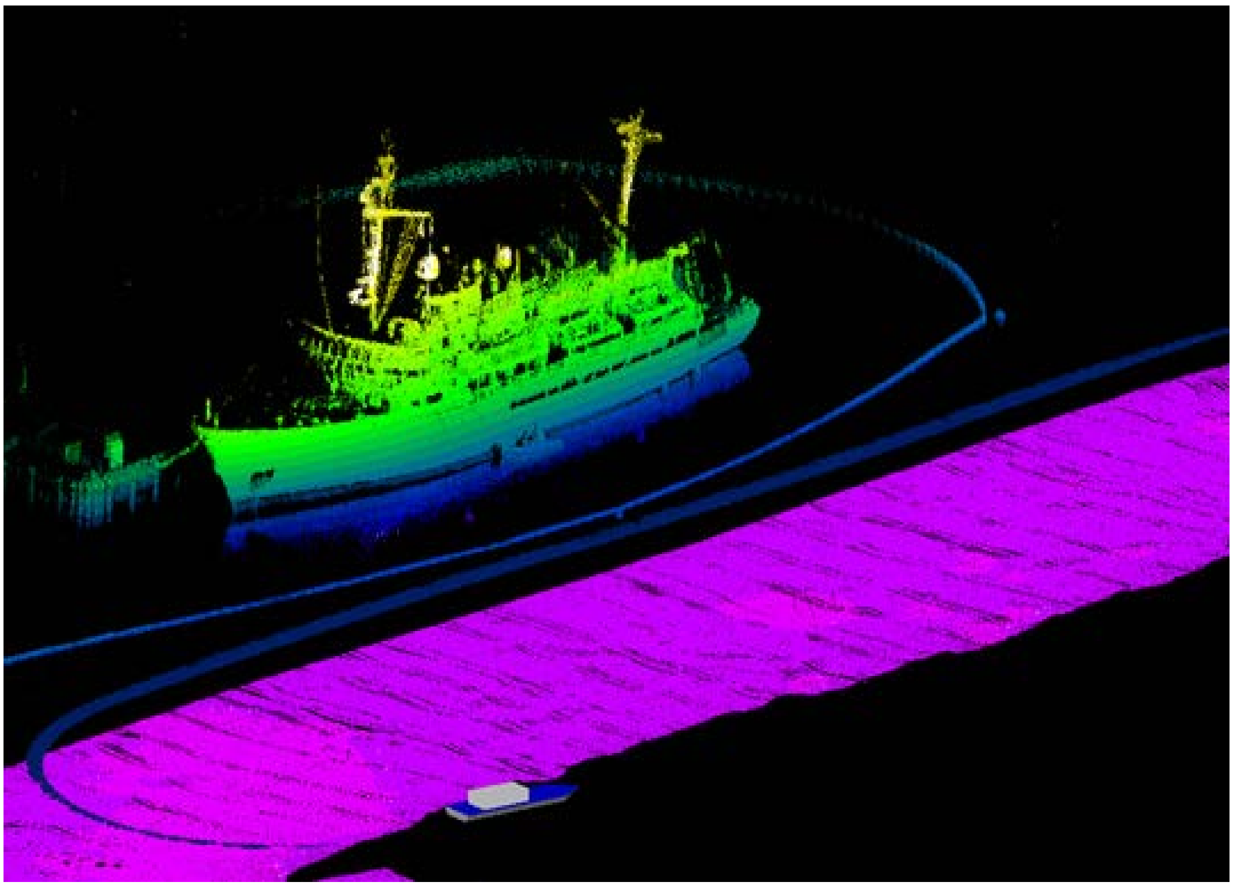
Velodyne VLP-16 Laser Scanner Acceptance

NOAA Ship Fairweather / HSTB
May 3-8, 2016



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Hydrographic Systems and Technology Programs

Executive Summary

The Velodyne VLP-16 laser scanner has been in use on the *Fairweather* for several evaluation projects. This report describes efforts taken during the May project in Tlevak Straight to perform a comprehensive assessment of the sensor. By performing research and operational tests, we have gathered the necessary data to provide a recommendation to accept this sensor for shoreline feature acquisition use.

During this acceptance, we have made the following significant findings:

- 'Sun Noise', both direct and reflected off the water's surface, provides a significant source of noise to the vertically mounted laser
- Rigid ATON structures provide excellent patch test targets
- By surveying a GPS Base station, accuracies of 20 cm in the horizontal and 1 cm in the vertical were found for the VLP-16 in one specific instance. Vertical uncertainties on the order of 30cm are expected for real time acquired features.
- By viewing targets at various ranges, an effective range for the VLP-16 was found to be between 50 and 70 meters
- The VLP-16 shoreline workflow integrates well within the existing feature attribution workflow
- Laser scanner shoreline acquisition is more accurate, safe, reliable, and efficient than conventional shoreline acquisition. Some concerns remain regarding the training and personnel required to move laser scanner operations into production. All of these points are addressed in detail later on in this report.
- The VLP-16 laser scanner data comprises on average 2.3% of the total acquired HSX data. (Reson 7125 and Applanix POS MV combined)

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Schedule and Overview

The Coast Survey Development Laboratory's Hydrographic Systems and Technology Branch (HSTB) procured and delivered the Velodyne VLP-16 laser scanner to the NOAA Ship Fairweather in January 2016. The scanner was integrated on a survey launch and evaluated over the course of two underway trials; one in February and one in April. These trials were primarily to determine the suitability of the scanner and test new features.

On May 2nd, the ship sailed to its working grounds in Tlevak Strait, AK. We ran the VLP-16 from Launch 2808 to scan assigned features during a four day negative tide window from May 8th to May 11th. Running the VLP-16 on project allowed us to build an understanding of its operational capabilities and efficiency as a shoreline acquisition sensor.

An outline of the project is provided below:

- May 2nd – NOAA Ship Fairweather departs Seattle, WA for Tlevak Straight via Inside Passage
- May 6th – Ship arrived on project OPR-O190-FA-16
- May 8th to 11th – VLP-16 acquisition on project
- May 12th to 18th – Data processing
- May 19th – Vessel arrives in Petersburg, AK

Hardware/Software Configuration

The Velodyne VLP-16 creates 360° 3D images by using 16 laser/detector pairs. The lasers are mounted in a housing that spins from 5 to 20 times a second. As a result, the scanner can acquire up to 300,000 points per second.

The scanner relies on the Garmin GPS antenna for timing. Power and Ethernet communications are provided through a separate interface box. The scanner is controlled using HYPACK on the acquisition computer. Figure 1 shows the complete setup below.

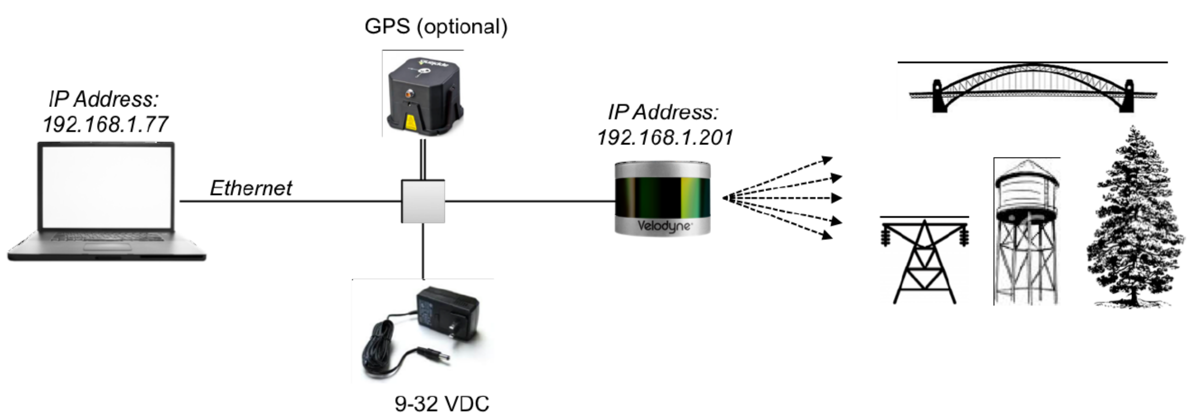

Figure 1: Overview of Velodyne VLP-16 System

Physical Installation

We designed a custom mount based off of designs by the Army Corps of Engineers for the VLP-16 to fit the survey launch. The mount has built in guide pins to keep the sensor stationary and prevent rotation. The sensor is installed facing up, maximizing data density in the alongtrack direction and preventing gaps in coverage. The mount was attached using c-clamps and ratchet straps to the starboard side of the top of the launch cabin. We intended this to serve as a temporary installation for this project, and planned to weld a permanent install post acceptance. A GoPro Hero 4 was positioned on the mount to provide pictures of acquired features. Figure 2 shows the specifications of the installation.

