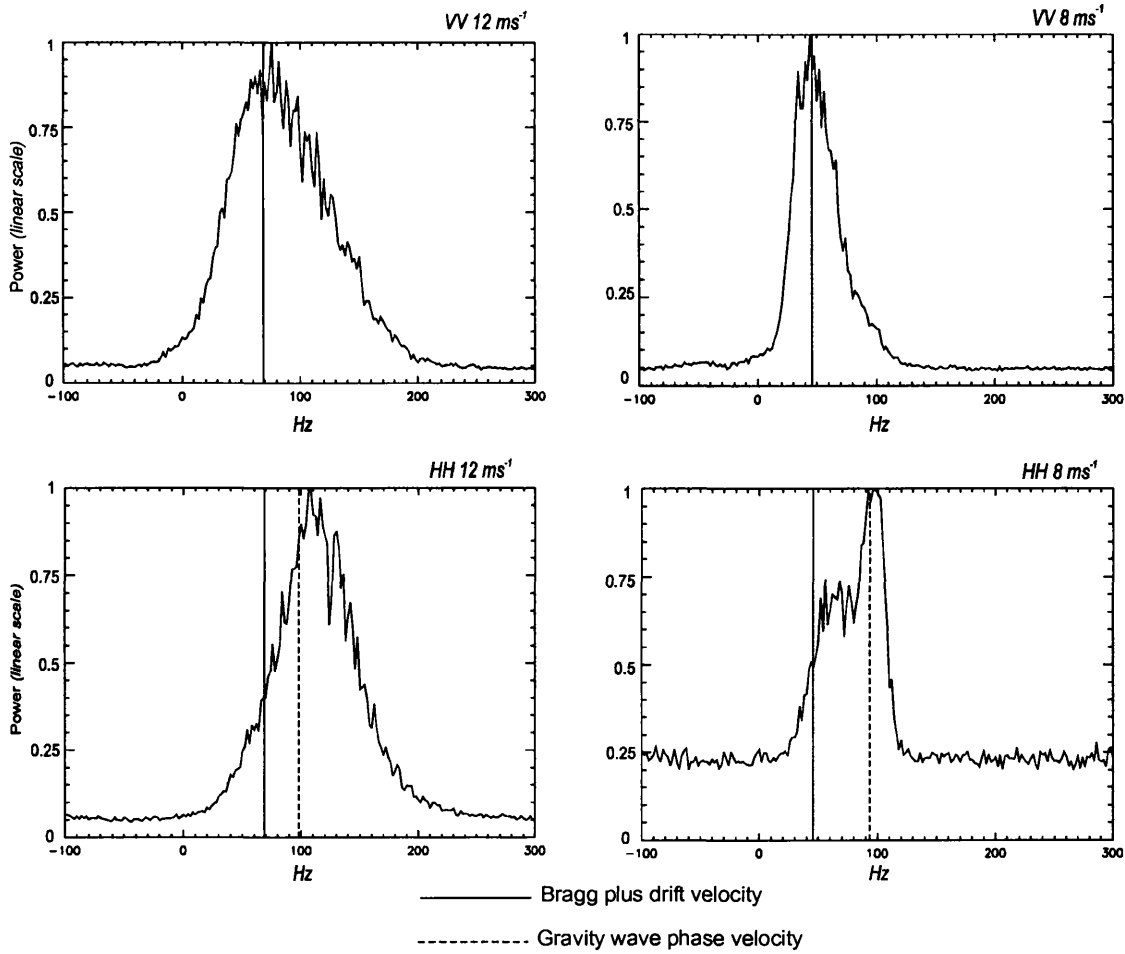
Data from the laser slope meter and previous experiments by the UCSB OEL staff have provided information on the wavelengths, heights and periods of the waves at each wind speed allowing for calculation of the Bragg resonant wave phase speed and so the expected Doppler shift of the VV peak. For Horizontal data, the spectrum is usually non-Bragg dominated, and assuming these non-Bragg scatterers are at the

peaks of breaking gravity waves, their speed will be given by the gravity wave dispersion relation

$$\Omega^2 = gK \quad [3-15]$$

$$c_p = \frac{\Omega}{K} = \sqrt{\frac{g}{K}} \quad [3-16]$$

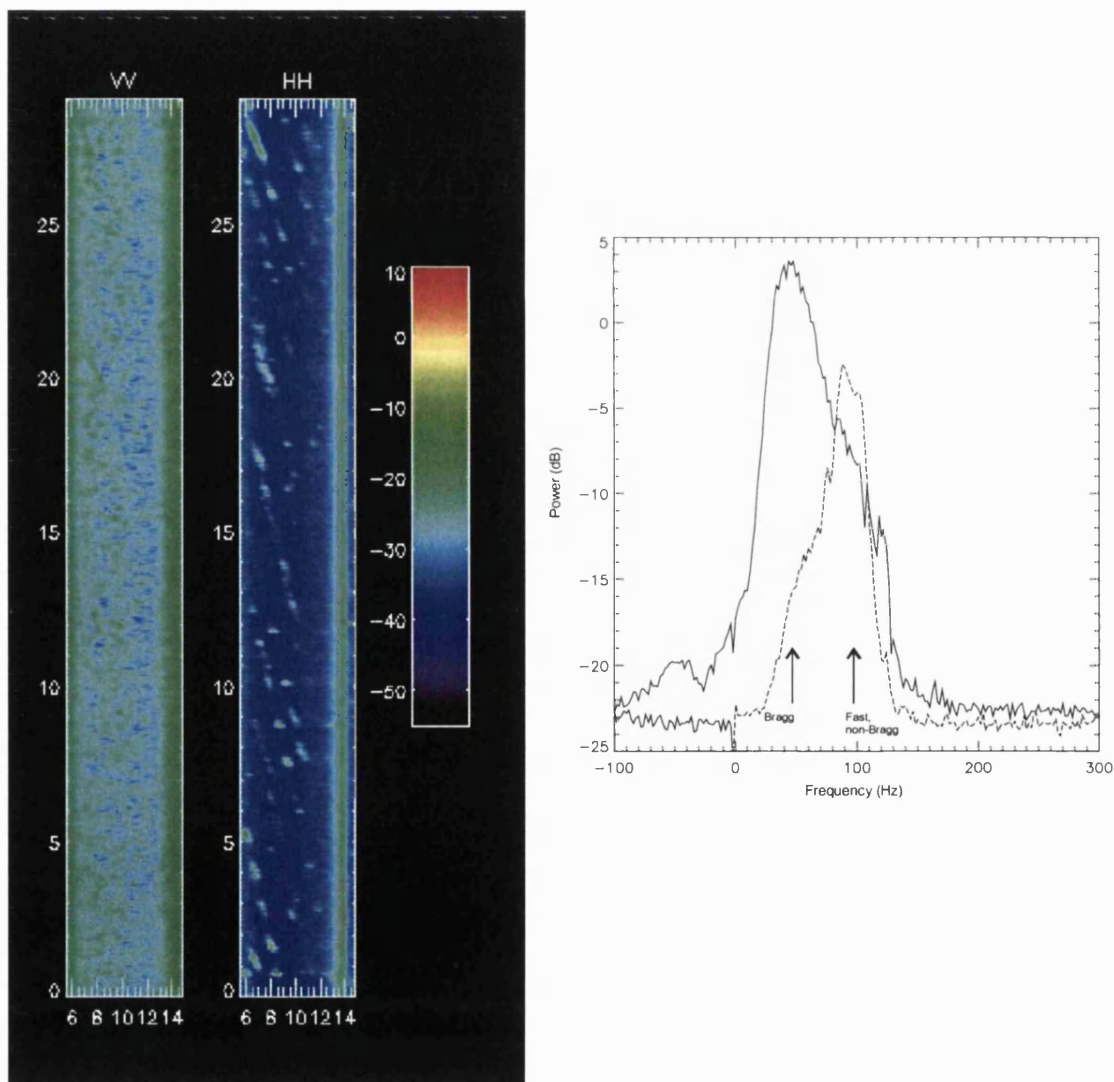
where c_p is the phase speed of the gravity waves and the other symbols have the same meanings as previously. This speed will then give the expected HH peak Doppler shift. Figure 3-18 shows VV (top) and HH spectra at 12 ms^{-1} and 8 ms^{-1} with the expected Bragg and gravity wave Doppler shifts marked. In each case these are very close to the VV and HH peaks respectively. This method of predicting the shifts is used further in chapter 4.



3-18 : Comparison of predicted and measured Doppler shifts at 12 ms^{-1} and 8 ms^{-1}

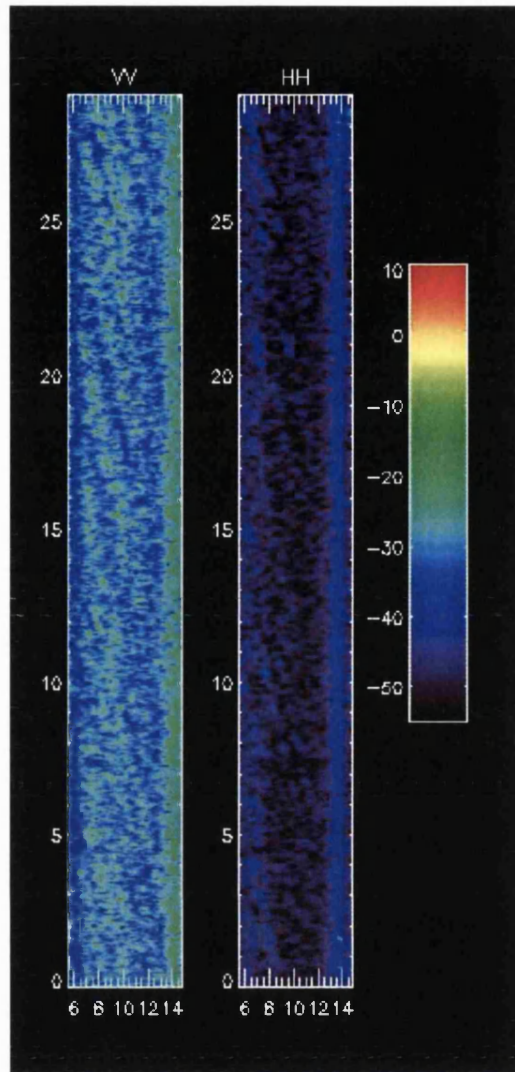
3.3.3 RCS measurements

The Doppler analysis of the previous section clearly shows the importance of non-Bragg scattering in wave tank data collected with the MIDAS radar. This implies that the best understood theoretical model for average RCS, the Bragg based composite model described in chapter 2, is unlikely to give good agreement with the data. However, we have also seen how Doppler analysis and in particular the technique of Doppler filtering can be used to isolate different scattering mechanisms, meaning it should be possible to isolate the Bragg component in the data and compare this to the theoretical result.

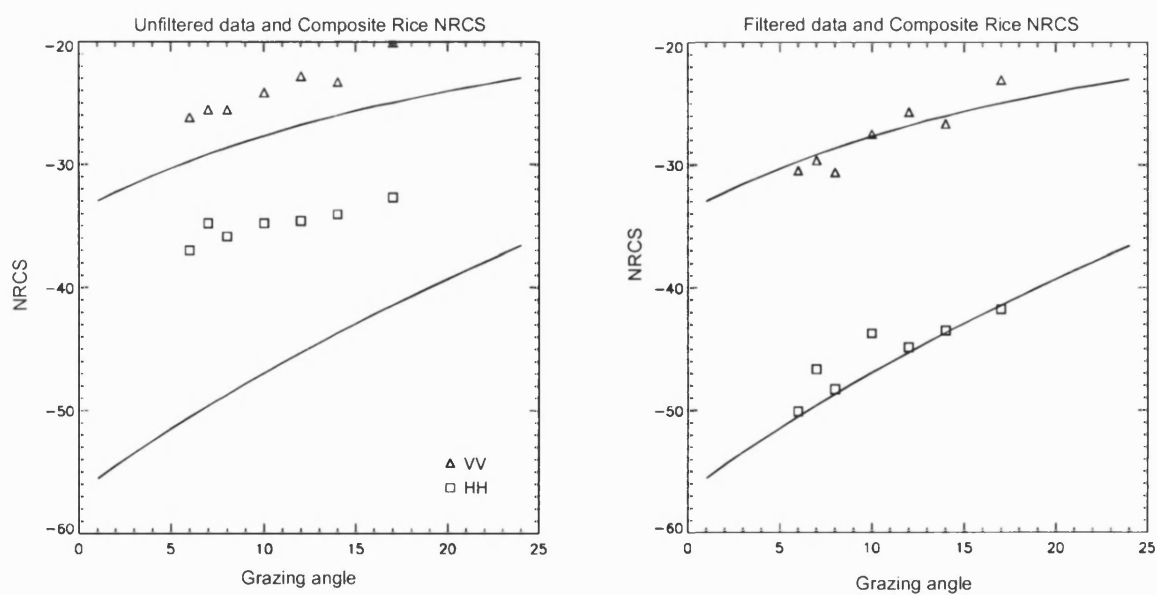


3-19 : Calibrated RTI plot and Doppler spectra recorded at J-band, 6° grazing angle and 8 ms^{-1} wind speed. Dotted line in the Doppler plot represents HH, solid is VV

Figure 3-19 shows a calibrated normalised RCS image recorded at 8 ms^{-1} and 6° grazing angle. Also shown are the Doppler spectra from the images, with the Bragg and non-Bragg positions marked. It is clear that Bragg scattering dominates in vertical polarisation, with the NRCS image being very uniform with no large individual spikes, and the Doppler spectrum shows that the majority of the power is returned at a shift corresponding to the Bragg speed. In horizontal polarisation, the image shows several distinct high RCS returns punctuating a low background level. The spectrum shows that these scattering events come from features that are moving faster than the Bragg ripples. However, some power is seen at the Bragg speed, and to make a valid comparison with the composite model it is this power which must be isolated. Figure 3-20 shows the data after Doppler filtering with a Hanning weighting centred on 45 Hz with a width of 30 Hz. This has eliminated all the high, non-Bragg events from the HH image, leaving the two polarisations looking very similar, but with the VV RCS much greater than HH. This is indicative of pure Bragg scattering, and the data is now in a form suitable for comparison with the composite model. This comparison is made in figure 3-21, using the composite model with an underlying root mean square tilt of 8.5° . The unfiltered data is also shown, to demonstrate the effect of non-Bragg scattering on the RCS of horizontal polarisation, and to a lesser extent, vertical polarisation. In the filtered data, the polarisation ratio and trends are well described by the model, indicating that the Doppler processing has indeed resulted in the RCS from just the Bragg scatterers. The fact that the vertical RCS was to some extent affected by filtering shows that there is also a non-Bragg contribution in this polarisation, even at the relatively low wind speed of 8 ms^{-1} .



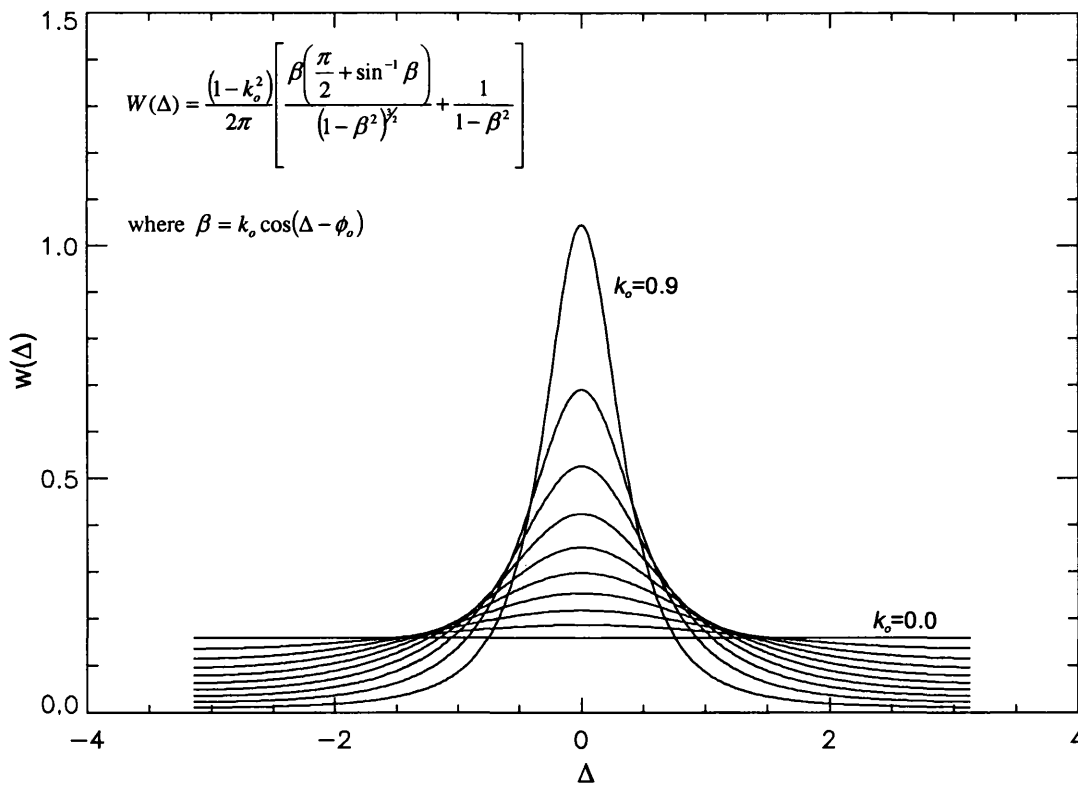
3-20 : RTI plot after Doppler filtering at the Bragg resonant wave speed



3-21 : Comparison of unfiltered and filtered data to the predictions of the composite Rice SMP

3.3.4 Polarimetric phase statistics

Whilst the amplitude statistics of sea clutter have been the subject of intensive study over the years, the phase statistics of polarimetric coherent radars have, by comparison, received little attention. As mentioned in chapter 2, studies have been conducted using interferometric systems and multi look SAR of land data, but it appears little work is published of maritime data. The wave tank, therefore, offers a unique possibility for a detailed and controlled look at this type of data. The theoretical form of the distribution of the phase difference in a multi-channel radar is given in equation 2-26, and derived in appendix B. The form of the curve for a number of shape parameters is given in figure 3-22.



3-22 : The phase difference distribution as derived assuming Gaussian statistics

The theory outlined in appendix B based on Gaussian statistics. However, it has been shown [Tough et al, 1995] that if the underlying mean power fluctuates with a Gamma distribution, as in the case of a K-distribution, then the theoretical phase distribution remains unchanged. Therefore, if it could be shown that the mean power

of the data recorded in the wave tank does indeed have a Gamma distribution with a Rayleigh amplitude speckle superposed on top, then one would expect the polarimetric phase statistics to conform to the Gaussian based theory. A way of testing for these precise characteristics in data is used by Ward [Ward et al, 1990] to demonstrate the applicability of the K-distribution to sea clutter. To test for the Rayleigh component, small samples of data are extracted and the cumulative distribution of the pulse to pulse data in that sample plotted on Weibull paper. If the data is taken over a short enough time period, then one can assume that the mean power has not varied and just the Rayleigh component will be left, which would give a straight line with a gradient of 2 in this representation. To test for the mean power fluctuation, data taken over much longer times can be integrated over some fraction of a second to remove speckle fluctuation and leave just the underlying power. This can then be tested against the Gamma distribution through the properties of the normalised moments of intensity, which are given by

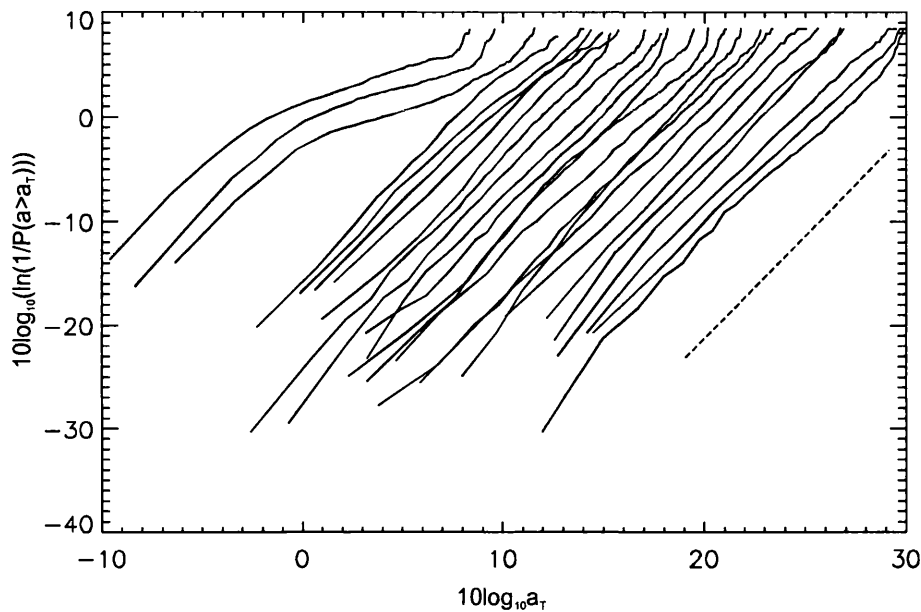
$$M_n = \frac{\langle I^n \rangle}{\langle I \rangle^n} = \frac{\Gamma(n + \nu)}{\Gamma(\nu) \nu^n} \quad [3-17]$$

where ν is the shape parameter which can be calculated from second moment via the relationship $M_2 = 1 + 1/\nu$.

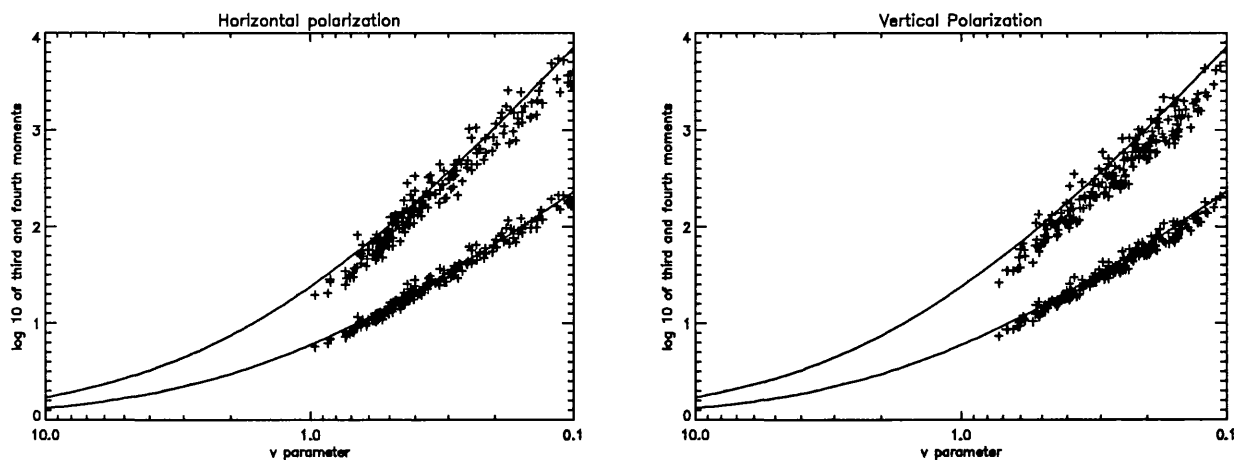
Figure 3-23 shows a number of one second chunks of wave tank data plotted on Weibull paper, with some of the lines shifted laterally to allow all the data to be seen more easily. The dotted line on the right of the plot shows a Rayleigh distribution with a gradient of 2 for comparison. The data covers both polarisations and a variety of wind speeds and grazing angles, and shows that in most cases, the data on this time scale does indeed have a gradient of close to 2, indicating Gaussian speckle. The three lines on the left of the plot are all horizontal polarisation and each was formed

from a one second time period which included some form of strong RCS feature. These deviate from Gaussian statistics considerably.

Figure 3-24 shows data sets again covering many geometries and wave conditions, integrated over 250 ms and with the third and fourth moments plotted against the calculated ν parameter. Overplotted are the expected relationships for Gamma distributed data.



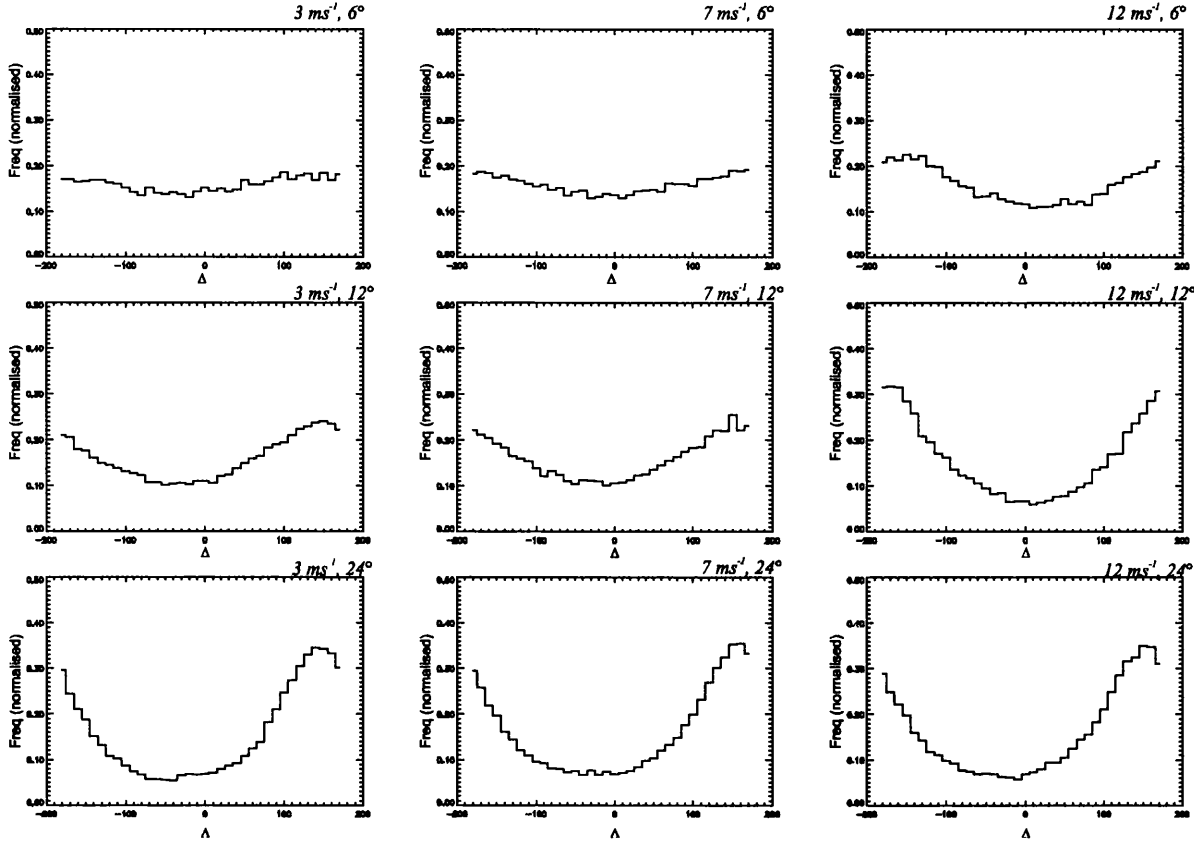
3-23 : One second data chunks plotted on Weibull paper. The dotted line represents a Rayleigh distribution with a gradient of 2. The three lines on the left are at HH polarisation and cover a strong RCS feature



3-24 : Third and fourth moments of data averaged over 250 ms compared to the expected value for a Gamma distribution

These plots suggest that whilst the compound form may be a reasonable description of much of the wave tank data, there are certain data sets which deviate from it substantially. This lack of agreement with a description which has proved so successful for open water sea clutter is not to be wholly unexpected – the close range necessary in the wave tank leads to a footprint on the water surface far smaller than that of cliff top or airborne radar operating at ranges of many kilometres, meaning that in the tank a single event can utterly dominate the return in one range cell on short time scales, leading to strongly non-Gaussian behaviour as seen in the three instances in figure 3-23. This dominance by a single feature is less likely with the larger range cells commonly used in surveillance radars. However, as it appears that much of the wave tank data does contain a Gaussian speckle and a Gamma power modulation, it is probable that the form of the phase difference distribution given in figure 3-22 will be applicable in many cases.

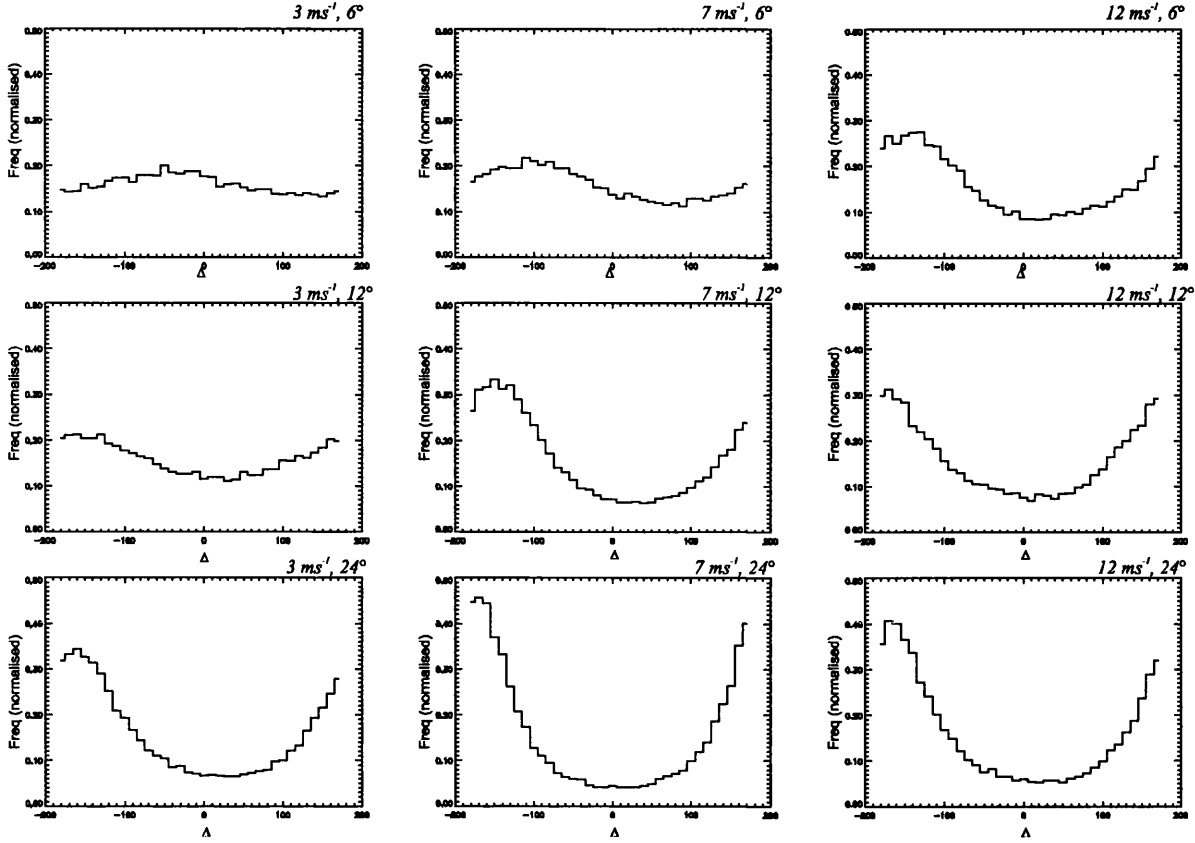
Figures 3-25 to 3-27 show the phase difference distribution as for F, I and J bands at a number of wind speeds and grazing angles. These plots were formed by taking the Hermitian product of 30 second time series of the two polarisations, the phase of which is the difference between the phases of the two channels, and producing a histogram. The fact that the distribution peaks at a non zero position suggests that the phases of the two channels have not been balanced. At each frequency, a similar trend is followed over the matrix of plots, with the shape of the distribution being flatter at low wind speeds and grazing angles, and more defined at higher values of these parameters. There is also a suggestion of a variation with radar frequency, with the J-band plots in general having a less distinct shape than those at F and I bands. This frequency dependence of the shape of the distribution is highlighted in figure 3-28 which shows K and M band data at 12 ms^{-1} and 24° . The shape of the distribution is completely washed out to a uniform level.



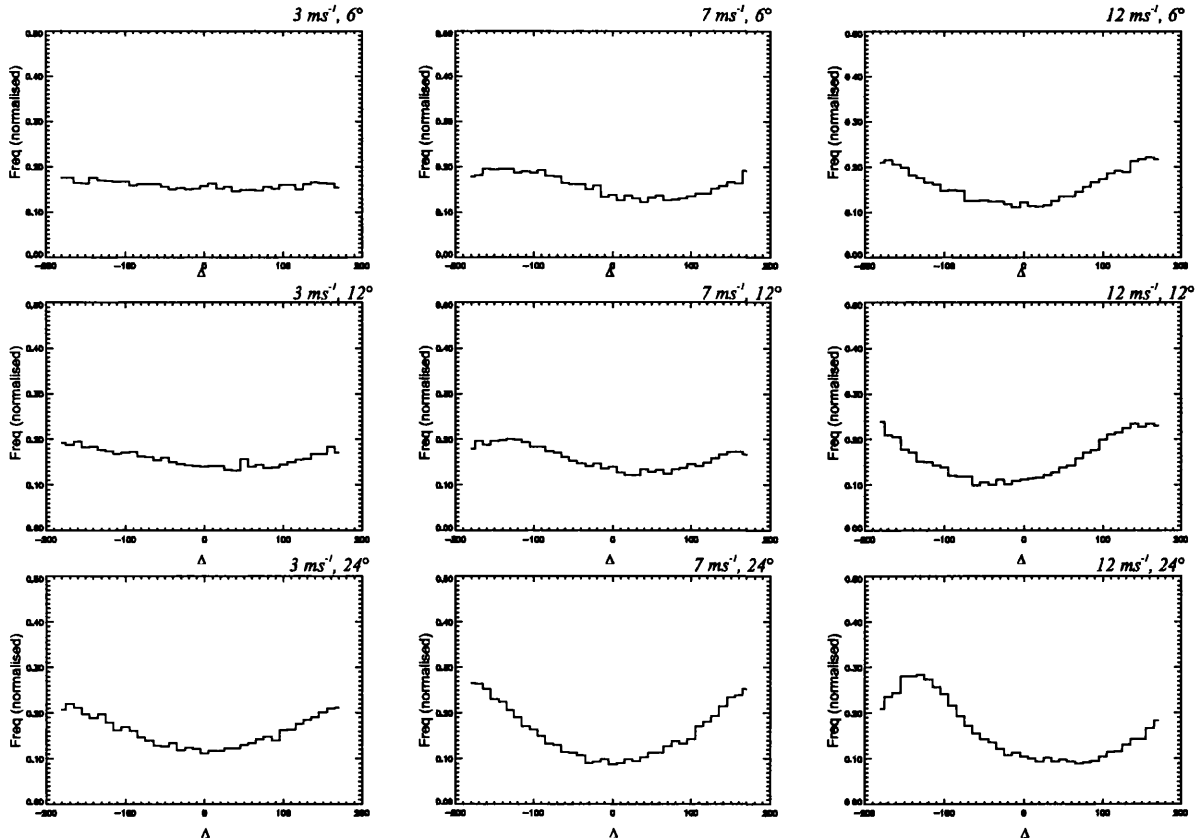
3-25 : Phase difference distributions at F-band, covering 3-12 ms^{-1} wind speed and 6° to 24° grazing angle

The origin of this change with frequency can be seen in figure 3-29, which shows the phases of HH and VV F, I, J and K-band data taken over approximately 0.25 seconds. At F-band, a scatterer may move only a small fraction of a wavelength between pulses, leading to a slow phase change and so a well defined phase difference between the two polarisations. With the much shorter wavelength at K-band, large fractions of wavelengths may be travelled by scatterers between pulses leading to the noise-like phases seen and so a uniform distribution of the phase differences.

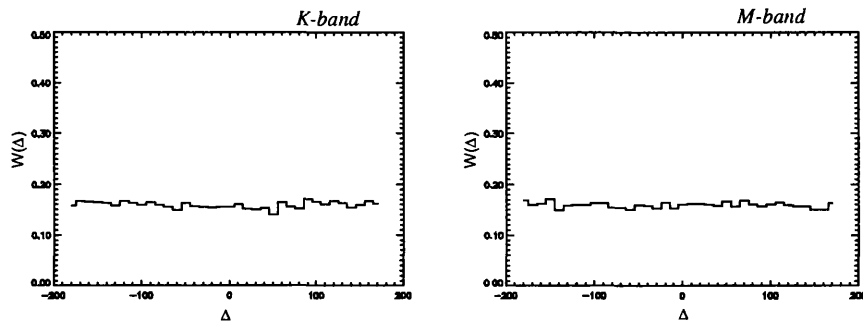
3 – Wave tank experiments and preliminary analysis



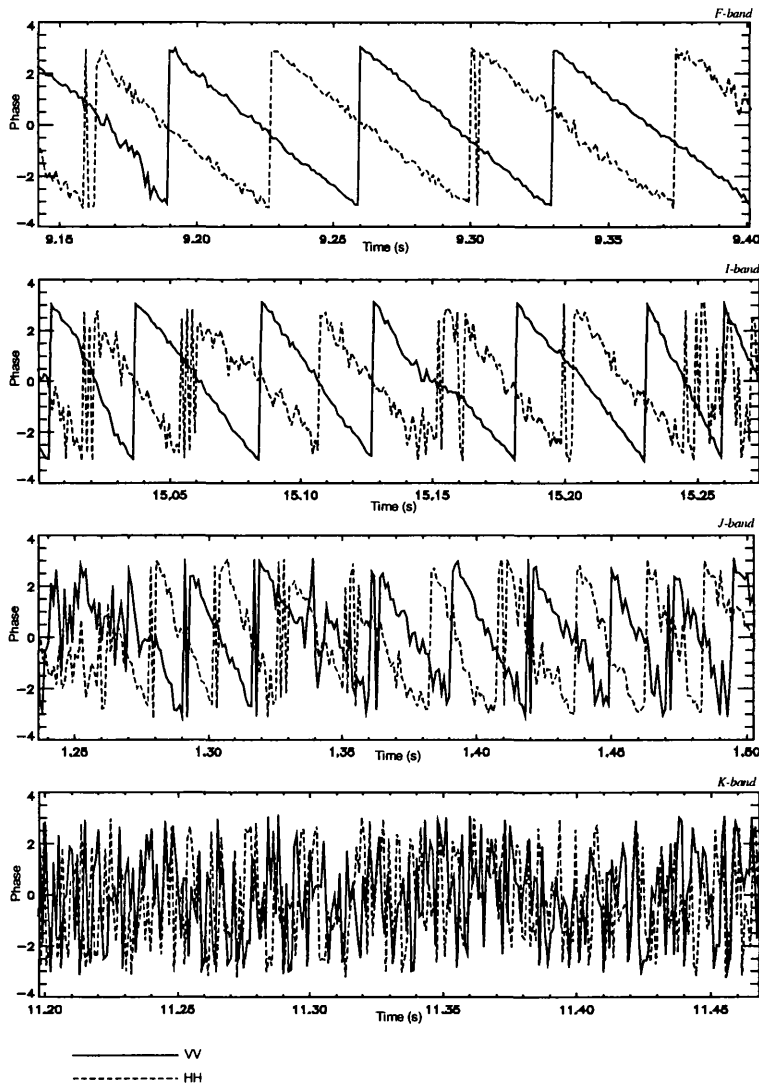
3-26 : Phase difference distributions at I-band, covering 3-12 ms⁻¹ wind speed and 6° to 24° grazing angle



3-27 : Phase difference distributions at J-band, covering 3-12 ms⁻¹ wind speed and 6° to 24° grazing angle



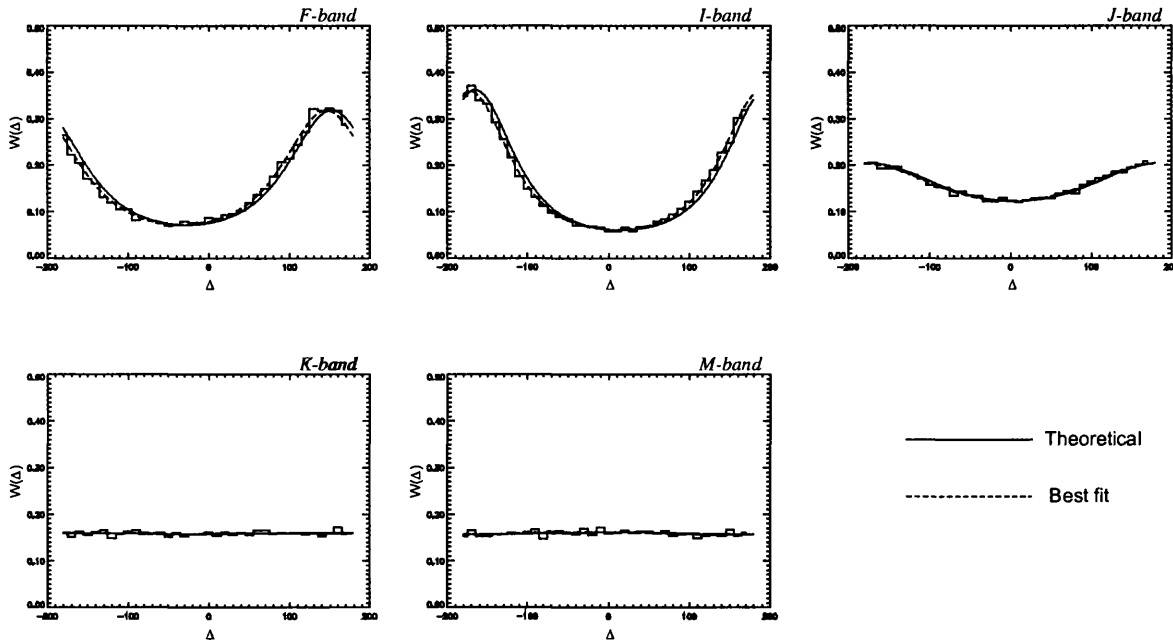
3-28 : Phase difference distributions at K and M-bands, 12 ms^{-1} wind speed, 24° grazing angle



3-29 : Phase history of F, I, J and K-bands over approximately 0.25 seconds

The distribution seen in the data was compared to the form given in 3-22 in two ways. First, by forming the complex correlation coefficient of the two polarisations, the parameters k_0 and ϕ_0 can be found (see appendix B equation B-8) and so a theoretical form of the distribution calculated from equation 2-26. Alternatively, a “best fit” curve can be formed by taking equation 2-26 and varying k_0 and ϕ_0 using an optimisation routine to minimise the χ^2 error statistic.

