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MEASUREMENT AND ANALYSIS OF OCEAN WAVE FIELDS IN FOUR DIMENSIONS

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ABSTRACT

Ocean wave data comprises either instrumentally measured data or model-derived data, and the former type of data is preferred in the offshore industry. Instrumental data can be considered to be comprised of both directly measured sea surface displacement data and derived data, from the acceleration of buoys.

It has been found that significant differences can occur between sea surface displacements, which are recorded in steep waves by fixed probes or lasers (Eulerian), or by free-floating buoys (Lagrangian). This has given rise to the situation where wave buoy data should not be used to estimate wave profiles in steep waves.

Short crested and heaped waves, in moderate to high sea states, can also cause a problem when recording wave data at a fixed point, when it comes to determining the representivity of the results across a wave field.

Recorded wave data is used as the basis for the development as well as the verification of all wave models and, given the above uncertainties, the authors propose a new wave measurement method, using the recently developed Automated Trinocular Stereo Imaging System (ATSIS), for the recording of three-dimensional surface wave displacements with respect to time.

The ATSIS is a novel system, which measures the temporal evolution of three- dimensional wave characteristics for analysis. An oblique configuration for the system effectively increases spatial coverage, allowing observations of wave phenomena over a broad range of temporal and spatial scales.

The details in the paper provide a solution of quantifying the behaviour of irregular, non-linear, and directionally spread (short crested waves), and provides an efficient method for developing better design criteria in the future.

INTRODUCTION

Characteristics of three dimensional waves are multifaceted, and their directions, heights, and surface slopes are important for the design of offshore and nearshore structures, as well for the development of an understanding of momentum, mass and heat transfer across the air water interface (Thorp, 1995;Melville, 1996).

The advantage of optical techniques for obtaining sea surface displacement data is that spatial information can be acquired without disruption of the surface wave field. This data, when collected sequential as a time series, provides valuable dynamic Digital Sea Surface Models (DSSM's) which can be analysed spatially and temporally to derive a very good understanding of the sea surface kinematics.

The proposed optical technique for the capturing of the digital Sea Surface Model data, referred to as the Automated Trinocular Stereoscopic Imaging System (ATSIS), is based on triangulation and linear algebra methods, as well as image processing techniques, to derive the height of the observed sea surface displacements. ATSIS details and methods have been fully described by Wanek and Wu (2006).

PROCESS NETWORK

The process for the collection and analysis of spatial and temporal wave field data includes the following activities as set out in Figure 1:

- The planning of the camera cluster
- The calibration of the camera cluster
- The carrying out of fieldwork
- Post processing
- The combining of individual Digital Surface Digital Model (DSSM) frames
- The development of selected DSSM Profiles
- The integration of sequential DSSM Profiles into time series for analysis.

