Proceedings of the Ninth (2010) ISOPE Pacific/Asia Offshore Mechanics Symposium
Busan, Korea, November 14-17, 2010

ISBN 978-1-880653-79-1: ISSN 1946-004X. www.isope.org

3D Spatial Definition of a Water Surface

Matthew Harry[1], Hong Zhang[1], Charles Lemckert[1], Gildas Colleter[2]
[1]Griffith School of Engineering, Griffith University, Gold Coast, Australia
[2]Aurecon Australia, Brisbane, Australia

ABSTRACT

Remote sensing of the environment with laser scanners can provide highly accurate 3D spatial definition of surfaces; however difficulties arise if the target surface is water. A feasibility experiment and a field test of terrestrial laser scanning technology for water surface measurements has been carried out and the results are summarised in this paper. The paper finds that a disturbed water surface as found in the surf zone is a suitable target for laser scanning and a case for further research utilising laser technology for water surface measurement is presented.

KEY WORDS: Remote sensing, terrestrial laser scanner, wave measurement

INTRODUCTION

The measurement of water levels and to some extent water surface profiles has spanned many centuries. Starting with basic methods such as manual level readings, initial technology could only provide limited information for people interested in monitoring water levels. Thanks to the development of accurate electronic sensors over the previous century water measurement devices have become autonomous and highly accurate. Water level measurement is an essential part of planning, design and monitoring in areas such as water supply, seafaring, agriculture, construction and scientific investigation. Laser scanning technology is investigated in this paper for the purpose of wave measurement and in doing so presents the technology as a mechanism for collection of data for numerical model calibration.

Remote sensing technology

The most common method for wave measurement in the field is the in-situ approach. Remote sensing has recently become a high-tech method for spatial data collection, especially in surveying, and provides an alternative to the in-situ approach to wave measurement. When compared it is evident that there are certain advantages and disadvantages of either in-situ measurement or remote sensing. As technology improves the advantages of remote sensing will increase and as a result hold the potential to become a powerful tool for spatial definition of water profiles and surfaces.

In relation to the measurement of wave parameters, such as wave height, wavelength and wave period, in-situ measurements are achieved by instruments located on the surface of or within a water body. Wave gauges, pressure transducers and wave buoys are examples of in-situ instruments (IOC, 2006) and are commonly used for coastal monitoring due to their accuracy and performance. These instruments collect data that can be presented, for example, as time series describing wave parameters at certain points within the study area. This is a limitation of in-situ instruments in that if the size of the study area is extensive or many intervals are to be monitored then a large number of instruments may be required.

However, this is not only a problem for in-situ instruments as some remote sensing devices can only provide time dependent location data. Examples of this type of instrument are acoustic measurement devices that collect water surface elevation data through ultrasonic time-of-flight calculations. Again, this device monitors a single location only and data is limited to a time series.

There are a number of remote sensing methods available that can provide 3D spatial data for a target location. Photogrammetry, or in particular videogrammetry, can be used for remote sensing through the analysis of images taken from multiple locations to construct geometry in three dimensions. Another method is particle image velocimetry, commonly used in laboratory experiments, that can obtain velocity measurements for 2D profiles and with special techniques a series of rapid profiles can provide 3D volumetric analysis.

In relation to remote sensing of water elevation satellite altimetry is the only method commonly used, however data is only collected on large scales, and generally only mean values for parameters such as wave height are recorded. Radar systems are another modern technology that can be used for remote sensing of water properties. Their main function is to measure water surface velocity although some systems such those installed on ships can provide limited surface elevation data. Based on currently available methods and instrumentation there is no evidence of a commercial product that can undertake remote sensing of a water surface with a degree of accuracy that compares to in-situ methods. The only exception to this is airborne LIDAR, although as discussed in the following section airborne LIDAR holds some limitations.

Laser Scanning for Wave measurements

The fundamentals behind laser scanning are well established and had originated soon after the development of laser technology. Laser (Light Amplification by Simulated Emission of Radiation) light is generally used for applications where a low divergence beam is desired. Laser light can also be produced with a narrow or broad wavelength spectrum and depending on the laser type and gain medium this can range from far ultraviolet to far infrared. These features make laser light useful for applications such as remote sensing where high precision is necessary.

