INTEGRATION OF BATHYMETRIC AND TOPOGRAPHIC LIDAR: A PRELIMINARY INVESTIGATION

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ABSTRACT:

At present there is no single technology that can measure both terrain heights and water depths to a suitable level of accuracy and density for applications such as storm surge modelling and coastal inundation studies. Conventional topographic LIDAR systems have been designed for measuring high resolution terrain heights, but they do not have the ability to penetrate water to yield bathymetric results. Bathymetric LIDAR systems have been specifically developed to measure water depth and can also measure terrain heights, but with typically lower accuracy and spatial resolution than available from the topographic equivalent. A further limitation of all bathymetric LIDAR systems is their inability to measure depths where the water is cloudy or turbid. Of particular importance to this project is the fact that bathymetric LIDAR systems cannot acquire dependable bathymetric data in the near-shore or surf zone. Accordingly, there is frequently a discontinuity between terrain height data acquired by topographic LIDAR systems and water depth data collected by bathymetric LIDAR systems. The height datums used by such systems also tend to be inconsistent in terms of the way they are realised, creating further difficulties when endeavouring to integrate the respective data sets. The Cooperative Research Centre of Spatial Information has been working with the Victorian Department of Sustainability and Environment on a pilot project to investigate issues and technical challenges that are faced in the development of a continuous LIDAR based terrain model that traverses the littoral zone. This paper summarises the results of this pilot project, which has been based on topographic and bathymetric LIDAR data collected over the southern part of Port Phillip Bay, Victoria, Australia.

1. INTRODUCTION

With recent advances in LIDAR (Light Detection and Ranging) technology, coastal managers now have the capacity to acquire high resolution digital elevation data covering the littoral or inter-tidal zone. The ability to accurately map this crucial zone creates the prospect of producing a seamless digital elevation model (DEM) that spans the land-sea interface.

Access to a harmonised and consistent elevation model containing both bathymetry and topography will aid numerous important applications. Examples include climate change studies, predicting the impact of sea level rise, coastal and marine boundary delimitation, the creation of high-resolution tide models, as well as the critical issue of storm surge and tsunami modelling where wave height is directly dependent on bathymetry and the impact of the resulting flood wave depends on topographic relief (McInnes and Hubbert, 2003; McInnes et al., 2002), .

The development of LIDAR technology commenced in the 1970s, with early systems built in the USA and Canada (Ackermann, 1999). However, the technology was not implemented in airborne systems until the late 1980s. In 1988 the U.S. Army Corps of Engineers (USACE) constructed an operational LIDAR system which was subsequently developed commercially by Optech Inc. (LaRocque and West, 1990). In the following year a contract was awarded to BHP Engineering and Vision Systems Australia to build the Laser Airborne Depth Sounder (LADS) system for the Royal Australian Navy (RAN) (LaRocque and West, 1990). Since its acceptance in early 1993, the LADS system has been used by the RAN to map Australia's coral reef systems, navigation routes, oil and gas exploration and strategic defence applications (Irish and White, 1998; Tenix LADS, 2006). The LADS system is also used commercially by Tenix LADS Corporation for hydrographic surveying and coastal engineering projects throughout Australia and around the world.

In 2007 the Victorian Department of Sustainability and Environment commissioned a pilot project in southern Port Phillip Bay. As Figure 1 shows, this project involved collecting overlapping topographic and bathymetric LIDAR data. The aim of the project was to analyse the performance of shallow water bathymetric LIDAR with a view to integration with the topographic LIDAR and thereby the creation of a seamless coastal zone DEM.