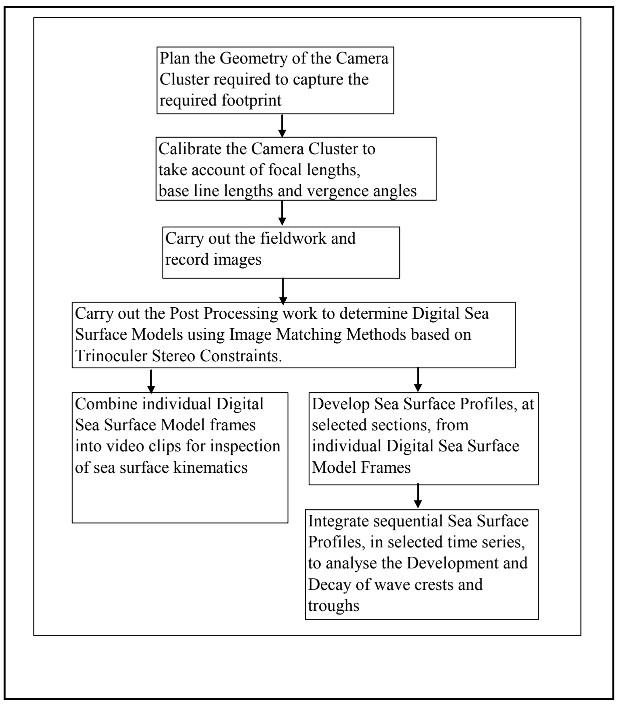


Figure 1: Process Network Diagram for the Analysis of Digital Sea Surface Models

CAMERA CLUSTER DETAILS

The ATSIS consists of three IEEE-1394 video cameras mounted to adjustable pan/tilt tripod head as shown in the above picture. The cameras are progressive scan and capable of capturing 100 frames per second at resolution of 640x480 or more. It is a portable system that can be easily managed in the field. An image photogrammetry processing technique, including area-feature hybrid matching, has been developed to accurately quantify the area of images taking from any oblique angle. The ATSIS has been found to be able to achieve 1 mm resolution in wave height measurement. Best of all is that this is a comprehensive, significantly automated system for the capturing of time series wave-field data, which is less labour intensive and it is also less inexpensive, than other methods on the market.

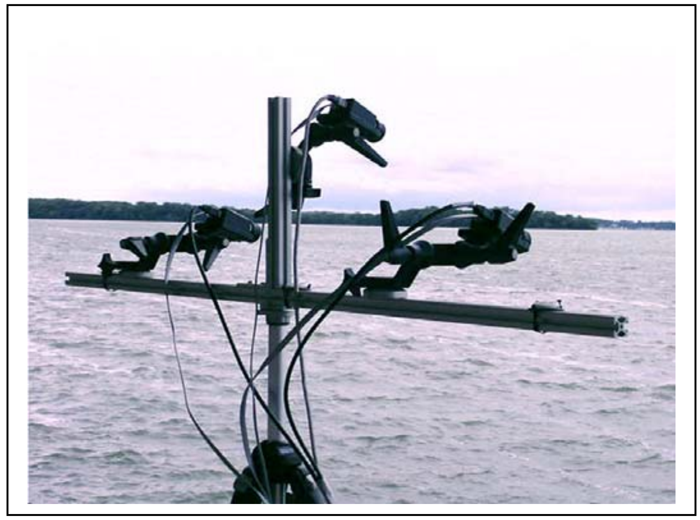


Figure 2**:** View of Camera Cluster for the capturing of Digital Sea Surface Models

Each camera is fitted with a 16mm lense with a field of view of 22^o x 160^o in the horizontal and vertical directions respectively with a resolution of 640 x 480 pixels. The three cameras are synchronized and captured images are directly recorded to a hard disk drive on a personal computer through IEEE 1394 cables.

CALLIBRATION OF CAMERA CLUSTER

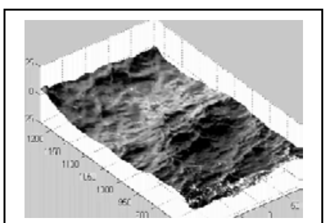
Camera calibration plays a major role in stereo imaging. Wanek and Wu have proposed a two-step procedure incorporating an interior calibration, with the purpose of correcting lens distortion and finding the location of the principle point, in the laboratory, prior to filed deployment and exterior calibration to obtain the orientation and position of ATSIS in the field.

POST PROCESSING

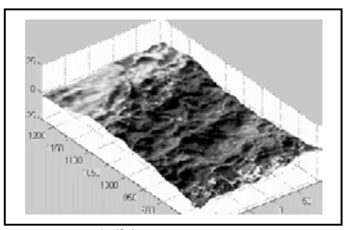
Post processing operations comprise the matching off a point on one image to a corresponding point on another image and this process is essential to obtain a three dimensional object co-ordinate. Wanek and Wu (2006) have used two area based matching schemes. The first method is based on an algorithm developed by Bhat and Nayar (1998) to resolve specular reflection, and the second method is based on a strict requirement to match a triplet of image points. The first method allows any two images to establish a match; but the object point depth is usually calculated using the left and right cameras whose base distance is the largest, thus maximizing depth resolution. The second method starts with the formation of a square window around pixel (x_{iL},y_{iL}) in the left image, and incorporates a one–dimensional search along an epipolar line in the centre image to identify the corresponding pixel. A normalised cross-correlation (NCC) of intensity values in the search and stationery window is used to measure the likelihood of a match. The centre pixel of the search window where the highest NCC value occurs is stored for subsequent sub-pixel matching if the NCC exceeds 0.7. If the highest NCC value does not exceed this value, it is regarded as a no-match. Once the corresponding point on the centre image is determined, the third point on the right image can readily be identified through the intersection of two epipolar lines, without any searching. Once the co-ordinates on the pixel in the right image (x_{iR},y_{iR}) have been determined, the three dimensional co-ordinates of the identified pixel can be derived.

