

# Automated 3D Spatial Measurement of Short Gravity-Capillary Waves

By A.P. Gracian†§, J-P. Muller†, P.G. Challenor§, M.A. Srokosz§

† Department of Photogrammetry and Surveying, University College London, Gower street, London WC1E 6BT, United Kingdom. Tel (+44) 071-387 7050 x2738 / Fax (+44) 071-380 0453, INTERNET : agracian@ps.ucl.ac.uk

§ James Rennell Centre for Ocean Circulation, Gamma house, Chilworth Research Centre, Chilworth, Southampton SO1 7NS, United Kingdom.

## Abstract

The use of close-range stereo wave imagery using photogrammetric cameras is being investigated as a method for deriving sea surface micro-topography and spatial statistics. This approach has the advantage over conventional wave measurement techniques, such as capacitance wave staffs, in allowing 3D-spatial information rather than data at a single point to be obtained. Furthermore it is a non-invasive measurement technique, which is important regarding the study of gravity-capillary waves, since any measuring device that penetrates the surface will modify the waves in this region of the spectrum. The approach described, differs from previous work primarily in that the process of measuring the wave height field from the imagery is automated. The effect of this is to reduce the total processing time, thereby making the method more viable and permitting a larger range of ocean-atmosphere parameters to be examined. The sea surface micro-topography is derived using a stereoscopic technique, based on Otto-Chau's Least Squares Correlation technique. Results of the automated measurement processes are presented, together with directional wave spectra.

**KEY WORDS:** Close-Range, Stereo-Matching, Gravity-Capillary Waves, Oceanography.

## I. INTRODUCTION

This paper describes results of a collaborative project on interpreting microwave scatterometer interactions with short gravity-capillary waves under wind forcing (Gracian et al., 1990, 1991). One of the main factors that effect microwave Bragg resonant backscatter signatures from sea surfaces are the surface spatial statistics and elevation wavenumber spectra, in the 4 Hz to 8 Hz wave spectrum region. For spaceborne sensors, such as the scatterometer that forms part of the Active Microwave Instrument on the European Remote Sensing Satellite -1 (ERS-1), sea surface waves in the 3 cm to 7 cm wavelength range can affect the Bragg-scattered signal (Ulaby et al., 1981). At present most algorithms for retrieving oceanographic parameters from data received from spaceborne sensors are empirical. It is hoped eventually that by analysis of coincident stereo imagery and ERS-1 data, a more fundamental basis for parameter retrieval can be provided.

A study of sea surface statistics in relation to the directional distribution of ocean-wave momenta and elevation wave number spectra is of great technological and fundamental scientific interest. For example it is high frequency waves that are damped out by surface pollutants such as oil slicks (Lombardini et al., 1989). However, there are several problems with conventional wave measurement techniques such as capacitance probe measurements (Tucker, 1991). The first is the difficulty in transforming the temporal frequency spectra directly into wave number spectra. This limitation arises from Doppler shifting by long wavelength waves of the shorter gravity-capillary waves (5–50mm range), which are possibly from different directions (Kitaigorodskii et al., 1975; Longuet-Higgins, 1983). The second point is that it is not possible to derive high resolution spatial information from point measurements. Thirdly, due to physical limitations such as wetting of the device and meniscus effects there is an upper limit to the frequency at which they work. This is generally of the order of 3Hz, which is into the gravity wave range.

The use of stereo photography to obtain sea surface micro-topography and derive sea surface statistics appears to be a possible solution to many of these limitations (Shemdin et al., 1988; Banner et al., 1989; Gracian et al., 1991). Indeed as far back as 1903 the use of stereo photography had been suggested by Kohlschuetter as a means of investigating waves (Laas, 1921). The use of close-range stereo photogrammetry also has the benefit of being a non-invasive measurement technique. This is important in relation to the study of gravity-capillary waves, since any measuring device that penetrates the surface will modify the waves in this region of the spectrum. However, the labour intensive requirement of manually processing stereo images has until now limited its oceanographic application. The approach outlined here differs from previous work primarily in that an attempt is made to automate the process. The effect of this is to reduce the total processing time, thereby making the method more viable and permitting a larger range of ocean-atmosphere parameters to be examined.

