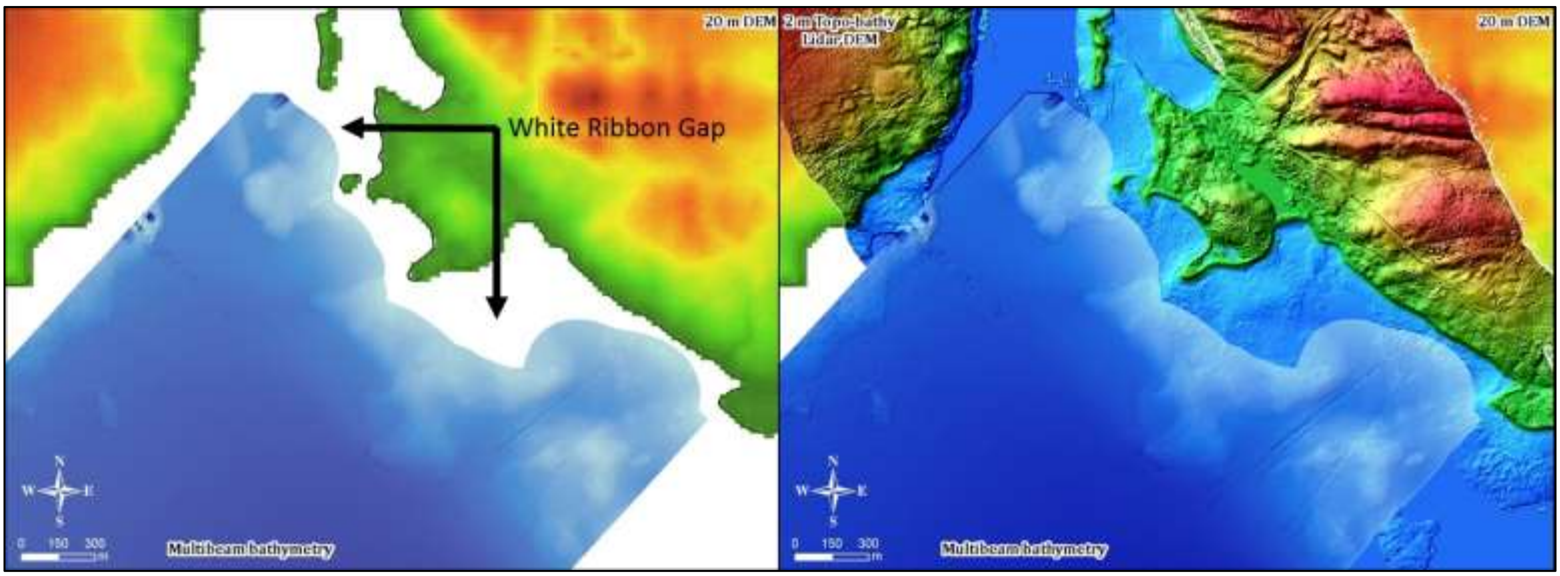
Bathymetric lidar to support pre-engineering analysis for marine liquefied natural gas transport infrastructure



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Executive Summary

A topographic-bathymetric lidar survey conducted on October 26, 2015 by NSCC's Applied Geomatics Research Group collected detailed elevation data for a site in Goldboro, Nova Scotia to support a pre-engineering analysis for a marine liquefied natural gas (LNG) terminal to be built by Pieridae Energy (PE). The topographic and nearshore bathymetric lidar survey results, collected with a Leica AHAB Chiroptera II lidar sensor, were merged with deeper bathymetric echosounder data provided by PE, and a hybrid elevation model was constructed. A multispectral orthomosaic of air photos, captured using an RCD30 60 MPIX camera installed in the lidar unit, was compared with the lidar intensity data, plus side-scan sonar data provided by PE, to confirm the best location for the new LNG wharf and jetty structure, which was digitized from a detailed schematic of the project also provided by PE. An optimal site was selected and a three-dimensional spatially accurate recreation of the wharf and jetty structure was built within ESRI's ArcGIS desktop suite of products. The hybrid lidar-echosounder elevation models were modified to include this new wharf and jetty structure, and volumetric estimates were derived to determine the amount of fill needed to be removed and added to build the structure. Prior to the lidar survey and analysis, PE had limited information in the nearshore area to assist them in their pre-engineering analysis and design. This report details the methods and results of the pre-engineering analysis of the LNG wharf and jetty structure in Goldboro, NS.

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1 Introduction

1.1 Background and Study Area

Pieridae Energy is a development company for energy-related infrastructure with a focus on liquefied natural gas (LNG) operations. Pieridae Energy (PE) is a relatively new company, founded in 2011, but has already developed contracts and partners with world-class resource supply companies to enhance its fully integrated LNG project. One such project involves the infrastructure development for a new east coast LNG terminal for Canada, which is to be located in Goldboro, Nova Scotia. The 'Goldboro LNG' project will include the development of an LNG processing facility, storage tanks, and marine works, which will include a wharf and jetty in Goldboro Harbour (Pieridae Energy, 2016). As such, PE collaborated with Nova Scotia Community College's (NSCC) Applied Geomatics Research Group (AGRG) through an NSERC-funded research grant to investigate the placement of a wharf and jetty in Goldboro, NS. The wharf and jetty are proposed to extend from the shoreline to approximately 1 km offshore into 20 m water depth. Accurate information on the geology and depth of the ocean bottom are required to plan construction of the facility, and consider the most suitable location in order to minimize environmental impact. A multibeam echosounder bathymetric survey currently exists for the study area in Goldboro, however depth limitations exist for traditional boat based surveys, as the boats face navigational hazards when approaching close to shore, resulting in a gap of no data along the nearshore and coastline.

The Nova Scotia Community College's (NSCC) Applied Geomatics Research Group (AGRG) has recently acquired a topographic-bathymetric (topo-bathy) lidar sensor which can be used to survey the elevations of the land and the nearshore submerged bathymetry. This sensor is well-suited for the shallow nearshore areas along the coastline, and can be used to fill the data gap that exists between traditional land and boat based echosounder surveys. In addition to the elevation data, the returning amplitude of the laser pulses sent out by the system gives information about the bottom cover from which it was reflected, which can be interpreted in a similar way as is done with the interpretation of backscatter from a multibeam echosounder. These data were used to interpret the nearshore environment to assist in the pre-engineering analysis for the wharf and jetty infrastructure.

We conducted ground truth data collection at Goldboro, NS on October 29, 2015 and completed an airborne topographic-bathymetric lidar survey on October 26, 2015. Details on fieldwork and instrumentation are presented in the Methods section, including details on the Chiroptera II lidar sensor used for the surveys (Section 2.1), lidar survey details (Section 2.2), meteorological conditions during the survey (Section 2.3), the ancillary data collected on the ground near the time of the lidar flights (Section 2.4), and the data processing methods (Section 2.5). The results include a continuous topographic and bathymetric digital elevation model (DEM) which was used to model the infrastructure and are found in Section 3.

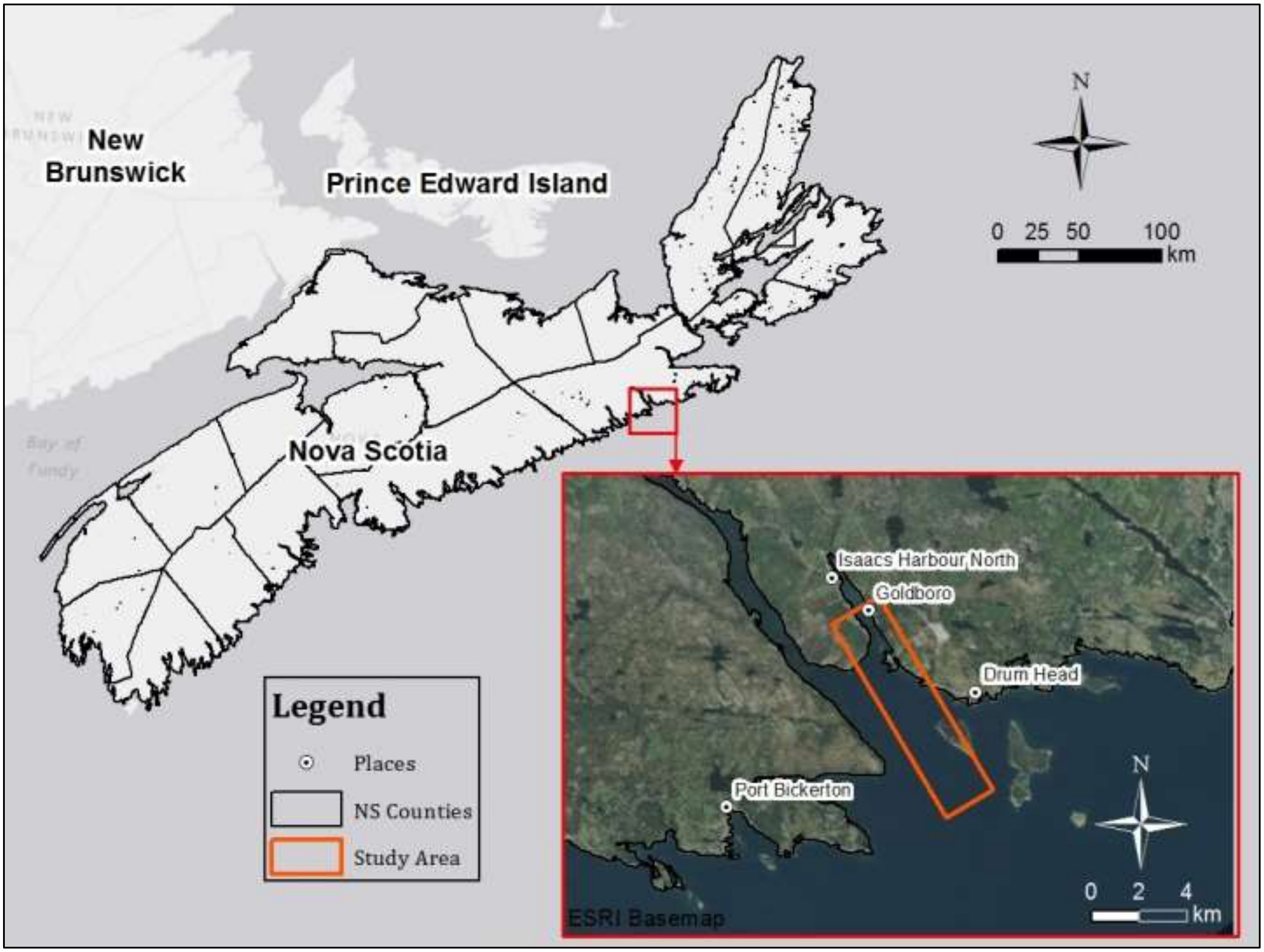


Figure 1: Goldboro, NS and the lidar bathymetric study area.

1.2 Copyright and Data Ownership

The Applied Geomatics Research Group of the Nova Scotia Community College maintains full ownership of all data collected by equipment owned by NSCC and agrees to provide the end user who commissions the data collection a license to use the data for the purpose they were collected for upon written consent by AGRG-NSCC. The end user may make unlimited copies of the data for internal use; derive products from the data, release graphics and hardcopy with the copyright acknowledgement of “Data acquired and processed by the Applied Geomatics Research Group, NSCC”. Data acquired using this technology and the intellectual property (IP) associated with processing these data are owned by AGRG/NSCC and data will not be shared without permission of AGRG/NSCC.

2 Methods

2.1 Sensor Specifications and Installation

The lidar sensor used in this study is a Leica Geosystems Chiroptera II integrated topographic-bathymetric lidar sensor equipped with the RCD30 60 megapixel multispectral camera. The system incorporates a 1064 nm near-infrared (NIR) laser for ground returns and sea surface and a green 515 nm laser for bathymetric returns (Figure 2). The lasers scan in an elliptical pattern, which enables coverage from many different angles, on vertical faces, causes less shadow effects in the data, and is less sensitive to wave interaction. The bathymetric laser is limited by depth and water clarity, and has a depth penetration rating of 1.5 x the Secchi depth (a measure of turbidity or water clarity using a black and white disk). The Leica RCD30 camera collects co-aligned RGB+NIR motion compensated photographs which can be mosaicked into a single image in post-processing, or analyzed frame by frame for maximum information extraction.

AGRG-NSCC does not own an aircraft, only the sensor. AGRG partnered with Leading Edge Geomatics to assist in the operations of the survey and supplied the aircraft. A twin engine aircraft was contracted that was certified to carry the Chiroptera II sensor suite and had a hole suitable to house the sensor head. The lidar sensor was installed in the aircraft in Fredericton, NB and calibration flights were conducted over Fredericton at an altitude of 400 m on October 23. The laser systems and camera were calibrated and aligned with the navigation system which consists of a survey grade GPS mounted on the roof of the aircraft and an inertial measurement unit (IMU) mounted above the laser system (Figure 3.)

The aircraft (Figure 3a) has a hole cut in the bottom for the laser to face the ground and installation involves fitting the control unit and the sensor head into the hole (Figure 3c). The system also includes a 5 megapixel quality assurance camera that the lidar operator is able to view during the flight, along with the waveform of the returning pulses and the flight plan (Figure 3b). Figure 3d shows the downward facing portion of the sensor head, including the NIR (topographic) and green (bathymetric) lasers, which shoot and return to the large red circles; the lenses on the left and right are the low and high resolution cameras, respectively.

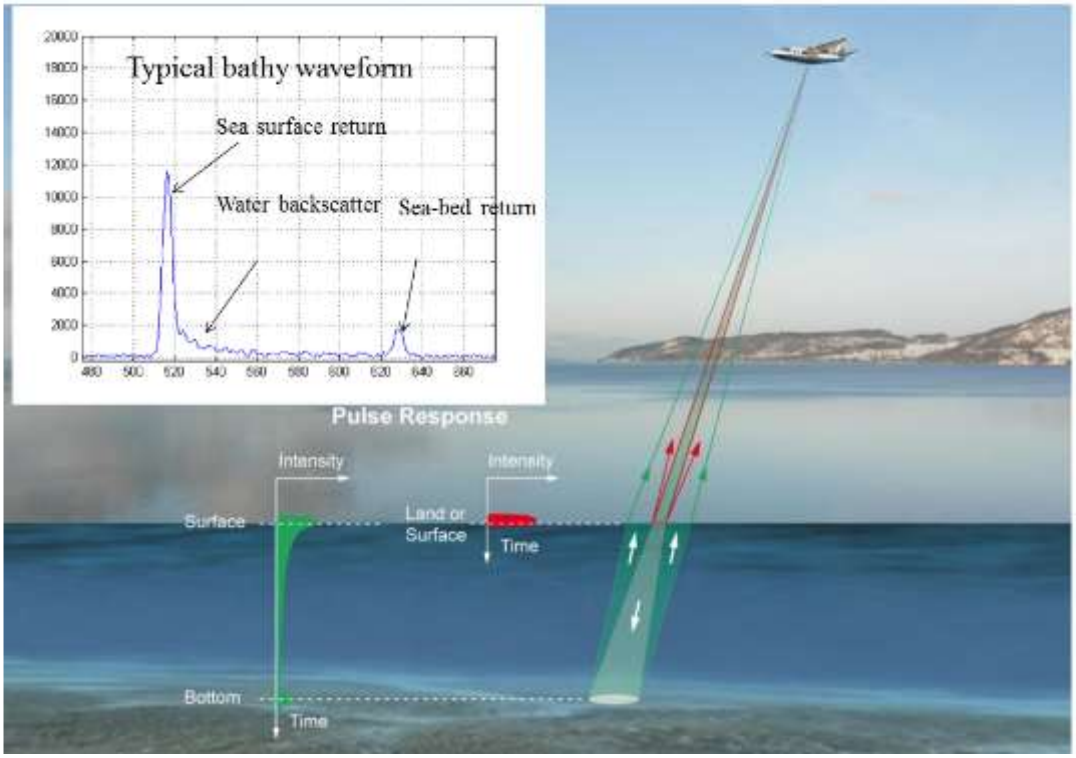


Figure 2: Principals of topo-bathymetric lidar. The system utilizes two lasers, a near infrared and a green laser to surface the land and marine topography.

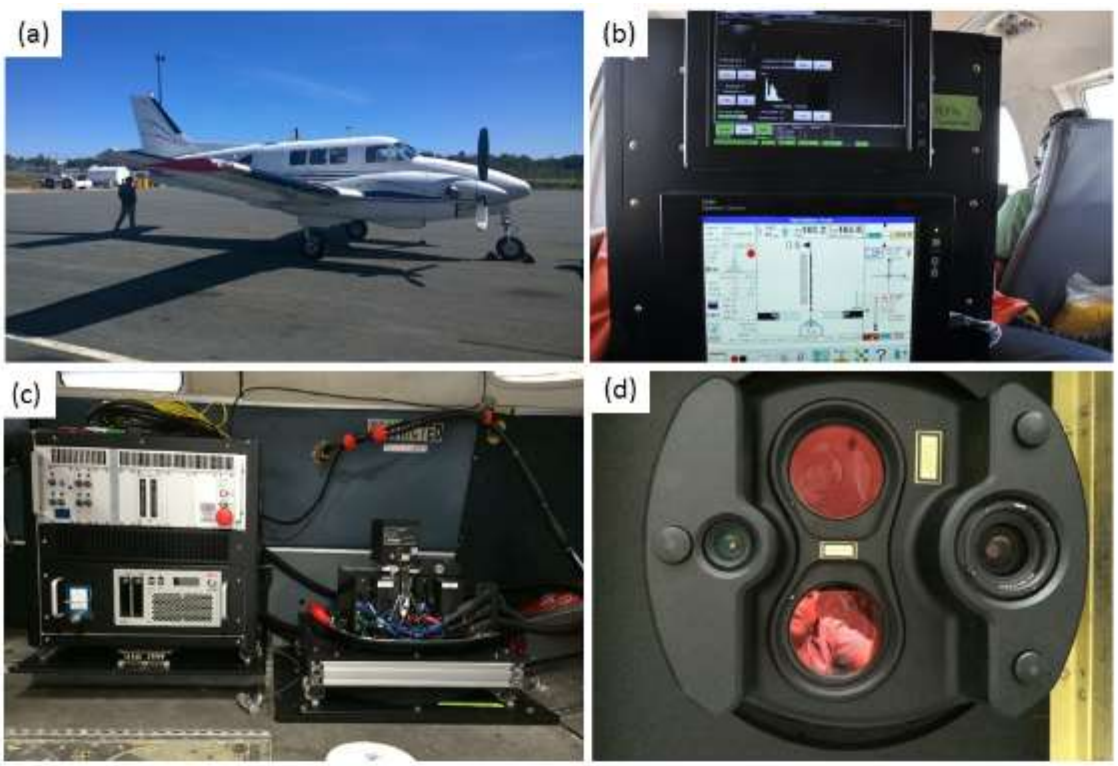


Figure 3: (a) Example of aircraft used for October 2015 lidar survey; (b) display seen by lidar operator in-flight; (c) example of the install of the main body of lidar sensor (left) and laser pointing through a hole cut in the bottom of the plane (right); (d) large red circles are the lasers; the RCD30 lens (right) and low resolution camera (left).

