DELINEATING THE LITTORAL ZONE USING TOPOGRAPHIC AND BATHYMETRIC LIDAR

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Abstract: The littoral zone – the region that nominally falls between the limits of high tide and low tide – is of growing importance for a variety of reasons. Environmentally, increasing levels of human activity in this zone threaten to adversely impact on the delicate ecological balance that exists. Economically, the littoral zone represents a valuable piece of "real estate" where commercial, industrial, private and recreational interests compete for rights of access, use and exploitation of natural resources. It is in light of such considerations that an automated technique has been developed that allows the consistent, accurate and up-to-date delineation of the boundaries of the littoral zone. This technique, known as the Automated Foreshore and Tide Intersection Model (AFTIM), depends upon the existence of a digital model of the coastal terrain and a digital model of the ocean tides.

In the context of implementing the AFTIM approach, this paper presents the issues and advantages of using a combination of topographic and bathymetric LIDAR data to define the terrain in the littoral zone. Using an Australian case study, available LIDAR data is combined with a tide model to illustrate the results of the AFTIM solution for realising the boundaries of the littoral zone. The difficulties in integrating topographic and bathymetric LIDAR to provide a seamless coastal digital elevation model (DEM) are also considered.

1. Introduction

The physical location of the coastline is commonly taken to be the line of intersection between a specified tidal datum and the terrain. Exactly which tidal datum is used for this purpose will of course lead to a different realisation of the coastline. For example, in delineating the seaward extent of land parcels, Mean High Water Mark (MHWM) is often used (Watson, 2004), whereas for defining marine boundaries such as the limit of the Territorial Sea and the Exclusive Economic Zone, the line of Lowest Astronomical Tide (LAT) is generally the relevant tidal datum (Mitchell et al., 2001). Thus, the term *coastline* is specific to the context and application at hand, leading to significant confusion and ambiguity over its spatial definition and physical realisation. To alleviate this confusion, the phrase *tidal line* is used throughout the remainder of this paper to describe the line of intersection between a specified tidal datum and the foreshore terrain.

The littoral zone contains a number of tidal lines. A difficulty in determining the location of any tidal line comes from the fact that they are ambulatory (time-variable). The ambulatory nature of tidal lines derives largely from the influences of erosion and accretion that cause foreshore terrain to change. These changes can be slow and sustained, or they may occur suddenly and dramatically as a result of storm surges and other severe weather events. A further reason to regard tidal lines as ambulatory is the impact of climate change and global sea level rise. Though the time-frame for measurable sea level rise is slow, scientific evidence indicates a sustained increase in sea levels over coming decades (Frew, 2006; Walsh et al., 2002). The long-term impact of rising sea-level on the definition and realisation of tidal lines as legally defined boundaries demands some careful thought.

2. Tidal Line Delineation Process

The shortcomings of past and present tidal line mapping techniques have prompted a consideration of ways to improve and automate the process of delineating tidal lines. One such approach is the automated foreshore and tide intersection model (AFTIM) (Quadros and Collier, 2008). This process is based on a mathematical technique that avoids the need for visual interpretation of aerial or satellite imagery and facilitates regular and rapid tidal line re-determinations as required (e.g. to account for coastal erosion and/or accretion).

Conceptually, AFTIM is very simple. It relies upon the existence of an appropriately accurate and up-to-date digital model of the foreshore terrain and a similarly reliable tide model. Given the existence of these two fundamental data sets, it becomes a relatively routine matter to use the tide model to define the relevant tidal datum and then to compute the intersection of the specified tidal datum with the foreshore terrain to produce the relevant tidal line. A simple two dimensional diagram of this process is seen in Figure 1.

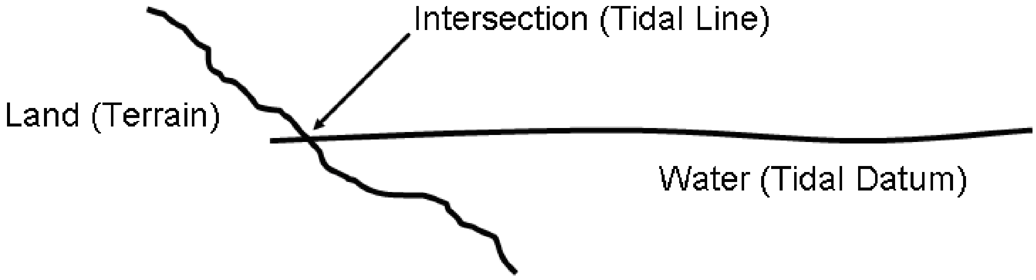

Figure 1 - The basic AFTIM concept

3. Using LIDAR to Map the Terrain in the Littoral Zone

LIDAR (Light-Induced Detection and Ranging) is the most promising measurement technique for routinely gathering terrain information in the littoral zone. LIDAR has the advantage of being an airborne system which provides access to coastal environments which may otherwise be inaccessible or inhospitable. It is also one of the most efficient and accurate techniques for providing both high resolution topographic and near-shore bathymetric data.

