Performance evaluation of the Velodyne VLP-16 system for surface feature surveying

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Abstract

Previous work, conducted between the Center for Coastal and Ocean Mapping and HYPACK, demonstrated the potential use of a low-cost industrial laser scanner as an alternative for survey-grade laser scanners for mapping of surface features such as piers, piles and rocks. In this paper, an in-depth performance evaluation that is currently being conducted using the Velodyne VLP-16 system will be discussed. This industrial laser scanner, which currently costs $8,000, uses 16 laser beams that cover a vertical field of view of ± 15°. These laser/detector pairs also rotate at an adjustable rate from 5 Hz to 20 Hz to cover a horizontal field of view of 360°. Although it is possible to output geo-referenced measurements with information such as position, azimuth and angle, range and intensity, the accuracy of these reported measurements is not clear. Based on a total propagation uncertainty model developed for laser scanner surveying, which incorporates auxiliary systems (i.e., GPS and IMU), the dependency of the laser measurements on different survey conditions was evaluated through experiments conducted in laboratory and field conditions. The study results show the changes in range estimation as a function of distance, angle of incidence, and surface roughness.

INTRODUCTION:

The National Oceanic and Atmospheric Administration (NOAA) Office of Coast Survey (OCS) provides up-to-date nautical charts and other navigational products and services to promote efficient maritime commerce along the United States inland and coastal waterways. The task of surveying along the 88,633 statute miles of United States coastline, specifically mapping coastline features, has proven to be time consuming and dangerous due to the need to navigate a survey vessel in close proximity to the shoreline and shoal hazards[1]. Small boats are often deployed to verify, update, disprove, or find new natural features such as exposed or slightly submerged rocks and obstructions, as well as anthropogenic features such as pilings and piers. Traditionally, surveyors are equipped with only pencil and paper, hand-held magnetic compasses, laser range finders, discrete point positioning software (e.g. Trimble® Backpack), and digital cameras. A common practice is to approach the feature of interest and extend the GPS antenna over the feature by using a pole to get precise positioning[2]. Although this method achieves excellent horizontal positioning for charting purposes, it is often dangerous due to the potential of grounding, striking the object, or loss of boat stability due to wave action. In cases of limited resources or logistical limitations, the survey of the feature is estimated by "*best means available*"[2]. In these cases, more subjective methods (e.g., visual estimation) are used to estimate the target's height above the water surface which by nature contain a large amount of uncertainty. The time it takes for a coxswain to safely navigate to a feature and a surveyor to record the required data using these methods is considered excessive. It is clear that a safer and more time efficient method is needed. The standards to which these surveys are held to are found in the International Hydrographic Organization (IHO) S-44 publication. This document states that the position uncertainty of topography significant to navigation must be less than 2 m at a 95% confidence level for Order 1a, 1b, and Special Order surveys[3].

Much like how lead-line surveys were improved upon by the implementation of single-beam and eventually multibeam echosounders, traditional shoreline feature mapping methods can be improved upon by the remote sensing capabilities of mobile laser scanners. This LiDAR technology uses a time-of-flight (TOF) approach by measuring the time it takes for a pulse of near inferred laser light to travel from an emitter, to reflect off of a surface or object, and to be received by a photodiode sensor. This time-of-flight measurement is then used to calculate range. When mounted on a mobile platform, such as an automobile, airplane, drone, or marine vessel, the use of positioning and orientation sensors are used to transform and rotate the data from a relative reference frame to a geographic reference frame. The scanning patterns, pulse repetition rates, and multichannel characteristics of these scanners create dense point clouds of locally-referenced xyz data with associated intensity values.