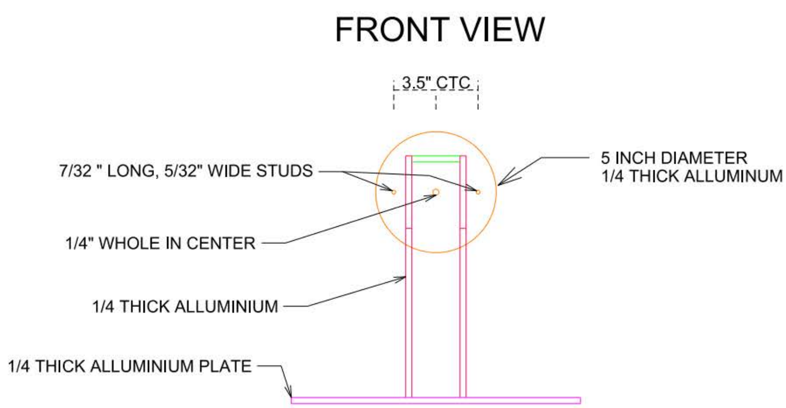

Figure 2: VLP-16 Custom Mount

There were two major disadvantages to the vertical mount. One, the scanner would record strong returns from the boat deck below. As Figure 3 shows, this corresponds to roughly the 340° to 020° sector of the scanner. We used filters to eliminate these returns. Filters are discussed later in this report. We positioned the sensor off to starboard in order to maximize its field of view on that side and reduce starboard side boat returns. While the sensor can still acquire targets off the port side, it became standard practice to acquire with the shoreline on the starboard side of the vessel. This also assisted the coxswain in positioning the boat relative to the feature, as the coxswain chair was also on the starboard side.

Figure 3: VLP-16 Orientation

Two, the sensor received strong returns from solar radiation, due to a large sector of the scanner point skywards. This is something that will be addressed in detail later in this report.

Offsets

Offsets were measured from the base of the starboard POSMV GNSS antenna on the top of the launch cabin to the VLP-16 using a tape measure. We positioned the antenna base with respect to the IMU during the most recent vessel survey. The X and Y offsets are given with the Applanix IMU as the reference point. The Z offset is given with respect to the waterline, which is 13 cm above the IMU. Table 1 shows the survey values, given in the sign convention used by HYPACK.

Table 1: VLP-16 Offsets

X (Positive Starboard)	Y (Positive Forward)	Z (Positive Down)
0.790 meters	-2.112 meters	-2.816 meters

By integrating the scanner into the IMU reference frame, all positioning and attitude correctors were seamlessly applied to the data within HYPACK.

HYPACK Software

Velodyne, in collaboration with Kitware inc., developed Veloview, a software package designed to display and capture data packets being sent from the VLP-16 scanner. This software records data in pcap format, and can export to XYZ and CSV. Veloview does not allow for integration with our existing suite of sensors and processing and acquisition software.

HYPACK has developed a device driver for the VLP-16 that allows for integration of the sensor into our acquisition and processing workflows. This driver allows for:

- The inclusion of sensor offsets and patch test values
- Filtering of data by angle and range
- Logging of data within HSX file format in TOP or RMB messages
- Simultaneous visualization of VLP-16 and MBES coverage
- Acquisition and attribution of points as S57 objects

All VLP-16 data was logged in TOP messages within HSX files. All multibeam data is logged within RSS and RMB records. Having multiple devices logging RMB/RSS records (i.e. multiple multibeam sonar systems) within a single HYPACK session will cause issues with Caris HSX conversion. Logging singlebeam data in RAW/BIN files would not cause an issue, as these records are segregated from multibeam HSX logging.

By logging VLP-16 in TOP format, we allow for the processing of the multibeam data logged in RMB/RSS records. Caris does not currently support TOP conversion. We have a request in with Caris to enable this functionality, although it is not a part of the recommended workflow.

Horizontal and Vertical Control

Final tides will be downloaded and applied through a CO-OPS provided zone definition file (ZDF) upon their delivery. Operating stations include the Port Alexander NWLON gauge and the tertiary gauge installed by *Fairweather* in Windy Cove. Final tides will be applied to the exported S57 object before delivery to the processing branch in Caris Notebook.

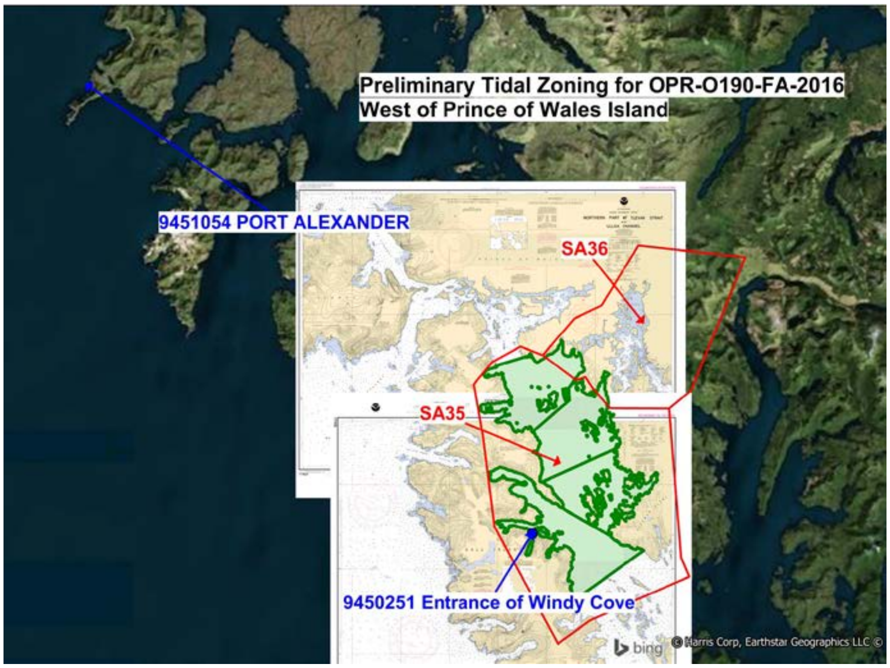

Figure 4: Tide Station Overview

Horizontal control was provided in real time using the positioning and attitude correctors from the POS MV v4. The USCG DGPS station at Annette Island, AK, provided differential correctors. There were no SBETs applied to the data prior to feature acquisition.

Patch Test

The patch test was run on an ATON at the mouth of View Cove, Tlevak Straight. Figure 5 shows an overview of the area.