2.2 Lidar Survey Details

The lidar survey was conducted on the afternoon of October 26, 2015. The survey was planned using Mission Pro software for a 30% flightline overlap to be flown at an altitude of 400 m above ground level at a ground speed of 65 m/s. The actual flight lines are shown in Figure 4. The aircraft required ground-based high precision GPS data to be collected during the lidar survey in order to provide accurate positional data for the aircraft trajectory. An active control network ground base station was used for this purpose. The active station used is based in nearby Sherbrooke, NS, as shown in Figure 5. The coordinates for the active control station, as well as any other reference base station used during the project, are found in Appendix A.

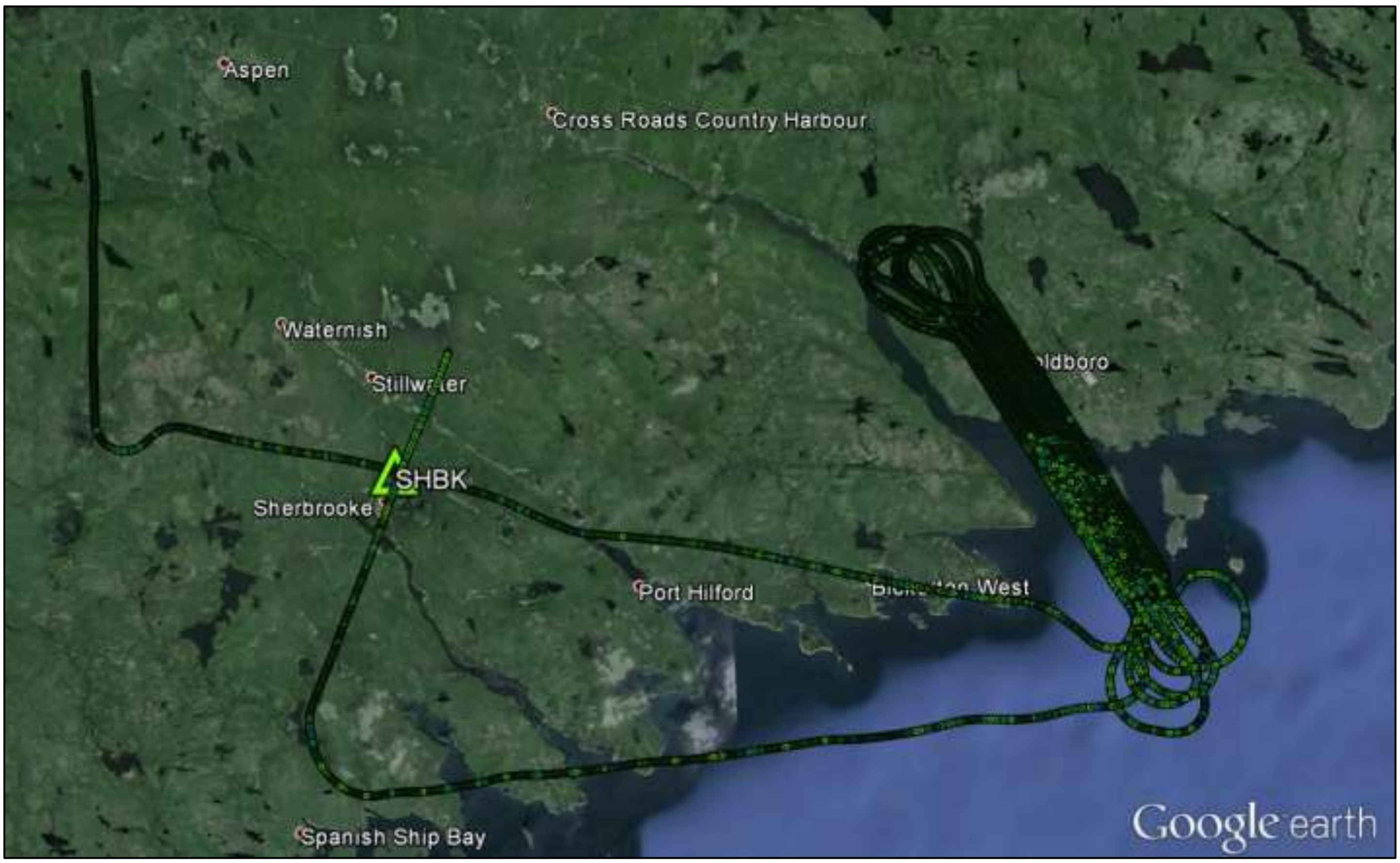


Figure 4. The plane's flight plan including lidar flight lines (12) show the plane flying in orthogonal directions over the active control ground base station in Sherbrooke (green triangle).

2.3 Meteorological Conditions

Meteorological conditions during and prior to topo-bathy lidar data collection are an important factor in successful data collection. As the lidar sensor is limited by water clarity, windy weather has the potential to stir up any fine sediment in the water and prevent good laser penetration. Rainy weather is not suitable for lidar collection, and the glare of the sun must also be factored in for the collection of aerial photography. Before and during the lidar survey, weather forecasts were monitored closely, current and past conditions using the two closestest weather stations to the Goldboro study site, which are operated by Environment Canada at Malay Falls and Port Hawkesbury (Figure 5). The week of the survey mission (Figure 6) brought moderate winds and rain to portions of the province but we anticipated any ill-effects from the storm had cleared up by Oct. 26, which started out as a relatively clear day (winds blowing towards the northeast at roughly 20 km/h). The first portion of the lidar survey was completed successfully, however precipitation moved into the area during the latter half of the survey, resulting in some data gaps in the topographic portion of the lidar products.

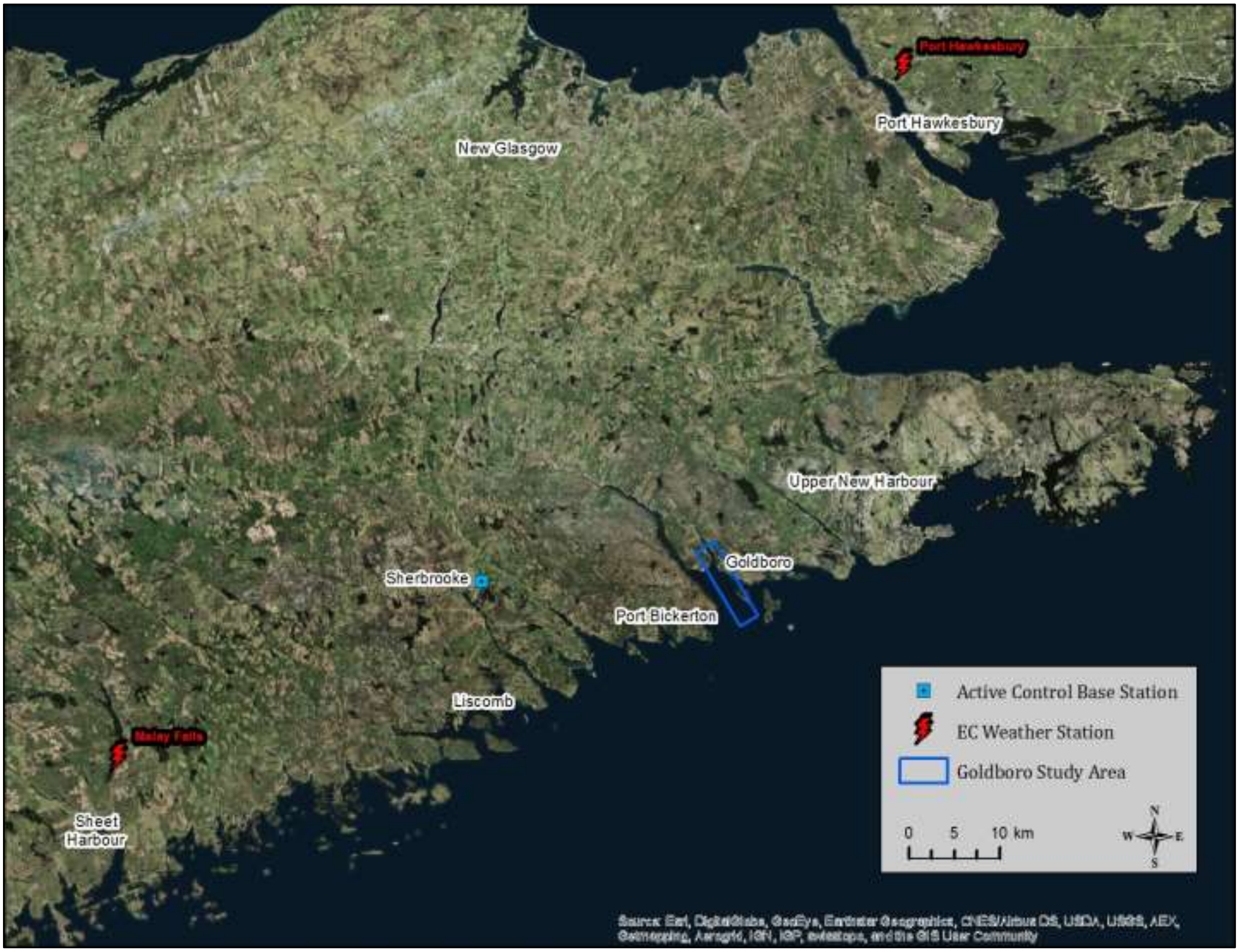


Figure 5: Location of the active control network control monument in Sherbrooke used during the lidar survey and the Environment Canada weather stations used to assess local weather prior to and during the survey.

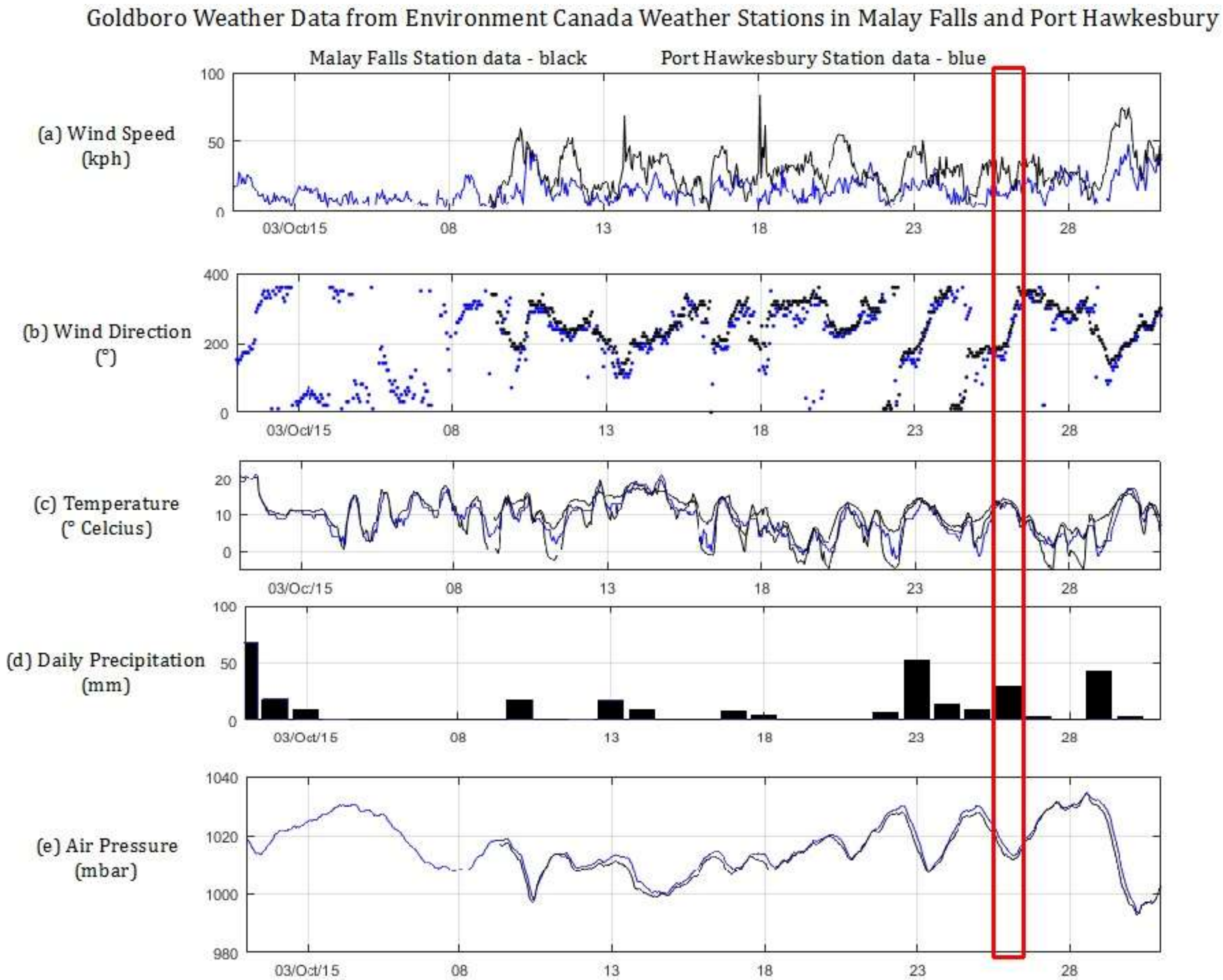


Figure 6: (a) Wind speed and (b) direction from which it is blowing; (c) temperature; (d) daily precipitation; and (e) air pressure collected at the Environment Canada weather stations located at Malay Falls (in black) and Port Hawkesbury (in blue) between October 3 and 28, 2015. The time of the lidar survey is indicated by the red rectangle and shows some precipitation fell at nearby Malay Falls on October 26, 2015.

2.4 Ground Truth Data Collection

Ground truth data is another important aspect of topo-bathymetric lidar data collection. In Goldboro, we conducted ground truth data collection on October 29, 2015 - three days post-lidar flight. For this ground truth data collection our Leica GS14 Real-time Kinematic (RTK) GPS system was used to set up a base station over a NS High Precision Network (HPN). The GPS base station was set to log observations at one second intervals and the RTK rover was used to collect lidar validation points on hard flat surfaces. The validation collected is shown in Figure 7.

Due to the remote location of the study site and the poor weather leading up to the survey, no boat-based ground truth data collection was acquired for this project. However, data from a multi- and singlebeam echosounder survey completed by Canadian Seabed Resources Ltd. on behalf of Golder & Associates for Pieridae Energy was provided to AGRG and echosounder points which overlapped with bathymetry collected by the lidar sensor were used to validate the quality of the lidar bathymetry. Additionally, RTK GPS transects collected along the coastline were also provided. These data can be seen in Figure 7. Information on the validation of these datasets is located in Section 2.5.3: Validation.

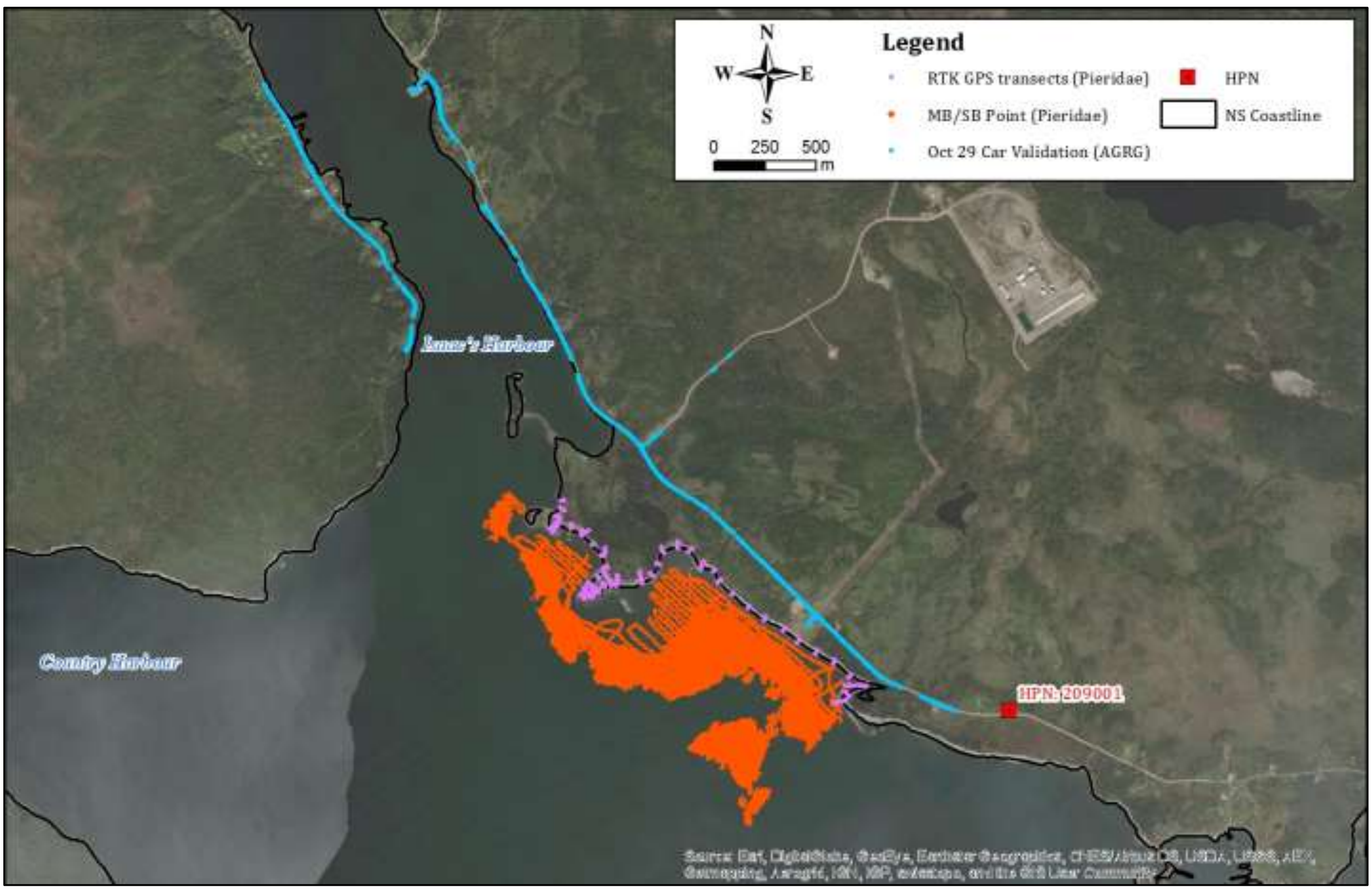


Figure 7: Three validation datasets used to confirm the quality of the lidar DEM are RTK GPS points along local roads (blue) collected by AGRG, and RTK GPS transects of the coastline (in pink) and multibeam and singlebeam echosounder points (in orange) collected for Pieridae Energy.