Several studies have been conducted in the past by NOAA hydrographers to explore survey-grade mobile laser scanners. In 2007, Brennan et al., aboard the NOAA vessel *Bay Hydrographer II*, tested a combination of videogrammetry and Riegl 2D mobile laser scanner along with a long range Riegl LMS-Z420i 3D mobile laser scanner within the inner Norfolk Harbor, Virginia[4]. During the spring and summer of 2011, the NOAA Ship *Thomas Jefferson* and NOAA Ship *Fairweather* experimented with the Applanix™ LANDMark™ mobile laser scanner in Inner Norfolk Harbor and Kodiak, AK, respectively [5]. In both studies, the laser scanners exceeded performance expectations and greatly minimized the time required to complete a survey of shoreline features when compared to traditional methods. However, these survey grade laser scanner systems are considered to be cost-prohibitive which on average cost $80,000-$120,000. In this study, a performance evaluation of the Velodyne VLP-16 system, a low-cost industrial-grade mobile laser scanning system, is presented in order to validate its usefulness in surveying surface features from a marine vessel.

EXPERIMENT DESIGN, SETUP, AND DATA PROCESSING

A laboratory experiment was conducted using the wave/tow tank facilities housed in the University of New Hampshire (UNH) Jere A. Chase Ocean Engineering Lab. The purpose of this experiment was to independently assess the VLP-16 laser scanner's position measurement performance on various targets at discrete ranges and incident angles. Target materials were selected with surface characteristics similar to features that would commonly be found in a port or harbor setting. From smoothest to roughest, the targets selected were whiteboard (analogous to a freshly painted boat or a metal buoy), wood (analogous to a wooden pier or piling), concrete (analogous to a weathered rock or concrete pier), and sand (analogous to a sand or pebble beach). In addition, the effects of intensity on the range estimates of targets at these discrete ranges and angles were assessed. Sensor specifications for the Velodyne VLP-16 can be found below in Table 1.

Velodyne VLP-16 Specifications	
Sensor:	• 16 channels • Measurement range 1 to 100m • Accuracy +/- 3 cm (typical) • Duel Returns (strongest and last) • Field of view (vertical): 30º (+15º to -15º) • Angular resolution (vertical): 2º • Field of view (horizontal/azimuth): 360º • Angular resolution (horizontal/azimuth): 0.1º-0.4º • Rotation rates: 5-20 Hz • Environmental protection: IP67 • Data output: ~0.3 million points/second
Laser:	• Class 1 – eye safe • 903 nm wavelength (min/max is 896/910 nm) • Firing sequence repetition rate: 55.296 μs/18.2 kHz • Maximum output energy: 31 Watts (0.19 micro Joules)

Table 1: Specifications of the Velodyne VLP-16 [6].

The wave/tow tank in the Jere A. Chase Ocean Engineering Lab's High Bay is a 36m long tank with a tow carriage mounted above that can be positioned with millimeter accuracy. This platform was used as a controlled reference frame to position targets at ranges of 5, 10, 15, 20, 25, and 29 m. The targets were also mounted on a rotating compass to accurately rotate the target frame to incident angles of 0^o, 15^o, 30^o, 45^o, 60^o, and 75^o where an incident angle of 0^o is when the lasers intersect the target orthogonally. The targets used for the experiment measured 60x60 cm (height and width) which was wide enough so that the laser beam footprint at the furthest range and at the largest incident angle would still be within the target's extent. At a range of 29 m and an incident angle of 75^o, the apparent width of the target was ~15 cm. The laser beam footprint at 5 m and 29 m is 1.5 cm and 8.7 cm, respectively. The VLP-16 laser scanner was mounted vertically on a static tripod at the edge of the tow tank to create a vertical 360^o scanning pattern.

Reference system alignment was achieved in two stages; first, the targets were positioned within the tow-tank's reference frame, and second, the scanner was positioned within the tow-tank's reference frame. Horizontal alignment of the target was achieved by using a laser line level along the lineal guides of the tow-tank. The target was adjusted horizontally until the center pin of the rotating compass aligned with the laser line level. Because the vertical extent of the laser tripod was a limiting factor, vertical alignment of the target was achieved by translating the height of the center of the scanner to the center of the target.