Section II describes the data acquisition process in terms of the photogrammetric cameras used, their synchronisation and mounting in relation to water surface, derivation of suitable control point information as well as ancillary wave staff measurements. The wave staff measurements were made to enable an inter-comparison with wavenumber spectra derived from the automated measurement process. In section III, stereo-matching as a method of automated wave height measurement is considered based on an adaptive least squares correlation algorithm. Coverage results of the automated matching process are presented together with the high frequency sea surface micro-topography. The corresponding one sided directional power spectral density is then derived in section IV, by the discrete Fourier transform of the auto-correlation function for the wave height distribution. Directional components of the derived spectra are then compared with two sets of point (or omnidirectional) wavenumber spectra above the spectral peak. Finally, sections V and VI discuss the results and future developments.

## II. DATA ACQUISITION.

The acquisition procedure for stereo wave photography is more difficult than conventional land based photogrammetry due to the "hostile and awkward" environment and the dynamic nature of the surface being observed. Furthermore the semi-specular properties of the water surface imposes tight constraints on the sky illuminance conditions under which the images are taken. Before a mature in situ sea based automated measurement system can be implemented, several stages of development are required. For this it was decided to use the Queen Elizabeth II reservoir near Hershham in the UK. It provided a nearby convenient location, having several towers in the middle for use as an anchor point for equipment as well as possessing a reasonably long fetch\* of about 1 km (Ewing, 1984). The main components of the acquisition system are, a pair of large format Rollei 6006 photogrammetric cameras (Figure 1), the bar on which they are mounted on and a control frame for photogrammetric restitution of the images. There was also ancillary equipment, such as a meteorological station and capacitance wave staff probes for obtaining coincident temporal frequency spectra.

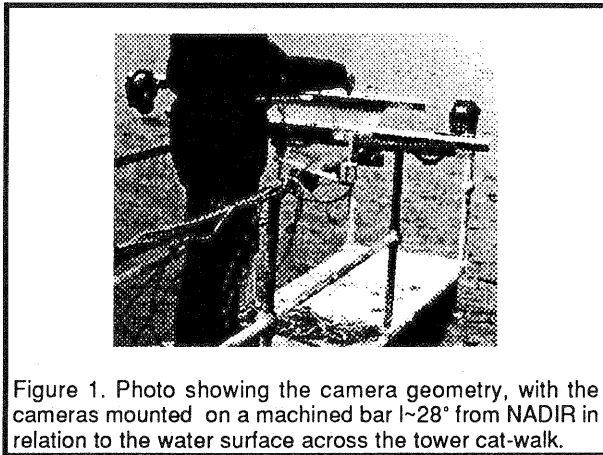


Figure 1. Photo showing the camera geometry, with the cameras mounted on a machined bar  $\sim 28^\circ$  from NADIR in relation to the water surface across the tower cat-walk.

The Rollei 6006 cameras had a 6cm x 6 cm plate and can be regarded as semi-metric cameras, having being fitted with reseau (Rollei, 1990). In order to minimise the effect of sun glint circular polarisation filters were used. The combination of overcast sky and use of polarisers resulted in low light conditions. This along with the requirement of a maximum exposure time of about 5ms (2ms was used) to avoid blurring of the waves and the need for high spatial film resolution imposes high demands on the performance requirements on the film. After trying various types of film it was found that Kodak TMAX ASA 400, using 120 film format was most suitable, though the processing had to be pushed to ASA 1000 to achieve acceptable image contrast. A further constraint is that the two cameras also need to be synchronised to within 5ms to achieve a stereo pair. For this a custom made synchronisation circuit was used to fire the shutters electronically giving an inter-camera delay of 3ms. The cameras were mounted on a bar tilted at an angle of  $28^\circ$  from nadir to improve the contrast, with base separations set between 0.5m to 1.5m. The mean camera to water height depends on the water level in the reservoir and varies between 3m to 6m. For the data presented in this paper the base to height ratio was 1.5m/5m or 0.3. Typically 40% overlap was obtained with a usable overlap of 1.5 m x 4m.

A limitation of some previous data sets has been the lack of suitable control information for accurate relative scaling of the

wave heights (Holthuijsen, 1983; Banner et al., 1989). Under the assumption that the optical axis of both the cameras are vertical and in an epi-polar geometry, a reasonable scaling approximation may be obtained, but this is probably inadequate for accurate measurements of small short wavelength waves.