2.5 Elevation Data Processing

2.5.1 Lidar processing

2.5.1.1 Point Cloud Processing

Once the GPS trajectory was processed for the aircraft utilizing the GPS base station and aircraft GPS observations and combined with the inertial measurement unit, the navigation data was linked to the laser returns and georeferenced. Lidar Survey Studio (LSS) software which accompanies the Chiroptera II sensor is used to process the lidar waveforms into discrete points. The data can then be inspected to ensure there was sufficient overlap (30%) and no gaps exist in the lidar coverage (Figure 8).

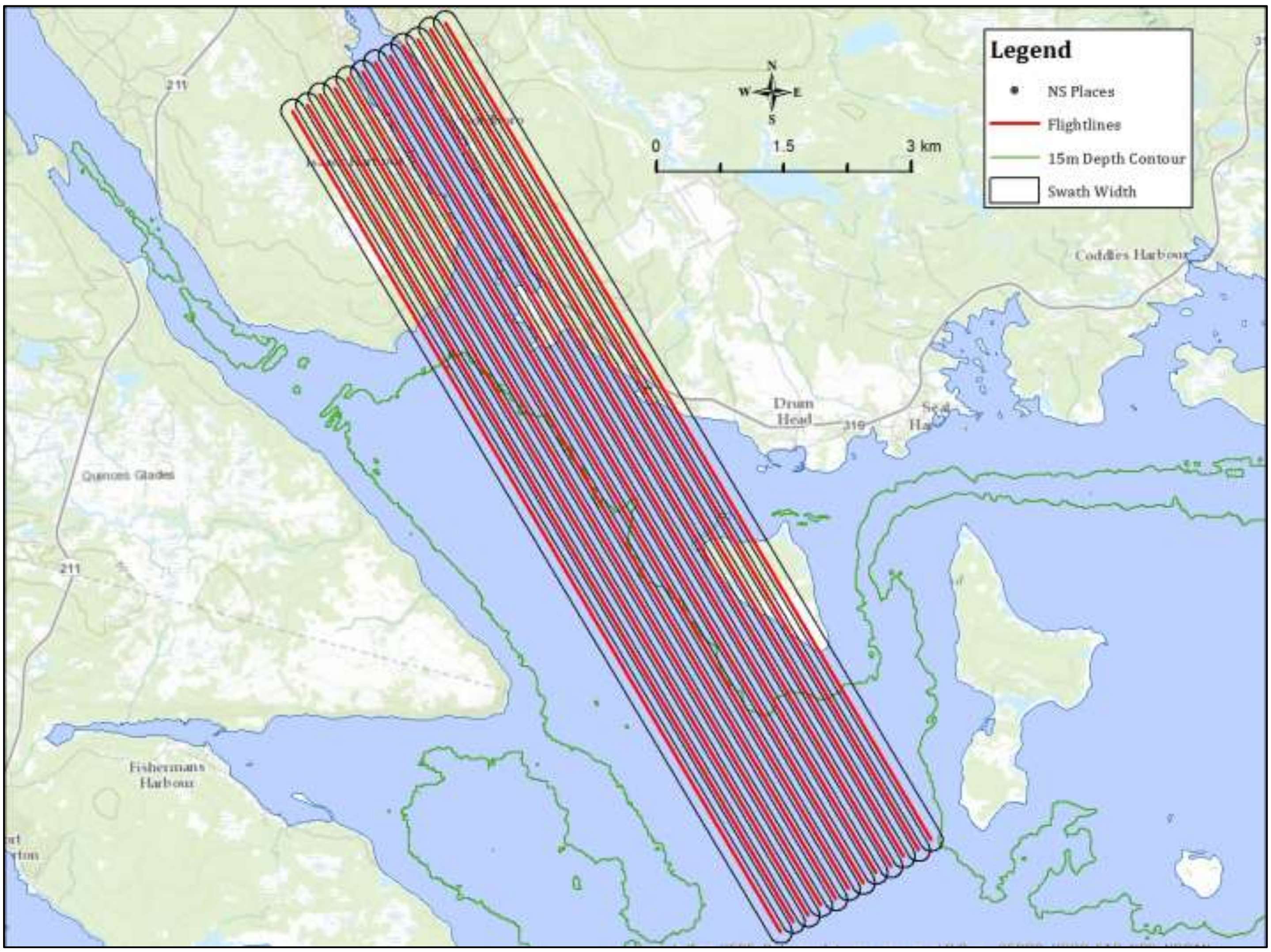


Figure 8. Swath coverage of lidar flight lines acquired for Goldboro. The survey was flown with 30% overlap.

One critical step in the processing of bathymetric lidar is the ability to map the water surface. This is critical for two components of georeferencing the final target or targets that the reflected laser pulse recorded: the refraction of the light when it passes from the medium of air to water and the change in the speed of light from air to water. The LSS software computes the water surface from the lidar returns of both the topo (TD) and hydro (HD) lasers. In addition to classifying points as land, water surface or bathymetry, the system also computes a water surface that ensures the entire area of water surface is covered regardless of the original lidar point density. As mentioned, part of the processing involves converting the raw waveform lidar return time series into discrete classified points using LSS signal processing; points include ground, water surface, seabed, etc. Waveform processing may include algorithms specifically for classifying the seabed. The points were examined in LSS both in plan view and in cross-section view (Figure 9). The waveforms can be queried for each point so that the location of the waveform peak can be identified and the type of point defined, for example water surface and bathymetry (Figure 9).

Terrascan was utilized to further classify and filter the lidar point cloud. Because of the differences in the lidar footprint between the TD and HD sensors (TD footprint has a 0.15 m and HD footprint a 2.1 m diameter on the ground), it was decided that the HD lidar point returns were used to represent the water surface and bathymetry points and the TD lidar points would be used to represent targets above ground. The total point cloud that utilized both sensors was processed in Terrascan where the ground was classified and erroneous points both above and below the ground were defined.

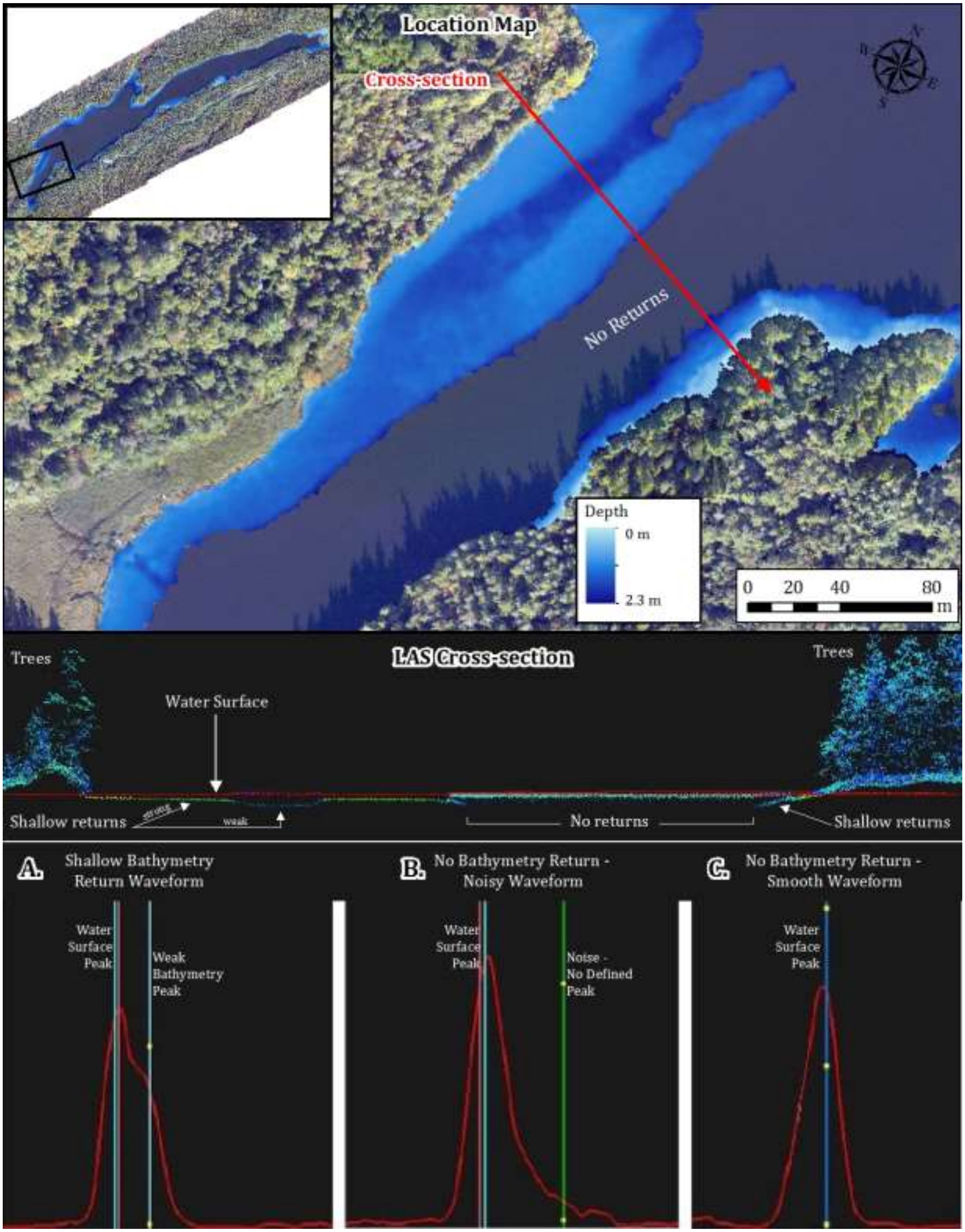


Figure 9. Example of a LAS cross-section and associated LSS waveforms. The cross-section shows bathymetry collected on the shallow edges of the channel and no data collected in the deeper middle. Waveform A shows a typical shallow-water bathymetry return, while waveforms B and C show examples of no bathymetric return with (B) and without (C) noise from around the top 1 m of the water column. Note the data shown here is not the Goldboro dataset.

2.5.1.2 Gridded Surface Model

There are three main data products derived from the lidar point cloud. The first two are based on the elevation and include the Digital Surface Model (DSM) which incorporates valid lidar returns from vegetation, buildings, ground and bathymetry returns, and the Digital Elevation Model (DEM) which incorporates ground returns above and below the water line. The third data product is the intensity of the lidar returns, or the reflectance of the HD lidar. The lidar reflectance, or the amplitude of the returning signal from the HD laser, is influenced by several factors including water depth, the local angle of incidence with the target, the natural reflectivity of the target material, and the voltage or gain of the transmitted lidar pulse. The original reflectance data are difficult to interpret because of variances as a result of water depth and loss of signal due to the attenuation of the laser pulse through the water column at different scan angles, as well as lack of bottom reflectivity.

2.5.1.3 Aerial Photo Processing

The RCD30 60 MPIX imagery was processed using the aircraft trajectory and direct georeferencing. The low altitude and high resolution of the imagery required that the lidar data be processed first to produce bare-earth digital elevation models (DEMs) that were used in the orthorectification process. The aircraft trajectory, which blends the GPS position and the IMU attitude information into a best estimate of the overall position and orientation of the aircraft during the survey. This trajectory, which is linked to the laser shots and photo events by GPS based time tags, is used to define the Exterior Orientation (EO) for each of the RCD30 aerial photos that were acquired. The EO, which has traditionally been calculated by selecting ground control point (x, y, and z) locations relative to the air photo frame and calculating a bundle adjustment, was calculated using direct georeferencing and exploiting the high precision of the navigation system. The EO file defines the camera position (x, y, z) for every exposure as well as the various rotation angles about the x, y and z axis known as omega, phi and kappa. The EO file along with a DEM can be used with the aerial photo to produce a digital orthophoto. After the lidar data were processed and classified into ground points, the lidar-derived DEM (above and below the water line) was used in the orthorectification process in Erdas Imagine software and satisfactory results were produced. An example, from another mission area, the relative alignment between the photos can be seen in Figure 10. In Figure 10, the GPS tripod (yellow legs) is setup over our temporary benchmark. The location of the tripod’s yellow legs and GPS antenna (white dot) move because of the different perspectives of the photo frames and flight lines. A green triangle has been drawn on the figure to represent the base of the tripod and the green dot represents the GPS benchmark on the ground. These features do not change significantly in the photos from frame to frame demonstrating the accuracy of the resultant orthophotos (Figure 10). While the Little Harbour study area is shown in this example, the same process was applied to the Goldboro study area.

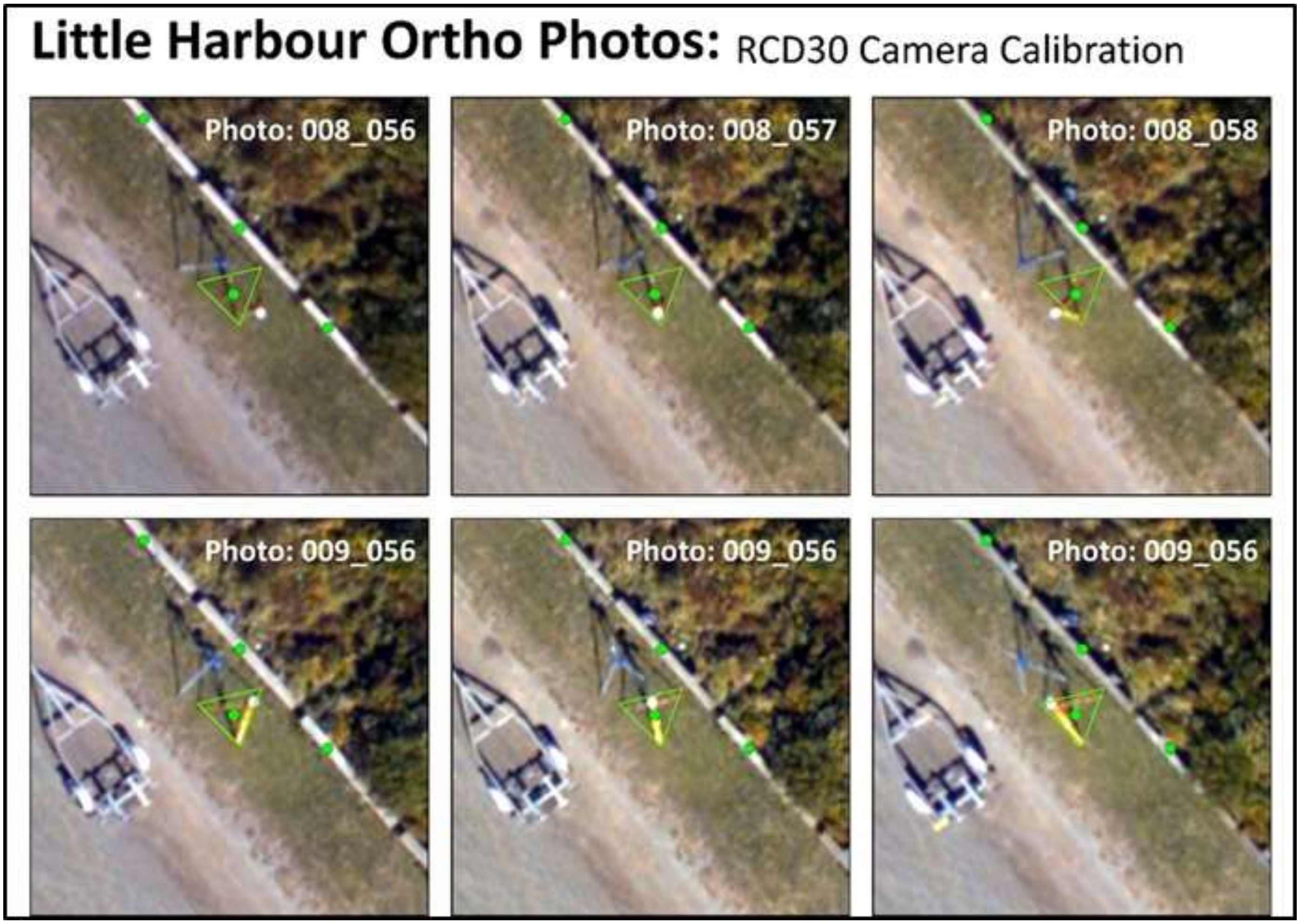


Figure 10. Example of multiple frames (56, 57, and 58) from multiple flight lines (008 on top and 009 below) of the GPS base station location at Little Harbour after orthorectification. The green dots are GPS locations along the parking lot rail and the aircraft control benchmark on the ground below the tripod where the bottom of the legs are represented by the green diamond.

2.5.2 Ellipsoidal to Orthometric Height Conversion

The original elevation of any lidar products are referenced to the same elevation model as the GPS they were collected with. This model is a theoretical Earth surface known as the ellipsoid, and elevations referenced to this surface are in ellipsoidal height. To convert them to orthometric height (OHt), which is height relative to the Canadian Geodetic Vertical Datum of 1928 (CGVD28), an offset must be applied.The offset between the geoid and ellipsoid varies across Nova Scotia (and the world), but the offset in the Goldboro area ranges from roughly -16.9 m to -16.4 m, thus the offset value must be added to the ellipsoidal height to compute the orthometric height. The offset was applied as a grid, thus, all ellipsoidal to orthometric conversions executed in this project, including to RTK GPS data collected, were within these values.

2.5.3 Validation

Three validation datasets were used to confirm the quality of the DEM elevations (Figure 7). The first dataset consists of Real-time Kinematic (RTK) GPS which was collected by AGRG along the only roads present in the study area to provide a measure of validation of the land component on a hard, flat surface. In all, 932 hard surface GPS points were collected, all of which possessed a vertical precision that exceeded the high quality needed for RTK validation (< 0.05 m). The elevations of the 932 GPS points were processed to orthometric height as per Section 2.5.2 to be consistent with the lidar DEM. These GPS points that represent the bare earth were then overlaid on the lidar DEM and the difference between the two elevations was calculated and then statistics were derived. The difference in elevation values, or DZ, can then be displayed graphically. The results will be shown in the results section.

