

Comparing LiDAR and Acoustic Bathymetry Using Total Propagated Uncertainty (TPU) and the Combined Uncertainty and Bathymetry Estimator (CUBE) Algorithm

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Abstract

In August 2007, Fugro Pelagos collected data with the SHOALS-1000T bathymetric LiDAR system in Shilshole Bay, Seattle, for NOAA OCS. Data were collected at various spot spacings, altitudes, and times of day, over an area previously surveyed with an 8101 multibeam echo sounder. In addition, the area contained targets of known size, built and placed on the seafloor by Fugro Pelagos in 2005.

Previously, when comparing LiDAR datasets to other LiDAR or acoustic datasets, the comparisons have always presumed that one control dataset is ultimately correct, with no errors. All error is attributed to the second dataset. Surface and target analysis methods have therefore been somewhat subjective.

However the use of TPU takes into account the fact that each depth or elevation point is an estimate with an associated uncertainty. These uncertainties can then be used by the CUBE algorithm to build an attributed bathymetry surface: now a required standard deliverable for NOAA OCS.

This paper discusses how TPU and CUBE were used for the first time to compare LiDAR bathymetry and acoustic datasets. It will include a review of the difficulties in developing the process, the parameters used and the results of the analyses.

Introduction

In August 2007, Fugro Pelagos collected data with the SHOALS-1000T bathymetric LiDAR system in Shilshole Bay, Seattle, for NOAA OCS. Data were collected at various spot spacings, altitudes, and times of day, over an area previously surveyed with an 8101 multibeam echo sounder. In addition, the area contained targets of known size, built and placed on the seafloor by Fugro Pelagos in 2005. Data were collected to study the Total Propagated Uncertainty (TPU) of the SHOALS-1000T LiDAR measurements and the system's target detection capabilities.

Target detection tests have been conducted previously over the Shilshole area, for the LADS, SHOALS-400 and SHOALS-1000T sensors (McKenzie et al., 2001; Lockhart et al., 2005). However previous comparisons, have always presumed that the multibeam control dataset is ultimately correct, with no errors. Therefore, all error is attributed to the LiDAR dataset. Surface and target analysis methods have consequently been somewhat subjective. In addition in areas with many targets, they can become very labor intensive. Target detection for hydrographic surveys is currently specified by the International Hydrographic Organization (IHO) Special Publication No. 44 (IHO, 1998).

The use of TPU takes into account the fact that each depth or elevation point is an estimate with an associated measurement uncertainty. These uncertainties can then be used by the Combined Uncertainty and Bathymetry Estimator (CUBE) algorithm developed at the University of New Hampshire (Calder and Mayer, 2001) to build an attributed bathymetry surface: now a required standard deliverable for NOAA OCS.

If surfaces can be built, with knowledge of the uncertainty, then there is the potential to use the CUBE algorithm to compare these different density multibeam and LiDAR datasets more objectively, including for target detection. In theory this would allow the analysis of the final surfaces to see if they represent the same seafloor, and targets, once the uncertainty of the measurements is taken into account.

Before the CUBE analysis can be conducted however, TPU models must exist for each dataset. Although TPU is now commonly used for multibeam data processing, a TPU model did not exist for the SHOALS-1000T data. Therefore the first step was to develop this uncertainty model.

Data Acquisition

Shilshole Bay in Puget Sound, Washington has been used extensively in the past by NOAA OCS and Fugro Pelagos to conduct multibeam sonar and LiDAR verification surveys. For this study, multibeam data was acquired with a Reson 8101 multibeam echosounder (MBES) in 2005, shortly after manufactured targets were placed on the seafloor. Figure 1 shows a color-coded DEM of the MBES coverage, the location of the targets and the planned extents of the LiDAR acquisition.