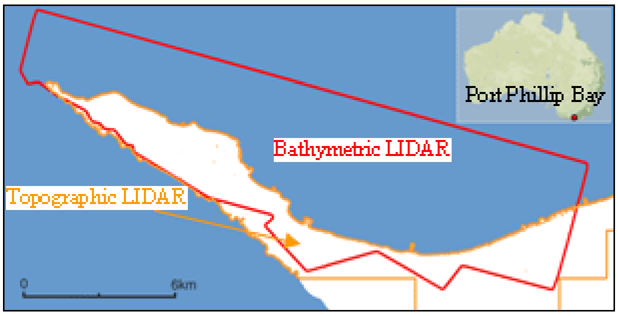

Figure 1. Data Location, Victoria, Australia

This paper focuses on the integration of the separately acquired topographic LIDAR and bathymetric LIDAR data in Port Phillip Bay. The data generated by each system have a number of differences that inhibit the integration process. These differences must be understood and resolved in order to combine the data in a continuous and consistent way and thereby create a seamless and dependable DEM.

2. LIDAR TECHNOLOGY

2.1 Technical Details of Topographic LIDAR

All LIDAR systems include a high frequency laser, a GPS (Global Positioning System) receiver and an IMU (inertial measurement unit). The laser includes an emitting diode that produces a light source at a specific frequency. The system is able to record the time difference between the emission of the laser pulse and the reception of the return signal (the time of flight). Knowing the speed of transmission and the time of flight allows the distance between the laser transmitter and the reflecting surface (the terrain) to be computed. The GPS and IMU devices are used to determine the 3D position and orientation of the laser scanner at each measurement epoch. (AAMHatch, 2006).

Using a rotating mirror inside the laser transmitter, the laser beam is swept perpendicular to the direction of travel. By reversing the direction of rotation of the mirror at a selected angular interval, the laser pulses can be made to scan back and forth during flight. The resolution of the system is determined through a combination of the scan angle and the aircraft flying height. Typically, the higher the flying height, the wider the swath width on the ground and the lower the resolution.

The vertical accuracy of topographic LIDAR is dependent on several external factors (Turton, 2006). These include:

- Flying height
- Beam divergence (this refers to the angle of incidence of the laser. As the beam gets further away from vertical it is more likely to pick up features obstructing the ground.)
- Location of a point within the swath
- GPS geometry
- IMU update and measurement frequency
- Turbulence
- Distance from GPS base station
- Topographic LIDAR classification reliability in separating ground and non-ground points

To account fully for the influence of all potential error sources, the 1 sigma vertical accuracy of topographic LIDAR is generally quoted to be ±0.15m (Turton, 2006).

In late April 2007, AAMHatch Pty Ltd collected topographic LIDAR data across the Mornington Peninsula, immediately adjacent to an area covered by a recent bathymetric LIDAR survey. The topographic data was flown only three weeks after the bathymetry was collected and within two hours of low tide to maximise overlap between the two data sets. Figure 2 shows the elevations derived from the topographic LIDAR, with areas of red being in the range 0-10m AHD (Australian Height Datum) and the white areas transitioning to black showing heights above 10m AHD.

Throughout this paper, the topographic LIDAR system referred to is the Optech ALTM 3100EA system (www.optech.ca) operated commercially by AAMHatch Pty Ltd.