The remaining two datasets were collected by Canadian Seabed Resources on Sept 25, 2015 on behalf of Pieridae Energy and comprise a multibeam (MB) and singlebeam (SB) dataset to compare with the bathymetry and various coastline RTK GPS transects to compare with the coastline of the DEM (Figure 11). The elevations of these data were provided in orthometric height so no conversion was required. These two datasets were then overlaid on the lidar DEM and the difference between the two elevations was calculated and then statistics were derived. The DZ can then be displayed graphically. The results for where the MB/SB points overlap with the DEM will be shown in the results section.

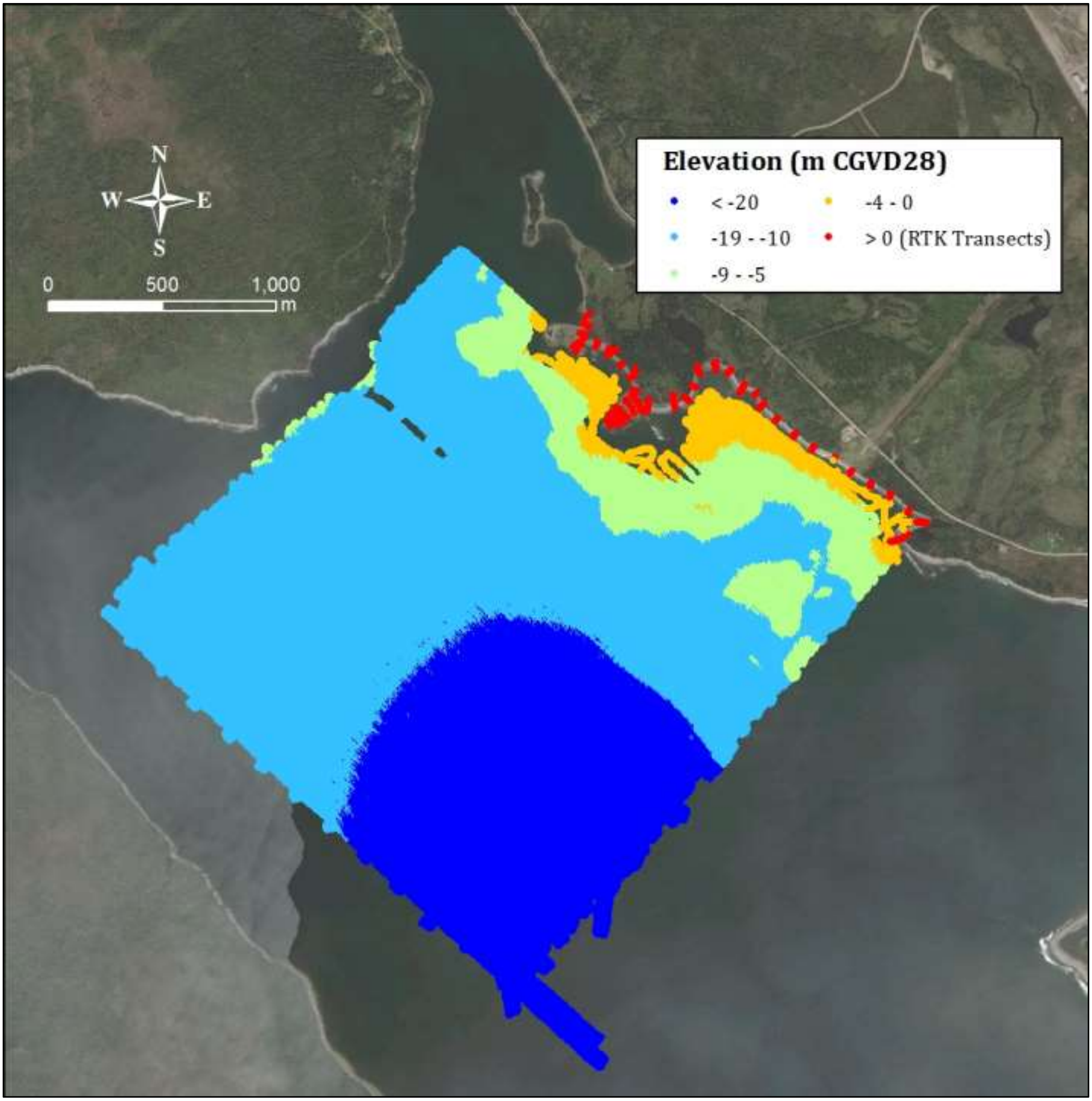


Figure 11. RTK GPS points along the coastline (in red, elevations > 0 m CGVD28) and multibeam/singlebeam derived elevations (from orange – dark blue, elevations < 0 m CGVD28) collected by Canadian Seabed Resources for Pieridae Energy on September 25, 2015 were used to validate the final Goldboro lidar DEM.

2.6 Construction of a Seamless DEM

To make the best use of all the available elevation data, one seamless elevation model was constructed which incorporates the topographic and bathymetric lidar results with the singlebeam and multibeam echosounder data in the deeper areas where the lidar could not penetrate. The lidar data achieved a maximum depth in Goldboro of approximately – 13 m CGVD28, while the MB/SB data which was collected for Pieridae extended much further into the channel. To merge the two datasets, a mask was made which included the area where MB/SB echosounder data existed and where no lidar returns were achieved (Figure 12). For areas containing overlapping lidar and echosounder data, only the lidar data was used for the final model. The mask was used, along with a series of raster calculations, to merge the 2 m echosounder data with the 2 m lidar data to achieve one seamless 2 m elevation model. This merged 2 m elevation model (Figure 13) was the final DEM used for the remainder of the analysis in this project.

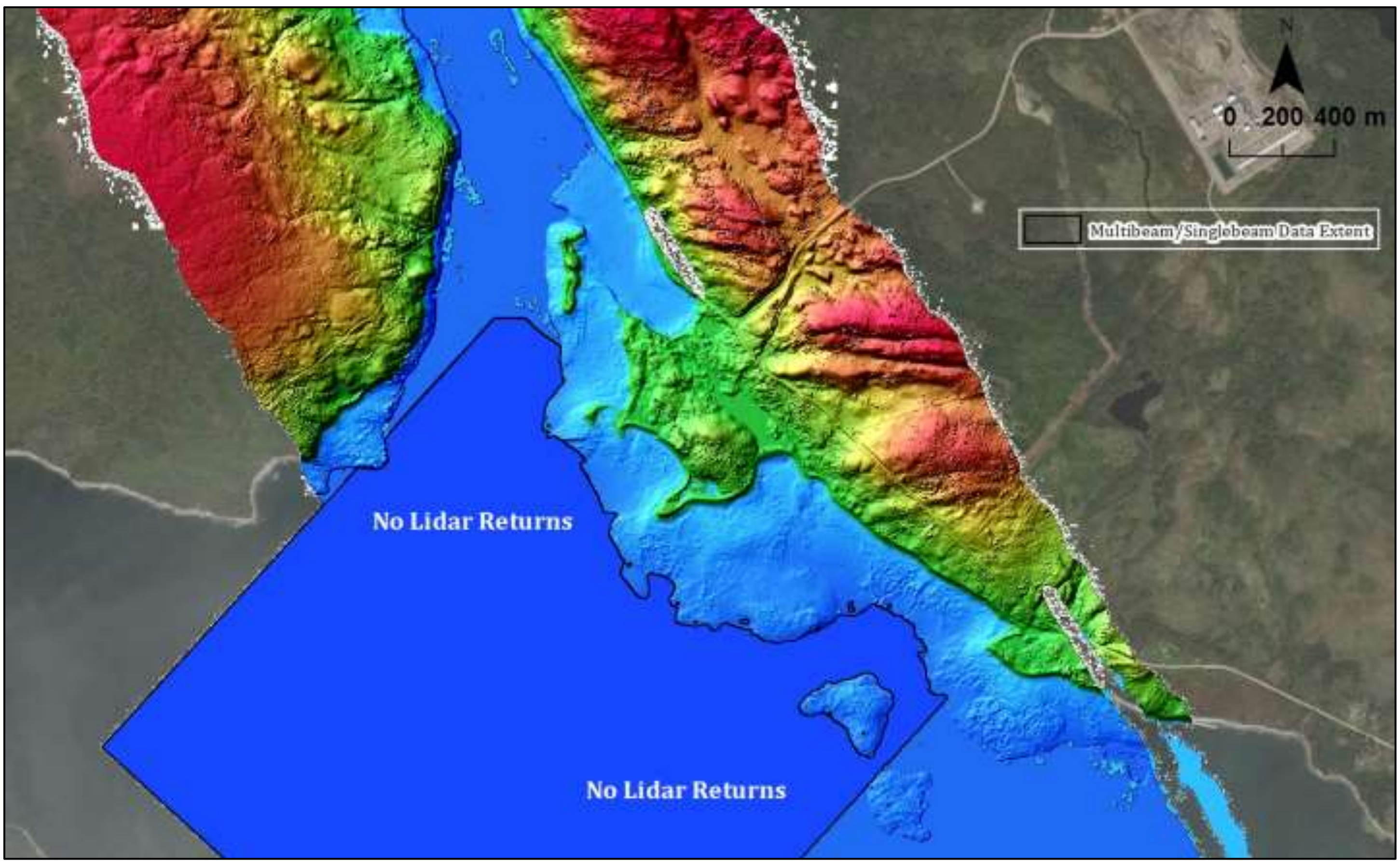


Figure 12. The areas where no lidar returns were achieved and where multibeam and singlebeam echosounder data does exist (black outline).

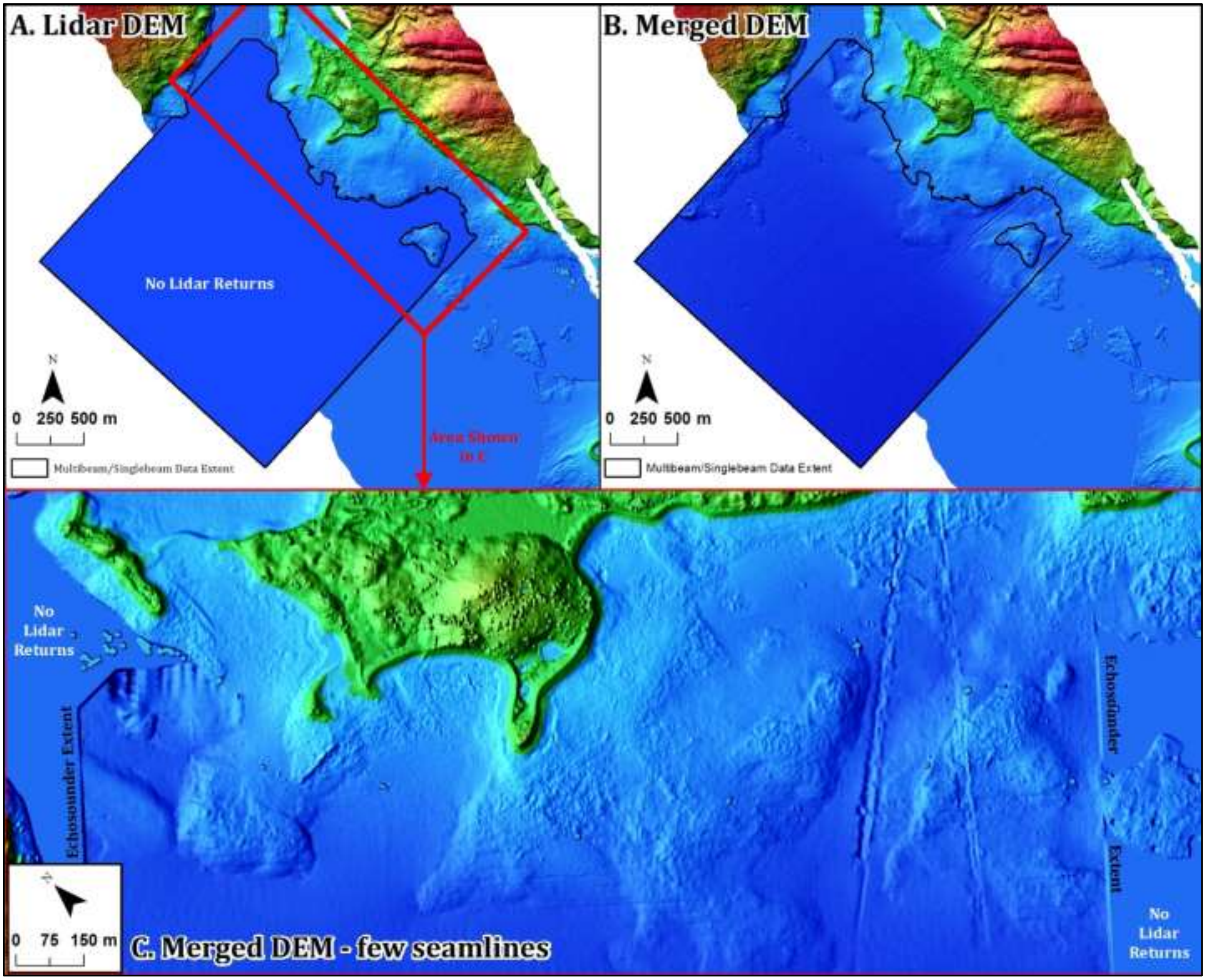


Figure 13. The colour-shaded relief of the lidar DEM before (A) and after (B) merging Pieridae's echosounder data. The area shown in (C) is outlined in (A), and shows few seamlines at the cutline between the merged datasets.

2.7 Jetty Construction and Site Selection

2.7.1 Jetty and Wharf Digital Construction

A detailed schematic of the proposed wharf and jetty structures were supplied to AGRG as a PDF (Appendix C: Detailed Schematic of Proposed Wharf provided by Pieridae Energy). The PDF was converted to a TIF file and the structure was digitized (Figure 14).

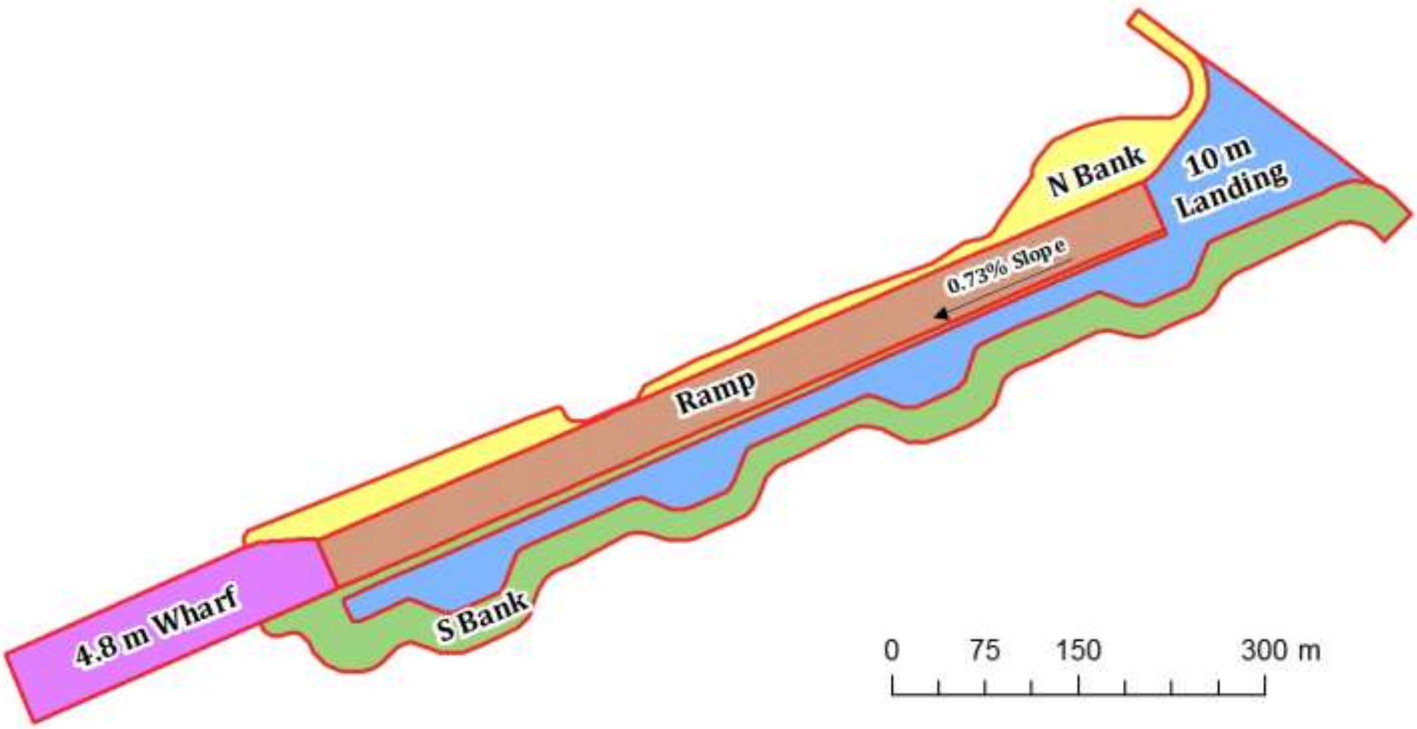


Figure 14. The 2-D digitized wharf and jetty structure which contains five separate segments. The 2-D shapefiles for the separate structure segments were used when constructing the 3-D rendering later in the project.

After a site was selected, the complete 2-D digitized structure was then overlain on various products such as the merged DEM, the lidar intensity raster, and the data provided by Pieridae such as side-scan sonar and surficial geology data (Figure 15) to support optimal site selection for the proposed structure.