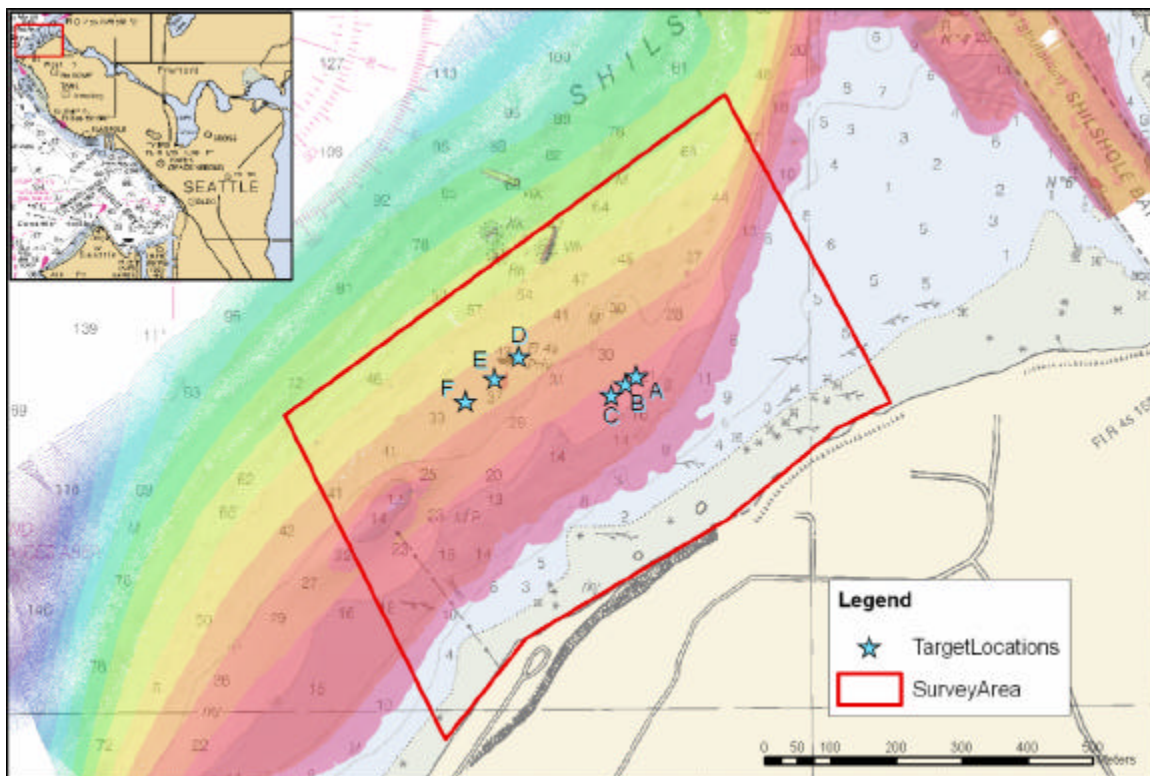


Figure 1 – Survey Location, Shilshole Bay, Puget Sound, WA

The targets themselves are boxes constructed from steel, as seen in Figure 2. Three sizes were constructed: 2x2x2m, 2x2x1m and 1x1x1m. One target of each size was placed 7m water depth (reduced), and another set of targets was placed at approximately 12.5m water depth, as indicated in Table 1. Although initially reflective, over time these targets reflectivity has become very similar to that of the surrounding seafloor (Figure 2).

Table 1 Shilshole Target Descriptions

Target ID	Target Description	Latitude	Longitude	Approximate Depth (m)
A	2x2x1m	47-40-16.42N	122-25-12.67W	7
B	2x2x2m	47-40-16.06N	122-25-13.47W	7
C	1x1x1m	47-40-15.53N	122-25-14.46W	7
D	2x2x1m	47-40-17.45N	122-25-21.19W	12.5
E	2x2x2m	47-40-16.38N	122-25-23.01W	12.5
F	1x1x1m	47-40-15.25N	122-25-25.10W	12.5

