Assessing the Potential of LiDAR/Bathymetry Integration within the Thames Estuary

Thomas LOWE, United Kingdom

Key words: Topographic LiDAR, single beam bathymetric data, Port of London Authority, inter-tidal zone, cost benefit analysis, OSGM02 geoid model, LiDAR/Bathymetry integration.

SUMMARY

Remote Sensing offers the potential to develop high resolution Digital Terrain Models (DTMs) of coastal areas, including the land adjacent to the shoreline, the near-shore and the inter-tidal zone. Laser ranging (LiDAR) technology has demonstrated its capability in producing DTMs with footprints of less than a meter, and vertical resolution at sub-decimetre levels. This project focuses on results recently obtained from a pilot project testing data from the UK Environment Agency's Airborne Laser Terrain Mapper (ALTM-1020) and Port of London Authority (PLA) acoustic single beam bathymetric data. An investigation was carried out to assess the cost effectiveness and viability of LiDAR to provide accurate, high resolution data which can be integrated with existing PLA bathymetric data to produce more effective products by enhancing coastal charting in near shore intertidal zones.

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1. INTRODUCTION

The inter-tidal zone is difficult and costly to chart accurately using traditional hydrographic methods. In addition there is also a horizontal limit to which shallow soundings may be safely acquired (shoreline proximity). By acquiring intertidal zone data at low tide using LiDAR, one can obtain continuous, 'full bottom coverage' allowing a seamless integration of LiDAR data with existing bathymetry. Rocks, shoals, and near shore infrastructure are critical features for the mariner and accurate description of wharves, docks, and navigation channels are required for Port of London Authority charts. Potential flood areas of coastline can also be accurately determined with high resolution Digital Terrain Models using ALTM LiDAR. The main aim of this project is to test the compatibility of hydrographic and LiDAR data sets within the intertidal zone. This will be achieved by comparing data points from the two techniques which occupy the same coordinates in the study area of Leigh Sands, situated on the Thames Estuary, London. A detailed knowledge of the errors within each data collection technique will be used to assess weather any offset found can be systematically removed and the data sets confidently integrated.

2. DATA COLLECTION TECHNIQUES

2.1 Topographic LiDAR

The LiDAR system used by the UK Environment Agency (UKEA) to collect the data for this project is the Optech ALTM 1020. The UKEA's aircraft flies at a height of approximately 800 metres above ground level, allowing a swath width of about 600m. Individual measurements are made on the ground at 2 metre intervals. The vertical accuracy (z) of the LiDAR data is +/- 15cm (1 sigma*) (Optech Inc. - http://www.optech.on.ca), and the horizontal accuracy is better than 1/2,000 x altitude. At a flying height of 800m, this corresponds to an error of 0.4m in x and y. The UKEA claim a relative vertical accuracy (allowing for Ordnance Survey transformation error using OSTN97 with OSGM91 geoid) of 11-25cm. With the new transformation, OSTN02 and geoid model, OSGM02, this relative accuracy will improve.

* 1 sigma specification, meaning ~68 percent of the data will fall within this limit; 2 sigma (95 percent) or 90 percent (1.6 sigma).

2.2 Single Beam Acoustic Bathymetry

Acoustic depth measurement systems measure the elapsed two-way travel time that an acoustic pulse of energy takes to travel from a transducer to the sea bed and back again. The travel time of the pulse depends on the velocity of sound propagation through water (v). As the transducer collects acoustic returns, the location of the data is simultaneously recorded using a precise differential GPS service. Bathymetry data was collected using PLA survey vessels over 2 surveys (i.e. 1 survey for original runlines, 1 survey for checklines).

3. STUDY AREA: LEIGH - SANDS - THAMES ESTUARY, LONDON, UK

A number of intertidal areas within the Thames Estuary were proposed for this pilot study including Blyth Sands, Hole Haven Creek (Canvey Island) and Leigh Sands. After a number of discussions with the UKEA, two 2km*2km tiles of LiDAR data for the Leigh Sands area were supplied in ASCII Grid format free of charge. Single Beam bathymetry data, including checklines, were supplied by the PLA in XYZ format. The LiDAR dataset is visualised below (Figure 1). Note: to enable the comparison to be successful, the LiDAR survey was undertaken at low tide, while the bathymetry data collection was undertaken at high tide.