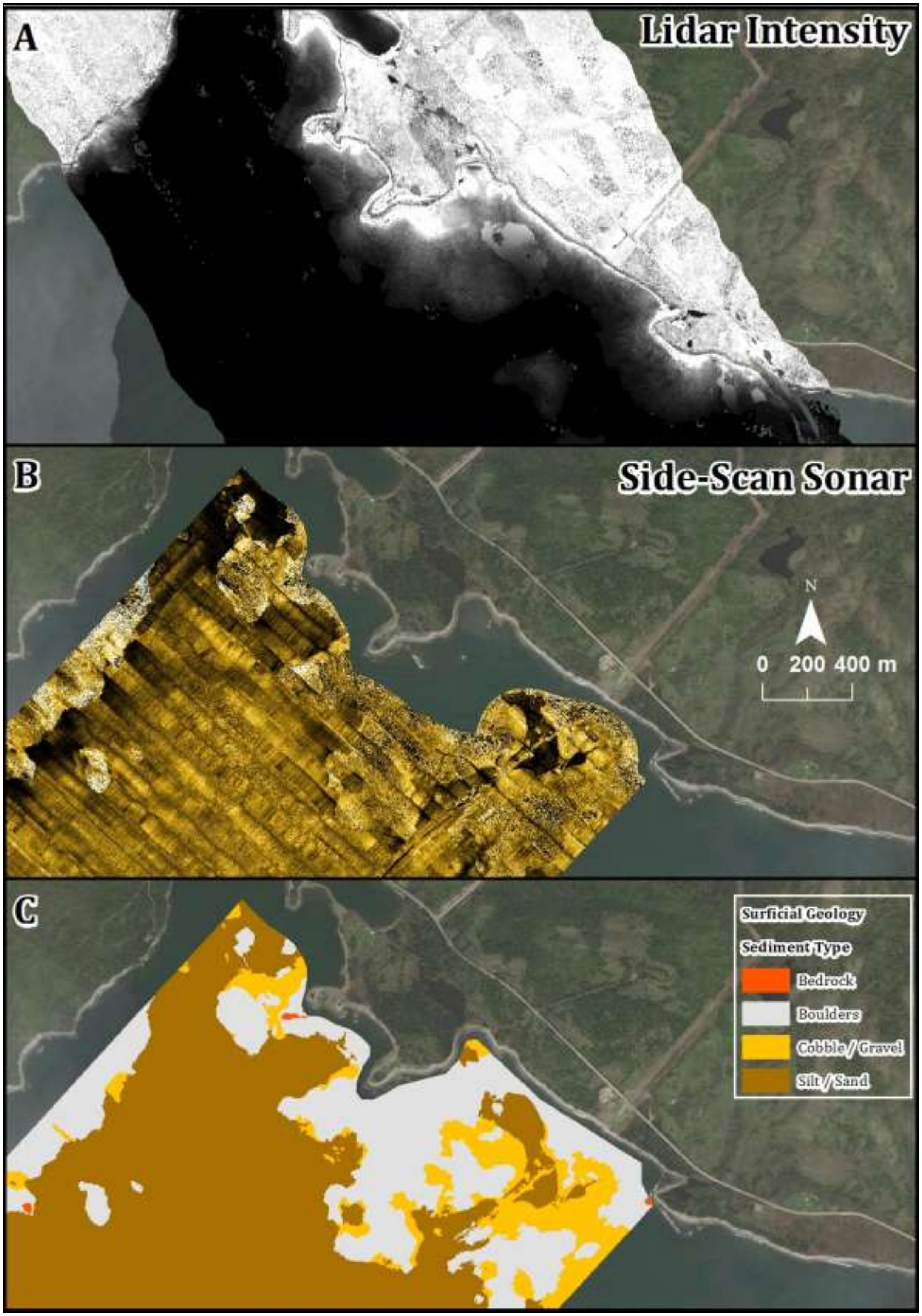


Figure 15. Data used for site selection includes AGRG's lidar intensity data (A) and the side-scan sonar (B) and surficial geology data (C) provided by Canadian Seabed Research.

2.8 Structure Site Selection

One strip of coastline was identified as being the closest in proximity to the LNG terminal in Goldboro, thus the site selection analysis took place along this area of coastline (Figure 16). Pieridae had provided side-scan sonar and surficial geology data which was compared with the lidar intensity data and the shaded-relief of the elevation model. Due to inclement weather around the time of the survey, no in-situ photographs of the seafloor were taken by AGRG to relate bottom type with intensity, thus the side-scan sonar data, as well as the high resolution air photos captured simultaneously with the lidar, were used in lieu.

The visual site selection process involved investigating areas which would minimize the disturbance of submerged vegetation and optimize naturally exposed features to reduce the amount of in-fill required. In addition, the analysis attempted to place the lengthy structure so to avoid it extending across the entire width of the harbour. Finally, areas with pre-existing submerged pipelines were to also be avoided.

Based on the shape of the proposed wharf and jetty structure, four initial locations were investigated (Figure 16). Locations 1 and 2 in Figure 16 (white and black outlines, respectively) were deemed unsuitable as the jetty would extend more than halfway across the harbour. Locations 3 (red outline) and 4 (yellow outline) were examined to determine which site would have more impact on submerged vegetation. For this analysis, the lidar intensity was compared with the side-scan sonar data and with the high resolution multispectral air photos collected with the lidar. Nearshore vegetation, sand, and rocks are easily identifiable in the 0.25 m air photos, thus these visual classifications were applied to the lidar intensity and side-scan sonar data (Figure 17). Unfortunately regarding the lidar intensity, the returned energy within shallow water areas was sufficient to saturate the bathy laser receiver. This did not impact elevation measurements but did result in an 'over exposed' intensity within a few small areas of the shallow water region, particlularly immediately adjacent to the rocky shoreline.

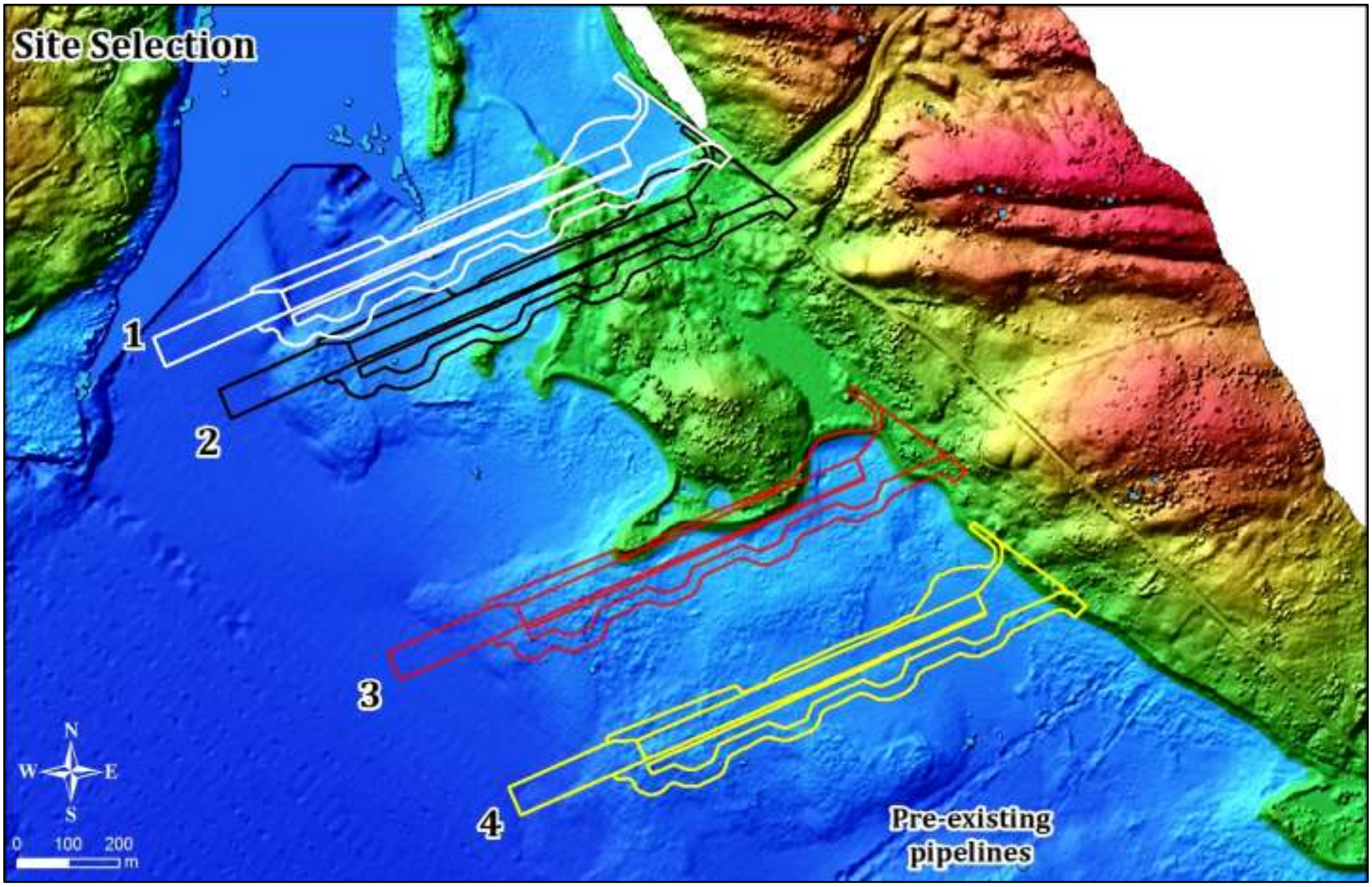


Figure 16. The four locations investigated for the wharf and jetty structure. Locations 1 (white) and 2 (black) were deemed unsuitable due to the narrow width of the harbour at these locations. Locations 3 (red) and 4 (yellow) were further examined with respect to submerged vegetation in these areas.

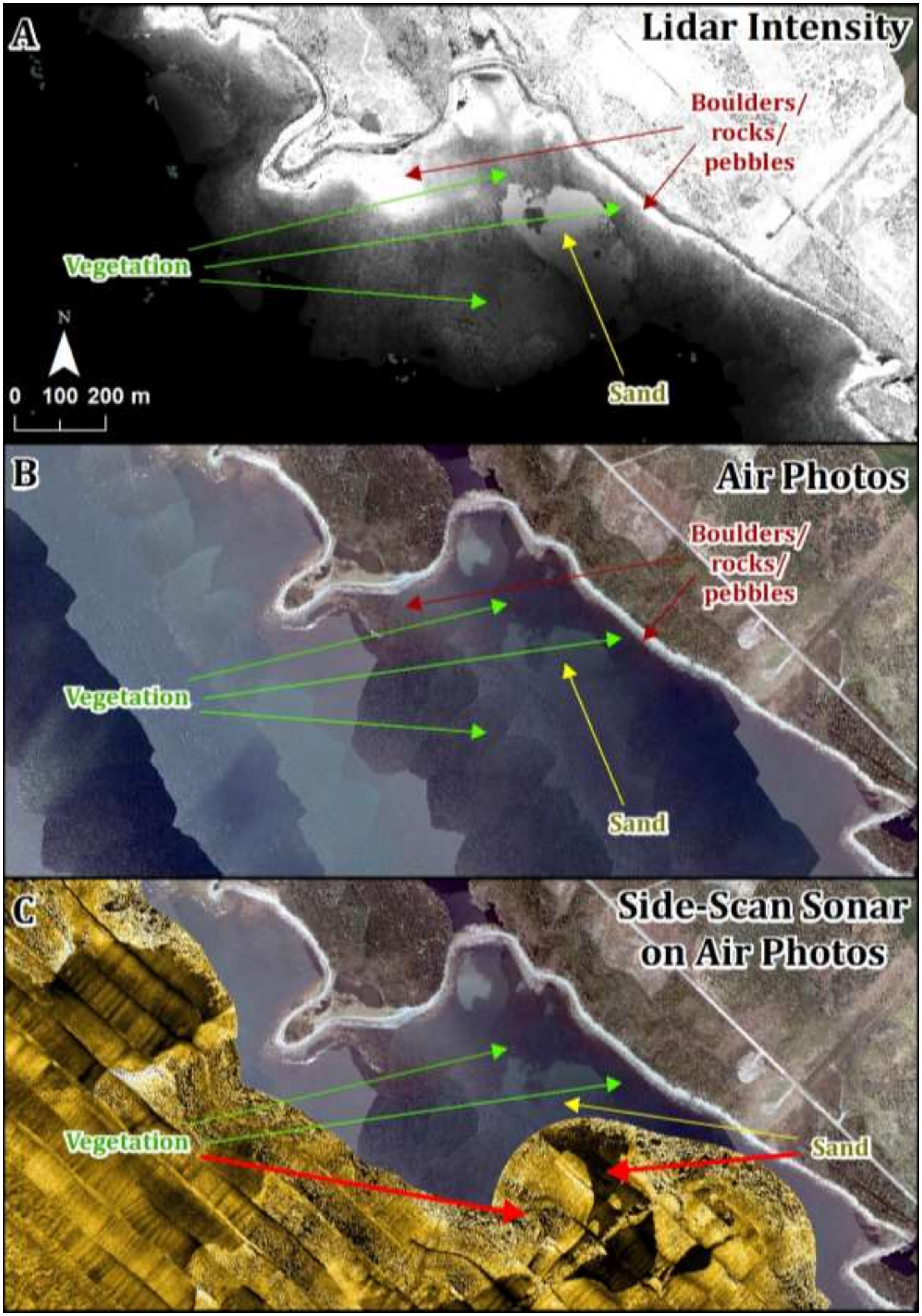


Figure 17. Nearshore vegetation, sand, and rocks are easily identifiable in the 0.25 m resolution air photos (B) supplied by AGRG, thus these same features were easily located in the lidar intensity (A) and side-scan sonar (C) data provided by Canadian Seabed Research.

2.9 3-D Wharf and Jetty Structure Construction

After the site had been selected for the wharf, a 3-D representation of the wharf and jetty structure was constructed from the detailed schematic provided by Pieridae and inserted into the merged lidar DEM. This was done ultimately by constructing a triangular irregular network (TIN) of each one of the various wharf and jetty structure segments (Figure 14) using the information provided in the schematic, and then inserting the resulting TIN-derived rasters into the DEM using various raster calculations. To construct the TIN, the digitized line shapefile for each segment was converted to points, and the elevations of each of the known points for that segment was added from information provided from the detailed schematic. The information of the unknown points, such as the points along the bottom of the structure where it makes contact with the ground or seafloor, were derived from the merged lidar DEM.

2.10 Volumetric Estimates and Elevation Profiles

After the wharf and jetty structure were added to the merged lidar DEM, an estimate of the volume of cut and fill required for the structure were calculated using ESRI ArcMap's 'cut/fill' geoprocessing tool. In addition, various before and after DEM elevation profiles were constructed for the selected site.

3 Results

3.1 Lidar Returns

The bathymetric lidar survey reached a depth of approximately – 13 m relative to CGVD28. Inclement weather pushed into the area towards the end of the survey, and a slight mist in the air during a couple of flightlines resulted in aerosol related noise which could not be resolved (Figure 18). Despite this loss of data, the results provide a seamless topographic-bathymetric lidar DEM which successfully fills in the 'white ribbon' gap of data between the 20 m provincial DEM and offshore MB/SB elevation models (Figure 19).

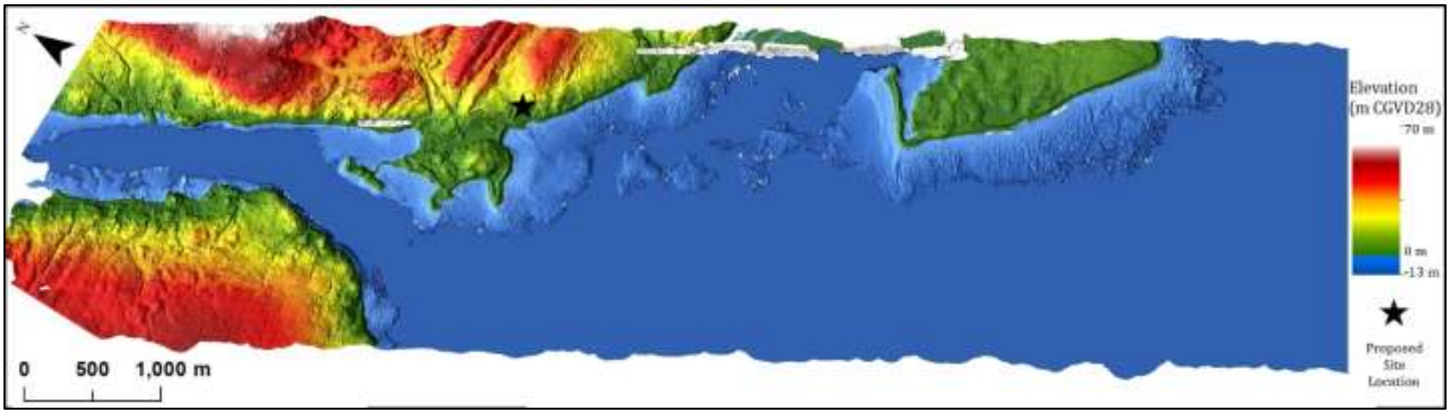


Figure 18. The derived 2 m lidar DEM shows bathymetric lidar results from approximately - 13 m CGVD 28, and various linear areas where no data was captured due to inclement weather pushing into the area. The black star is the location of the proposed site.

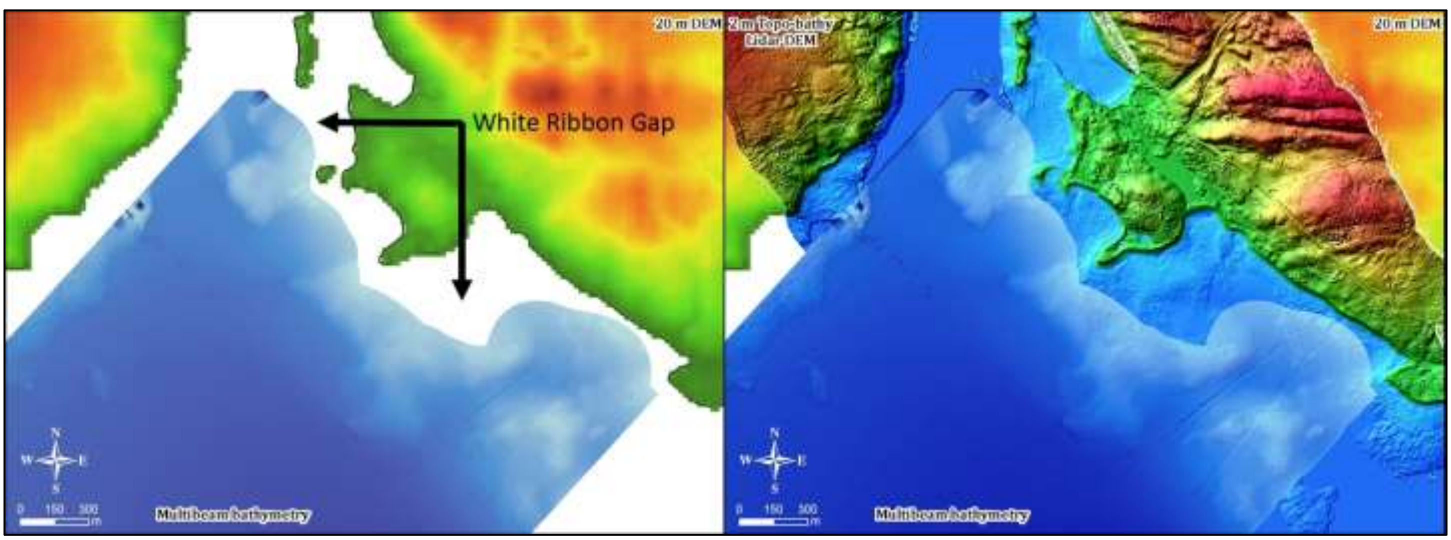


Figure 19. (L) The 'white ribbon' gap resulting from a lack of nearshore elevation data which traditionally exists between the 20 m provincial DEM (or other topographic surveys) and traditional echosounder surveys is filled in with seamless topographic-bathymetric lidar elevation data (R).