The general terminology applied to the methods that use laser technology for measurement of distant targets is LIDAR (LIght Detection And Ranging). Terrestrial laser scanning (TLS) and airborne LIDAR rely on the same basic principles of laser technology. The systems used for airborne LIDAR are much more complex than TLS due to the need for rapid updating of location and time (GPS) as well as extensive processing adjusting data in regards to aircraft position.

Ranging of the target surface with most LIDAR systems is generally achieved through what is called the time-of-flight (TOF) principle. A pulsed laser system is required for this principle to apply rather than continuous wave laser. A laser pulse will travel at the speed of light towards the target, reflect from a surface, and travel at the same speed returning to the source of the laser where the reflected pulse can detected. The time it takes for the laser pulse to return to the source can then be used to determine the distance that the laser pulse travelled. Equation (1) determines the range, R, of the target from the laser pulse source,

$$R = \frac{c \cdot t}{2} \quad (1)$$

where c is the speed of light in m/s and t is the total time taken between the emitted and detected laser pulse. Time-of-flight is accurate as long as phenomena such as refraction through multiple mediums or echo signals from deflected pulses are accounted for.

All types of laser scanners use an opto-mechanical device that combines optical technology with mechanical operation and movement (Wehr & Lohr, 1999). An opto-mechanical design allows for rapid changes in the angle of the laser beam or pulse. Generally a rotating or swivelling mirror provides the surface from which the laser light deflects. Rotation of the opto-mechanical device is in one axis only, so for airborne LIDAR systems three dimensional data is collected through movement of the aircraft and for TLS systems through rotation of the entire unit.

The return signal for each laser pulse is detected with the systems receiver that processes the signal for computation. Time-of-flight and return signal intensity are the most important properties for ranging a target surface. The properties of the target surface significantly contribute to the quality of the return signal. Specular reflecting materials are the most difficult to range as most of the laser light is directly reflected at an angle equal to the incident angle. A diffuse reflecting material has rough surface that a laser pulse will reflect from at many angles meaning a high chance of the reflected signal reaching the receiver.

Although TLS has been employed for measurement of coastal features such as cliff erosion and beach profiles (see Rosser et al. 2005 and Kaufman 2005 respectively) there has been minimal effort in using the technology for water elevation measurement. The difficulty in using TLS for detecting a water surface in the surf zone is that the quality of data collected can depend on many environmental factors unique to the coastal setting. Noise in laser scanner data has been studied extensively (Axelsson, 1999; Lee & Ehsani, 2008; Sun et al., 2009) and care must be taken during set up of a scan to ensure accuracy of results. According to Soudarissanane et al. (2009) the four main factors that can influence terrestrial laser scanner data are: instrument calibration; atmospheric conditions; object properties and; scanning geometry. Focusing on scanning geometry, Soudarissanane et al. (2009) investigates point cloud quality in relation to angle of incidence at the scanned surface. The paper concludes that the contribution of angle of incidence to the return signal noise budget equals to approximately 20%. This is relevant to laser scanning of the surf zone as generally there are seldom locations where the equipment can be set up to ensure low angles of incidence.

It can be expected that the angle of incidence may be a significant contributing factor to signal noise for surf zone measurements in the field due to the siting of the equipment on the foreshore or in a location that may be only a few meters above the water level.

Another factor that can impact laser water surface measurements is the transmission of a large percentage of light through the water body. Early research undertaken by Hickman & Hogg (1965) that lead to the development of airborne LIDAR for bathymetric surveys found that up to 90% of light will be transmitted through the water surface and detected off a submerged target if the water surface is roughly normal to the laser light path. Airborne LIDAR has developed into a powerful tool for coastal monitoring (Penny et al., 1986; Irish & White, 1998; Guenther et al., 2000) and accounting for integration with other technologies (Baltsavias, 1999) the data it provides is greatly beneficial for coastal studies.

In the case of utilising a TLS for water surface measurements in the surf zone, it would be difficult for this scanning system to detect a laser pulse return from the water surface even if there are many potential incident angles along a wave profile. A study by Koepke (1984) found that the effective reflectance of whitecaps is approximately 22% in the visible spectral range. Considering this it can be assumed that the prevalence of whitewash within the surf zone may provide a suitable surface from which TLS can obtain a return signal. However other factors such as atmospheric conditions, or more specifically humidity and sea spray, could affect the point cloud data quality. These factors must be considered when determining the accuracy of the TLS data if the scanner is to be set up for measurements in a coastal location.