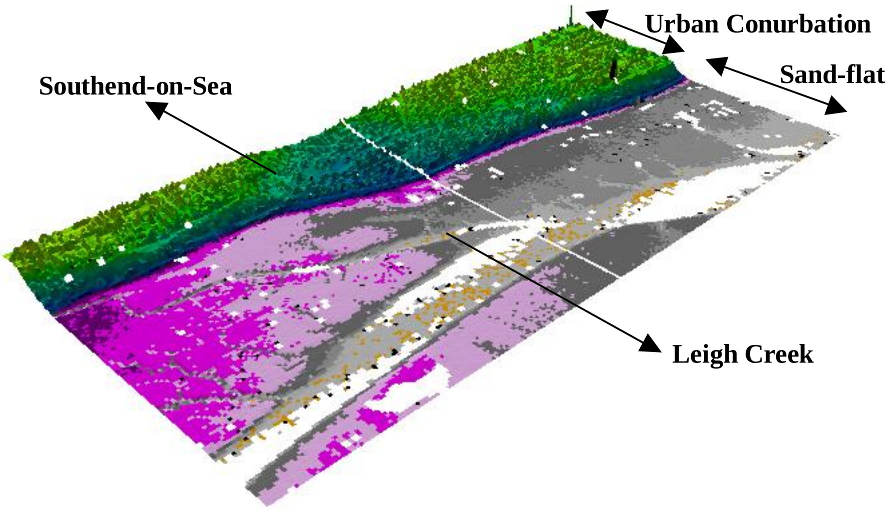

Figure 1 – UKEA LiDAR Data Tiles

4. METHODOLOGY AND APPROACH FOLLOWED

The purpose of this research is to test the compatibility of integrating hydrographic and LiDAR data sets within the intertidal zone. This was achieved by first of all referencing both datasets to the same horizontal and vertical reference systems (OSGB36 (X and Y) and ODN (Z)), and extracting a number of profiles for comparison. Data points from both techniques were selected which co-exist in the same position in space (i.e. have the same or similar x, y coordinates). A comparison can then be made and their agreement concluded.

4.1. Integration within a GIS Environment

To enable the 2 datasets to be analyzed a GIS environment was used (ESRI ArcMap/INFO). The bathymetry data was reduced to Ordnance Datum Newlyn (the local datum for the UK – orthometric height) and converted from its XYZ format into .shape file format. The LiDAR dataset was provided in ASCII raster grid format; this makes xyz extraction more difficult.

To allow the conversion of a raster grid dataset to a more usable format, an avenue script was incorporated into the GIS. This script converted the raster grid to the desired xyz format. Access to the new geoid for the UK – OSGM02 (providing geoid-ellipsoid separation values) was available and was incorporated into the LiDAR data to improve conversion to UK local vertical datum ODN.