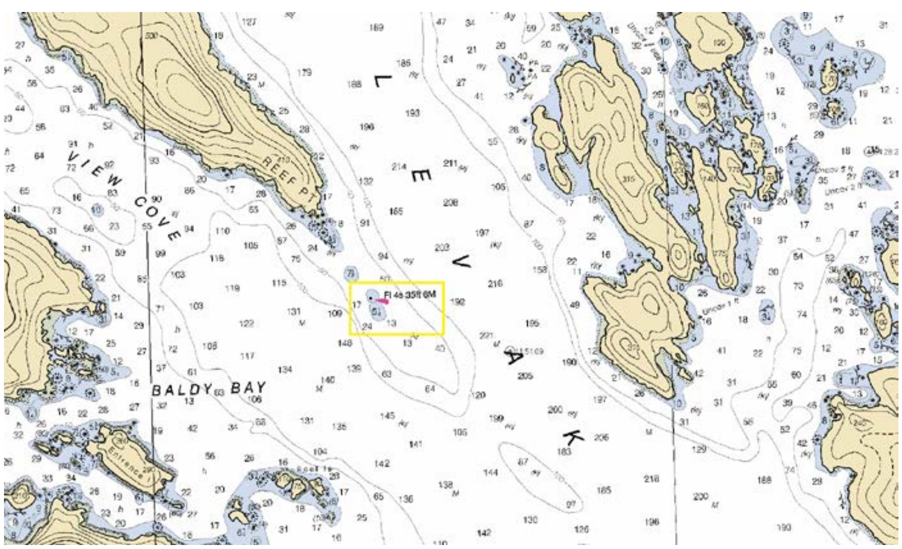

Figure 5: Patch Test Target Overview

In order to patch the laser scanner, it was important to find a prominent target that was approachable on all sides. As with multibeam patch test targets, finding one with prominent features and fine detail was crucial. The ATON featured a daymark and structural lattice that served exceptionally well for this, as seen in Figure 6.

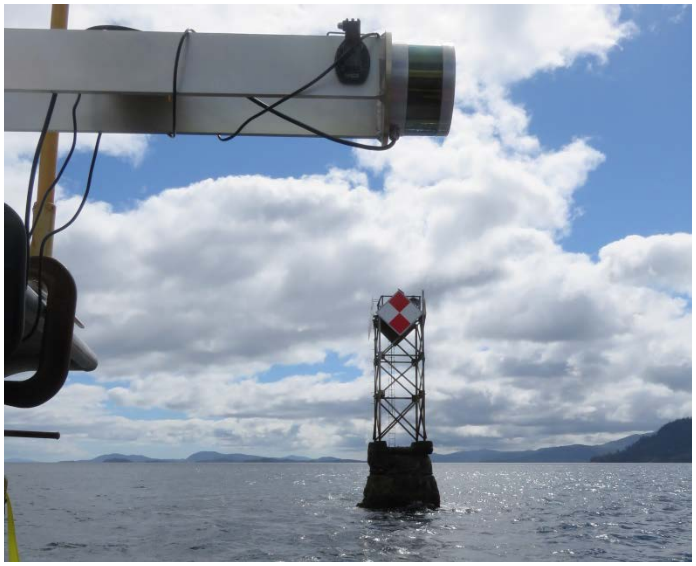

Figure 6: Patch Test Target

We ran four patch test lines in total; one on each side of the target. This plan was based off of guidance provided from HYPACK [1] for patch testing laser scanners. We loaded the data in HYPACK MBMAX64 to perform the patch test processing. Only rough cleaning was done for the test. No additional correctors were applied outside of the zero tide values loaded from the TID record in the HSX files. Patch test values were determined in the following order: roll, pitch and then yaw. By selecting the HYPACK patch test tool and dragging a line across the target parallel with two of the survey lines, we allow for easy visualization of changes in roll, pitch and yaw as shown below.

1. <u>Roll</u> – adjust to line up the flat bottom of the surface. A roll bias is seen as a vertical translation of the feature, as shown in Figure 7. As the surface of the water is not acquired with the VLP-16, roll was determined under the assumption that the base of the feature would begin around 0 meters relative to the zero tide water level datum.

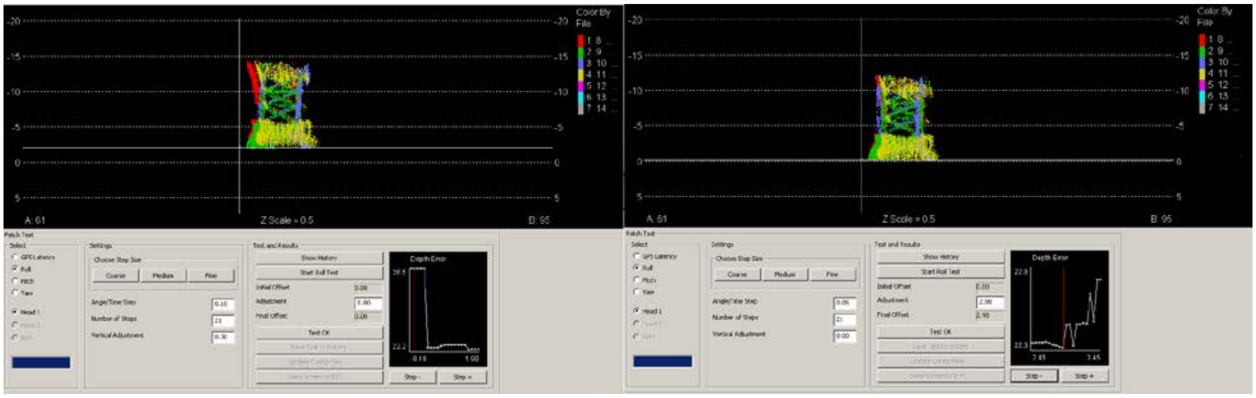

Figure 7: Roll Patch Test

2. Pitch – adjust to line up the top of the feature. Changes in pitch will cause the feature to spread out from the base, as shown below.

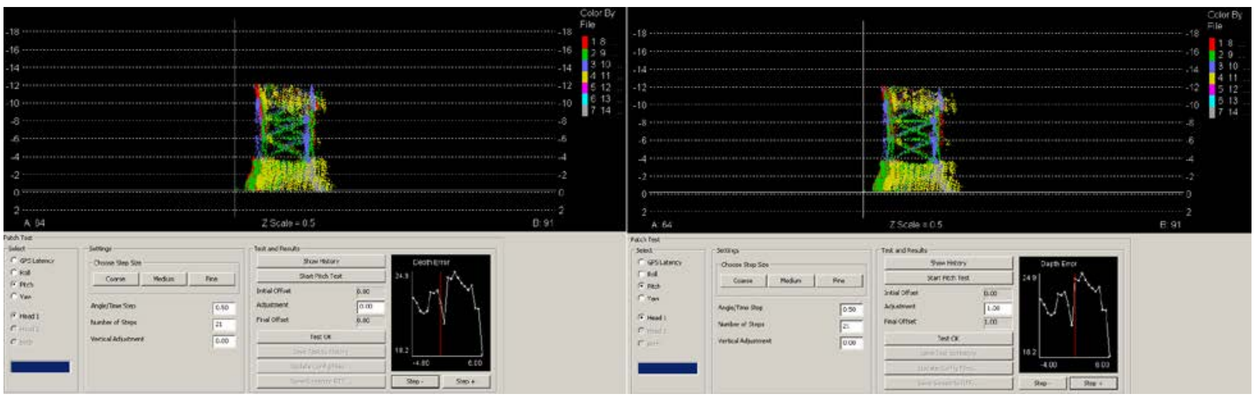

Figure 8: Pitch Patch Test

3. Yaw – adjust to minimize any horizontal translation of the feature. There was no yaw offset found in the VLP-16 installation.

