Shoreline Mapping from Airborne LIDAR in Shilshole Bay, Washington

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Abstract

The national shoreline provides the critical baseline for demarcating America's marine territorial limits, including its Exclusive Economic Zone, and for the geographic reference needed to manage coastal resources. The method used today by the National Oceanic and Atmospheric Administration (NOAA) to delineate the shoreline is stereo photogrammetry using tide-coordinated aerial photography. Aerial photography has its limitations, especially in harsh weather environments and areas with large tidal ranges. Since the majority of the NOAA hydrographic survey effort is being concentrated in Alaska, a more efficient and cost effective method of acquiring shoreline is needed. NOAA has been testing alternative technologies for shoreline mapping, including Light Detection and Ranging (LIDAR). LIDAR has been used by NOAA in Alaska to obtain the near-shore hydrography and shows promise as an economical way of obtaining shoreline if properly tested and proven.

Shilshole Bay, Washington was chosen as a test site for LIDAR technology due to the existence of a NOAA hydrographic test patch that can be used for the hydrographic LIDAR verification. The test patch also has similar weather and shoreline features to those of Alaska. Multiple LIDAR datasets from different sensors were acquired over a two year period. The data, combined with a recent GPS ground survey to establish ellipsoidal – tidal relationships, proved useful in auto-extracting Mean High Water (MHW) shoreline for a local area like Shilshole Bay. NOAA is currently developing a vertical datum transformation tool (VDatum), which will simplify the methodology used here and also extend this capability to regional areas. This paper will highlight some of the results from using multiple LIDAR datasets for shoreline mapping.

Introduction

The United States has a coastal boundary approximately 95,000 nautical miles in length. NOAA has the congressional mandate to determine this boundary, which is defined as the planimetric position of the shoreline at a specific stage of tide. On NOAA nautical charts two shoreline vectors are represented, the Mean Lower Low Water (MLLW) and Mean High Water (MHW). The MLLW shoreline is significant because it defines the baseline for computing the Exclusive Economic Zone, the High Seas, and America’s marine territorial limits. In addition, the MLLW vector depicts the planimetric position of the vertical datum of NOAA’s charts. The MHW shoreline defines the boundary between land and sea.

Hydrographic surveys rely heavily on accurate shoreline information. The hydrographer uses the shoreline information to plan the hydrographic mission and to ensure the safety of the surveying parties during launch and near-shore operations. Shoreline acquired prior to 1970 is of limited use to the hydrographer because of changes caused by human-induced or natural events, such as glacial recession and earthquake activity. It is imperative for safety reasons that up-to-date accurate information is acquired prior to the start of the ship based hydrographic survey.

NOAA’s current shoreline mapping efforts provide this information, however, only two-thirds of the coastline has been mapped and of those two-thirds, only approximately ten percent has been collected using modern stereo photogrammetric techniques (after 1970). In Alaska, where 45 percent of the 95,000 miles of shoreline exists, the challenge has been to obtain shoreline with aerial photography at a specific tide stage and sun angle. NOAA has been experimenting with sensors less restricted by weather to provide more current shoreline information to the hydrographer. These sensors include Synthetic Aperture Radar (SAR), Satellite Imagery, and topographic and bathymetric LIDAR.

Airborne LIDAR Technology

Since the 1970s the application of airborne LIDAR for topographic and bathymetric mapping has matured at a rapid pace. Much of this growth has directly tracked advances in high speed digital and analog electronics along with orders of magnitude increases in computer memory, storage capacity and processing speed (Wright and Brock, 2002). The principles of topographic and bathymetric LIDAR mapping rely on the accurate round trip travel time of a laser pulse transmitted from the LIDAR system to a surface target. These measurements, coupled with kinematic GPS and precise attitude positioning of the aircraft, provide a rapid and cost effective way to obtain coastal topographic and bathymetric information.

This study implemented LIDAR data from three different commercial systems, two bathymetric and one topographic. Optech, Inc., of Toronto, Canada, manufactures both the Airborne Laser Terrain Mapper (ALTM) and the Scanning Hydrographic Operational Airborne LIDAR Survey (SHOALS). The fundamental difference between the two systems is laser wavelength, the ALTM operates in the near infrared region of the electromagnetic spectrum, while SHOALS uses a green laser for water penetration. Laser pulse repetition rates also vary between the ALTM and SHOALS systems. ALTM systems currently operate at a much higher frequency of 50 kHz compared to the 400 Hz pulse repetition rate used by SHOALS.