ANALYSIS OF TIME SERIES SPATIAL DATA FRAMES

Three dimensional wave features can be derived and examined for selected wave-field footprints, as illustrated in Figure 3 where six sequential scenes, each 1.0 second apart, are shown:



3(a)



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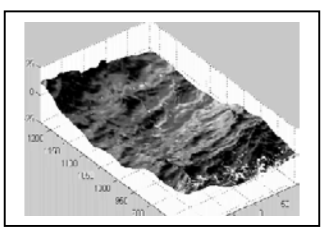

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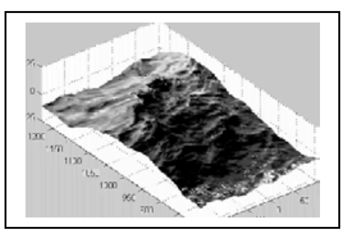
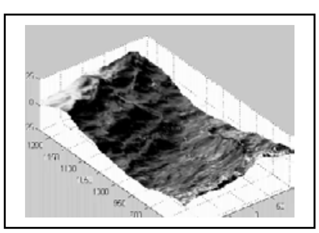


3(d)



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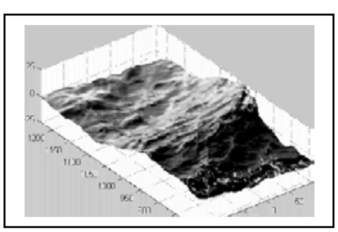


3(f)

Figures 3(a), (b), (c),(d), (e) and (f): Typical sequential series of Digital Sea Surface Model scenes in open water.

ATSIS not only provides a record of direct visual observations in open water, but also provides quantitative information on three-dimensional wave breaking characteristics, which can be measured, as shown in Figure 4.

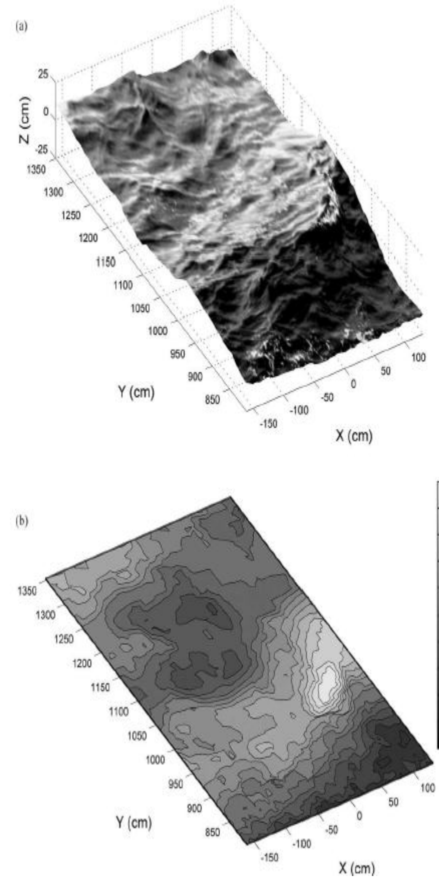
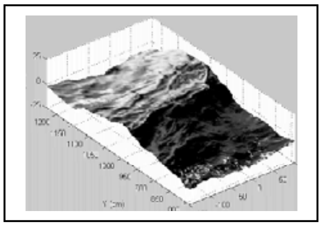
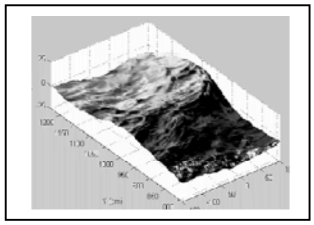