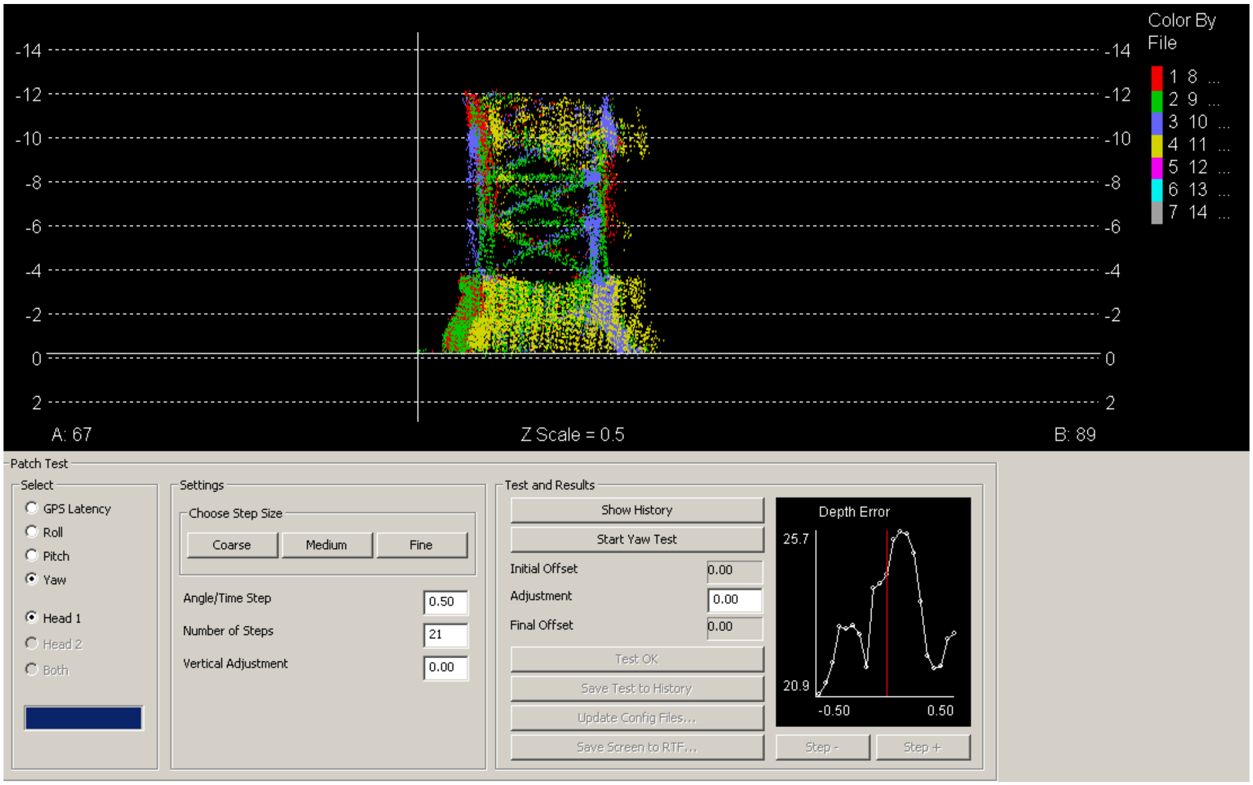

Figure 9: Yaw Patch Test

Figure 10 shows the resulting point cloud. Table 2 shows the values determined by the patch test.

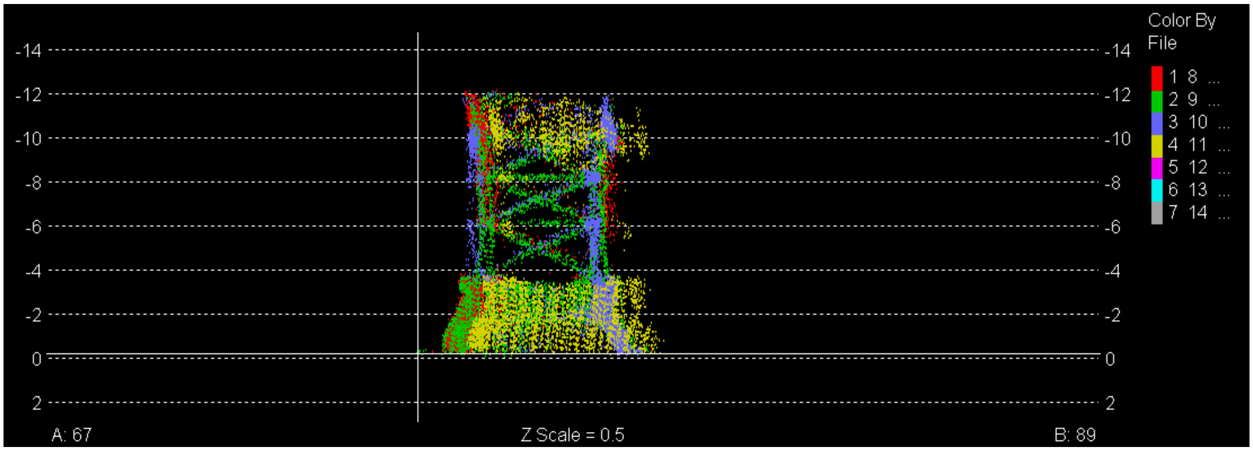

Figure 10: Patch Test - HYPACK MBMAX64 Point Cloud

Table 2: Patch Test Values

Roll (Positive Port Up)	Pitch (Positive Bow Up)	Yaw (Positive Clockwise)
2.90	1.00	0.00

Verification of Calibration

In order to demonstrate the capability of the sensor to position features with accuracy, we needed to determine a known point that could serve as a basis for comparison. Upon arrival at their working grounds, *Fairweather* had installed a GPS base station on a small island near The Sentinels, north of Nichols Island. An overview of the area is shown in Figure 11 below.

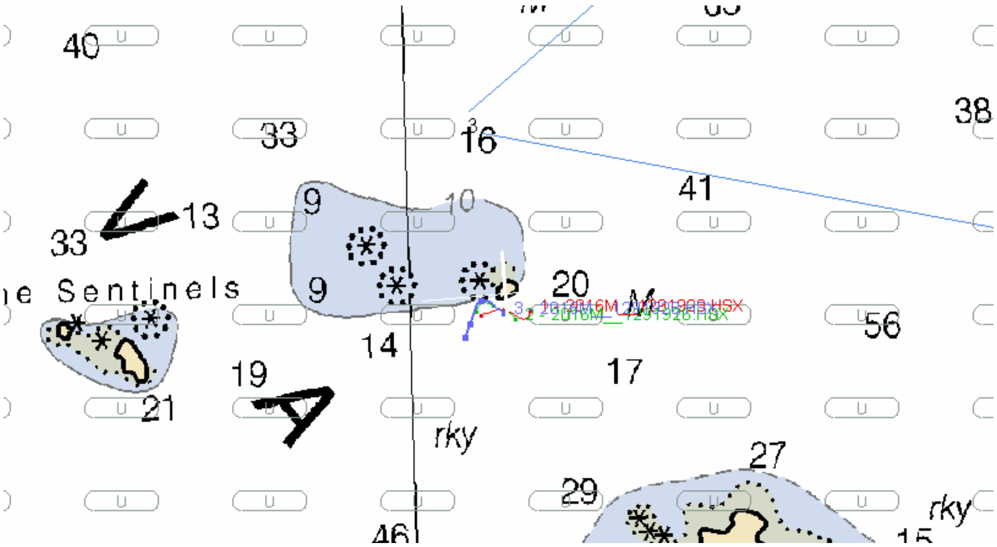

Figure 11: GPS Base Station Location - The Sentinels, Tlevak Straight

Our goal was to make several passes of the station location using the VLP-16 to position the top of the geodetic antenna. A total of three survey lines were done. By viewing the point cloud in MBMAX64, we can examine and target the top of the antenna. Figure 12 shows the resulting point cloud and target.