The Laser Airborne Depth Sounder (LADS) Mark II, developed commercially to support the Royal Australian Navy, is a bathymetric system which operates at 900 Hz, also using a green laser for water penetration. Similar to SHOALS, LADS typically operates at lower altitudes (1200 ft to 1800 ft) than ALTM operations (up to 10,000 ft). One shared characteristic of all bathymetric LIDAR systems is the need for non-turbid water conditions.

Study Area

Shilshole Bay, located in Washington's Puget Sound, was chosen as a study area for several reasons. A test patch of NOAA ship multi-beam hydrography exists within the project area that can be used as "truth" to evaluate the hydrographic LIDAR datasets (Fig. 1). In addition, Washington State has similar weather and shoreline feature types to those of Alaska, where future LIDAR requirements are likely to evolve. The close proximity to NOAA's Pacific Marine Center (PMC) also makes Shilshole Bay an excellent area for sensor validation and research.

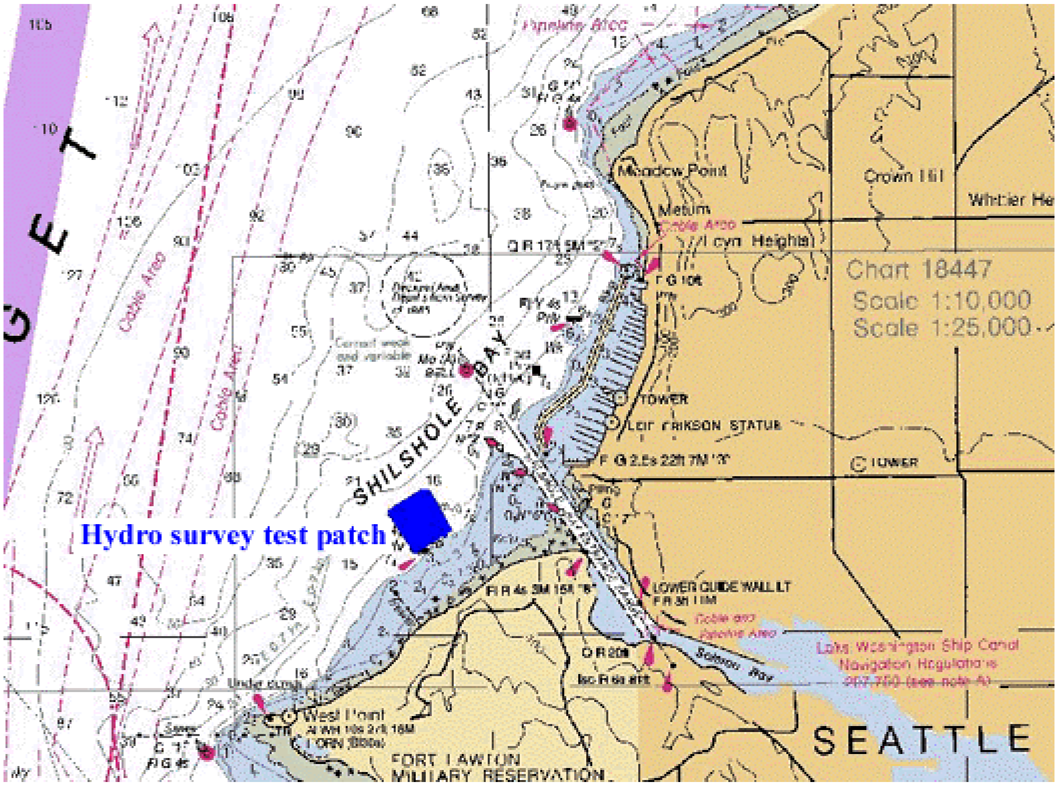


Fig. 1 Study area with NOAA Ship surveyed hydro test patch

Methods

Before deriving shoreline, comparisons of elevations and soundings within the coverage area from each LIDAR system and from NOAA ship multibeam data were conducted (Fig. 2-3). Using software developed at NOAA, the x,y,z point data were compared using a search radius matching the native spatial resolution of each dataset (Table 1). Results in Table 2 show the agreement between LADS and SHOALS data, a mean of 6 cm and a standard deviation of 0.57 m was determined between the two datasets. Other comparisons of LADS and SHOALS with the topographic LIDAR and NOAA ship multibeam data are at the sub 20 cm level of agreement.