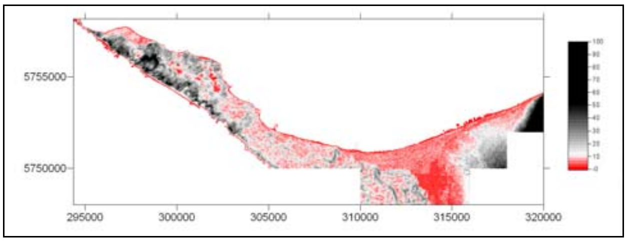

Figure 2. Topographic LIDAR Data, Victoria, Australia

2.2 Technical Details of Bathymetric LIDAR

Bathymetric LIDAR systems are primarily built to gather near-shore bathymetry. The main difference between a bathymetric LIDAR system and the topographic equivalent is in the type of laser used. In topographic LIDAR an infra-red laser is employed (Leatherman, 2003) which is not able to penetrate water and therefore cannot be used to acquire bathymetry. On the other hand, a bathymetric LIDAR system employs two lasers of different wavelengths. As illustrated in Figure 3, two wavelengths are used because the seafloor needs to be measured separately from the sea surface. An infrared laser with a wavelength of 1064nm is used to detect the water surface, and a green laser with a wavelength of 532nm is used to detect the sea floor (Irish and Lillycrop, 1999; LaRocque and West, 1990; Wozencraft and Millar, 2005). The wavelength of the green channel is optimal for penetrating water and therefore measuring the water depth. The return red signal gives the height of the plane above the water. The water depth is calculated from the time difference between the two return signals (Emery and Thomson, 2001; Lin, 1995). As the green laser pulse travels through the water column and reflects off the sea floor, it undergoes absorption, scattering, and refraction. These processes attenuate the laser return energy, limiting the depth of water that can be measured. The maximum depth for bathymetric LIDAR technology is influenced by the interaction of bottom radiance and water turbidity, along with incident sun angle and intensity (Irish and White, 1998). Under ideal conditions, bathymetric LIDAR systems have measured depths of up to 60 metres (Wozencraft, 2003). However, in typical Australian waters the depth limits are between 25-40 metres (Barker, 2007). This depth limitation means that bathymetric LIDAR systems will not completely replace traditional bathymetric surveying methods, as maritime vessels are still required to conduct surveys in deeper water and in shallow water where there is significant turbidity.

The original Tenix LADS bathymetric LIDAR system has been in operation by the Royal Australian Navy Hydrographic Service since February 1993, and has surveyed well over 100,000 sq km of ocean (Tenix LADS, 2006). Since 1998 Tenix LADS Corporation has used the LADS MK II system to conduct contract bathymetric surveys throughout Australia and around the world (Tenix LADS, 2006). Unlike its earlier counterpart, LADS Mk II has the advantage of being able to acquire terrain heights above the waterline, but with lower accuracy and resolution than dedicated topographic LIDAR systems.

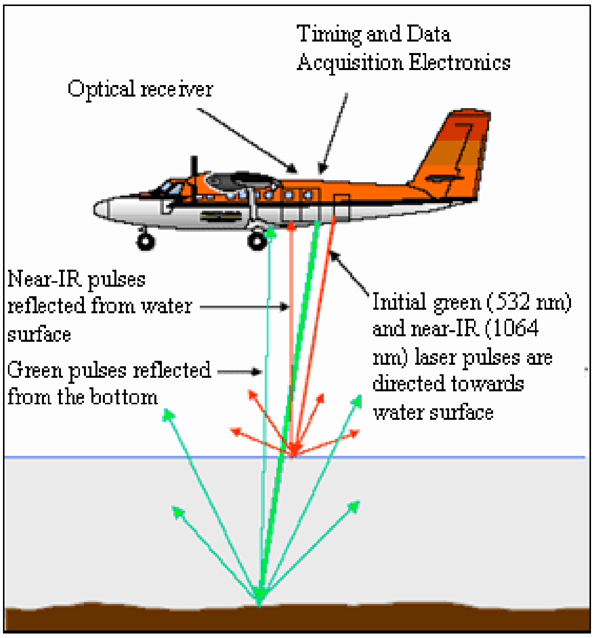

Figure 3. Bathymetric LIDAR System (LaRocque and West, 1990)

The bathymetric LIDAR data used for this project was gathered by Tenix LADS Corporation between 2-5 April 2007 (Barker, 2007). The data, as shown in Figure 4, was collected from Point Nepean in the west to Rosebud in the east. The white areas in Figure 4 are terrain heights around 0m AHD with the brown area showing terrain heights above 0m AHD and the blue area showing graduations in bathymetric depths below 0m AHD. Overall the data was of high quality, with water depths up to 33m being measured in some areas. Not withstanding the quality of the data, some data gaps existed in deeper areas (e.g. the shipping channels), in areas of high turbidity and in the near shore surf zone and where the water was very shallow (<0.3m).