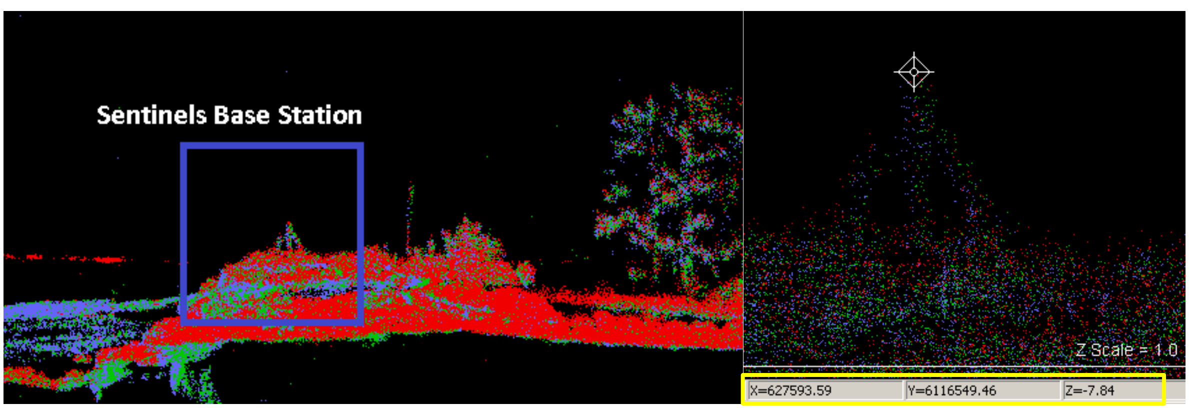

Figure 12: Sentinels Base Station and Target Location

We can now compare the HYPACK acquired coordinates with the OPUS reported UTM Zone 8 coordinates. Table 3 shows the results of that comparison. By taking the square root of the sum of the squared differences, we can determine the total horizontal error of the HYPACK target position in reference to the OPUS solution, which reports positions to within a few centimeters.

Table 3: Results of HYPACK/OPUS Comparison

	Northings (meters)	Eastings (meters)
HYPACK	627593.59	6116549.46
OPUS Solution	627593.774	6116549.686
Difference	0.18	0.22
Total Horizontal Error	**0.28**	

In order to verify the capabilities of the sensor to position features in the vertical, some additional data was required. We took the resulting target shown above and determined the exact time of acquisition using HYPACK's sounding info tool. Knowing the exact time of the sounding allowed us to determine the ellipsoid height from IMU for the vessel using the Applanix POSPac Realtime Trajectory – Altitude graph. We accommodated for a VDatum derived vertical difference of 2 cm between ITRF2000 (POSPac) and IGS08 (OPUS). By determining the ellipsoid height for both vessel and target, we were able to compare the HYPACK target height and derived target height. We found a difference of 1 cm, as shown in Figure 13 below.

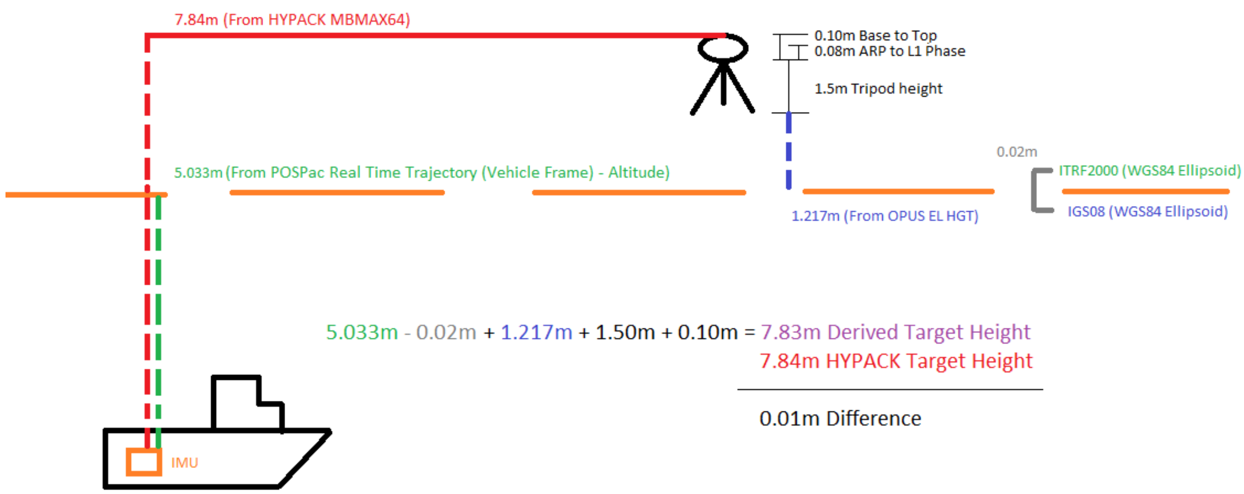

Figure 13: HYPACK and Derived Target Height Comparison

We did not undertake any additional post processing of positioning data in order to better simulate the real time workflow we intend to use in the field. The experimentally determined 0.28 m total horizontal accuracy is on par with the expected accuracy of the tightly coupled POS DGPS solution. The 0.01 m vertical accuracy is unusually low; the positional accuracy of both the SBET and OPUS antenna height are on order of a few centimeters, the alignment accuracy, particularly in roll, is limited by the empirical nature of the patch test. While this does not provide a comprehensive assessment of the positional accuracies of this method, it does demonstrate that we can position features with some confidence in both the horizontal and vertical.

Because we plan, at least initially, to follow the existing features workflow and correct the field measured heights using water levels, we expect that, absent integration errors, the uncertainty of the vertical control to dominate the uncertainty of the reduced heights. This uncertainty would include:

- Approximately 5cm for dynamic draft at survey speeds, unaccounted for in HYPACK
- Approximately 5cm for heave from Applanix POS MV
- Approximately 3cm for waterline measurements
- Approximately 20cm for final tides (zone or TCARI)
- For total RMS uncertainty of 21 cm.

Effective Range

The VLP-16 has a listed maximum range of 100 meters. It was our intention to test the effective range for both small and large features. We define effective range as the range at which the feature becomes recognizable and acquirable. In this test, we ran three survey lines each at approximately 50, 75 and 100 meters for both a small and large rock. Figure 14 shows the results for the small rock.

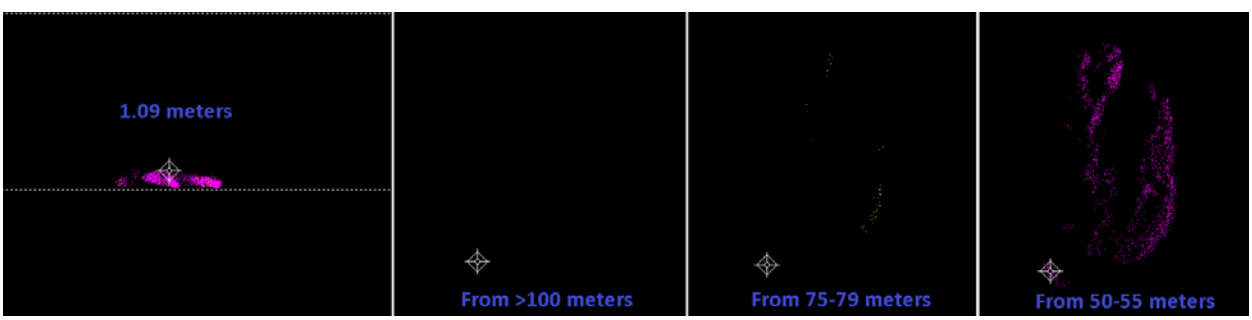

Figure 14: Small Rock Effective Range

This rock is approximately 1 meter tall above the water. The rock lacks a prominent face and would not be expected to show a strong return in the laser. From roughly 100 meters, no returns are spotted. At about 75 meters, the outline of the rock can be seen but would not be considered a useable target. Only at about 50 meters or so is the rock recognizable. In this case, the sensor would have a roughly 50 meter effective range for similar targets.

Figure 15 shows a large rock approximately 3.3 meters above the water. This rock has a more prominent face and should be expected to produce a strong return for the matrix. Here we see several returns at around 80 meters, but nothing recognizable. At about 50-70 meters, the rock is recognizable and acquirable. At about 50 meters, the rock is well defined and easily acquired.