The development of shoreline from this dataset was an after thought to the initial bathymetric LIDAR data collections. Both SHOALS and LADS were asked to collect data in Shilshole Bay for the purpose of determining their viability in NOAA hydrographic survey operations. Similar comparisons have been done by Thales and NOAA on previous occasions and may not agree exactly with the results in this paper due to different software packages used in the comparisons.

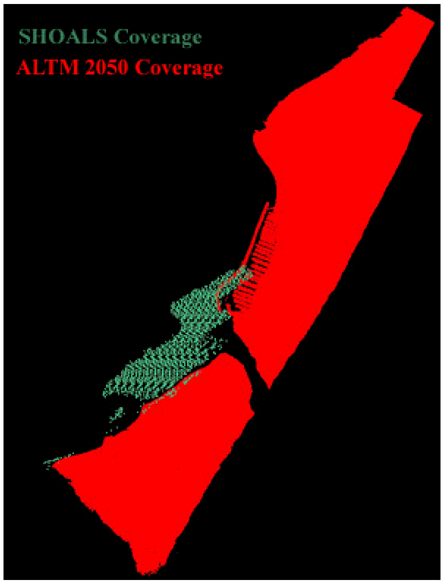


Fig. 2 SHOALS and ALTM 2050 Coverage

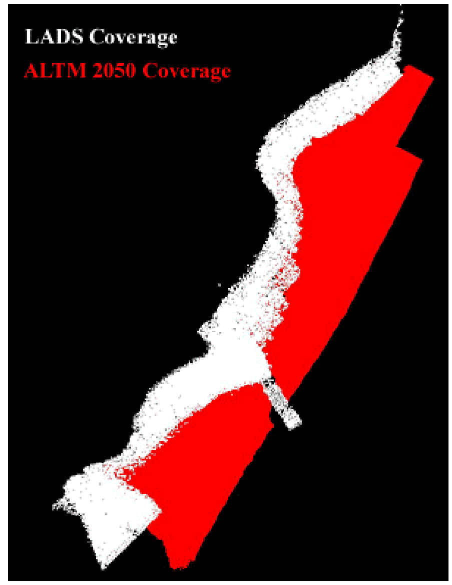


Fig. 3 LADS and ALTM 2050 Coverage

Data Spot Spacing	(m)
LADS	4
SHOALS	4
ALTM 2050	1
NOAA ship multibeam	0.5

Table 1

Data Comparisons	Search radius (m)	Mean dz (m)	Std dev (m)
LADS to SHOALS	4	0.056	0.566
ALTM 2050 to LADS (beach area)	1	0.073	0.195
ALTM 2050 to SHOALS (beach area)	1	0.161	0.132
NOAA ship multibeam to LADS (test patch)	1	0.114	0.164
NOAA ship multibeam to SHOALS (test patch)	1	0.023	0.099

Table 2

A static ground GPS survey was conducted to obtain ellipsoidal information on the closest tidal benchmark to the project area. These data related the tidal measurements, heights above MHW and MLLW, to the ellipsoid and provided an elevation correction to bring all LIDAR datasets to a common vertical datum (Table 3). In addition, this constant provided the numerical contour interval to auto-extract a shoreline vector. This methodology is limited to relatively small project areas with low variability in tidal dynamics. Data transformed using this method will be less accurate if extrapolated from the tidal benchmark to another tidal zone.

NOAA is addressing these issues through the development of VDatum, a vertical datum transformation tool (Fig. 4). This tool is necessary when combining data from various sources to produce a uniform dataset. Vertical datums have traditionally come in two categories: those based on a form of Mean Sea Level (MSL), called Orthometric Datums, and those based on tidally-derived surfaces of high or low water, called Tidal Datums (Parker et al.). A more recent reference consisting of 3-dimensional datums realized through space-based systems such as the

Global Positioning System (GPS) also exist and are commonly referred to as 3-D Datums. For merging topographic and bathymetric datasets, the key element to VDatum is the hydrodynamic model. These models are not currently available in VDatum format for the Shilshole Bay area, however, when they become available, the methodology used here will be simplified to processing data points through a graphical based software tool, bringing all data to a common vertical datum.

