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Author

Harry, M, Zhang, H, Colleter, G

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REMOTELY SENSED DATA FOR WAVE PROFILE ANALYSIS

Matthew Harry[1], Hong Zhang[1] and Gildas Colleter[2]

Laser scanning technology (LiDAR) is a form of remote sensing from which a water surface can be measured rapidly and accurately without in-situ sensors. An experimental setup for the measurement of waves in a wave flume is detailed with an analysis of various wave parameters. The experiments function as a source of reliable laboratory controlled data while the data analysis presents the range of research fields that the data can be applied to.

Keywords: LiDAR, remote sensing, wave measurement

INTRODUCTION

In the field of wave transformation, wave shape study and other temporal and spatially dependant research, increasingly complex models are used to describe the processes within the surf zone and beyond. These complex models depend on sound physical theories as well as comprehensive data from the laboratory and the field. To keep up with this increasing demand on hydrodynamic data new and innovative measurement techniques need to be developed and employed. This paper describes the use of a Terrestrial Laser Scanner (TLS) as a relatively simple yet powerful tool for aiding in providing highly accurate yet extensive data.

Remote sensing of wave parameters can have a number of advantages over traditional in-situ methods. In-situ methods are well established and contribute much of the experimental and field data of wave parameters used in research. Water wave research generally makes use of wave staffs (Carvalho & Parente 2000), pressure transducers (Bishop & Donelan 1987) and wave buoys (Barstow & Krogstad 1984). There are a wide range of in-situ instruments that are commonly deployed in coastal waters (IOC 2006) while capacitance wave probes meet the requirements for most laboratory experiments.

However, in-situ devices are limited to measurement of only one location and therefore cannot provide spatial profiles individually. Some techniques can be employed to work around this limitation, such as fixing such a device to a moving platform (Brevik 1980) or the use of arrays of in-situ devices. For flume experiments this can be relatively easy to incorporate as installation and cost are generally not limiting factors. However, this may not be the case in the field as the size of the area to be monitored can require a large number of sensors. Remote sensing overcomes these problems by allowing the instrument to be located in a convenient location whilst still providing similar providing data from a large area.

Remote sensing has been applied to velocity measurements through particle image velocimetry (Liu et al 1992), wave elevation time series through acoustic gauges, and construction of water surface geometry through photogrammetry. Although these methods perform as intended, they cannot combine measurements in both a large spatial domain and over a period of time.

Considering all remote sensing techniques such as satellite altimetry and RADAR, visible light based instruments may be most suitable for high accuracy and relative portability. LIDAR (light detection and ranging) is one such technique based on laser technology for spatial measurements of distant targets.

The basis of LIDAR is the time-of-flight principle in that the time taken for a pulsed laser system to emit and receive the echo of a laser pulse determines the distance to the target. LIDAR was first introduced for use in the coastal environment following on from research undertaken by Hickman & Hogg in 1965. The LIDAR systems were attached to aircraft allowing relatively fast bathymetric surveys over large areas. Remote sensing at large distances (up to 1km) is proposed in Maslov et al. 2000 with the use of shore based LIDAR mounted on a high structure. One concern with using LIDAR for ocean water measurements is the reflectivity of the water surface, however in the field particulate matter such as plankton, capillary waves on the water surface and foam can all increase the intensity of the return signal (Belmont 2007).

A TLS is a specialised instrument based on LiDAR principles that is generally used for surveying purposes and the high accuracy of TLS. This paper employs the use of a commercially available TLS for wave flume experiments. The main advantage of TLS over other LIDAR techniques is that it can provide extensive spatial data from a relatively compact and portable design.

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[1] Griffith School of Engineering, Griffith University, Gold Coast, Queensland, Australia
[2] Aurecon Australia, Brisbane, Queensland, Australia

EXPERIMENT SETUP

The experiments were carried out within the UNSW Water Research Laboratory’s 1m wave flume. The flume is approximately 35m long, its width is 0.9m and its total depth is 1.4m. To produce breaking waves in the flume a sloping timber beach face (1:10 slope) was installed with the beach intersecting the water level at approximately 18m from the generator end. A water depth, h, of 1m was set for all runs. A Canadian Hydraulics Centre GEPDAP/NDAC general purpose software system is used to control the drive signal for the wave paddle. The wave generator is a paddle type hydraulic piston that moves laterally to produce both regular and irregular waves.