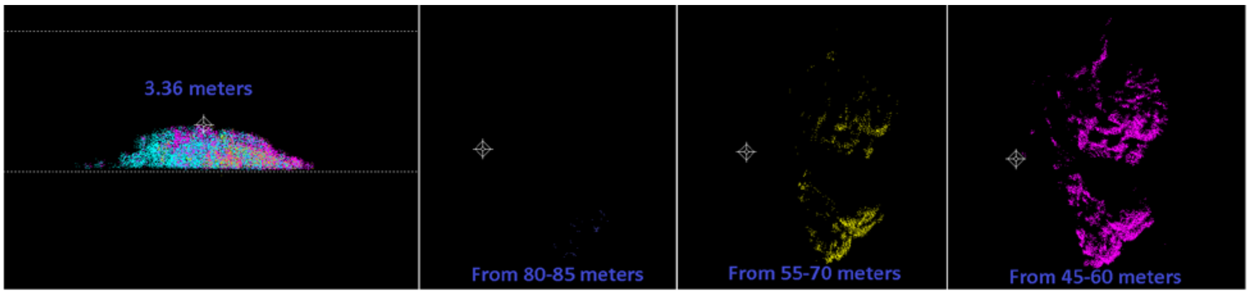

Figure 15: Large Rock Effective Range

As a result of this test, it can be seen that the effective range of the scanner is around 50-70 meters, depending on the size and type of feature. Any future acquisition plans should be based off of this range.

Precision and Range Accuracy

The University of New Hampshire (UNH) conducted several experiments to assess the VLP-16 laser scanner's ability to accurately position various targets at varying ranges and angles [2]. The scanner was mounted to a static tripod at the edge of a tow tank. The target was mounted to a tow carriage within the tank that could position itself at ranges of 5, 10, 15, 20, 25 and 29 meters from the scanner. The carriage could also rotate up to 75°, allowing for the testing of a variety of incident angles. This setup can be seen in Figure 16 below.

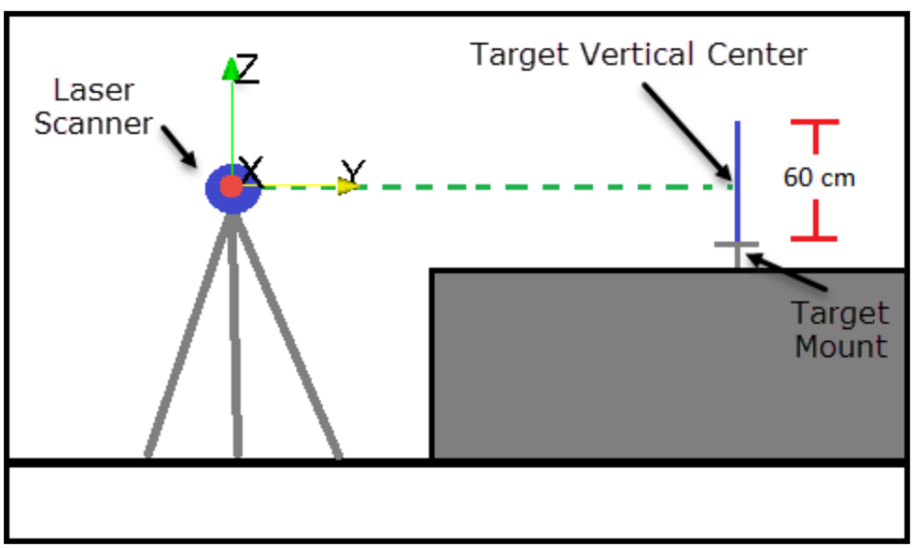

Figure 16: Laser Scanner and Target Mount

The results of this experiment include recorded average deviation from the expected range and the calculated two sigma confidence interval for the spread of the data across the beam footprint (precision). Both statistics are dependent on incidence angle, range and material type. The average two sigma confidence interval for all setups was within ± 1.2 cm. Extrapolating the average slope out to 100 meters results in a roughly ± 3.0 cm precision, as shown in Figure 17.

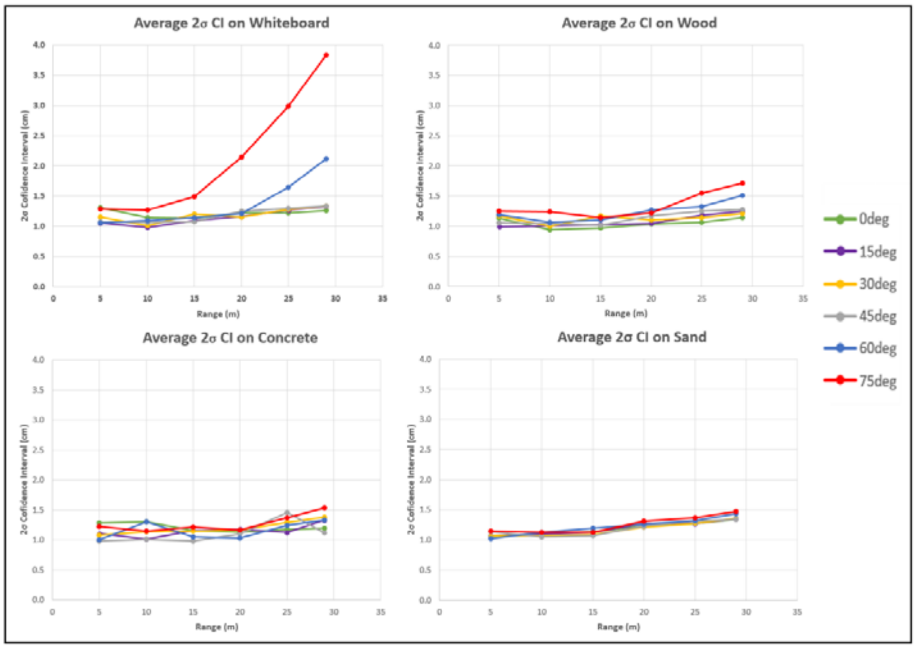

Figure 17: Average Two Sigma Confidence Interval for UNH VLP-16 Experiment (from [2])

This precision level matches the manufacturer's stated accuracy of ± 3.0 cm.

Noise and Filters

The laser scanner has the advantage of only picking up on specific sources of outside interference. With multibeam sonar, we have to be concerned with debris and marine life in the water column as well as secondary returns and side lobe interference. The laser scanner produces mostly clean data, with the exception of the following:

- Objects in motion, which appear in the data as smeared
- Vessel wake or otherwise breaking waves
- Sun noise, either direct or reflected off the water

The first two of these can be remedied by going out in good weather and avoiding moving objects, such as other small vessels or wildlife, which clutter the dataset and at times obstruct assigned features. Sun noise, however, provides constant interference to laser acquisition. It is mitigated slightly by the 'sun noise' reduction filter developed by Velodyne in late 2015.

On sunny days, we would still receive strong 'sun noise' returns above 30°, depending on time of day. An example of this is shown in Figure 19 below. It quickly became standard procedure to attempt to position the feature off to starboard and the sun off to port, whenever possible.

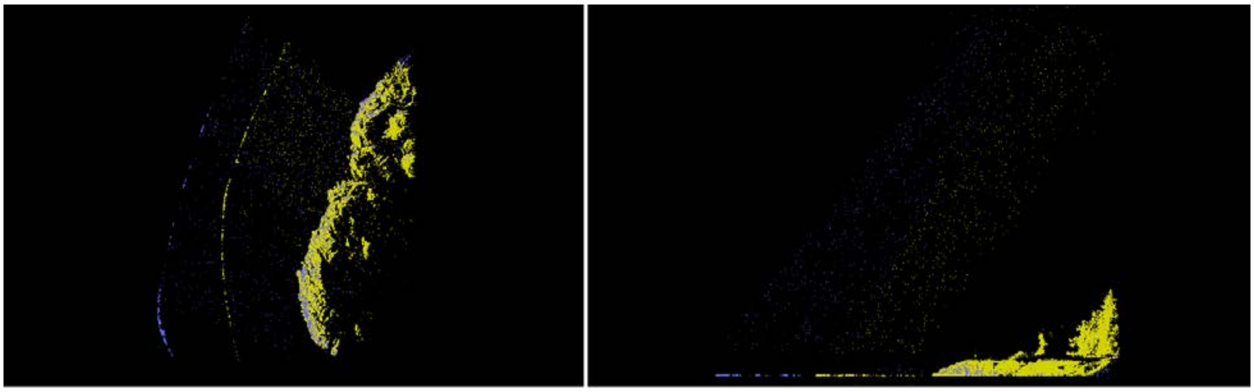

Figure 18: Sun Noise, Overview on Left, Profile View on Right

In addition, sun noise can be seen in smaller quantities reflected off of the water surface. This creates a trail of noise that follows the vessel around. An example of this is shown in Figure 20 below.