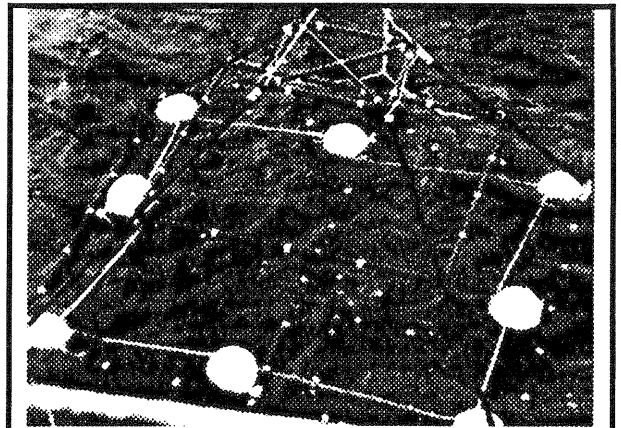


Figure 2 Photograph of the 2m by 2m by 1m high control frame with the target array floating on the water surface.

Shemdin introduced scaling into his measurements by placing a T-bar within the field of view in the overlap region. However due to the geometry of the tower at the QEII reservoir it is not possible to use quite the same arrangement. Control information at the QEII reservoir was obtained using a metal frame covered with an array of fifty targets, whose location relative to an arbitrary origin is accurately known having been surveyed with a theodolite by intersection (figure 2).

For each roll of film the control frame was towed into the field of view, two or three "control" images were taken and then the frame removed and a series of "normal" images were taken. Finally, the frame was towed back into the field of view to take a "control" image at the end of each roll to check for any relative camera motion. The purpose of the "control" images was purely for later photogrammetric restitution of the unperturbed waves in the later images. This process assumes minimal variation in the relative camera orientation over the measurement period. The final component of the acquisition setup was a single teflon coated capacitance wave staff probe, to enable an inter-comparison with wavenumber spectra derived from the automated measurement process (Tucker, 1991). Wave staffs have been used for a long time to determine frequency wave spectra from point time series data, either at a single point to produce omni-directional frequency spectra (or point spectra) or in low resolution arrays, producing directional frequency spectra.

Generally between 4 and 8 rolls of film were taken per camera with twelve frames per roll at each visit. A Leica Kern DSR 11 analytical plotter was used for photogrammetric restitution and digitisation of the images (Li, 1987). The resulting 8bit digital images were transferred over to a unix workstation for stereo-matching. A close-up detail of one image pair is shown in figure 3 overleaf.

\* fetch is the distance over the water surface that the wind blows to generate waves.