Data at each frequency along with the theoretical and best fit curves are shown in figure 3-30. The data was taken at 24° grazing angle and 5 ms^{-1} wind speed, a set up in which the data would not be expected to be particularly non-Gaussian or “spiky”. Table 3-1 gives the parameters used in the theoretical and best fit cases, along with the normalised intensity variance of each polarisation as a measure of the data’s spikiness (Gaussian data would give a value of one). The plots and the table show good agreement between the theoretical and best fit curves, which both describe the data well, and the normalised variance is low on all cases.



3-30 : Comparison of theoretical and best fit distributions to each frequency at 5 ms^{-1} and 24° grazing angle

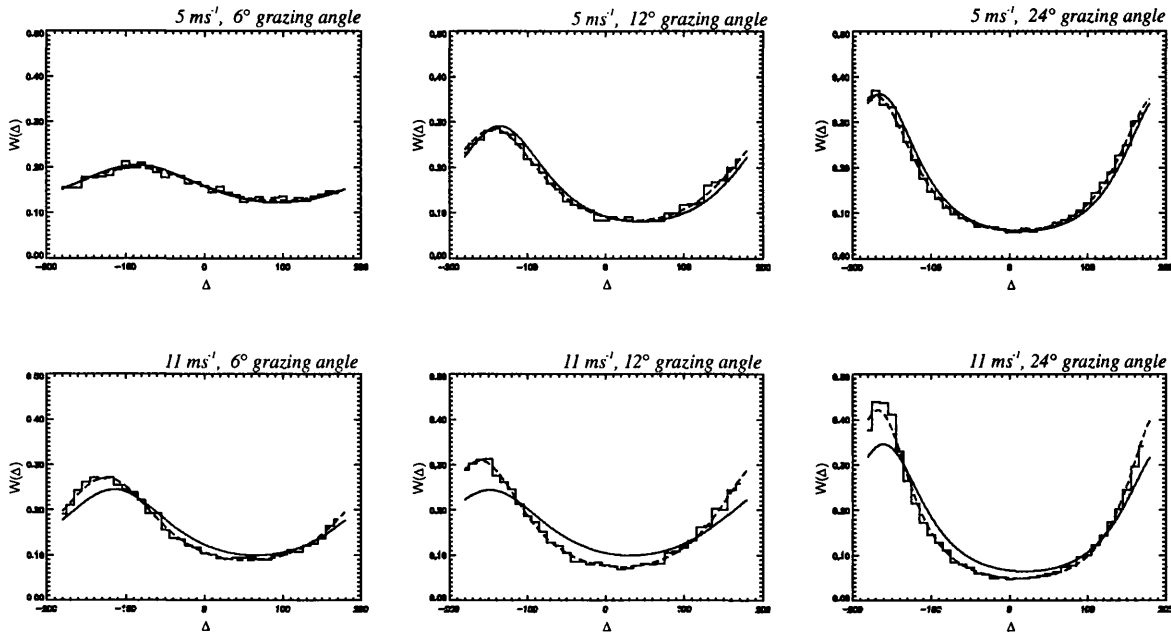
	F-band	I-band	J-band	K-band	M-band
k_0 theoretical	0.444	0.516	0.161	0.004	0.010
ϕ_0 theoretical	152.5	-165.2	-174.6	150.9	8.8
k_0 best fit	0.442	0.512	0.159	0.002	0.012
ϕ_0 best fit	145.6	-171.6	-179.6	139.8	-19.8
VV norm. var.	1.27	1.09	1.02	1.00	1.13
HH norm. var.	1.17	3.75	1.31	1.02	1.06

Table 3-1 : Comparison of theoretical and best fit parameters at each frequency, and the VV and HH normalised variance

Figure 3-31 shows I-band data taken at 5 ms^{-1} and 11 ms^{-1} wind speed, each at 6° , 12° and 24° grazing angle. Again, solid curves show the theoretical distribution calculated from the correlation coefficient, and the dotted lines show the best fit. The parameters to each plot are given in table 3-2. At both wind speeds, the data shows its characteristic variation with grazing angle. At the lower wind speed, the two curves are once again virtually coincident, with the parameters in the table reflecting this. At the higher wind speed, however, the curve derived from the complex correlation coefficient does not give a good fit to the data. Whilst the value of ϕ_0 predicted remains reasonably accurate (within 13° of the best fit), the value of k_0 predicted falls some way short of the best fit value. Note that in all these cases, the value of the HH normalised variance is much greater than one. The data is, however, still described by equation 2-26 as the best fit curve shows. It is simply not described by equation 2-26 with the parameters calculated from the complex correlation coefficient.

	$5 \text{ ms}^{-1}, 6^\circ$	$5 \text{ ms}^{-1}, 12^\circ$	$5 \text{ ms}^{-1}, 24^\circ$	$11 \text{ ms}^{-1}, 6^\circ$	$11 \text{ ms}^{-1}, 12^\circ$	$11 \text{ ms}^{-1}, 24^\circ$
k_0 theoretical	0.161	0.387	0.516	0.279	0.278	0.491
ϕ_0 theoretical	-85.4	-135.4	-165.2	-114.9	-147.9	-160.7
k_0 best fit	0.142	0.373	0.512	0.343	0.425	0.597
ϕ_0 best fit	-85.4	-143.6	-171.6	-124.8	-160.5	-167.9
VV norm. var.	1.41	1.20	1.09	1.39	1.56	1.25
HH norm. var.	1.09	2.02	3.75	10.14	8.65	4.54

Table 3-2 : Comparison of theoretical and best fit parameters at different wind speeds and grazing angles, and the VV and HH normalised variance



3-31 : Comparison of low (top) and high (bottom) wind speed data and theoretical and best fit distributions

The results seen in figure 3-31 and table 3-2 are representative of all the data investigated. That is, by use of a best fit routine, it was possible in all cases to find a form of $W(\Delta)$ which described the data very well. In the cases where the HH normalised variance was close to 1, the curve derived from the correlation coefficient was virtually coincident to this. In cases where the normalised variance was much greater than 1 (roughly speaking, 4 or more) the curve derived from the correlation coefficient did not fit to the data, the value of k_0 being too low. These cases tended to be high wind speed / low grazing angle.

3.4 Conclusions from preliminary analysis

In this chapter, the experimental set-up and facilities available in each of the wavetank experiments have been introduced, and the calibration procedure and preliminary analysis of the data from the MIDAS radar presented. The important conclusions from this analysis can be summarised as follows:

- Calibrated range-time-intensity images have shown very high RCS values in horizontal polarisation from mechanically generated breaking waves. In simultaneous vertical images, backscatter from wind waves dominated.
- Doppler analysis has clearly identified slow, Bragg and fast, non-Bragg components in the spectra, VV data being dominated by the former and HH by the latter of these. Analysis of individual strong features has suggested that there are two types of fast scatterer – one seen at lower wind speeds in HH only, and one at high wind speeds seen in both polarisations.
- Lee's Doppler lineshape analysis technique has been shown to provide good fits to the data examined, with results in agreement with published work. However, it is suggested that there are certain shortcomings in the physical insight which this technique can lend to the actual scattering processes operating, in particular the lack of any connection between the components ascribed to the two polarisations, given that polarisation invariant fast scattering is so often seen.
- Doppler filtering at the Bragg speed has been shown to recover the composite SPM RCS result over a range of grazing angles.
- It has been demonstrated that the distribution of the phase difference between the two polarisations contains useful information. It has a shape dependent on wind speed, grazing angle and radar frequency, and the trends with each of these parameters have been identified. The shape of the distribution conforms to the Gaussian-based model in cases in which the normalised variance of the data is close to unity, but deviates from the expected shape slightly when the variance becomes higher.

Chapter 4 A new Doppler model and application to wave tank data

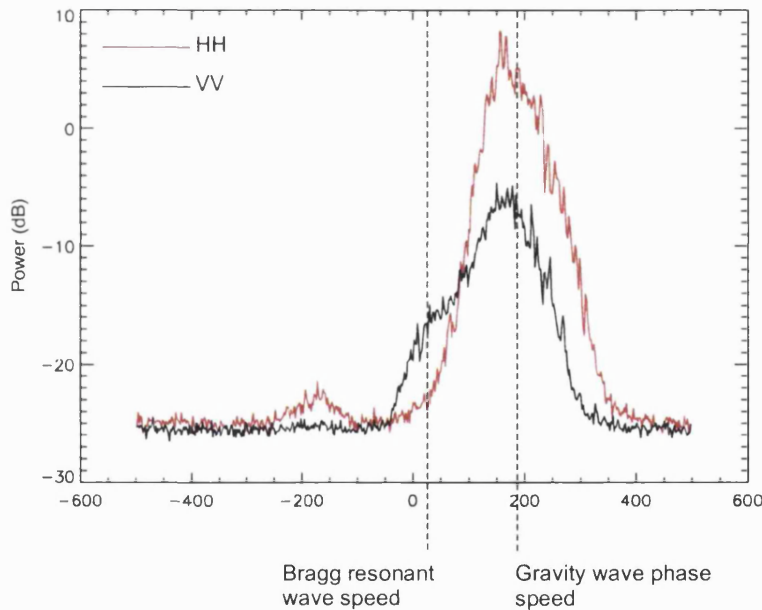
4.1 Introduction

The previous chapter clearly showed that pure Bragg scattering theory is not sufficient to describe data recorded in the wave tank in terms of either the Doppler shifts observed or the RCS and polarisation ratio seen in the data, results which mirrored those seen by other authors in open water sea clutter. Lee's lineshape analysis technique proved successful in providing good fits to the data, but was somewhat unsatisfactory in its treatment of the two polarisations separately, and it appeared that more information about the origin of the components of the spectra could be gained by examining the data in the time as well as the frequency domain and, from this, inferring the type of wave which caused the feature.

In this chapter, this method of analysis is taken further and formalised somewhat. By use of the synchronous video and radar data from the UCSB C-band radar experiment the need to infer the wave causing the backscatter is eliminated, as it can be seen directly in the video data. After analysis of several waves in this way, dominant scattering mechanisms can be identified and these used as the basis of a new Doppler model which describes Bragg and non-Bragg scattering components in both vertical and horizontal polarisation.

4.2 Synchronous radar and video data

Although the ultimate goal of this work is to develop a Doppler model for radar backscatter from wind blown waves, mechanically generated breaking waves can, at least initially, be more useful. As mentioned in the previous chapter, the field of view of the high speed video camera was only around 1 m, meaning that in one data capture run (typically about 10 seconds long) it is simply down to luck as to whether a wind blown wave will break in the camera's footprint. The breaking of the larger, mechanical waves, however, can be accurately controlled making them a better starting point for the study of the different scattering mechanisms present in sea clutter.

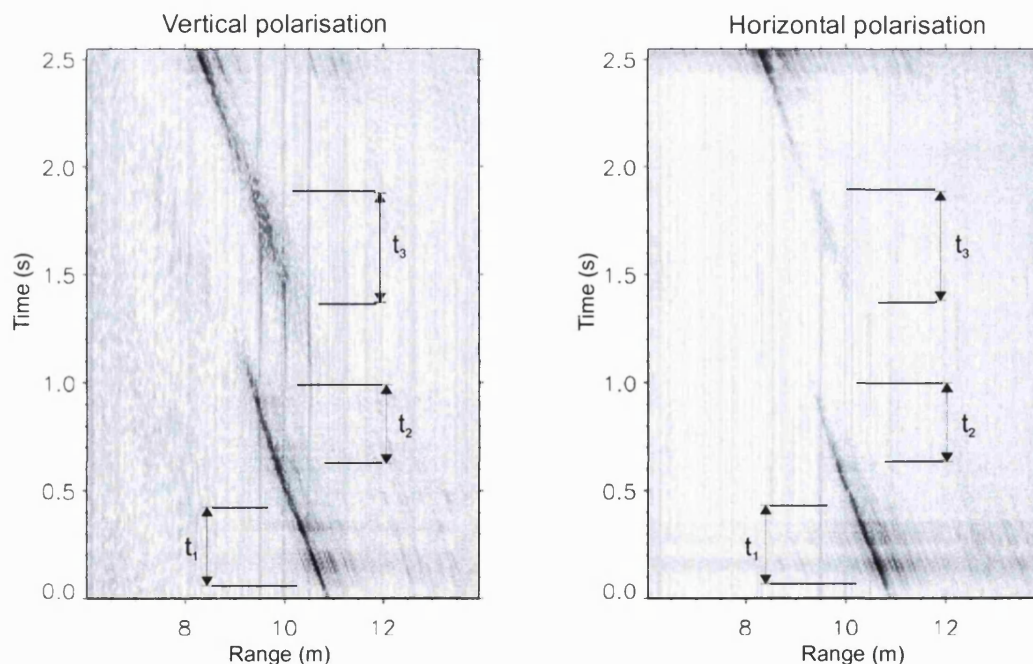


4-1 : Doppler spectra at J-band, 6° grazing angle of 2.3 m wavelength breaking wave groups taken with the MIDAS radar

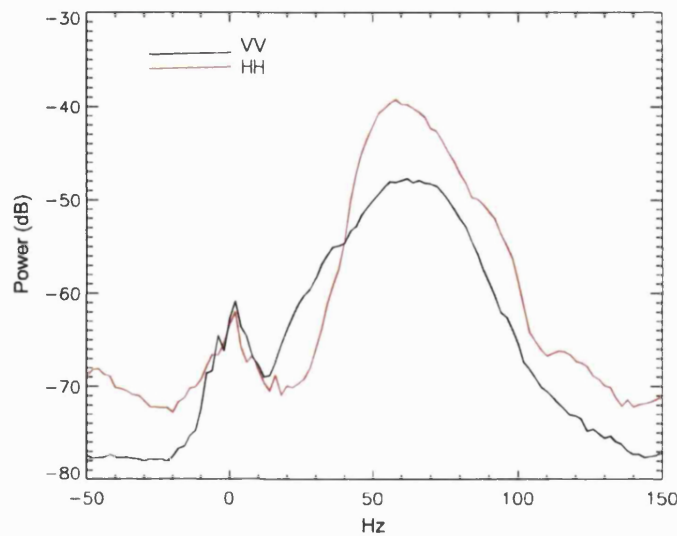
Before examining the UCSB C-band data of individual breaking waves, it is useful to look at some of the MIDAS data taken over 4 minutes and so covering around 80 waves. The spectra shown in figure 4-1 were taken at J-band, 6° grazing angle of 2.3 m breaking waves. Also marked on the plot are the approximate free Bragg wave phase speed and 2.3 m gravity wave phase speed. Vertical polarisation shows clear returns at the Bragg speed, but unlike in wind waves, the spectrum does not peak

here but at the much higher gravity wave phase speed. In horizontal polarisation, no Bragg component above the noise floor can be seen, and the peak at the gravity wave speed is far higher than that seen in vertical. To ascertain the precise origins of each of the components seen in these spectra, one can now examine the high resolution C-band data of an individual breaking wave and its accompanying video data.

Figure 4-2 shows range-time-intensity plots of backscatter from 2.3 m breaking wave groups, taken with the UCSB radar. The images cover approximately 2.5 seconds in time and 8 m in range. The Doppler spectra shown in figure 4-3 are averaged over the entire image. Whilst the velocity resolution in the UCSB radar is somewhat coarser than that of MIDAS, and also recalling that figure 4-1 is an average over many waves, the same general features are present in the two plots. (Note that the peak at 0 Hz in figure 4-3 is an artefact, possibly of the FFT routine, not a backscatter feature). At lower shifts, VV is again seen to be greater than HH, whilst both spectra peak at a higher shift of approximately 65 Hz, where HH exceeds VV.

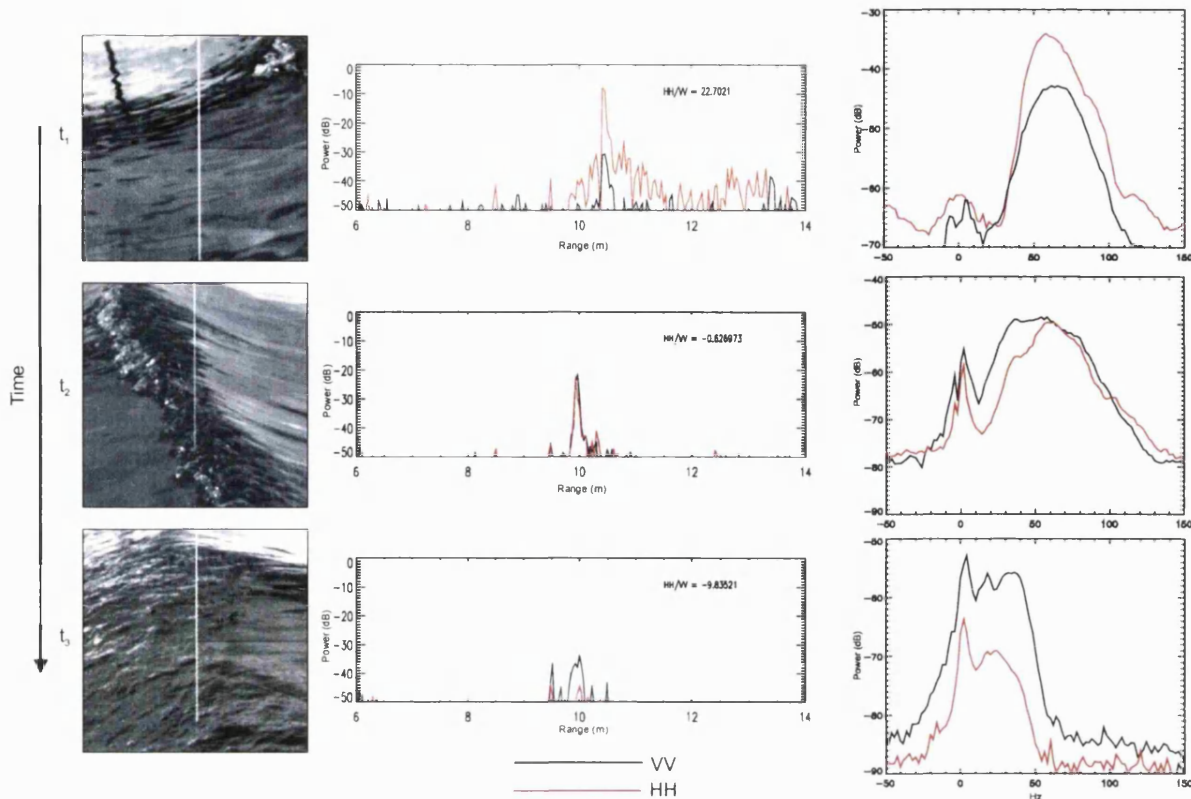


4-2 : RTI plots from the UCSB C-band radar of 2.3 m breaking waves. Regions t_1 , t_2 and t_3 cover different stages in the wave's breaking process



4-3 : Doppler spectra averaged over the entire breaking process. The peak at 0 Hz is an artefact, not a clutter feature

Marked on figure 4-2 are three time periods – t_1 , t_2 and t_3 – which each cover different portions of the wave breaking process. Video frames, range profiles and Doppler spectra taken from each of the periods are shown in figure 4-4. (The vertical line seen in the video frame is string marking the 10 m point). Across the top of the figure, data is shown taken from period t_1 . The spectra averaged over only this time show no region significantly above the noise floor in which VV exceeds HH, and again both polarisations peak at around 65 Hz. The video frame shows, in the top right corner, that the wave has just started to spill, and the range profiles show that at this point the HH/VV ratio is 22.7 dB. The strong HH return is very localised in range, covering perhaps two range gates. This is clearly non-Bragg scattering, as HH exceeds VV. The Doppler spectra show that the peak returns are at about the wave phase speed. This type of radar backscatter will, from here on, be referred to as a *spike*.



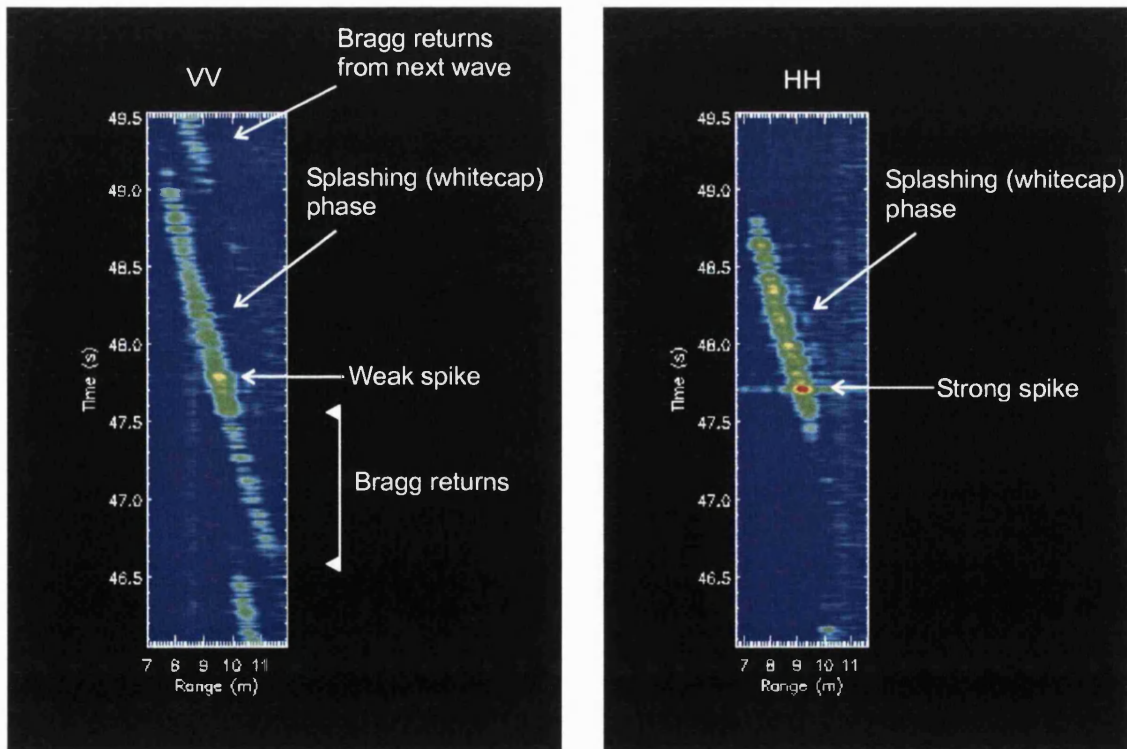
4-4 : Video frame, simultaneous range profiles and Doppler spectra from t_1 (top), t_2 (middle) and t_3 (bottom)

Across the centre of figure 4-4 is shown data taken from period t_2 , around half a second later. The video frame shows that the now fully broken wave has moved directly into the field of view of the camera and gives a range profile which is virtually polarisation independent. Note that between t_1 and t_2 the peak in the HH range profile has dropped by over 10 dB, whilst that in VV has increased by 10 dB. The strong returns are once again localised in range and the spectra of the two polarisations are also near identical except for the lower frequency VV component. Owing to the form of the wave which causes it, this type of backscatter will from here be referred to as a *whitecap*.

The bottom video frame shows the water surface about one second later, clearly roughened by the splashing of the previous wave and tilted slightly towards the radar. The Doppler plot now shows VV greater than HH everywhere, and both polarisations

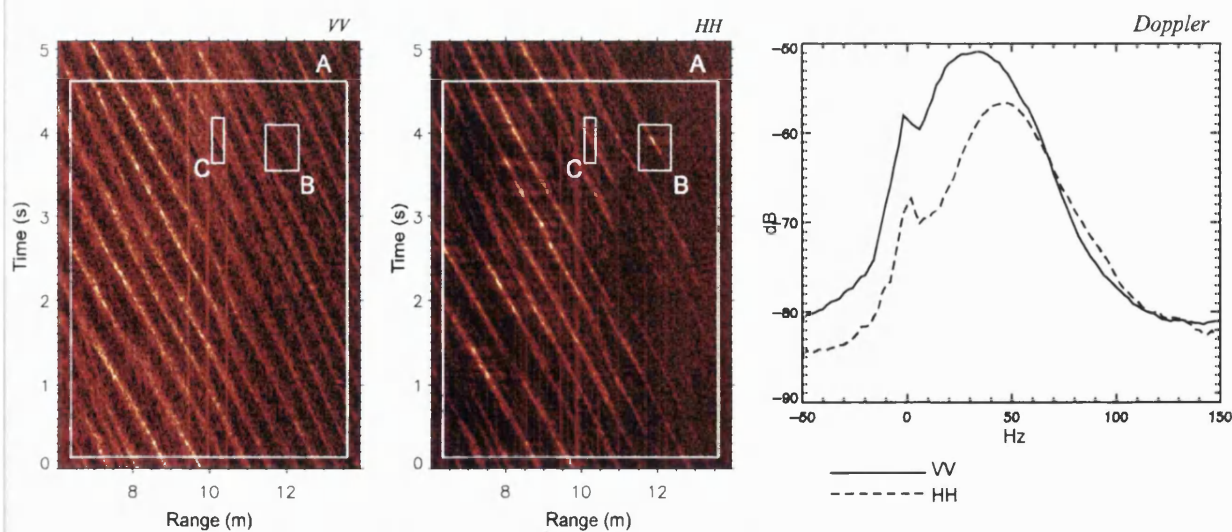
peak at a much lower frequency than before. This is consistent with Bragg resonant scattering from a slightly rough tilted surface, with VV greater than HH, in line with Rice's theory, and the smaller Doppler shift resulting from the scatterers now being capillary waves moving more slowly than the dominant waves. In the RTI plot of figure 4-2, particularly in VV, the Bragg scattering region in t_3 is seen to be spread over quite a number of range gates, as opposed to the non-Bragg regions which are localised in range.

All of the above indicates that radar backscatter from these waves can be defined in terms of three dominant components – Bragg scattering, non-Bragg HH enhanced spikes and non-Bragg polarisation independent whitecaps. These three stages are in broad agreement with the detailed analysis of breaking waves given by Fuchs [Fuchs et al, 1999], and figure 4-5 shows a calibrated RTI plot taken from the MIDAS radar, showing the same features as seen in the UCSB C-band images.

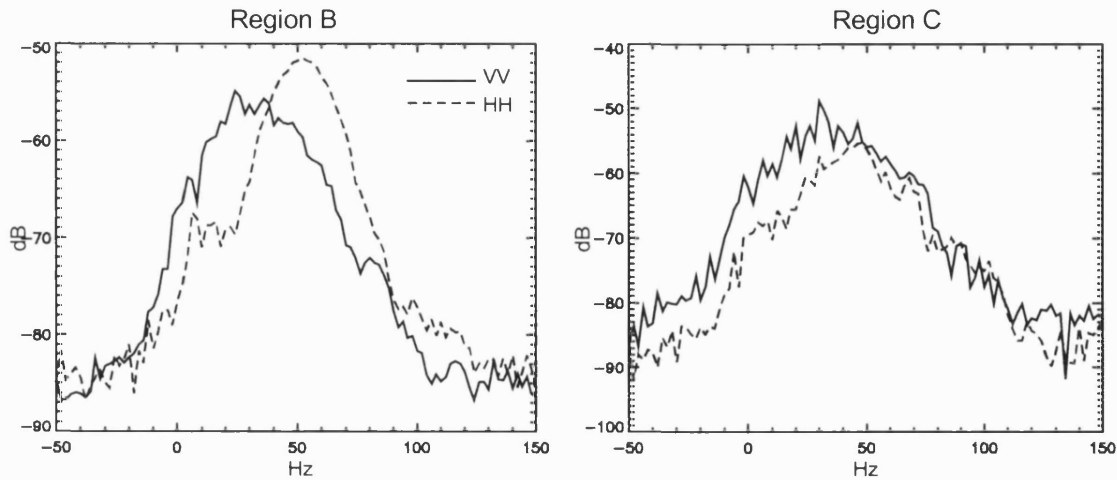


4-5 : Breaking wave RTI plots from the MIDAS radar at J-band showing the same features as the UCSB C-band radar data

Although the same type of analysis with wind blown waves can be more difficult, as capturing a breaking wave must be left a little more to chance, it can be shown using wind waves that the same three dominant scattering components are present. Figure 4-6 shows HH and VV RTI plots taken with the UCSB radar at 12 ms^{-1} wind speed covering 5 seconds in time. The Doppler spectra shown are averaged over the large region A, and show the characteristic form of a Bragg dominated VV spectrum peaking at a lower speed than HH, with the two showing close to coincident fast sides. Figure 4-7 shows Doppler spectra averaged over the small areas B and C shown on the RTI. In the spectra taken from region B, which covers a strong HH event, horizontal polarisation is seen to rise well above vertical at a speed far higher than the Bragg speed, at which VV peaks. Unfortunately, this event is well outside the field of view of the video camera. However, the form of the spectra, with HH much greater than VV, and the localisation in range of the spike, is similar to that seen in figure 4-4 at the onset of breaking of a mechanically generated wave.

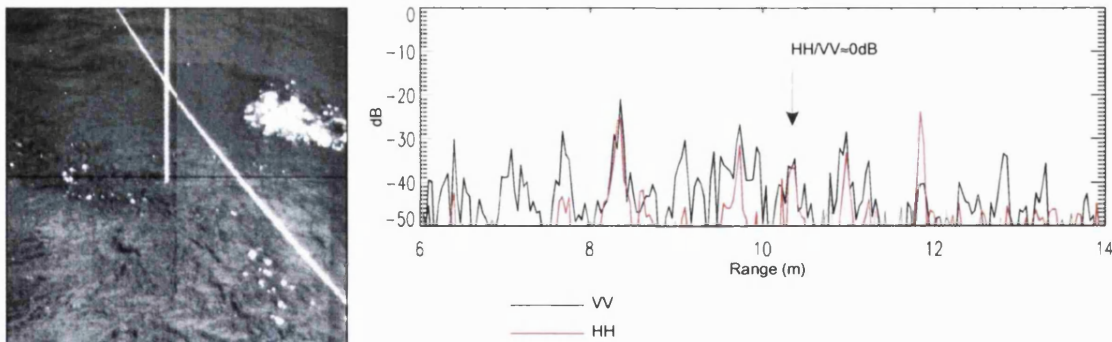


4-6 : RTI plots of 12 ms^{-1} wind waves taken with the UCSB radar, and Doppler spectra averaged over range-time area A



4-7 : Doppler spectra averaged over range-time areas B and C covering a wind blown spike and a whitecap respectively

The boxed area C is within the camera's field of view and figure 4-8 shows the video data and range profiles. The video frame shows the whitecap of a broken wave clearly on the right hand side, at a range of a little over 10 m. This point, highlighted in the range profile, is seen to have a polarisation ratio of approximately 0 dB. The spectra of the two polarisations are seen to be very nearly coincident, other than the slow VV Bragg scattering still present.



4-8 : Simultaneous range profiles and video frame from the range-time area C. The possible polarisation independent whitecap return is highlighted

This data shows that the two forms of non-Bragg scattering identified in mechanically generated waves are also present in wind blown waves. The overall wind blown wave Doppler spectrum is therefore a combination of a Bragg component at its

characteristic speed, a polarisation independent whitecap component at the wave phase speed, and an HH spike component, also at the wave phase speed.

4.3 Doppler modelling

4.3.1 Description of the model

This section presents the mathematical detail of the Doppler model to be used to describe the wave tank data. The aim of this model is to, in as succinct a form as possible, capture the gross polarisation and Doppler characteristics of the data, with each component used having a clear physical basis suggested by the data analysis in the previous section. In contrast to the lineshape analysis described in chapter 3, clear relationships between the two polarisations are preserved in the form of the Bragg scatterers and the polarisation independent whitecap term. An HH spike term is included with no VV counterpart as, although weak spikes are seen in VV in the initial stages of wave breaking, they are utterly drowned out by strong VV Bragg and whitecap contributions and have negligible effect on the average Doppler spectrum. Gaussian basis functions are used to build up the spectra, as the goal here is not to capture possible nuances in the shape of each component but to reproduce the most important features of the data, such as the Doppler shift, relative RCS contribution and polarisation nature of each scattering process.

The model of the Doppler power spectrum $\Psi(\nu)$ for each of the two polarisations is given by equations 4-1 and 4-2 below.

$$\Psi_V(\nu) = B_V\psi_B(\nu) + W\psi_w(\nu) \quad [4-1]$$

$$\Psi_H(\nu) = B_H\psi_B(\nu) + W\psi_w(\nu) + S\psi_s(\nu) \quad [4-2]$$

where subscripts V and H refer to the polarisation and B, W and S indicate Bragg, whitecap and spike components respectively. Each of the components are given Gaussian lineshapes

$$\psi_B(\nu) = \exp\left(\frac{-(\nu - \nu_B)^2}{w_B^2}\right) \quad [4-3]$$

$$\psi_W(\nu) = \exp\left(\frac{-(\nu - \nu_P)^2}{w_W^2}\right) \quad [4-4]$$

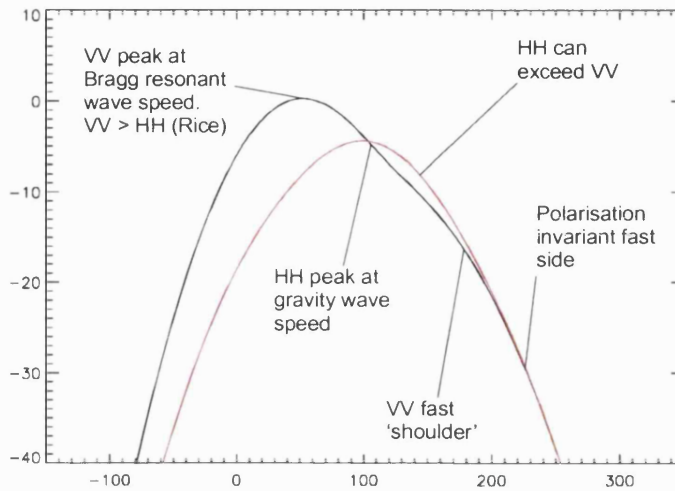
$$\psi_S(\nu) = \exp\left(\frac{-(\nu - \nu_P)^2}{w_S^2}\right) \quad [4-5]$$

where ν_B and ν_P are the frequencies corresponding to the Bragg resonant wave speed and the gravity wave phase speed respectively, as calculated from the speeds given in equations 3-12 to 3-16, converted to frequencies via the Doppler shift formula (3-11).

The widths of each of the spectral components (w_B , w_W and w_S in equations 4-3, 4-4 and 4-5) are left as free parameters to be varied to get a best fit to the data. The coefficients B_V and B_H in equations 4-1 and 4-2 are set using the composite surface Bragg scattering model as described in chapter 2, equations 2-10 to 2-14. The coefficients W and S in equations 4-1 and 4-2, which describe the relative strengths of the contributions of the non-Bragg whitecaps and spikes, are not set here as the variation of these components over wind speed and grazing angle is not well understood.

Figure 4-9 shows a graphical representation of the model with representative values taken for each of the parameters. This plot shows that the simple form given in equations 4-1 and 4-2 can reproduce all of the features seen in the data. The Bragg

dominated VV spectrum peaks at a low shift but is skewed over to the fast side by the whitecap contribution. At the high shifts, HH can be greater than VV because of the spike term, whilst at low shifts it is significantly below VV, in line with the composite Rice values of $HH/VV \approx -20$ dB. The model does not include the 0 Hz artefact noted in figure 4-3 or the noise floor.



4-9 : Schematic of the Doppler model, showing all the main features seen in Doppler spectra

4.3.2 Application to wave tank data

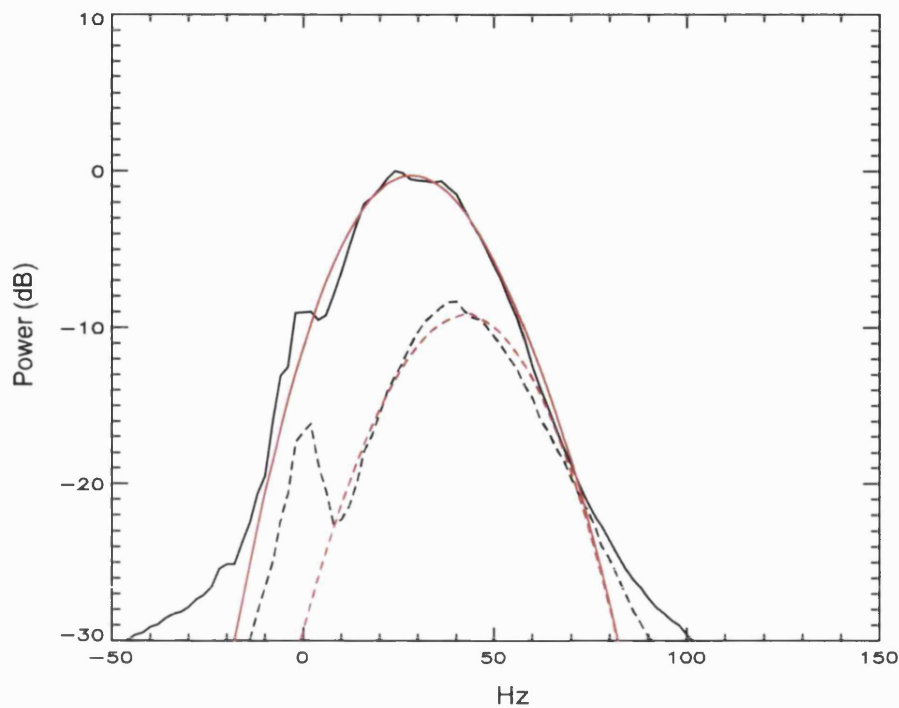
The first problem in using this model in a comparison with data collected at the wave tank comes from the two dimensional wavenumber spectrum, $\Psi(k_x, k_y)$ in equation 2-10, which was not recorded during the experiment. Given that the wavenumber power spectrum is not available, one can still proceed using an 'uncalibrated' version of the model. Although the absolute RCS values predicted by the Rice model are heavily dependent on the form of Ψ , the polarisation ratio of HH/VV is not. (In the standard, non-Composite Rice model, the spectrum actually cancels out in the polarisation ratio. Although this is not true for the composite model, at the relatively small root mean square tilt values considered here the exact form of the spectrum has a negligible effect on the value of the polarisation ratio.) Therefore, one can use the composite model to set the value of HH/VV (B_H/B_V in equations 4-1 and 4-2) and

then leave the absolute value of VV (B_V) as a free parameter. Other values required to feed into the model such as the root mean square tilt of the gravity waves at different wind speeds, the trough to crest wave heights, wave periods and dominant water wavelengths have been provided by a laser slope meter. Overall, therefore, the values fixed are B_H/B_V (from the composite scattering model), v_P (from the wave phase speed) and v_B (from the Bragg plus Stokes drift model), and the free parameters are W , S , B_V and the widths w_B , w_W and w_S . A minimisation routine was used to vary these free parameters to find a best fit to the data, in terms of a minimum chi squared value.