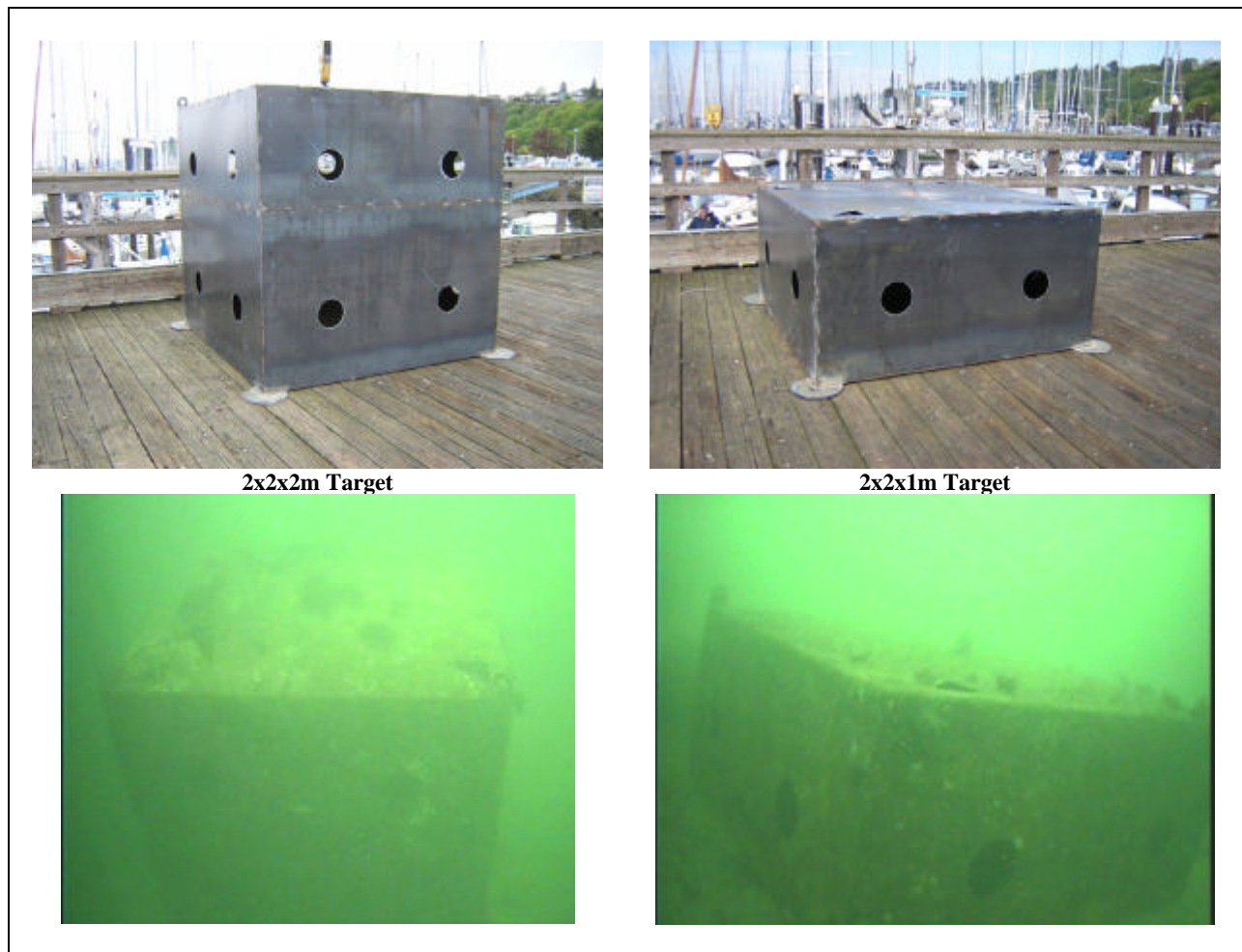


Figure 2 - Targets: Constructed and on the Seafloor in December 2007

The SHOALS-1000T survey took place on August 27 to 29, 2007 during which the following data were collected:

- Bathymetric LiDAR data from the SHOALS-1000T
- Digital Aerial Photography from the SHOALS-1000T
- GPS Ground Control

The hydrographic LiDAR flight lines were planned to collect data from the approximate location of the mean high water (MHW) line out to the 20m depth contour. The survey limits included the area where targets were set on the seabed in 2005.

Survey flight missions were conducted at various spot spacing, flight altitudes, flight line directions and time of the day as shown in Table 2. In all instances lines were planned with 20% overlap. These multiple datasets were collected so that percentage of data coverage (i.e. 100%, 200%, 300%, etc...), flight altitude, flight direction and time of day could be assessed to see how each factor may or may not affect bathymetric LiDAR target detection.