Four capacitance wave probes were used for the experiment to measure water surface elevation at specific points along the flume. Capacitance wave probe data was logged at with the GEDAP/NDAC system at a frequency of 120Hz. Figure 1 illustrates the general layout of the flume including placement of the capacitance probes and the TLS. The distances of each wave probe (WP1, WP2, WP3 and WP4) from the TLS are approximately 10.7m, 9.4m, 7.9m and 5.45m respectively.

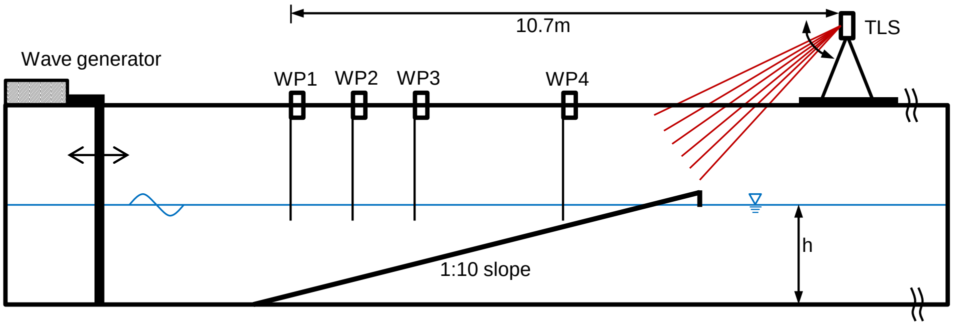

Figure 1 Diagram illustrating the experiment setup. The TLS is mounted above the wave flume to increase the visible water surface.

The TLS used for wave measurements was a Leica ScanStation2 mounted above the flume so as to provide a clear view of the length of the flume. The TLS can record three-dimensional spatial data of targets within the specified line of sight. The TLS opto-mechanical design produces rapid changes in the vertical angle of the emitted laser pulses. This combined with a gradual rotation of the TLS unit in the horizontal plane allows a view of all targets surrounding the TLS. Spatial resolution was set at 5cm (H) x 1cm (V) @ 20m range. Therefore for locations toward the TLS the resolution increases.

An important note is that the TLS (or any LiDAR technology used for this application) requires a particulate matter dispersed within the water or on the water surface. Initial test runs had confirmed that clear water, such as that found in the laboratory, is not a suitable medium for reflection of the laser pulses. Two methods were employed for preparing the water in the flume. The first is the use of kaolin forming clay dispersed throughout the water body which required regular stirring. The second is the combination of the kaolin forming clay and small foam balls (<2mm diameter) that remain on the water surface. It is assumed that this combination could represent a high energy surf zone (including significant white wash) in the field.

A mixture of regular and irregular waves was included in the experiment. Data for a total of 15 runs was obtained. Irregular waves use a JONSWAP spectrum to imitate a random sea state. Table 1 lists all 15 runs and their corresponding start conditions. Each run is approximately 11.5 seconds long.

Table 1 Details of all experimental runs

Run	H(m)	T(s)	Wave type	Water status
1	0.3	2.02	Regular	clay
2	0.3	2.02	Regular	clay
3	0.3	2.02	Regular	clay
4	0.3	1.65	Regular	clay
5	0.3	1.65	Regular	clay
6	0.3	1.65	Regular	clay
7	0.3	1.65	Regular	clay
8	0.3	1.43	Regular	clay
9	0.3	1.43	Regular	clay
10	0.21	1.62	Irregular	clay
11	0.21	1.62	Irregular	clay
12	0.21	1.62	Irregular	clay
13	0.21	1.62	Irregular	clay
14	0.3	2.02	Regular	foam balls
15	0.3	2.02	Regular	foam balls

Initial checks of the wave profile had given an indication as to the quality of data obtained from the three water types (clear, clay, clay and foam balls). With clay only tests the front face of individual waves which are closer to perpendicular to the direction of the laser pulses are accurately measured, however acute angles such as the rear slope do not provide a return signal. Also there is no observed difference between regular or irregular wave data quality, although there is a possibility that smaller waves may be shadowed by larger waves blocking the line of sight.

With foam balls added to the surface of the water the data contains more points that were within reflection intensity limits of the scanner allowing the measurement of a full wave profile rather than approximately half a wavelength of the clay conditions. However, for this experiment set up the use of foam balls for runs more than approximately 10 seconds is not recommended as they tend to build up due to the wave motion and expose the water surface.