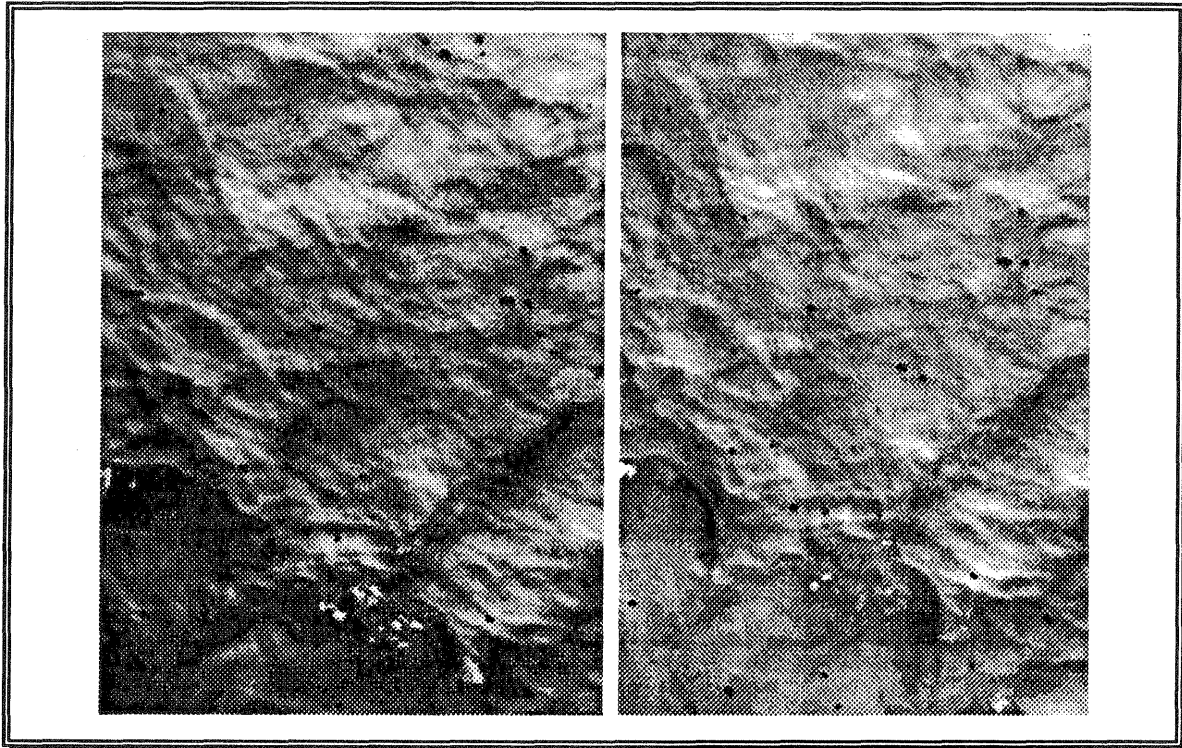


Figure 3. Close-up detail of part of the negative of the overlap region of a stereo pair (approx 0.5m x 0.6m). The black spots on the negative arise from foaming and surface debris.

### III. STEREO-MATCHING.

The digital image pairs were stereo-matched using an implementation of an area based adaptive least squares correlation technique, described in (Gruen, 1985; Otto and Chau, 1989). This texture based region growing algorithm has been used extensively on SPOT satellite images as well as a variety of other topographic data-sets, with a considerable degree of success (Day and Muller, 1989). The matching process is set up within the context of a Gauss-Markov estimation model, achieved by a least squares approach.

Two sea surface image regions are defined as conjugate regions of a stereo pair in the left and right images respectively. The process starts by choosing a pair of points, whose locations are assumed to be the same in both images, known as seed points. This is achieved automatically using a Forstner operator, the detailed of which is beyond the scope of this text (Forstner et al., 1987). The position of these seed points are then used as an estimate for eight initial transformation parameters that account for the image deformations between the picture and template patch. The change in the transformation parameters is then estimated from unbiased minimum variance estimators.

The new transformation parameters are then recalculated and the process is repeated iteratively, until the change in the parameters is within a specified tolerance, at which point the patches are assumed to be matched. Neighbouring points to the seed point (now the matched point) are then considered in a similar manner. However, the new initial estimate for the transformation parameters are a function of the final transformation parameters and local slope of the previous

matched point and the vector between the matched and unmatched point.

This continues in a sheet growing fashion by considering neighbouring points to the previous match point until the match falls outside a specified precision, at which point the sheet stops growing and the next best seed point is examined. The matching eventually stops when all potential seed points have been considered. The precision measure of a matched point,  $\lambda$ , is defined as the maximum variance of the spatial position of the match point in any direction within the x-y image plane. Figure 4 overleaf shows the output of the stereo-matcher, based on an upper bound on  $\lambda$  of 100, which equates to a high tolerance. The lighter region superimposed shows the distribution of  $\lambda$  for the matched area.

Having matched corresponding points in the left and right hand image, the disparity between the two images was transformed into wave heights by means of an affine transformation, based on inner and outer relative orientation parameters.

The resulting wave height distribution was high-pass filtered to de-trend the data and remove the low frequency waves. This was done by applying a bi-quadratic least squares fit to the sea surface and then subtracting this parabolic surface from the data. The remaining high frequency wave height distribution was Delauny triangulated and Lambertian shaded, to produce a Digital Elevation Model as shown in figure 5.