Figures 4-10 to 4-14 show the best fits provided by the model to data taken at several radar frequencies and wave conditions. The model parameters are given in table 4-1. Note that the noise floor can be seen in some of the data and, as noise is not included in the model, the predictions fall away from the data at the edges of the spectrum.

Figure	Transmit frequency	Windspeed/wavelength	B_H/B_V	W/B_V	S/B_V	w_B	w_W	w_S
4-10	6 GHz	12ms^{-1}	-18.60	-8.85	-18.10	17.4	19.6	0.85
4-11	9.75 GHz	10ms^{-1}	-21.0	-9.79	-5.95	22.2	19.8	12.8
4-12	15.75 GHz	10ms^{-1}	-20.74	-6.17	-4.89	27.3	23.2	30.1
4-13	35 GHz	12ms^{-1}	-19.30	-3.44	3.01	82.3	101.2	60.6
4-14	15.75 GHz	2.3 m	-25.0	10.2	22.5	57.0	59.5	50.0

Table 4-1 : Three component model parameters used in the fits to the data in figures 4-10 to 4-14. Ratios in dB and widths in Hz

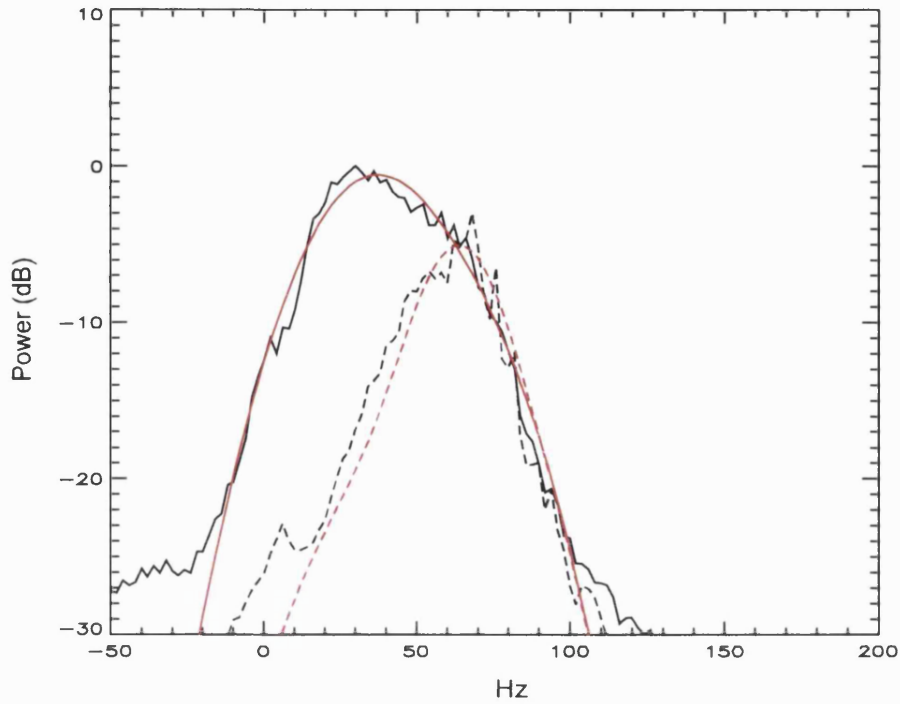


4-10 : UCSB C-band radar data at 12 ms^{-1} wind speed, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH

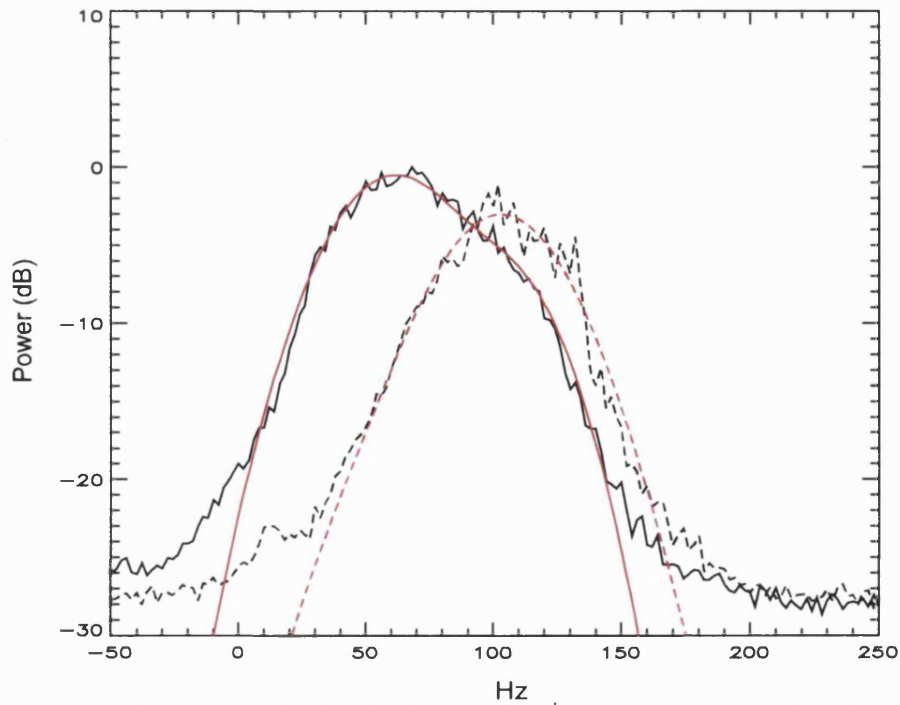
Figure 4-10 shows the result of applying the model to data collected with the UCSB radar at 12 ms^{-1} wind speed. The fit to both polarisations is seen to be very good, with the data showing the often seen form with near to coincident fast sides and no region of HH greater than VV. In response to this, the minimisation routine has set the HH spike component to almost 0 leaving just the polarisation independent whitecap term to describe the fast scatterers. The strong Bragg term dominates VV, and the low frequency artefact around 0 Hz is again seen in HH.

Figure 4-11 is data collected with the multi frequency radar at I-band and a wind speed of 10 ms^{-1} . Once again, the spectra show coincident fast sides and the model provides a good fit to this. Figure 4-12 shows J-band data taken again at 10 ms^{-1} wind speed. This time, the horizontally polarised spectrum clearly exceeds the vertical at high speeds, and this is accounted for by the HH spike component. Note

also how the polarisation independent whitecap term gives the VV spectrum its shoulder at about 100 Hz.

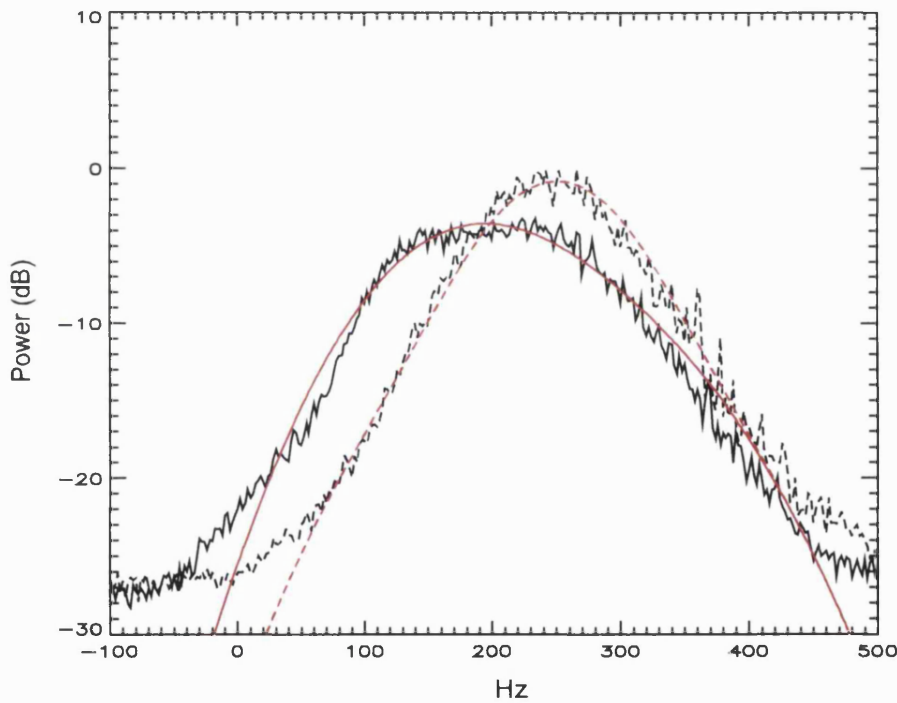


4-11 : MIDAS I-band radar data at 10 ms^{-1} wind speed, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH



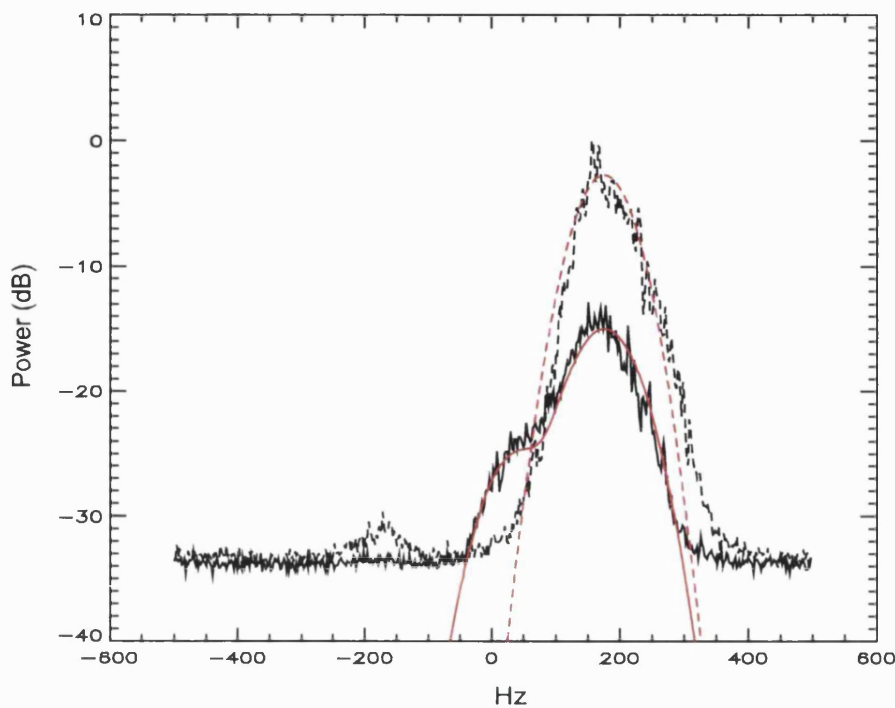
4-12 : MIDAS J-band radar data at 10 ms^{-1} wind speed, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH

Figure 4-13 shows data taken at K-band now at the higher windspeed of 12 ms^{-1} . Once again, the addition of the polarisation dependant HH spike term accounts for the high HH peak seen in the data, whilst the whitecap term gives the VV spectrum its extra width towards the fast side and the HH spectrum a broader base, (note the relative widths of the whitecap and spike terms in table 4-1). In all the cases shown, although the HH Bragg term is very small compared to the non-Bragg terms, the agreement between model and data on the low frequency side of the spectra show that this component, too, is correct.



4-13 : MIDAS K-band radar data at 12 ms^{-1} wind speed, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH

The versatility of this model is highlighted in figure 4-14. This shows the spectra of 2.3 m breaking wave groups (shown in figure 4-1) together with the fits provided by the model. Even in this case, in which non-Bragg scattering is dominant in both polarisations, the model is seen to provide a very good fit to both the main peaks and the slower, Bragg scattering shoulder in VV.



4-14 : MIDAS J-band radar data of 2.3 m breaking wave groups, with the Doppler model overlaid. Black lines are data, red are the model. Solid lines are VV, dashed are HH

4.4 Discussion and conclusions

By using synchronous radar and video data recorded in the UCSB OEL wavetank, three stages in the evolution of a breaking wave have been identified and different scattering mechanisms, giving rise to different polarisation and Doppler characteristics, inferred. These are:

- Bragg scattering, described by the composite form of Rice's theory.
- Polarisation independent scattering from the whitecaps of broken waves.
- HH enhanced sea spike scattering from the crest of a wave, just before or as it spills.

Thus, the radar and video data has shown that non-Bragg scattering events do indeed come in more than one form as suggested by analysis of the radar data alone in the previous chapter, and the properties of these two scattering components have been investigated in some detail. A simple Doppler model based on the three

mechanisms shown to be dominant was found to describe Doppler spectra from two different radars, taken at a variety of radar frequencies and wind conditions, very well. As well as providing a good description of spectra with polarisation independent fast sides, the HH spike term allowed the model to give good fits to spectra which showed strong polarisation dependence of fast scatterers. In this work, Gaussian lineshapes have been used for all of the components, in contrast to the work of Lee et al, in which Voigtians and Lorentzians are used for the non-Bragg scatterers. The Gaussian was used in the interests of simplicity, and in order to focus on capturing the gross features of the spectra, highlighting similarities and differences between the two polarisations and links to the wave evolution seen in the video data. The figures show that these Gaussian components describe the data to quite a high degree of accuracy. It is possible that detailed analysis of the shape of the spectra would show that the fit could be improved by use of the alternative lineshapes, but this would not alter the fundamental Doppler and polarisation characteristics of each of the components.

A shortcoming of the model as presented here is that it makes no predictions about the non-Bragg scatterers other than their Doppler shift. In that sense, it is not a full predictive model, but can be used as a tool to investigate the non-Bragg scattering present in a Doppler spectrum. By using the model this way, and investigating a large amount of data, it is possible that the behaviour of non-Bragg scatterers over a range of wind conditions and grazing angles could be found and so modelled empirically. Also, the data considered here was all recorded in the controlled conditions of a laboratory wave tank which, whilst useful in its ability to provide repeatable and controllable waves, cannot accurately reproduce open or coastal water environments because of very large scale features such as swell waves. The application of the model to such data is considered in the next chapter.

Chapter 5 Analysis of cliff top radar data

5.1 Introduction

Whilst the previous chapter clearly identified the three scattering mechanisms which are dominant in the wave tank set up, and successfully demonstrated how a model based on these matched closely the recorded Doppler spectra, the question of whether such a description is also valid outside of the laboratory must now be considered. This chapter first of all presents an overall comparison of data recorded in the wave tank with that recorded by a static cliff top radar imaging waters off the south coast of England. As well as the form of the Doppler spectra of the two polarisations, the average RCS values, polarimetric phase statistics and amplitude statistics are considered. After these comparisons, a detailed analysis of individual features in cliff top data is carried out, to confirm (or otherwise) the presence of the same dominant scattering mechanisms as seen in the tank, and from this to comment on the applicability of the model to the data. Finally, the model is used to investigate the type of scattering mechanisms which lead to the visibility of large scale ship generated internal wave wakes in cliff top radar imagery, and possible enhancements of such features are discussed.

5.2 A comparison of cliff top and wave tank radar data

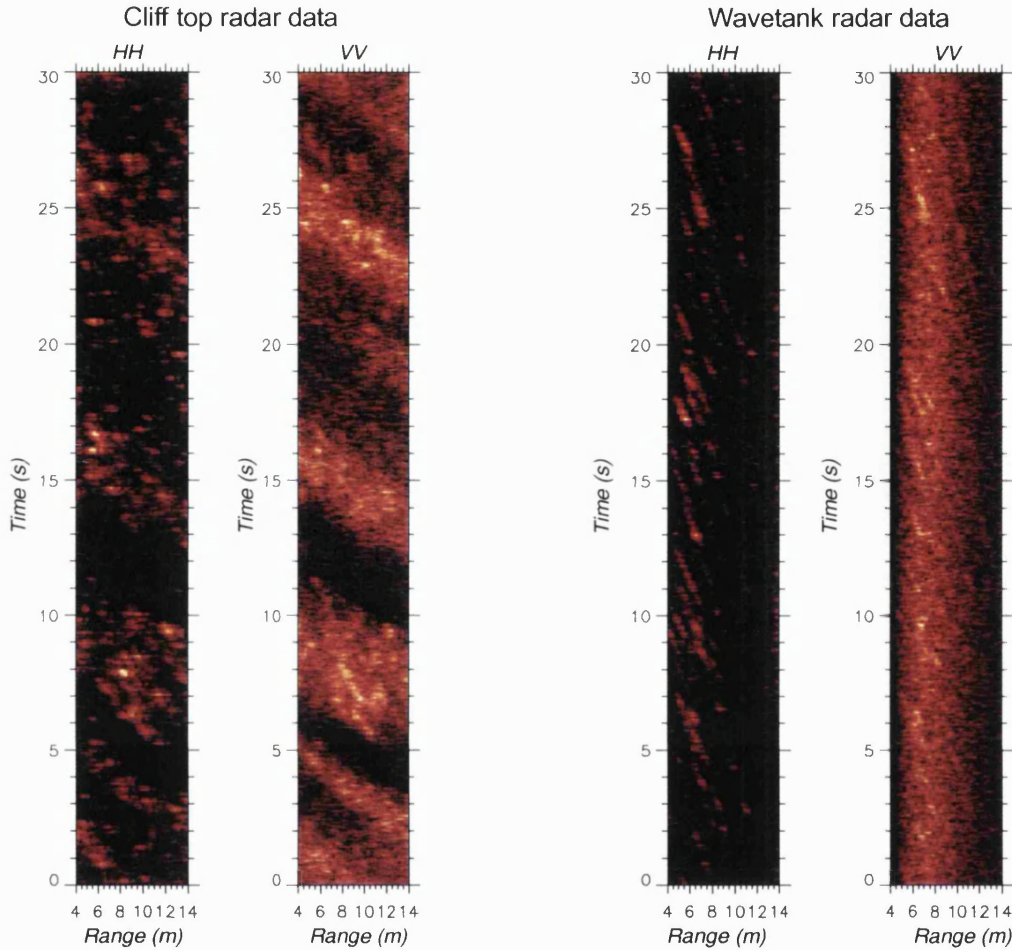
5.2.1 Cliff top radar set-up

The cliff top radar data used in this study was collected using the Thales Defence (formerly Racal-Thorn Wells) Maritime Cliff-top Radar (MCR). This system is almost identical to the MIDAS radar used in the UCSB experiment, the principal difference being that MCR can operate only at F, I and J bands. Again a 500 MHz linear FM chirped pulse was used with a PRF of 2 kHz and pulse to pulse polarisation agility. The system was mounted on a cliff top site on the Isle of Portland, Dorset, at a height of 64 m. The direction of look in azimuth and elevation was variable.

Whilst the radar system itself is very similar to that used in the laboratory, the differences in the scale of the set up have some important consequences. In the laboratory, with a beamwidth of 5° and operating at a range of 10 m, the area covered by a 30 cm rangecell is 0.26 m^2 . The MCR has a beamwidth of 2° and operated typically at a range of 1 km (a 3.6° grazing angle). At the same range resolution of 30 cm, this equates to a rangecell area of 10.47 m^2 , around 40 times as large. One would expect this to mean that a single event such as a breaking wave is less likely to dominate totally the return in a rangecell in the cliff top radar data than in the wavetank. Also, large scale features such as swell waves, impossible to replicate in the tank, would be expected to be prominent in cliff top data.

Figure 5-1 shows RTI plots of cliff top and wave tank data. The cliff top data has had a small 10 m x 30 s section extracted for ease of comparison with the laboratory data. Swell waves are clearly visible in the cliff top data as a series of light and dark bands, particularly in VV. Aside from this, however, the cliff top and wave tank data compare relatively well – in both, vertical polarisation gives a uniform strong backscatter with few prominent individual events, whilst horizontal has a very low

background punctuated by spikes. This shows that even with the larger footprint area of the cliff top set-up, HH retains its spiky nature.

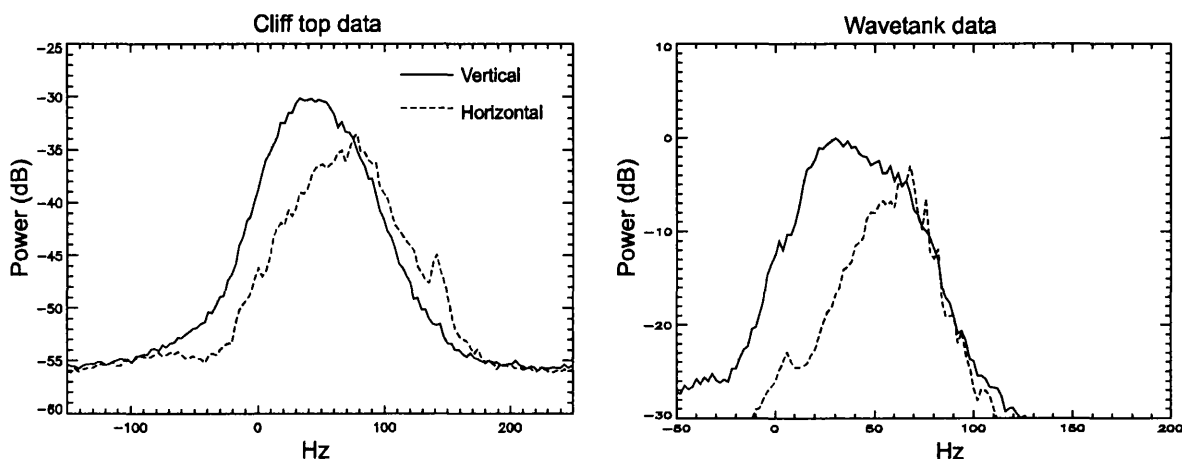


5-1 : RTI plots of I-band cliff top radar data and wave tank data

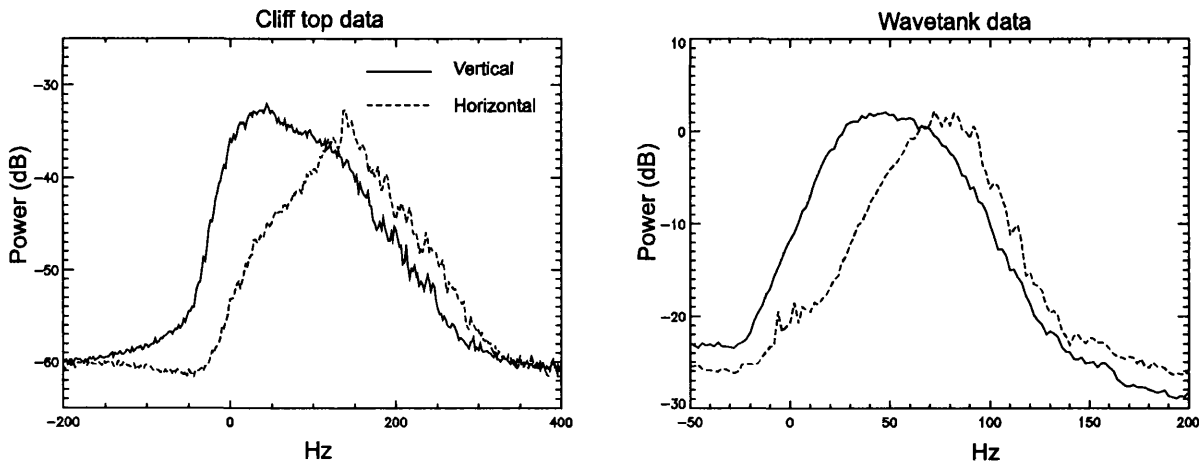
5.2.2 Comparison of Doppler spectra

A comparison of the Doppler spectra is central to taking the step of using the three component model developed using wave tank data to applying it to cliff top data. Here, moderate and high windspeed VV and HH spectra are examined qualitatively and quantitatively, in terms of peak shift and half power width. Also, Lee's lineshape analysis is used on each polarisation individually to ascertain whether this established method decomposes the laboratory and cliff top data into the same basis functions.

Figure 5-2 shows I-band cliff top and wave tank data plotted on a log scale. The cliff top data was recorded looking approximately into the wind, with a mean wind speed of 5 ms^{-1} gusting to 9 ms^{-1} . The grazing angle was approximately 3.6° . The wave tank data was taken looking into a constant 10 ms^{-1} wind at 6° grazing angle. The spectra look remarkably similar. In both situations the VV peak is at a higher power but lower shift than the HH. Both pairs of spectra have near to coincident fast sides, but show VV clearly greater on the slow sides. Figure 5-3 shows similar data now taken at a slightly increased wind speed. The cliff top data was recorded looking into a wind of 10 ms^{-1} gusting up to 15 ms^{-1} . The wave tank data was taken at a constant 12 ms^{-1} . Both sets of data now show the HH fast side noticeably above VV, and the HH peak at virtually the same power as the VV. Table 5-1 summarises the position of the Doppler peak and the full width at half maximum values of the wave tank and cliff top data. This table shows that although we have seen qualitative similarities in the spectra, the absolute dimensions do not tally particularly well, with the possible exception of the VV peak shifts. This is to be expected as, even though the wave tank is producing very similar wind speeds to those of the cliff top data, the fetch of only 30 m in the tank cannot reproduce the large scale surface drift currents and swell produced by a fetch of many kilometres.



5-2 : Doppler spectra of cliff top and wave tank radar data taken at moderate wind speeds



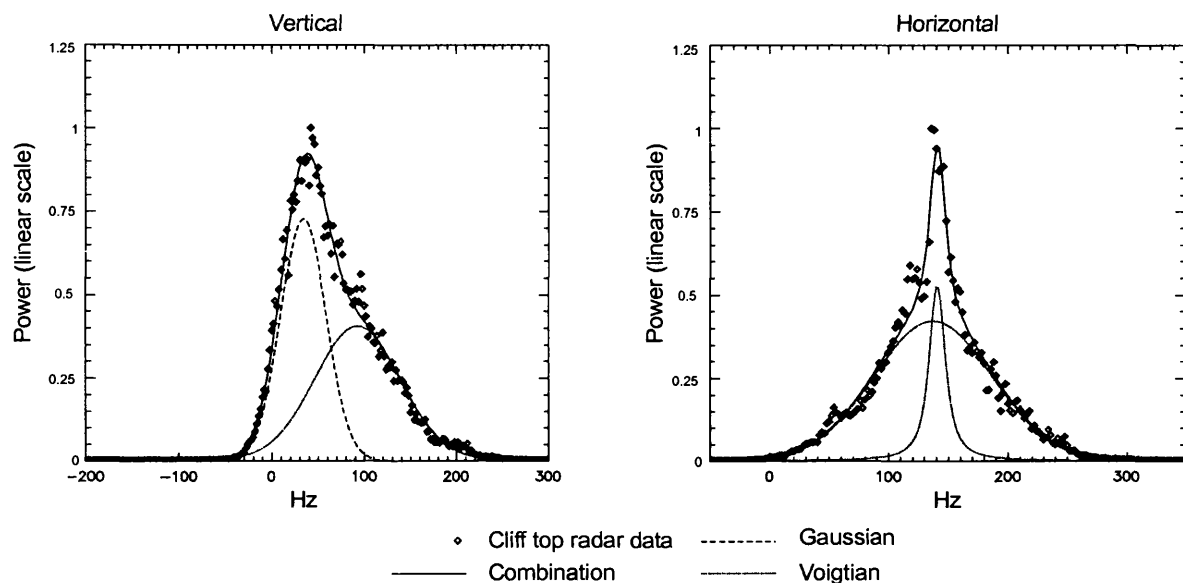
5-3 : Doppler spectra of cliff top and wave tank radar data taken at higher wind speeds

	Vertical		Horizontal	
	Peak (Hz)	Width (Hz)	Peak (Hz)	Width (Hz)
Cliff top fig 5-2	33	48	78	30
Tank fig 5-2	30	26	68	26
Cliff top fig 5-3	44	86	138	16
Tank fig 5-3	48	50	72	34

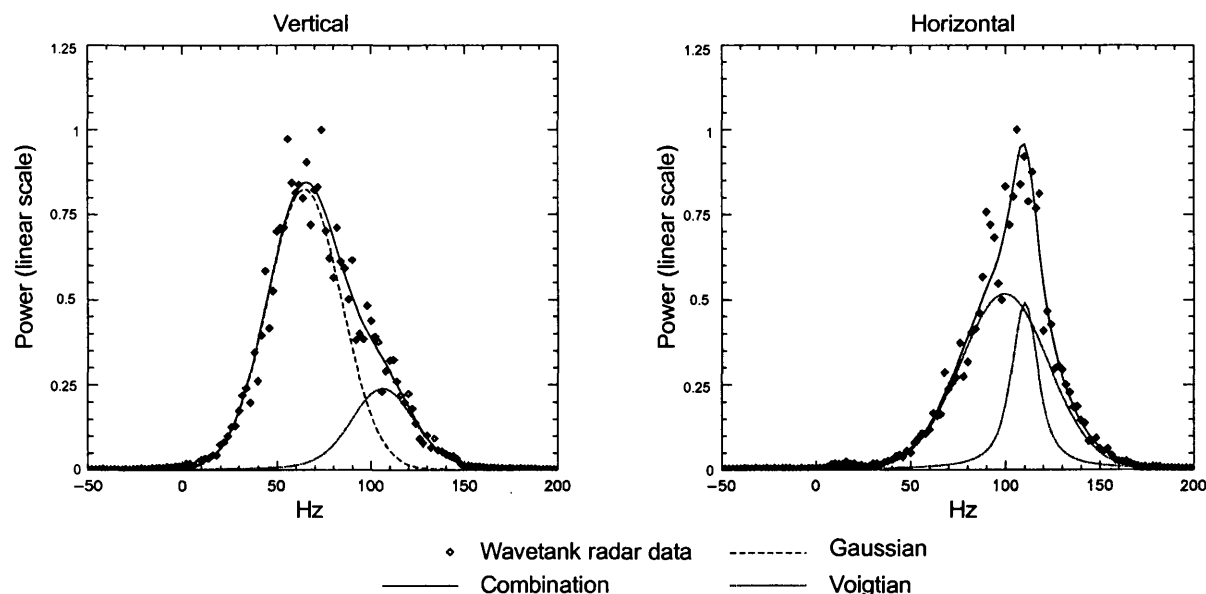
Table 5-1 : Peak shift and Doppler width (full width at half maximum) for cliff top and wave tank data

Using only the data contained in table 5-1, one would probably conclude that there is very little similarity between the Doppler spectra recorded in the wave tank and that recorded from a cliff top. However, we have seen that there is a qualitative similarity from the figures 5-2 and 5-3, and this can be explored further by employing lineshape analysis. Figure 5-4 shows the decomposition of VV and HH data from Portland into basis components. The spectra are normalised and plotted on a linear scale for easy identification of the basis functions. Again, the radar is looking into the wind and the wind speed is 10 ms^{-1} gusting to 15 ms^{-1} . Looking first at VV, we see that the best fit to the data is given by a combination of a slow Gaussian defining the peak with a high speed, wider Voigtian. This can be interpreted as showing that the VV peak

comes from Bragg scatterers with a Gaussian spread in speed, with non-Bragg scatterers skewing the spectrum to the fast side. The HH spectrum is totally dominated by fast, non-Bragg scatterers, with the best fit coming from a combination of two Voigtians, one very broad and Gaussian-like, and one very narrow and tending to the Lorentzian, defining the peak.



5-4 : Lineshape analysis applied to cliff top data



5-5 : Lineshape analysis applied to wave tank data

Figure 5-5 shows lineshape analysis applied to wave tank data taken at 11 ms^{-1} wind speed. All of the features seen in the cliff top data are reproduced here – the Bragg

dominated VV spectrum, the non-Bragg HH spectrum, the wide Voigtian envelope and narrow, close to Lorentzian component defining the peak. It appears that, although the shifts and half power widths may vary between the cliff top and laboratory data, the general form of the spectra are the same, suggesting that the same scattering mechanisms are present. This is encouraging for the application of the new three component Doppler model to cliff top data, discussed in section 5-3.

5.2.3 Further comparisons

Whilst the comparison of Doppler spectra is the key issue in the extension of the analysis from laboratory to cliff top radar, it is interesting to examine other characteristics of the data recorded in the two environments. In chapter 2, the Georgia Institute of Technology (GIT) and RSRE empirical sea clutter models were cited as examples of sea clutter RCS predictions based on many measurements taken in open waters. It is instructive to compare values based on these models to those seen in the wave tank. (Details of the GIT model can be found in [Horst and Dyer, 1978], and the RSRE model in appendix C).

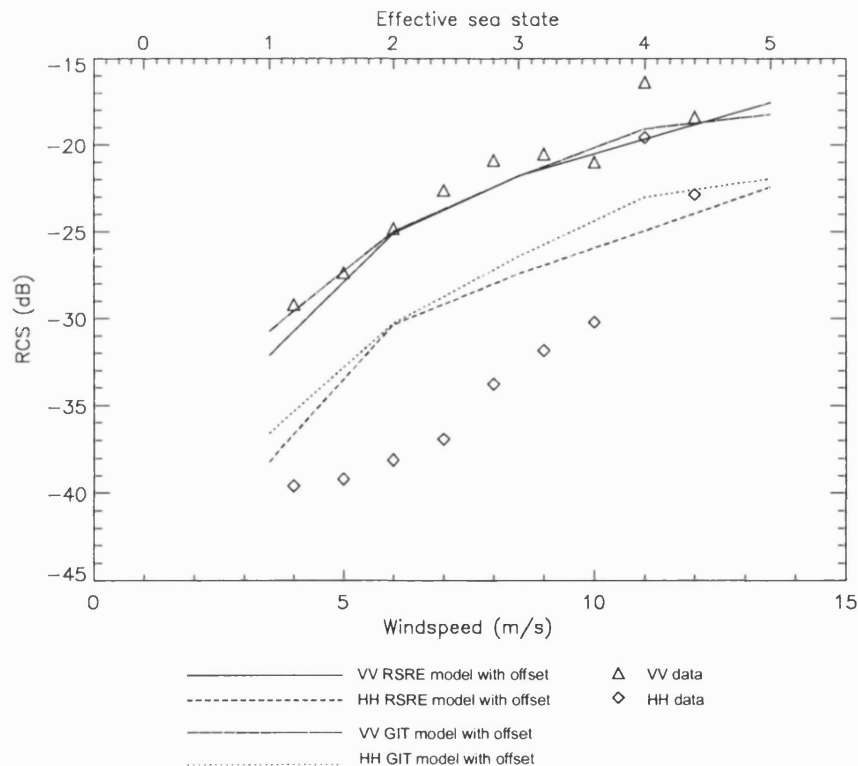
An initial problem in comparing the RSRE model to data collected in the laboratory is that it is very difficult to assign a 'sea state' to the condition seen in the tank. Although approximate conversion tables between sea states, wave height and wind speed are available, they are not easily carried over to the wave tank. For example, in Skolnik, Chapter 26 [Skolnik, 1970] a wind speed of 24 knots (approximately 12 ms^{-1}) is assigned an average wave height of over 5 feet (sea state 4), many times larger than the waves seen at 12 ms^{-1} in the tank. This discrepancy is probably a consequence of the limited fetch of the tank. Also, an initial look at typical values given by the two models, and some vertical polarisation RCS values from the tank (table 5-2) show that at all wind speeds, the values recorded in the tank are greater than those predicted. However, if one assumes that the increase in the RCS can be

represented by a constant offset, then a simple linear map of wind speed to an 'effective' sea state can be found which reproduces the trends in the VV data well.

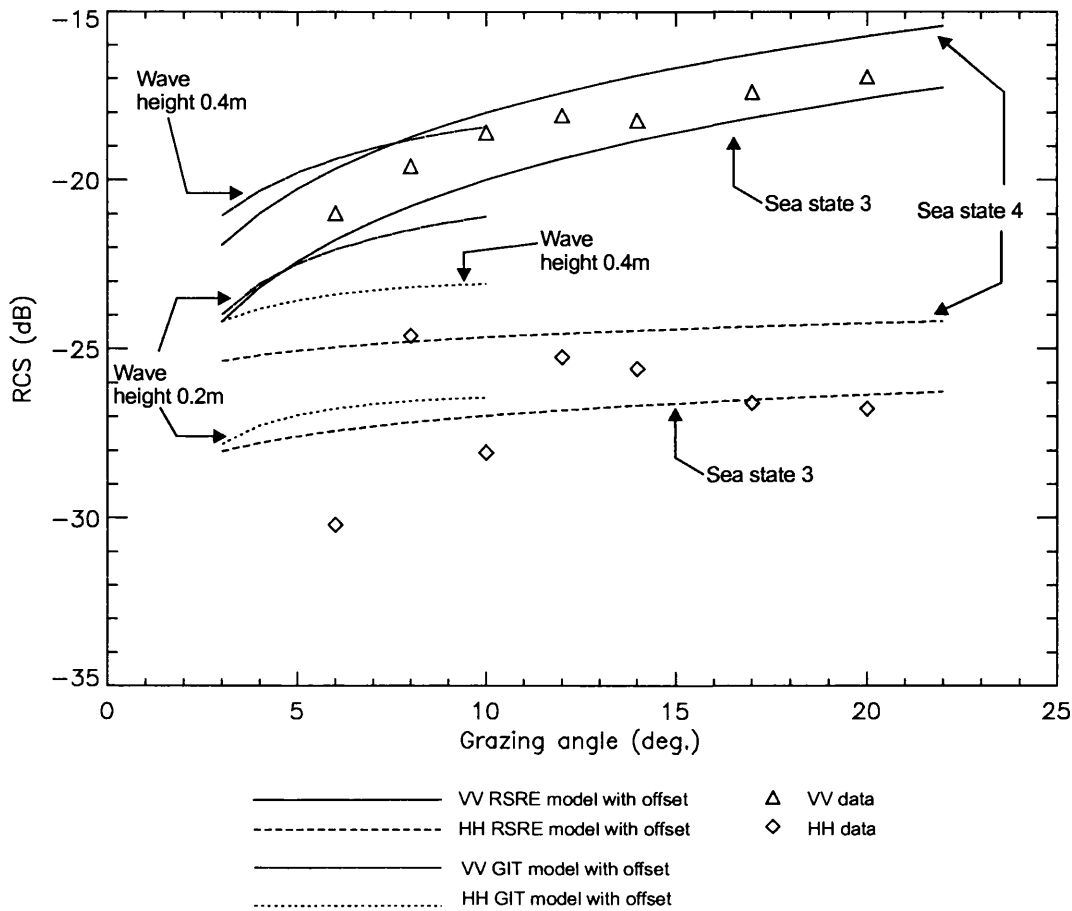
Windspeed (ms^{-1})	4	6	8	10	12
Data RCS	-29.2	-24.8	-20.9	-21.0	-18.4
Sea state	1	2	3	4	5
RSRE RCS	-45.1	-38.1	-34.7	-32.6	-30.5
Wave height (m)	0.05	0.1	0.2	0.4	0.5
GIT RCS	-43.7	-38.0	-34.8	-32.0	-31.2

Table 5-2 : Comparison of vertical polarisation RCS values as measured in the wave tank, and predicted by the GIT and RSRE models

Figure 5-6 shows data from the wave tank taken at 6° grazing angle and wind speeds of 4 to 12 ms^{-1} . Overplotted are GIT and RSRE models, both with a 13 dB offset added, and with wind speed and effective sea state related by $\text{windspeed} = (2.5 \times \text{sea state}) + 1$. (Note that this is an entirely empirical relationship which simply fits well to the VV data). Using this relationship, one can see that the VV data can be well represented by both of the models, though the lower wind speed HH data is not.