The main advantage of TLS over airborne LIDAR is its portability and simplicity thanks to its recent extensive commercial development. For wave measurement, the main difference between the two methods is that a TLS can be place at certain location and provide continuous water surface elevation data in the surf zone, whereas airborne LIDAR can capture surface elevation at one point in time only. Therefore this paper focuses on TLS technology only for the purpose of water surface elevation measurement. There are many challenges to be faced in adopting laser scanning technology for surf zone measurement purposes. Nevertheless, the advantages of rapid scan rates and the convenience of commercially available systems means that there is a high potential for the success of wave measurement using TLS.

FEASBILIITY EXPERIMENT

A feasibility experiment was setup up to determine the water surface measurement capabilities of terrestrial laser scanners. For this initial test a Leica Scanstation2 operated by Leica Cyclone point cloud processing software on a mobile PC was used for data collection. The ScanStation2 laser scanning system uses a Class 3R, green, pulsed laser. Scan rate is up to 50,000 points per second and point spacing of less than 1mm.

The experiment set up included a test object that was suitable as a control point as well as being able to contain water. Due to the high accuracy of the scanner and the need for only qualitative results, the test object decided upon was a drinking cup. The dimensions of the cup are approximately 100mm high with a diameter of 90mm. Fig 1 provides a general overview of the experiment set up.

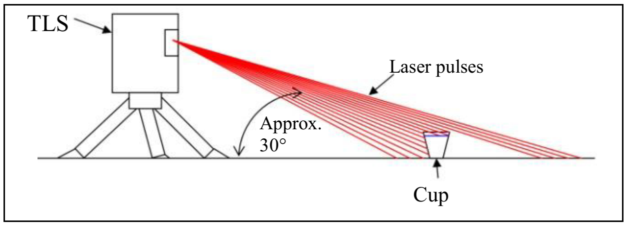


Fig 1Diagram illustrating feasibility experiment set up

Compared to a wave flume lab experiment or field test, the small scale of the initial experiment will not be representative of point spacing accuracy as this depends on range of target surface. Additionally, the level of accuracy of the data collected in the initial test may not be similar to that of a field test as there is greater risk of influence due to atmospheric conditions outside of the controlled conditions. However, the interaction between the laser light and different mediums can be observed to assess the feasibility of TLS for water measurement.

A total of three scans were completed and for each scan the contents of the cup were changed. The first scan was of the empty cup, the second was of the cup containing water filled to 10mm from the rim and the third was of water filled to 10mm of the rim and the addition of a layer of bubbles on the water surface. For all three scans the angle between the cup and the source of the laser pulses is approximately 30°. A comparison of the data for all three scans provides a starting point for further research into the technology and in particular the effect that a surface layer such as bubbles has in providing a reflective target surface.

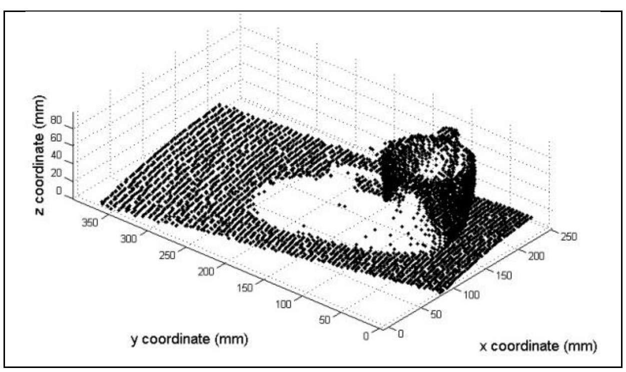


Fig 2 Three dimensional point cloud data of scan of empty cup

Fig 2 demonstrates the remote sensing capabilities of the Leica ScanStaion2 and provides a three-dimensional view of the point cloud data collected for the first test scan. Note that the scanner can only provide data for objects within its line of sight. A 'shadow' can be observed at locations where an object is obstructing the laser pulses, for example behind the cup.