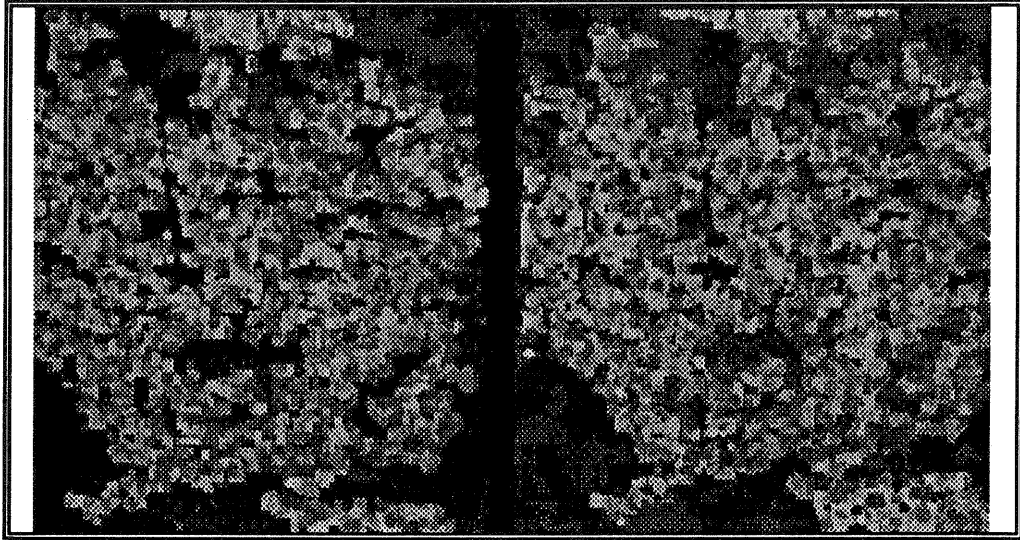


Figure 4. Output of the stereo-matcher coverage (lighter region) superimposed on the original image.

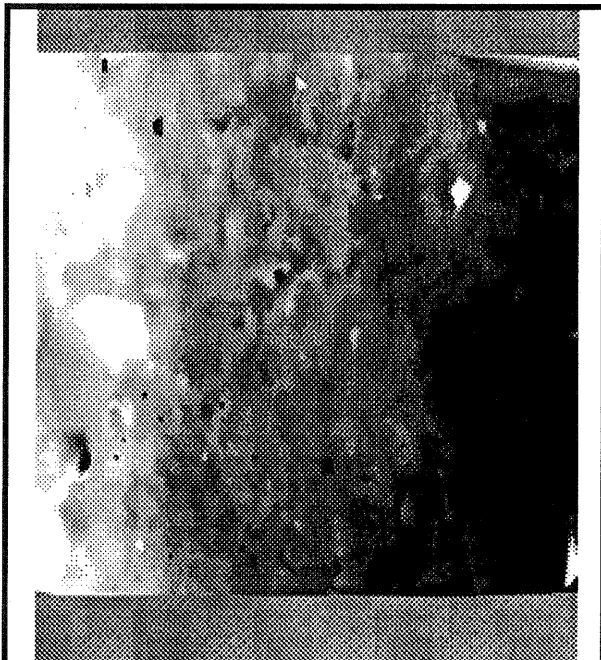


Figure 5. High frequency wave height distribution for a 1.5m by 1.5m area, derived using automated stereo-matching. Solid black and white regions due to holes in the matched region.

#### IV. DERIVATION OF THE DIRECTIONAL POWER SPECTRAL DENSITY.

To an oceanographer, apart from spatial information, one of the most important metrics of the sea surface is the one sided directional power spectral density or elevation spectra. Since the matched areas in the automated wave height fields are not continuous and have irregular outlines, a simple two dimensional discrete correlation and Fourier transform using centric systematic sampling is not possible. Instead the elevation spectra is calculated in terms of a directional semi-variogram of the inter-point spacing,  $d$ , as  $v_2(d, \theta)$ , and the

variance. If the total number of matched points in a direction  $\theta$  is  $N_\theta$ , then

$$v_2(d, \theta) = \frac{1}{2N_\theta} \sum_{N_\theta} \sum_d (z_a - z_b)^2 \quad (1)$$

Where  $v_2(d, \theta)$  is the semi-variance of all point pairs  $a$ ,  $(x_a, y_a, z_a)$ , and  $b$ ,  $(x_b, y_b, z_b)$ , of a given radial separation  $d$ , for all the matched points along the look angle  $\theta$ . Inter-point separations up to a 0.6m were considered at 2mm bins. Look angles between  $0^\circ$  and  $180^\circ$  were considered at  $10^\circ$  intervals. Once  $v_2(d, \theta)$  has been derived,  $r_2(d, \theta)$  can be calculated as set of 1-D functions along lines of constant  $\theta$ , using:

$$r_2(d, \theta) = 1 - \frac{v_2(d, \theta)}{\mu_2} \quad (2)$$

where  $\mu_2$  is the variance of the sea surface elevation. The directionally dependent elevation spectra,  $S(\kappa, \theta)$ , as a function of wave number,  $\kappa$ , is then given by:

$$S(\kappa, \theta) = \sum_d r_2(d, \theta) e^{-j\kappa d} \quad (3)$$

$S(\kappa, \theta)$  is determined in cylindrical coordinates by using eqn. (3) as series of 1-D discrete Fourier transforms, again along lines of constant  $\theta$ , as shown in figure 6 overleaf. The correct scaling of the wave spectra is achieved by the variance preserving property of the spectrum (volume under the spectrum equals  $\mu_2$ ).