4.2. Profile Extraction

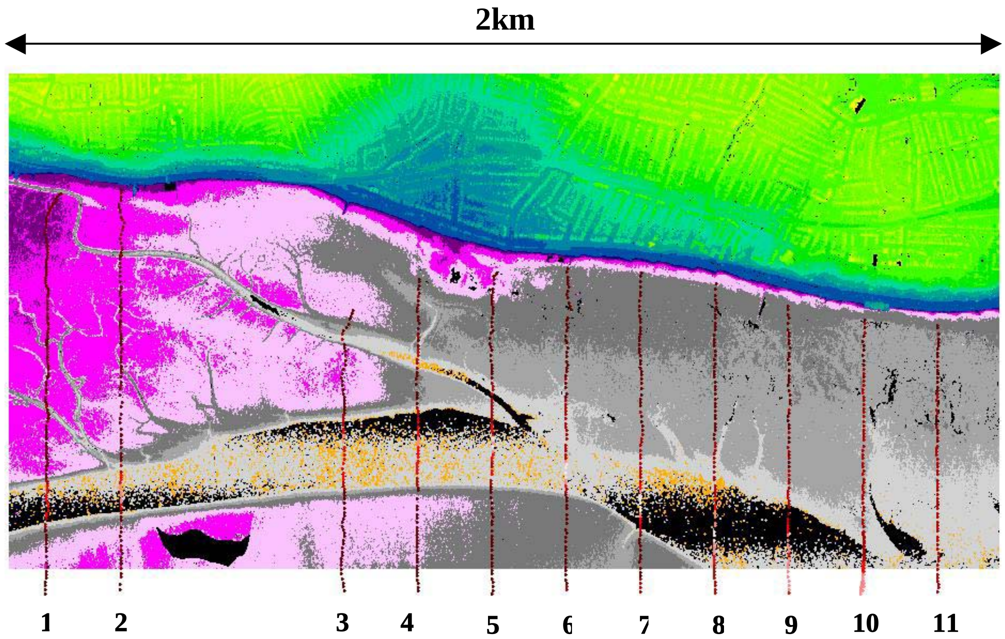

Figure 2 – LiDAR / Bathymetry dataset overlay

The profiles are defined by the bathymetry survey lines; there are 11 in total (figure 2). In addition, a number of check-lines were run perpendicular to those shown above to enable a degree of quality control to the hydrographic dataset. It is understood that the LiDAR and bathymetry data points will very rarely coexist in identical positions along the run lines. Therefore within ArcMap, data points from the LiDAR dataset that are within a radius of 1m to points in the bathymetry dataset were selected. Any pairs more than the defined 1m radius was rejected.

5. ANALYSIS

Fourteen (14) profiles in total were extracted from the GIS and inspected graphically in Microsoft Excel. The majority of profiles extend over 1500m and therefore appear in an exaggerated manner when graphically visualised. Eleven of the sets represent the original survey profiles, while the additional 3 checklines make up the remaining sets of profile graphs. The original survey was run perpendicular to the coastline in a northerly direction. To asses the change in height along the profile, height (z) was plotted against y (Easting). The checklines were surveyed parallel to the coastline in an easterly direction, therefore height (z) was plotted against x (northing).