Theoretical performance of laser scanner in feasibility experiment

Before the feasibility experiment results are presented the expected theoretical performance of the laser scanner is purported. In order to compare with the results in the next section, the theoretical interaction of the laser pulses and the drink cup is visualised from the side showing a 2D vertical cross section (Fig 3). Observing two axes only will allow for an easy comparison of high density regions of the point cloud data for each scan.

It is expected that if a laser pulse can be returned from a water surface then a high density of data points within the point cloud will be located at the water level and will be easily identifiable. Fig 3 illustrates the expected laser pulse paths that land inside the rim of the cup for all three scans. The path of each laser pulse travels from the top left of each figure.

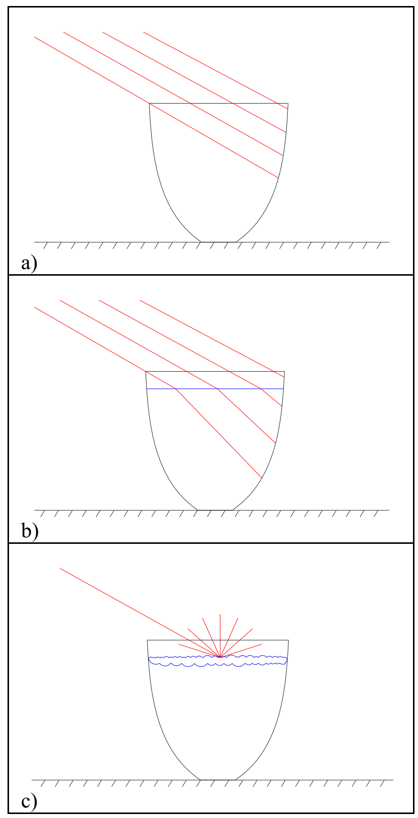


Fig 3 The expected laser pulse paths landing within the rim of the cup for the; a) empty cup scan; b) cup containing water scan and; c) cup containing water and bubbles on surface scan

Based on the expected laser pulse paths in Fig 3 a) the first scan should provide a clearly defined point cloud accurate enough to determine the dimensions of the empty cup. This scan will demonstrate the capability of the TLS to carry out a task in which it was designed for.

Fig 3 b) demonstrates the interaction of laser light and the water surface of the second scan. Theoretically a laser beam or pulse that is directed at a smooth water surface will reflect and refract light due to the nature of the medium and its surface properties. The reflection of the laser from a smooth water surface will be specular and therefore reflect at an angle equal to the angle of incidence. Considering this principle the capabilities of current terrestrial laser scanners cannot be used for the spatial definition of a smooth water surface by direct reflectance if there is anything but a small angle of incidence between the water surface and the origin of the laser light.

Light that does not reflect will pass through the air-water interface and refract at an angle according to Snell's Law as illustrated in Fig 3 b). Assuming refractive indices of 1 and 1.333 for air and water respectively and an angle of incidence of 30° the refracted angle of the laser light theoretically is 40.5°. Therefore the laser pulses will be refracted at a lower angle below the water and the return pulses will be reflected from a lower point on the wall of the lee side of the cup. This in effect increases the time of flight for each pulse and as a result the range of each data point will be greater than if compared to an unrefracted pulse of the same incident angle.

Fig 3 c) illustrates diffuse reflection of a single laser pulse. The introduction of a layer of bubbles on the surface of the water attempts to provide a surface that reflects light in many directions. Based on certain properties of bubbles diffuse reflection is possible due to the colour of the surface and the many angles across the surface of individual bubbles that the laser pulses can reflect from.

Results

The results of the three scans are presented in Fig 4. Point cloud data is plotted and oriented to allow comparison with each other and to the theoretical performance diagram of Fig 3.

As expected the first scan produces a 3D point cloud that can be easily identified as the empty cup. The laser light travels form the upper left corner of the figure towards the test object at approximately 30° and so the front surface of the cup is well defined. There is noticeable noise in the data, especially on the lee side of the cup. This is mostly due to instances where a laser pulse has reflected off the edge of a surface, such as the rim of the cup, and on to a surface beyond the edge resulting in an erroneous range for that pulse.