In order to compare the stereo-matched derived wavenumber spectra with the coincident wave staff spectra the staff spectra first needs to be transformed from the frequency space into the wavenumber domain.

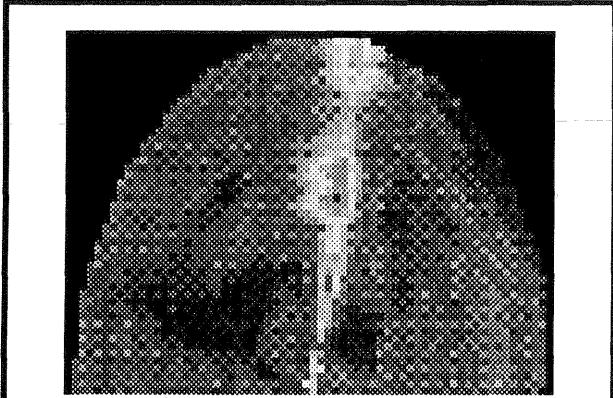


Figure 6. Directional wavenumber spectra, 0° to 180 in cylindrical coordinates. The origin of the spectra is at the bottom, in the centre. Light areas indicate high energy. The maximum energy "plume" coincides with the principal wind direction at the time the stereo pair was taken.

If Doppler shifting due to long wavelength modulation is assumed to be negligible, the dispersion relation for the waves in this part of the spectrum can be solved as a cubic in  $\kappa$ , which in non-radian units is:

$$\frac{T}{\rho} \kappa^3 + g\kappa - f^2 = 0 \quad (4)$$

where  $f$  is the frequency in Hertz,  $T$  is the surface tension (0.074 N/m at 10°C),  $\rho$  is density of water (1.072 kg/m<sup>3</sup> at 10°C) and  $g$  is acceleration due to gravity. The resulting wavenumber spectra after applying the mapping in eqn. (4) is shown in figure 7 below.

## V. DISCUSSION.

Figure 7 below shows a log-log inter-comparison of three sets of wavenumber spectra, the two QEII spectra and the 1989 point spectra from Banner. Each of these data sets map out three different regions of the spectra with some overlap between the high wavenumber end of Banners spectra and the low wavenumber end of the QEII automated spectra. Theory suggests that the log-log curve in the high wavenumber region above the spectral peak should be linear, though the actual value for the log-log slope is somewhat in dispute. The slope value for the wave staff spectra, the directional components of the automated spectra and Banners spectra are -2.5, (-2.2 to -2.5) and just below -3 respectively, though it should be realised the automated spectra have not been directionally averaged.