There are two types of airborne LIDAR system. Topographic systems are used to gather terrain heights above the waterline, whilst bathymetric systems are primarily used to measure the depth of the sea-floor. The main difference between the two systems lies in the type of laser used. In topographic LIDAR systems an infra-red laser is employed (Leatherman, 2003). Such a system is ideal for rapid, dense and accurate sampling of terrain, but is not able to penetrate water and therefore cannot be used to measure bathymetry.

The bathymetric LIDAR process requires two lasers of differing wavelengths. As shown in Figure 2, a vertically pointing infrared laser is used to measure the height of the plane above the water surface, and a scanning green laser is used to map the sea surface and the sea floor simultaneously (Irish and Lillycrop, 1999; LaRocque and West, 1990; Wozencraft and Millar, 2005). The water depth is calculated from the time difference between the return signals of the two lasers (Emery and Thomson, 2001; Lin, 1995). Bathymetric LIDAR systems can also obtain terrain heights above the waterline, although the lower accuracy relative to topographic LIDAR systems means that this data is not ideal for terrestrial applications.

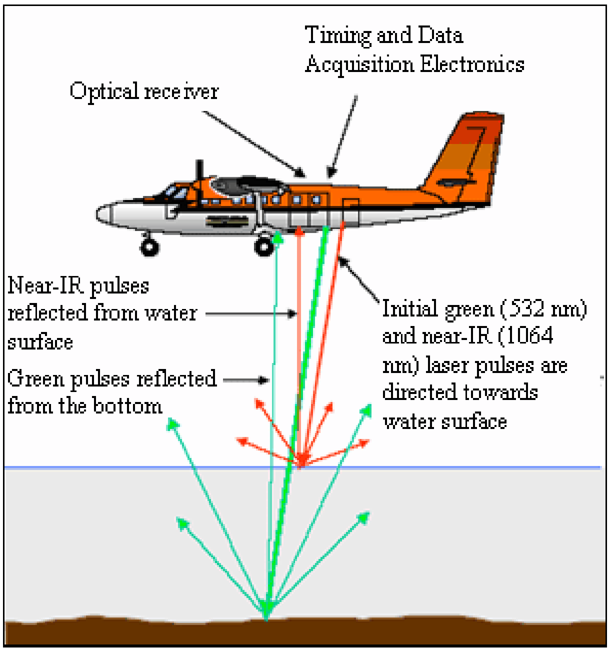

Figure 2 – The setup of a bathymetric LIDAR System (LaRocque and West, 1990)

Both topographic and bathymetric LIDAR systems include a high frequency laser, a Global Positioning System (GPS) receiver and an inertial measurement unit. The system is able to record the time differential between the emission of the laser pulse and the reception of the return signal. Therefore, knowing the speed of light and the time the signal takes to travel from the aircraft to the object and back, the distance to the object can be computed. The height of the “terrain” is determined from this information while the position and orientation of the scanner is determined using kinematic GPS and the inertial measurement unit (AAMHatch, 2006). The laser is swept in a direction perpendicular to the flight line using a rotating mirror inside the laser transmitter. By reversing the direction of rotation at a selected angular interval, the laser pulses can be made to scan back and forth along a scan line.

The maximum detection depth for bathymetric LIDAR technology is influenced by the bottom radiance and water turbidity, along with incident sun angle and solar intensity (Irish and White, 1998). Bathymetric LIDAR systems have been used to measure depths up to 60m (Wozencraft, 2003), however, in Australian coastal waters the depth range is usually between 25-40m (Barker, 2007). This depth limitation means that bathymetric LIDAR systems will never completely replace more traditional ship-borne hydrographic methods.

4. Tidal Datum Modelling

There are two main options for modeling tidal datums. The first is a based on mathematical interpolation/extrapolation of tidal datum heights derived from tide gauge observations. This method is generally well accepted in the vicinity of reliable tide gauges. However, in areas where there is a lack of tidal observations and site-specific influences such as rivers, channels, bays distort tidal flows, interpolated heights are often unreliable. Large sections of the Australian coast fall a substantial distance from a primary tide gauge, which places a significant practical limitation on deriving a reliable tidal datum model by this technique.

The second option for modeling tidal datums is to use a hydrodynamic tide model (Hess, 2001). Hydrodynamic tide models are important to AFTIM because they attempt to mathematically reproduce the movement of the oceans. In the coastal environment this includes modeling the sea-surface height and tidal currents. The creation of a hydrodynamic model is a more complex process than producing an interpolated tidal datum model from tide gauge data. However, the result is a more rigorous model which can more reliably model tidal datums in areas of complex terrain.

5. Port Phillip Bay Case Study

The case study used in this paper lies in the southern part of Port Phillip Bay (PPB), Victoria, Australia. The bay itself, which is shown in Figures 3 and 4, consists of a single narrow entrance about 3-4km across, has a coastline length of approximately 264km and covers an area of 1930km^2. Immediately north of the entrance is a large shallow sand area, known as the Great Sands, that extends for 20-30km northward. This shallow zone delays the inflowing tidal stream by about 5hrs. Beyond the Great Sands, PPB widens and deepens, allowing the tide to travel faster and more evenly into the rest of the bay.