The point cloud resulting from the second scan is shown in Fig 4 b) and did not contain any data that defines the water surface. All laser pulses were either refracted upon entering the water or experienced specular reflection. The refracted points are visible on the lee side of the cup starting from the water level, approximately 10mm from the rim, and flaring out at an angle of approximately 37° for another 40mm below this location. The differences between the predicted angle of refraction of the laser light and the observed angle (40.5° and 37° respectively) could be due to a number of reasons. The refractive index of water is dependent on the wavelength of the electromagnetic radiation passing through, and the value of 1.333 is derived from the wavelength of yellow light (Thormahlen et al., 1985). In the case of the Leica ScanStation2 however, the green laser consist of a lower wavelength and so the refractive index is not expected to be the same. Also the observed angle of the refracted data points beneath the water surface is not a true indication of the refracted angle as the lower section of the cup wall curves towards the centre.

For the final scan bubbles were introduced to the surface of the water. On observation the upper extent of the bubble layer was 1-2mm below the rim of the cup. Therefore the bubble layer was approximately 8-10mm thick consisting of various sized bubbles and appeared white in colour. The bubble layer is intended to provide a reflective target surface, however they are also a good medium for the simulation of whitecapping and sea foam which would be present in a field test of the surf zone.

In Fig 4 c) it can be observed that the concentration of data within the point cloud is of a high density at the expected elevation of the bubble layer. The results show that reflectance from the bubbles is high enough that the entire bubble surface is returned. As the total reflected light as a percentage of the incident light largely depends on the surface colour, the white of the bubble layer is likely to be the contributing factor to the observed results.

It is not clear which path the laser path takes as it contacts the bubbles. Specular reflection may occur on the surface of an individual bubble and so the pulse is directly reflected back. However it is more likely that diffuse reflection occurs as the pulse reflects from one bubble to the next, and even internally. The bubbles may act as an isotropic radiator reflecting in all directions (Koepke, 1984).

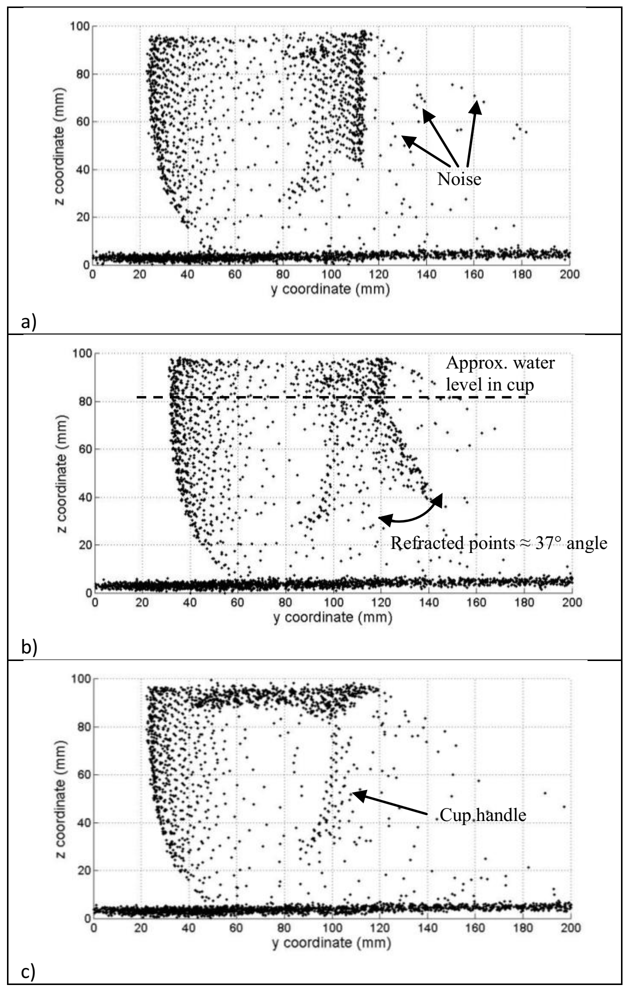


Fig 4 Point cloud data results visualisation for the; a) empty cup scan; b) cup containing water scan and; c) cup containing water and bubbles on surface scan

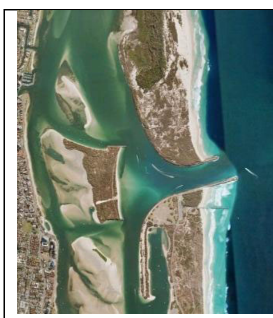
Furthermore, it can be observed in Fig 4 c) that the layer of bubbles varies from 5-10mm in elevation. Random bubble sizes could account for this variation, however diffuse and internal reflection increasing the time-of-flight of each pulse cannot be discredited. An increased time of flight would lead to a longer range from the scanner and therefore an incorrect position of that point. However, application of the TLS on a larger scale would negate the concern over this unknown as the small differences would be negligible.