5-6 : Comparison of RCS measured in the wave tank to GIT and RSRE models at various wind speeds

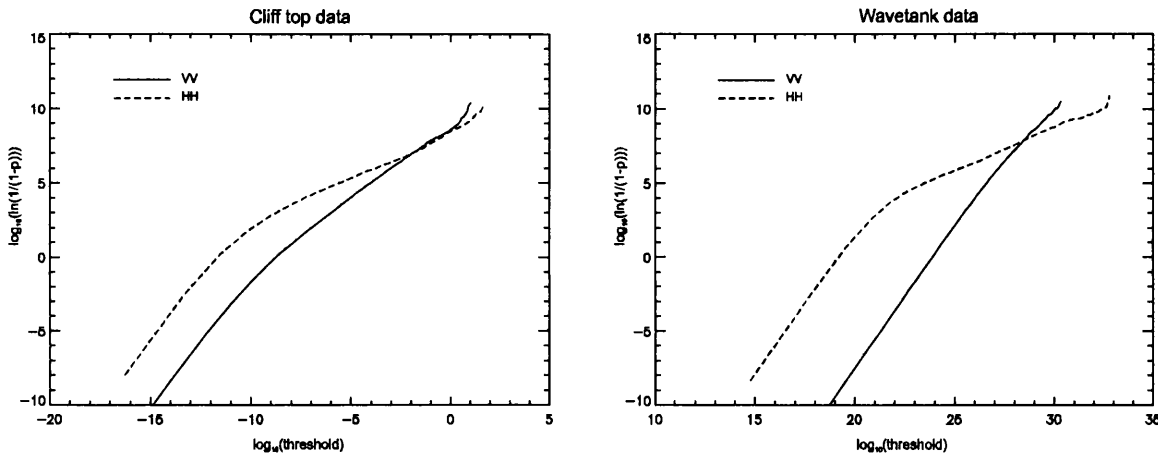


5-7 : Comparison of RCS measured in the wave tank to GIT and RSRE models at various grazing angles

Figure 5-7 shows data taken at 10 ms^{-1} windspeed, which according to the ad hoc mapping given above, translates to an effective sea state of between 3 and 4. The VV data is again well described by the RSRE model and, as far as can be seen, the GIT model with a wave height of between 0.2m and 0.4m (the GIT model in [Horst & Dyer, 1978] is quoted only up to 10° grazing angle). The HH data at low grazing angles shows a large scatter, but at higher grazing angles comes close to the RSRE model. It is possible that the low wind speed and low grazing angle HH data is approaching the noise floor.

Sea clutter models such as these are often quoted with an accuracy of $\pm 5 \text{ dB}$. Even errors of this size cannot account for the 13 dB offset observed. It must therefore be

concluded that the water surfaces produced by the wave tank have a higher RCS than sea surfaces. A possible explanation for this is the level of directivity given to the waves by the long, thin shape of the tank. All waves are moving with the wind, directly towards the radar. In open or coastal waters, even if the radar is pointed into the prevailing wind direction, waves will be travelling in all directions and the sea surface will be more isotropic than the water surface in the tank. It is possible that this increased isotropy will reduce the direct backscatter, and so the recorded RCS. However, it appears that, particularly in vertical polarisation, the wave tank reproduces the RCS *trends* of the open water models.

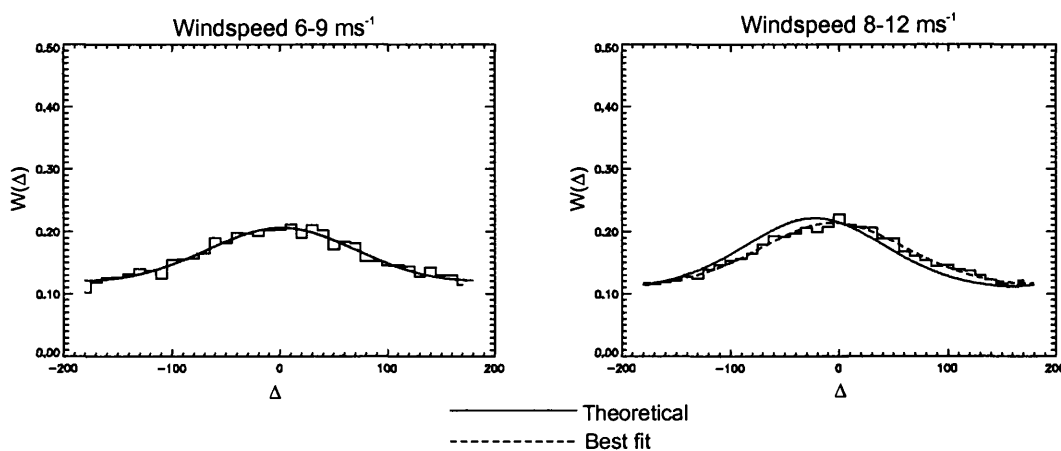


5-8 : Amplitude distributions of cliff top and wave tank data plotted on Weibull paper

Touching briefly on the statistics of the clutter, figure 5-8 shows cliff top data (into wind, 5 ms^{-1} gusting 9 ms^{-1}) and laboratory data (8 ms^{-1}) in the form of Weibull plots. One can immediately see that none of the plots show a Weibull distribution as the lines are curved. In fact, the lower portion of each line has a gradient close to 2 (indicative of a Rayleigh distribution), but curves away to a lower gradient, the HH data dramatically so. This curving away is further indication of high amplitude spikes, which is why it is more pronounced in HH. Whilst at first glance the plots from the two set-ups seem similar, there are some subtle differences. In the tank data, the bottom portion of each line has a gradient of almost exactly 2, whilst in the cliff top data the

gradient is actually slightly less. In HH the change of gradient in the tank data is much more pronounced than in the cliff top data, possibly suggesting more HH spikes in the tank. This quick inspection, however, does nothing to suggest dramatic differences between the amplitude statistics in the two environments.

The polarimetric phase difference distribution of laboratory data was presented at some length in chapter 3. Figure 5-9 shows the phase statistics of two sets of cliff top data taken at different wind speeds. The plot on the left is from data taken at 6 ms^{-1} gusting to 9 ms^{-1} , whilst that on the right has a wind speed of 8 ms^{-1} gusting to 12 ms^{-1} . The solid line represents the theoretical curve, and the dotted line the best fit, as in chapter three's analysis of wave tank data. At low wind speed, these two curves are coincident and both describe the data well (HH normalised variance = 4.5). At the higher wind speed, we see that the two curves do not match up (HH normalised variance = 47.3), and the theoretical curve does not fit well to the data, whilst the best fit curve does provide a good fit. This is broadly in agreement with the results from the tank. The fact that the distributions here peak at 0° suggest that in this experiment, the phases of two channels has been balanced.



5-9 : Cliff top radar polarimetric phase difference distributions with comparisons to theoretical and best fit curves

5.3 Doppler modelling of cliff top data

5.3.1 Methodology

Having established that the Doppler spectra and certain other characteristics of laboratory and cliff top data compare well, the specific existence of the three dominant scattering mechanisms must now be investigated. Data from the Portland experiment is analysed to determine whether the Bragg, whitecap and spike features identified in wave tank data are present in cliff top radar data and, if so, whether the average Doppler spectrum can be well described by the three component Doppler model. In the laboratory study, synchronous radar and video data were used to match up features on the water surface with the associated radar returns. It is much harder to collect such accurate data in open or coastal waters, and so more difficult to confirm directly that the same three scattering mechanisms associated with the same three types of wave are present. In the absence of video or some other surface truth data, the scattering mechanisms and surface features responsible for them must be inferred from the radar data itself. This can be done through a qualitative and quantitative analysis of the averaged Doppler spectra, and detailed analysis of the time histories on a much shorter time scale, allowing the characteristics of prominent features to be seen on a pulse to pulse basis. The time history, Doppler spectra and decorrelation time of these features can be used to infer which, if any, of the scattering mechanisms outlined in the previous chapter are responsible.

A further difficulty in extending the model to sea clutter is that in the laboratory, the water surface was measured in terms of height and slope by wire wave gauges and a Laser Slope Meter. Such surface truth data is not available from the Portland '96 experiment meaning that certain parameters such as the Bragg scattering HH/VV ratio and the Doppler shift of Bragg and non-Bragg components, which were calculable in the wave tank, are now unknown. They must therefore be determined empirically. This is reasonably straightforward in the case of the Doppler shifts, as

the VV and HH spectra show the Bragg and non-Bragg shifts clearly. The Bragg polarisation ratio, however, must be left as a free parameter and varied to get a best fit. In this way the Doppler model acts as a tool which allows the Bragg ratio to be extracted from the overall Doppler spectra.

In order to use the radar data alone to infer which scattering mechanism is responsible for a particular feature, the characteristics of each mechanism must be clearly defined in terms of polarisation ratio, Doppler shift, appearance in the time domain and decorrelation time. These characteristics can be summarised as:

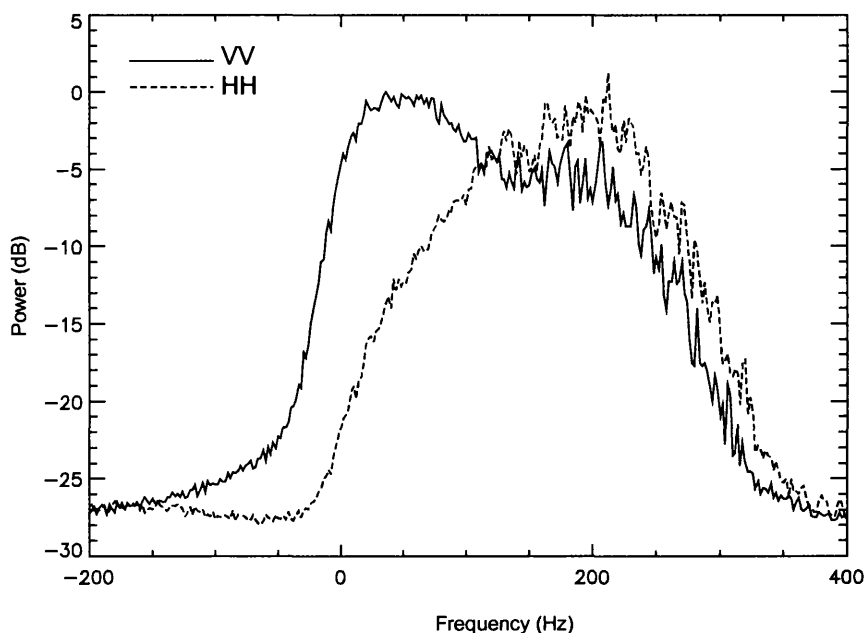
Bragg scattering - VV amplitude is greater than HH, as predicted by the composite surface theory. Both polarisations peak at a frequency corresponding to the velocity $v = v_B + v_D$ where v_B can be obtained via the gravity-capillary wave dispersion relation and v_D is a term encompassing the drift and orbital velocities of the underlying gravity waves. The decorrelation times of the two polarisations are short (tens of milliseconds).

“Whitecap” scattering - The backscattered amplitudes of the two polarisations are roughly equal, and are noticeably stronger than the background Bragg scatter, particularly in HH in which the Bragg scattering is weak. In a time profile, the events may be seen to last for times of the order of seconds, but are noisy in structure and decorrelate quickly (again, in milliseconds). Doppler spectra are broad and centred at a speed noticeably higher than the Bragg speed, at or around the phase speed of the larger gravity waves.

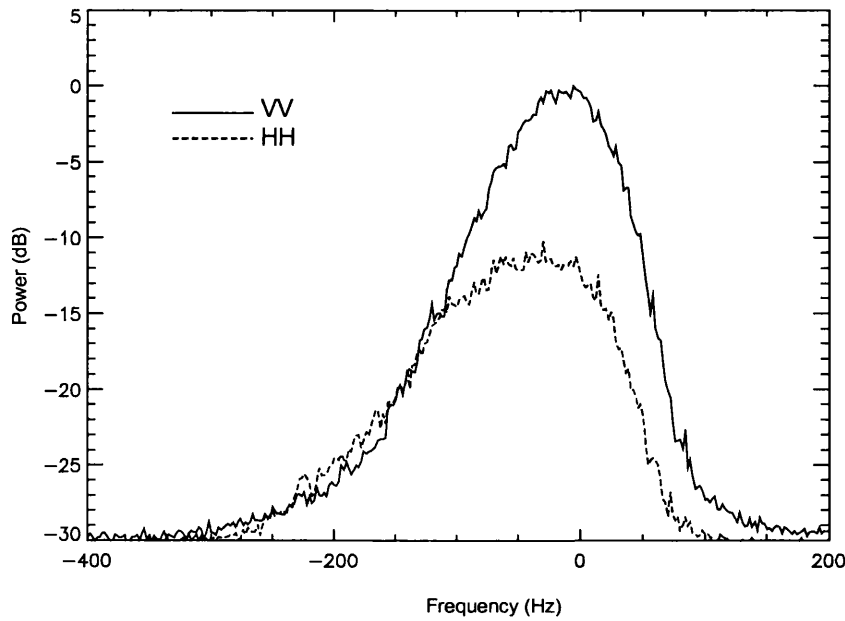
“Spikes” - Strong in HH, but virtually absent in VV, with a Doppler shift higher than the Bragg shift. They last for a much shorter time than the whitecap returns (of the order of 0.1 s) but remain coherent over that time.

5.3.2 Confirmation of the scattering mechanisms

Looking first at the overall Doppler spectra, figures 5-10 and 5-11 show data taken on two separate days, averaged over 30 s in time. The spectra in figure 5-10 were taken with the radar looking directly into the wind, with the wind speed recorded as 10 ms^{-1} gusting up to 15 ms^{-1} . Figure 5-11 was taken with the wind blowing in the opposite direction, that is, with the radar looking with the wind. The wind speed was 7 ms^{-1} gusting up to 10 ms^{-1} . Several qualitative points can be made about the spectra in figure 5-10 immediately. First, not only is there peak separation, indicating strong non-Bragg scattering in HH, but the VV spectrum is clearly bimodal, with prominent slow and fast components. This shows that there is strong non-Bragg scattering in VV as well as HH. The HH peak, however, exceeds VV at this point, indicating that the overall non-Bragg scatter is polarisation dependent. This all fits qualitatively with the Bragg, whitecap and spike components of the Doppler model. The slow VV peak comes from the Bragg component, with HH many dBs lower, and the fast VV shoulder comes from the whitecap term. The HH spike term, at the same shift, lifts it above VV at this point.



5-10 : 30 second average Doppler spectra, looking upwind, wind speed 10 ms^{-1} gusting to 15 ms^{-1}

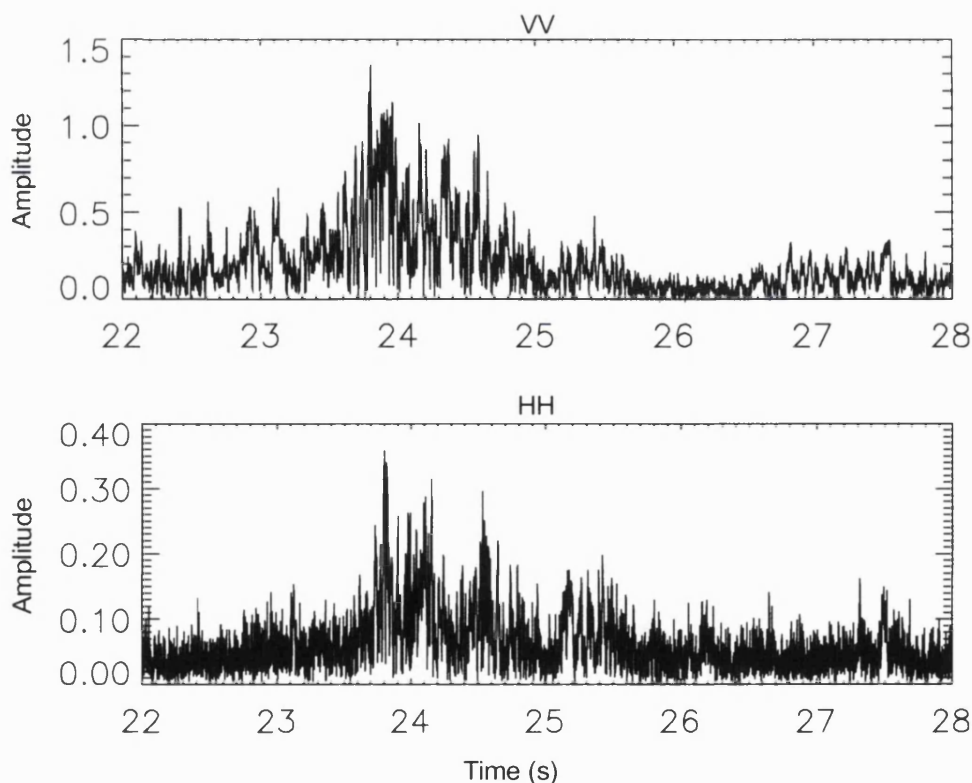


5-11 : 30 second average Doppler spectra, looking downwind, wind speed 7 ms^{-1} gusting to 10 ms^{-1}

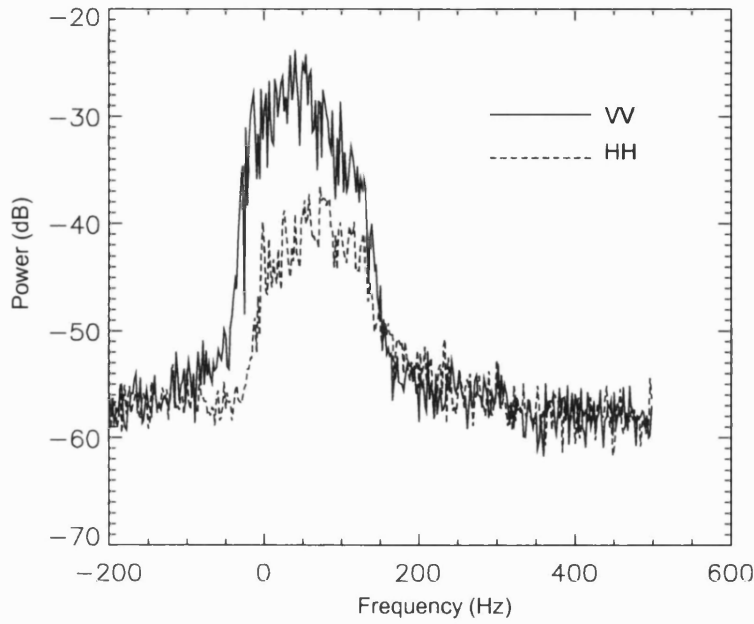
The Bragg resonant wave speed (v_B) for I-band ($\lambda = 3 \text{ cm}$), is 23 cms^{-1} , which translates to a Doppler shift of 15 Hz. Thus, to give the observed shift of approximately 50 Hz, the orbital and drift velocities must combine to give v_D of around 50 cms^{-1} , a not unreasonable value. The spectra shown in figure 5-11 are somewhat different in their form to those in the upwind case. Not only is the overall Doppler shift now negative (as would be expected, as the dominant wave direction is now *away from* the radar), but there is no longer any clear peak separation, and no significant region of HH exceeding VV. There is, however, a clear skewing of the spectra to the fast (quickly receding, high negative) side, with the two polarisations coincident. All these features are still consistent with the Doppler model. As the radar is imaging the back of the waves, the sharply crested and spilling wave shape just before breaking, which gives rise to HH spikes, is not visible. The highly disturbed water surface of a whitecap, however, is still seen by the radar, resulting in polarisation independent non-Bragg scattering. The slow Bragg peaks now dominate both spectra, indicating that the overall non-Bragg contribution is smaller at this lower wind speed. The Bragg component Doppler shift is -15 Hz , exactly the speed of the

Bragg resonant capillary waves, indicating that there is either no wind drift affecting the ripples or that some complex wind-current interaction is leading to an almost complete cancellation of the v_D term.

To further confirm the applicability of the three component model, short time series have been extracted from the data set to allow the fine detail to be examined. Figure 5-12 shows HH and VV time series from the first data set (looking into the wind) taken over six seconds and plotted against an arbitrary amplitude scale, with figure 5-13 showing the associated Doppler spectra. The VV clutter is seen to be much stronger than HH in both the time and the frequency domain, and the spectra show no region of HH exceeding VV, with both peaking well below the 200 Hz point seen as the fast peak in figure 5-10.



5-12 : Time series, looking upwind, showing Bragg scattering

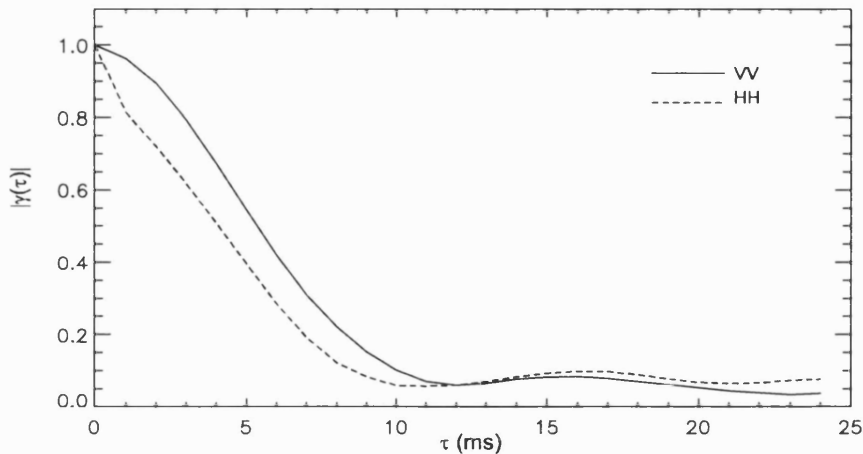


5-13 : Doppler spectra of data in figure 5-12

Figure 5-14 shows the modulus of the autocorrelation function of each polarisation, defined as

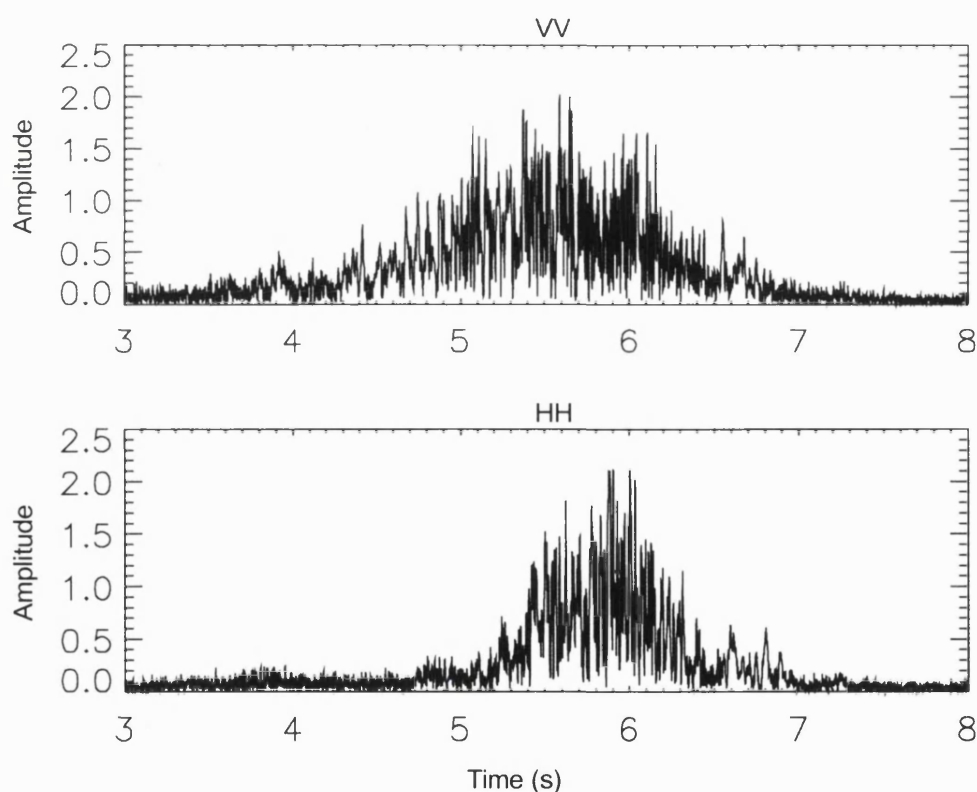
$$\gamma(\tau) = \frac{\langle E^*(t)E(t+\tau) \rangle}{\langle E^*(t)E(t) \rangle} \quad [5-1]$$

where E is the complex amplitude and τ is a time lag. Both of the polarisations are seen to decorrelate in approximately 10 ms. All these characteristics are indicative of Bragg scattering.

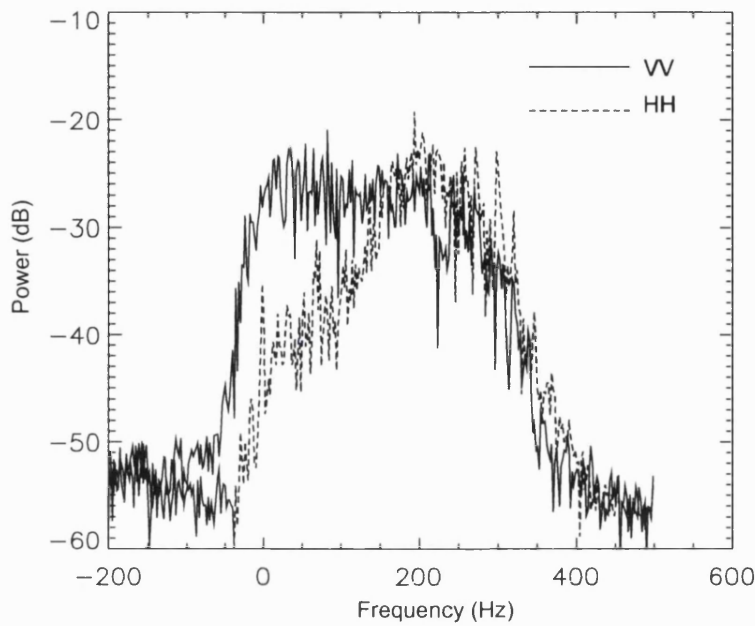


5-14 : Autocorrelation functions of data in figure 5-12

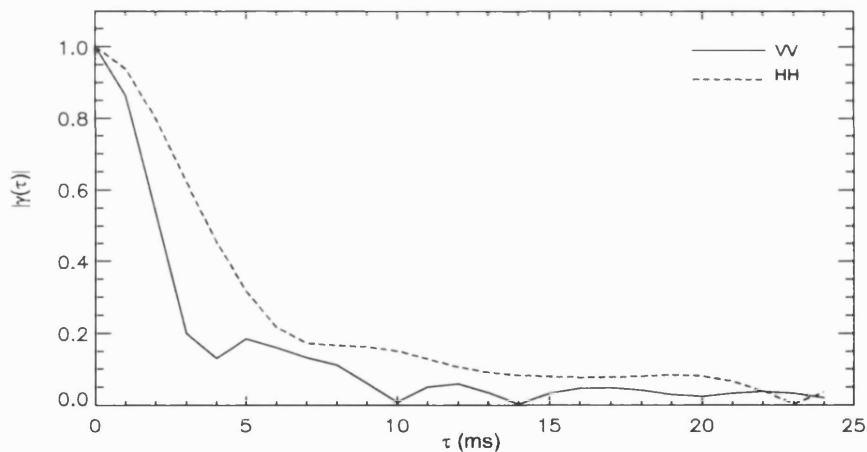
Figure 5-15 shows a region of very strong returns in both polarisations. The maximum value seen in the time series of each of the polarisations is the same, and both Doppler spectra in figure 5-16 show a noisy, broad, polarisation independent fast component. The presence of a slow peak in VV, and the period between 4 and 5 s in the time series in which VV exceeds HH, suggest that this portion of the data still includes some residual Bragg scattering. The autocorrelation function in figure 5-17 again shows that each of the polarisations decorrelates quickly. This is consistent with this feature being the result of scattering from a whitecap.



5-15 : Time series, looking upwind, showing a whitecap

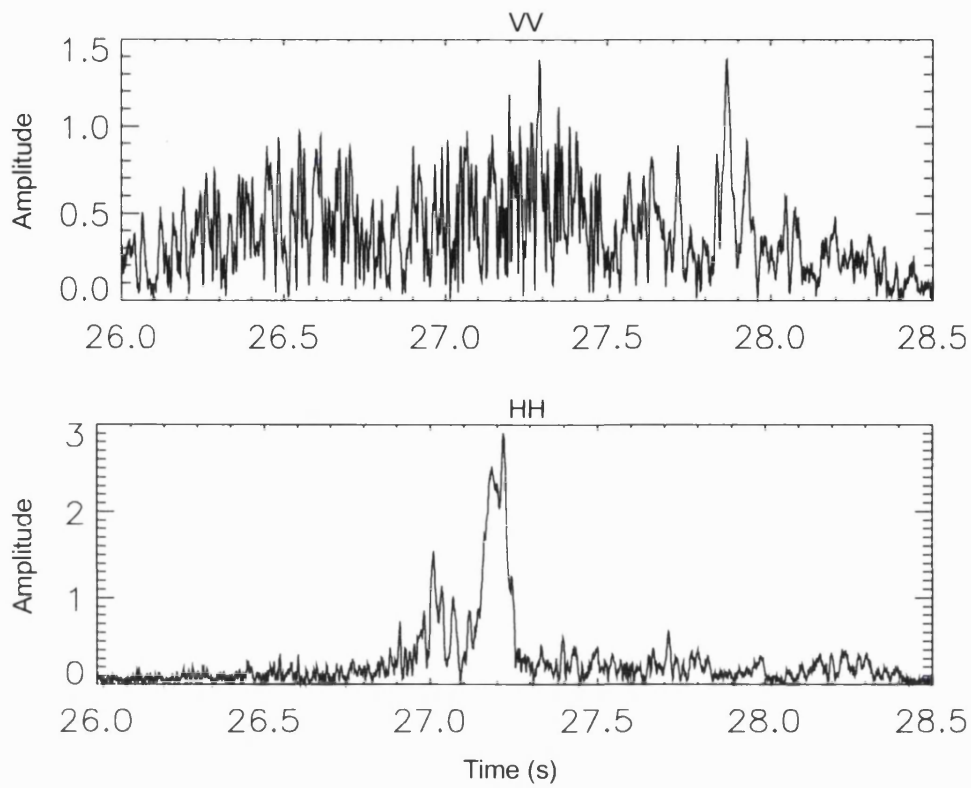


5-16 : Doppler spectra of data in figure 5-15

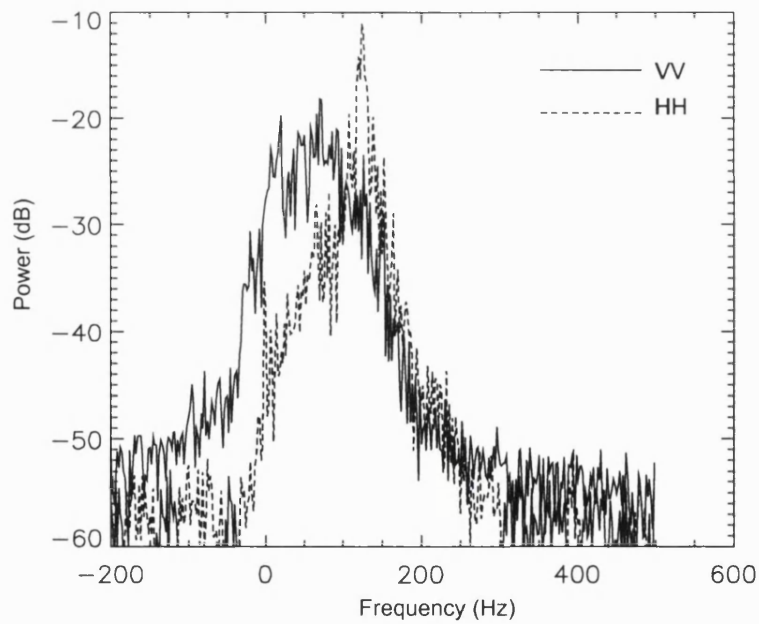


5-17 : Autocorrelation functions of data in figure 5-15

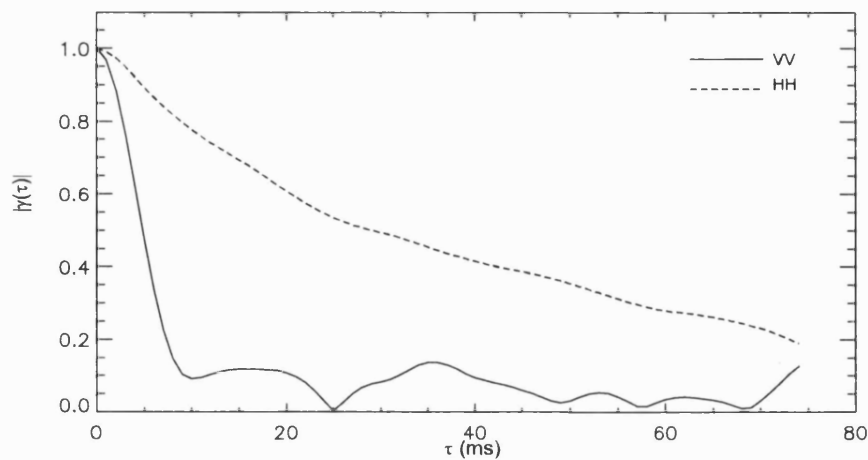
Figure 5-18 shows a 2.5 s section encompassing a prominent feature in horizontal polarisation. This feature is around 3 times greater in HH amplitude than VV at the corresponding time, that is, an RCS ratio of approximately 10 dB. In the frequency domain (figure 5-19), the scatterer speed is seen to be well defined and faster than the Bragg speed. The decorrelation time as seen in figure 5-20 is around 75 ms, far greater than the VV decorrelation time, and far greater than any of the features so far considered. This is a clear example of a coherent HH spike.



5-18 : Time series, looking upwind, showing an HH spike

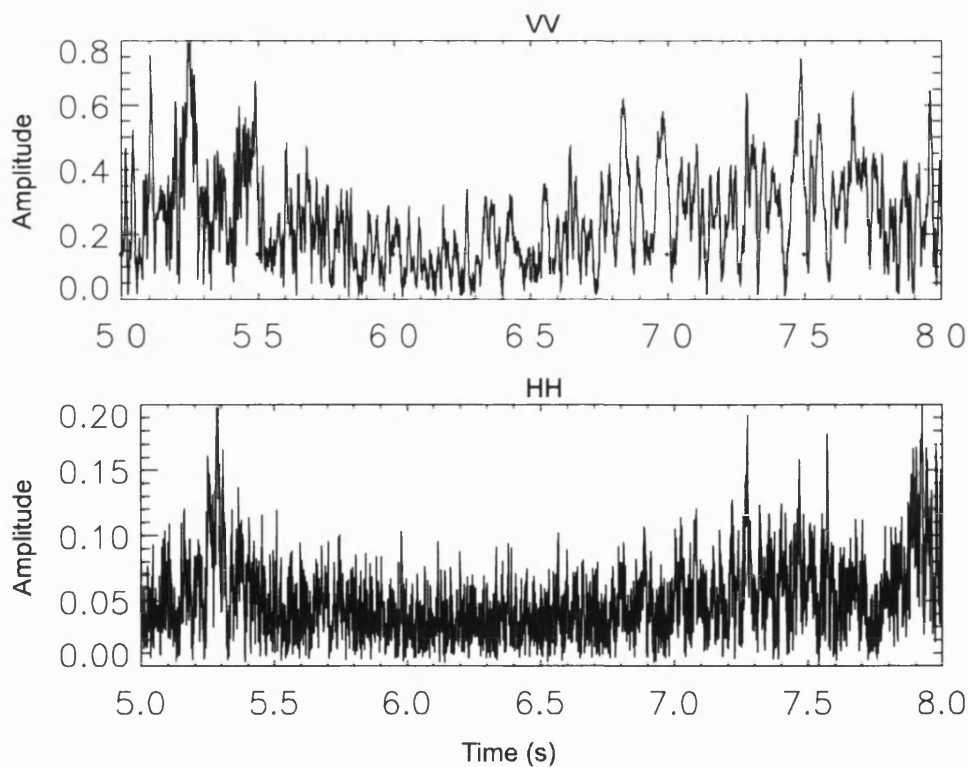


5-19 : Doppler spectra of data in figure 5-18

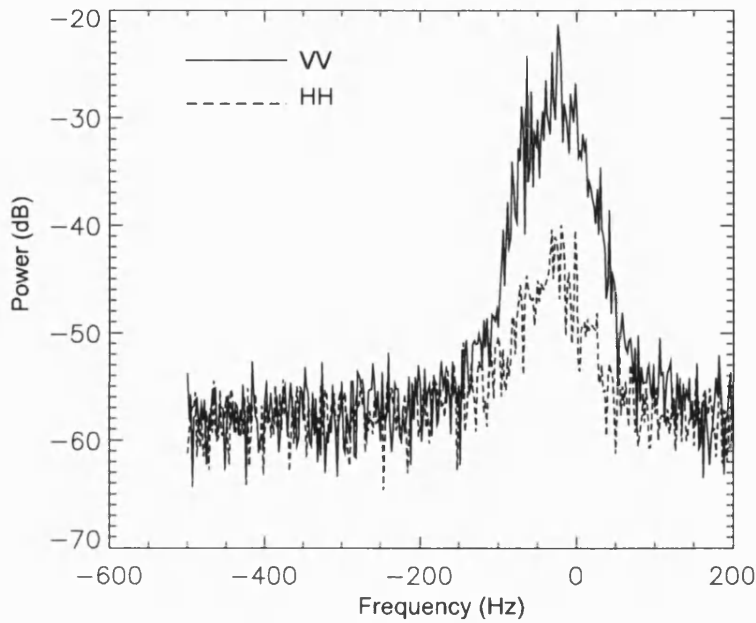


5-20 : Autocorrelation functions of data in figure 5-18

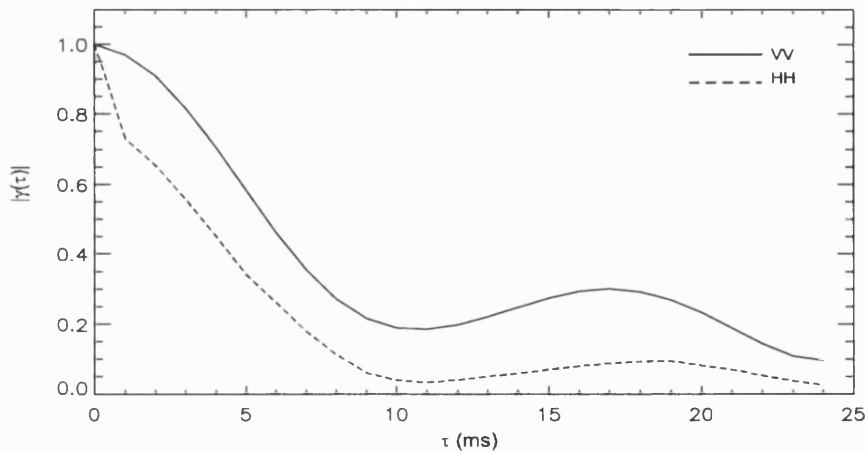
Turning now to the downwind data, figures 5-21 to 5-23 show time series, Doppler spectra and autocorrelation functions taken from the data set which produced figure 5-11. These plots show an example of Bragg scattering, with VV greater than HH in both the time and frequency domain, and the Doppler shift low. The decorrelation times are of the order of 10 ms for both polarisations.