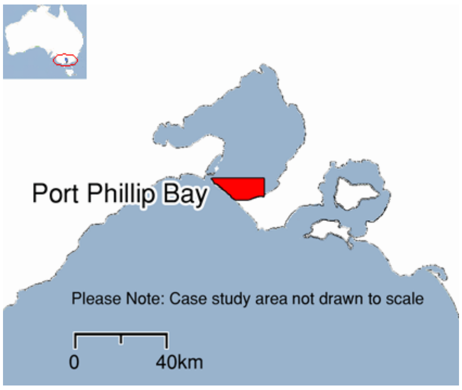

Figure 3 – Case study location, southern Port Phillip Bay, Australia

PPB has a complex tidal regime, which creates difficulties for the construction of a tide model. The narrow opening poses the biggest challenge for the hydrodynamic approach. To use this technique, an accurate representation of water flow through the entrance is required in order to model the behaviour of the tidal stream throughout the remainder of the bay. To achieve this objective, a hydrodynamic grid with a resolution of 50-100m would be required (Hubbert, 2007). A hydrodynamic model with this resolution was simply not available for the purposes of this case study. Therefore, a model for the tidal datums in PPB was developed based on interpolation between existing tide gauges. The locations of these tide gauges are shown in Figure 4.

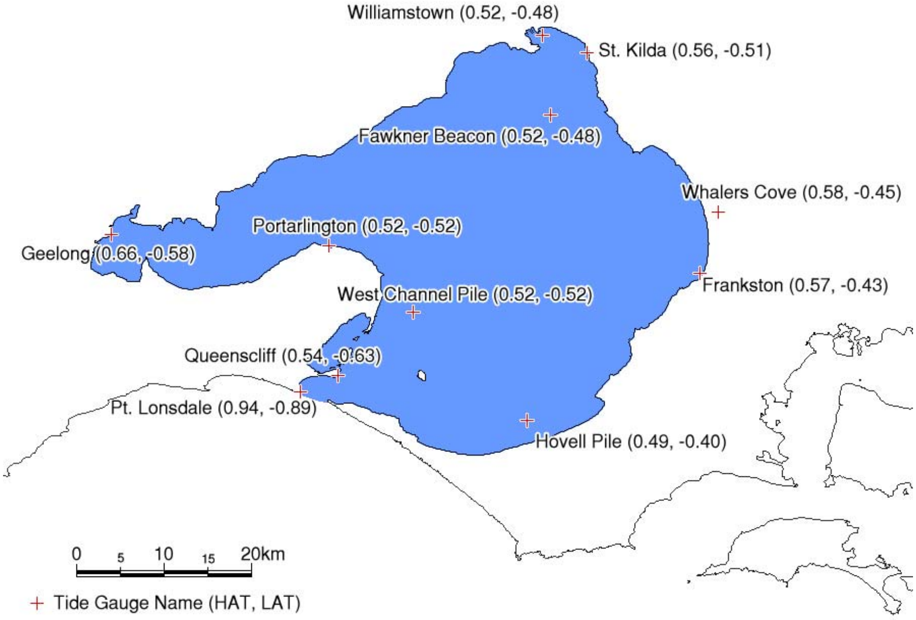

Figure 4 - Port Phillip Bay tide gauges and tidal datum heights relative to the Australian Height Datum

Interpolation based on an inverse distance weighted solution was used to create a gridded tide model for PPB for both Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT) relative to the Australian Height Datum (AHD). Contours of these two models are shown in Figures 5 and 6 respectively.