The results gathered from the feasibility experiment support the theory that TLS technology is unable to provide 3D spatial definition of a smooth water surface and it is necessary to scan a surface medium such as a bubble layer to define the surface.

FIELD TEST

Following on from the results of the feasibility experiment a field test was organised to determine whether the findings were applicable to measurement of the water surface in the surf zone.

For the field test a Riegl VZ-400 scanner (Fig 5) was used and with the ability for standalone operation a mobile PC was not required. The scanner contains a Class 1 near-infrared pulsed laser. Vertical scan speed is up to 120 lines per second and horizontal rotation of the unit is up to 60° per second. The laser of the Riegl VZ-400 has the advantage of near-infrared wavelength over the Leica ScanStaion2's green wavelength. Near-infrared is commonly used in airborne LIDAR systems for measurement of the water level and so this wavelength is more suited scanning the surf zone. Although the Riegl VZ-400 has the ability to scan in 'line mode' in which the horizontal rotation of the unit is locked, only the full 3D scan was available at the time of the field test.


a)

b)

Fig 5 a) Aerial imagery (source: Google Earth) of the Gold Coast seaway (north pointing up) b) Riegl VZ-400 TLS set up for field test at Gold Coast seaway southern training wall

The field test was conducted from the pedestrian walkway on the southern training wall of the Gold Coast Seaway, QLD, Australia (approx. 27°56'09"S, 153°25'52"E). The initial bearing of the unit was approximately 270° with anti-clockwise rotation of the unit during the scan. The conditions were calm with whitewash limited to the immediate trail of broken wave bores. The time and date of the scan was approximately 11:00 AM on the 06-Apr-2010. Offshore wave conditions for the time of the scan were provided by the Queensland Department of Environment and Resource Management (DERM) waverider buoy located just south of the field test. The half hour mean sea state for this buoy at 11:00 AM recorded a significant wave height (H_s) of 1.3m, maximum wave height (H_{max}) of 1.95m and a mean period (T_z) of 5.9s.

A comparison between the point cloud data obtained during the field test and an aerial image of the field test location is shown in Fig 6. The scanner was located on the walkway atop the training wall approximately centre of the image. In Fig 6 b) the position of the scanner can be seen as the circular shaped region along the training wall that shows no data points. For reference the two images in Fig 6 can be easily compared by observing the high density of data points along the training wall, the beach foreshore and the sand pumping jetty furthest from the scanner location.

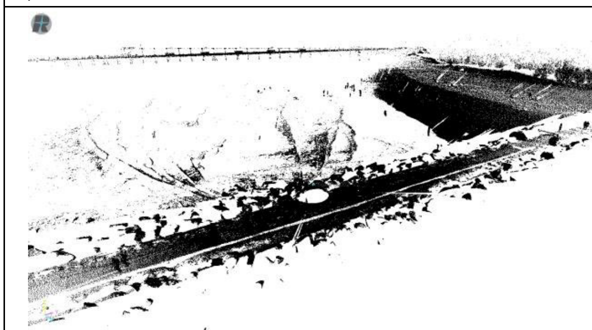
a)

b)

Fig 6 a) Aerial imagery (source: Google Earth) viewed at low angle facing bearing approximately 200° b) Point cloud data visualised with similar orientation to a)

The point cloud data visualised in Fig 6 b) can be qualitatively analysed in regards to the performance of the scanner for wave measurement. As the results of the initial feasibility experiment had demonstrated, the field test proves that an unbroken water surface is an unsuitable target for laser remote sensing with commercially available equipment. Much of the water surface within the scanned field of view does not provide a return signal and so there are vast gaps between data points.