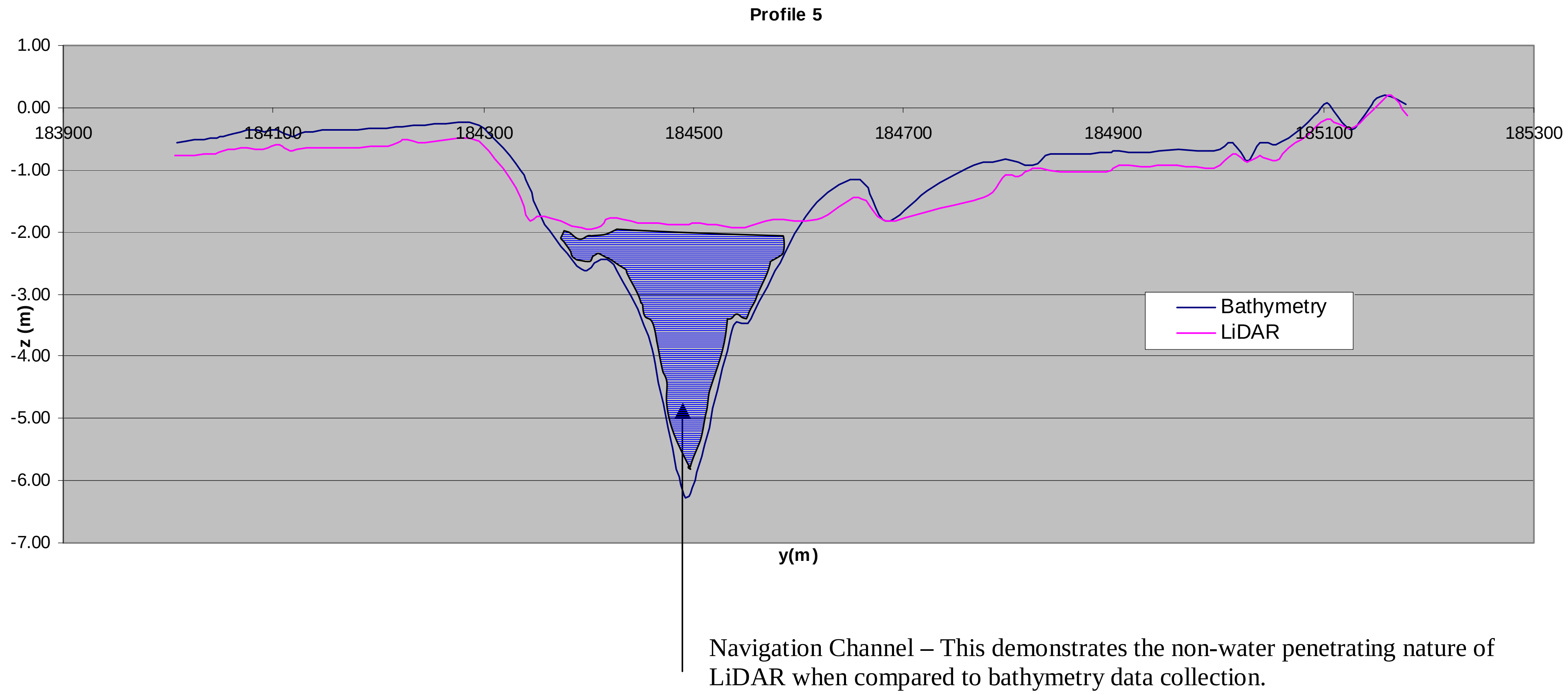

Figure 3 – Profile no. 5

Figure 3 is a common example of the type of profiles which were produced. From this figure it can be seen that the visual agreement between the 2 sensors is generally very good. An *averaged difference* (δz) of 0.19m and a standard error (σ) of 0.12m was found between the LiDAR and bathymetry datasets across *all* profiles. Note the navigation channel present in this figure 3. Many of the profiles demonstrate the non-water penetrating nature of LiDAR, and give a clear representation to the location of these water channels. In these areas there is little agreement between the 2 sources due to limitation of the LiDAR sensor. It is appropriate to filter out this type of anomaly as the LiDAR return is not realising the topographic features of the sands, but is describing the waters surface. Figure 3 demonstrates how the LiDAR return (purple) is reflected by the waters surface, and how the bathymetry profile (blue) describes the full topography of the channel. This effect is clear over many of the profiles, often more than once. All profiles were inspected for anomalies (i.e. a non-constant offset). It is important that the cause of the anomalies are fully realised and understood as any future filtering or integration with hydrographic data must take these variances into account to prevent the collection of false data. A number of anomalies were found while inspecting the profiles including; human error in filtering, puddling of water on sand-flats, spikes caused by vessels drying out on the flats at low tide during the LiDAR pass, and water logging towards the east of the study area.

To fully understand the quoted averaged difference and standard errors we must first look at the error sources of each system and decide weather we can *remove the constant difference* and integrate the datasets within set tolerances.

6. SYSTEM ERROR BUDGETS

6.1. Topographic LiDAR

When discussing the accuracy of LiDAR data, it is important to keep in mind that the theoretical error based on a rigorous engineering analysis of the system is generally not achievable in the field. Operational considerations, such as variations in GPS quality or poor weather conditions will significantly affect the final accuracy of the data. The **total error** for a LiDAR system is the contributing error budgets from each of the subsystems; the laser range finder, the GPS positioning, and the IMU orientation error. Contributions include such factors as the inbuilt pointing error of the laser, sensor mounting biases (small angular misalignments between the laser reference frame and the IMU reference frame) and the error in recording the scanner angle at the moment of each laser pulse. Unfortunately, the operational accuracy that can be achieved is generally worse than the theoretical error limit. As a result there is a lack of a clear definition of what is meant when stating accuracy for LiDAR data. A number of important issues need to be considered when discussion LiDAR accuracies are:

- Accuracies will vary under different conditions across a project, such as areas of steep slope or from the maximum angle of the scan to the minimum angle of scan.
- The complex interaction of the transmitted pulse energy with the finite footprint on the target needs to be carefully considered. A bright target within the footprint can skew the return signal away from its geometric centre.

- An understanding of Geoid height model errors is needed as these will impact final accuracy.

Hill et al. (2000) believe that the inherent error budget of LiDAR sensor is 0.2 metres (vertical), however, a number of independent studies have demonstrated vertical accuracies nearer 0.15m (UK EA, Optech Inc, Infoterra). The UK EA claim a relative vertical accuracy (allowing for OS transformation error using OSTN97 with OSGM91 geoid) of 0.11-0.25m. With the new transformation, OSTN02 and geoid model, OSGM02, this relative accuracy will improve to approximately 0.11-0.20m. Accuracies can be further enhanced with additional ground survey control. An accuracy of +/-0.2m will be used in this project.

6.2. Single Beam Acoustic Echo Sounder

The total error of the system is a sum of both constant and depth dependent errors. The International Hydrographic Organisation (IHO) has quoted error limits for depth accuracy in hydrographic surveys using the equation below. The total sounding error at the 95% confidence level shall not exceed:

$$\pm\sqrt{[a^2+(b\times d)^2]}$$

For order 1 surveys, i.e. harbours and harbour entrances up to 100m depth:

- a= 0.5m and represents the sum of all constant errors,
- (b x d) represents the sum of all depth dependent errors,
- b = 0.013 and is a factor of depth dependent errors,
- d= depth (m)

For a depth of 6m, the total sounding RMS error must not exceed **+/- 0.51m.** This is a very safe estimate of error, but will be used in this project.