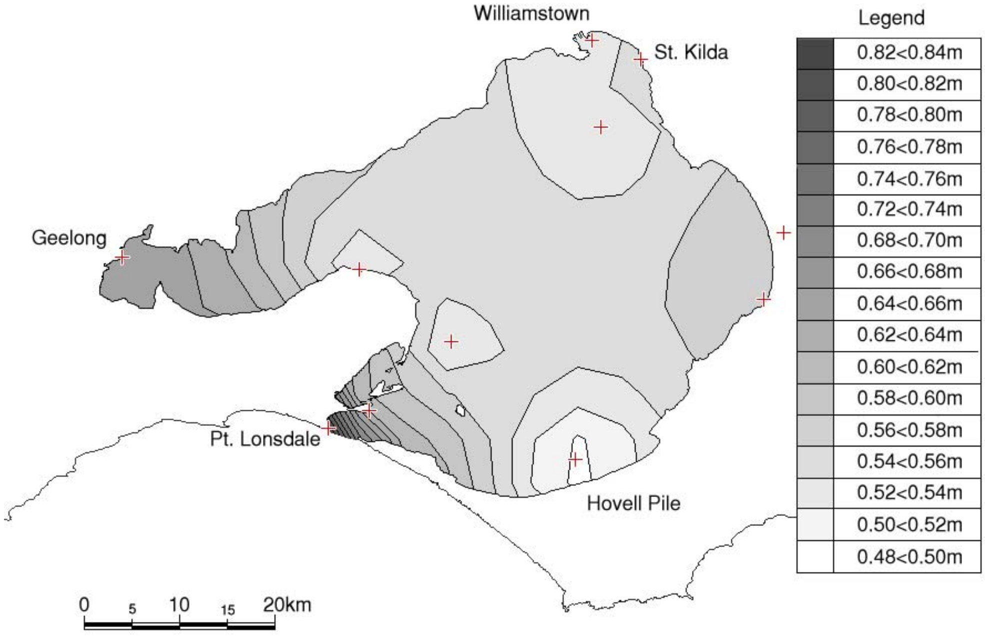

Figure 5 - Port Phillip Bay HAT model from tide gauge interpolation

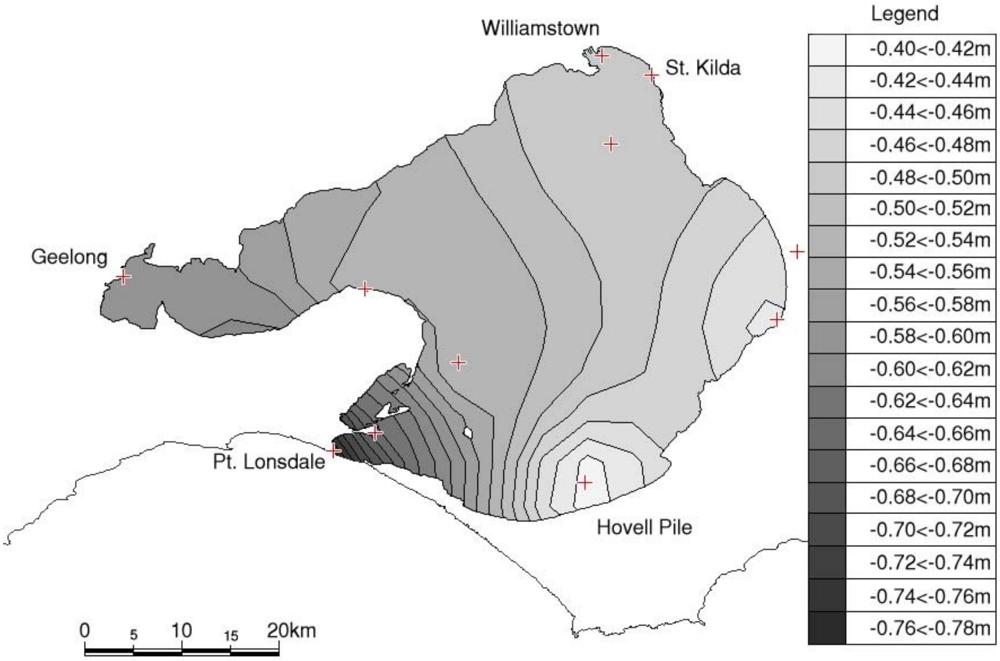

Figure 6 - Port Phillip Bay LAT model from tide gauge interpolation

The bathymetric LIDAR data in the case study area, as shown in red in Figure 7, was collected from the 1st-5th April, 2007 (Tenix LADS, 2007). A De Havilland Dash 8-202 aircraft was used for this purpose, equipped with the LADS MkII bathymetric mapping system (Barker, 2007). Some additional survey lines were flown to fill shallow water gaps, however small data gaps remained in regions where the seabed extended beyond the depth capabilities (33m) of the system. The bathymetric survey was conducted using a laser footprint size of 2.6m, enabling an average point separation of 5m (AAMHatch, 2007). The 5m point separation provided the basis for creating a 5m DEM grid across the survey area. The grid nodes for the DEM were interpolated using linear triangulation from the raw data points.

Heights for the bathymetric LIDAR data were referenced to the mean sea-surface at the time of survey. The mean sea-surface was subsequently referenced to the height of the tide at the closest tide gauges (Barker, 2007) and thence to AHD so that all bathymetric data was related to the national height datum.

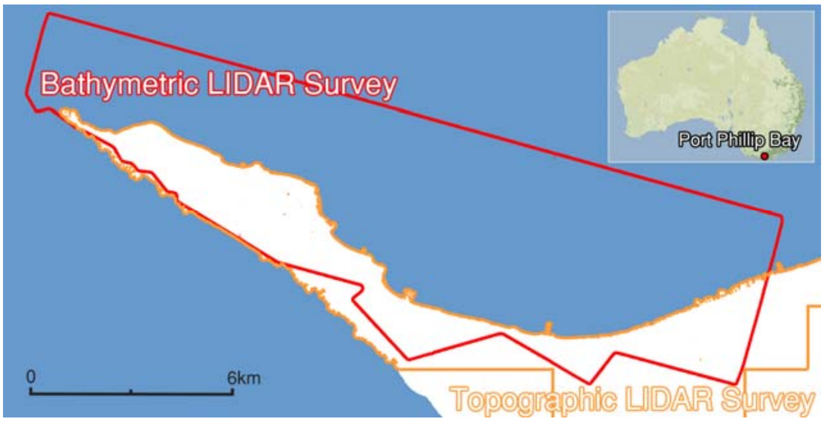

Figure 7 – Case Study LIDAR Data, Southern Port Phillip Bay, Australia

The topographic LIDAR survey, shown in orange in Figure 8, was flown by AAMHatch over the foreshore adjacent to the bathymetric LIDAR survey between 24th April and 3rd July 2007 and covered an area of approximately 470km^2. All data was collected within two hours of low tide to maximise overlap with the bathymetric data. The topographic survey was conducted using a laser footprint size of 0.2m, enabling an average point separation of 0.8m (AAMHatch, 2007). The higher resolution topographic data provided the basis for creating a 1m DEM. The grid nodes for the topographic DEM were interpolated using linear triangulation from the raw data points.