Table 2 Bathymetric LiDAR Acquisition Missions

Mission	Spot Spacing (m)	Altitude	Direction	Time of Day
1	3x3	400m	E → W	Day
2	3x3	400m	W → E	Day
3	3x3	400m	E → W	Day
4	3x3	400m	E → W	Night
5	3x3	400m	W → E	Night
6	3x3	300m	E → W	Night
7	3x3	300m	W → E	Night
8	2x2	400m	E → W	Day
9	2x2	400m	W → E	Day
10	4x4	400m	E → W	Day
11	4x4	400m	W → E	Day

LiDAR Data Processing

Raw SHOALS-1000T data from the airborne system were downloaded into the Optech SHOALS Ground Control System (GCS) on Windows XP workstations. GCS includes links to Applanix POSPac software for GPS/inertial processing and to IVS Fledermaus software for data visualization and 3D editing. GCS was used to apply the KGPS/inertial solutions, apply tide data, auto-process the LiDAR waveforms, edit data and export point cloud files to ASCII XYZ format files. The ASCII XYZ files were used for TPU calculations.

Edited data were also imported to CARIS HIPS for analysis with the CUBE algorithm.

In order to assess the affect of data coverage percentage, flight altitude, flight direction and time of day, on target detection, flight missions were organized into processing datasets (Table 3) prior to data editing,. Each dataset was processed independently, so that the data editor did not gain additional knowledge by looking at all flight missions at once.

Table 3 Processing Datasets

Dataset	Missions Included
A	400 m @ 3x3 200% coverage with flight in opposite directions
B	400 m @ 3x3 200% coverage with flight in same directions
C	400 m @ 3x3 200% coverage with flight in opposite directions at night
D	400 m @ 3x3 300% coverage
E	400 m @ 3x3 400% coverage
F	400 m @ 3x3 500% coverage
G	300 m @ 3x3 200% coverage with flight in opposite directions
H	400 m @ 2x2 200% coverage with flight in opposite directions
I	400 m @ 4x4 200% coverage with flight in opposite directions

Derivation of SHOALS-1000T TPU Model

The TPU can be understood as the sum of all random and systematic uncertainties in the measurement process, including the uncertainty contribution of all sensors embedded in the SHOALS-1000T system. Determining each sensor’s uncertainty independently to develop a TPU is a work in progress. Due to the complexity of the physical interaction of the laser pulse with the sea surface, sea water and sea floor an analytical TPU may not be possible. Therefore, at this time, an alternate method must be used to derive a TPU estimate for the SHOALS 1000T system.

This study uses depth variance as a proxy for an analytical TPU. Because the bathymetric LiDAR footprint spreads with depth, as the light scatters and absorbs in the water column, the SHOALS data were separated into ASCII XYZ files with discrete depth ranges, starting at 2 m water depth down to 16m, at 2m step increments. For each depth interval, variance is estimated as a function of horizontal radius. This variance function is then calculated for a radius of zero giving vertical variance for that depth interval.

For all depth intervals, total variance is expected to grow with each incremental search radius; however, variance growth as a function of distance, defines a function that allows the estimation of variance at zero radius, which cannot be resolved directly. A variogram is used to determine the node variance when the constant of a polynomial fit is found, as shown in Figure 3. Variance functions for each depth interval are shown in Figure 4.