Shilshole Bay Ellipsoidal – Tidal relationship	MLLW	MHW
	(m)	(m)
BM 7265 A 1977	5.047	1.902
Ellipsoid height	-19.339	-19.339
Height above tide	5.047	1.902
Ellipsoid height relative to tide stage	**-24.386**	**-21.241**

Table 3 **Ht. above MLLW** **Ht. Above MHW**

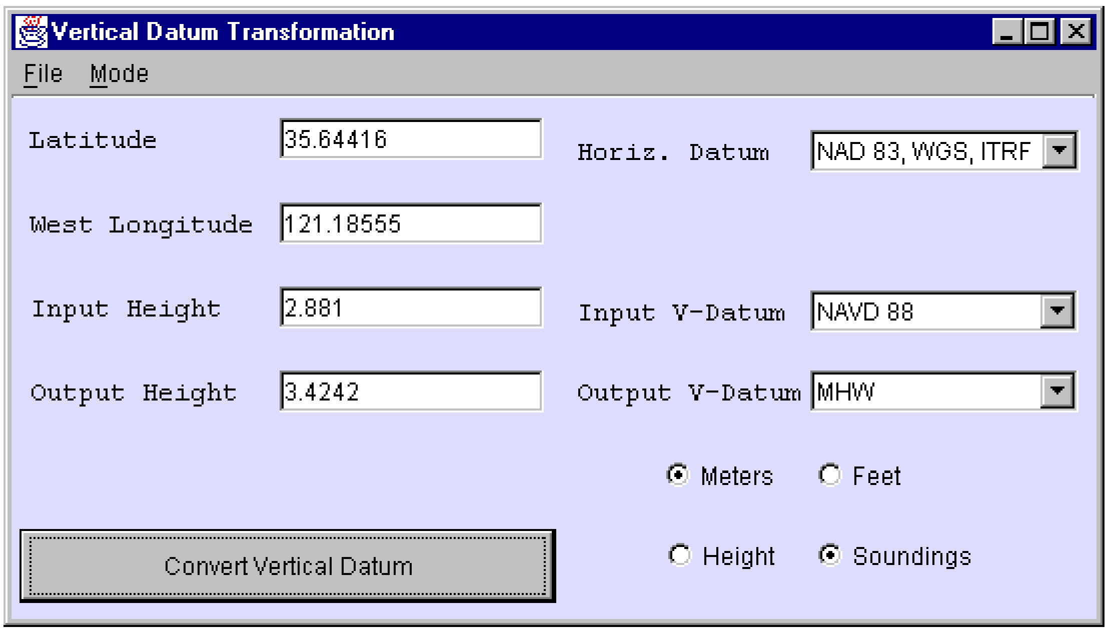


Fig. 4 VDatum - Vertical Datum Transformation Tool

MHW shoreline vectors were derived from both the 1 m ALTM 2050 and 4 m LADS LIDAR data for the Shilshole Bay test site. The coverage of the SHOALS LIDAR collection was not sufficient to provide shoreline data for this experiment. Fig. 5 and Fig. 7 show the ALTM 2050-derived shoreline vector in red and its agreement with the NOAA nautical chart at West Point and the entrance to Lake Union. Fig. 6 and Fig. 8 highlight the same areas showing the LADS-derived shoreline in white and its agreement with the existing NOAA chart.