5-21 : Time series, looking downwind, showing Bragg scattering

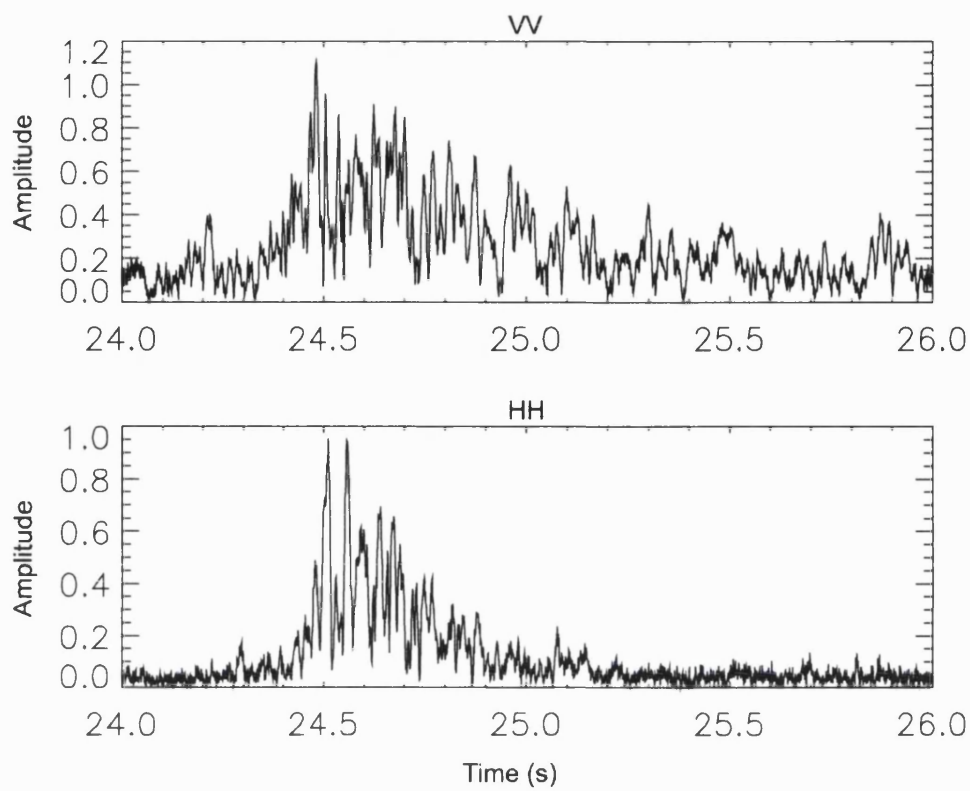


5-22 : Doppler spectra of data in figure 5-21

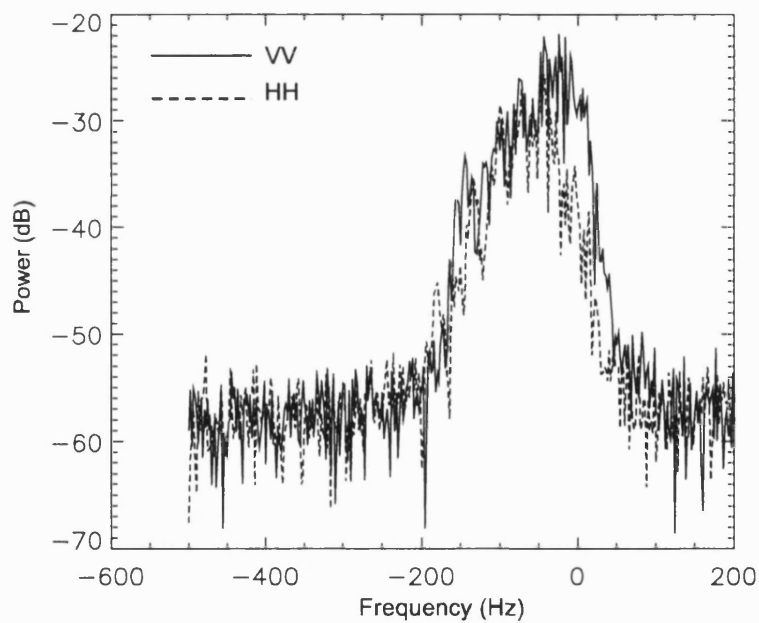


5-23 : Autocorrelation functions of data in figure 5-21

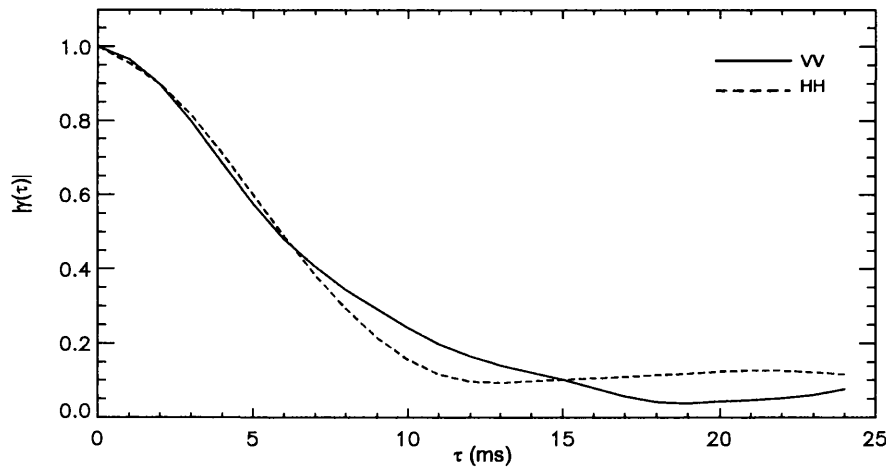
Figures 5-24 to 5-26 show a prominent whitecap event, with the two polarisations displaying extremely similar behaviour in all three plots. The scattering is strong, the Doppler shift high and the decorrelation times short. No evidence to suggest the presence of strong coherent HH spikes was found in this data set.



5-24 : Time series, looking downwind, showing a whitecap



5-25 : Doppler spectra of data in figure 5-24

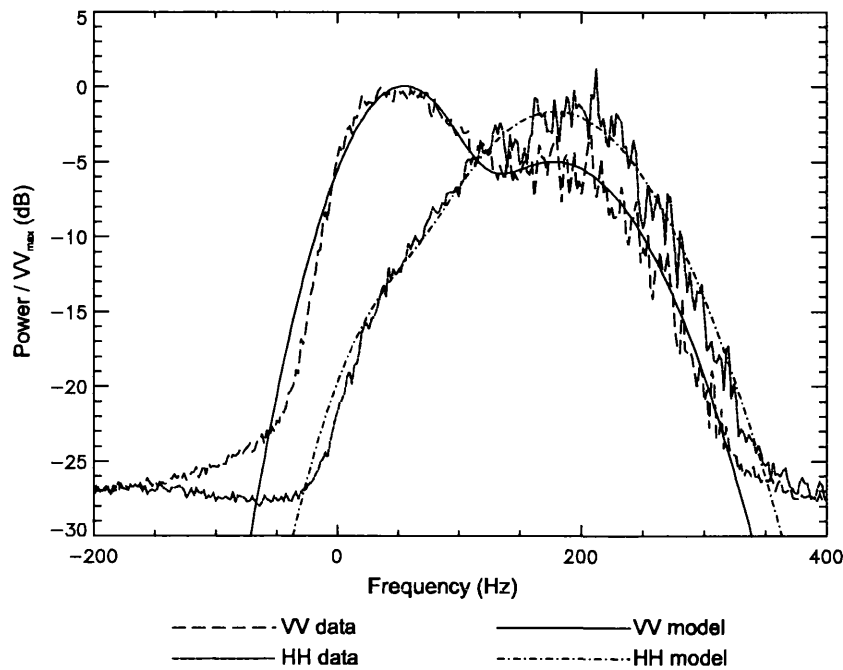


5-26 : Autocorrelation functions of data in figure 5-24

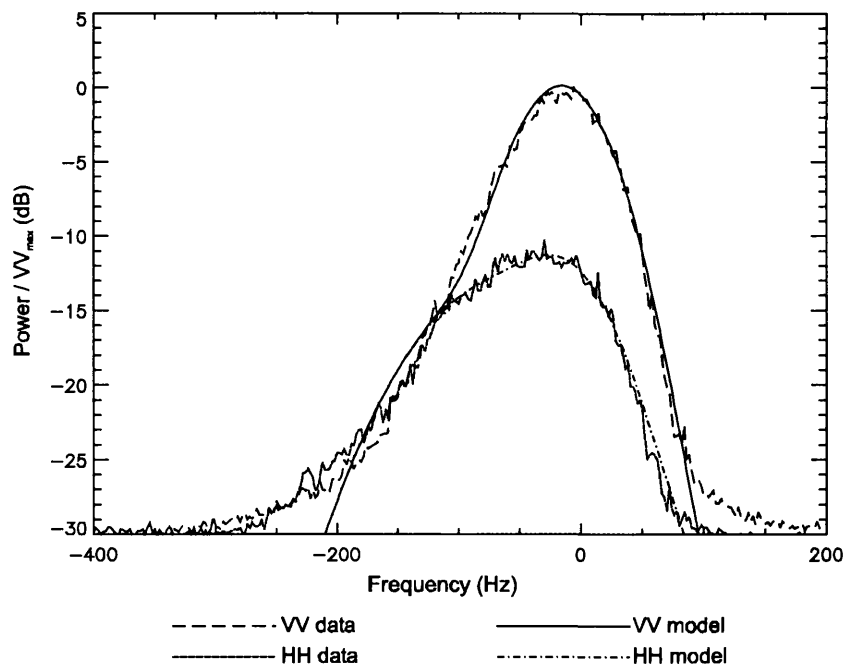
This analysis has shown that all of the prominent features in the two data sets examined here have characteristics consistent with one of the components of the Doppler model and, further to this, it is strongly suggested that the HH spike component is dependant on the look direction of the radar with respect to the prevailing wind direction. HH spikes are clear when looking into the wind, but absent when looking with the wind. The same is not true of the Bragg scatterers or the non-Bragg whitecap features. The success in attributing one of the three scattering mechanisms to each of the features examined means that one can now proceed in applying the Doppler model to this data confident that each component retains its physical explanation.

5.3.3 Application of the three component model

To apply the Doppler model to the data, the widths and relative amplitudes of the Gaussian lineshapes were varied using a Powell minimisation algorithm, whilst holding the empirically determined shifts constant, to give a best fit in terms of a minimum χ^2 value. The results are shown in figures 5-27 and 5-28, and table 5-3 gives the values of the parameters used in the plots.



5-27 : 3 component model fitted to upwind data



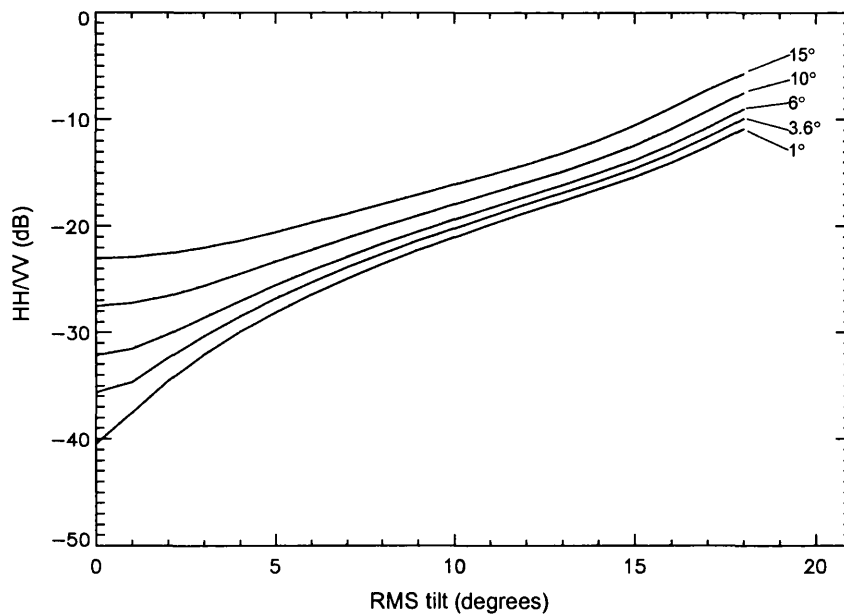
5-28 : 3 component model fitted to downwind data

In each case the model well describes the general form of the spectra. In figure 5-27, the VV Bragg peak and non-Bragg fast shoulder are accounted for by the Bragg and whitecap components, whilst the spike term defines the fast peak at which HH exceeds VV. In the spectra of figure 5-28, the HH spike term has been set to zero in response to the absence of coherent HH features in this data set. The non-Bragg

term is small compared to both polarisations' Bragg peaks, and is polarisation independent. The ratio of the areas under the HH and VV spectra gives the overall polarisation ratio of the data. Figure 5-29 shows the polarisation ratio as predicted by the composite surface Bragg scattering model, as a function of the root mean square tilt of the underlying gravity waves, for several grazing angles.

	B_H/B_V	WB_H	S/B_H	ν_B	ν_G	W_B	W_W	W_S
Upwind	-15.1	11.5	12.8	54	178	47.5	66.0	74.5
Downwind	-14.0	0.2	-	-15.3	-63.9	40.4	74.11	-

Table 5-3 : Three component model parameters used in the fits to the up and downwind data



5-29 : Bragg scattering polarisation ratio as calculated from the composite Rice SMP at various grazing angles and RMS tilt angles

Recall that the grazing angle for this experiment was 3.6°. For the upwind data, the overall HH/VV ratio is -1.4 dB, far higher than predicted by the composite model. However, by taking the ratios of the Bragg components from the model, one can determine a 'true' Bragg ratio. This value comes out at -15.1 dB, still far higher than the standard (zero RMS tilt) Rice ratio of -35.6 dB, but consistent with composite surface theory for a surface with an RMS tilt of 14.5°. Whilst the overall HH/VV ratio

of the downwind data is -9.3 dB, the ratio of the Bragg components is found to be -14.0 dB, a similar value to the previous result. These results give a strong indication that the components used to build up the Doppler model do not simply provide a good fit by eye to the data, but contain real physical meaning and can be used as a tool to deconstruct spectra into separate scattering mechanisms.

5.4 Scattering mechanisms in ship wake imagery

5.4.1 Aims

The previous section has illustrated that the Doppler model proposed to describe wavetank data can also be used to model sea clutter data taken with a cliff top radar. In this section, Doppler modelling is used to investigate the effect on radar backscatter of an internal wave wake generated by a ship as imaged by a cliff top radar. Generating an internal wave wake in ideal conditions is an excellent way of producing a moving surface current field which will modulate the surface waves. Natural and ship generated internal waves are often seen in SAR and real aperture radar images [Watson et al, 1992], although the precise scattering mechanism which makes them visible is not fully understood. It is possible that decomposition by the application of the three component Doppler model could shed some light on this subject.

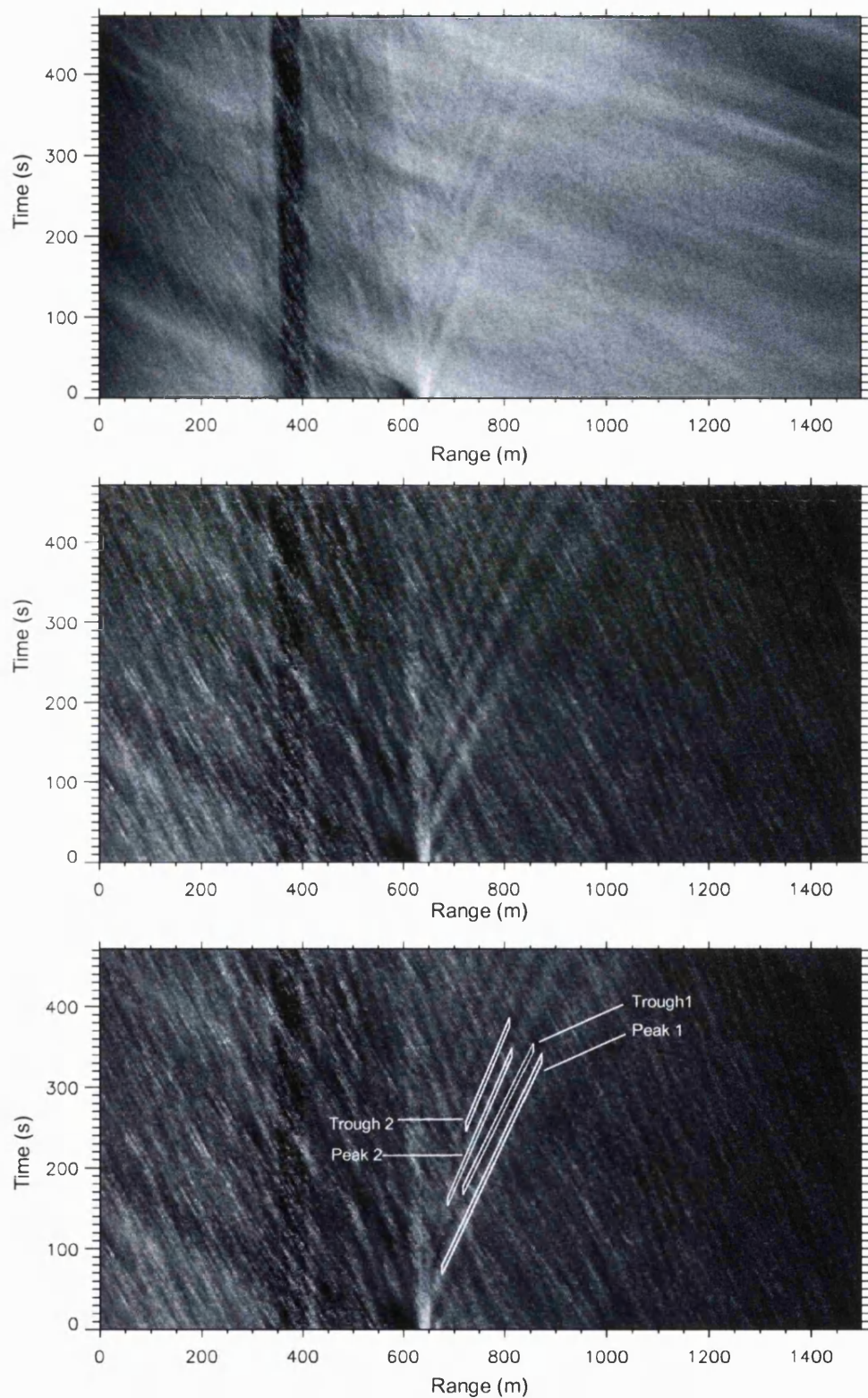
For this analysis, data collected in 1995 at Sognefjord on the Norwegian coast is used. This area is known to have a strong, shallow pycnocline owing to fresh water run-off from melting snow, conditions conducive to the generation of internal wave wakes by ships. The MIDAS radar was used to image the wake, positioned approximately 800 m above the fjord working at grazing angles between 15° and 25° . Again the data was I-band with polarisation agility pulse to pulse. The bandwidth used was 100 MHz and the PRF 500 Hz per polarisation.

5.4.2 Imagery and Doppler spectra

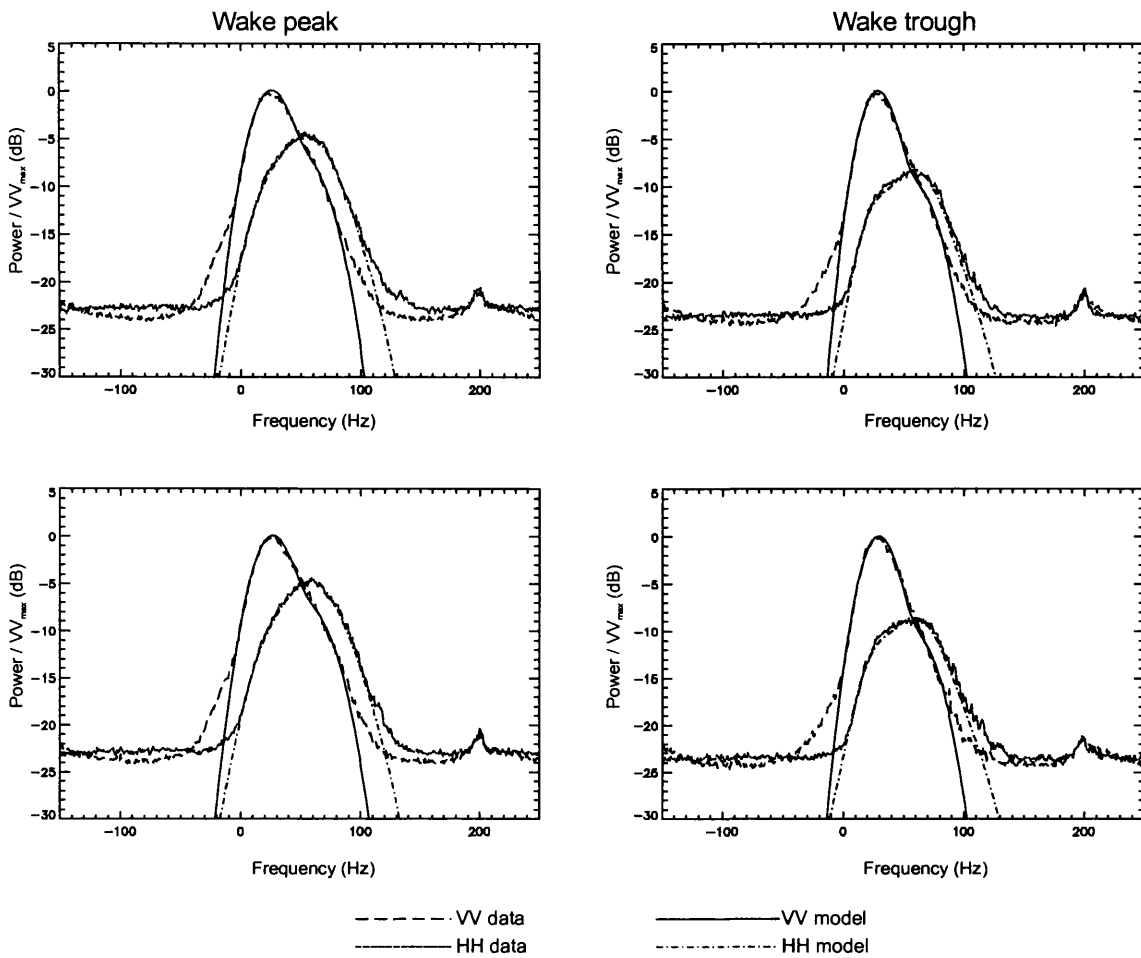
Figure 5-30 shows example RTI images from the Sognefjord experiment which clearly show one side of an internal wave wake. The figures cover close to 1.5 km in range and 8 minutes in time. The wake generating vessel has just moved off the bottom of the image at about 650 m from minimum recorded range. The top and middle figures show simultaneous VV and HH images respectively, whilst the bottom figure shows the HH image again with boxes outlining consecutive wake peaks and troughs. Figure 5-31 shows Doppler spectra taken from each of these boxes, with the two from the wake peaks on the left and those from the wake troughs on the right. One can immediately see that a good fit to the data is provided in all cases, the only deviation worthy of note coming in the tails on the negative side of the VV spectra. The excellent fit to the main body of each spectrum suggests that the modulations seen in the images are not caused by a mechanism other than one of those already considered, but rather by a variation in the strength of one (or more) of the three components which make up the model. One can also see a clear change in the polarisation ratio on and off the wake peak, with the maximum of the HH spectra being just 5 dB down on VV in the case of data taken from the peak, compared to 10 dB in data from the trough. The parameters used in the fits, and values found for ambient clutter, are given in table 5-4.

Region	Ambient	Trough		Peak	
		Area 1	Area 2	Area 1	Area 2
HH/VV (total, dB)	-6.1	-6.2	-6.3	-3.3	-3.4
HH/VV (Bragg, dB)	-15.8	-13.6	-13.9	-12.8	-14.8
Whitecap/HH _{Bragg} (dB)	6.3	4.5	4.3	5.5	7.5
Spike/HH _{Bragg} (dB)	6.9	3.8	4.4	7.7	9.9

Table 5-4 : RCS ratios calculated using the three component model for an ambient clutter area, and areas covering wake peaks and troughs



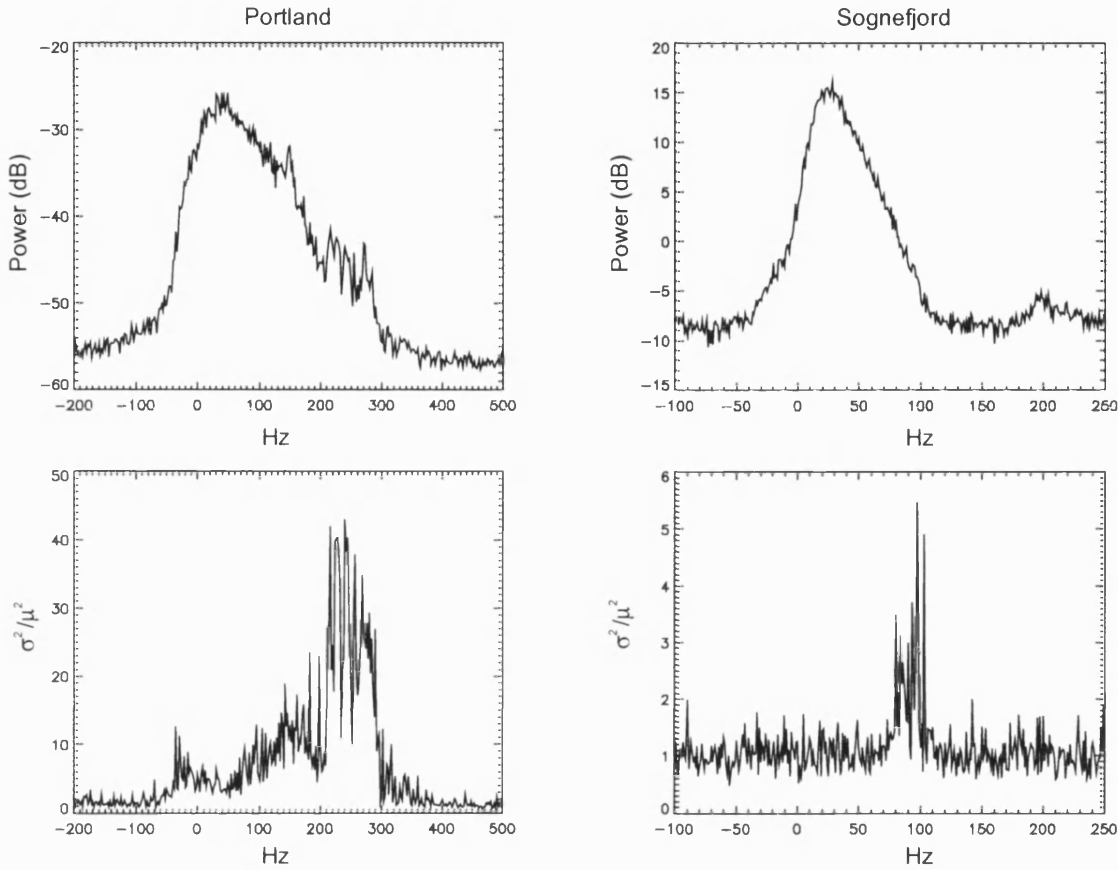
5-30 : RTI plots of a ship generated internal wave wake. VV (top), HH (middle) and HH with wake peaks and troughs boxed (bottom)



5-31 : Doppler spectra and three component fits for wake peaks (left) and troughs (right)

The data in table 5-4 shows that the overall HH/VV ratio increases by around 3 dB on a wake peak as opposed to a trough, and that the value on a trough is very similar to the ambient value. Looking at the HH/VV ratio of just the Bragg components, however, no such trend is seen indicating that the increased backscatter from the wake arm comes from the fast non-Bragg scatterers rather than the small Bragg ripples. Looking at the two non-Bragg HH components, the clearest effect is seen in the ratio of the HH spike to the HH Bragg component, which is much higher on the peak than in the trough. This suggests that, whilst other mechanisms may be affected to some extent by the passage of an internal wave, the HH spike component is the most strongly affected. This would be consistent with observations of naturally occurring internal waves reported in [Churyumov & Kravstov, 2000], in which the fact

that internal waves are more visible in HH than VV is explained by arguing that non-Bragg scattering from mesoscale breaking waves is the dominant processes in such situations.



5-32 : Doppler spectra (top) and variance spectra (bottom) of vertical polarisation data from the Portland and Sognefjord experiments

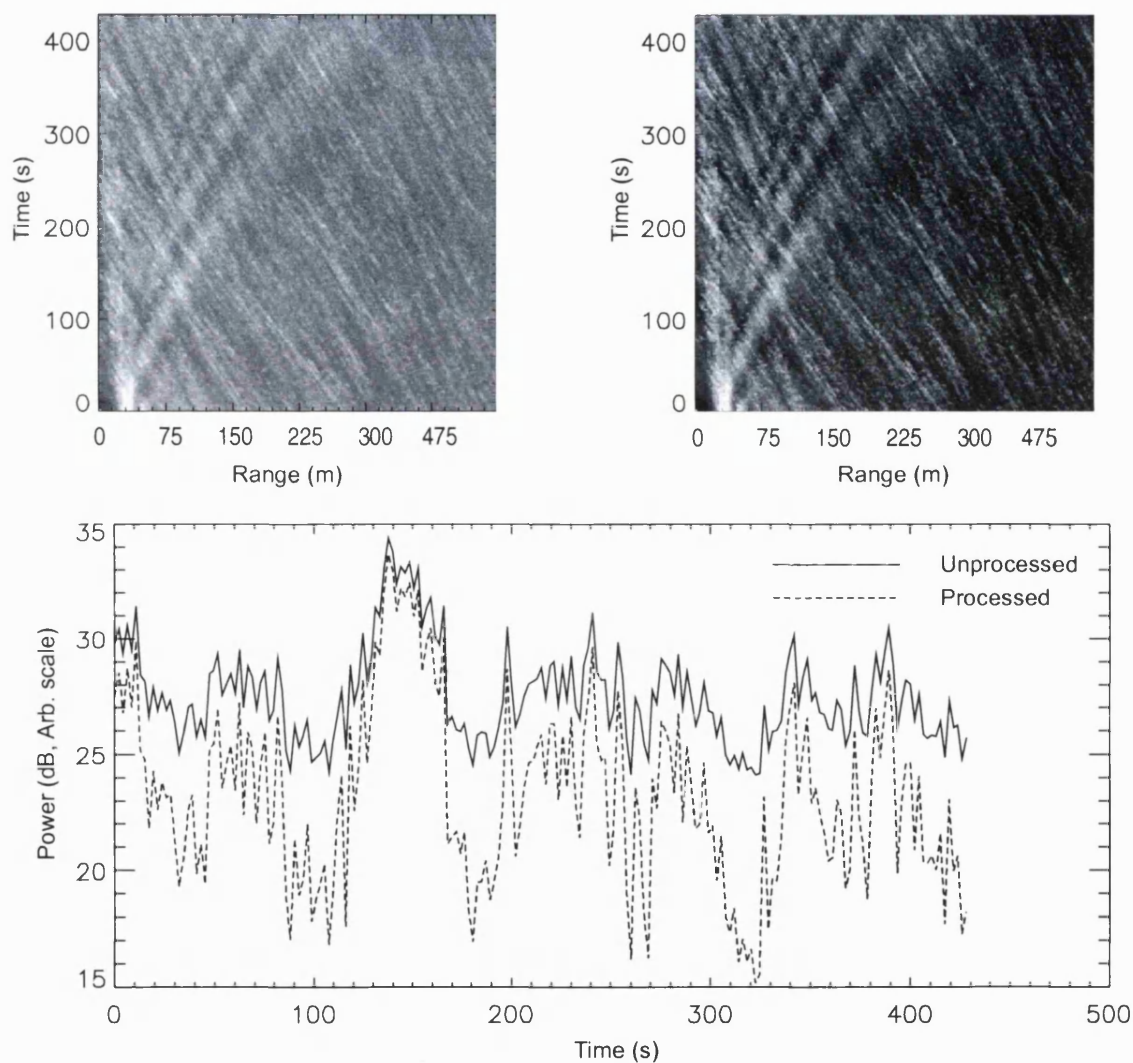
The deviation of the VV data from the model at low negative shifts mentioned above is clearly an effect not described by this three component model. It is possible that this is some entirely different scattering mechanism and is, as such, worthy of further discussion. The behaviour of the high and low frequency edges of low grazing angle Doppler spectra have been examined before (eg [Ward *et al* 1990]) and shown to have higher normalised variances than the main body of the spectrum. This result is repeated in figure 5-32 for the Portland data used earlier in this chapter and for the Sognefjord ambient data. The top left plot shows a Portland VV Doppler spectrum averaged over 30 seconds, with a plot of the normalised variance in each frequency

bin below. This shows peaks in the normalised variance at the high and low frequency wings of the Doppler spectrum. The two plots on the right are taken from a patch of ambient clutter from the Sognefjord data, with a grazing angle of around 20°. Here, whilst the Doppler spectrum has a similar form to that of the Portland LGA data, the normalised variance shows only one peak, on the fast side of the spectrum. It would appear that some condition of the environment of the fjord experiment, such as the higher grazing angle or possibly the sheltered nature of the site, reduces the variance of slow scatterers. Given that the low frequency feature is seen only in the VV Doppler spectrum, and that it appears not to be very 'spiky', it is probable that it is caused by Bragg scattering from waves propagating *away from* the radar, such as those seen in [Plant & Keller, 1990] at grazing angles of 30° and above, and so does not represent a mechanism outside of the three component model, but is a different manifestation of a type of scattering already considered.

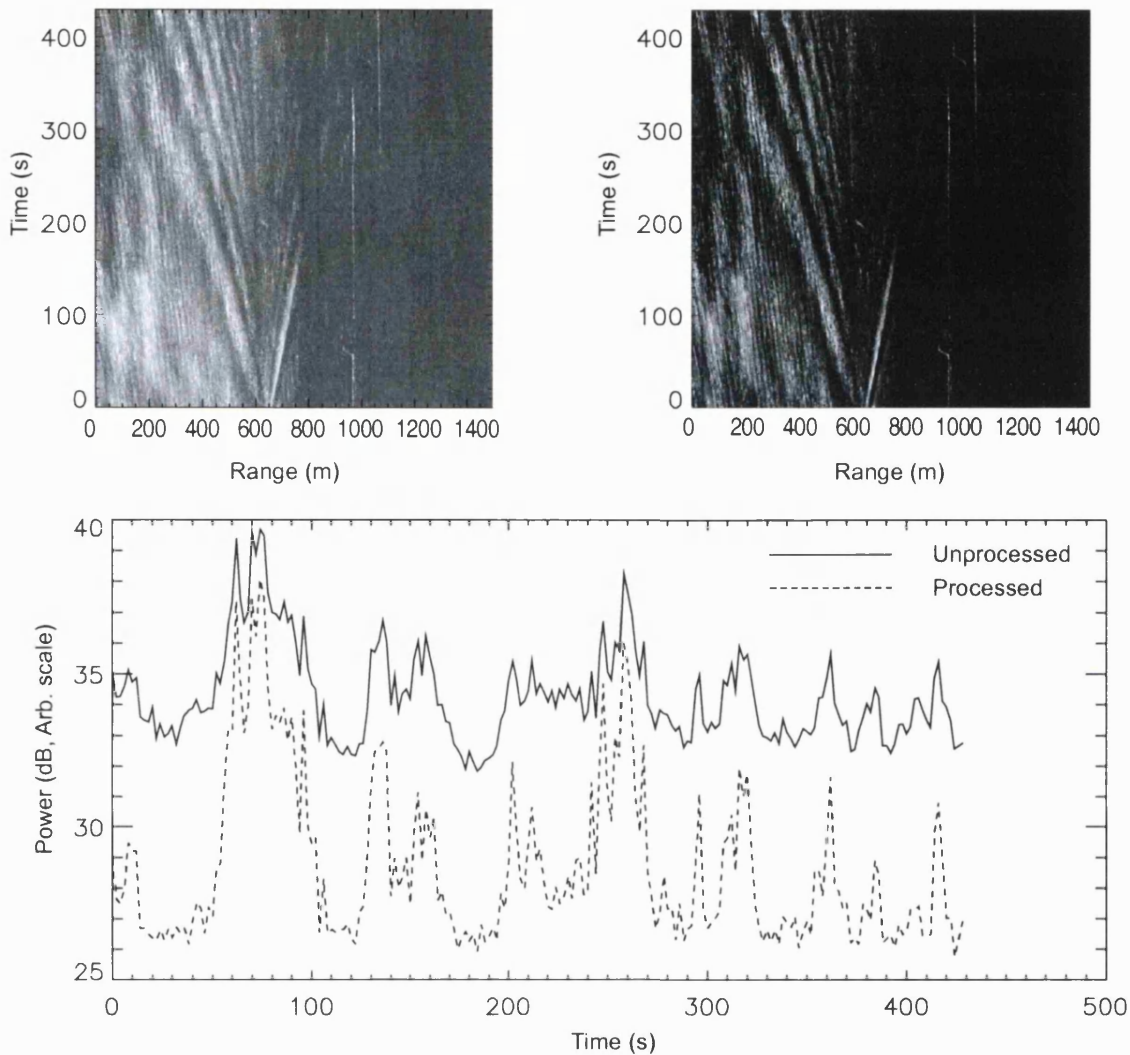
5.4.3 Image enhancements

Armed with the knowledge of what is happening to each of the scattering mechanisms at different places on the wake, it is possible to attempt to isolate or remove certain types of scattering mechanisms to increase the visibility of weaker events. If this were successful it would add weight to the physical basis of the Doppler model. Several techniques for enhancing the scattering on the wake have been attempted with some success. The most promising was eventually found to be one of the simplest. This method involved taking an ambient spectrum, well away from the wake in range and time and treating this as a background 'noise' to be removed. The image was then formed by taking Doppler spectra over very small range-time areas (2 seconds by 3 m), subtracting out the 'noise' spectrum and summing up the remaining power to give a pixel value. The result of such processing on the HH wake image in figure 5-30 is shown in figure 5-33. Here, only the portion of

the image in which the wake is clearly visible has been processed and the original and enhanced images are shown along with a vertical cut through the image taken at a range of 60 m. The wake is visually clearer in the processed image, and the cut through the image shows that the modulations are greatly increased by lowering the pixel brightness in the troughs significantly whilst leaving the peaks virtually unaffected. Figure 5-34 shows the same type of processing on an image taken on a different day, with similar results. The cut here is taken at 540 m.



5-33 : Unprocessed (top left) and processed (top right) RTI images, and cuts through the images at 60 m



5-34 : Unprocessed (top left) and processed (top right) RTI images, and cuts through the images at 540 m

It is unlikely that this very simple technique is the best method of enhancement for internal wave backscatter, and further study may yield an optimum method. It has been shown, however, that Doppler analysis using the new model can lead to important physical insights into the scattering mechanisms and imaging processes associated with internal waves and that further analysis of this kind could well lead to new physically motivated processing methods.

5.5 Conclusions

In this chapter, radar data recorded in the UCSB OEL wave tank has been compared to cliff top radar sea clutter in order to assess the applicability of the laboratory developed three component Doppler model to more operationally relevant environments. The comparison was made in terms of form of the Doppler spectra, average radar cross section, amplitude statistics and phase statistics. Although the mean RCS values found in the tank differed considerably from those predicted by standard and often used empirical models, the amplitude and phase statistics showed many similarities and basic lineshape analysis strongly suggested that the overall spectra in each case could be decomposed in the same way.

By analysing up and down wind cliff top data sets in terms of the average Doppler spectrum, the time history and Doppler spectra of individual features and their autocorrelation functions, it has been shown that the same three mechanisms identified in the wave tank experiments appear to be sufficient to describe the main features of sea clutter spectra. It was found that Bragg scattering occurred in both upwind and downwind data, as did polarisation independent whitecap scattering from highly disturbed water. Strong HH spikes were, however, only seen in the data in which the radar was looking into the prevailing wind. These spikes were seen to have a lifetime of the order of 100 ms, over which time they appeared highly coherent, whereas the whitecap returns were found to have lifetimes of the order of seconds, but decorrelated in milliseconds. By applying the Doppler model to the data, it was possible to extract the Bragg scattering polarisation ratio, which was found to be in line with the predictions of a composite surface model with similar RMS tilts for both the upwind and downwind cases.

Performing the same Doppler analysis on images showing the interesting scattering phenomenon of internal wave wakes, it was found that the modulation which makes

the wake visible against the background clutter comes principally from non-Bragg scattering, with the HH spike component showing the largest changes on and off the wake peaks. This type of analysis re-enforces the physical motivation behind the make up of the model.

Chapter 6 EM scattering calculations

6.1 Introduction

Thus far any scattering calculations presented have been based on the Small Perturbation Model (SPM) in the form given by Valenzuela [1978], which gives the backscattered RCS after making certain approximations about the scattering surface. Recent advances in computing power have, however, led to a number of new methods for calculating electromagnetic scattering from an given surface by numerically solving the magnetic field integral equations (MFIE). One such method, due to Holliday and colleagues of Logicon RDA, is the Forward-Back method [Holliday et al, 1996]. This method, of which more details can be found in Appendix A, was developed specifically to investigate scattering from deterministic features thought to be important in low grazing angle radar backscatter, the regime in which the greatest discrepancies between experimental data and the predictions of physical optics and perturbation models are seen. It is an iterative method for solving the MFIE for a dielectric azimuthally homogeneous surface, and is an extension and improvement of earlier iterative methods used to calculate scattering from wedge-like surfaces [Holliday et al, 1995].

At the centre of the Forward-Back (FB) method, and the step which gives the technique its name, is the splitting of the MFIE and the surface current into two terms, one representing primarily the forward scattered energy and one representing

primarily the backward scattered energy. This leads to coupled integral equations for the forward and backward propagating currents, and it is found that these converge to a stable answer in far fewer iterations than the earlier methods which did not split up the currents.