Because the scanner's 16 laser beams are divided into a $\pm 15^o$ FOV, there does not exist a laser on the 0^o angle in the laser scanner's reference system. To align the 1^o laser beam up with the tow-carriage reference frame, it was assumed that the horizontal translational alignment of the laser scanner was perfectly within the tow-tank's range axis. From this, the x-coordinate of the center of the target at various ranges were calculated and compared with the real-time data viewed within the Velodyne native visualization software, Veloview. When these values matched, the laser scanner-target pair were considered to be well-aligned. To accurately detect the central rotation axis of the target with the laser scanner, a narrow strip of aluminum was rigidly mounted vertically on the target frame and horizontally aligned with the rotation axis. This easily identifiable target was also used to establish the 0^o incident angle by slowly rotating the target back and forth until the maximum intensity was achieved. Figure 1 shows a cross-sectional illustration of the experimental set up with the laser scanner's reference frame. Once the laser scanner/target pair were well-aligned, data were collected for 8 minutes at each 144 setup configurations (6 ranges x 6 angles x 4 materials) to insure a data density high enough for statistical significance.

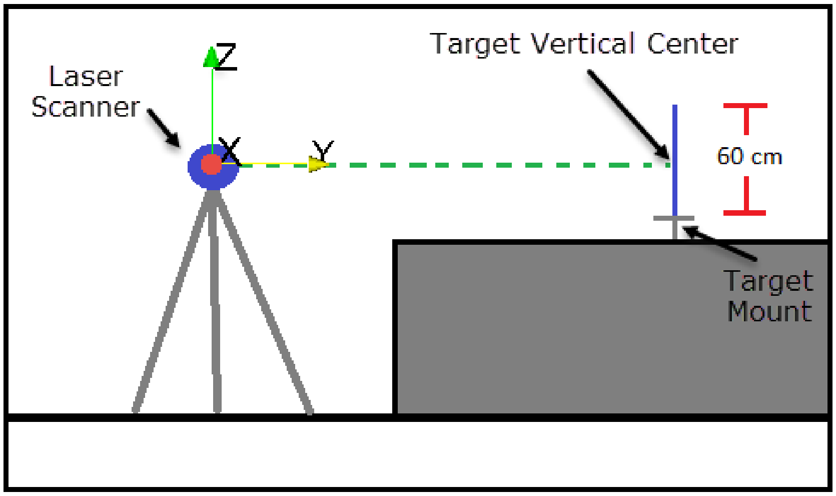

Figure 1: Illustration of experiment set-up with laser scanner's reference frame (side view).

Data processing was conducted in MATLAB. First, the data was rotated about the x-axis so that the laser scanner's x-y plane intersected the target where a high intensity specular return was observed. With this last reference frame alignment, the laser scanner's y-axis intersected all targets orthogonally at all ranges when in the 0^{o} incident angle configuration. Next, the data was clipped so that only the near-nadir returns were considered, specifically, ±5 cm. This was accomplished by calculating an azimuth window for each range and filtering out data outside of that window. The data were then normalized by subtracting of the expected range from the y-coordinate to center the data, collected at various ranges, on a common origin. Data were then binned into 2.5 cm vertical bins and statistics (mean and standard deviation) were calculated for each setup configuration including the average deviation from the expected range (∆range), the 2*σ confidence interval (CI), and the average intensity.

RESULTS AND DISCUSSION

Scatterplots were generated for each setup to visualize the data as seen in Figure 2. An obvious decrease in intensity can be seen as the incident angle of the target increases. This decreasing intensity trend is due to less laser light being backscattered at larger incident angles and most of the energy being forward scattered. The average Δrange values for each plot also show a decreasing trend with larger incident angles. This is interpreted as the targets are registering closer to the laser scanner as the incident angle increases. This trend can be partially explained by the physical characteristics of the laser beam footprint intersecting the target at oblique angles as seen in Figure 3[7]. Correcting for this phenomenon, a residual Δrange still exists for most targets and ranges easily seen at incident angles of 75° shown in Figure 4. This residual Δrange, defined as the deviation from the expected range not due to the laser beam footprint intersecting the target at oblique angles, is interpreted to be due to a slight alignment offset that was unable to be resolved using the methods described in the experimental setup.