Figure 4: Three-dimensional Topographic and Contour Maps of the sea surface, showing breaking wave conditions

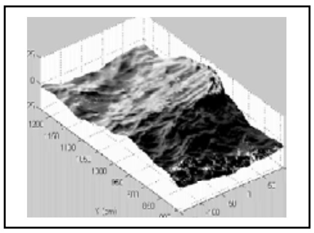
The image in Figure 4 shows a three-dimensional breaking wave with a short and well defined crest length. The shape of the breaking wave can clearly be determined from the topographic map and its height and length can be calculated from the contour plot. Another advantage of the ATSIS output is that wave steepness trends, along the wave crest, can also be quantified and analysed.

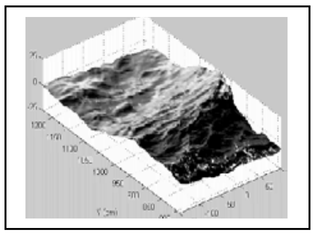
The development phase of a breaking wave has been shown in Figure 5, with a time interval of 0.1 seconds, and it can clearly be seen how the crest changes shape, as the steepness on the wave increases to the point of breaking.





5 (a) 5 (b)





5 (c) 5 (d)

Figures 5(a), (b), (c),(d), (e) and (f): Typical sequential series showing the development of a breaking wave in the open ocean.

Quantitative information on wave fronts, in a wave field, can clearly be located at each instant of time by the analysis of sequential contour plots of the wave field. Wave crest speeds and direction of travel can be derived from the contour plots as well.

Sea Surface Profiles can be drawn at selected sections, from the data in the Digital Sea Surface Model, as shown in Figure 5 (a) and 5(b), and they can either be compared individually or, as previously noted, included in a sequence to investigate breaking wave kinematics.

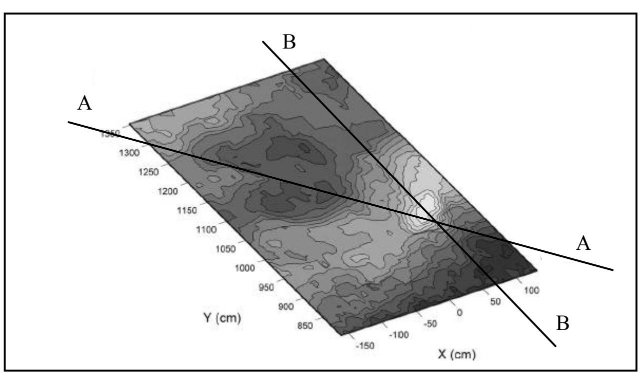


Figure 6(a): View of Contour plot of the sea surface showing the location of the sections drawn in figure 6(b).

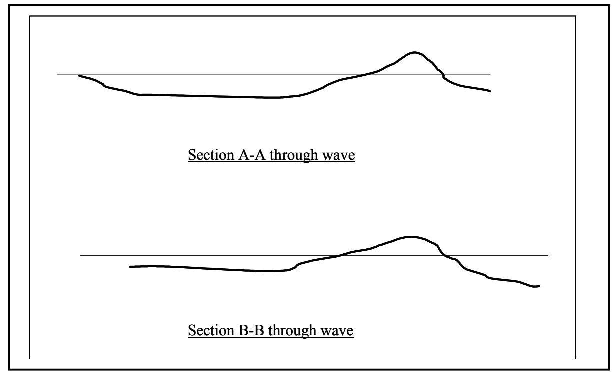


Figure 6(b): Profiles of two sections through the breaking wave in figure 6(a).