One drawback of the shorebased type of TLS is the requirement of a target that exhibits diffuse reflection, therefore the angle of incidence and the surface reflectivity need to be considered to ensure quality data is collected. This was tested by measuring the distance that the still water level was able to reflect the laser. At an incident angle of 15.5° and lower the water level could not be detected in the clay case. For the floating foam ball condition the minimum angle was at most 10.3°, however this was at the limit of foam ball coverage due to proximity to the wave paddle. It can be concluded that the minimum angle of incidence with a highly reflective surface is less than 10°. For field application this is a good result as there are generally only low instrument mounting positions on open beaches. It is would be preferable to set up in the field atop a sea wall or jetty for best performance.

RESULTS AND DISCUSSION

Wave shape, wave steepness and breaking depth can be easily observed from LiDAR derived wave profiles, which traditionally can only be measured with specialised instruments. Furthermore, measuring these parameters is certainly more difficult to do in the field without this technology. This is perhaps the main advantage of TLS for wave measurements, the instrument can simplify what would traditionally be a difficult task to undertake in the laboratory and the field.

There are two important aspects of the results obtained with the TLS, validation against wave probe data and the application of the data as wave profiles for analysis. Prior to analysis of these results there was significant processing of the data for all of the runs.

Validation

Validation of the point cloud against the capacitance wave probes was achieved by first separating individual scan lines (to produce wave profiles) and then extracting the scan data at the corresponding location of the four wave probes.

The frequency of the TLS to record each scan line depends of the selected viewing angle, however for all runs this remained constant to provide an average frequency of 3.5Hz. Due to the non-uniform spatial distribution of the scanned wave profiles the closest point along the x-axis, within 5cm of the wave probe location, was chosen for comparison at each time interval.

In Figure 2 the TLS elevation data at the four wave probe locations for all runs are plotted against their corresponding wave probe measurements. A total of 1346 data points are plotted. A linear regression analysis for this data results in a coefficient of determination (R2) value of 0.7924. The average elevation difference between the TLS data and the wave probe data for all runs is approximately 0.9mm. It can be observed that there are a number of points that notably deviate away from agreement. This can be caused by obstruction to the TLS line of sight by a wave probe or interference from the flume walls.

In Figure 2 it can also be observed that there is a greater concentration of data points at elevations below 0m. This can be attributed to the relatively large number of data points at WP4 (closest to scanner). There is good agreement between the TLS data wave probe data from the breaking point and towards the beach slope.

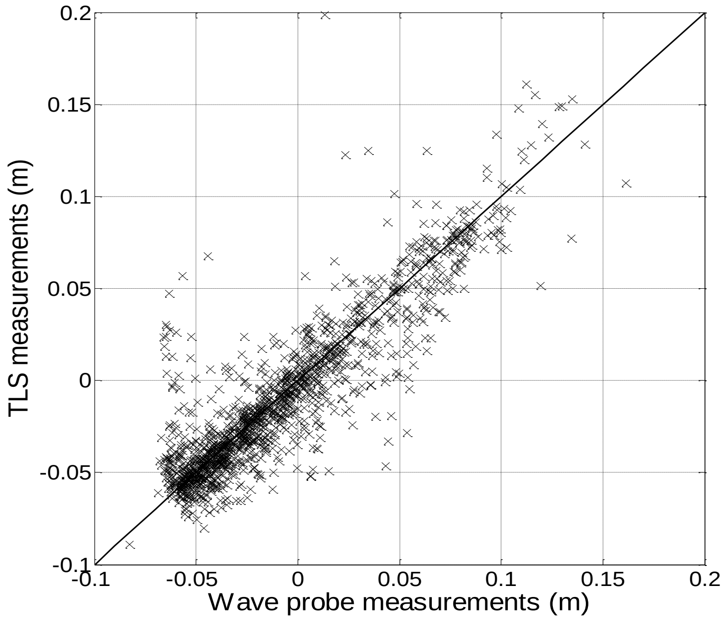

Figure 2 Comparison between TLS data and wave probe data

Wave Analysis

The TLS measurements allow for not only the determination of basic wave parameters such at wave height and wave period, but also for the construction of the time evolution of wave profiles. A series of consecutive wave profiles can be measured for two-dimensional surface elevation motion analysis.

The greatest advantage of obtaining LiDAR data of water surface profiles is that numerous methods of wave analysis are possible from the one data set. This is due to the significant amount of data points available from each scanned profile, which is true even more so if the profile frequency is high.

The following analyses explore the use of water surface profile data for use in wave shape and wave transformation studies as examples. Although the data can be applied relatively easily to these types of studies, there is the possibility of a much wider application to any study that uses conventional wave height or water surface observation instrumentation.