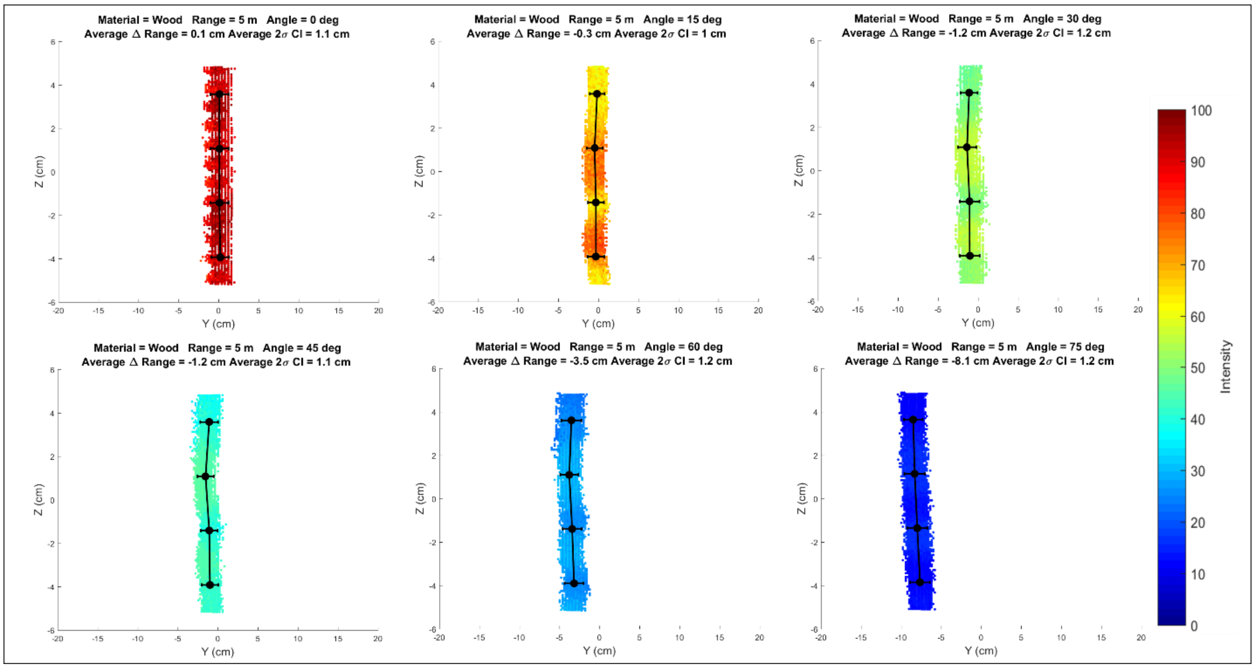

*Figure 2: Side-view scatterplots of data on wood within the ±5 cm vertical section of the target at 5 m and at incident angles of 0°, 15°, 30°, 45°, 60°, and 75°. Data points are colored by intensity. Large black dots show 2.5 cm bin average Δrange, horizontal error bars show 2*σ CI.*

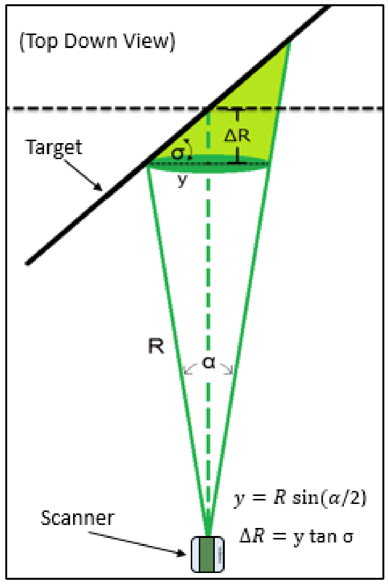

Figure 3: Geometric example of a laser beam footprint intersecting an oblique target. ΔR is the range anomaly caused by the outer edge of the laser beam intersecting the target at an incident angle of σ. α is the beam divergence, 0.003 radians for the VLP-16 unit[7].