3.2 Validation

Datasets collected for Pieridae and a dataset collected by AGRG were compared with the final DEM to determine the mean vertical offset of the lidar DEM when compared with the various datasets. The datasets collected for Pieridae which were used for validation were the multibeam/singlebeam bathymetry data as well as the land RTK GPS transects of the coastline (Figure 11). The dataset collected by AGRG which was used for validation was the in-situ RTK GPS measurements collected along various roads in the study area. For each point of validation data (bathymetry or RTK GPS), the validation data elevation was subtracted from the DEM elevation (ie. DEM elevation – RTK GPS elevation or DEM elevation – bathymetry elevation). The overall results can be seen in Figure 20 and in Table 1.

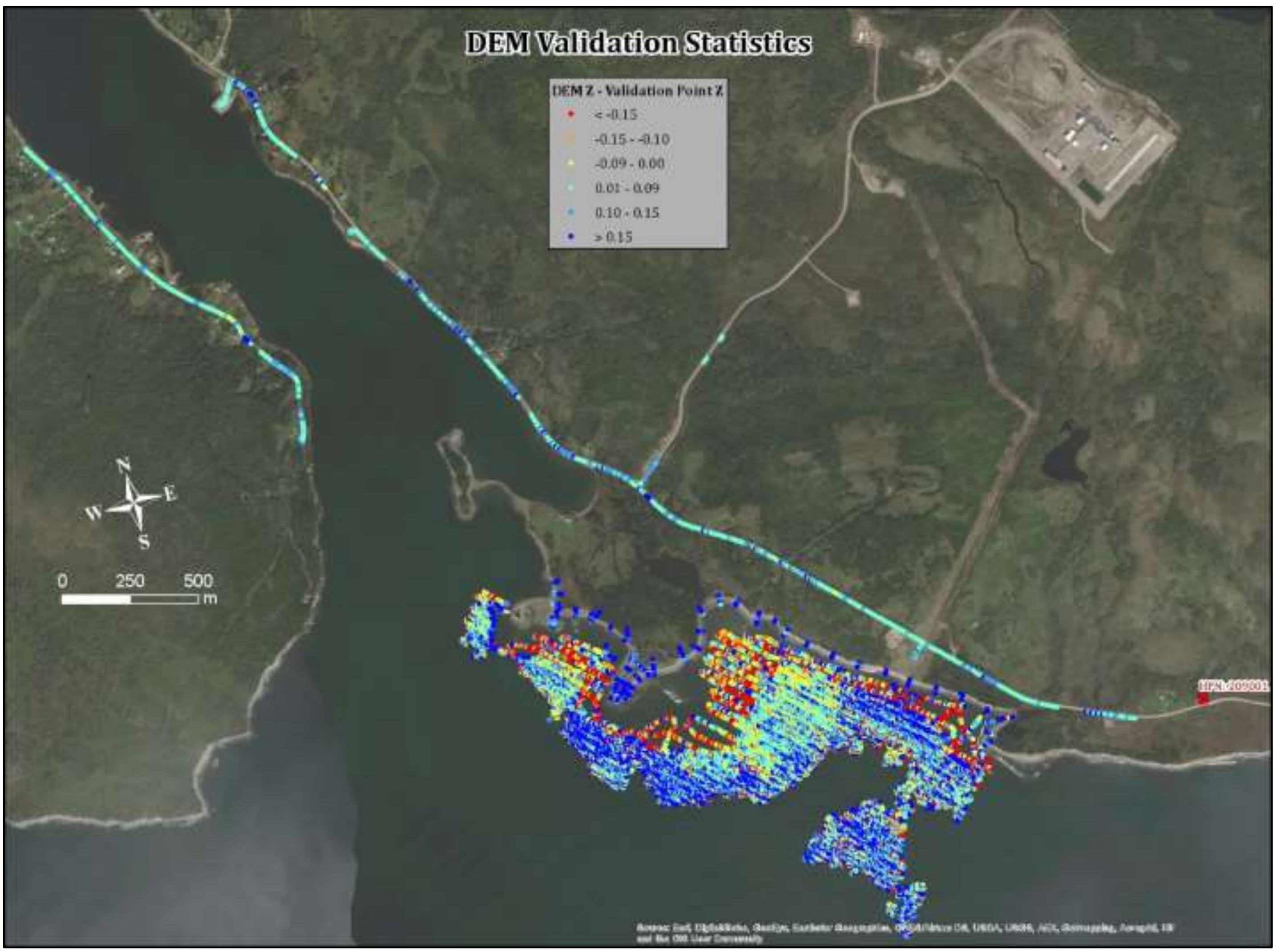


Figure 20. The three datasets used to determine the accuracy of the DEM are symbolized based on the result of the DEM elevation value minus the validation point elevation value.

Table 1. The mean vertical offset between the lidar derived DEM and three datasets provided for validation and consist of an RTK GPS dataset of road elevations in the area (collected by AGRG), RTK GPS transects of the shoreline and multibeam & singlebeam echosounder bathymetric elevation points (collected for Pieridae).

	DEM Z – Validation Point Z	
Validation Dataset	**Mean Vertical Offset**	**Std. Deviation**
RTK GPS of roads (AGRG dataset)	0.07	0.04
RTK GPS transects of shoreline (Pieridae dataset)	0.28	0.35
Multibeam + singlebeam points (Pieridae dataset)	0.08	0.19

The comparison with the hard, flat surfaces in the topographic portion of the DEM resulted in a mean difference of 0.071 m ±.0.04 m (Figure 21) which is within the specifications of the sensor (< 0.15 m). The error is seen in a normal distribution.

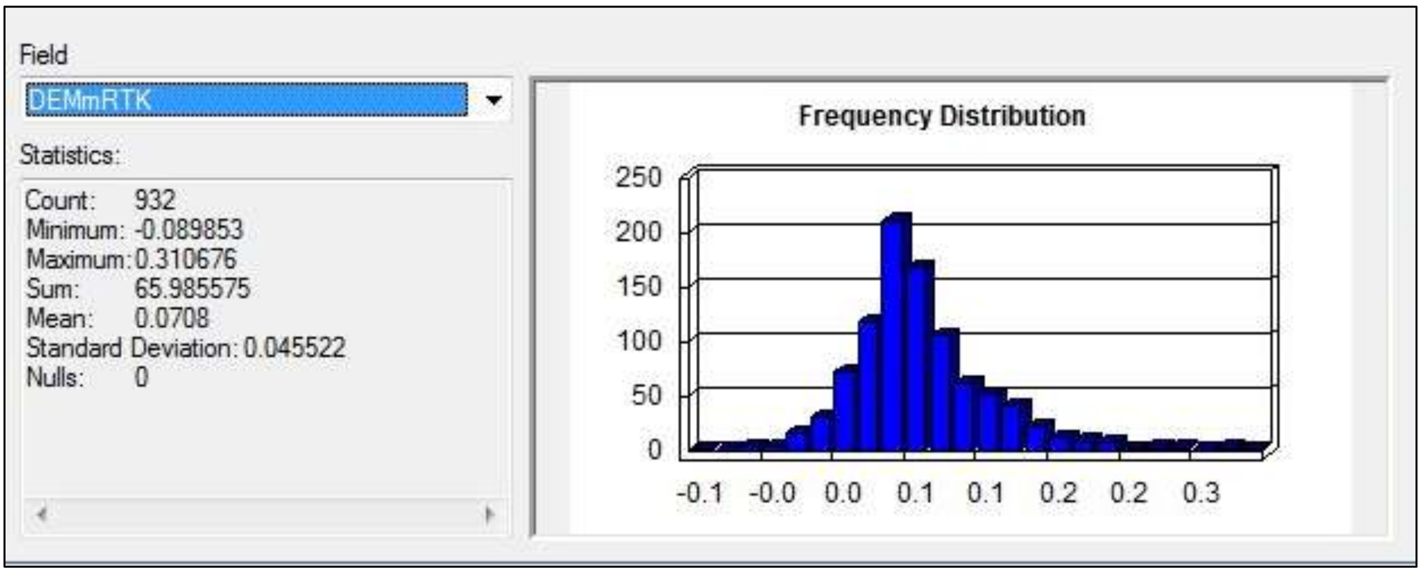


Figure 21. Histogram of the difference in elevation, DZ, between the lidar DEM and the RTK GPS points (DEM z – RTK GPS z). The mean difference is 0.07 m with a standard deviation of 0.045 m, seen in a normal distribution.

The multibeam/singlebeam bathymetric points which overlap the bathymetric portion of the DEM (Figure 11) were used to assess the DEM accuracy. Difference in elevations between the two datasets (DEM z – MB/SB z) resulted in a mean difference of 0.08 m with a standard deviation of 0.19 m with a normal distribution (Figure 22).

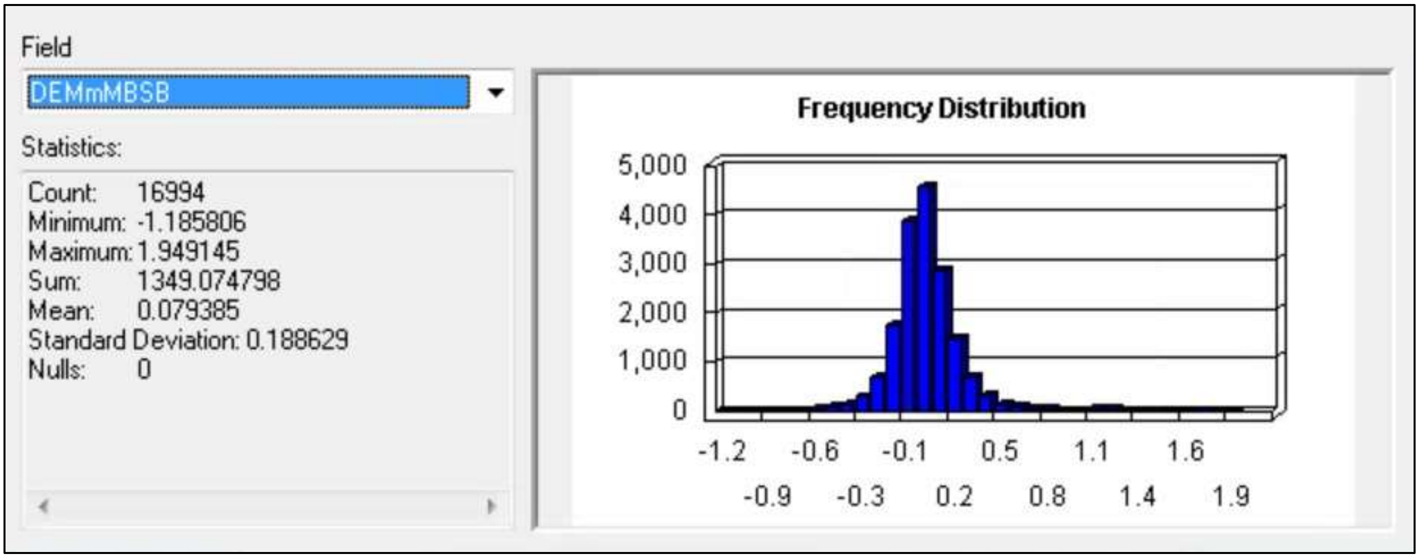


Figure 22. Histogram of the difference in elevation, DZ, between the lidar DEM and the multibeam(MB) or singlebeam (SB) points (DEM z – MB/SB z). The mean difference is 0.079 m with a standard deviation of 0.189 m, seen in a normal distribution.

3.3 Site Selection

After visually investigating and manually classifying the vegetation and bottom types in both site 3 and site 4, the optimal location for the wharf and jetty structure was chosen as site 3, a site abutting a nearby piece of land. The two potential sites are quite similar - the wharf at both sites would extend to approximately 15 m water depth. However, site 4 is closer to the pre-existing submerged pipelines, and while site 3 disturbs more exposed land than site 4, site 3 appears to disturb less submerged vegetation than site 4. Thus, all subsequent analysis was carried out for a structure located at site 3.

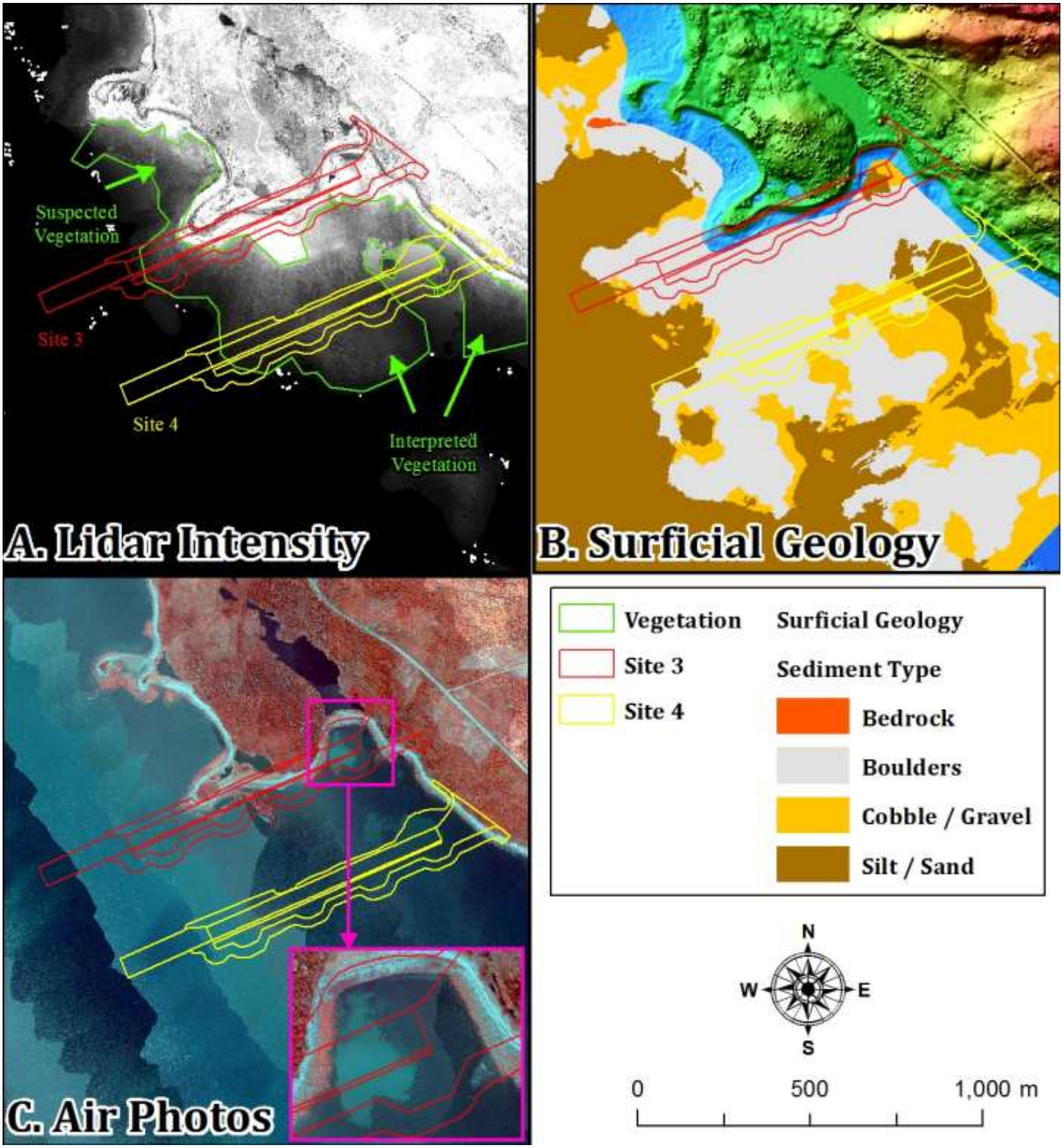


Figure 23. Visual investigation of suspected vegetation from the intensity data (A) and surficial geology data (B) with respect to sites 3 and 4. Multispectral (RGB-NIR) air photos (C) were used to interpret likely vegetation from the intensity data.

3.4 3D Wharf and Jetty Structure Construction

The proposed structure was provided with a framework of elevations, thus the upper limits of the structure were pre-determined as per Figure 24. The elevations of the base of the structure were derived from the 2 m merged lidar DEM. Each individual piece of the structure shown in Figure 24 was converted to a point shapefile, and a TIN was constructed from the elevation of the points for each piece of the structure. The various TINS were then converted to 2 m rasters (to accord with the resolution of the DEM) and merged together using a series of raster calculations (Figure 25). The final structure raster was then fused with the merged lidar DEM and colour-shaded reliefs were generated (Figure 26 and Figure 27).