6.3. Ensonified Areas

The size and interaction of the sensor's footprint with the seabed can have a number of important effects on the depth/height value recorded by the sensor. These interactions will be discussed in this section.

6.3.1 Bathymetry

Each acoustic ping will ensonify an area of the sea bed. The size of this ensonified area is a function of the transducer beam width and the depth. The footprint size of a transducer can be computed as follows:

$\tan(\alpha/2) = r/D \rightarrow r = D\cdot\tan(\alpha/2)$

$Area = \pi\cdot r^2 \rightarrow Area = \pi\cdot D^2\cdot \tan^2(\alpha/2)$

Footprint area coverage: (m^2) $= \boldsymbol{\pi\cdot D^2\cdot \tan^2(\alpha/2)}$

The linear coverage of the footprint = 2r $\rightarrow$ ***2 (D · tan (α / 2))***

Leigh sands is a drying zone, therefore any surveys undertaken in this area would be at depths equal to or less than the value of high tide. The largest footprint will occur in the deepest water. This has been estimated to be 6m (on a good spring tide).

	Frequency (kHz)	
@ 6m depth	**33**	**200**
Beam Angle (˚)	16.5	8
Footprint (m^2)	2.38	0.55
Linear coverage (m)	1.74	0.84

Table 1 – Acoustic footprints of a single-beam echo sounder

Due to the shallow operating depths of this project, the acoustic footprints calculated are relatively small. This will reduce the acoustic return and shoal bias errors to a minimum, as the return is being averaged over a smaller area and the depth recorded is the true depth at nadir. In addition, Leigh Sands is a topographically flat area. Depth changes at a rate of no more than 2m over 1000m and there are very few rocks or steep gradients which may add shoal bias to the return signal. Combined with a shallow survey depth, this will reduce these errors further.

6.3.2 LiDAR

The method used to calculate the LiDAR footprint is identical to the footprint calculated for the bathymetry above. The LiDAR sensor has an angle resolution of 0.01˚, and a flying height of 800m.

Footprint area coverage: (m^2) = $\pi \cdot 800^2 \cdot \tan^2 (0.01 / 2) = 0.02m^2$
The linear coverage of the footprint = 2r $\rightarrow 2\ (800 \cdot \tan\ (0.01 / 2)) = 0.14m$

6.3.3 Footprint Comparison

The footprint and linear coverage for both sensors are compared below (table 2.)

	Sensor	
@ 6m depth	**Echo-Sounder**	**LiDAR**
Footprint (m^2)	0.55	0.02
Linear coverage (m)	0.84	0.14

Table 2 – A comparison of sensor footprints

The footprint and linear coverage of the LiDAR sensor is significantly smaller than that of the bathymetry sensor. This difference can have a marked effect on the first return, hence the depth/height recorded. For example (figure 4), if the shoalest depth is at point 1 (outside the footprint of the LiDAR sensor) then at these coordinates, the echo-sounder will record a shallower depth than the LiDAR sensor. If the shoalest depth is at point 2 (within both footprints) then both sensors will record the same return and the agreement of the sensors will improve.

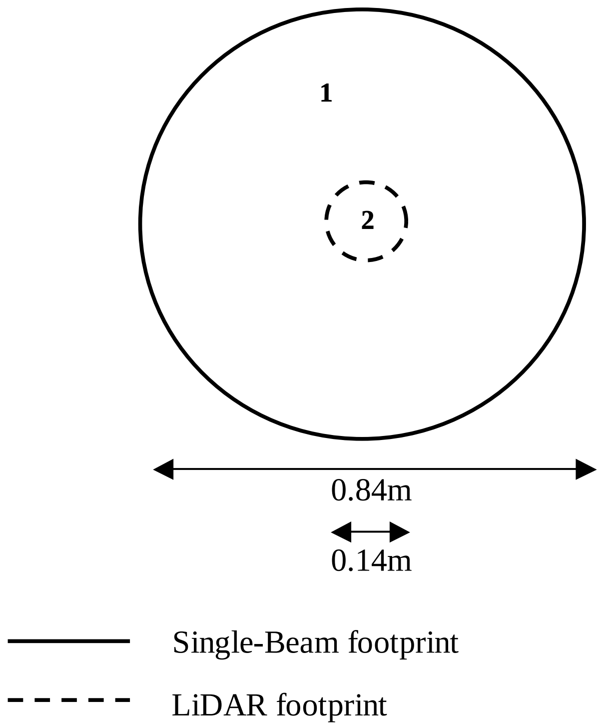

Figure 4 – Footprint comparison

The probability of the shoalest depth *only* occurring in the echo-sounder footprint is far larger than the probability of it occurring within both footprints. Therefore the single-beam return will record shoaler depths more often than the LiDAR sensor. This hypothesis is reflected in the profile graphs where the single-beam sensor consistently records shoaler values than the LiDAR sensor.