In contrast to the bathymetric survey, AHD heights from the topographic LIDAR survey, were derived by applying a local geoid model to the ellipsoidal heights acquired from the on-board kinematic GPS receiver. The use of different methods to establish AHD heights can (and did in this case) result in a vertical offset between the two datasets, which in turn can lead to problems when attempting to integrate the data to create a unified DEM across the littoral zone. A single, seamless DEM that spans the inter-tidal zone is ideally what is required for automated tidal line delineation using the AFTIM approach. Problems in the creation of such a DEM will be discussed more fully in the next section.

6. Delineating the Littoral Zone in Southern Port Phillip Bay

This first stage of the research involved computing the line of HAT using both the bathymetric and topographic LIDAR DEMs. Typically, in this case, the bathymetric LIDAR data is higher than the topographic LIDAR data by about 30-40cm. This resulted in the line of HAT derived from the bathymetric LIDAR being seaward of the HAT line derived from the topographic LIDAR. For the case study area, the 30-40cm vertical offset between the two datasets translates into a 2-15m shift in the horizontal position of the line of HAT, depending on the steepness of the foreshore.

Figure 8 shows the HAT lines for both cases in a small section of the case study area, overlaid on aerial imagery. In this case, the HAT lines have an average horizontal separation of 4m. Visually, it is clear that the topographic LIDAR data gives a more accurate delineation of HAT than the bathymetric data. This is predominantly a result of the higher resolution and better vertical accuracy of the topographic data, but also reflects the impact of the aforementioned vertical offset.

Figure 8 - Comparing HAT lines derived from bathymetric and topographic LIDAR - near Port Phillip Heads, Victoria

The vertical offset between the two LIDAR data sets creates a problem when faced with the task of integration to create a smooth and seamless DEM across the littoral zone. It is suggested that this problem primarily results from the use of different techniques to establish the connection to AHD. Other issues also impact on the task of data integration, making it the subject of ongoing research. These include:

- *Narrow Overlap* – Invariably, the topographic and bathymetric data sets have minimal overlap. In practice, this overlap can be maximized by collecting the topographic LIDAR data at low tide and the bathymetric data at high tide, but even still, the breadth of the overlap zone will be relatively narrow, making the integration process inherently weak in a geometric sense.
- *Data Gaps* – Both the topographic and the bathymetric data sets contain gaps in the foreshore region. In the topographic case, these gaps are generally caused by

pockets of shallow water left by receding waves and/or tide. The bathymetric LIDAR system invariably leaves gaps in very shallow water caused by difficulties in distinguishing between the bottom and surface reflections of the laser when the water is less than about 0.3m deep. Data gaps can be problematic if they impose the need for extended areas of interpolation and/or extrapolation.

- *Resolution* – Because of the different technical requirements of bathymetric and topographic LIDAR systems, they acquire data at different spatial resolutions. Typically, a topographic LIDAR system will have an average point spacing of 1m, whereas bathymetric systems tend to operate at 5m spacing (see Figure 9). These different resolutions further complicate the integration process.
- *Lack of Height Control* – It is not common to find reliable ground control in the foreshore region. For this reason, establishing "true" heights from the two overlapping LIDAR data sets can be difficult. Not knowing which data set is closest to the truth, makes it hard to develop a strategy that will yield an accurate integrated DEM.
- *Data noise* – In the case study region, the standard deviation of the height differences between the two datasets ranged from ±0.3 to ±1.2 m depending on the foreshore terrain. Any integration technique will need to take account of the variable relationship between the two datasets and their relative accuracies. Normally more weight would be given to the topographic data in this process, as such data is inherently more precise.

Because of the difficulties experienced in the data integration process, creating the need for on-going research, subsequent investigations relied on the DEM derived from the topographic data to derive the line of HAT and that derived from the bathymetric data to derive the line of LAT.

Due to gaps in the LIDAR data in the foreshore region, the second stage of the research involved assessing the coverage of the topographic and bathymetric LIDAR data in the littoral zone. Figure 9 shows the individual measurement points for both the bathymetric (brown) and topographic (blue) LIDAR data. To unclutter the figure, all points above 8m AHD have been removed from the topographic LIDAR data. The figure shows the line of HAT derived from the topographic LIDAR DEM. It can be seen that there are a significant number of topographic LIDAR measurements on both the seaward and landward sides of this line. If the topographic LIDAR had been collected at high tide, this may not have been the case, likely preventing the line of HAT from being delineated using the topographic LIDAR data. This example illustrates another reason why it is important to collect the topographic LIDAR data at low tide.

Figure 9 also shows the typical shallow water gap that occurs in the bathymetric LIDAR data. For most of the PPB case study area, LAT occurs at depths beyond the shallow water gap and so it does not cause a problem in the delineation of LAT. As shown in Figure 9 however, there are some sections of the LAT line which require interpolation across the shallow water gap. This interpolation process would only represent a significant problem if the shallow water terrain was highly variable, making interpolation inaccurate.