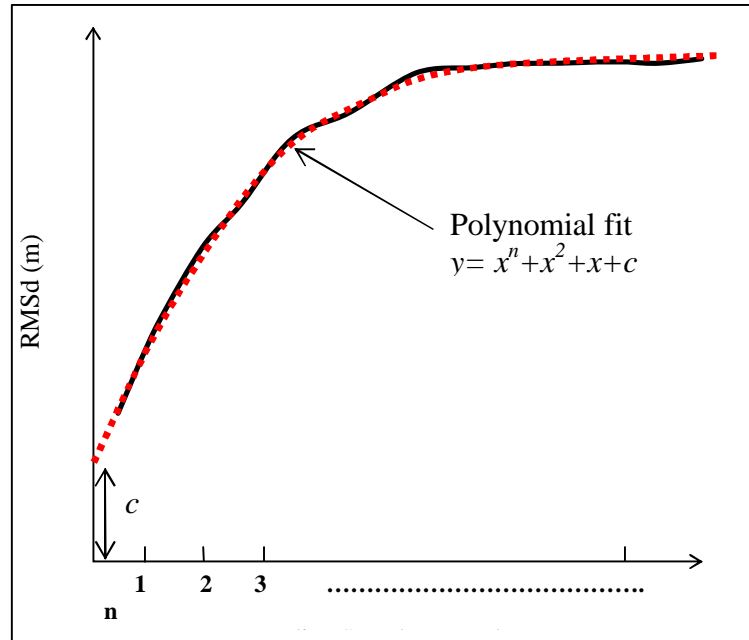


Figure 3 - Variogram for Determining Node Variance

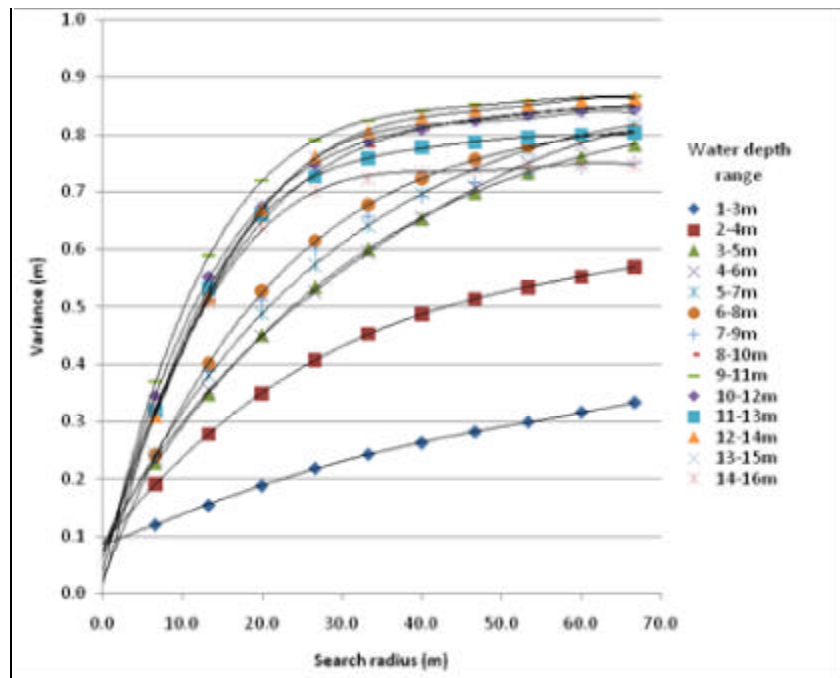


Figure 4 - Variance Function for each Depth Interval (including Zero Radius)

Calculated node variances for each depth interval are shown in Figure 5. From this, one can see that variance fluctuated between 0.07-0.09m to 15 m water depth and then grew to about 0.125 m at 20m water depth.

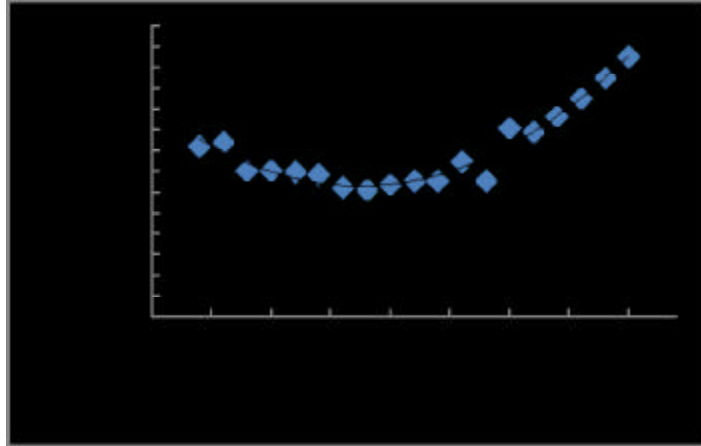


Figure 5 –Variance as a Function of Water Depth

This total variance estimate (σ^2_T) calculated as described above, includes the variance from the sensor measurements as well as the variance inherent in the seafloor (σ^2_s) due to slope and roughness. Therefore to produce an estimate of sensor measurement variance (σ^2_m), an estimate of seafloor variance needs to be calculated or modeled and removed from the total variance, as presented in the form:

$$\sigma^2_m = \sqrt{(\sigma^2_T)^2 - (\sigma^2_s)^2}$$

To model the natural seafloor variance in the LiDAR data, introduced by slope and bottom roughness, a morphology trend was observed and determined from the gridded multibeam DEM surface. The slope gradient, and the amplitude and frequency of the general bottom roughness, were used in the creation of a synthetic surface grid model. Variance analysis was conducted on the synthetic surface using the variogram approach to provide an estimate of variance solely from the slope and bottom roughness.

Different synthetic surface point densities (0.5m, 1m, 2m and 3m) were used to account for potential sub-sampling effects. Figure 6 shows the results of the synthetic surface variance analysis showing clearly that variance as function of distance remains constant and follows a linear trend not affected by different point density. It was found that the variance for the modeled synthetic seafloor averaged 0.015m. However, due to the use of a synthetic surface, it is likely that this is a low estimation of actual seafloor variance. Estimated seafloor variance was then removed from the total variance to provide an estimate of the sensor variance. The square-root of final sensor variance (standard deviation) was then used as the TPU estimate, with the value varying dependent on water depth.

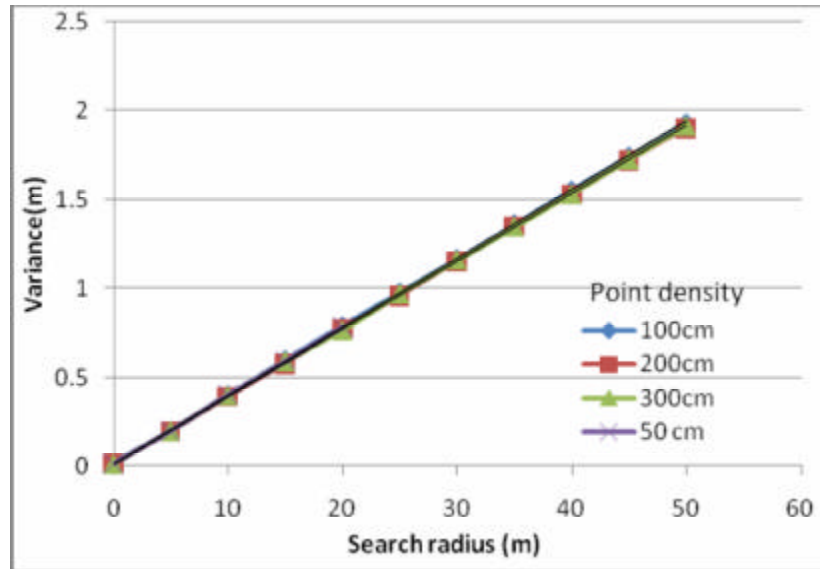


Figure 6 – Variance of the Synthetic Seafloor at Varying Point Density

Table 4 shows the calculated TPU for the Shilshole Bay survey, where maximum bottom depth detection was at about 16 meters. TPU was attributed to each LiDAR depth in CARIS HIPS and used to create attributed uncertainty DEM products.

It should be noted that uncertainty calculated still includes any uncertainty present from the tide application. It would be beneficial to repeat this exercise using PPK GPS LiDAR data on the ellipsoid, to provide a result which more closely represented the sensor uncertainty alone.

Table 4 also shows for comparison the depth accuracy specification for IHO Order 1 given, in the form:

$$= \sqrt{a^2 + (b + d)^2}$$

where d is water depth, and values for a and b are 0.5 m and 0.013 m, respectively.

Comparing numbers in columns 5 and 6, it can be deduced that accuracy for the SHOALS-1000T bathymetric LiDAR depths in Shilshole Bay are within the acceptable accuracy limits of IHO Order 1.