Wanek and Wu (2006) validated the water surface displacement of the Digital Sea Surface Model with a wave gauge wire, and found an excellent correlation between the surface displacements measured by the different means.

DISCUSSION

Forristall (2006) notes that ocean waves are dispersive and directionally spread, changing in size and shape as they propagate. For this reason the maximum crest height over an area, in a given length of time, will be substantially larger that the maximum crest height at a single point.

The ATSIS system will go a long way to shedding new light on wave crest kinematics and will be able to provide quantifiable data to evaluate the aforementioned feature in a scientific way.

In the conventional approach, the shape of the highest wave crests can usually be found by simulation, using a Jonswap spectrum with a selected peak period, and it is possible to derive the average shape of the maximum wave from theory, by using both autocorrelation and directional spreading functions (Forristall GZ, 2006).

The Authors believe that this approach could very well be enhanced or complemented by the analysis of wave fields using the ATSIS.

The conceptual basis of current conventional surface wind waves forecast and modeling was developed in the 1950s and early 1960s. The central concept is the recognition of the predominance of wave energy spectrum as the overriding representation of the ocean surface being a Gaussian random process. The essence of the wave forecasting model is based on the premise that the rate of change of the wave energy spectrum is equal to a source function that consists of an empirical wind input term, a semi-empirical dissipation term, and a theoretical nonlinear wave-wave interaction term.

The current conventional wave measurement methods were also mainly developed during the 1950s and 1960s time period and adhered to the wave spectrum concept: measuring surface wind wave in terms of a fixed length time series, usually 20 minutes to provide nominal wave spectra, at a single point with wave staffs, wire gages, buoys, or more recently using underwater acoustic sensors.

The primary elements of the conventional wave modeling and measurement have not been changed for many years, even though there has been continuous explosive technological advancements during this period. The long standing wave measurement practice has effectively limited the basic time element of wave modeling and wave analysis to be of 20 minutes. We have come to recognize that many well-known physical processes such as wave breaking, wave grouping, and freak or rogue wave occurrences are all better characterized as instantaneous phenomena taking place at time scales much smaller than 20 minutes.

Consequently many indications have shown that conventional wind wave modeling is not able to sustain or improve its accuracy in spite of continuous efforts of model refinements. The current state of conventional wave modeling can only be described as generally useful but stagnant at best.

The field of ocean wind wave forecasting has a proud 50 years history but it needs new direction and a new approach. As surface wind waves are primarily three dimensional phenomena which can never be fully described with one dimensional, single point, measurement, this recent development of three-dimensional surface wave measurement really inspired us to expect conducting a trial of this new measurement approach in the South Indian Ocean, off the coast of South Africa.

The idea of using stereo photogrammetry for measuring waves is not new. Some primitive attempt had been made in the 1950s over a large area using airplanes. The new system of Wanek and Wu, the Automated Trinocular Stereo Image System (ATSIS), really makes the best use of advanced digital camera and present day computational technologies to make continuous measurement of three-dimensional surface waves into an exciting reality.

CONCLUDING REMARKS

Wanek and Wu successfully developed trinocular stereo imaging scheme to provide realistic ocean surface measurements in different data representations, and we feel that the ATSIS could potentially revolutionize the conventional wave measurement and wave modeling world and lead us to the new frontier of ocean wave studies. All it needs is a fixed platform in the ocean to accommodate the system.

ACKNOWLEDGEMENTS

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REFERENCES

Bhat, DN and Nayar SK, 1998. “Stereo and specular reflection. International Journal of Computer Vision 26 (2), 91-106.

Forrestall, GZ, 2006. “Maximum wave heights over an area and the air gap problem”

Melville, WK 1996. “The role of surface-wave breaking in air sea interface. Annual Revue of Fluid Mechanics 28, 279-321.

Thorp, SA, 1995. “ Dynamical processes of transfer at the sea surface. Progress in Oceanography 36, 315-352.

Wanek JM and Wu CH, 2006, “Automated trinocular stereo imaging system for the three dimensional surface wave measurements,” Ocean Engineering, **33**, 723-747.