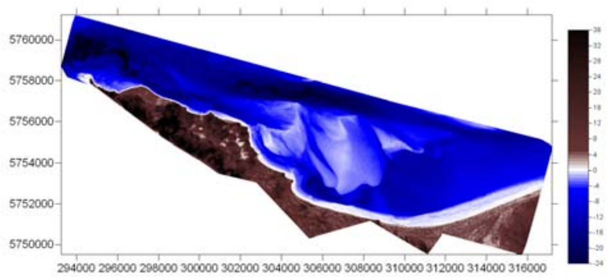

Figure 4. Bathymetric LIDAR Data, Victoria, Australia

2.3 Comparing Topographic and Bathymetric LIDAR

One of the key advances in the development of bathymetric LIDAR systems has been the ability to survey across the littoral zone through the acquisition of near shore topography and bathymetry with a single system (Irish and Lillycrop, 1999; LaRocque and West, 1990). This capacity raises the question as to why bathymetric LIDAR technology is not used more frequently to survey the terrain above the waterline. To answer this question, it is necessary to examine the differences between topographic and bathymetric LIDAR systems. The main differences are summarised in Table 1.

Category	Topographic LIDAR (Optech ALTM 3100EA)	Bathymetric LIDAR (LADS Mk II)
Hardware Specifications	• Higher frequency • Pulse rate: <100khz • Laser: Near infra-red • Lower power laser can take more measurements per second	• Lower frequency • Pulse rate: <1khz • Laser: Green and near infra-red • Higher Power laser results in less measurements per second
Flying Height	• 800-2200 metres	• 366-500 metres
1σ Vertical Accuracy	• Approx. ±15cm @ 1100m altitude	• Approx. ±50cm bathymetry • Approx ±1 m topography
Horizontal Accuracy	• ±1/3000 x altitude • Typically better than 0.6m	• ±5 metres
Vertical Datum	• GPS heights • Geoid model used in computations	• No geoid model • Established from local tide gauges
Resolution	• Higher Resolution • Typically 1-2 metres	• Lower Resolution • Typically 2-5 metres
Footprint	• 0.24m @ 1200m altitude (narrow beam) • 0.96m @ 1200m altitude (wide beam)	• 2-3 metres
Swath	• 800 to 2184 metres • Variable: 0 to 0.93 x altitude (m) • eg. 800m swath @ 1100m altitude	• 50 to 300 metres • Independent of altitude
Data Processing	• Lower costs per area • First return used to define vegetation and building height • Last return used for ground height	• Higher costs per area • "Least Depth" criteria adopted • First return is used to define terrain height

Table 1. Differences Between Topographic and Bathymetric LIDAR systems (AAMHatch, 2006; Barker, 2007; Hicks, 2006)

The hardware characteristics used for each system impact on horizontal data spacing. The laser power required to take bathymetric measurements is significantly higher than that required for topographic measurements, resulting in fewer measurements per second and a lower pulse rate. Further, in bathymetric surveys, the flying height is generally lower but, due to system design, this has minimal impact on the accuracy, laser footprint size and swath width, whereas in a topographic surveys the flying height directly affects all of these factors. In this paper, a typical flying height for topographic LIDAR of around 1100-1200m is used for comparison purposes. This flying height results in a higher resolution, smaller laser footprint and larger swath width for topographic LIDAR, demonstrating the advantage of dedicated topographic LIDAR systems over bathymetric LIDAR systems being used to measure the terrestrial environment. Another point of distinction is that the vertical accuracy of ±15cm for topographic LIDAR is significantly better than the ±1m for bathymetric LIDAR systems measuring the terrain.

Ultimately, vertical accuracy of any LIDAR system is dependent on the data processing strategy. For example, terrain heights from bathymetric LIDAR are generally derived from the *first return* laser signal. In the marine environment, this approach will yield the shallowest water depth, which is generally what is of interest in hydrographic surveying. However, in the terrestrial environment, processing the *first return* signal will often yield the height of vegetation or buildings rather than the ground. Thus for topographic applications, the *last return* should be used in order to determine true ground elevations. This is the approach employed in processing data from purpose-built topographic LIDAR systems when a ground DEM is required.