An implementation of the FB method has been developed by TW Research under contract to DERA [Ward et al, 1999] and in this chapter this code is used to calculate the backscattered field from a number of simulated surfaces and the results, where possible, are compared to data from the UCSB tank experiments. The breaking wave surfaces used in this chapter are the outputs of two numerical hydrocodes, LONGTANK [Wang *et al*, 1995] and CHY [Dold, 1992]. The former of these is a simulation of the waves generated in the UCSB wave tank.

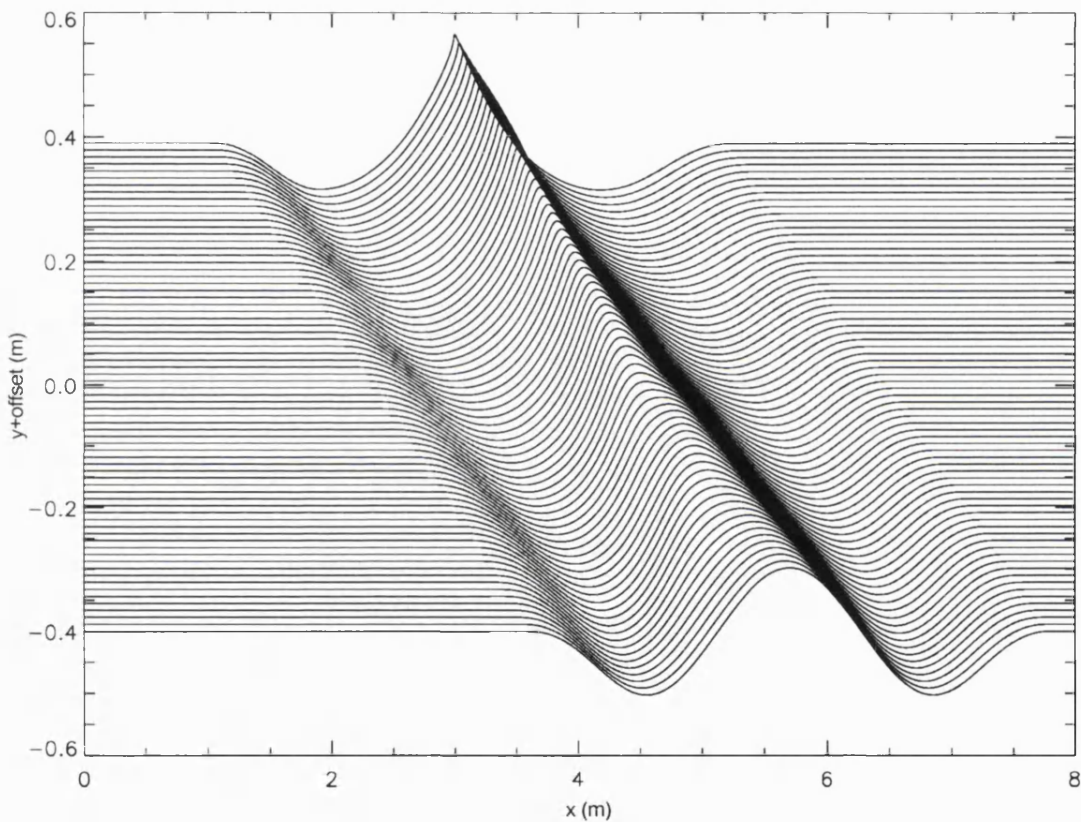
6.2 The need for numerical solutions

6.2.1 The failure of resonant models

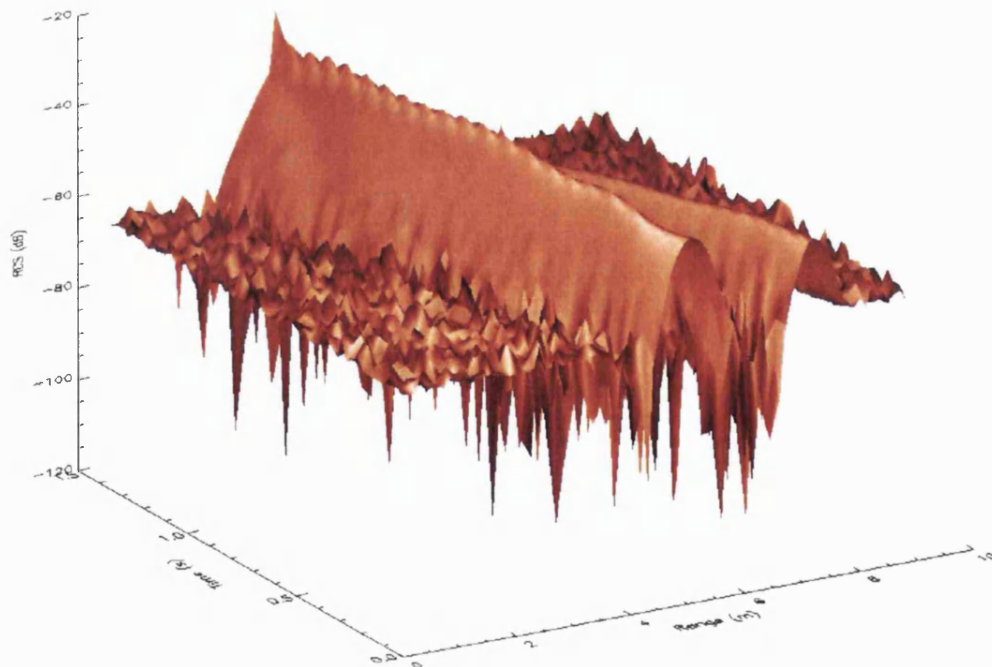
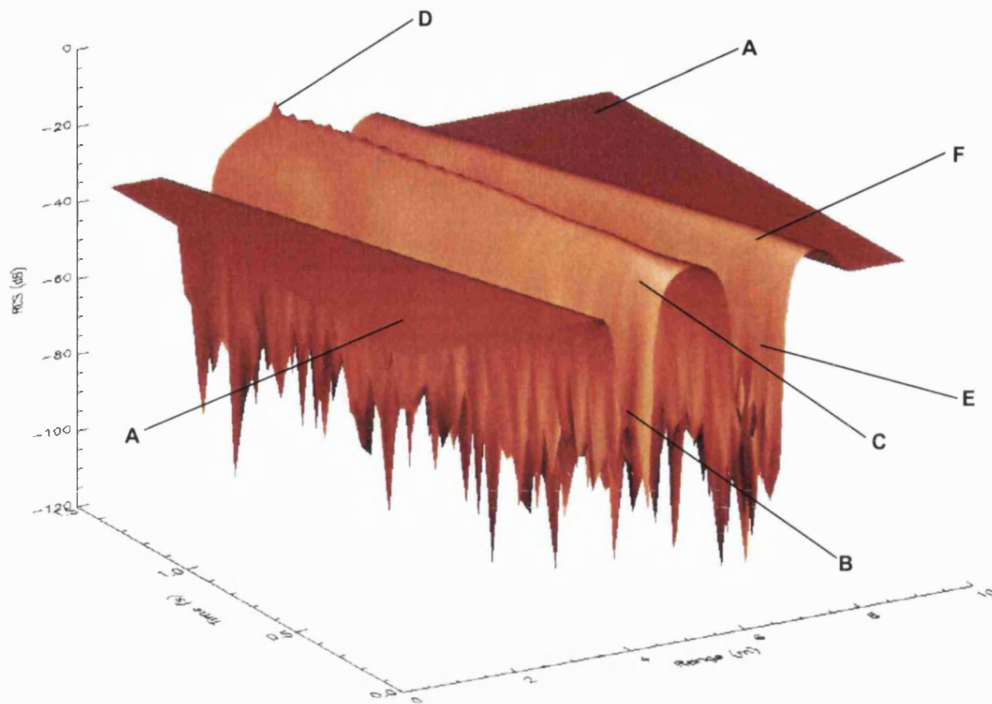
Figure 6-1 shows a series of waves generated by the CHY code. The waves are generated as periodic functions, starting as a sine wave and evolving into a steep, crested wave. Here a single cycle from this wave train has been isolated and, using a fifth order polynomial to match the first and second derivatives, the surface has been returned smoothly to zero height.

To demonstrate the need for a code such as forward-back, the scattering from these surfaces is first calculated using a 'tilted Bragg' model. In this calculation, the surface is split into 10 cm range gates and the Bragg RCS calculated within that gate using an effective grazing angle which is equal to the local tilt plus the true grazing angle. This type of calculation assumes that the wave shape is the underlying modulation upon which a spectrum of small, resonant capillary waves travels, and shows how the Bragg RCS would vary as the wave steepens. The grazing angle was set to 6°

and regions in geometric shadow were assumed to give no return. A random Gaussian noise floor was set at -65 dB. Figure 6-2 shows the scattering results in vertical polarisation (top) and horizontal (bottom). Letters A – F indicate the main features of the plots.



6-1 : A steepening wave approaching breaking point produced by the CHY numerical code



6-2 : RCS scattering surface as calculated using Rice SPM with underlying tilt modulation given by the CHY waves in 6-1. The ridges along the top of the wave represent the breakdown of the resonant model owing to steepness and curvature beyond the model's region of validity

- A** Untilted Bragg scattering from the flat regions before and after the passage of the wave. These regions are much higher in VV than HH, as can be seen by the visibility of the noise in region A of the bottom plot.
- B** Shadowed region where the surface tilts away from the radar. RCS drops into the noise floor
- C** RCS rises quickly to a level above that of region A. This is scattering from the front face of the wave. Horizontal polarisation is more sensitive to this change in local tilt angle than vertical
- D** The ridges along the top of each plot represent the breakdown of the Bragg scattering model. The local tilt angle and local curvature at the crest of the wave go beyond the model's region of validity.
- E** Shadowed region on the rear face of the wave.
- F** As the surface is returned smoothly to zero, it is again tilted towards the radar and give enhanced scattering.

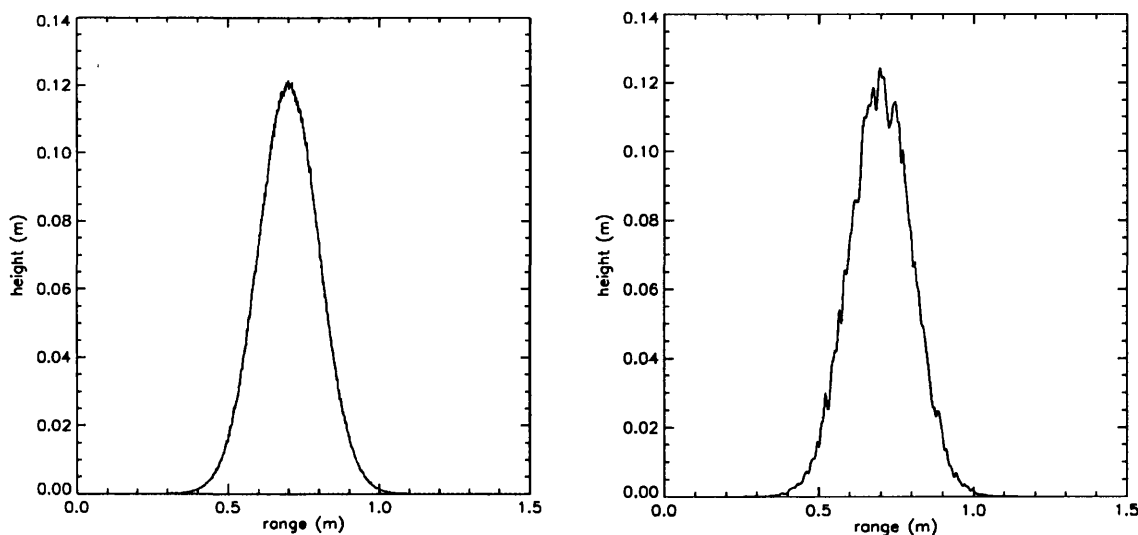
It is in order to find the RCS in the region D above that a code such as forward-back is necessary. Numerous experiments in addition to the work detailed in the previous chapters have indicated that at or around the point of breaking the backscatter from a wave is very strong and, in some cases, can be confused with a small target.

6.2.2 Previous work

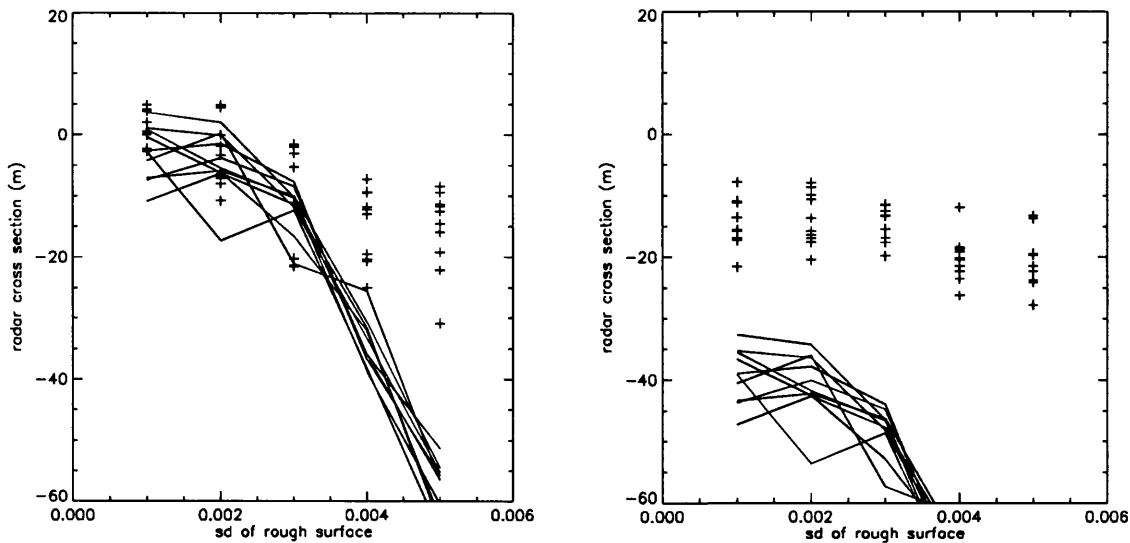
Following the initial work detailing the actual Forward-Back method, results were published by Holliday of FB scattering calculations from a set of UCSB LONGTANK waves. The calculations were conducted using a incident radiation of frequency 10 GHz, and with water waves of 2.3 m wavelength. The backscattered RCS from waves approaching breaking showed very fast rises (over 10 dB in under 0.1 s) and instances in which HH exceeded VV by several dBs. This is definitive sea spike

behaviour, indicating that the code can reproduce the very phenomenon seen in sea clutter which cannot be explained by Bragg based models.

The second type of non-Bragg scattering identified in earlier chapters, that from highly disturbed white water, is exceptionally difficult to simulate owing to the extreme roughness on many length scales of the scattering surface. However, recent attempts have been made to reproduce these features using the FB code with some success. The data in figures 6-3 and 6-4 is reproduced from work by Ward [Lamont-Smith *et al*, 2001] in which random Gaussian noise is added to a smooth underlying Gaussian surface as a simplified whitecap. Figure 6-4 shows the backscattered RCS as calculated by FB (crosses) and Rice SPM (lines) as a function of the RMS heights of the roughness. At each roughness ten realisations were calculated. It is clear that as the roughness increases, the FB code predicts that two polarisations can become equal, just as found in the radar data from whitecaps and at odds with the Rice SPM. These calculations were, however, done using a perfectly conducting surface as opposed to a dielectric.



6-3 : Examples of simplified whitecap surfaces (after Ward, 2001). Correlated random Gaussian noise is added to a Gaussian hump. The noise amplitude is increased from very small (left) to larger values (right)



6-4 : Variation in VV (left) and HH (right) RCS with increasing amplitude of Gaussian noise roughness. Solid lines represent the Rice resonant values, crosses represent FB calculated results

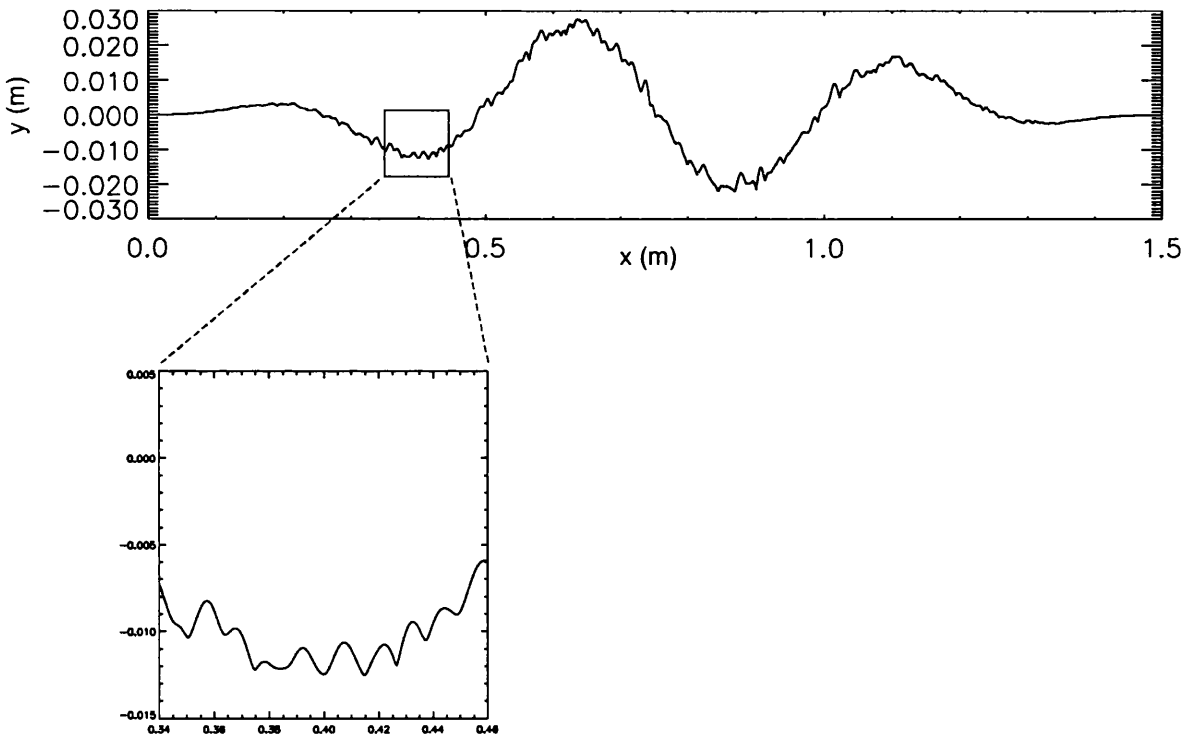
Thus work by other researchers using the FB code has qualitatively reproduced spikes and gone some way to reproducing whitecaps. However, to complete the elements included in the three component model, Bragg scattering must be demonstrated using FB. Also, data recorded at the wave tank covered frequencies from 3 GHz to 94 GHz, offering the possibility of comparisons to data over a wider range than carried out before.

6.3 Bragg scattering with Forward-Back

6.3.1 RCS variation with grazing angle

The variation of the Bragg scatterers' RCS with grazing angle as recorded in the tank at J-band was presented in chapter 3 (see figures 3-19 to 3-21). Here Doppler processing was used to isolate the Bragg scattering component in order to compare it to the Rice SPM prediction. To attempt to use the FB code to reproduce this result, a suitable scattering surface must be simulated. The surface must contain small amplitude roughness on a resonant scale (approximately 1 cm for J-band) and a larger underlying wave to tilt this surface towards and away from the radar. A realisation of such a surface is shown in figure 6-5. Random Gaussian noise is

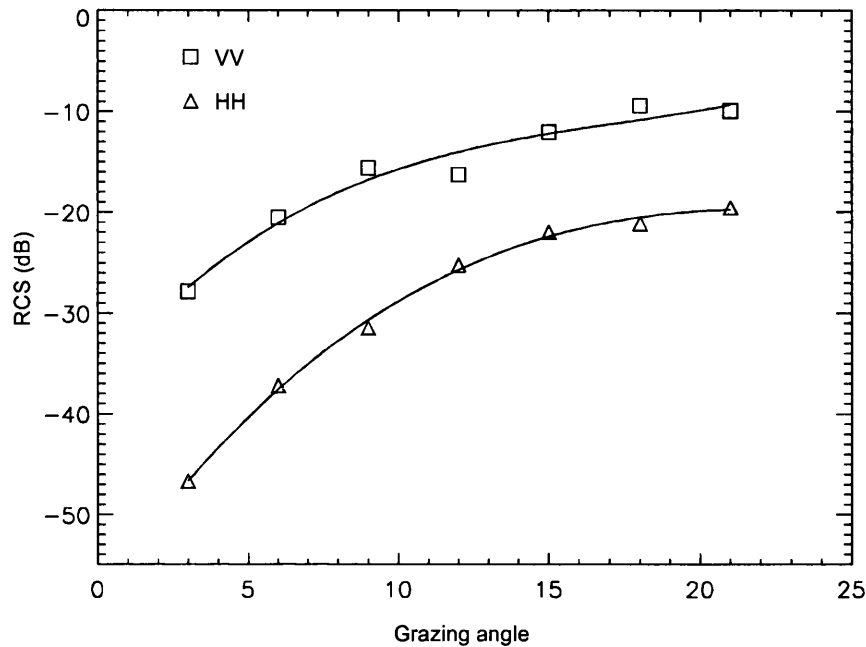
filtered in the Fourier domain to give the required correlation properties, and this roughness is added to a 0.5 m wavelength underlying sine wave. The entire 1.5 m surface is then Hanning weighted to ensure zero amplitude and gradient at the extremes. The enlarged portion in the box shows the roughness is actually smooth on a point-to-point basis (the sampling interval is 0.00015 m) and has a 'wavelength' of the order of 1 cm, the resonant value.



6-5 : Simulated tilted rough surface for Bragg scattering calculations using the FB code. Correlated Gaussian noise is added to an underlying long sine wave, and the whole surface is Hanning weighted to give zero height and slope at the edges.

Ten realisations of this surface were produced and the FB code run over each at grazing angles with 3° intervals from 3° - 21° . The mean RCS values at each angle are shown in figure 6-6 with third order polynomial fits overplotted. The general trend is very similar to that seen in figure 3-21 – VV is greater than HH, both increase with grazing angle, but at a decreasing rate, and the difference between the two (the polarisation ratio) decreases. Whilst the form of the scattering surface is obviously something of an oversimplification, in that it includes no hydrodynamics and so

cannot be a true representation of the water surface, this is still a very encouraging result and gives confidence that the FB code can accurately reproduce Bragg scattering RCS values and trends.



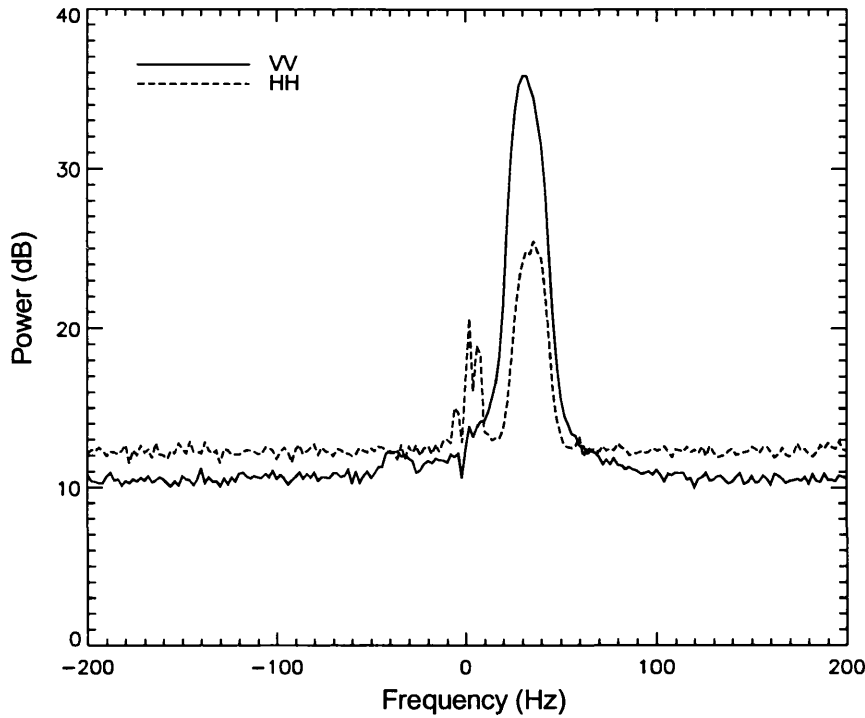
6-6 : FB calculated RCS variation with grazing angle. Each point is the mean of the calculation from 10 realisations of a surface such as the one in figure 6-5

6.3.2 Doppler spectra

As the FB code calculates the amplitude *and phase* of the scattered magnetic field, it is possible, given a time varying surface, to calculate the Doppler spectrum. Such calculations have not been made previously owing to computational limitations. To calculate a Doppler spectrum, the FB code must be run over very many surfaces (100+), which only several years ago could have taken days, if not weeks. Using parallel processing techniques on a 16 processor High Performance Computer (HPC), such time scales have been vastly reduced.

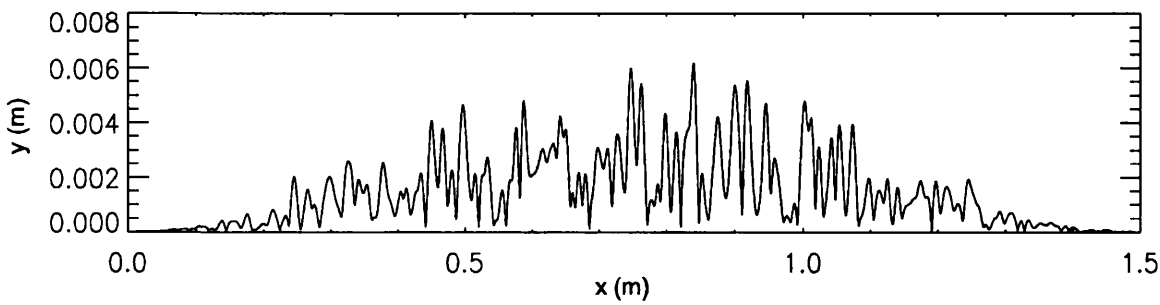
For means of comparison with recorded radar data, figure 6-7 shows MIDAS radar Doppler spectra from a wavetank data set carefully selected to be Bragg dominated in both polarisations. The plot shows J-band data recorded at very low wind speed (3

ms^{-1}) to eliminate returns from very steep and breaking waves. In order to maximise the backscatter from the Bragg ripples, the highest grazing angle available of 24° was used. Both polarisations are seen to peak at the same frequency, and VV is greater than HH everywhere, with both spectra being roughly symmetrical, (the 0 Hz spike in HH is probably artefact, not a clutter feature, as noted previously).



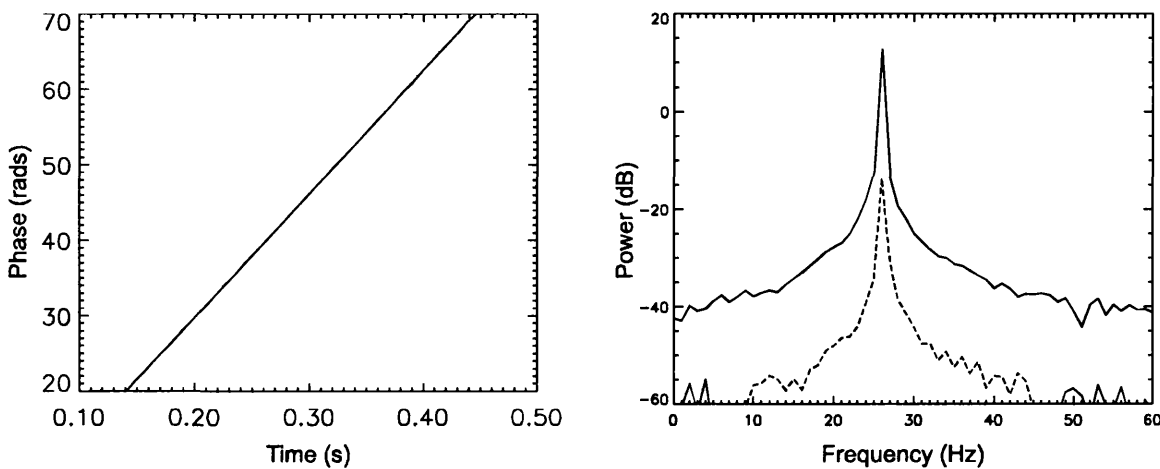
6-7 : J-band Doppler spectra from the MIDAS radar, 3 ms^{-1} , 24° grazing angle

The expected Doppler shift as calculated from the Bragg resonance formula and the dispersion relation (equations 2-9 and 3-12) is 26 Hz. The data in figure 6-7 shows a shift of a little over 30 Hz, indicating a slight additional motion of the surface due to wind drift or longer wavelength gravity waves. To attempt to reproduce these Doppler spectra using the FB code, a time evolving resonant surface must be simulated. To do this including all of the correct hydrodynamics is well beyond the scope of this work. However, a vastly simplified surface can be sufficient to demonstrate the capacity of the code to reproduce Bragg like Doppler results. Two such methods are described here.



6-8 : Simulated resonant surface with no underlying tilt

In the simplest case, a 1D correlated random rough surface was generated as in section 6.3.1, but this time with no underlying gravity wave for simplicity. This rough surface was then Hanning weighted (see figure 6-8) and “slid” 26 cm towards the simulated radar position in 128 steps. This is equivalent to a radar of PRF 128 Hz imaging a wave with a speed of 26 cm s^{-1} . The unwrapped phase from a 0.4 second portion the HH data, and the Doppler spectra of both polarisations, are shown in figure 6-9. The phase is seen to increase uniformly with time, and the spectra are approximate delta functions. This lack of width in the spectra arises from the fact that every point on the scattering surface is moving with precisely the same velocity, which is in contrast to a true water surface. Note, however, that as in the real data, both polarisations have the same Doppler shift (here 26 Hz) and VV is greater than HH everywhere.



6-9 : Example of phase variation with time (left) and Doppler spectra (right) as calculated by the FB code for the ‘sliding’ rough surface

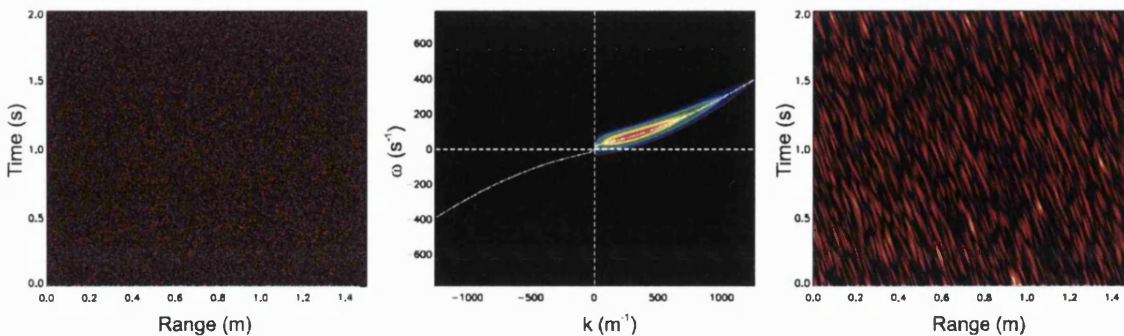
A second method attempts to include some physical time variation in the surface and so produce more realistic spectra. To include the correct dispersive properties in the scattering surface, a 2D array of random Gaussian noise was produced and filtered in the Fourier domain (ω - k space) to introduce correlations in the x and y (space and time) directions. The data was multiplied by a Rayleigh weighting in the k -direction, with the variance (σ^2) set to the radar square of the wave number, and a Gaussian filter in the ω direction, centred on the gravity-capillary wave dispersion relation. The resulting 2 dimensional filter $f(\omega, k)$ is given by

$$f(\omega, k) = k \exp\left(\frac{-k^2}{2\sigma_k^2}\right) \exp\left(\frac{-(\omega - \omega_o)^2}{2\sigma_\omega^2}\right) \quad [6-1]$$

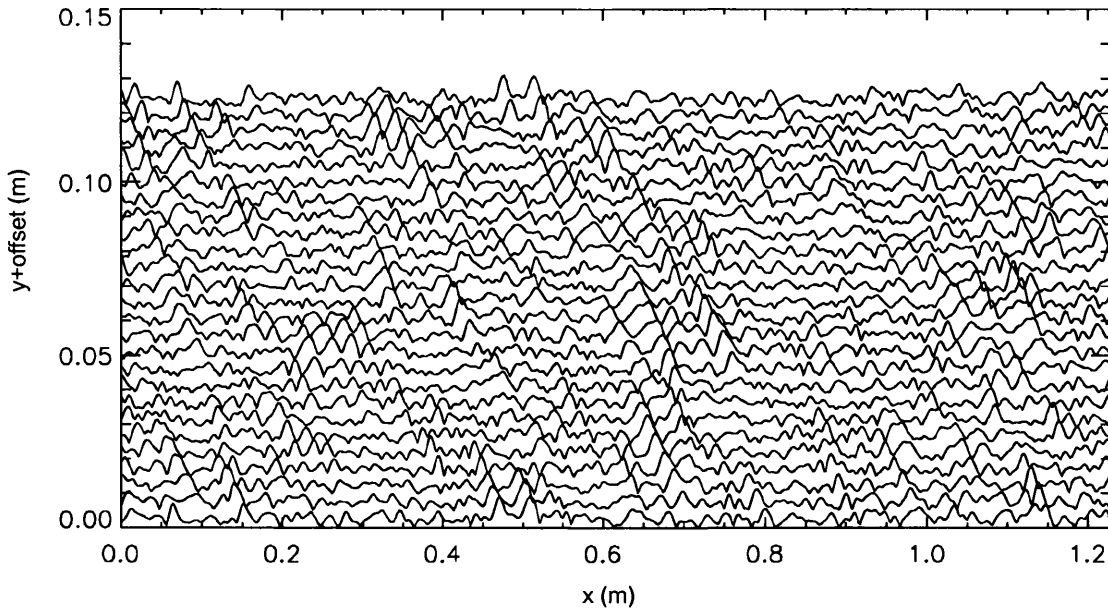
where ω_o is given in terms of k by

$$\omega_o = \sqrt{gk + \gamma k^3} \quad [6-2]$$

where γ is again the surface tension divided by the density. σ_k was set to $2\pi\lambda_{\text{radar}} = 315 \text{ m}^{-1}$, and σ_ω was set to 20 s^{-1} to give a correlation time of the order of 0.3 s. The filtering process is shown in figure 6-10, with the uncorrelated random Gaussian noise shown on the left, and the scattering surface shown on the right after multiplication in the Fourier domain with the filter shown in the centre. The surface is also shown as a waterfall plot in figure 6-11. These surfaces were Hanning weighted and used to simulate a 128 Hz radar as in the earlier example.

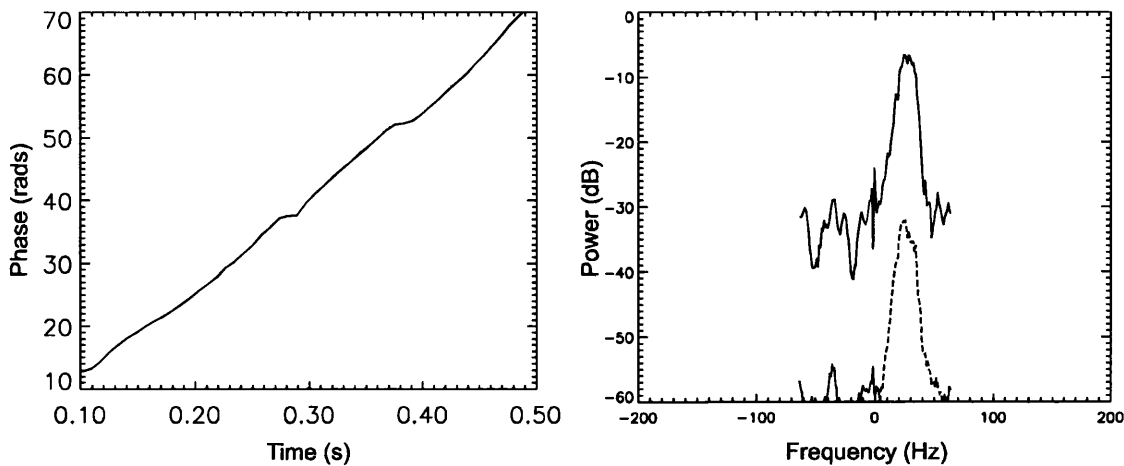


6-10 : The 2-dimensional filtering process to produce a correlated range-time surface with characteristics defined by the capillary wave dispersion relation



6-11 : Waterfall plot of the range-time scattering surface

Figure 6-12 shows the phase and Doppler spectra resulting from running the FB code over these surfaces. Although the simulated PRF of the radar of 128 Hz gives a Doppler bandwidth of ± 64 Hz, the data is plotted with the range extended to ± 200 Hz for ease of comparison with figure 6-7. The simulated data now shows a less uniform phase change than that seen in figure 6-9 and, whilst retaining a mean shift of 26 Hz, the spectra are no longer delta functions, but have a width comparable to that of the real radar data. Again, VV is greater than HH everywhere. The overall qualitative similarity between the simulated and real Doppler spectra is considerable.



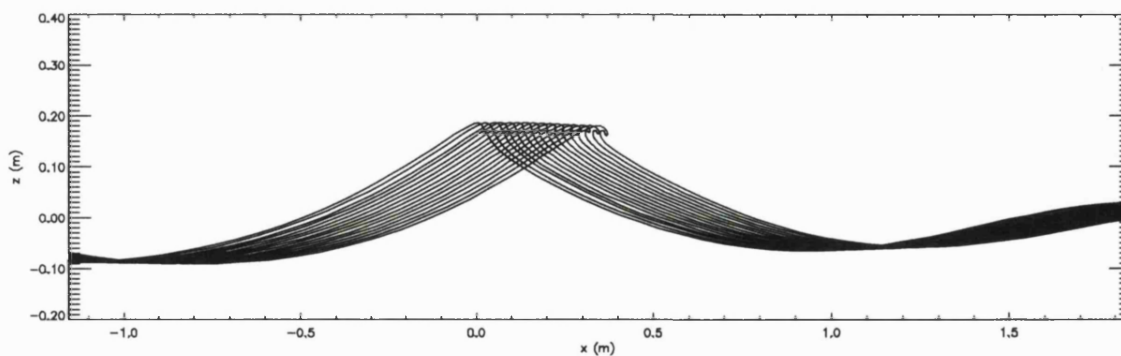
6-12 : Example of phase variation with time (left) and Doppler spectra (right) as calculated by the FB code for the range-time surface

Whilst these simulations are far from perfect in their treatment of the hydrodynamics of capillary waves, they are sufficient to demonstrate without question that useful Doppler information can be extracted from the output of the FB code, and that all the main characteristics of Bragg scattering can be reproduced.

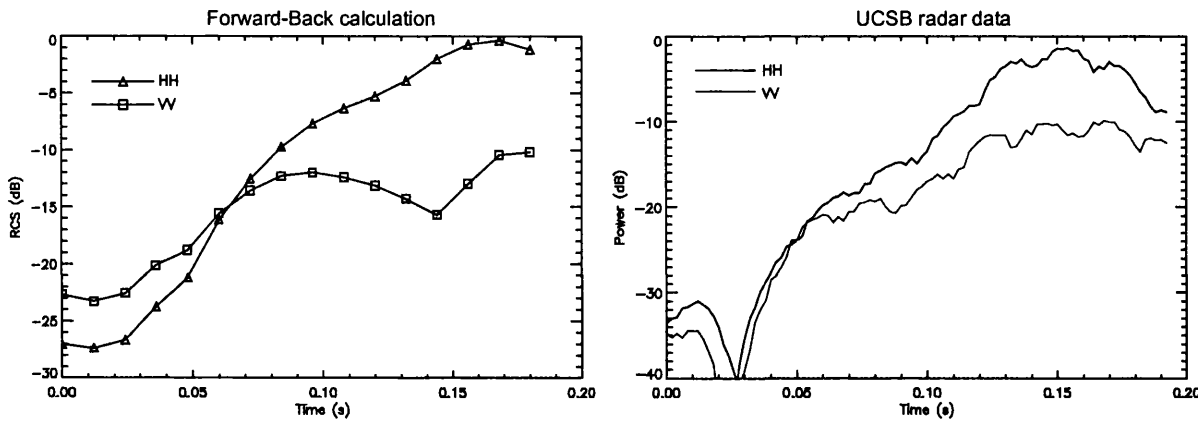
6.4 Non-Bragg scattering

6.4.1 Forward-Back calculations from breaking waves

The investigation of low grazing angle sea spikes was one of the primary driving factors in the formulation of the Forward-Back technique, and as already mentioned, published work has shown that the method can reproduce spike-like results for scattering from steepening and breaking waves. Figure 6-13 shows 2.3 m wave profiles, produced by LONKTANK, provided to DERA by Logicon RDA [De Raad, 1999]. These profiles were used in FB scattering calculations at 6° grazing angle and 6 GHz transmit frequency, and compared to data recorded by the UCSB C-band radar. This comparison is shown in figure 6-14. Whilst it should be borne in mind that the radar returns from these breaking waves are very variable (the extent of this variation is discussed later in this chapter), the similarity to the FB simulation is quite striking. In both the rise in RCS over the 0.2 s shown is approximately the same, and the separation of the polarisations leading to a ratio of around 10 dB is also seen in each plot.