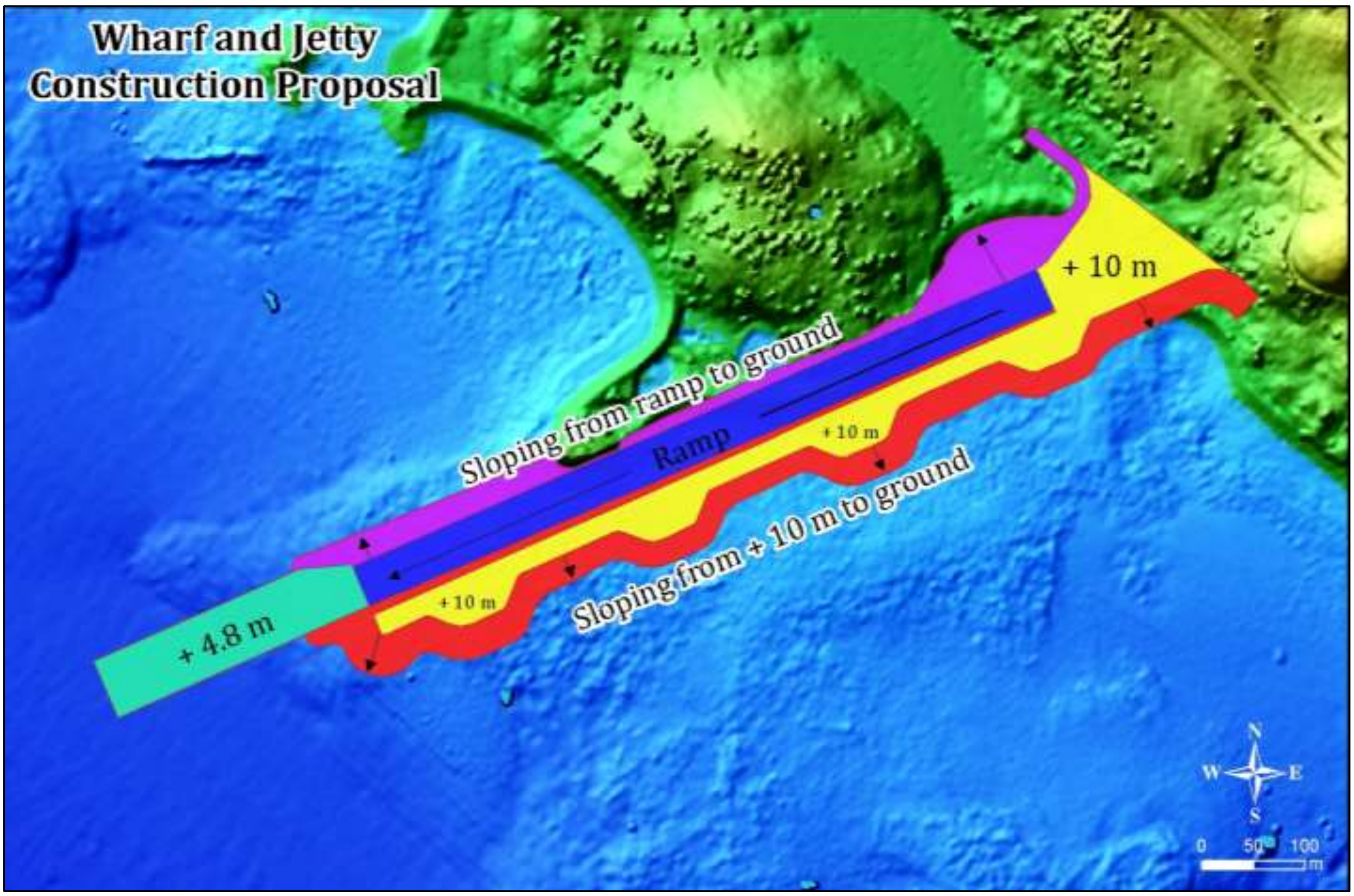


Figure 24. The pre-determined elevations of the top of the wharf and jetty structure (shown here as a 2-D polygon shapefile) shown on a colour-shaded relief of the 2 m merged lidar DEM.

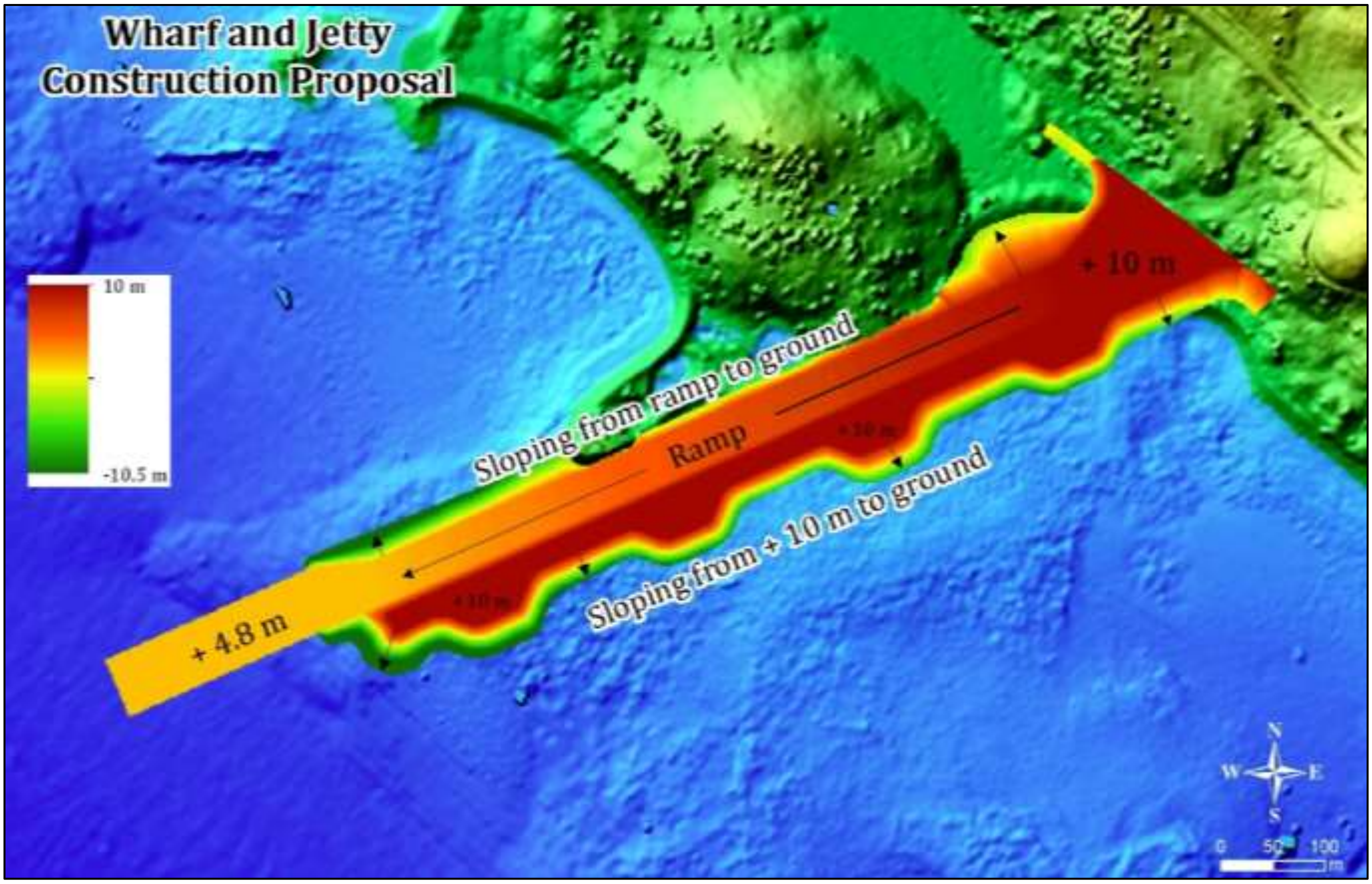


Figure 25. The final 2 m raster of the wharf and jetty structure shown on a colour-shaded relief of the 2 m merged lidar DEM.

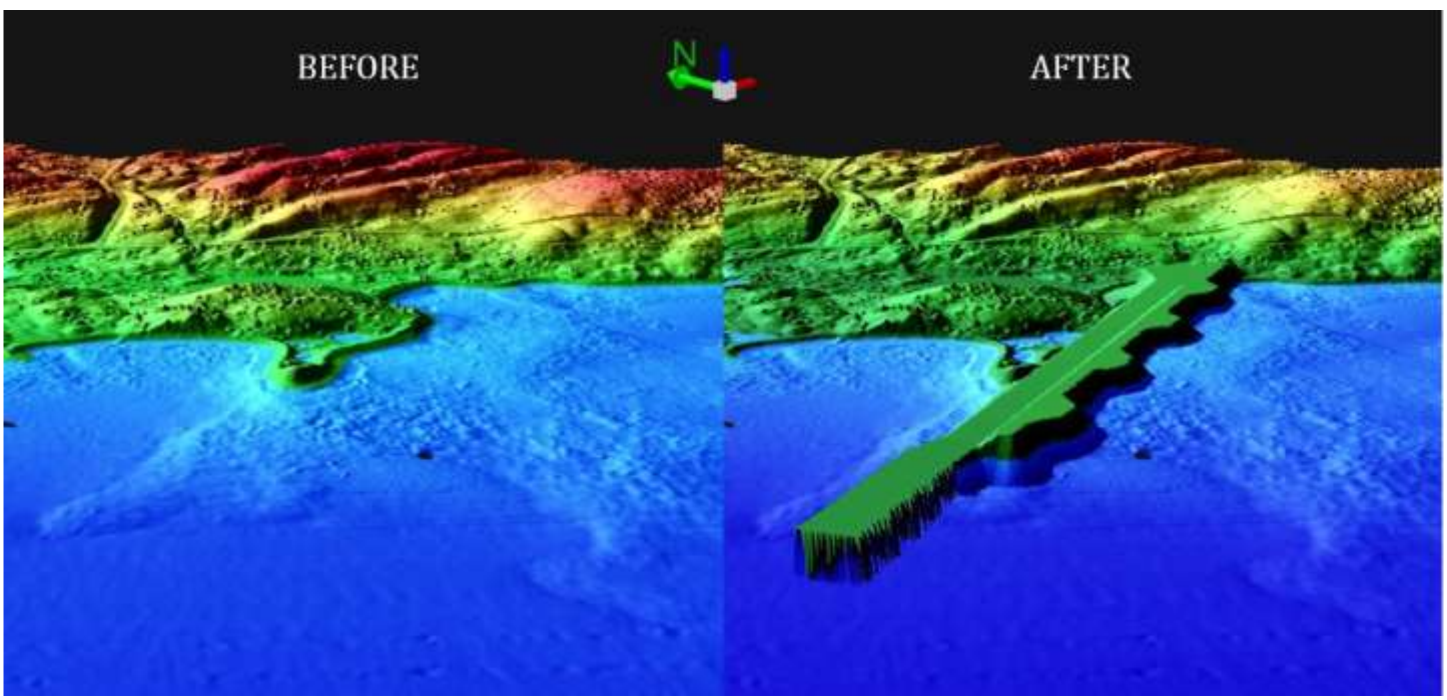


Figure 26. The colour-shaded relief of the DEM before (left) and after (right) the wharf and jetty raster was merged, shown from the southwest.

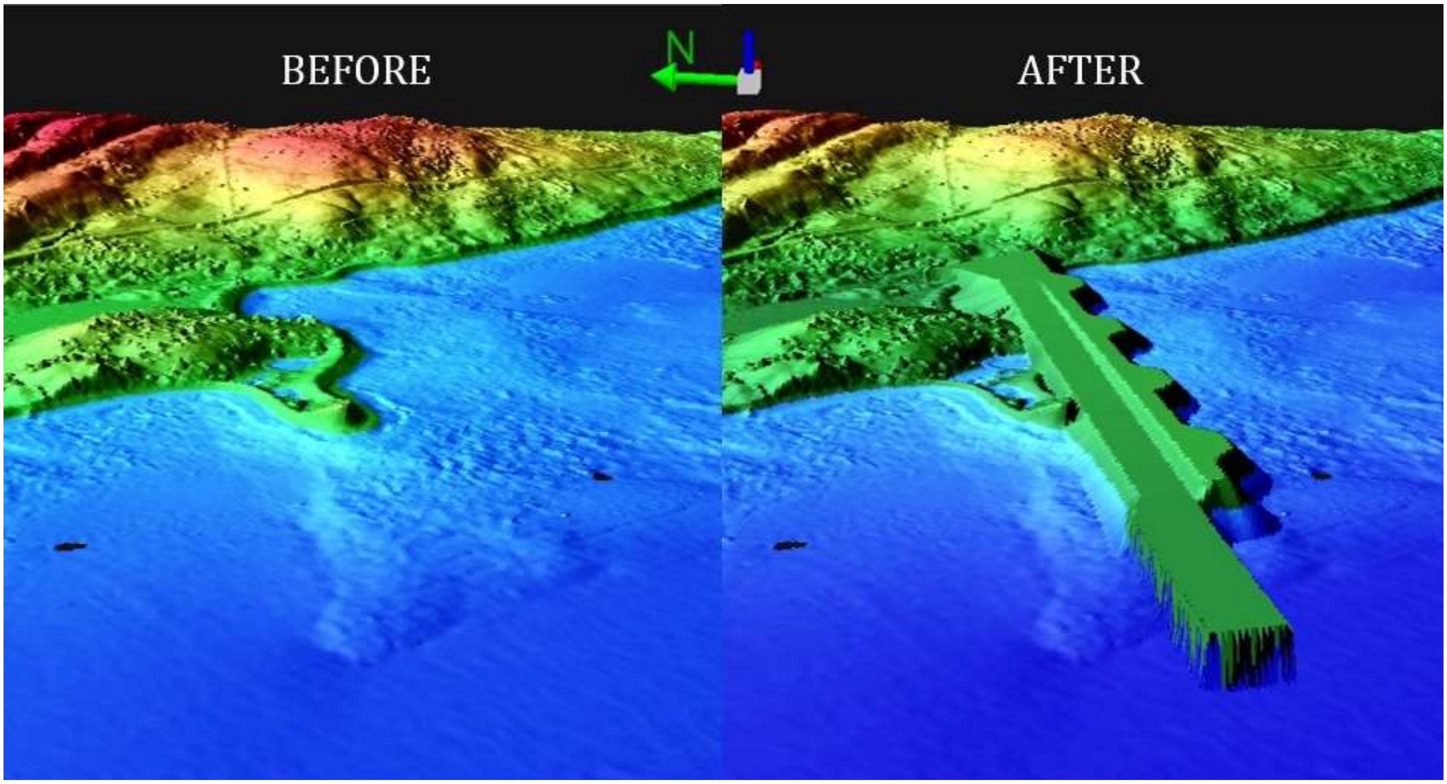


Figure 27. The colour-shaded relief of the DEM before (left) and after (right) the wharf and jetty raster was merged, shown from the west.

3.5 Volumetric Estimates and Elevation Profiles

A volumetric estimate was generated for the fill that would need to be lost and gain to develop this wharf and jetty structure. As shown in Table 2 the volume of fill which would need to be removed for the entire structure (provided the 4.8 m wharf is a hollow structure) is 156 m^3, in both the north and south bank sections of the structure (Figure 28), while the volume of fill which would need to be filled in is 927,050 m^3. If the 4.8 m wharf is to be a solid structure then the volume to fill in would be 1,210,292 m^3 while the volume to remove would remain the same.

Table 2. The approximate volumes of fill that will need to be removed and filled in to produce a wharf and jetty structure as proposed in the selected site at Goldboro.

	Volume to Remove (m^3)	Volume to Fill (m^3)
Ramp	0	238,409
North Bank	66	87,202
South Bank	90	229,754
10 m Landing	0	371,685
4.8 m Wharf	0	283,242
Total (hollow wharf)	156	927,050
Total (solid wharf)	156	1,210,292

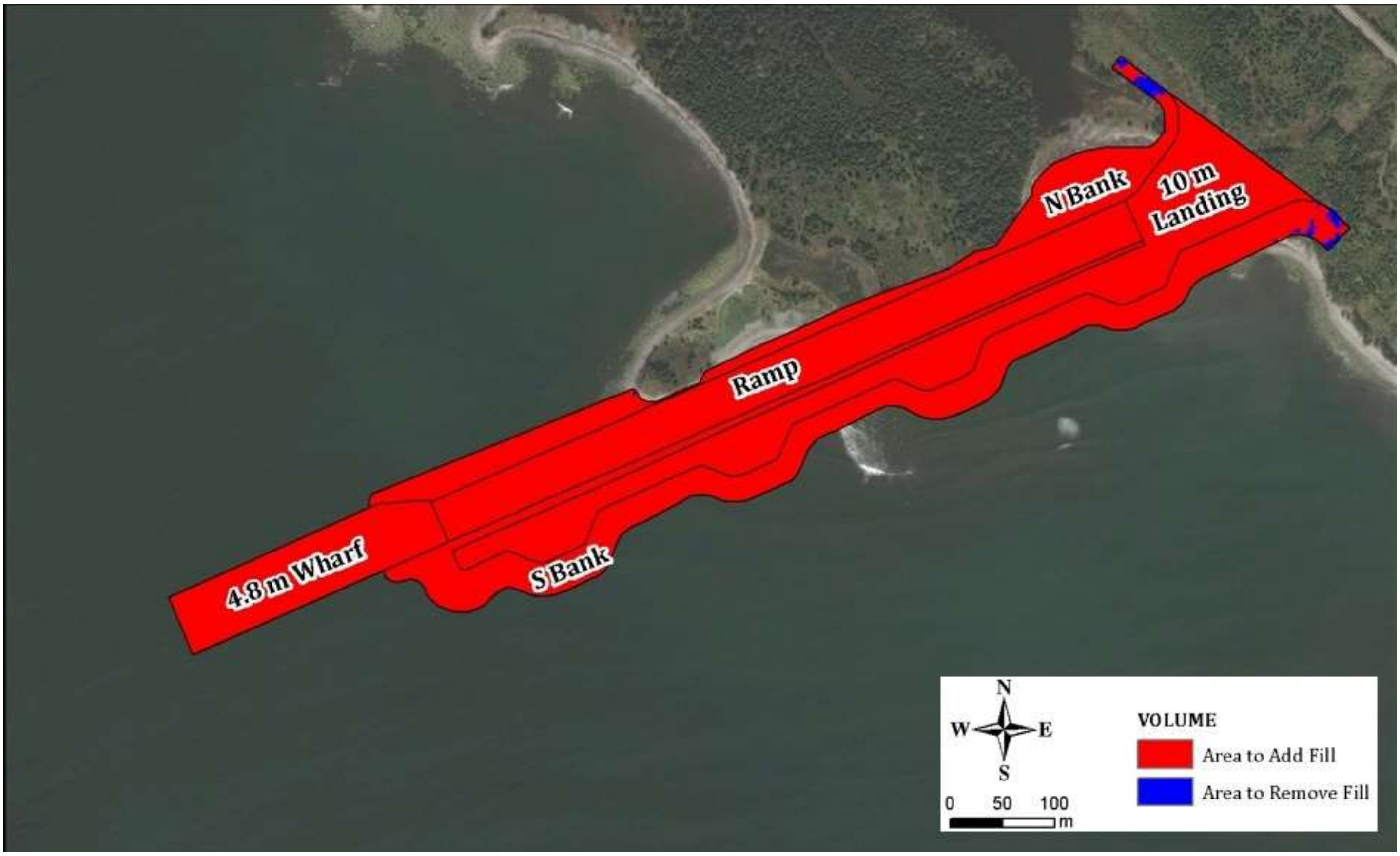


Figure 28. The locations where area needs to be added (red) and removed (blue) for the new structure, shown on an ESRI basemap.

Three transverse cross-section elevation profiles and one longitudinal profile were constructed of the DEM before and after the structure was superimposed (Figure 29). The cross-section profiles (Figure 30) show the new structure adding as much as 15 m (transverse cross-section 2, Figure 30, top right) height to the seafloor.