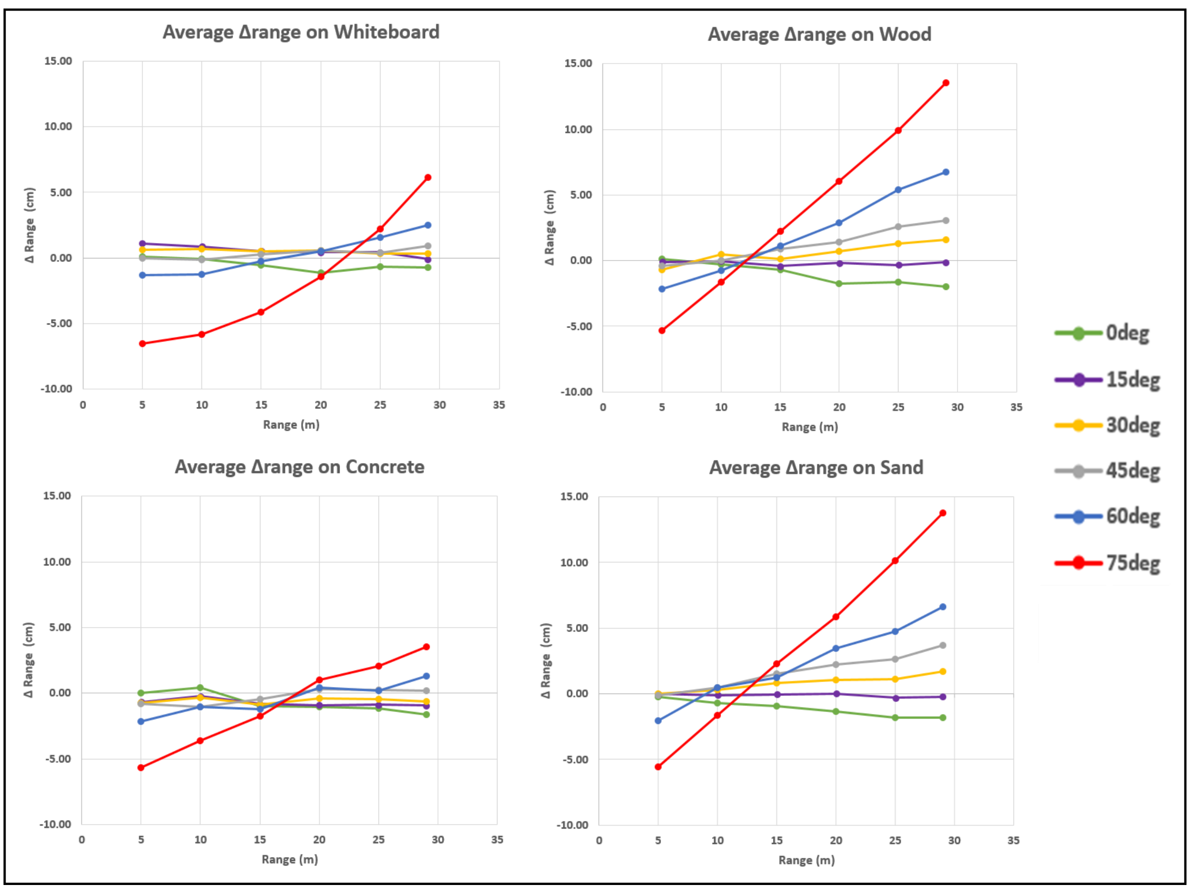

Figure 4: Residual Δrange for all targets at all range/angle configurations after beam footprint correction.

To assess the precision of the laser scanner, the spread of the data in the y-direction was evaluated by calculating the 2σ CI for each 2.5 cm bin. Results, shown in Figure 5, show that the laser scanner performed exceptionally well. For most range/angle configurations, the 2σ CI values fell below ±2 cm. Generally, as the roughness of the target increased, the precision of the scanner also increased, especially at large incident angles.