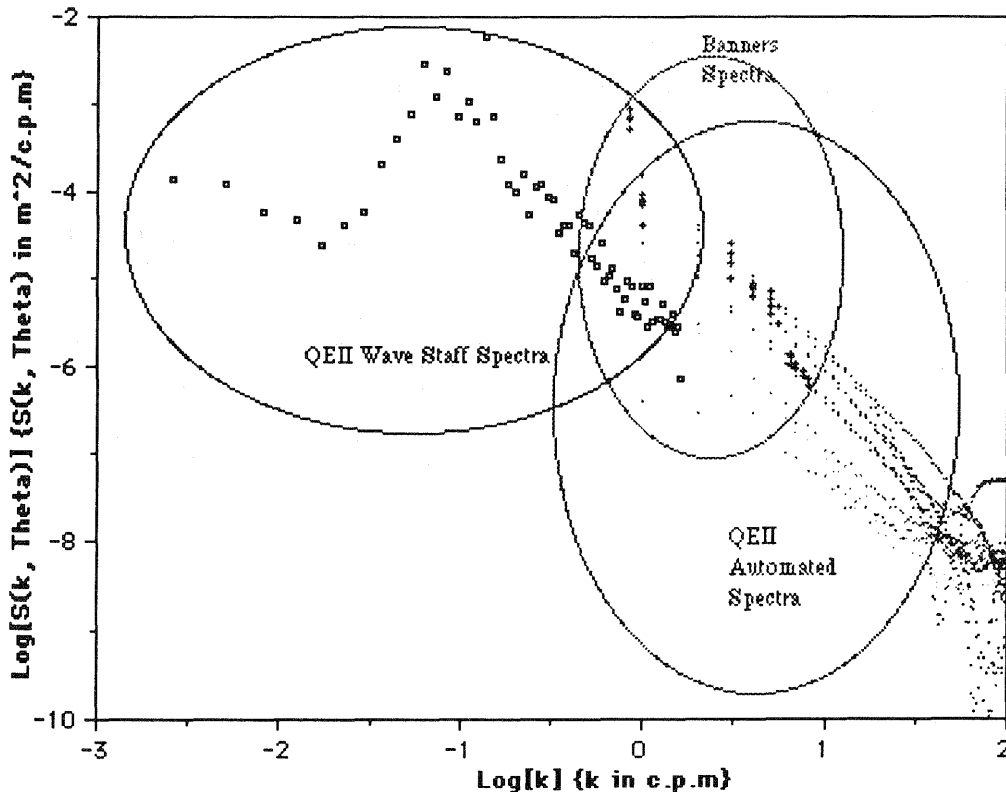


Figure 7. Log-Log inter-comparison of the QEII Wave staff point wavenumber spectra (transformed via a dispersion relation), directional components of QEII automated stereo-matcher spectra and Banner (1989) point spectra.

The noise at the very high wavenumber end of the QEII automated spectra most probably arises from two sources. Firstly there is almost certainly some aliasing folding back the spectrum above the Nyquist sampling wavenumber which for the semi-variogram bin size of 2mm has a log value of 2.6. The other factor is the finite spatial resolution of the images

themselves and the stereo-matching process. Propagated errors in the camera model, speckle from film processing and finite grain size, loss of dynamic range and noise in the digitisation process, blunders in the stereo-matching and stereo-specularity will all contribute to limiting both the spatial and spectral resolution.

## VI. FUTURE WORK.

Regarding future work there are several levels at which it is intended to extend technique and data analysis. Firstly it would be interesting to take the stereo images at different coverages, through varying the camera to water height. This would both allow the exploration of spatial statistics at different wave scales and also extend the range of the automated wavenumber spectra both up to higher wavenumbers, well into the capillary range and to lower wavenumbers up to and beyond the spectral peak.

Secondly the use of shape from shading as an alternative means of deriving automated sea surface elevation would provide an interesting complimentary technique to stereo-matching, with the possibility of a higher spectral resolution (Frankot and Chellappa, 1988). Work on this is being undertaken. It is hoped to have a direct spatial and spectral comparison of results from the two techniques using the same images in the near future. This together with spot height measurements on an analytical plotter will provide an extensive analysis of the field.

Thirdly, though wave staffs have the limitations outlined in section I, they never the less represent one of the most important ways of cross validating wave spectra derived using the automated imaging techniques. Therefore it would be interesting to both extend the point wave staff spectra to higher wavenumbers and obtain directional wave staff spectra, allow a direct comparison of directional spectra. Measurements are currently being made with an array of seven wave staffs rather than the single staff which will provide directional information, though these only still resolve up to 3Hz. To resolve higher wavenumbers up to 8Hz we will be collaborating in the near future with a group in Venice who are using a novel wave probe based on an X-band microwave probe (Fiscella et al., 1982, 1991). Such an inter-comparison will provide a unique opportunity for investigating the resolution and, strengths and weakness of these different approaches at the high frequency end of the spectrum. Finally, these results open the possibility for investigating a whole range of non-gaussian spatial statistics, and their relationship to microwave returns, not possible in such detail until now (Longuet-Higgins, 1983; Srokosz, 1986). It is intended to extend the data analysis to explore these aspects of the results.

The viability of the automated stereo-matching of water images to derive short gravity-capillary wave height distributions and directional high wavenumber power spectra has been proved. Consistency has been shown between the wave staff spectra and automated wave height measurements and in the linearity of the resulting wave number spectra with another author. It is hoped that such a technique will soon make possible the rapid automated processing of the large quantities of data generated in the oceanographic study of wind-generated waves and permit the long-term development of microwave inversion techniques for geophysical parameter extraction from spaceborne measurements.

## Acknowledgements.

The authors thank Dr C. Clayson, Mr M. Hartman & Mr M. Conquer of the Institute of Oceanographic Science Deacon Laboratory, Wormley, UK, for their significant contribution in the data acquisition process and Ms H. Marshall of UCL for her assistance in the photogrammetric restitution process on the analytical plotter. This research is funded by the Natural Environment Research Council under case studentship.