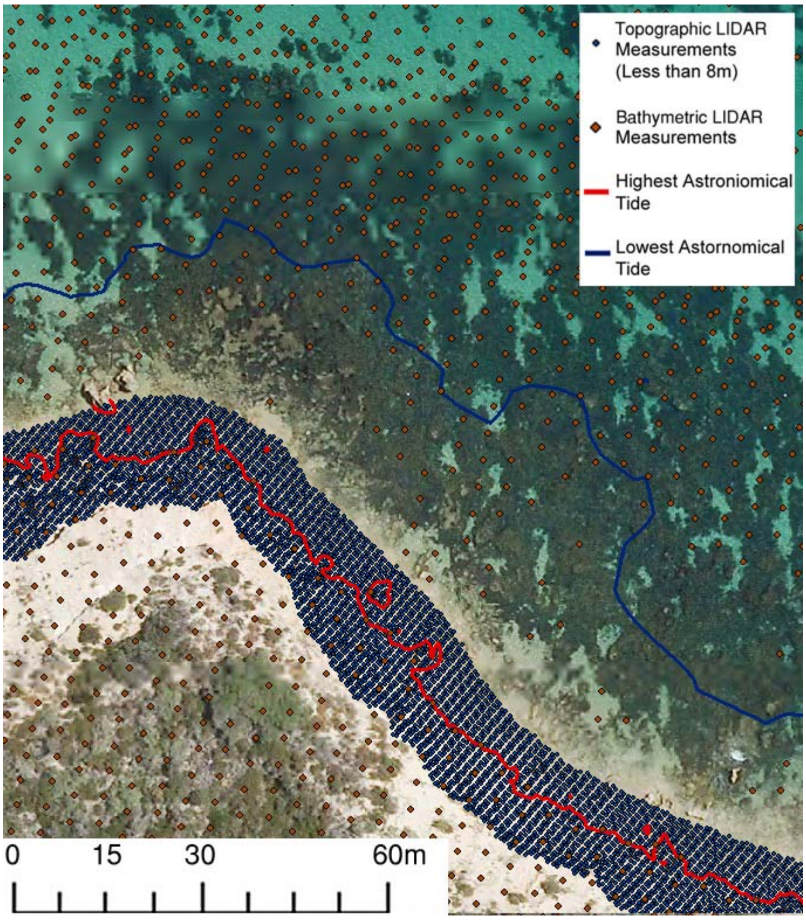

Figure 9 - The extent of the littoral zone and the raw topographic and bathymetric data

The final stage of research involved the production of the littoral zone boundaries for the case study area using the AFTIM procedure. Figures 10 and 11 provide two examples of the AFTIM solution where HAT has been derived from the topographic LIDAR DEM and LAT has been derived from bathymetric LIDAR DEM. Figure 10 shows a 500m section of coast which has a 25-60m variation in the width of the littoral zone. This example illustrates the effectiveness of the AFTIM solution when appropriate terrain and tide models exist.

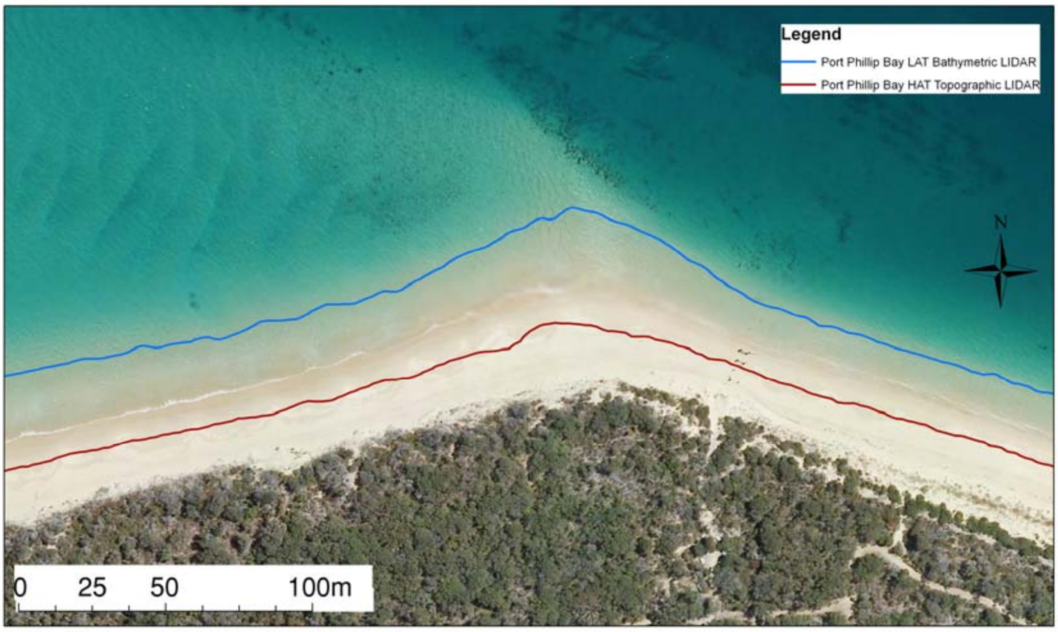

Figure 10 - Littoral zone boundaries (HAT and LAT) as defined by bathymetric and topographic LIDAR

Figure 12 shows a different section of the littoral zone in Port Phillip Bay, where the separation between LAT and HAT is up to 300m. This increased width is due to the flatness of the foreshore rather than an increase in the tidal range. It is interesting to note the appearance of small “islands” in the line of LAT which occur on account of sand banks, which are likely transient features.