It is clear from Table 1 and the discussion above that having different LIDAR systems to map bathymetry and topography is a reality that exists because of the challenges posed by each environment. While technological capabilities may change this situation in the future, the present reality is that discrete systems exist for each application. However, in light of the objective of creating a smooth seamless DEM that spans the land/sea interface, the question arises as to how overlapping topographic and bathymetric LIDAR data can be combined in an optimal and rigorous way.

A problem that emerges when attempting to combine topographic and bathymetric LIDAR data is that very different approaches are used to establish the vertical datum. In bathymetric LIDAR, all heights/depths are initially related to a local tidal datum (Barker, 2007). This is done by measuring the height of the plane above the mean sea surface at the time of observation and by knowing the relationship between the mean sea surface and the tide datum from nearby tide gauge observations. If the LIDAR derived heights/depths must be expressed relative to a national height datum such as the AHD, a simple transformation between the height datum and the tide datum is determined and applied across the survey area. The biggest disadvantage suffered by this approach is that it is practically impossible to ground-truth the measured depths, though topographic heights can of course be checked.

The approach used to establish the vertical datum for topographic LIDAR is quite different. A geoid model is employed to convert ellipsoidal heights, derived from kinematic GPS, to orthometric heights (heights above the geoid). Subsequently, benchmarks are used to check for any localised discrepancies between the national height datum and the derived orthometric heights. Where significant (>0.1 m) differences are found, planar surface modelling is employed to further rectify the scanned heights to the local height datum.

While conceptually these two approaches should yield comparable results, in practice vertical datum differences can and do occur and these must be dealt with during the data integration process. The datum establishment technique used for topographic LIDAR is intrinsically more accurate and more precise than the bathymetric approach and this should be given due consideration in the integration computations.

Finally, it should be pointed out that bathymetric LIDAR systems are designed primarily to provide data for hydrographic charting. In this context they return the depth of the highest feature within the bounds of the laser spot. They are therefore referred to as being “shoal biased”. Because the laser spot is quite big in comparison to a topographic LIDAR system, it will often be the case that, in the overlap area, bathymetric LIDAR will return a terrain height above than that returned by a topographic laser scanner.

3. TOPOGRAPHIC AND BATHYMETRIC LIDAR IN THE LITTORAL AND NEAR-SHORE ZONE

The objective here is to investigate the integration of bathymetric and topographic LIDAR data in light of the ultimate goal of creating a continuous and seamless DEM that spans the inter-tidal zone.

To help identify and explain the key issues that impede data integration, an analysis of the relationship between bathymetric LIDAR and topographic LIDAR data in the Port Phillip Bay case study area has been undertaken. The results of this analysis are presented principally in relation to vertical datum differences and horizontal gaps in the data sets.

3.1 Vertical Alignment

In the Port Phillip Bay case study area, separate (1m x 1m) DEMs were created from the bathymetric and topographic LIDAR data. In the area of overlap, principally along the foreshore, heights from matching grid nodes were extracted and compared. This comparison avoided the problem of first return (bathymetric DEM) versus last return (topographic DEM) by ensuring that in the area of overlap, no vegetation or buildings were present to corrupt the analysis.

The mean height difference in the overlap area between the two DEMs put the bathymetric LIDAR data +0.359m above the topographic LIDAR data. This difference varied considerably, depending on topography. Where the terrain was relatively flat, the differences were generally smaller and more consistent (e.g. +0.341±0.317m in the east). Where there were cliffs and a steeper beach profile the differences were greater and more variable (e.g. +0.401±1.200m in the west). Regardless of the topography, however, heights derived from the bathymetric LIDAR data were always above those derived from the topographic LIDAR data. This result implies a potential problem in the registration of the two data sets to a consistent vertical datum and possible influences caused by the shoal-biased nature of the LADS data, particularly in steep and irregular terrain.