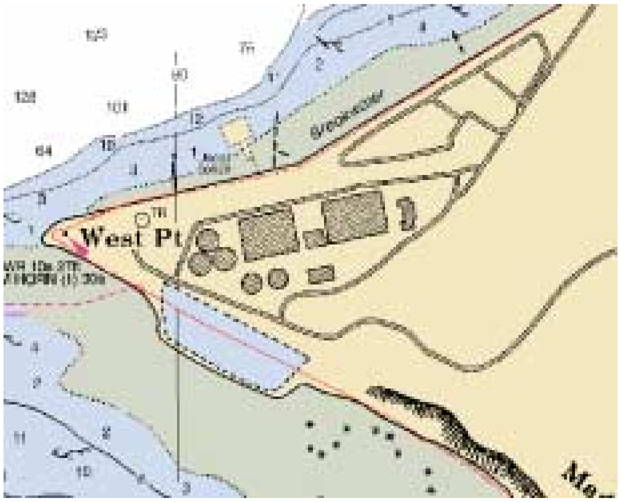


Fig. 5 ALTM 2050 derived MHW shoreline

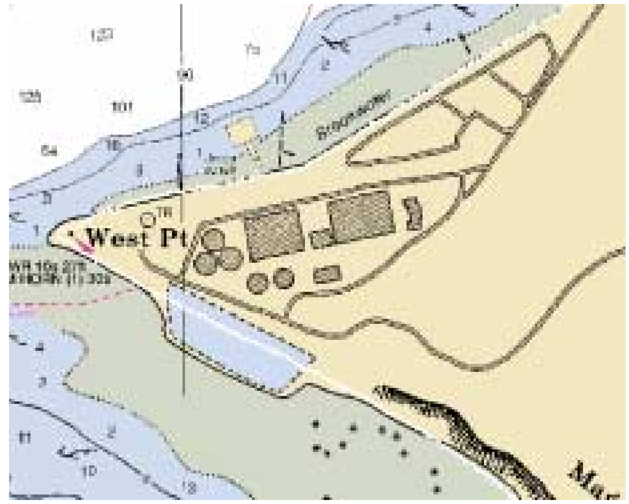


Fig. 6 LADS derived MHW shoreline

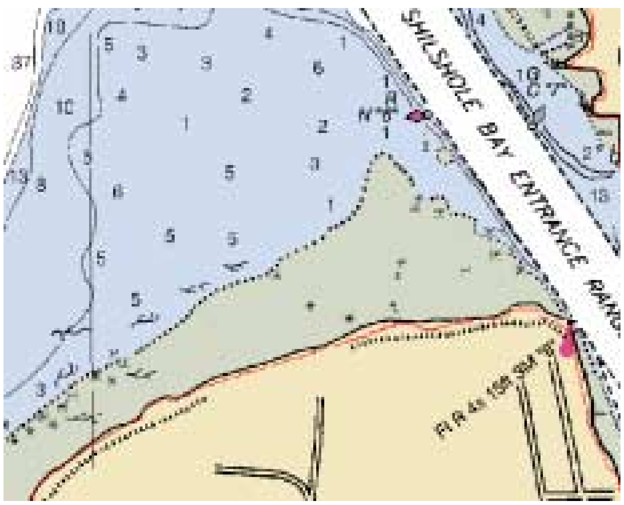


Fig. 7 ALTM 2050 derived MHW shoreline

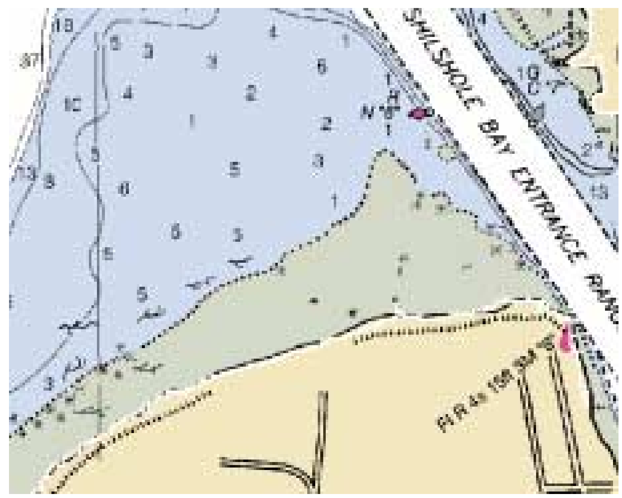


Fig. 8 LADS derived MHW shoreline

Quantitative Comparison of Two Vectors

A method was developed to describe the relationship between two vectors that have different resolution and shape. The goal is to quantify the relationship between these two vectors by calculating the distance from each point of the first vector to the nearest location on a second vector. This difference is determined by computing the distance between each point of the first vector and the location perpendicular on a line segment defined by the nearest two points of the second vector. The method produces an evaluation of directional difference vectors (DDV), which can be used to quantify the match between two data sets. The large number of distances computed allows for many calculations and provides for a statistical evaluation of the differences between the two vectors and the visualization of a histogram.