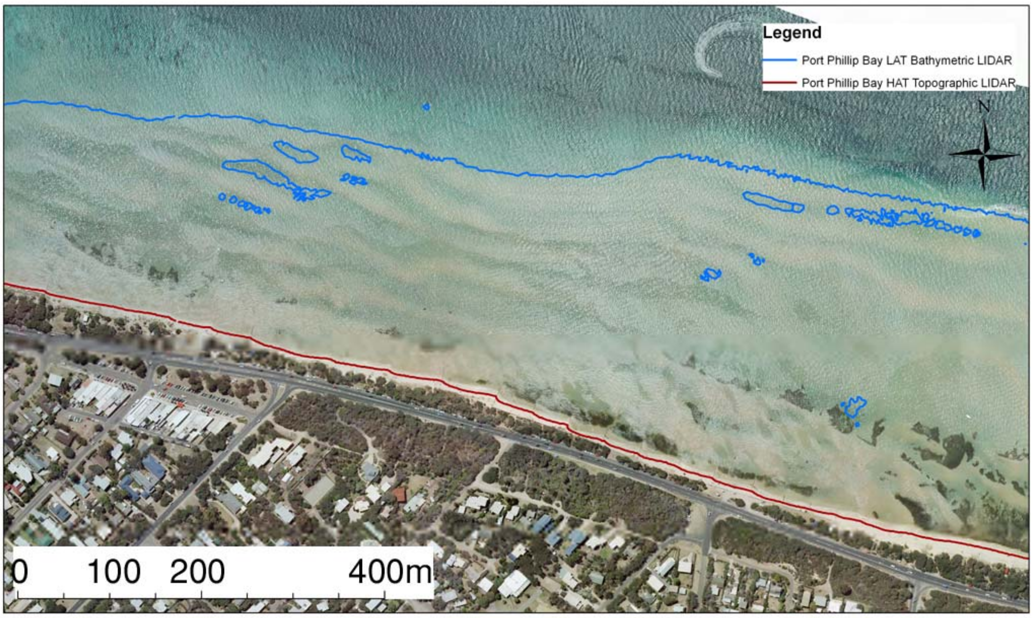

Figure 11 - Littoral zone boundaries (HAT and LAT) as defined by bathymetric and topographic LIDAR, Blairgowrie

Figure 12 shows the littoral zone for the entire case study area. This area includes sections of wide open beach in the east and some steep cliffs in the west. Variation in foreshore topography is evidenced in Figure 12 by the changing width of the littoral zone.

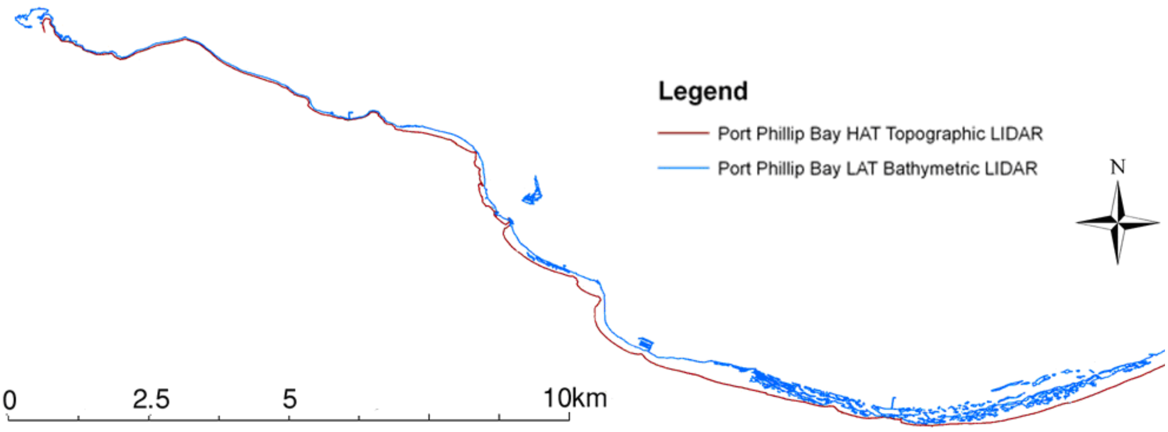

Figure 12 - The Littoral Zone for the Port Phillip Bay Case Study

AFTIM provides an automated technique for the delineation of tidal lines. This study has illustrated the application of AFTIM by showing the computation of the lines of HAT and LAT in the case study area of Port Phillip Bay. The rigorous nature of generating the tidal lines from the intersection of a tidal datum and the foreshore terrain defines a line with accuracy not previously achievable, except on a very local scale. This gives AFTIM the ability to define separate tidal lines within the littoral zone, rather than defining a single approximate coastline, which has historically been the case. The ease with which the solution can be expanded, extended and updated provides a significant advantage in maintaining an up to date record of the location of the relevant tidal lines, which offers various scientific, environmental, planning and administrative benefits.