The first analysis is the use of LiDAR data for determining the exact wave shape of a propagating wave and comparing to steady wave theory. For the steady wave theory to apply, a number of conditions need to be considered in order for there to be any relevance to measured data. Furthermore, the most significant of these is that the steady wave theory best reproduces wave shape assuming flat topography, although if the change in topography is small then the theory may still apply.

For this experiment the theoretical steady wave shape was to be compared with measured waves prior to the point at which they are influenced by the sloping bed. The data at this point however is affected by limitations of the optical properties of the water surface. The wave shape theory comparison is given for the clay and foam balls case, however due to the proximity of the wave paddle to the limited area suitable for the steady wave conditions, foam balls were not covering the surface. Hence the earliest point at which the wave can be analysed is subsequent to the wave propagating over the start of the bed slope.

The program FOURIER (Fenton, 2012) was used to calculate the water surface elevation of a steady wave. The inputs for this program require a basic query of the LiDAR data at each point in time to be analysed. Due to the large number of measured data points in each profile the crest trough and wavelength are easily determined. Comparison between the steady wave theory and measured profiles is shown in Figure 3.

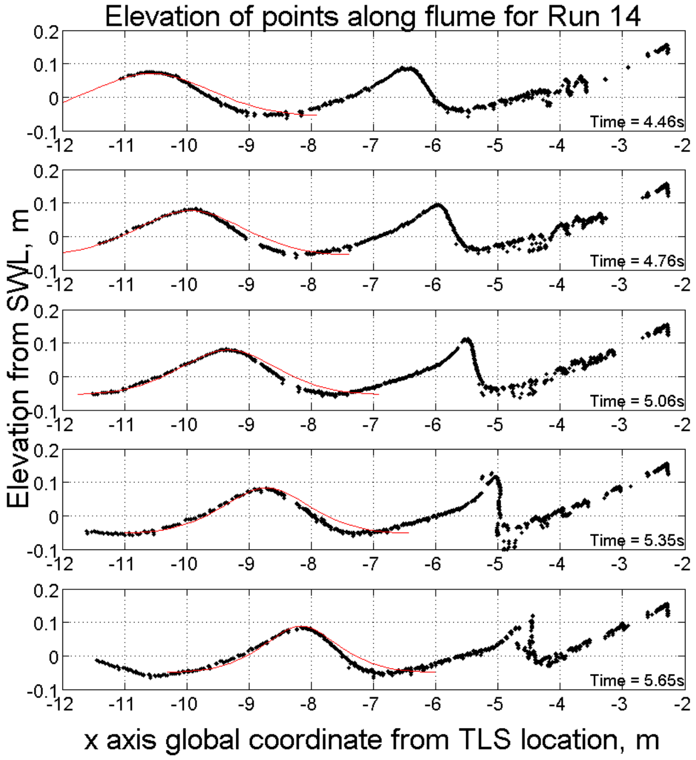

Figure 3 Steady wave Fourier approximation (solid red line) and measured wave profile (black points) comparison

Taking into consideration that the bed slope is 1:10 the steady wave theory performs as expected when compared against the measured data. The most obvious difference between the measured and the calculated surface profile is the steepening of the wave face as the wave propagates toward shore. On the lee side of the wave, however, the calculated profile coheres to the measured very well. In this figure the advantages of the high resolution LiDAR data are apparent. Although the most suitable comparison could not be made in this experiment, the results nevertheless indicate the strengths of the measurement technique employed.

Determining wave transformation parameters for use in engineering design generally involves the use of linear wave theory or an empirical relationship between known wave parameters. In the next analysis the LiDAR data is used as a source for validation of an empirical method to obtain the breaker index. The following equations from Weggel (1972) are used as the theoretical basis for the analysis.

$$\gamma_b = b - a\frac{H_b}{gT^2} \qquad (1)$$

$$a = 43.8\left(1 - e^{-19\tan\beta}\right) \qquad (2)$$

$$b = \frac{1.56}{\left(1 + e^{-1905\tan\beta}\right)} \qquad (3)$$

Where γ_b is the theoretical breaker depth index, H_b is the breaker height, T is the wave period and β is the bed slope. Weggel (1972) had derived the equations from laboratory data of monochromatic waves breaking on a plane slope, similar to the flume set up employed in this experiment. This provides an excellent basis for comparing the empirical results to the ones measured in this experiment. The breaker information was obtained from the LiDAR data using a system of visual checks of each profile around the time of breaking. Figure 4 illustrates the selection of the breaking point. The exact spatial coordinates of the break point are known as well as the time.