## References

- Banner, M. L., Jones, I. S. F., & Trinder, J. C. (1989). Wave number spectra of short gravity waves. *J. Fluid Mech.*, 198, 321-344.
- Day, T., & Muller, J-P. (1989). Digital Elevation Model Production by Stereo- Matching SPOT image pairs A comparison of algorithms. *Image and Vision Computing*, 7(2), 95-101.
- Ewing, J. A., Clayson, C. H., Birch, K. G., & Pascal, R. W. (1984). Report on the measurement of high frequency surface waves (Internal Document No. 212). IOSDL.
- Fiscella, B., Gomez, F., Pavese, P., Trivero, P., Zecchetto, S., Curiotto, S., & Umigesser, G. (1991). The "Venice" SAR-580 Experiment (Internal report No. ICG 242/91). Istituto Dinamica Grandi Masse, Venice.
- Fiscella, B., Lombardini, P. P., & Pavese, P. (1982). Interferential Microwave Probe for Measuring Sea Ripples. *Il Nuovo Cimento*, 5C(2), 247-254.
- Forstner, W., & Gluch, E. (1987). A Fast Operator for detection and precise location of distinct points corners and centres of circular features. In *ISPRS Intercommission Workshop*, Interlaken: ISPRS.
- Frankot, R. T., & Chellappa, R. (1988). A Method for Enforcing Integrability in Shape from Shading Algorithms. *IEEE Trans. on Pattern analysis and machine intelligence*, 10(4 (July)), 439-451.
- Gracian, A. P., Muller, J-P., Challenor, P. G., & Srokosz, M. A. (1990). Automated Stereo measurements of Short Gravity-Capillary Waves. In Gruen (Ed.), *Close range photogrammetry meets machine vision*, 139 (pp. 1008-1015). Zurich: ISPRS Commission V Symposium, Sept.91, SPIE.
- Gracian, A. P., Muller, J-P., Challenor, P. G., & Srokosz, M. A. (1991). Automated 3D-Spatial measurement of Short Gravity-Capillary Waves. In *Surface Waves: New Methods of prediction & Observation*, . Society of Chemical Industry, London:
- Gruen, A. W. (1985). Adaptive Least Squares Correlation A Powerful Image Matching Technique. *S. Afr. J. of Photogramm., Rem. Sens. and Cart.*, 14(3), 175187.
- Holthuijsen, L. H. (1983). Observations of the directional distribution of ocean-wave energy in fetch-limited conditions. *J. Phys. Oceanography*, 13(32), 191-207.
- Kitaigorodskii, S. A., Krasitskii, V. P., & Zaslavskii, M. M. (1975). On Phillips' theory of the equilibrium range in the spectrum of wind generated gravity waves. *J. Phys. Oceanog.*, 5, 410-420.
- Laas, W. (1921). *Photographic Measurement of Sea Waves*. In *Proc. of the Institute of Oceanography*, 7. University of Berlin:
- Li, M. (1987). A Comparative Test of Digital Elevation Model Measurement Using the Kern DSR-11 Analytical Plotter. *Fotogrammetriska Meddelanden*, 53.
- Lombardini, P. P., Fiscella, B., Trivero, P., Cappa, C., & Garett, W. D. (1989). Modulation of the Spectra of Short Gravity Waves by sea surface films: Slick detection and Characterization with a Microwave probe. *Journal of Atmospheric and Oceanic Technology*, 6(6), 882-890.

Longuet-Higgins, M. S. (1983). Can optical measurements help in the interpretation of radar backscatter? In T. D. Allan (Eds.), Chapter 7 of Satellite Microwave Remote Sensing (pp. 124-127). Ellis Harwood.

Otto, G. P., & Chau, T. K. W. (1989). "Region-Growing" Algorithm for Matching of Terrain Images. *Image & Vision Computing*, 7(2 (May)), 83-94.

Rollei (1990). Hands on Rollieflex 6008. *Industrial Photogrammetry*, 39(May )

Shemdin, O. H., Tran, H. M., & Wu, S. C. (1988). Directional Measurements of short ocean waves with stereophotography. *J. of Geophysical research*, 93(11), 12891-13901.

Srokosz, M. A. (1986). On The Joint Distribution of Surface Elevation and Slopes for a Nonlinear Random Sea, With Application to Radar Altimetry. *J. of Geophy. Res.*, 91(1 (Jan)), 995-1006.

Tucker, M. J. (1991). *Waves in Ocean Engineering, Measurement, Analysis, Interpretation*. Ellis Horwood Ltd.

Ulaby, F. T., Moore, R. K., & Fung, A. K. (1981). *Microwave Remote Sensing-Active & Passive*. Addison-Wesley.