Water surface data is available for small areas near the training wall and close to the shoreline. Observations regarding the state of the water surface were made during the scan. Whitewash was limited due to the calm conditions and was prevalent only after waves had broken. At the time of the scan a series of four clearly visible waves passed close to the scanners location. A significant amount of data for these four waves was collected producing a high quality surface definition within a small area. The wave crests for the four waves can be seen in the point cloud visualisation left of centre of Fig 6 b).

Nevertheless the relatively slow horizontal rotation of the unit renders full 3D measurements unreliable for wave measurement. Although the results prove that it is possible to collect spatial data for waves in the surf zone using TLS technology the dynamic nature of the water surface means that a single point cloud does not correctly represent one instance in time. Evidence for this can be observed in the point cloud data of the four wave crests mentioned in the previous paragraph. It was observed at the time of the scan that the wave crests were normal to the training wall or slightly curved towards it, as would generally be expected considering diffraction and refraction effects along a wall on a sloping beach. In Fig 6 b) this is obviously not occurring for all waves based on the point cloud data. The relatively slow anti-clockwise scan about the horizontal plane allowed the enough time for each wave to propagate some distance before the entire wave crest was scanned.

It is evident that TLS technology is not ideal for 3D spatial definition of a water surface due to the limitations of current instrumentation. Highly accurate and spatially extensive 3D water surface measurements are very difficult to obtain due to the dynamic nature of the surf zone. However, laser scanners such as the Riegl VZ-400 are capable of line scans and could hold the potential in providing continuous 2D profile measurements of water elevations within the surf zone. This would require favourable environmental conditions if long range measurements into the surf zone are desired. Considerable whitewash would need to fully cover the water surface; therefore storm conditions are preferable for further data collection in the field. Breaking waves however typically exhibit bubbles at the top of the wave and these could provide a highly detailed breaking wave crest elevation and position.

High quality wave profile data can be collected as shown in Fig 7. The data presented in this plot is a section of data extracted from the full 3D field scan. The water surface is viewed in profile and clearly a number of wave parameters can be analysed. As this is a visualisation of the 3D scan data, problems previously discussed affect the quality of the plot such as the wavelength which will be shorter than the actual. A 2D line scan of a transect through the surf zone would overcome these problems. The full wave profile similar to the plot below can be produced in a fraction of a second depending on the scanner used (Riegl VZ-400 vertical scan up to 120 lines per second).

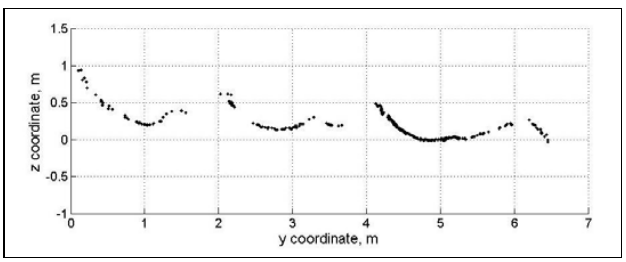


Fig 7 Plot of surf zone wave surface elevation data extracted from 3D point cloud

There is a noticeable ‘shadow’ behind the wave peaks due to the line of sight from the scanner. Higher placement of the scanner would reduce the loss of data depending on wave steepness. Most wave parameters such as crest elevation, trough elevation, wavelength and wave steepness can be determined even if there are some data points absent from the wave profile.

Comparing the data quality of the feasibility experiment and the field test it can be proposed, not conclusively, that the near-infrared wavelength of the Riegl VZ-400 does not have a noticeable advantage over the green wavelength of the Leica ScanStation2 for water surface measurement. This may be due to the fact that the angle of incidence is so great that any wavelength of laser light from commercially available laser scanners will only result in specular reflection or transmission into the water. For subsequent field studies for quantitative analysis the primary requirement would be the use of a scanner capable of 2D line scan and favourable sea state conditions.

FURTHER RESEARCH

The next step in the development of terrestrial laser scanning technology for wave measurement is a controlled laboratory experiment. Rather than utilising a TLS for 3D wave measurements as was attempted in the field test, 2D wave profile measurements should be the focus of wave flume laboratory experiments.