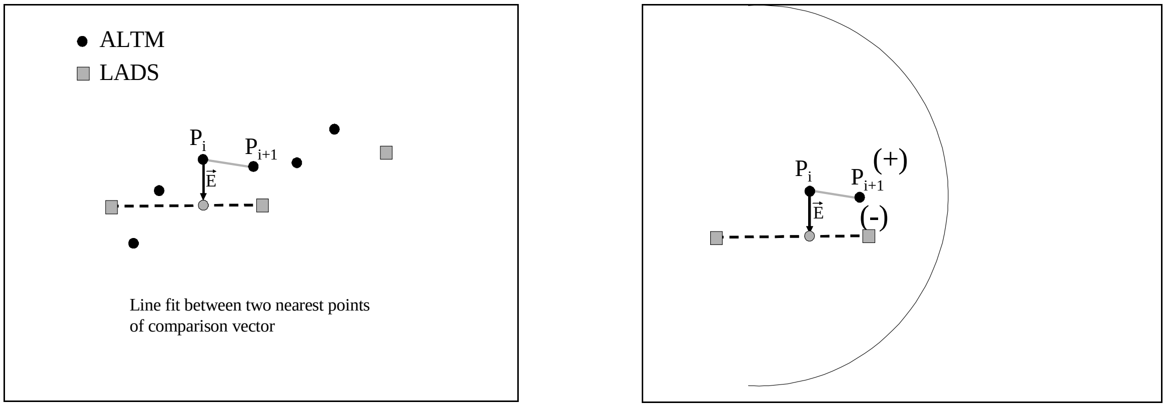


Fig 9   Determination of (left) Magnitude of Difference Vector and (right) Direction of Difference Vector

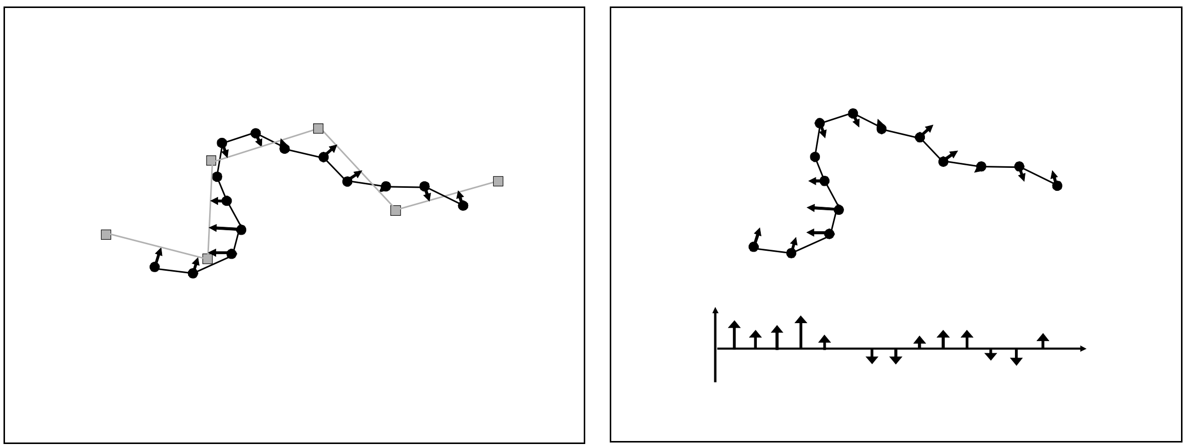


Fig. 10 (Left) Relationship of Directional Difference Vectors to Points in the "Test" Vector. (Right) Characterization of the "Test" Vector Using an Array of Directional Difference Vectors

The first vector is the one-meter resolution shoreline of Shilshole Bay derived from ALTM data. The comparison vector is the lower resolution LADS data, which has four-meter spacing. For each point, P_i, of the ALTM vector, the nearest two points on the LADS vector are determined and a line is drawn through those two points (Fig 9). The perpendicular distance, or magnitude of E, between P_i and that line is recorded as the error measurement. A directional component is assigned to the error measurement. If the direction of the perpendicular line from P_i to the nearest two points is to the right of the line from P_i to the next point in the test vector, P_{i+1}, then the error measurement is assigned a negative value. Otherwise, the error measurement remains positive. This sign assignment method is pictured on the right side of Figure 9. Using this method, the general location of the “truth” vector to the left or right of the “test” vector along its run length can be ascertained.

The process is continued for all points of the ALTM-derived vector. The result is a number of error measurements equal to the number of points in the ALTM vector. Statistical analysis can subsequently quantify the relationship between the ALTM and LADS vectors and be displayed along an axis reflecting the run length of the ALTM vector (Fig 10). The mean and standard deviations of the magnitudes of the set of difference vectors characterize the degree to which the ALTM vector agrees with the LADS vector.