It is important to note that TPU estimation using the method presented above is valid for the water conditions at the time of the survey. Bathymetric LiDAR measurement uncertainty will vary depending on local water column conditions and seafloor reflectance. However, if water conditions and depth of bottom detection are very similar in other locations sharing common environments, the model can be applied. To use in a different environment, TPU would need to be recalculated. However with the method described, this is possible.

This method can also be refined by the use of Kriging, which will allow uncertainty relationships in the along-track and across-track direction to be modeled. This is currently being examined by Fugro Pelagos.

Table 4 Final Sensor Variance and TPU Values Compared to IHO Order 1

1	2	3	4	5	6	7
Depth (m)	Total Seafloor Variance $[(\sigma_T)^2]$	Sensor Variance $[(\sigma_s)^2]$	Sensor StDev (TPU)	Sensor 2-StDev	IHO Order 1 (2-StDev)	Status
1	0.094	0.065	0.256	0.511	0.564	Passed
2	0.083	0.058	0.240	0.481	0.501	Passed
3	0.085	0.059	0.243	0.486	0.502	Passed
4	0.072	0.050	0.223	0.446	0.503	Passed
5	0.072	0.050	0.223	0.446	0.504	Passed
6	0.071	0.049	0.222	0.443	0.506	Passed
7	0.070	0.048	0.220	0.440	0.508	Passed
8	0.064	0.044	0.210	0.419	0.511	Passed
9	0.063	0.043	0.208	0.416	0.514	Passed
10	0.065	0.045	0.212	0.424	0.517	Passed
11	0.067	0.046	0.215	0.430	0.520	Passed
12	0.067	0.046	0.215	0.430	0.524	Passed
13	0.076	0.053	0.230	0.459	0.528	Passed
14	0.067	0.046	0.215	0.430	0.532	Passed
15	0.092	0.064	0.253	0.507	0.532	Passed
16	0.090	0.063	0.250	0.501	0.537	Passed

Comparison of LiDAR and Multibeam using CUBE

CUBE transforms measured points at relatively random locations into regularly spaced depth estimates in a grid. On each grid node, four values are produced: depth, uncertainty (from depth TPU), number of hypothesis and hypothesis strength. Depending on how close or sparse vertically contributing depths are to resulting node value, the algorithm develops more than one potential depth candidate but selects one as the most likely one.

CUBE was designed to aid in the processing of dense multibeam echosounder datasets. However it is not commonly used on sparser bathymetric LiDAR datasets. Some experiments were run to identify suitable CUBE parameters to be used with the LiDAR data points. In the example below (Figure 7), which shows 400% LiDAR coverage, there are 5 LiDAR hits on the target. CUBE successfully generates a likely primary hypothesis (green cubes) from these 5 data points which represent the target. However the primary hypothesis representing the target is relatively weak. The cubes in the image indicate the uncertainty of the measurement in the vertical, with the strength of the hypothesis indicated by the width of the cubes. The CUBE algorithm also generates an alternate hypothesis, shown by the red cubes.

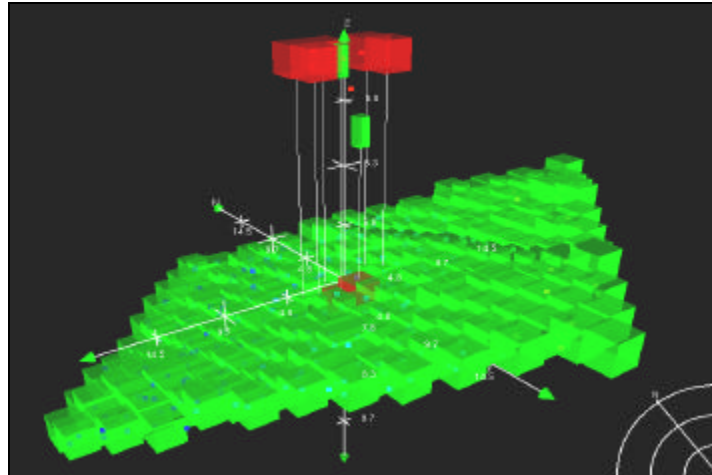


Figure 7 - CUBE Hypotheses for Target B (2x2x2m) in 7m Water Depth with 400% Coverage