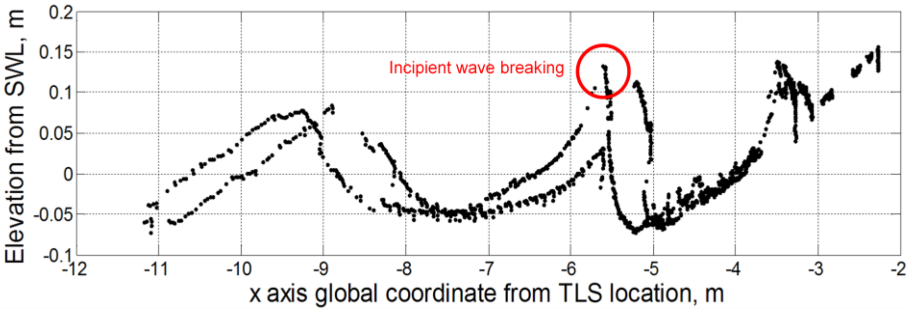

Figure 4 Observation of breaking point over consecutive profiles

The results of the breaker analysis are provided in Table 2. These results compare the theoretical breaker depth index γ_b, and the mean of all measured breaker indexes, $\gamma_{b,m}$. The measured breaker index was determined by measuring the wave height and wave depth at the incipient of breaking for each at least 6 waves for each wave period. Only regular wave runs were included and they span over three different wave periods.

Table 2 Breaker index analysis

Period (s)	γ_b	Mean $\gamma_{b,m}$	Std. dev. (m)	%RSD
1.43	1.024	0.989	0.068	6.83%
1.65	1.087	1.036	0.043	4.16%
2.02	1.197	1.096	0.104	9.46%

For each period the relative standard deviation (%RSD) is low even though the slope is impermeable and reflection was not eliminated which would induce variations from a regular monochromatic wave. The data represented in Figure 5 shows the comparison between the theory and measured as well as the individual breaker height indices for each sample. This figure shows that for this flume set up the Weggel (1972) equations consistently overestimated the breaker height index for each wave period. The difference is likely due to the limitations of the instrument in that the TLS only measures each profile at 3.5Hz. This results in just less than a third of a second between subsequent measurements of the breaking point crest height. Therefore the actual breaking height for each sample is less than what was actually reached. To ensure that this problem is mitigated it is suggested that for further studies a higher scan profile frequency is used.

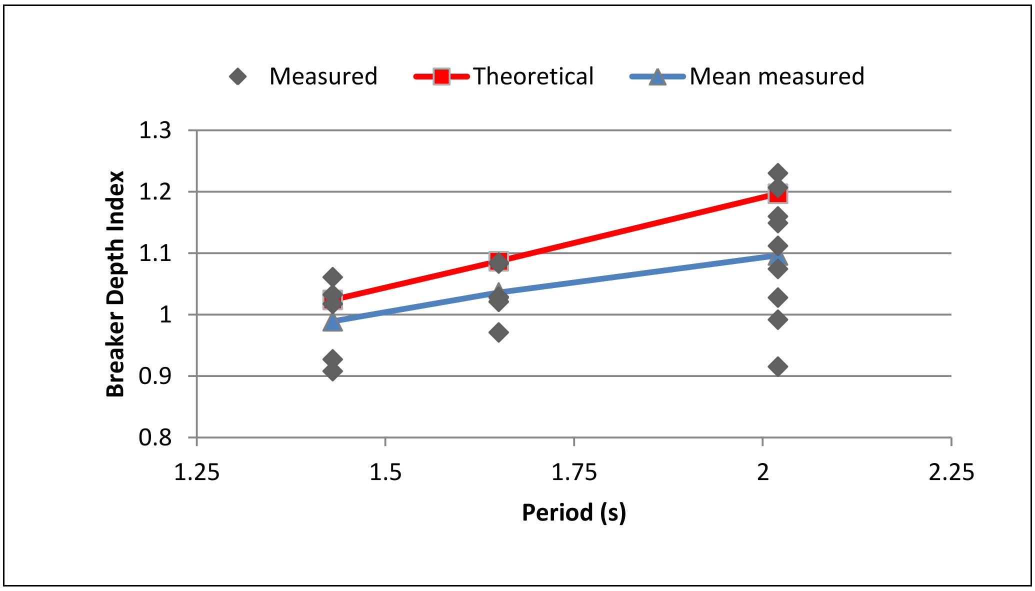

Figure 5 Breaker height index comparison

Finally, another directly related study using LiDAR data is to construct maximum wave crest profiles (or trough profiles). Figure 6 shows the maximum wave crest profile for Run 2 and its relation to the beach slope. The wave crest profile was determined by plotting the maximum data point within 0.5m interval, however this can be optimised with the use of a more suitable algorithm. The measured crest profile is shown in comparison to a simple wave transformation model (Smith 2003 from CEM-II-3, swash zone not included) which shows the approximate crest height through the surf zone. Using a TLS that has a higher frequency profile scan would be suitable for a more complex transformation model.