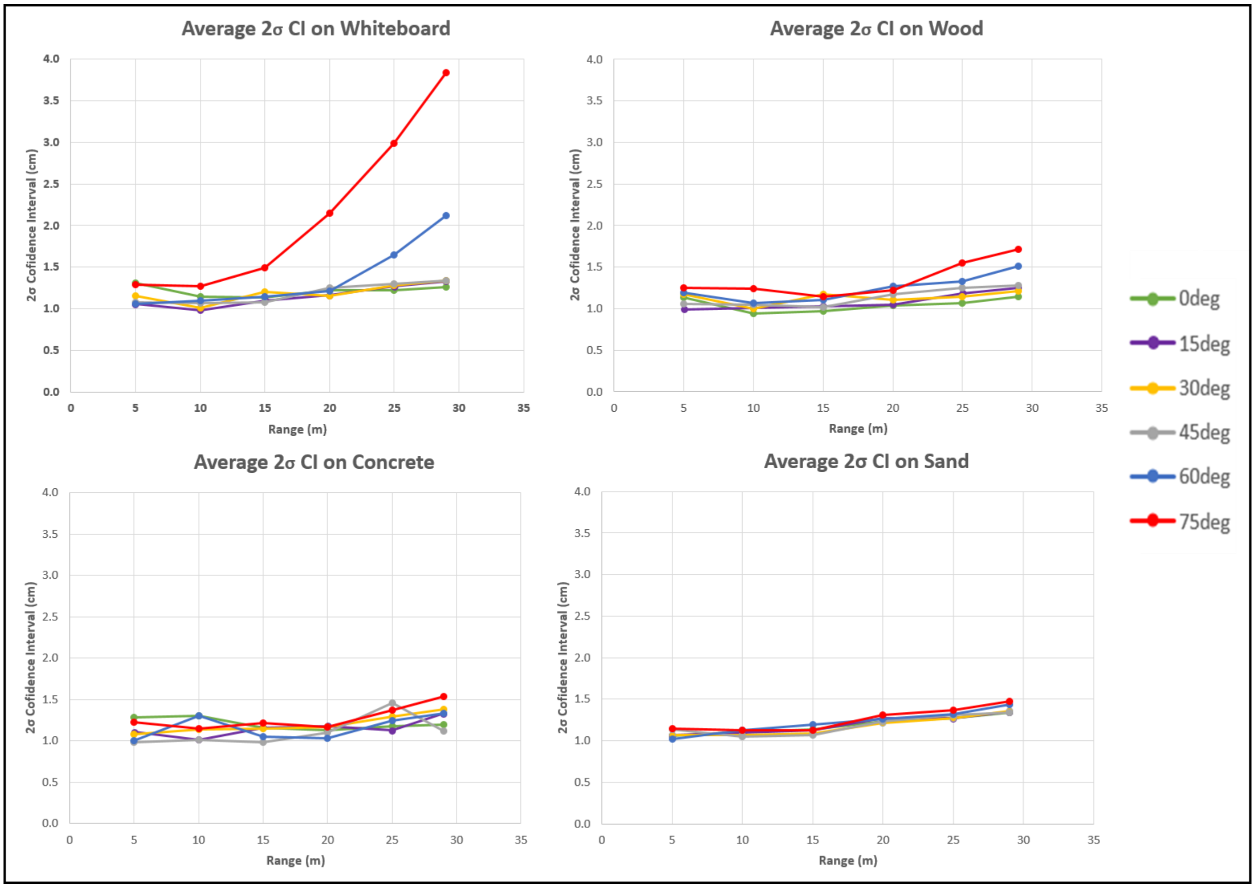

Figure 5:2σ CI for all targets at all range/angle configurations.

As mentioned before, the effects of intensity on range estimates was also evaluated. For the most part, the range estimates seemed to be independent of intensity measurements with one exception. In areas where the registered intensity values were saturated, above a value of 100, there was an apparent shorter range, ~1 cm. A side-view scatterplot of the data on the entire whiteboard target at a range of 5 m and an incident angle of 0^{o} shows this range anomaly in Figure 6. This is most likely due to a digital signal processing technique embedded in the Velodyne VLP-16.