6.4. Sounding Comparison

A sounding comparison was made between the original bathymetric survey and the checkline survey, in order to validate the accuracy of the bathymetry data. The agreement between the 2 surveys was very good (averaged difference (δz) of 0.06m and a standard error (σ) of 0.10m) and proves that the bathymetry data is of high quality.

7. DISCUSSION

The total averaged difference for all data pairs is *0.19m* and standard error (σ) of *0.12m*. The statistical values quoted above compare favourably to previous studies involving LiDAR comparisons. The University of Texas recently studied the accuracy of Optech's ALTM 1020 at a similar altitude by comparing ALTM data with GPS ground surveys along 50Km of roads (www.beg.utexas.edu/coastal/survey/altm.htm). A mean elevation difference (δz) of -0.184m and a standard error (σ) of 0.152m were determined. The 'negative δz' indicates the LiDAR sensor is recording lower heights than the reference surface (GPS survey). This is also seen in this project where all LiDAR values are consistently lower than the bathymetry soundings (by 0.19m). These values represent elevation bias (δz) and a noise component (σ) within the ALTM system. The GPS survey used in the study undertaken by the University of Texas made it a highly accurate reference surface on which to compare LiDAR. And the majority of the difference can be attributed to the LiDAR sensor. In this project (Leigh Sands), both sensors may have equally large or small errors within their systems. This makes it extremely difficult to assign specific errors and define the cause of the constant offset. Figure 5 visually demonstrates the situation. The calculated averaged difference (δz) of 0.19m has been used as the offset between the LiDAR and bathymetry heights. The error margins for the sensors have been discussed in section 6 have been used.

From figure 5 it can be seen that one can adjust either the LiDAR or Bathymetry datasets by 0.19m and remove the constant offset, hence improving agreement and allowing integration. All of this can be achieved within the defined error margins

The LiDAR dataset and not the Bathymetry dataset should be adjusted for a number of reasons. The first reason involves the practicalities of the integration processes. The PLA's aim is to integrate the LiDAR data into their bathymetry database, and not the other way around. If the bathymetry data was corrected then the whole PLA database would also have to be corrected by 0.19m, making this alternative out of the question. Additionally, when undertaking hydrographic surveys for port surveying (i.e. safety of navigation), one must always operate on the side of caution to ensure optimal safety to the mariner. It is therefore sensible to display shoalest depths to the end user. Here, this is achieved by adjusting the LiDAR dataset to represent shallower depths rather than adjusting the bathymetry dataset to represent deeper depths. Figure 5 demonstrates that adjusting the LiDAR values by +0.19m will still leave it within the tolerated error bounds of both sensors (as defined in section 6), yet allow successful integration. This is an extremely important point and is one of the major factors in determining the successful integration of these systems. The cause of the averaged offset has not been found. However the hypothesis stated in section 6.3 concerning footprint differences between the 2 sensors may be possible cause of such an offset. This cannot be proved but a detailed GPS survey may resolve this issue in the future