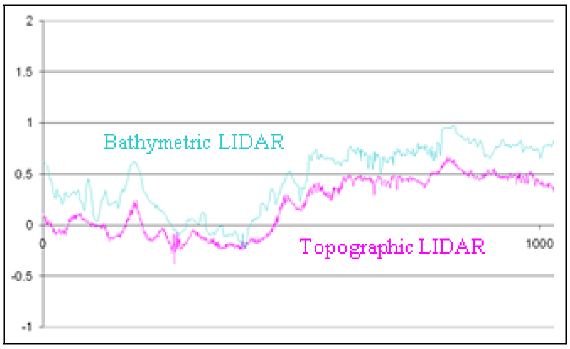

Figure 5. LIDAR Foreshore Profile Comparison

Figure 5 shows a one kilometre section of a profile taken along the foreshore in the eastern part of the case study area where the beach was open and relatively flat (no cliffs). The diagram illustrates the typical nature of the relationship between the two data sets in the vertical sense, with the LADS data generally above the topographic LIDAR data.

3.2 Horizontal Gaps

Figure 6 shows the topographic LIDAR measurements in red and the bathymetric LIDAR soundings in black for a short length of the eastern section of the near-shore zone of the Port Phillip Bay case study area. It can be seen that four distinct cases exist in relation to gaps in and between the data sets:

- Case 1: No gap – LADS and topographic LIDAR overlap (simultaneous black and red)
- Case 2: Gap – No LADS or topographic LIDAR data (white)
- Case 3: Gap – Hole in the LADS data (red only)
- Case 4: Gap – Hole in the topographic LIDAR data (black only)

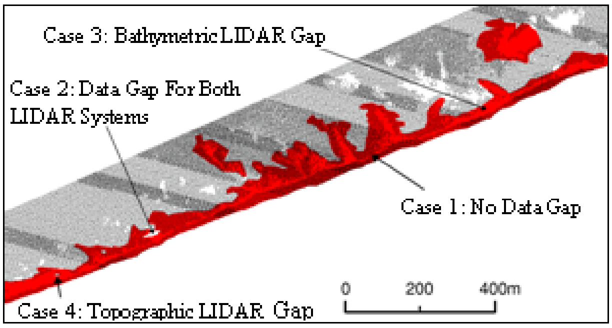

Figure 6. Horizontal Data Gaps

In order to integrate two datasets mathematically there must be a reasonable degree of overlap. While data gaps can be dealt with, in the interests of maintaining quality in the generated DEM, they should in general be small and infrequent. The greater the prevalence of data gaps, the more challenging will be the integration process. Conversely, the higher the degree of overlap, the higher the probability of achieving a smooth, seamless and realistic integrated solution. As can be seen from the typical example above, the extent of overlap between topographic and bathymetric LIDAR datasets in the near-shore region varies considerably, depending mainly on the width and, to a lesser extent, the slope of the beach. A wide beach maximises the potential overlap. However if the beach is very flat, the bathymetric LIDAR system will likely struggle to acquire dependable depth measurements in the very shallow water (<0.3m). All bathymetric LIDAR systems suffer from the difficulty of not being able to measure depths shallower than about 0.3m. The problem arises due to an inability to distinguish between the surface and the bottom return pulses when they are very close together in time.

Any proposed data integration strategy must not only bring together the LIDAR datasets in the area of overlap, it must also provide a means of extrapolating across the data gaps. The extrapolation process is inherently dangerous as there is generally no "ground truth" to constrain the result or to test the validity of the solution. Thus the objective during any data collection process must be to minimise the data gaps and to maximise the overlap. As a first step, this can be done by collecting the bathymetric LIDAR data at high tide and the topographic LIDAR data at low tide. Conforming to these conditions will produce the best possible dataset to perform the integration and will minimise (though likely not eliminate) the need for extrapolation.

4. MATHEMATICAL SOLUTIONS AND CONSIDERATIONS FOR THE INTEGRATION PROBLEM

4.1 Integration Techniques

This section provides a brief overview of possible integration techniques. For the purposes of this discussion, it is assumed that, due to its lower vertical accuracy, the data derived from the bathymetric LIDAR system will be shifted to conform to the topographic LIDAR data.