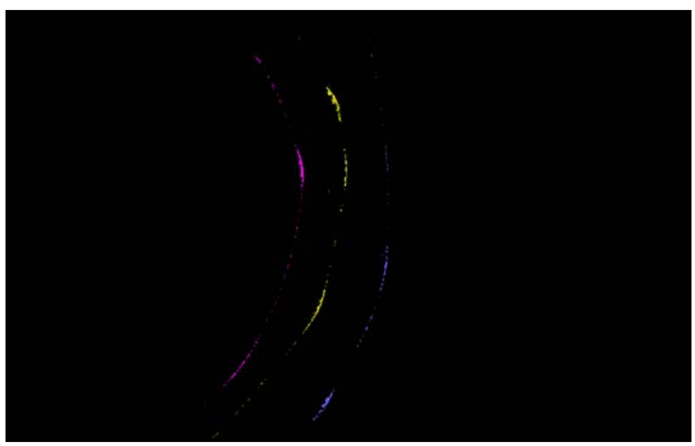

Figure 19: Sun Noise Reflected off of Surface

HYPACK range and angle filters were used to combat sun noise. Figure 21 shows an example setup used during testing. Setting the range filter to exclude anything closer than 4 meters eliminates returns from the vessel and any wake off the starboard side. It also eliminates the majority of sun noise reflected from the water surface. An angle filter excluding everything outside of 30° to 180° eliminates most of the direct sun noise and sets the useful sector of the scanner.

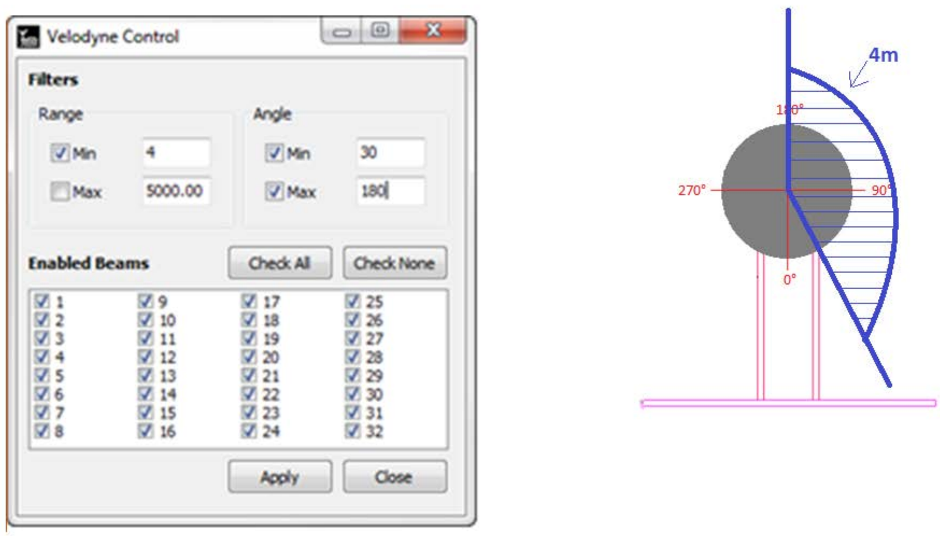

Figure 20: HYPACK Range and Angle Filter

Any scanning of targets above or off the port side will require reconfiguration of the VLP-16 filter, which is easily done during acquisition through the HYPACK interface.

Workflow and Efficiency

Laser scanner acquisition was performed in conjunction with traditional shoreline operations. Traditional shoreline was conducted from the *Fairweather* skiff using Trimble DGPS backpacks and Caris Notebook. Laser range finders (LRF) were used to determine offsets to features from the GPS reported position. Detached Position (DP) forms were used to record the information and metadata.

The Velodyne workflow replaces the backpacks and LRFs with the VLP-16 scanner and the DPs with HYPACK target metadata. The product is mostly the same, with an attributed s57 feature file containing heights and positions of all new features. Figure 22 shows the integrated Velodyne workflow.

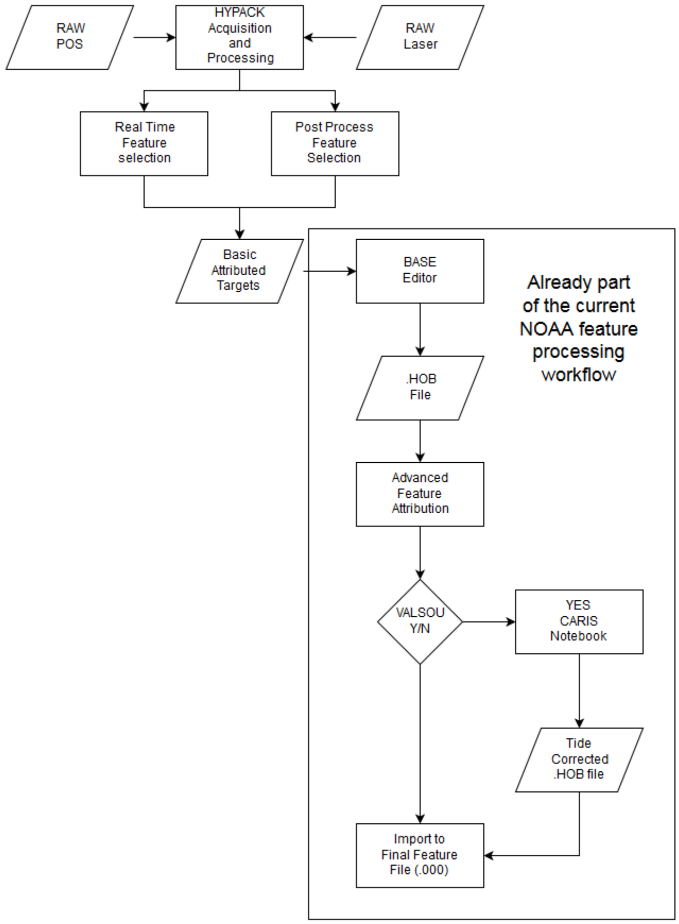

Figure 21: Laser Scanner Workflow

All of the features acquired during this project were collected in real time. The post processed workflow was developed in case features had to be created after acquisition. As there was enough time during acquisition to create the features, this turned out to be unnecessary.

Having both shoreline methods in operation simultaneously allowed for some research into their respective efficiencies. We recorded the amount of acquisition time, number of features addressed and total features positioned for both traditional and laser scanner methods. The traditional shoreline vessel only went out for two days of the four day negative tide period. Table 4 shows the data gathered during the comparison. It can be seen that the laser scanner vessel acquired and addressed at least as many features as the shoreline vessel.

Table 4: Traditional Versus Laser Scanning Shoreline Efficiencies

	Traditional Shoreline	**Laser Scanner Shoreline**
DN 129	None performed	3.5 hours of acquisition
		71 features addressed
		24 targets created
DN130	3 hours of acquisition	3 hours of acquisition
	38 features addressed	65 features addressed
	15 detached positions	17 features created
DN131	3 hours of acquisition	3 hours of acquisition
	58 features addressed	65 features addressed
	18 detached positions	17 features created
DN132	None performed	2.5 hours of acquisition
		49 features addressed
		29 features created

In addition to these metrics, the laser scanner vessel acquired 27.8 NM of near shore multibeam data. As the laser scanner vessel was sometimes required to make three passes to get close enough to the feature, much of the acquisition time was spent acquiring this multibeam data. If coverage existed prior to shoreline operations, we would expect efficiency gains of 200-300%, as the time devoted to multibeam acquisition could be devoted to laser scanning.