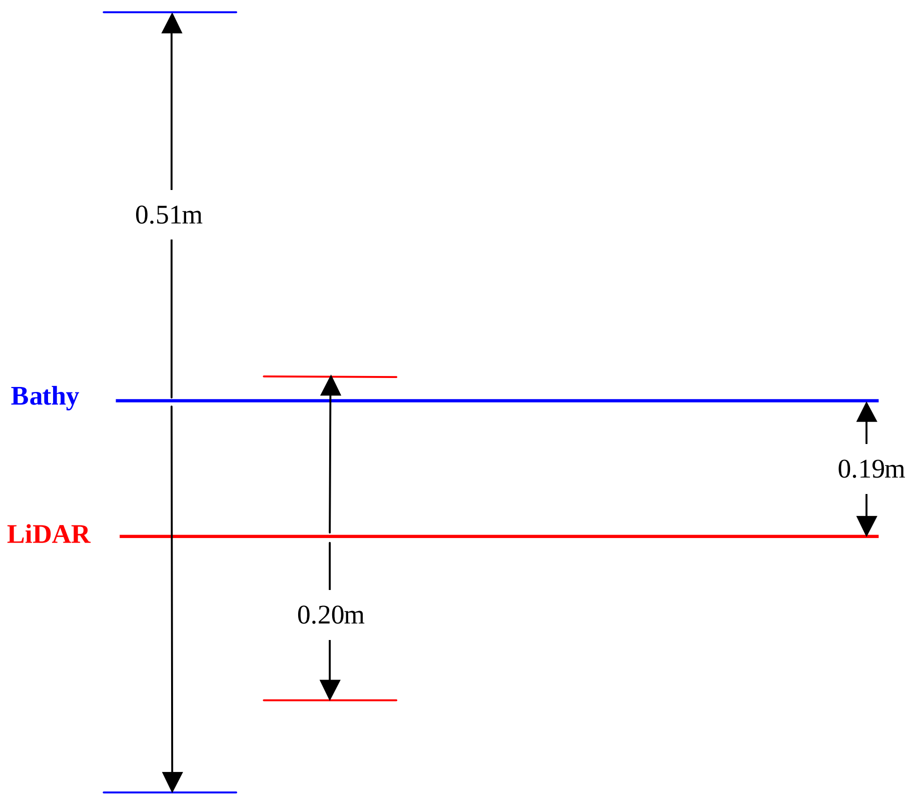

Figure 5 – Error margins

8. COST BENEFIT ANALYSIS

In order to make a thorough recommendation to the PLA regarding the use of topographic LiDAR to map the inter-tidal areas of the Thames Estuary, a cost benefit analysis (CBA) was formed. The aim of the CBA was to compare the PLA's existing method of inter-tidal mapping (single-beam bathymetry) with the potential of using topographic LiDAR and integrating it within the PLA bathymetric database. A number of indicators will be used including; cost, time, accessibility and safety, and overall efficiency.

8.1. Cost

8.1.1 <u>Hydrographic Survey</u>

In order to form a realistic costing sheet for this project, a number of assumptions had to be made regarding hours of survey, survey speeds, tidal heights, and a number of logistical issues. A detailed survey plan was constructed for each of the major intertidal zones of the Thames taking into consideration the above factors. An example of the costing sheet can be seen in Appendix A. Table 3 below summarises the 6 costing sheets produced.

Intertidal Area	Cost (£)
Southend and Chapman Sands	1,213.75
Blyth Sands and Yantlet Flats	1,451.89
Sheerness	760.51
Hole Haven Creek	1,160.75
Maplin Sands	6,668.91
Remaining sands in Estuary	3,943.31
TOTAL	**£ 15,199.12**

Table 3 - Estimated cost for hydrographic survey of intertidal Thames

8.1.2 Topographic LiDAR

The UK Environment Agency has quoted a survey price of £300/km^2, with a minimum project value of £10,000. The total intertidal area to be mapped is 43 km^2;

43 km^2 @ £300/km^2 = £12,900

The LiDAR survey must be flown during low tide; preferably during spring tidal ranges to enable maximum terrain to be mapped. The price calculated compares favourably to the hydrographic survey. However a number of other issues must be considered before a recommendation is made.

8.2. Time

8.2.1 Hydrographic Survey

From the detailed survey plans produced, the total survey time to cover all intertidal areas = 105.39 hours and would be surveyed over 2-3 weeks.

8.2.2 Topographic LiDAR

The LiDAR survey is very efficient, the UKEA believe this could be completed within *1 week*, weather depending (Nick Holden, EA).

8.3. Accessibility and Safety

8.3.1 Hydrographic Survey

There are a number of areas throughout the Thames where accessibility to hydrographic survey pose considerable problems. The two areas where the limitations of hydrographic techniques are most pronounced are Maplin Sands and Hole Haven Creek. Maplin sands are the 3rd largest in the UK, and prove a vast area to survey using traditional hydrographic techniques (approximately 50 survey hours). This area is also highly inaccessible due to its designation as a firing practise area, where any attempt to carry out a survey would cause significant disruption to range activities. Accessibility is a major issue in Hole Haven Creek. In this area, hydrographic surveys must be meticulously planned to enable maximum data collection at high tide extending into the upper reaches of the creek. The surveyor must first 'recce' the area on foot to ensure all parts of the creek are accessible at high tide. Timing is essential as the turn of the tide can be very quick, much care and planning must be taken to allow safe passage out of the creek on the ebb tide. Inadvertent grounding of the vessel on the ebb may leave the surveyor stranded over a large area of quick sand or mud.