In almost all cases, when LiDAR acquired a data point on a target, CUBE correctly created a primary hypothesis, which in some way represented that target. This is likely due to the sparseness of the data, which in many cases with 200% LiDAR coverage or less, prevents the possibility of multiple hypotheses. However the primary hypothesis over the targets was usually weak. In a typical product flow, the primary CUBE hypothesis is then used to create a surface. But if the hypothesis is weak, the surface will not be ‘pulled’ to the top of the target and will not therefore accurately represent the shallow data points. Further work is still required in order to identify a set of CUBE parameters that will provide a strong primary hypothesis on the targets when they are observed in the LiDAR data.

In addition, and perhaps more detrimental to this experiment, there were also problems when using CUBE to create the multibeam hypotheses. In Figure 8, the image on the left shows a cross section of multibeam data over target B. The CUBE processing example, shown on the right, depicts the target depth hypotheses in red, which means they are not selected as the most-likely primary hypothesis depths, despite the number of hits on the target. More work is required to select suitable CUBE parameters, which will successfully select the target as the primary hypothesis. Fugro Pelagos continues to pursue this problem. Until these parameters are identified, it is not possible to complete the goal of comparing the two datasets, accounting for their uncertainties.

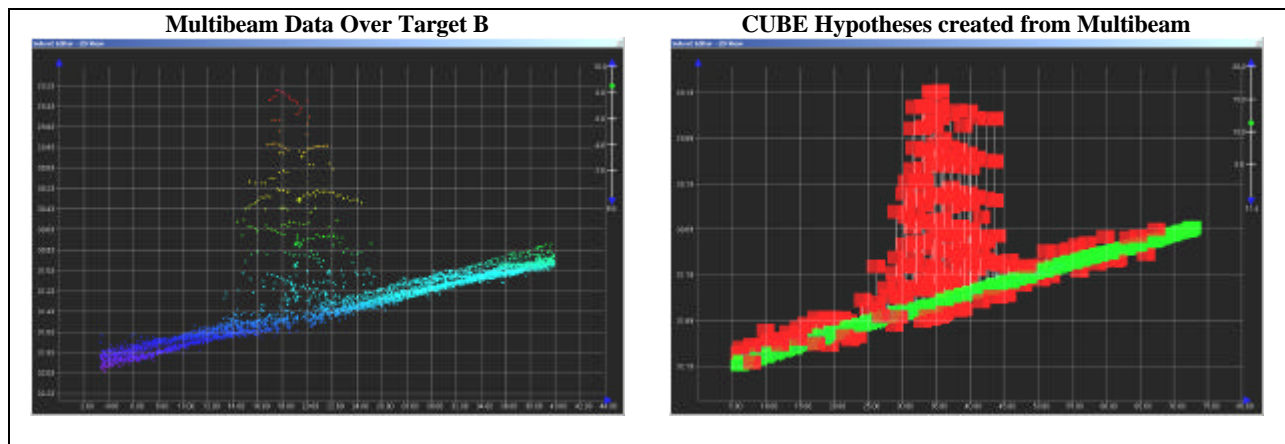


Figure 8 - MBES Data in CARIS, and the CUBE Hypothesis

Conclusions

TPU can be estimated for LiDAR depth intervals through variance node analysis. The analysis can be performed over a small control area in water conditions very similar to the actual main survey area, and therefore could be calculated on a project-by-project, or area-by-area basis.

The calculated TPU presented here for Shilshole Bay still includes any uncertainty present from the tide application to the LiDAR data. It would be beneficial to repeat this exercise using PPK GPS LiDAR data on the ellipsoid, to provide a result which would more closely represent the sensor uncertainty alone.

This methodology for calculating TPU should be further refined and automated with the use of Kriging.

At the time of writing, CUBE has not been successfully used to compare the LiDAR and multibeam datasets. However the authors feel that with further effort, particularly in choosing suitable CUBE parameters for hypothesis selection, this can be accomplished.

Acknowledgements

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Author Biographies

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