Aside from the additional multibeam coverage, there are some other distinct advantages to laser scanner acquisition over traditional shoreline, including:

- Accuracy – The DGPS backpacks can achieve positional accuracies of about 1 meter. Position offsets determined by eye will naturally have some error associated with them. Offsets found by LRF will be dependent on the ability to shoot the correct point from a moving vessel. By contrast, the VLP-16 allows for motion corrected feature acquisition and analysis. Based on the results of the 'Verification of Calibration' section, we have seen that a feature can be positioned with roughly 20cm horizontal and 1cm vertical positioning error relative to the OPUS solution for that feature. This does not reflect a general accuracy level for the scanner, but does demonstrate the capability of the system to position features with a reasonable level of accuracy.

- Efficiency – Laser scanner shoreline can be conducted underway at survey speed. Metadata is acquired automatically through target information versus hand written DP forms. Both of these elements lead to greater efficiency for laser scanner shoreline operations.

- Safety – Laser scanner operations allow us to maintain an approximate 50 meter buffer between vessel and target. In addition, the concurrent multibeam coverage allows for better estimation of the Navigable Area Limit Line (NALL) and what features are navigationally significant. As such, there is no need to make contact with features in order to acquire them using the laser scanner.

- Reliability – Laser scanner operations use survey launches and gear that are checked for readiness on a daily basis. Traditional shoreline operations rely on DGPS backpacks, Caris Notebook and the *Fairweather* skiff; none of which are in use nearly as often. As such, it is common to find traditional shoreline operations interrupted by equipment failure or technical issues related to unfamiliar gear and operations.

There are some distinct disadvantages to laser scanner operations including:

- Training – Managing the HYPACK Real Time Cloud window and visualizing targets for acquisition requires some training and experience. Also, the HIC has to understand the operational range and requirements of the VLP-16 to provide guidance to the coxswain. Several *Fairweather* individuals have been involved as operators at this point and have quickly picked up on the concept of laser scanning and what is required as operator/HIC. Overall, given the complexity of the rarely used DGPS backpacks and Caris Notebook, we expect the laser scanner workflow to require less training than the traditional shoreline method.

- Personnel - Based on the operations during this leg, we have determined that running with a sonar operator and separate laser scanner operator are required to manage near shore acquisition. With the installation of sonar that requires less user interaction, this would become less of a requirement. As it currently stands, managing range scales and gain values on the Reson 7125 as well as target acquisition in the Real Time Cloud window is a job for two hydrographers.

File Size Analysis

We took 15 survey lines and performed an analysis to determine a sample data rate and capacity estimate for future laser scanner acquisition. They contained HYPACK navigation, POS MV, Reson 7125 multibeam operating at 200 kHz and Velodyne VLP-16 data. By splitting the laser scanner data from the rest of the line using a Python script and examining the occurrence and length of the TOP messages (which correspond to VLP-16 'pings') in relation to the rest of the line in an Excel spreadsheet, we found that the VLP-16 data comprised on average 2.3% of the file. Figure 22 shows these results.

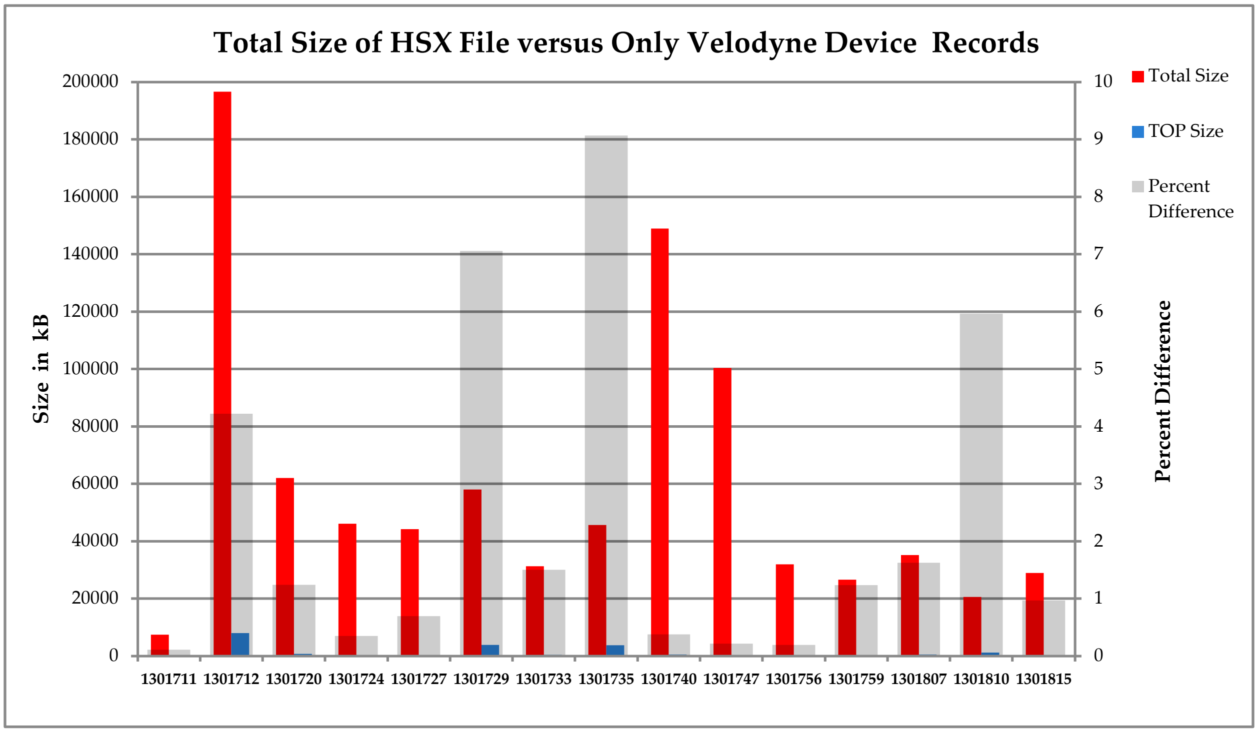

Figure 22: Data Capacity Analysis

Based on these results, we can see that the laser scanner data takes up a relatively insignificant portion of the total acquisition data rate and capacity. By splitting the Velodyne data from the rest of the HSX line, we also have the ability to submit only the multibeam data to the processing branch.

Conclusion

The Velodyne VLP-16 is more than capable of positioning shoreline features within the horizontal and vertical uncertainty standards set in the NOAA Hydrographic Specifications and Deliverables, 2016. This sensor provides an entry point into the world of small boat laser scanning. Hardware and software development to improve reliability and performance are still ongoing by both Velodyne and HYPACK. We have a number of open requests with HYPACK, including:

- Troubleshooting Realtime Cloud Window and S57 export issues
- Addition of UWTROC acquisition within Realtime Cloud Window
- Addition of Velodyne error model within TPU editor
- Target autoconversion needs to retain height and time

Based on the results of this acceptance, we recommend the immediate implementation of the VLP-16 laser scanner for shoreline use. We have found that *Fairweather*, with her four survey launches, would be best outfitted with two active systems and one spare unit. This allows for the continuation of shoreline operations with the loss of a sensor and/or survey launch. A full list of sensors for all four hydrographic platforms would be as follows:

- *Fairweather* – two scanners in operation, one as a spare
- *Rainier* – two scanners in operation, one as a spare
- *Thomas Jefferson* – one scanner in operation, one as a spare
- *Ferdinand Hassler* – one scanner in operation one as a spare

This plan would require a total of 10 VLP-16 scanners. It is recommended that two additional scanners be procured for HSTB use. HSTB would continue to work to develop tools and assess future laser scanner technology as it is developed.

References

[1] D. Maddock, "Patch Testing Topographic Lasers," HYPACK, Middletown, CT, 2016.

[2] J. Kidd, S. Pe'eri, Eren, A. Armstrong, "Performance Evaluation of the Velodyne VLP-16 System for Feature-Surface Surveying Scanner," Canadian Hydrographic Conference 2016, Halifax, NS, Canada, 2016.