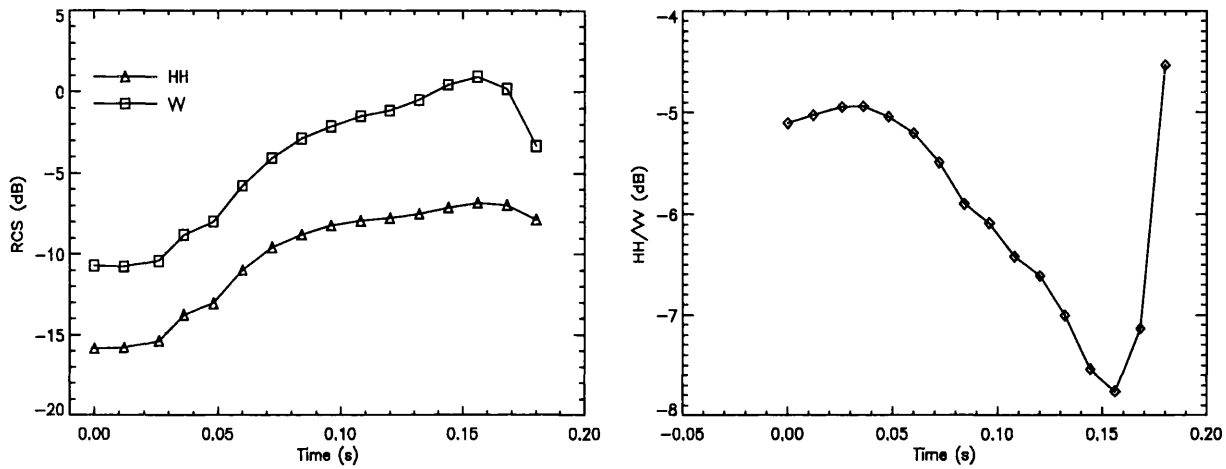
6-13 : A steepening and breaking wave generated by the numerical code LONGTANK



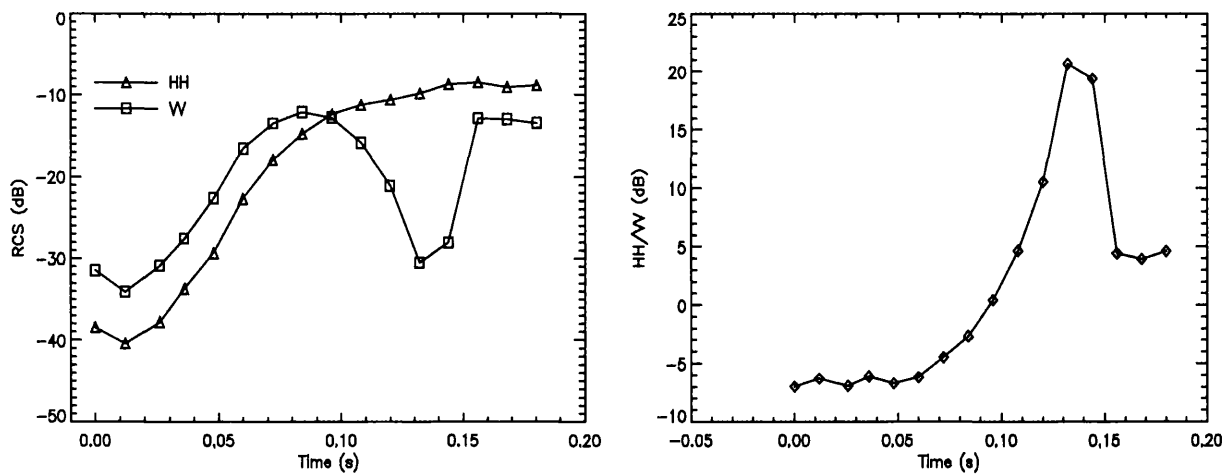
6-14 : Comparison of FB calculations from the LONGTANK waves with an example of a breaking wave RCS profile as measured by the UCSB C-band radar

Figures 6-15 to 6-19 show the FB results of 6° backscatter from the LONGTANK waves at each of the MIDAS frequencies from 3 GHz to 94 GHz. Sticking here to Holliday's definition of a spike as a rise of over 10 dB in under 100 ms [Holliday, 1998], each of the radar frequencies shows sea spike behaviour in both polarisations except the F-band data, although at this band too an increase of over 10 dB is seen in the VV data, albeit in the slightly longer time of 150 ms. The HH data increases by slightly under 10 dB in this time. However, it should be noted that, although the F-band data does not show as fast a rise as the other frequencies, the eventual peak RCS values of 1 dB and -5 dB for VV and HH are comparable to, and in some cases greater than, the other bands' peak values. Therefore, although the F-band data does not give a sea spike by the definition adopted here, the RCS of the wave just before breaking is as high as that seen at other frequencies. The reason for the lack of a fast rise in the F-band case lies in the differences in the scattering of each frequency from the first wave in the series. Looking at the returns from the first wave, at time zero, the RCS is seen to decrease as radar frequency increases. At M-band, the RCS at time zero is down to the level of the numerical noise floor, indicating no backscatter. At this wavelength (3 mm), the wave tip is very large compared to the radar wavelength and the scattering is probably primarily specular. In contrast to this,

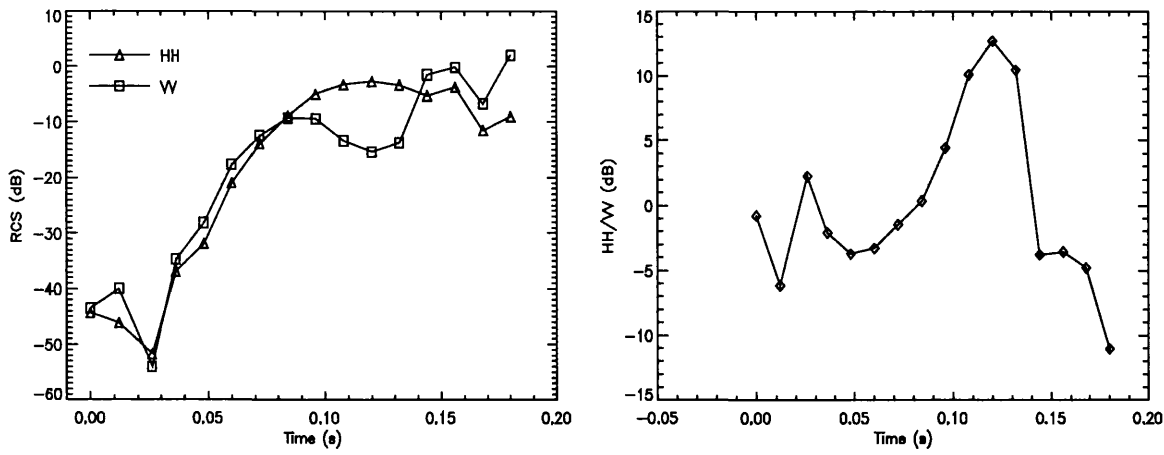
the F-band wavelength, at 10 cm, is of approximately the same size as the wave tip in the early stages and it is possible that some form of resonant phenomenon is occurring and giving the observed higher return. From this high starting point, the F-band data cannot exhibit as fast a rise as is possible for the other bands. It should also be noted that each of the bands I-M show polarisation ratios far exceeding that predicted by Bragg scattering, and in the cases of I, J and K bands, values of HH/VV of 10-20 dB are observed, as seen in spikes both in wave tank and cliff top data.



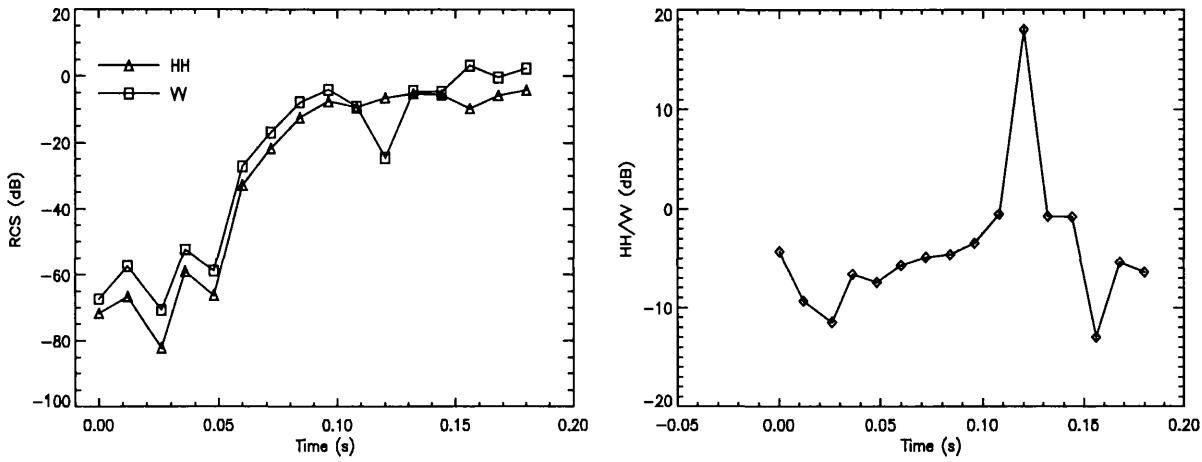
6-15 : F-band RCS and polarisation ratio as calculated by the FB code



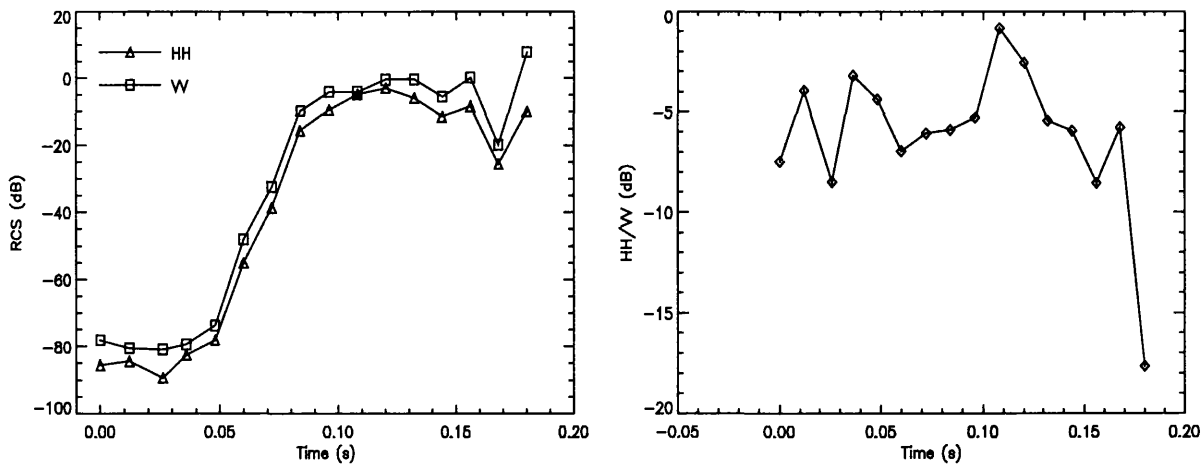
6-16 : I-band RCS and polarisation ratio as calculated by the FB code



6-17 : J-band RCS and polarisation ratio as calculated by the FB code



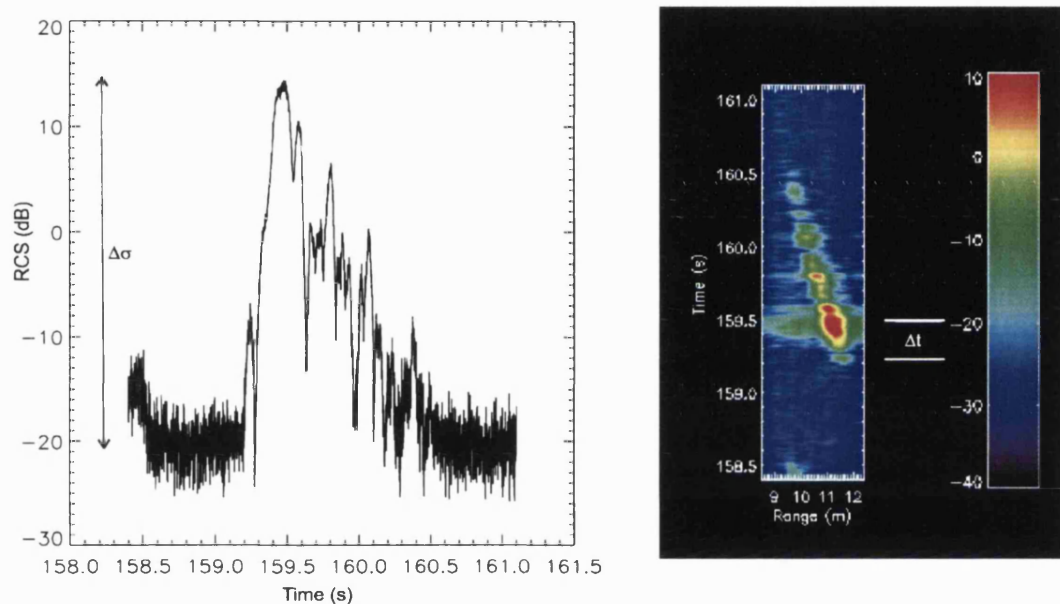
6-18 : K-band RCS and polarisation ratio as calculated by the FB code



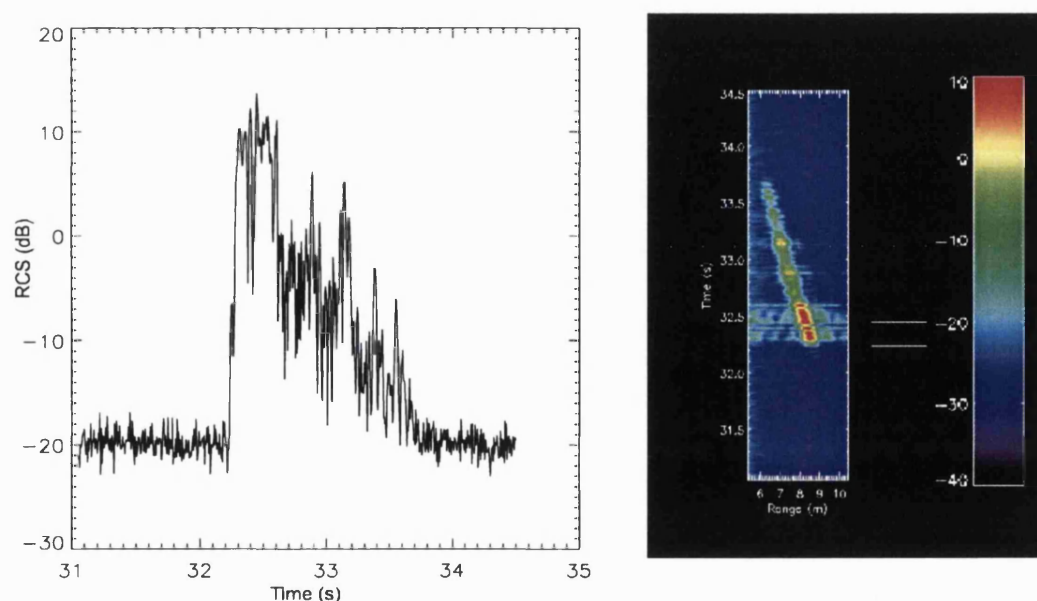
6-19 : M-band RCS and polarisation ratio as calculated by the FB code

6.4.2 Radar data from breaking waves

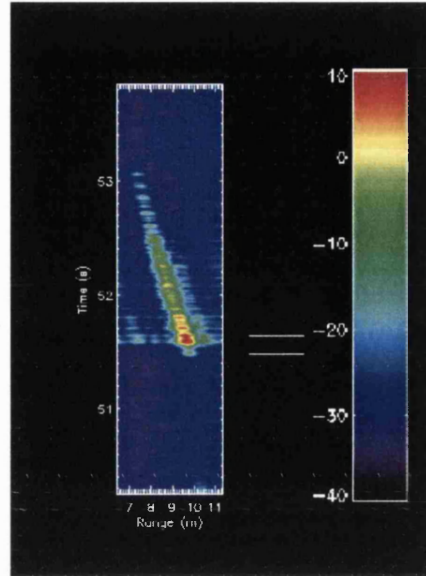
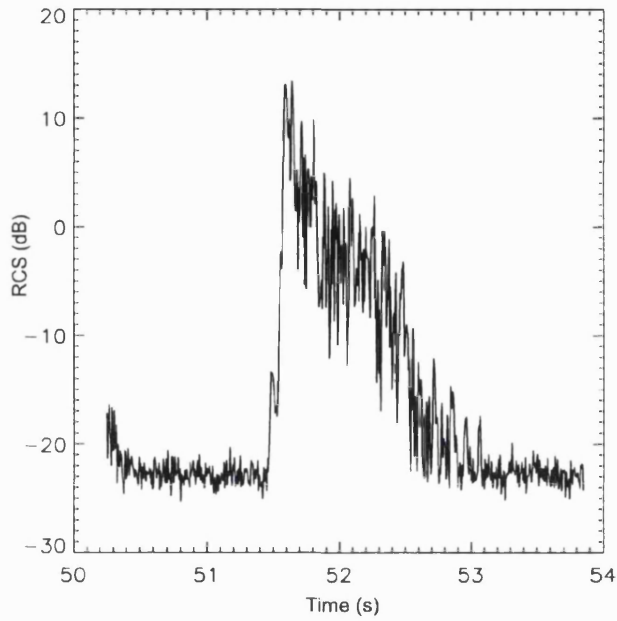
Figures 6-20 to 6-24 show 2.3 m breaking waves recorded at 6° grazing angle at each of the MIDAS frequencies. Only HH data is shown as these have the clearest spikes and virtually no Bragg scattering (in contrast to VV, which shows a weak spike and strong Bragg returns (see fig 4-5)). Each figure shows a single breaking wave RTI and a profile taken along the wave.



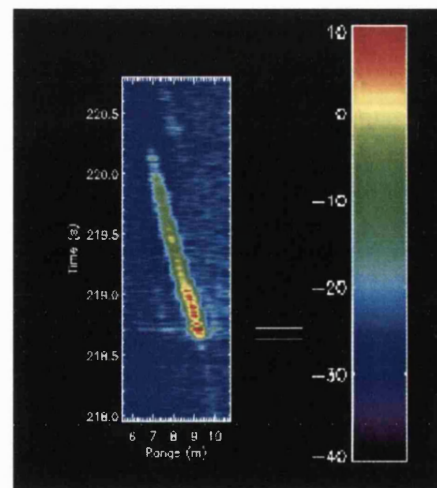
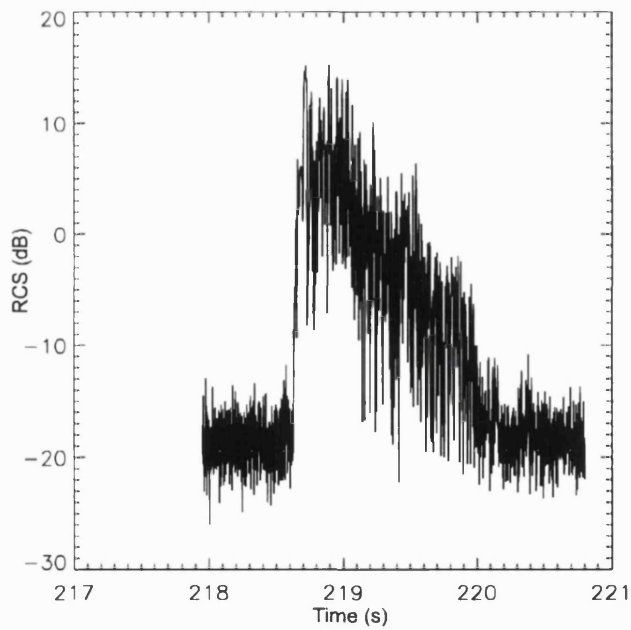
6-20 : MIDAS radar F-band time profile (left) and RTI of 2.3 m breaking wave (right)



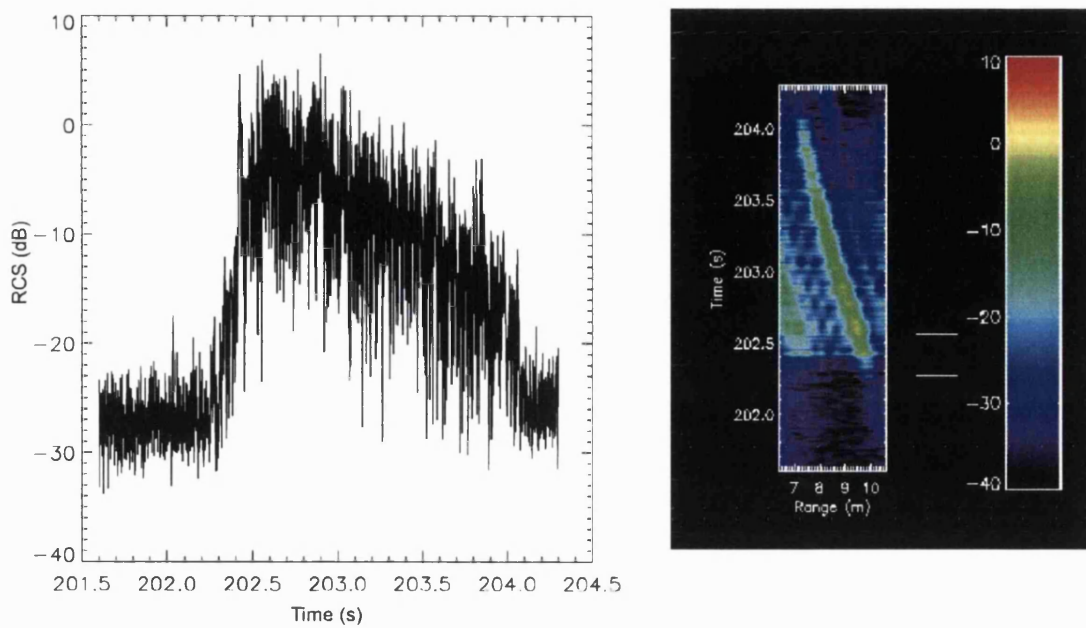
6-21 : MIDAS radar I-band time profile (left) and RTI of 2.3 m breaking wave (right)



6-22 : MIDAS radar J-band time profile (left) and RTI of 2.3 m breaking wave (right)



6-23 : MIDAS radar K-band time profile (left) and RTI of 2.3 m breaking wave (right)

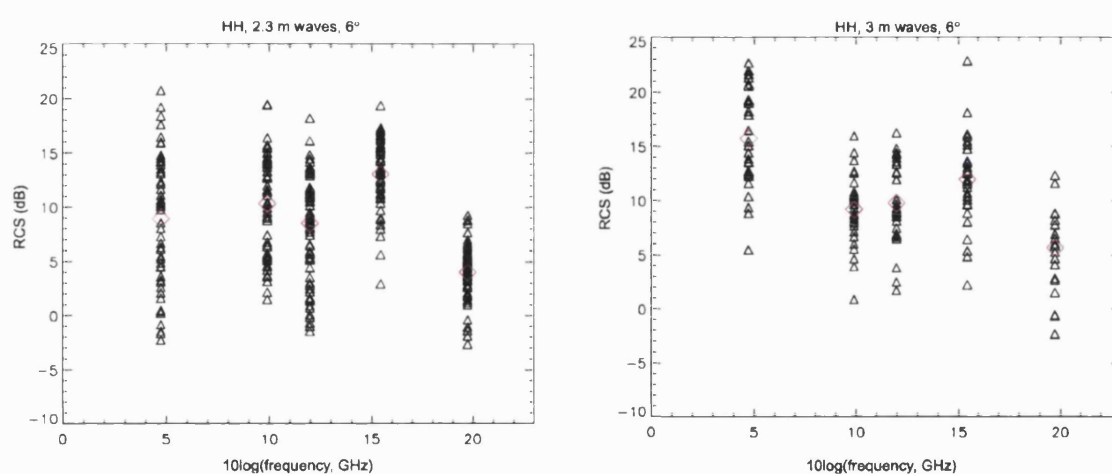


6-24 : MIDAS radar M-band time profile (left) and RTI of 2.3 m breaking wave (right)

Given that the FB code and simulated wave profiles representative of those in the tank are available, one would like to perform a direct comparison of the RCS as predicted by the code and that as measured in the tank. To this end, for each radar frequency used and each breaking wave group wavelength (1.5 m – 4 m), 4 minutes of radar data was processed and the peak RCS of each wave imaged in that time period extracted. Variations in this peak value with radar frequency and water wavelength could then be examined. However, several points should be noted. First, as can be seen from examination of the image in figure 6-24, the data collected at M band was of lower quality than would be desirable, with poor pulse compression leading to high sidelobes and a 'ghost' image of the wave to the left of it. This does not necessarily render the data unusable, but should be borne in mind when looking for trends in the following plots.

Second, as the wavelength of the water waves is increased, so the number of wavegroups imaged in the time period decreases. With a wavegroup of 1.5 m wavelength, approximately 100 individual waves could be recorded in 4 minutes. At a

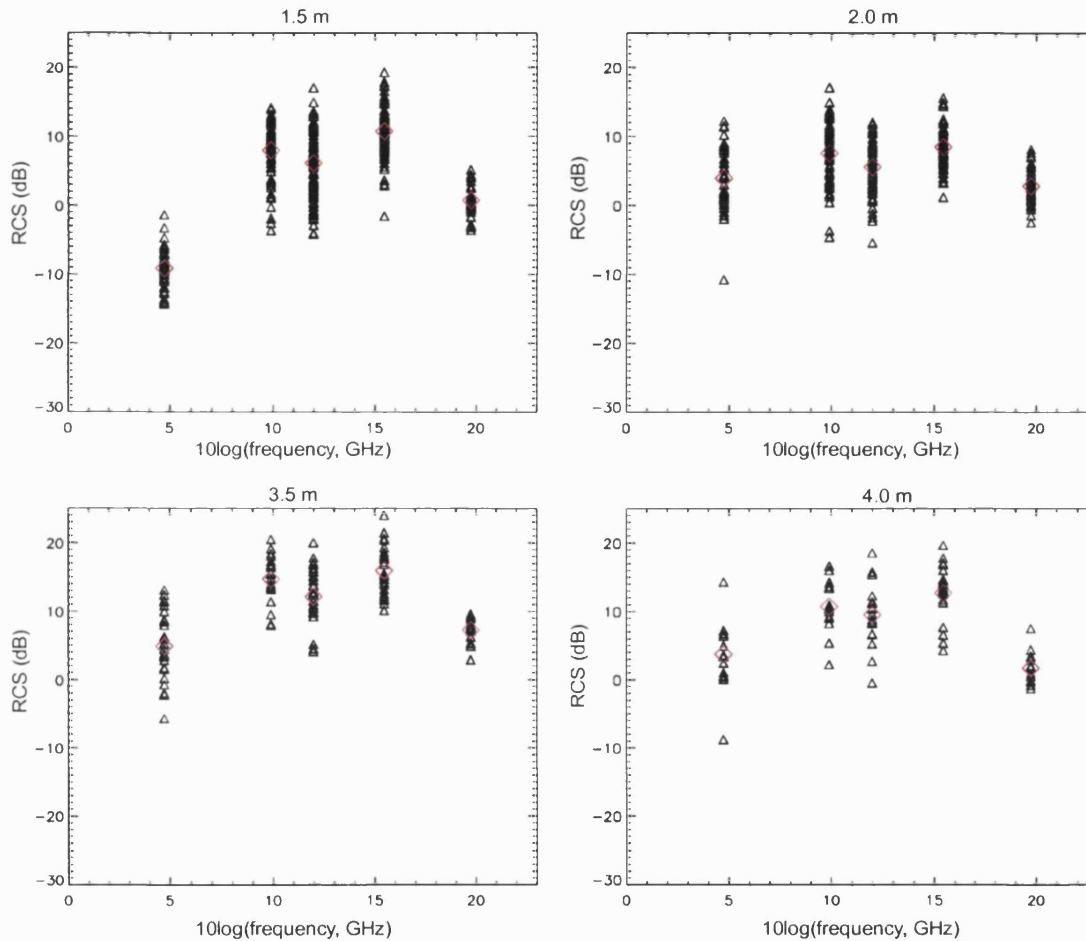
wavelength of 4 m, this number falls to approximately 20. A similar difficulty is encountered in the variation of grazing angle. At 6° , the radar footprint on the water surface covers around 10 m. By 21° this has fallen to a little over 2.5 m. In a four minute period, it is impossible to guarantee that the peak RCS of a reasonable number of 4 m waves will be imaged in a 2.5 m window. All of this makes a comparison of radar data to FB results across the entire matrix of radar modes, water wavelengths and grazing angles virtually impossible.



6-25 : 2.3 m and 3 m wave RCS values at various frequencies recorded over 4 minutes.

A further difficulty in extracting trends from the data is encountered on examination of figure 6-25. These plots show the peak RCS values of each wave recorded at each frequency, at 6° grazing angle and with wavelengths of 2.3 m (left) and 3 m (right). The spread in the points is immense, over 20 dB in several cases. Although the waves in the tank are visually and hydrodynamically repeatable, it appears that the small variations which are inevitable at the point of breaking from one wave to the next give rise to very large RCS changes. This wave to wave variation appears to swamp any trend which the data may contain. Given that such a large spread is present, keeping the sample size large takes on more importance, making the high grazing angle/long wavelength comparisons even more difficult. Figure 6-26 shows

the same plots at the other water wavelengths. Again, a large spread is seen in almost all cases.



6-26 : 1.5 m, 2 m, 3.5 m and 4 m RCS values at various frequencies recorded over 4 minutes

It is possible to quantify how many measurements would be needed in order to find the mean of a population to a given accuracy. Table 6-1 gives, for 3 m waves at 6° grazing angle, the number of waves imaged, mean RCS (in m^2) and standard deviation of the sample. If one were to take 20 m^2 as a representative value of the standard deviation, then it is easy to show via the central limit theorem (see appendix D) that, to obtain the mean RCS to within 5 m^2 at 95% confidence would require 61 measurements – twice as many as available here. However, given the small number of measurements actually made, and the fact that the distribution they are drawn from may not be Gaussian, the central limit theorem may not apply. In this case, one

can use the Chebyshev inequality (appendix D) to obtain a more cautious but realistic number. To now obtain the mean RCS to within 5 m² at 95% confidence would take 320 measurements. Given that 30 waves are imaged in 4 minutes, this would require 43 minutes of continuous recording, which at the data rate used in the UCSB/MIDAS experiment would give 85 Gb of raw data. With the smaller footprint available at 21° grazing angle, this increases to 170 minutes and 341 Gb, a prohibitively large amount of data for a single average RCS value

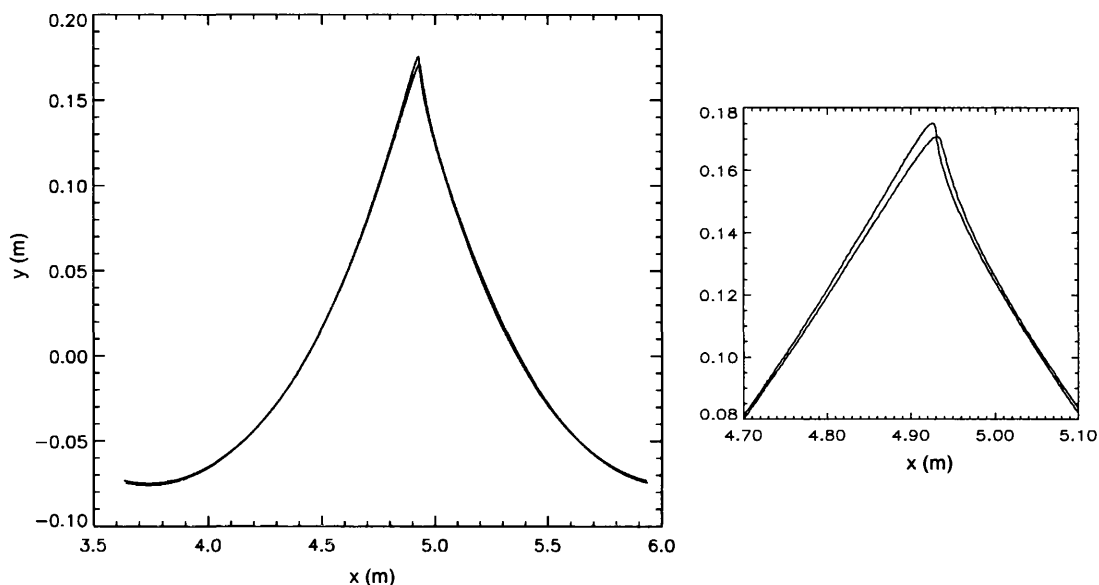
Band	F	I	J	K	M
n	31	30	34	32	21
Mean	58	10	12	24	5
S. Dev.	51	8	10	33	4

Table 6-1 : Number of waves imaged in 4 minutes, mean RCS (m²) and standard deviation for each radar band

Given that a very large variation in RCS from supposedly repeatable waves is the overriding result that can be taken from the data, then the question of whether the FB code can reproduce this feature must be addressed. Figure 6-27 shows two nearly identical wave profiles produced by the CHY code. The expanded plot on the right shows the small difference at the tip of the wave. The backscattered field from each of these two profiles at 6° grazing angle and 0.02 m incident radiation (J-band) was calculated and the results are given in table 6-2. This demonstrates that with a very slight change in the form of the tip of the wave, and negligible change in the gross shape, the RCS of each polarisation can increase by well over 10 dB. Given that a change in height of around 5 mm to a 2.3 m wavelength wave can have such a dramatic effect, it is unsurprising that a large spread of values is seen in the data from nominally identical and repeatable waves.

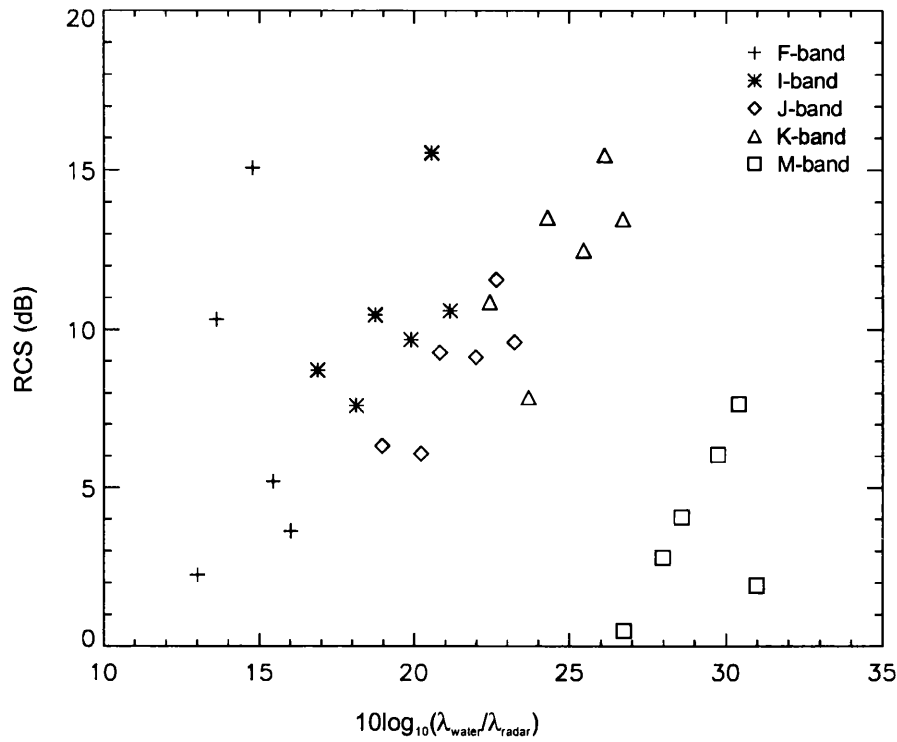
	$ B_{VV} ^2$	$ B_{HH} ^2$
Lower wave	-5 dB	-18 dB
Higher wave	7 dB	-4 dB

Table 6-2 : Comparison of scattered field intensity for two close to breaking waves



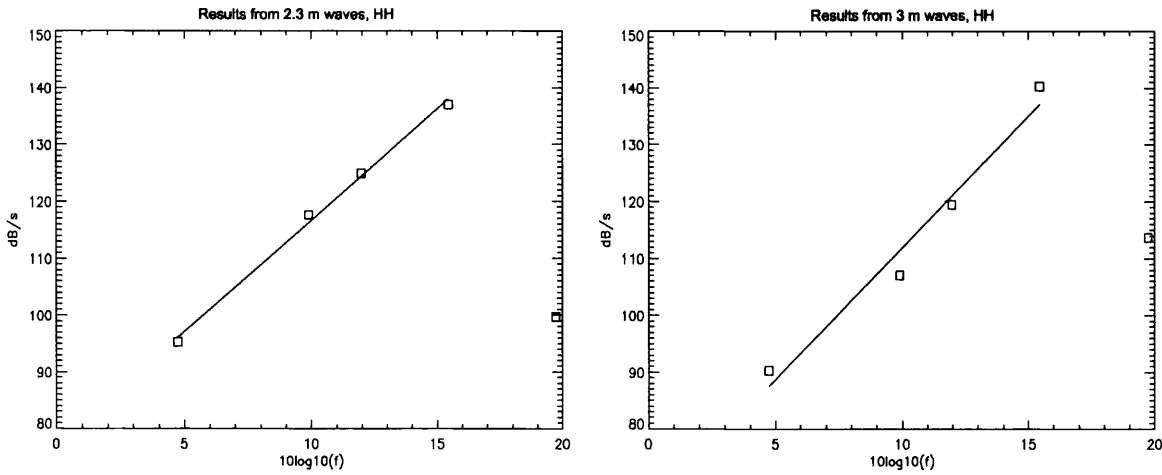
6-27 : Two close to identical breaking wave profiles (left) and an expanded view of the tip (right) produced by the CHY numerical code

Work done by researchers at UCSB [Fuchs *et al*, 1997b] has suggested that trends in the peak HH RCS may be more evident if the mean RCS values are plotted against the ratio of the water wavelength to the incident radar wavelength. The simple statistical analysis presented here suggests that to confidently reproduce such a result one would need to have many times more data than was actually collected during the experiment. Bearing this in mind, figure 6-28 is a plot of average RCS against the wavelength ratio. A cursory inspection gives the impression of an almost random scatter, particularly as each one of the points plotted is the mean value of a sample with a 20 dB spread. However, if one were to ignore the M-band data (the squares, which as already mentioned exhibited poor sidelobe performance), it is possible that there is some correlation between the wavelength ratio and RCS, with the RCS increasing with $\lambda_{\text{water}}/\lambda_{\text{radar}}$. The plot is, however, far from conclusive.