4.1.1 Mean Height Difference: This method involves shifting the entire bathymetric dataset by the mean height difference derived from comparison against the topographic data in the overlap zone. As already seen, the mean difference can be highly variable, making the results of this technique somewhat unsatisfactory. Obviously, a more sophisticated modelling technique would yield a more acceptable solution.

4.1.2 3D Conformal Transformation: This method is frequently used in geodesy and photogrammetry to co-register 3D data sets. The conformal transformation shifts, rotates and scales one data set to best fit the other. The computation of reliable transformation parameters requires strong spatial overlap between the datasets and the existence of at least three well-defined common points distributed evenly across the area of overlap. These pre-conditions are never satisfied in the case of integrating bathymetric and topographic LIDAR, since the overlap region is generally very narrow and common points do not exist. If the conformal transformation approach was to be applied to this problem, it is likely that unstable and unreliable results would be achieved, particularly when extrapolating beyond the overlap area.

4.1.3 Iterative Closest Point (ICP): The ICP algorithm was developed for co-registering terrestrial laser scanning data of the same or overlapping objects, but gathered with respect to different coordinate systems (Bae, 2004). Unlike most other transformation techniques, the ICP algorithm offers the advantage that it does not require the existence of common points. Rather, it is based on the principle of minimising the difference between the two "surfaces" represented by the respective point clouds. However, in the context of the current integration problem, ICP suffers from the rather serious limitation that it maintains the shape of each data set and therefore, in a vertical sense, only has the ability to eliminate the vertical datum difference in much the same way as subtracting the mean height difference, making it equally inappropriate for the problem at hand.

4.1.4 Least Squares Collocation (LSC): Like the 3D conformal transformation approach, LSC generally requires the existence of common points in order to derive a covariance function to represent the spatial relationship between the two data sets. While, as already pointed out, common points do not normally exist at the raw data level, it may be possible to perform the integration at the DEM level, in which case matching grid nodes could be used as the basis for developing the covariance function. The principle advantage of LSC is that it provides a smooth point-based interpolator that simultaneously offers a means of controlling the influence of the topographic data on the offshore bathymetry. Thus the offshore impact of the integration process can be minimised, retaining the integrity of the original data set.

4.1.5 Other Surface Fitting Techniques: If integration can be done at the DEM level rather than the raw data level, a plethora of other integration techniques emerge, including multiple regression surfaces and minimum curvature surfaces. It should be pointed out however that the very limited overlap that inevitably exists between bathymetric and topographic LIDAR data will restrict the applicability and performance of all of these techniques.

4.2 Integration Considerations

Once an appropriate model is chosen to perform the data integration there are still several considerations to take into account. These include:

- Whether to shift the bathymetric LIDAR to the topographic LIDAR or to do a weighted shift of both datasets, taking into account their relative accuracies.
- Whether to perform the integration in 3D or just vertically.
- How to taper the shift beyond the area of overlap. Typically, the overlap is relatively narrow and there seems little justification in changing heights significantly beyond this zone. As previously mentioned, the LSC technique offers a good strategy for tapering the impact of the transformation.

5. CONCLUSION

It is clear that in the first instance topographic and bathymetric LIDAR data cannot be readily integrated for three main reasons. Firstly, though each system aims to relate height/depth data to a common datum (e.g. AHD), different methodologies used to realise this datum lead to differences that must subsequently be accounted for. Secondly, even under ideal conditions, the extent of the overlap of the data sets in the littoral zone is inevitably limited. This problem is further exacerbated by the fact that both bathymetric and topographic LIDAR systems suffer physical limitations in the dynamic littoral zone that can at times produce extensive data gaps. Thirdly, while topographic LIDAR systems tend to produce more reliable data in the overlap zone, neither system is perfect. Both are subject to the influence of random measurement errors (statistical noise). The existence of noise must be realistically accommodated in the integration process.

A number of techniques can be considered as valid options for performing the integration computations. The LSC technique is potentially the most promising. However, no matter what strategy is employed, the very limited overlap between the data will inevitably pose a challenge to achieving a satisfactory solution.

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