User Selection of Conjugate Points

The DDV approach is meaningful only if the ALTM vector contains no significant biases which can be identified using a conjugate point and feature-based matching approach. The purpose of obtaining conjugate points is to be able to estimate positional translations and rotations between the two vectors. An affine transformation using least squares techniques produces translation, rotation, and scale parameters that can be applied to the data to improve the correlation of the two data sets. The method identifies user-selected conjugate points by clicking directly on an image of the vector data on screen. These points are run through a four parameter affine transformation that removes positional biases by performing a least squares solution to estimate translation and scale errors present. The transformation is applied to the primary data set.

Feature-Based Matching

In addition to conjugate point matching, a feature-based matching strategy allows for a correlation of features within user-selected areas. The feature-based matching uses these features to identify a transformation of one vector compared to another. Feature-based in these terms refers to a method which does not use individual points. For each user-selected area, the vector points are converted to raster form. A frequency-domain correlation is used as an image matching technique to calculate the best fit between the two raster images. The final translation is the unweighted mean of x and y values for the correlation images for all of the feature areas selected throughout the full project.

The program updates the transformation parameters obtained in the previous step by calculating a mean translation for the cross correlation of all areas. This feature-based process is useful to improve the estimation of transformation parameters if conjugate points are difficult to identify.

Execution of Code

A comparison of the ALTM to LADS data shows that there is a close relationship between the two data sets. An image of the area of Shilshole Bay created by the IDL code is displayed below (Fig. 11). As described in Table 4 below, the initial comparison of the vectors reveals an overall mean of the directional distance vectors of 0.63 m. The standard deviation is 3.82 m. The final translational shift computed by the conjugate point matching and feature-based algorithm was -1.46 m in X and -0.55 m in Y which is below four meters, the resolution of the LADS data.

	Mean	Standard Deviation
Vector comparison	0.63 m	3.82 m

Table 4 The mean and standard deviation between ALTM and LADS

	X	Y
Translational shift	-1.46 m	-0.55 m

Table 5 The final translational shift between the two vectors

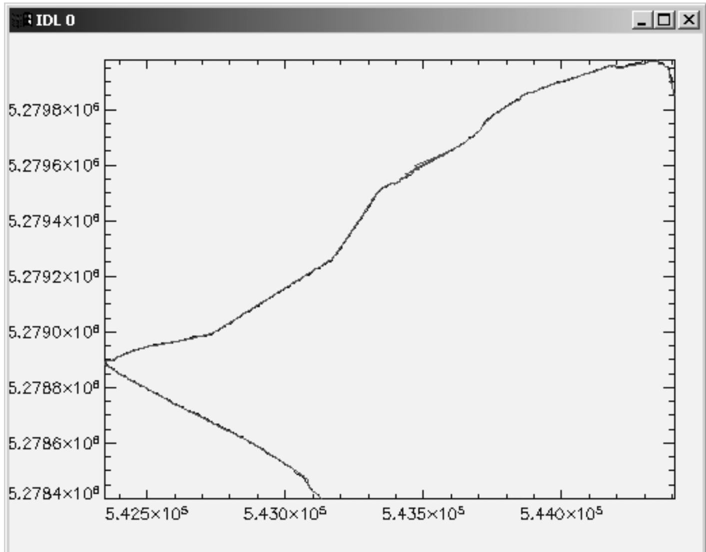
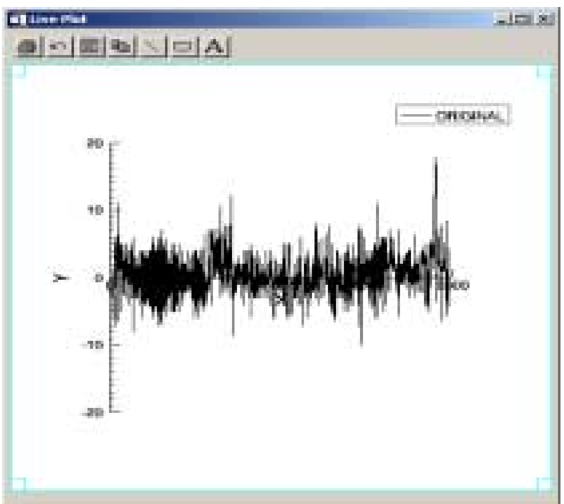


Fig. 11 Plot of the two vectors overlaid (all units UTM meters)