In a controlled experiment verification of wave profile data gathered by a TLS can be compared with time series data from in-situ wave measurement devices such as wave gauges or pressure sensors. Time series data could be collected by the TLS from a line scan that time stamps each data point. Equipment normally associated with airborne LIDAR can provide data time stamping through GPS timing.

TLS time stamped data can be used to produce time series plots similar to in-situ devices. However, the main advantage of TLS over conventional measurement methods is that there is no limitation to wave profile coverage as the entire profile can be scanned. A large number of in-situ devices would be necessary to collect a similar percentage of the water surface profile. Full water surface profile data provided by TLS technology could be used for accurate calibration and verification of numerical wave models.

CONCLUSIONS

Terrestrial laser scanning holds great potential for water surface elevation measurement. An initial feasibility experiment and field test have shown that water is difficult to detect with 3D laser scanning systems, however a broken surface or one that consists of an upper layer of a reflective substance can provide a suitable target surface. Further studies are required, and indeed are underway, to further determine the range such devices can be used for coastal water surface monitoring.

ACKNOWLEDGEMENTS

I would like to acknowledge the Australian Postgraduate Award scholarship that has supported the research undertaken to produce this paper. Also I would like to acknowledge Aurecon Australia for the supply of the Leica ScanStation2 for test purposes. Special thanks to Francois Du Bois from CR Kennedy for supply of the Riegl VZ-400 unit and for the time given for support. Final acknowledgement is to Queensland DERM for access to waverider buoy data.

REFERENCES

Axelsson, P (1999). "Processing of laser scanner data – algorithms and applications," *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol 54, pp 68-82.

Baltsavias, E (1999). "A comparison between Photogrammetry and laser scanning," *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol 54, pp 83-94.

Boehler, W, Bordas, V, and Marbs, A (2003). "Investigating laser scanning accuracy," *Proc CIPA 2003 XVIII Int Symp*, IAPRS, Antalya, Vol 34, 5/C15, pp 696-701.

Guenther, G, Brooks, M, and LaRocque, P (2000). "New capabilities of the “SHOALS” Airborne Lidar Bathymeter," *Remote Sensing of Environment*, Vol 73, pp 247-255.

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.

Irish, J, and White, T (1998). "Coastal engineering applications of high-resolution lidar bathymetry," *Coastal Engineering*, Vol 35, pp 47-71.

Kaufman, C (2005). "Beach erosion mapping using LIDAR and 3D laser scanner: Folly Beach, South Carolina," *Geological Society of America Abstracts with Programs*, Vol 37, No 7, pp 146.

Koepke, P (1984). "Effective relectance of oceanic whitecaps," *Appl Opt*, Vol 23, pp 1816-1824.

Lee, K, and Ehansi, R (2008). "Comparison of 2D laser scanners for sensing object distances, shapes, and surface patterns," *Computers and Electronics in Agriculture*, Vol 60, pp 250-262.

Penny, M, Abbot, R, Phillips, D, Billard, B, Rees, D, Faulkner, D, Cartwright, D, Woodcock, B, Perry, G, Wilsen, P, Adams, T and Richards, J (1986). "Airborne laser hydrography in Australia," *Applied Optics*, Vol 25, No 13, pp 2046-2058.

Rosser, N, Petley, D, Lim, M, Dunning, S, and Allison, R (2005). "Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion," *Quaterly Journal of Engineering Geology and Hydrogeology*, Vol 38, No 4, pp 363-375.

Soudarissanane, S, Lindenbergh, R, Menenti, M and Teunissen, P (2009). "Incidence angle influence on the quality of terrestrial laser scanning points," *Proc ISPRS Workshop Laserscanning 2009*, ISPRS, Paris, Vol 38, 3/W8, pp 183-188.

Sun, X, Rosin, P, Martin, R, and Langbein, F (2009). "Noise analysis and synthesis for 3D laser depth scanners," *Graphical Models*, Vol 71, pp 34-48.

Thormahlen, I, Straub, J, and Grigull, U (1985). "Refractive index of water and it dependence on wavelength, temperature and density," *J Physical and chemical Reference Data*, Vol 14, No.4, pp 933-945.

Wehr, A, Lohr, U (1999). "Airborne laser scanning – an introduction and overview," *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol 54, pp 68-82.