The AFTIM technique is particularly relevant for the consistent and accurate delineation of maritime boundaries by means of an offset from a tidal line (usually LAT). The offset boundary generated at a specified distance from a tidal line has a reliability which is inextricably linked to the accuracy of the tidal boundary. It is for this reason that tidal lines need to be located with good statistical confidence so that the error propagated to the offset marine boundary is minimised.

7. Conclusion

The Port Phillip Bay case study has shown that topographic LIDAR provides a means for accurately delineating the line of HAT. Likewise, bathymetric LIDAR provides an accurate means for delineating the line of LAT. Although a hydrodynamic tide model is preferred as a means to define tidal datums, interpolation between tide gauges can be used in locations with a sufficiently dense tide a gauge network, as shown in the Port Phillip Bay case study used in this paper.

Differences between the topographic and bathymetric LIDAR datasets need to be overcome if a seamless, integrated LIDAR DEM is to be used to derive the littoral zone boundaries. An integrated LIDAR DEM would provide an optimal solution for the delineation of consistent, high resolution tidal lines using the described AFTIM approach.

8. References

AAMHatch, 2006. Airborne Laser Scanning Factsheet, http://www.aamhatch.com.au (accessed 27 Sept. 2006)

AAMHatch, 2007. Airborne Laser Survey - Mornington. Volume 1279A15NOM. Melbourne, pp. 13.

Barker, R., 2007. Discussion of ALB Trial Tenix, AAMHatch, Victorian DSE. Melbourne.

Emery, W.J. and Thomson, R.E., 2001. *Data Analysis Methods in Physical Oceanography*. Elsevier Science B.V.: Amsterdam, The Netherlands, pp. 317.

Frew, W., 2006. Sydney's Vanishing Future. Sydney Herald-Sun. Sydney, 3.

Hess, K.W., 2001. Generation of Tidal Datum Fields for Tampa Bay and the New York Bight. NOAA Technical Report NOS CS 11. Silver Spring, Maryland, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, pp. 43.

Hubbert, G.D., 2007. Personal Commmunication, Melbourne, 8 June 2007

Irish, J.L. and Lillycrop, W.J., 1999. Scanning laser mapping of the coastal zone: the SHOALS system. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 54, No. 2-3, pp. 123-129.

Irish, J.L. and White, T.E., 1998. Coastal Engineering Applications of High-Resolution LIDAR Bathymetry. *Coastal Engineering*, Vol. 35, No., pp. 47-71.

LaRocque, P.E. and West, G.R., 1990. Airborne Laser Hydrography: An Introduction. *ROPME/PERSGA/IHB Workshop on Hydrographic Activities in the ROPME Sea Area and Red Sea* (Kuwait City).

Leatherman, S.P., 2003. Shoreline Change Mapping and Management Along the U.S. East Coast. *Journal of Coastal Research*, Vol., No. Special Issue 38, pp. 5-13.

Lin, C.S., 1995. Airborne lidar remote sensing of terrain and ocean. *Geoscience and Remote Sensing Symposium, 1995. IGARSS '95. 'Quantitative Remote Sensing for Science and Applications', International*, pp. 2316-2318.

Mitchell, D.J., Collier, P.A., Leahy, F.J. and Murphy, B.A., 2001. The United Nations Law of the Sea and the Delimitation of Australia's Maritime Boundaries. *The Trans Tasman Surveyor*, Vol., No. 4, pp. 50-57.

Quadros, N.D. and Collier, P.A., 2008. A New Approach to Delineating the Littoral Zone for an Australian Marine Cadastre. *Journal of Coastal Research*, Vol. 24, No. 3, pp. 780-789.

Tenix LADS, 2007. Airborne LIDAR Bathymetric Survey. Melbourne, 48.

Walsh, K., McInnes, K. and Abbs, D., 2002. Sea Level Rise Projections and Planning in Australia. *Coast to Coast 2002* (Tweed Heads, NSW).

Watson, P., 2004. The Modified Doctrine of Erosion and Accretion & MHWM Boundary Re-determination in NSW. *NSW Coastal Conference* (Lake Macquarie, NSW).

Wozencraft, J.M., 2003. SHOALS Airborne Coastal Mapping: Past, Present and Future. *Journal of Coastal Research*, Vol., No. Special Issue 38, pp. 207-216.

Wozencraft, J.M. and Millar, D., 2005. Airborne LIDAR and Integrated Technologies for Coastal Mapping and Nautical Charting. *Marine Technology Society Journal*, Vol. 39, No. 3, pp. 27-35.

9. Biography

Nathan Quadros is near the completion of his PhD, where he has been studying the intersection of LIDAR data with tide models as a means to delineate the littoral zone. Currently, he is managing the acquisition, delivery and quality assurance of the Victorian state-wide coastal bathymetric and topographic LIDAR project. The data acquired through this project will form the basis for storm surge, recession and coastal vulnerability modeling in Victoria, Australia.

Dr. Philip Collier is a Senior Lecturer in the Department of Geomatics at the University of Melbourne, Australia. He is also the Assistant Research Director in the Cooperative Research Centre for Spatial Information (CRC-SI).