6-28 : Mean RCS value plotted against the ratio of the water wavelength to the radar wavelength

Another trend noted in earlier work with the FB code [Lamont-Smith et al, 2001] and also visible to some degree in figures 6-15 to 6-19 is the increase in the RCS rise rate (that is, RCS increase per unit time) with radar frequency. It is possible to extract this value from the data in figures 6-20 to 6-24 by taking the RCS difference from the mean noise floor to the peak ($\Delta\sigma$) and the time taken for this rise (Δt) to give the ratio $\Delta\sigma/\Delta t$ for each frequency. Looking at the RTI plots in figures 6-20 to 6-24, Δt shows a clear decrease from F through to K-bands, though this pattern is not continued for M-band. Figure 6-29 shows plots of rise rate averaged over 4 minutes of 2.3 m and 3 m breaking waves at each frequency. Discarding the M-band data, a correlation which is very close to linear on a log-log scale is seen, suggesting a power law relationship. The gradient of the line fitted in both cases is very close to 4, indicating $\Delta\sigma/\Delta t \propto f^4$. This relationship is put forward only very tentatively, however, owing to the large spread in the peak RCS values, as discussed previously.



6-29 : Mean rise rate plotted against radar frequency for 2.3 m and 3 m breaking waves

6.5 Conclusions

The work in this chapter has attempted, with mixed success, to compare directly the results recorded in the UCSB tank experiment to the predictions of the Forward-Back numerical scattering code. The code requires an exact, deterministic input surface requiring simulation of any type of wave from which the scattering is to be calculated.

Using simple rough, time evolving surfaces, the FB code has been used to reproduce all of the main characteristics of Bragg scattering. The variation of RCS with grazing angle has been reproduced by scattering off a set of surfaces consisting of correlated Gaussian noise superposed onto long wavelength sine waves, to simulate the tilting of large gravity waves. The FB results compare very well to the composite model and to data collected in the UCSB wave tank. The fact that the phase of the field calculated by the FB code contains useful information has been demonstrated by formation of Doppler spectra from moving rough surfaces. As a step towards achieving a measure of realism without entering into the complexities of the full hydrodynamic solutions for capillary wave motion, a two dimensional array was formed with correlation properties along its two axes defined by filtering Gaussian noise along the capillary wave dispersion relation. The resulting surface was

resonant at the radar wavelength in the range direction, had a decorrelation time of around 0.3 s in the time direction, and each frequency component “moved” at the correct capillary wave phase speed. The resulting Doppler spectra compared well to those recorded in the tank.

By using a tilted Bragg calculation from a steepening wave, it has been demonstrated that such scattering models are not sufficient to describe the sea spike behaviour often seen in low grazing angle radar data. The FB code has been shown to reproduce the fast RCS rise and high HH/VV polarisation ratio characteristic of such events. Direct comparison of FB results to radar data, however, was hampered by experimental constraints and the large spread in RCS values observed. Given that this spread was itself the defining feature of the data, it was investigated by calculating the FB backscatter from two very similar waves with slight differences near the peak. A change of approximately 14 dB in the backscattered field was found.

Whilst quantitative comparisons have proved difficult, the FB code has now qualitatively reproduced the main characteristics of Bragg, whitecap and spike scattering, the three processes shown in chapters 4 and 5 to be the dominant scattering mechanisms from the sea surface. This suggests that given a complete, realistic input surface, the Forward-Back method could accurately reproduce all of the main characteristics of LGA radar sea clutter.

Chapter 7 Discussion

In summarising the work described in the previous chapters, it is worth once again considering exactly what the motivation for using laboratory data is and how this relates to the theoretical and applied aspects of the radar sea clutter problem.

First of all one must relinquish any hope of accurately recreating “the sea” in an enclosed tank of any practical dimensions. Wind, wave and hence clutter characteristics can vary markedly from one location to another around the world’s seas, and conditions in mid ocean cannot be expected to be the same as those in coastal areas. Wind, current, swell and tidal flow, each with their own magnitude and possibly acting in different directions, will all have an effect on the radar backscatter. Thus, what can one hope to achieve in the confines of the laboratory wave tank? The answer is that the tank can reproduce all of the main elements, the building blocks, that contribute to the overall backscatter, though not necessarily in the same proportions or manifesting themselves in the same way as in the open sea. An example of this is the high RCS HH spike. This type of event is highly prevalent in the tank, and whilst they are also certainly found in open water sea clutter, they occur relatively infrequently. The reason for this is the geometry of the wind, waves and radar. In the tank, the wind direction and dominant wave direction are always directly towards the radar, meaning that any breaking wave will be in the correct orientation to give an HH spike. Examination of cliff top radar sea clutter carefully chosen to

have the same wind-wave-radar geometry also showed strong HH spikes, whilst imaging in the downwind direction produced no spikes. It is highly likely that these spikes are produced only by waves travelling directly towards the radar and so their occurrence would be expected to fall off quickly as radar look direction deviates from directly upwind. The result is that in most scenarios, HH spikes will not greatly alter the average RCS measured, as they occur too infrequently, and will also have little effect on the Doppler spectra as recorded over a reasonable length of time. The HH spike remains, however, an important clutter feature despite this as its strong, coherent nature can make it appear very much like a small target. The wave tank accurately reproduces this clutter feature, but in far greater numbers that would be expected in an operational environment. It is for this reason that the work presented here has made no attempt to calculate, for example, number of spikes per unit area or average non-Bragg RCS as a function of wind speed, as this would do nothing but characterise this particular experimental facility, and could not be expected to apply to open water sea clutter. That said, the high frequency and controllability of HH spikes from breaking waves, and the ability to simultaneously record the scattering surface visually and at close range, has allowed for the precise form of the wave which leads to a spike to be identified and, most importantly, differentiated from the second important type of non-Bragg scattering, the “whitecap” return. This distinction is crucial and could only be confidently made in a laboratory set-up. Once the distinction has been made, many of the well known characteristics of sea clutter fall into place. Rare, strong, coherent “superevents” noted in many pieces of published work are HH spikes from an appropriately oriented breaking wave. The majority of fast, non-Bragg scattering, however, is from highly disturbed broken water which would be visible at all look angles, is polarisation independent and lasts considerably longer than an HH spike. Thus one must constantly bear in mind that the tank does not reproduce the sea, but it does hold up, on a plate as it were, important individual

features which can be recorded, isolated and characterised leading to fresh insights into certain events already known to be present in actual sea clutter.

The tank is also expected to provide a direct link to theoretical scattering predictions. The fact that it can produce stable, controllable wind wave fields and reproducible breaking waves should make comparisons with theory far easier than if only open water data were available. In fact it appears that this is only true in the case of wind waves, though through no real fault in the design of the tank or the experiment. The evidence here suggests that, by their nature, spikes from breaking wave groups are somewhat inconsistent not only in their frequency but also in their measured RCS. Despite the fact that the waves are considered hydrodynamically reproducible, the variation wave to wave of the RCS is so large as to make measurements made over any reasonable time scale impossible to compare to theory. Considering the calculation made in chapter 6 (and Appendix D) on the amount of data needed to accurately find the mean breaking wave RCS, and taking it to its ultimate conclusion, one finds that a continuous measurement campaign of well over a year would be needed to cover the same matrix of measurements as was covered in the 3 week UCSB experiment. The (somewhat scant) consolation here is that scattering calculations do indeed reproduce the large RCS variation observed for close to identical waves.

Comparison of theory to wind waves is, however, somewhat more successful. The fact that wind waves are channelled down the tank leads to a corrugated surface and so allows reduction to a 2 dimensional scattering problem, with all tilts directly towards or away from the radar. Excellent agreement was found between suitably processed radar data and the compound form of Rice's theory for the Bragg RCS, and predictions based on in-water measurements also yielded Bragg and non-Bragg Doppler shifts. The RCS variation and Doppler spectra of Bragg waves in the tank

were also reproduced by numerical scattering methods, despite the fact that detailed hydrodynamics were not included in the surface generation. Thus the tank has fulfilled its primary function – to act as a stepping stone between purely theoretical scattering calculation and actual sea clutter. It has directly confirmed the correctness of established scattering theory, and given confidence that new numerical methods are applicable to real radar data. It has given insight into the nature of the ill understood non-Bragg scatterers and led to the formation of a model for the polarisation and Doppler characteristics of the three main mechanisms in sea scattering.

The model itself is a simple, flexible and effective way of capturing all the important features of clutter. Each component has a clear physical basis and well defined characteristics. Whilst closely related to the lineshape analysis technique of Lee *et al*, there are several key differences. The motivation for the different lineshapes in Lee's work is statistical – the shape of each component is based on whether the assumed scattering mechanism is lifetime dominated with a single speed (Lorentzian), continuous with a spread of speeds (Gaussian), or a convolution of the two (Voigtian). No link is made between the components used to describe the two polarisations. The new model presented here is based only on direct experimental observation, with each components' Doppler shift, polarisation ratio and lifetime defined by the simultaneous radar and video data and linked to a definite form of scattering surface. The model implicitly links the two polarisations and, whilst not dwelling on the subtleties of the components' shapes, describes a variety of spectra in the tank accurately. The physical origin of each of the components comes to the fore when the model is applied to data outside of the laboratory. By decomposing spectra of ship generated internal wave wakes, the precise type of wave responsible for the visibility of the feature can be found. The close encounters with spikes which

the wave tank affords allows them to be recognised and isolated at distance, and so provides useful input to real radar applications.

All of this said, the Doppler model must be used with some care. In all there are up to nine free parameters, many of which can be calculated and fixed in the wave tank but which are not known for open water data and so must be varied to get the best fit. This variation must be checked in order to ensure that the result retains its physical meaning – an excellent fit by eye to the data is meaningless without the link back to the physical scattering processes and the wave types which cause them. In many ways, more important than the fitting of a functional form to a spectrum is the basic idea of the building blocks and their characteristics. The use of high resolution radars in today's surveillance systems necessitates the understanding of clutter on the level of individual events, and presenting these events, fully characterised, as a handful of discrete building blocks considerably enhances understanding and interpretation of clutter data and offers a simple path to building up a full clutter model. This is discussed as possible future work in the following chapter.

Each of the Bragg, whitecap and spike mechanisms has been clearly shown in the tank and coastal waters, and reproduced using the numerical scattering code (with acknowledgement to Ward for the whitecap result). In addition to this, many other pieces of experimental and theoretical work in the open literature support the three component model. As mentioned in chapter 2, several laboratory based studies have sought to empirically determine the characteristics of non-Bragg backscatter and from this infer the mechanisms responsible. The work of Rozenberg *et al* [1995, 1996], for example, in a laboratory set up which allowed both upwind and downwind measurements to be made, came to conclusions consistent with those reached here, namely that in terms of the peak Doppler return, the HH data looking into the wind was associated with the long gravity waves, whilst the HH data looking with the wind

and all of the VV data were associated primarily with Bragg resonant capillary waves. Experimental evidence for there being two forms of non-Bragg scattering in open waters has also been published before. Using data collected with a polarimetric cliff top radar, Ward *et al* [1990] examine short time histories of single range cells containing prominent features, and note that in some cases “the overall behaviour of the two polarisations is similar, however detailed structure is different”, which corresponds exactly to the description of whitecap scattering given here. At other times, it is noted, “there are occasional large amplitudes in the HH record [which are] highly polarisation sensitive and appear discrete in nature”. These events correspond to those which have herein been labelled spikes.

Nor is it only in past experimental data that we find strong supporting evidence for the three scattering mechanisms. The theoretical basis for Bragg scattering is well documented, and there has been much recent research into electromagnetic scattering calculations from wave-like surfaces. Trizna [1997] uses a ‘bore’ type wave in calculations that show the backscattered ratio of HH/VV from such a feature can exceed unity by many dB, in direct contradiction to Bragg theory but in agreement with the HH spikes seen in experimental data. Similar calculations from a crested feature by Churyumov and Kravtsov [2000] also conclude that the backscatter is much greater in HH than VV if the angle of incidence is close to the Brewster angle (about 7° grazing at X-band). The Forward-Backward calculations of sea spikes made by Holliday have already been detailed.

The problem of scattering from a highly disturbed broken wave is a challenging one, as the water surface is roughened on many length scales and the air-water boundary is ill defined, consisting of pockets of air in water and drops of water in air. Calculations have been performed at optical wavelengths [Wang, 1998] where one can make the assumption that the drops of water are large compared to the incident

radiation wavelength, and these calculations show that scattering would be polarisation independent. With particular reference to radar scattering from the sea surface, Jakeman *et al* [2000] calculate the polarisation characteristics and fluctuations of scattering from spheroidal particles at various heights above a surface and conclude that when a realistic value for the dielectric constant of the sea is taken, and the scatterer height distribution is larger than a wavelength, the polarisation ratio will be of the order of unity, that is, $HH=VV$. This is consistent with the whitecap scattering.

It can thus be argued that the three component model has not only been shown to accurately describe data collected in a laboratory wave tank and the cliff-top data, but that historical observations taken both within and out of the laboratory, and the most recent EM scattering calculations, all support the three mechanisms which form the basis of the model. That is not to say that these mechanisms are the *only* ones which contribute to backscatter from the sea surface – simply that in most situations the three components are able to capture the major features of the clutter spectrum, and through the knowledge of the wave type attributed to each component useful information about the sea surface can be extracted.

Chapter 8 Conclusions

8.1 Summary of conclusions

This piece of work was undertaken with the overall goal of achieving a more complete understanding of sea clutter through investigation of the physical scattering mechanisms present in the sea scattering process. More specifically, this was to be achieved by a combination of experimental data analysis and theoretical calculation, a combination made possible and linked via the use of a laboratory wave tank. The importance of the information which could be gained from the Doppler spectrum above and beyond the peak shift and width was to be stressed throughout.

Preliminary analysis of wave tank data gave good confidence that the facility was fit for purpose. Whilst controllable and measurable to a degree impossible in open waters, it was found to retain many of the features present but poorly understood in sea clutter – early in the analysis it became apparent that non-Bragg scattering was prevalent in more than one form. Some brief statistical analysis at this point also showed strong trends with radar frequency, wind speed and grazing angle in the distribution of the phase of the Hermitian product of the two polarisations, with a suggestion of similar trends noted later in field data. The strong trends seen in a wide matrix of measurements in the laboratory data represent, to the best of the author's knowledge, a new result.

Key to the increased physical understanding of non-Bragg scattering were the insights given by synchronous high speed video and radar data. Analysis of such data from breaking waves and wind waves led directly to the formulation of a new Doppler model for sea clutter. This model, comprising of Bragg scattering from resonant waves, polarisation independent scattering from broken white water and HH enhanced spikes from steep or crested waves, was found to describe data taken in a wide variety of radar modes and of a number of different wave types very well. After the same three components were identified in time and frequency domain analysis of cliff top radar data, the model was shown to be able to describe spectra in this environment too, and physical interpretation of the Doppler components gave new understanding of the mechanisms responsible for the visibility of internal wave ship wakes in radar imagery.

Each of the three scattering mechanisms incorporated in the model was reproduced using a numerical EM scattering code. In the case of Bragg scattering the code was shown to reproduce the polarisation and Doppler characteristics seen in the wave tank data to a high degree. The code was also found to reproduce the large variation in RCS seen in data when the scattered field was calculated from two close to identical breaking waves.

By presenting the experimental evidence for the Doppler model, it is hoped that this work has succeeded in increasing the physical understanding of scattering mechanisms in sea clutter. By demonstrating the presence of the same three processes in cliff top radar *and* in the predictions of numerical scattering calculations, an attempt has been made to draw together two sometimes unconnected methods of attacking the sea clutter problem – experimental analysis and theoretical calculation. An increased amount of contact between these two strands of research and a greater

drive to compare the predictions of new scattering techniques to actual radar data can only be of benefit to the subject as a whole.

8.2 Further work

Several specific pieces of further work are suggested by the results presented here :

- *Polarimetric phase statistics.* In chapter 3 it was demonstrated that information was held in the phase difference of the two polarisations, and trends were noted. This work could be taken further by more laboratory work and a similar examination of cliff top data. The lab work should concentrate on the precise reasons for the departure from the theoretical model presented here, and the derivation of a more correct form. Open water experiments should seek to clarify to what extent the polarimetric phase information can augment RCS and Doppler measurements in characterising the sea surface in order to gain meteorological information (wind speed, direction etc) or differentiate between clutter and a target of interest.
- *Directional sensitivity of non-Bragg events.* In chapter 5 it was shown that whitecaps are visible in both up and downwind data, whilst spikes are seen in upwind data only. This analysis could be extended to intermediate and cross wind look directions to ascertain the sensitivity of spikes to the radar/wind angle. Ideally this would be conducted in a controlled environment with a known or recorded surface wave spectrum.
- *Whitecap scattering calculations.* Particularly if it is confirmed that non-Bragg scattering at most look directions is whitecap dominated, further efforts should be made to calculate the theoretical backscatter from such a surface.
- *Physically motivated image processing.* The enhancements seen in images containing internal wave wake features is encouraging. Further research should be carried out into how knowledge of the scattering mechanisms which make the

wake visible can be incorporated into image processing and enhancement techniques.

- *Sea clutter simulation.* Using the three components of the model as a basis, it may be possible to simulate a clutter time series in a more realistic way than before. Using suitably correlated complex Gaussian noise as a Bragg background (which would lead to a Gaussian Bragg Doppler spectrum), strong coherent HH spikes and longer, less coherent whitecaps could be added in with, say, a Poisson distribution of occurrences. The resulting overall time series would then intrinsically contain the three scattering mechanisms and the average Doppler spectra would have the three component form found to be so successful at describing real data. A statistical analysis of the series simulated in such a way and comparison of these results to data would be a good test of validity of this clutter generation method.

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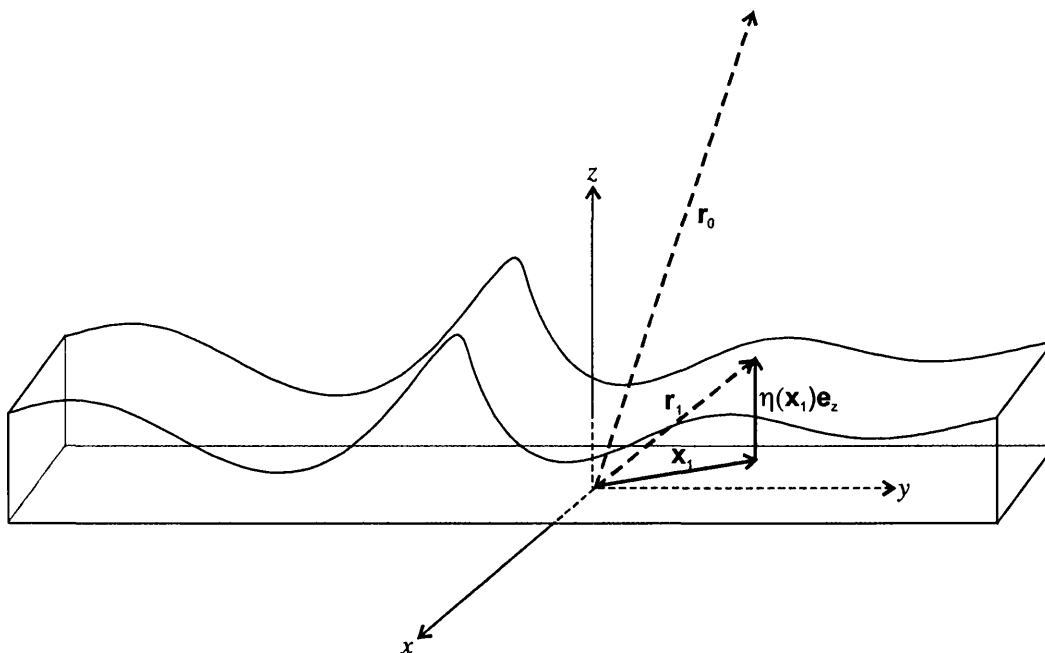
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Appendix A The Forward-Back method for EM scattering calculations

What follows is a brief description of the Forward-Back method for the computation of a scattered field from a corrugated surface. This formulation of the method is taken from a number of published and unpublished sources ([Holliday et al 1996], [Tough, 1996], [Shepherd, 1998]) and concentrates only on the case of a perfectly conducting surface. The extension to a finite conductor (such as the sea surface) is given in [Holliday 1998b]



A-1 : Schematic scattering surface

Consider first a corrugated surface such as shown in figure A-1. The position vector $\mathbf{r}$ is given by

$$\mathbf{r} = x\mathbf{e}_x + y\mathbf{e}_y + z\mathbf{e}_z \quad [\text{A-1}]$$

where $\mathbf{e}_i$ is the unit vector in the i direction. If $\mathbf{x}$ is any vector in the $z=0$ plane ($\mathbf{x}=x\mathbf{e}_x+y\mathbf{e}_y$), then the surface height above any point $\mathbf{x}$ is given by $\eta(\mathbf{x})$. If $\mathbf{r}_1$ is a point on the surface then

$$\mathbf{r}_1 = \mathbf{x}_1 + \eta(\mathbf{x}_1)\mathbf{e}_z \quad [\text{A-2}]$$

and the vector normal to the surface is defined as

$$\mathbf{n} = -\nabla\eta + \mathbf{e}_z \quad [\text{A-3}]$$

The scattered magnetic field at a point $\mathbf{r}_0$ above the surface is given by the Stratton-Chu equation

$$\mathbf{B}(\mathbf{r}_0) = \mathbf{B}_{\text{in}}(\mathbf{r}_0) + \frac{1}{4\pi} \int d^2x_1 [\mathbf{n}(\mathbf{r}_1) \wedge \mathbf{B}(\mathbf{r}_1)] \wedge \nabla^{(1)} G(\mathbf{r}_0, \mathbf{r}_1) \quad [\text{A-4}]$$

where $\mathbf{B}_{\text{in}}$ is the incoming (transmitted) field and $\mathbf{B}(\mathbf{r}_1)$ is the field at some point on the scattering surface. The Helmholtz Green's function in three dimensions takes the form

$$G(\mathbf{r}_0, \mathbf{r}_1) = \frac{\exp(ik|\mathbf{r}_0 - \mathbf{r}_1|)}{|\mathbf{r}_0 - \mathbf{r}_1|} \quad [\text{A-5}]$$

where k is the incident wavenumber. If $\mathbf{r}_0$ is now allowed to approach and lie on the scattering surface, then [A-4] becomes an integral equation for the magnetic field on the surface

$$\mathbf{B}(\mathbf{r}_1) = 2\mathbf{B}_{\text{in}}(\mathbf{r}_1) + \frac{1}{2\pi} \int d^2x_2 [\mathbf{n}(\mathbf{r}_2) \wedge \mathbf{B}(\mathbf{r}_2)] \wedge \nabla^{(2)} G(\mathbf{r}_1, \mathbf{r}_2) \quad [\text{A-6}]$$

This can be re-expressed as a surface current using $\mathbf{j} = \mathbf{n} \wedge \mathbf{B}$, in terms of the vector $\mathbf{x}_1$ which lies in the horizontal plane.

$$\mathbf{j}(\mathbf{x}_1) = \mathbf{j}_{\text{in}}(\mathbf{x}_1) + \frac{1}{2\pi} \mathbf{n}(\mathbf{x}_1) \wedge \int d^2x_2 \mathbf{j}(\mathbf{x}_2) \wedge \nabla^{(2)} G(\mathbf{x}_1 + \mathbf{e}_z(\mathbf{x}_1), \mathbf{x}_2 + \mathbf{e}_z(\mathbf{x}_2)) \quad [\text{A-7}]$$

where $\mathbf{j}_{in} = 2\mathbf{n} \wedge \mathbf{B}_{in}$. If we now specialise this result to a corrugated surface, the three dimensional scattering problem becomes effectively two dimensional. This reduction can be performed by integration in the direction of the corrugated ridges. The current integral equation in terms of the distance y in the horizontal direction thus becomes

$$\mathbf{j}(y_1) = \mathbf{j}_{in}(y_1) + \frac{ik}{4} \mathbf{n}(y_1) \wedge \int dy_2 \mathbf{j}(y_2) \wedge \left[\frac{(\mathbf{u}_1 - \mathbf{u}_2)}{|\mathbf{u}_1 - \mathbf{u}_2|} H_1^{(1)}(k|\mathbf{u}_1 - \mathbf{u}_2|) \right] \quad [\text{A-8}]$$

where $\mathbf{u}_i = y_i \mathbf{e}_y + z_i \mathbf{e}_z$. Here the integration of the three dimensional Green's function over the x co-ordinate has yielded the zeroth order Hankel function of the first kind, which has then become first order via the Bessel function identity

$$\frac{d}{ds} H_0^{(1)}(s) = H_1^{(1)}(s) \quad [\text{A-9}]$$

At this point, we separate and consider individually the cases of horizontally and vertically polarised radiation (these descriptors referring to the E-field). If the wave vector is set to $-\mathbf{k}$ (ie, it points *towards* the radiation source) and the angle of incidence is θ then the magnetic field can be written as

$$\mathbf{B}_{in}(y, z) = \mathbf{B}_0 \exp(-i(y \sin \theta + z \cos \theta)) \quad [\text{A-10}]$$

In the case of horizontal polarisation, we have

$$\mathbf{B}_0 = -\cos \theta \mathbf{e}_y + \sin \theta \mathbf{e}_z \quad [\text{A-11}]$$

As the surface normal vectors also lie in the y - z plane, the induced current will be in the x -direction, and so can be written as $\mathbf{j}_H(y) = j_H(y) \mathbf{e}_x$. Thus

$$\mathbf{j}_H(y_1) \wedge (\mathbf{u}_1 - \mathbf{u}_2) = j_H(y_1) \mathbf{e}_x \wedge (\mathbf{e}_y(y_1 - y_2) - \mathbf{e}_z(\eta(y_1) - \eta(y_2))) \quad [\text{A-12}]$$

$$= j_H(y_1)(\mathbf{e}_z(y_1 - y_2) - \mathbf{e}_y(\eta(y_1) - \eta(y_2))) \quad [\text{A-13}]$$

Forming the vector product with the surface normal (eq A-8) leads to the integral equation satisfied by the surface current

$$j_H(y_1) = j_{H,in}(y_1) + \int_{-\infty}^{\infty} dy_2 j_H(y_2) g_H(y_1, y_2) \quad [\text{A-14}]$$

where

$$g_H(y_1, y_2) = \frac{ik}{2} (\eta(y_1) - \eta(y_2) + \eta'(y_1)(y_2 - y_1)) \frac{H_1^{(1)}(k|\mathbf{u}_1 - \mathbf{u}_2|)}{|\mathbf{u}_1 - \mathbf{u}_2|} \quad [\text{A-15}]$$

where $\eta' = \frac{d\eta}{dy}$. If one now explicitly separates the phase and amplitude components such that

$$j_H(y) = J^H(y) \exp(-ik(y \sin \theta + \eta(y) \cos \theta)) \quad [\text{A-16}]$$

and

$$g_H(y, y') = G^H(y) \exp(-ik((y' - y) \sin \theta + (\eta(y') - \eta(y)) \cos \theta)) \quad [\text{A-17}]$$

then

$$J^H(y_1) = 2(\cos \theta - \eta'(y_1) \sin \theta) + \int_{-\infty}^{\infty} dy_2 J^H(y_2) G^H(y_1, y_2) \quad [\text{A-18}]$$

For vertical polarisation, the magnetic field is entirely in the x direction (the direction of the corrugation), so equation A-11 becomes

$$\mathbf{B}_0 = \mathbf{e}_x \quad [\text{A-19}]$$

and following through the same steps as for horizontal one finds that

$$J^V(y_1) = 2 + \int_{-\infty}^{\infty} dy_2 J^V(y_2) G^V(y_1, y_2) \quad [\text{A-20}]$$

Thus far all calculations have been performed in Cartesian co-ordinates. However, in certain cases such as surfaces which are multi-valued in z for a given y , (such as is the case for overturning waves produced by the UCSB LONGTANK wave generation code) one must convert to a co-ordinate system based on the path length along the surface, l , such that surface height and slope are given by $\eta(l)$ and $\eta'(l)$, and $dl = dy \sqrt{1 + \eta'(y)^2}$. This leaves the results derived above unchanged but must be considered in their numerical implementation. In this path length notation, both equations A-18 and A-20 have the form

$$J(l) = D(l) + \int_{-\infty}^{\infty} dl' J(l') G(l, l') \quad [\text{A-21}]$$

which can be split into two terms, one representing the surface current induced primarily by forward propagating radiation, and one the current induced by backward propagating (multiple bounce) radiation

$$J_F(l) = D(l) + \int_l^\infty dl' [J_F(l') + J_B(l')] G(l, l') \quad [A-22]$$

$$J_B(l) = \int_{-\infty}^l dl' [J_F(l') + J_B(l')] G(l, l') \quad [A-23]$$

If one then assumes that the function $\eta(l)$ is only non-zero over some finite region between l_+ and l_- , then $J_F(l) = D(l)$ for $l \geq l_+$, and $J_B(l) = 0$ for $l \leq l_-$. This leads to

$$J_F(l) = D(l) + \int_{l_+}^\infty dl' D(l') G(l, l') + \int_l^\infty dl' J_B(l') G(l, l') + \int_l^{l_+} dl' J_F(l') G(l, l') \quad [A-24]$$

$$J_B(l) = \int_{-\infty}^l dl' J_F(l') G(l, l') + \int_{l_-}^l dl' J_B(l') G(l, l') \quad [A-25]$$

This means that, if $J_B(l)$ were known then $J_F(l)$ could be found by the Volterra method for forward scattering (see Holliday 1995). If $J_F(l)$ were known, then $J_B(l)$ could likewise be found by backwards stepping. This implies an iterative procedure to find the total current J , and it is found that this method converges more rapidly than previous methods.

The scattered fields at any angle of reflection θ_R (with angle of incidence given by θ_I) can now be calculated.

$$\begin{aligned} B_H(\hat{k}) = & k \int_{l_-}^{l_+} dl [J^H(l) \exp(-i(\phi_I(l) + \phi_R(l))) - 2y'(l) \cos \theta_I \exp(-ik(\sin \theta_I + \sin \theta_R)y(l))] \\ & + k \int_{l_+}^\infty dl [J^H(l) - 2 \cos \theta_I] \exp(-ik(\sin \theta_I + \sin \theta_R)y(l)) \\ & + k \int_{-\infty}^{l_-} dl [J^H(l) - 2 \cos \theta_I] \exp(-ik(\sin \theta_I + \sin \theta_R)y(l)) \end{aligned} \quad [A-26]$$

$$\begin{aligned}
 B_V(\hat{k}) = & k \int_{l^-}^{l^+} dl \left[J^V(l) (y'(l) \cos \theta_R - z'(l) \sin \theta_R) \exp(-i(\phi_I(l) + \phi_R(l))) \right. \\
 & \left. - 2y'(l) \cos \theta_R \exp(-ik(\sin \theta_I + \sin \theta_R)y(l)) \right] \\
 & + k \int_{l^+}^{\infty} dl [J^V(l) - 2] \cos \theta_R \exp(-ik(\sin \theta_I + \sin \theta_R)y(l)) \\
 & + k \int_{-\infty}^{l^-} dl [J^V(l) - 2] \cos \theta_R \exp(-ik(\sin \theta_I + \sin \theta_R)y(l))
 \end{aligned} \tag{A-27}$$

in which

$$\phi_I(l) = k(y(l) \sin \theta_I + z(l) \cos \theta_I) \tag{A-28}$$

$$\phi_R(l) = k(y(l) \sin \theta_R + z(l) \cos \theta_R) \tag{A-29}$$

which, after residual fields from outside the computational domain have been estimated and removed, is the final answer. Holliday converts these fields to an RCS by assuming some value for the lateral extent of the wave L,

$$\sigma = \frac{|B|^2 L^2}{4\pi} \tag{A-28}$$

whilst an alternative [Shepherd et al 1998] is to calculate an RCS in metres as

$$\sigma = \frac{|B|^2}{4k} \tag{A-29}$$

Appendix B Polarimetric phase statistics

In this section the background statistical theory used for comparison to the experimental data in section 3.3 is summarised (see also [MacDonald, 1949]).

Consider the radar returns in the two co-polar channels of a coherent radar, $\mathbf{S}_V = A_V \exp(i\phi_V)$, $\mathbf{S}_H = A_H \exp(i\phi_H)$. Forming the Hermitian product of these two signals, we get

$$\mathbf{S}_V \mathbf{S}_H^* = A_V A_H \exp i(\phi_V - \phi_H) \quad [\text{B-1}]$$

that is, a quantity the phase of which is the phase difference of the two polarisations. To find the distribution of this phase difference, one must first make some assumptions about the distributions of $\mathbf{S}_V$ and $\mathbf{S}_H$.

If we define the polarimetric data vector $\mathbf{x}$ as

$$\mathbf{x} = \begin{bmatrix} \mathbf{S}_V \\ \mathbf{S}_H \end{bmatrix} \quad [\text{B-2}]$$

and assume that the data may be described by a bivariate, zero mean complex Gaussian process, then we can write

$$P_{\mathbf{x}}(\mathbf{x}) = \frac{1}{\pi^2 |\underline{\mathbf{C}}|} \exp(-\mathbf{x}^+ \underline{\mathbf{C}}^{-1} \mathbf{x}) \quad [\text{B-3}]$$

where $\underline{\mathbf{C}}$ is the covariance matrix and $\mathbf{x}^*$ denotes the conjugate transpose of $\mathbf{x}$. The covariance matrix given in full is

$$\underline{\mathbf{C}} = \begin{pmatrix} \sigma_v & \psi \rho_0 \\ \psi \rho_0^* & \sigma_H \end{pmatrix} \quad [\text{B-4}]$$

where

$$\sigma_i = \langle |\mathbf{S}_i|^2 \rangle \quad [\text{B-5}]$$

$$\psi = \sqrt{\sigma_v \sigma_H} \quad [\text{B-6}]$$

$$\rho_0 = \frac{\langle \mathbf{S}_v \mathbf{S}_H^* \rangle}{\psi} \quad [\text{B-7}]$$

The parameter ρ_0 is the complex correlation co-efficient, and will prove to be very important in the formation of a phase difference distribution. By combining equations B-5 to B-7, it can be written as

$$\rho_0 = \frac{\langle \mathbf{S}_v \mathbf{S}_H^* \rangle}{\sqrt{\langle |\mathbf{S}_v|^2 \rangle \langle |\mathbf{S}_H|^2 \rangle}} = k_0 \exp(i\phi_0) \quad [\text{B-8}]$$

Using these relations, equation B-3 can be re-written in terms of the amplitude and phase variables

$$P(A_v, A_H, \phi_v, \phi_H) = \frac{A_v A_H}{\pi^2 \psi^2 (1 - k_0^2)} \exp \left(- \frac{\sigma_v A_H^2 + \sigma_H A_v^2 - 2\psi k_0 A_v A_H \cos(\phi_v - \phi_H - \phi_0)}{\psi^2 (1 - k_0^2)} \right) \quad [\text{B-9}]$$

where $A_v A_H$ is the Jacobian of the transformation. By a further change of variables, $z = A_v A_H$ and $\Delta = \phi_v - \phi_H$, and by recognition of the integral form of the modified Bessel function K_0 (see [Barber, 1993]), we obtain

$$P(z, \Delta) = \frac{2z}{\pi \psi^2 (1 - k_0^2)} \exp \left(\frac{2k_0 z \cos(\Delta - \phi_0)}{\psi (1 - k_0^2)} \right) K_0 \left(\frac{2z}{\psi (1 - k_0^2)} \right) \quad [\text{B-10}]$$

and finally, integrating over z gives the desired phase distribution.

$$W(\Delta) = \frac{(1 - k_0^2)}{2\pi} \left[\frac{\beta \left(\frac{1}{2}\pi + \sin^{-1} \beta \right)}{(1 - \beta^2)^{3/2}} + \frac{1}{1 - \beta^2} \right] \quad [\text{B-11}]$$

where $\beta = k_0 \cos(\Delta - \phi_0)$.

All of the above assumes Gaussian statistics for the amplitude distributions of each of the polarisations which, as mentioned in the introduction, is not an assumption one can make with high resolution radar sea clutter returns. However, taking the example of the compound K-distribution as a good representation of the true statistics of sea clutter, it can be shown that this distribution is equivalent to a Gaussian process modulated by an underlying Gamma distributed power fluctuation. This is equivalent to making the average power (given by $\psi = \sqrt{(\sigma_V \sigma_H)}$ in equation B-6) a random variable described by

$$P(\psi) = \left(\frac{\nu}{\psi_0} \right)^\nu \frac{\psi^{\nu-1}}{\Gamma(\nu)} \exp\left(\frac{-\nu\psi}{\psi_0} \right) \quad [\text{B-12}]$$

The effect on the phase distribution of this underlying fluctuation is considered in [Tough *et al*, 1995], where it is shown that although the *amplitude* distribution of the Hermitian product is altered, the phase as given in equation B-11 is not. This suggests that the phase distribution of sea clutter with K-distributed amplitude statistics would be as derived above.

Appendix C The RSRE sea clutter model

The following describes the experimentally derived RSRE sea clutter model [Potter, 1975].

Given a sea state S and radar grazing angle θ , the backscattered normalised RCS (in dB) is given by

$$\sigma^o = a(S-1) + b(S-1)\log_{10} \theta \quad \theta < 1^\circ \quad [\text{C-1}]$$

$$\sigma^o = a(S-1) + d(S-1)\log_{10} \theta \quad \theta \geq 1^\circ \quad [\text{C-2}]$$

The coefficients a , b and d are different for the two polarisations. These are given in the table below.

S	1	2	3	4	5	6
VV						
a	-55.1	-45.5	-41	-38.5	-36	-34.5
b	15	12	11.5	11	9.5	8
d	8.2	9.5	8	7.5	7	6.5
HH						
a	-52	-46	-42	-39	-37	-35.5
b	21	17.5	12.5	10.5	7	3.5
d	1.015	3.39	2.03	1.35	2.03	2.37

Table C-1 : Parameters for use in the RSRE sea clutter model

Appendix D Application of the Central Limit Theorem and Chebyshev's inequality

Suppose n measurements of some population with mean μ and variance σ^2 are made. If the measurements are $\{X_1, X_2, X_3, \dots, X_n\}$, then the central limit theorem states that

$$Z_n = \frac{\sum_{i=1}^n X_i - n\mu}{\sigma\sqrt{n}} \quad [\text{D-1}]$$

will have an approximate Gaussian distribution with unit variance. Therefore, the probability of estimating the mean to an accuracy of k is

$$P\left\{-k \leq \frac{\sum_{i=1}^n X_i}{n} - \mu \leq k\right\} = P\left\{-k \leq \frac{Z_n \sigma \sqrt{n}}{n} \leq k\right\} \quad [\text{D-2}]$$

$$= P\left\{\frac{-k\sqrt{n}}{\sigma} \leq Z_n \leq \frac{k\sqrt{n}}{\sigma}\right\} \quad [\text{D-3}]$$

$$= 2\Phi\left(\frac{k\sqrt{n}}{\sigma}\right) - 1 \quad [\text{D-4}]$$

where $\Phi(x)$ is the area under the unit variance Gaussian to the left of x . If, for example, 95% confidence were required then one can deduce the number of measurements required.

$$2\Phi\left(\frac{k\sqrt{n}}{\sigma}\right) - 1 = 0.95 \quad [\text{D-5}]$$

$$\Phi\left(\frac{k\sqrt{n}}{\sigma}\right) = 0.975 \quad [\text{D-6}]$$

From standard tables of Φ

$$\frac{k\sqrt{n}}{\sigma} = 1.96 \quad [\text{D-7}]$$

$$n = \left(\frac{1.96\sigma}{k}\right)^2 \quad [\text{D-8}]$$

An alternative to using the CLT which avoids assuming Gaussian statistics is Chebyshev's inequality. This states that if X is a random variable with mean μ and variance σ^2 , then for any value $k > 0$

$$P\{|X - \mu| \geq k\} \leq \frac{\sigma^2}{k^2} \quad [\text{D-9}]$$

For n samples $\{X_1, X_2, X_3, \dots, X_n\}$, of X then

$$E\left[\frac{\sum_{i=1}^n X_i}{n}\right] = \mu \quad \text{Var}\left(\frac{\sum_{i=1}^n X_i}{n}\right) = \frac{\sigma^2}{n} \quad [\text{D-10}]$$

and the Chebychev inequality becomes

$$P\left\{\left|\frac{\sum_{i=1}^n X_i}{n} - \mu\right| \geq k\right\} \leq \frac{\sigma^2}{nk^2} \quad [\text{D-11}]$$

If, for example, it is required to find the number of samples needed to estimate the mean to an accuracy of $\pm k$, to 95% confidence, then taking the limit of the inequality

$$0.05 = \frac{\sigma^2}{nk^2} \quad [\text{D-12}]$$

$$n = \frac{\sigma^2}{0.05k^2} \quad [\text{D-13}]$$