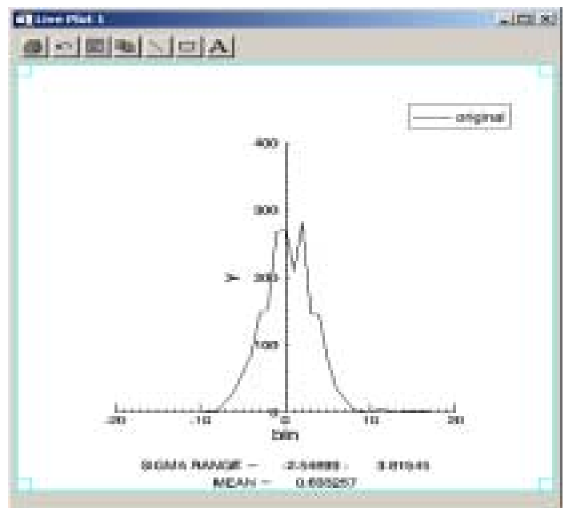


Fig. 12 (Left) Plot of offsets along the Y-axis in meters from one vector to the other at each of the 2000 points

Fig. 13 (Right) Histogram of the offsets

Conclusions

This experiment has shown the application of shoreline mapping from airborne LIDAR has promise. Both qualitative and quantitative conclusions drawn from 1m topographic and 4m bathymetric LIDAR datasets suggest more research should be conducted in this area. The methodology used here to derive shoreline can be applied to any 3-D dataset; however, varying beach types and different spatial resolutions of coastal data may produce shorelines of lesser quality than desired for charting purposes. Future experiments should examine the spatial resolution and spatial accuracies necessary to represent different beach types. The VDatum tool will significantly improve this methodology, eliminating the GPS field work necessary to establish the ellipsoid – tidal offsets.

The usefulness of merging topographic and bathymetric LIDAR goes beyond the application of shoreline mapping. Visualizations of such data can provide a new view to the mariner, depicting the shoreline in far more detail than a 2-D planimetric nautical chart (Fig 14). In the future, this fusion of data sources should be the focus of new and improved mapping products for the maritime community.

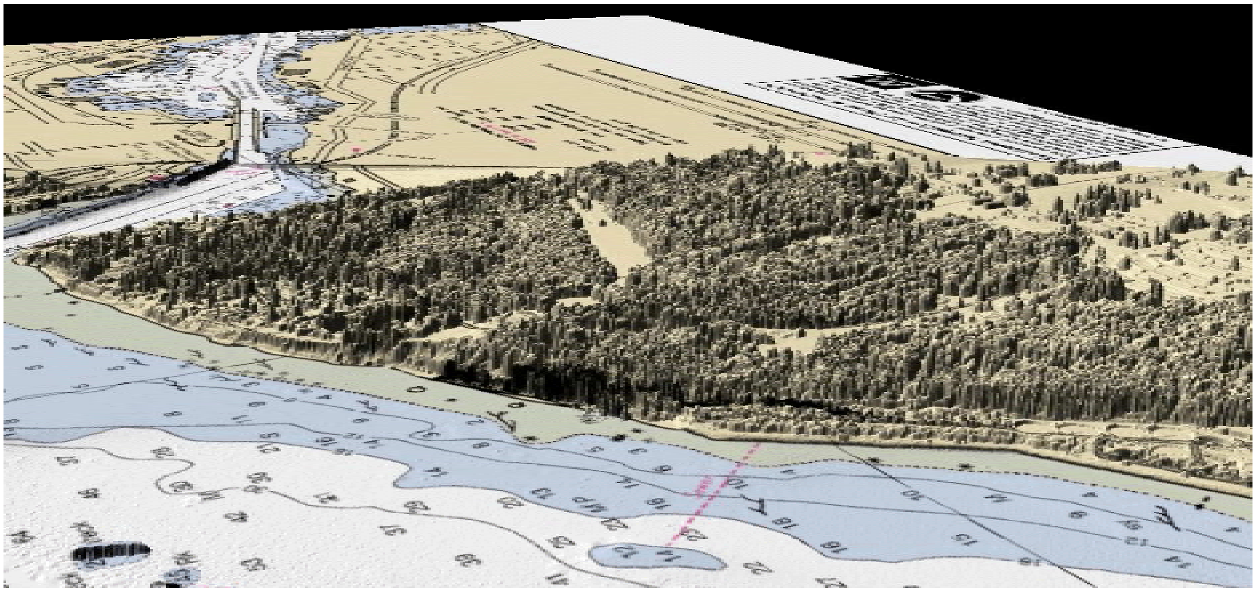


Fig. 14 Nautical chart for Shilshole Bay merged with topographic and bathymetric LIDAR

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