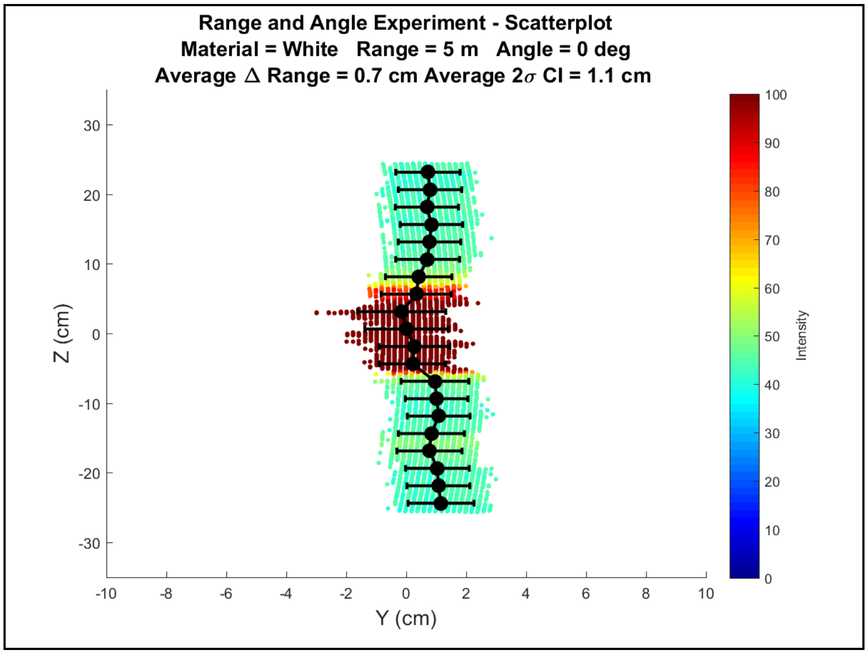

*Figure 6: Side-view scatterplot of data on whiteboard for entire target at 5 m and at incident angle of 0°. Data is colored by intensity. Large black dots show 2.5 cm bin average Δrange, horizontal error bars show 2*σ CI.*

CONCLUSIONS AND FUTURE RESEARCH

The performance of the Velodyne VLP-16 in this controlled experiment seems to indicate that the scanner is more than sufficient to be used for conducting shoreline survey which greatly exceed IHO specifications. The average 2σ CI for all setups was within ±1.2 cm. Due to the limited size of the tow tank, performance could not be tested at the maximum range of the laser scanner, 100 m. A larger 2σ CI would be expected at these ranges due to the compounding effects of the associated larger time uncertainty. Extrapolating the average slope of the 2σ CI curves to a range of 100 m results in a value of ±3.0 cm, the advertised accuracy of the system. As part of estimating the performance of the laser scanner system, an alignment procedure was developed for a first-order approximation of the geometry between the laser and tow-carriage reference systems. Future work will include integrating the laser scanner on a marine survey vessel and modeling the laser characteristics at the full operational range of the laser.

Studies have been conducted in the past by NOAA hydrographers to explore survey-grade mobile laser scanners which ultimately concluded that even though this technology could vastly improve the shoreline feature mapping process, they were cost-prohibitive. This study demonstrates that industrial-grade laser scanners such as Velodyne VLP-16 can exceed IHO specifications while costing approximately 10 times less than survey-grade scanners.

REFERENCES

1. The Coastline of the United States United States. (1975). doi:NOAA/PA 71046

2. NOS Hydrographic Surveys Specifications and Deliverables. (2016).

3. IHO Standards for Hydrographic Surveys - Special Publication No. 44. **5,** 160 (2008).

4. Brennan, R., Canter, P., Van Rans, J. & Silva, A. Surface imaging capabilities on marine hydrographic vessels. *Hydro Int.* **12,** 14–17 (2008).

5. Wyllie, K., Froelich, G., Cove, K. & Hart, K. Process for Capturing Real World Features from 3D Laser Scanned Point Clouds. in (2012).

6. VLP-16 User's Manual and Programming Guide. (2015).

7. Baltsavias, E. P. Airborne laser scanning: Basic relations and formulas. *ISPRS J. Photogramm. Remote Sens.* **54,** 199–214 (1999).

BIOGRAPHICAL NOTES

Lt. j.g. John Kidd graduated with a BS in Ocean Earth and Atmospheric Science from Old Dominion University. He joined the NOAA Corps in 2011, and has sailed aboard three NOAA hydrographic vessels. Currently he is pursuing a MS degree in Ocean Mapping at the University of New Hampshire.

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