8.3.2 Topographic LiDAR

LiDAR is a more flexible system, as it can be flown during the day or night. This provides increased access to low (spring) tides and improves efficiency. The issues raised above regarding accessibility are easily solved using LiDAR as large areas of terrain can be covered in a non-intrusive manner. For example, the firing range at Maplin Sands may not have to be closed at all, as the LiDAR survey could be flown at night, or at a sufficient altitude to cause no disruption to range activities. The meticulous planning and safety issues which were described for surveying Hole Haven Creek would be minimized during a LiDAR survey. At a flying height of 800m and a swath width of 600m the majority of this area could be mapped in one pass, and would not be pressurised by the ebbing tide.

The cost benefit analysis has concluded that using topographic LiDAR to survey the intertidal Thames is both cost effective and significantly more efficient than traditional hydrographic techniques. Large expanses of sand flat (e.g. Maplin sands) can be mapped efficiently in a non-obtrusive manner, while smaller more inaccessible areas (e.g. Hole Haven Creek) can be mapped with little regard to the meticulous survey planning and safety issues which plague traditional hydrographic surveys in these areas.

9. CONCLUSION

There were 2 main aims of this study. The primary aim was to test whether single-beam acoustic bathymetry data could be successfully integrated with topographic LiDAR for intertidal zone mapping. The secondary aim was to perform a cost benefit analysis to assess whether integrating these 2 data sources was a cost effective and efficient solution for intertidal mapping within the Port of London. Leigh Sands was selected as the pilot study area to test the data integration processes. Data was obtained from the UK EA and the Port of London Authority. Geodetic datums played an important part in this project. The new geoid for the UK (OSGM02) was successfully incorporated into the datum transformation parameters, thus improving data accuracy. Fourteen profiles were extracted from the study area; both graphical and statistical comparisons were used to assess the agreement between the 2 sensors. Following a programme of detailed filtering, a systematic offset was defined and used to correct the LiDAR dataset. Successful integration with the bathymetry dataset was achieved within the tolerance of all standard errors. Close attention must be paid to the profile anomalies highlighted in this project, where detailed detection and filtering must be addressed during any future work in this area. The cost benefit analysis proved that using topographic LiDAR to survey the intertidal zone saved both money and time. Within the profile discussion there was still some uncertainty to the cause of the constant offset found. To resolve this question, future directions of study may involve performing a detailed RTK GPS survey of the study area to enable an accurate reference surface on which to compare existing datasets. In addition, future work may involve developing a filtering algorithm to remove a number of the anomalies highlighted within the dataset. The PLA should be advised that using topographic LiDAR for surveying the intertidal Thames is both a cost effective and efficient option which they must consider. There are however various issues, as outlined above, which do require further investigation before integration can be put into practise. This includes an essential study into the definition of rigid standards to which data integration must perform, and an increased awareness of the data sharing initiatives currently in use by the Ordnance Survey, UK Hydrographic Office and the Environment Agency

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BIOGRAPHICAL NOTES

This paper is a brief summary of my MSc Thesis in Hydrographic Surveying undertaken at UCL in 2002. I am currently working in the offshore sector as a hydrographic surveyor.

CONTACTS

Mr. Thomas J Lowe
University College London
UNITED KINGDOM
Email:tom@ukshells.co.uk

Appendix A - Budget - Hydrographic Survey

Item	Rate / hr
Verifier	162.00
Yantlet	64.00
Brent	14.00
Hydrographic Surveyor	29.47
Master Grade 7	27.40
Mate Grade 9	21.40
AA Grade 12	13.72

Southend and Chapman Sands

Line spacing @ 0.3km*	0.6		
Length of lines (km)	1.5		
Survey Speed (kts, ms^{-1}, $kmhr^{-1}$)	5	2.57	9.26
Cruising speed (kts, ms^{-1}, $kmhr^{-1}$)	16	8.22	29.63
Distance to survey area - return (km)	40		

	No. of lines	Time / line (hr)	Total Time (hr)	Rate / hr	Total (£)
Vessel (Yantlet) @ 5knots	32	0.16	5.18	64.00	331.75
Time between lines	32	0.02	0.65	64.00	41.47
Mobilisation (x2) ** @ 16knots			2.70	64.00	172.79
Hydrographic Surveyor			8.53	29.47	251.42
Master Grade 7			8.53	27.40	233.76
Mate Grade 9			8.53	21.40	182.57
				Sub TOTAL	**£1,213.75**

**Survey performed over 2 high tides (i.e. 2 days)

* Lines run in 2 sets (near shore then offshore), therefore line spacing of 0.3km = 0.6km as effectively survey is run twice