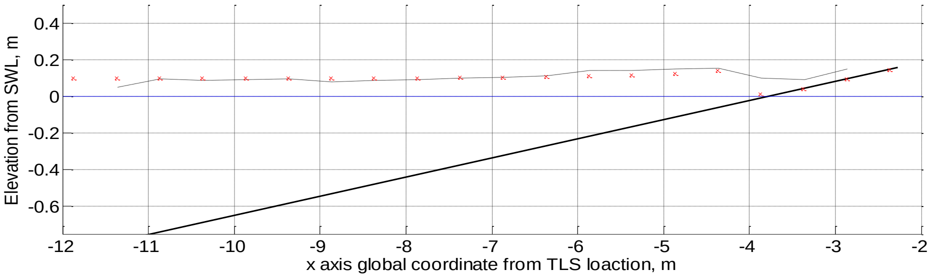

Figure 6 Wave crest profile (dashed line) and modelled crest (red star)

CONCLUSIONS

The use of TLS (and LiDAR in general) for water wave measurement in wave flume experiments is a unique method that provides highly accurate spatial data, including that of a wave profile evolution. There is a great potential for comprehensive laboratory and field studies to develop the technology as a coastal engineering research tool. It is suggested that an avenue of research into steady wave theory against propagating waves over various bed slopes can be explored with the use of LiDAR. The limits which bind the steady wave theory (for instance applied using a program such as FOURIER) would be relatively easy to study using a LiDAR instrument due to the high spatial resolution they can provide. This is one of many applications that can benefit from the use of LiDAR derive spatial profiles.

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REFERENCES

Barstow S.F. and Krogstad H.E. 1984. General analysis of directional ocean wave data from heave/pitch/roll buoys, *Modelling, Identification and Control*, Vol. 5, No. 1, pp. 47-70.

Belmont, M.R. Horwood, M.K. Thurley, R.W.F. Baker, J. 2007. Shallow angle wave profiling Lidar, *Journal of Atmospheric and Oceanic Technology*, Vol. 24, pp. 1150-1156.

Bishop, C.T. and Donelan M.A. 1987. Measuring waves with pressure transducers, *Coastal Engineering*, Vol. 11, Iss. 4, pp. 309-328.

Brevik, I. 1980. Flume experiments on waves and currents II. Smooth bed, *Coastal Engineering*, Vol. 4, pp.89-110.

Carvalho, J.L.B., and Parente C.E. 2000. Directional wave measurements using a slope array system, *Applied Ocean Research*. Vol. 22, Iss. 2, pp. 95-101.

Fenton J.D. 2012. FOURIER. Available from: http://johndfenton.com/Steady-waves/Fourier.html. Last updated: 24 May, 2012.

Hickman, G. and Hogg J. 1969. Application of an airborne pulsed laser for near shore bathymetric measurements, *Remote Sensing of Environment*, Vol. 1, pp. 47-58.

IOC 2006. *Manual on sea-level measurements and interpretation, Volume 4: An update to 2006*, JCOMM Technical Report No. 31, Intergovernmental Oceanographic Commission of UNESCO.

Liu, A. Shen X. Smith G.H. and Grant I. 1992. Particle image velocimetry measurements of wave-current interaction in a laboratory flume, *Optics and Lasers in Engineering*, Vol. 16, No. 4-5, pp. 293-264.

Maslov, D.V. Fadeev V.V. and Lyashenko A.I. 2000. A shore-based lidar for coastal seawater monitoring, *Proc. EARSeL-SIG-Workshop LIDAR*, Dresden/FRG

Smith, J.M. 2003. Surf Zone Hydrodynamics, *Coastal Engineering Manual*, Part III, Chapter 4-2 , Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C.

Weggel, J.R. 1972. Maximum Breaker Height, *Journal of the Waterways, Harbours and Coastal Engineering Division*, Vol 98, No. WW4, pp 529-548.