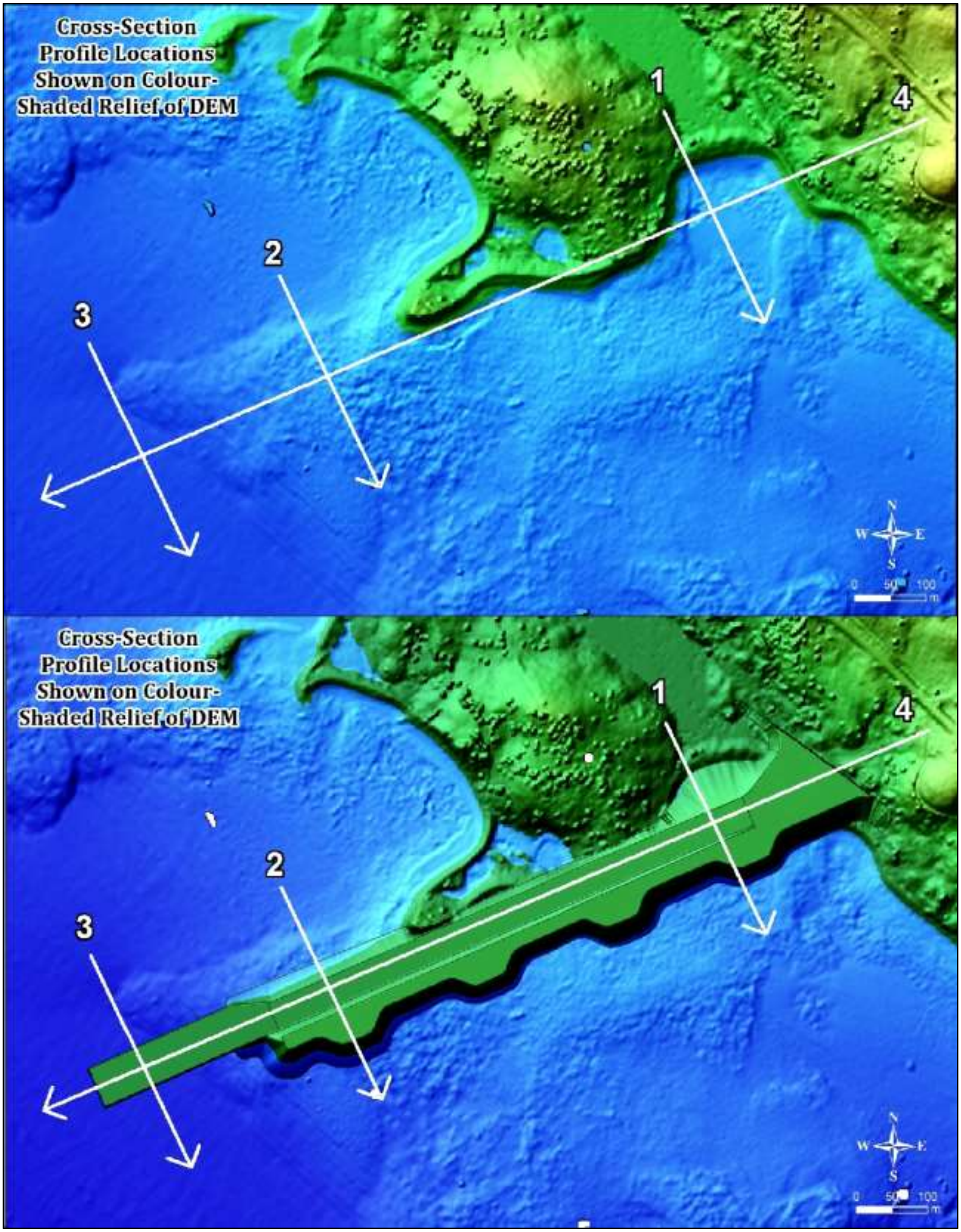


Figure 29. The location and direction of each cross-section elevation profile without (on top) and with (on bottom) the wharf and jetty structure superimposed on the DEM.

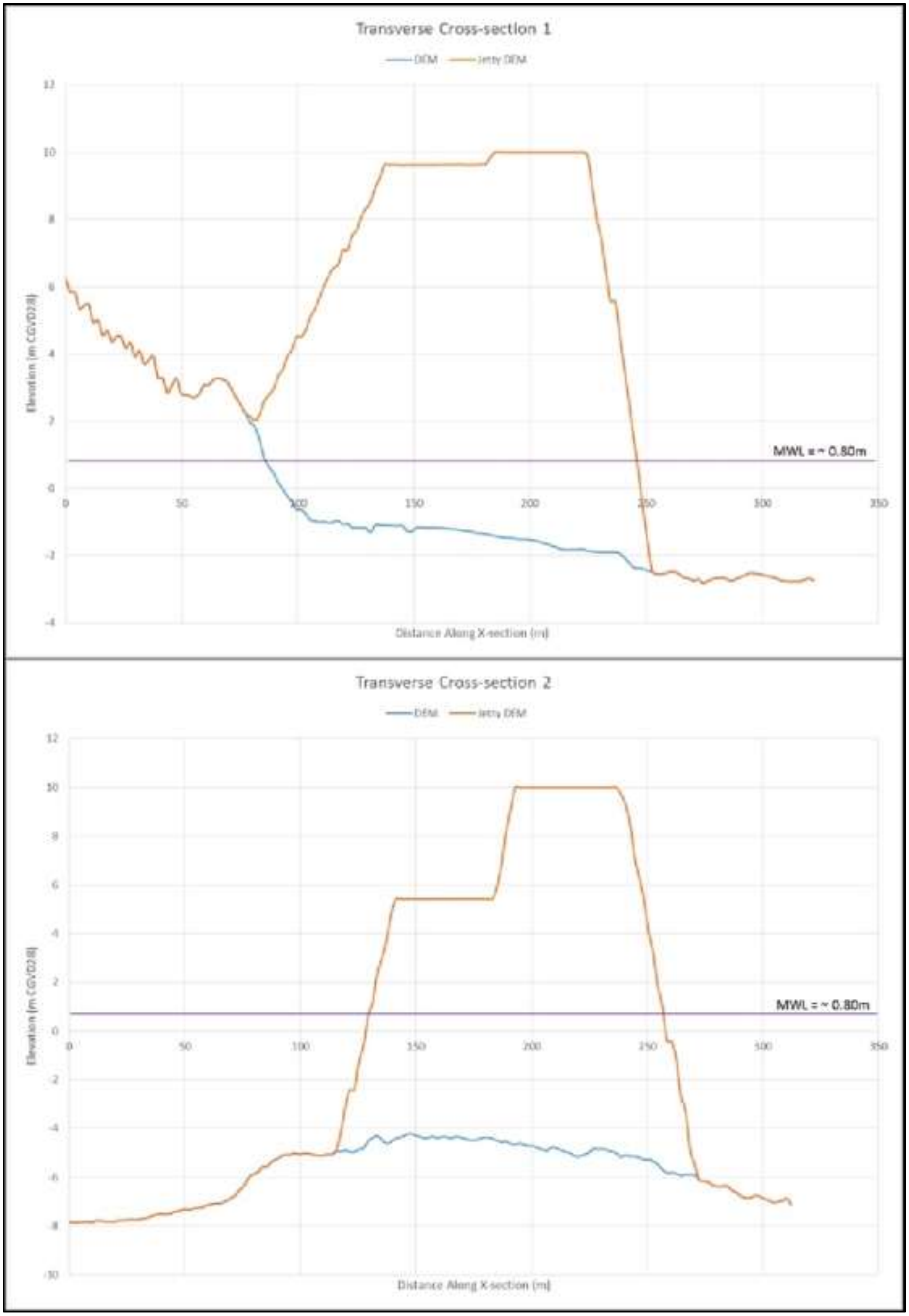


Figure 30. Cross-section profiles 1 and 2 derived from the merged lidar DEM with and without the structure. The scale factor for each cross-section is elevation in metres relative to CGVD28. The mean water level (MWL) of -0.80 m CGVD28 is superimposed by the purple line.

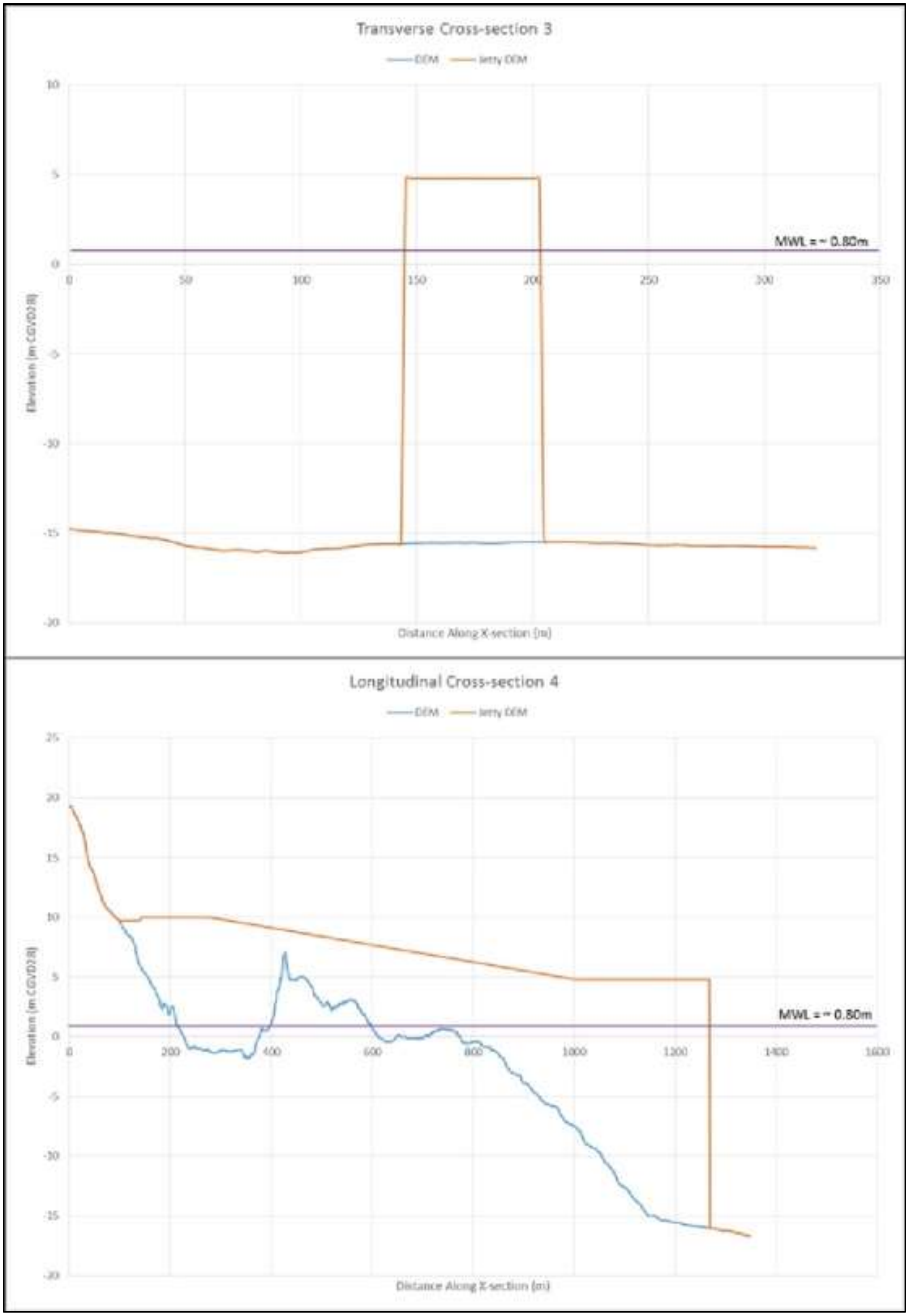


Figure 31. Cross-section profiles 3 and 4 derived from the merged lidar DEM with and without the structure. The scale factor for both cross-sections is different but the units for each is elevation in metres relative to CGVD28. The mean water level (MWL) of -0.80 m CGVD28 is superimposed by the purple line.

4 Discussion

The DEM showed good agreement with the validation collected by AGRG along hard surfaces in the study area. The DEM also showed good agreement with the multi- and singlebeam echosounder points collected for Pieridae. However, the coastline RTK GPS points collected by Pieridae show a mean vertical offset of 0.28 m (+/- 0.346 m) with the RTK points being a higher elevation than the DEM. The most likely root of this offset is within the primary vertical control point used for RTK DGPS surveys executed for Pieridae. According to Appendix III of the Goldboro Bathymetry Survey Report (Canadian Seabed Research Ltd., 2015), the vertical control point used for these surveys is a Nova Scotia Control Monument (NSCM, 10740) whose accuracy is corrected for horizontal but not vertical changes over time. The Nova Scotia High Precision Network (HPN) monuments are the only control monuments whose accuracy is corrected for both horizontal and vertical changes over time which have been observed and calculated using GPS, and thus HPN 9001 is this the primary control point referenced in the AGRG RTK survey. Thus, the published geodetic elevation of NSCM 10740 referenced to ATS77 is 9.046 m CGVD28 which is not necessarily reflective of the actual elevation at this time. In addition, the same Appendix III of the Goldboro Survey Report states that the coordinates used are all referenced to NAD83 (CSRS) 1997 epoch, UTM Zone 20. However, the elevation for NSCM 10740 listed is 9.046 m CGVD28, which according to the published values on the Nova Scotia Coordinate Referencing System's website lists this elevation as being referenced to the horizontal reference frame of ATS77. Furthermore, HPNs have GPS observation-derived coordinates, whereas NSCMs have older line of sight derived coordinates.

5 Conclusions

Topographic-bathymetric lidar is an effective method of surveying large areas of the nearshore coastal zone for pre-engineering assessments of proposed nearshore structures such as the wharf and jetty to be installed at Goldboro. Due to the limitations of traditional echosounder surveys reaching the nearshore, lidar is an ideal platform for obtaining the information for the gap resulting from such traditional surveys. Additionally, lidar intensity data is useful for identifying bottom type, particularly when combined with multispectral air photo analysis, though the quality of these results is diminished by the lack of ground validation. Furthermore, high resolution lidar data provided the necessary information to allow for the required cut and fill calculations to be completed for the jetty design.

6 Acknowledgements

We would like to thank Pieridae Energy and The Natural Sciences and Engineering Research Council of Canada for funding support. We would also like to thank Canadian Seabed Resources and Golder and Associates who provided data collected for Pieridae and assistance to AGRG, as well as David Kristiansen and Sean Dzafovic of NSCC's AGRG for their assistance with collection of ground truth data for Goldboro. Thanks to staff from Airborne Hydrography and Leica Geosystems, AND LEG staff for operations support and AGRG staff for administrative support.

7 References

Canadian Seabed Research Ltd. (2015). Goldboro LNG Project Bathymetry Survey Report (Porters Lake, Nova Scotia). CSR Project Number 1332; Golder Report Number 13-1250-0139-CSR-REP-0009-Rev0

Pieridae Energy (2016). Goldboro LNG. www.goldborolng.com

8 Appendix A: Colour-Shaded Relief of the Lidar DSM

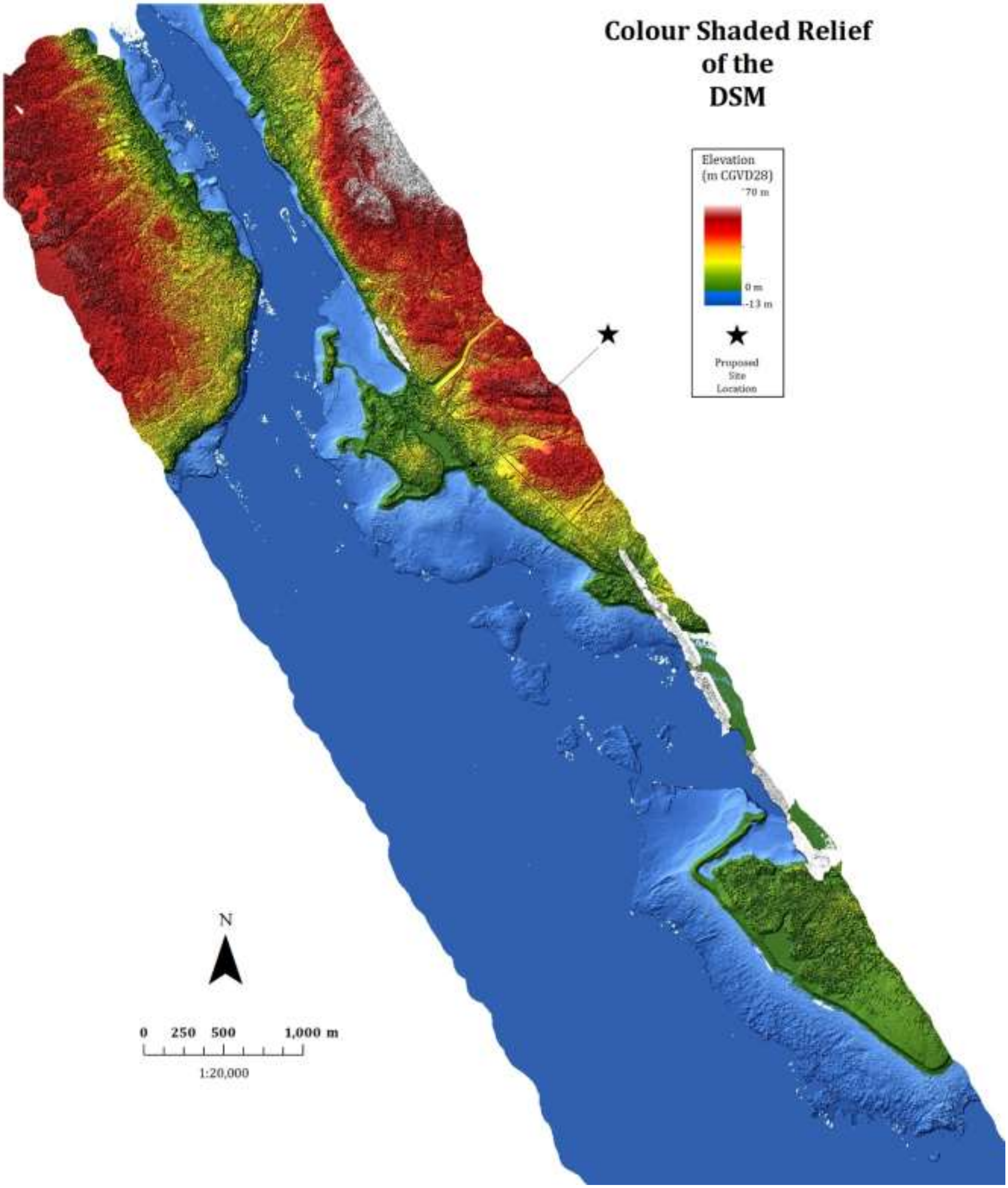


Figure 32. The colour-shaded relief of the lidar DSM.

9 Appendix B: Colour-Shaded Relief of the Hybrid Lidar-Echosounder DSM with Wharf and Jetty

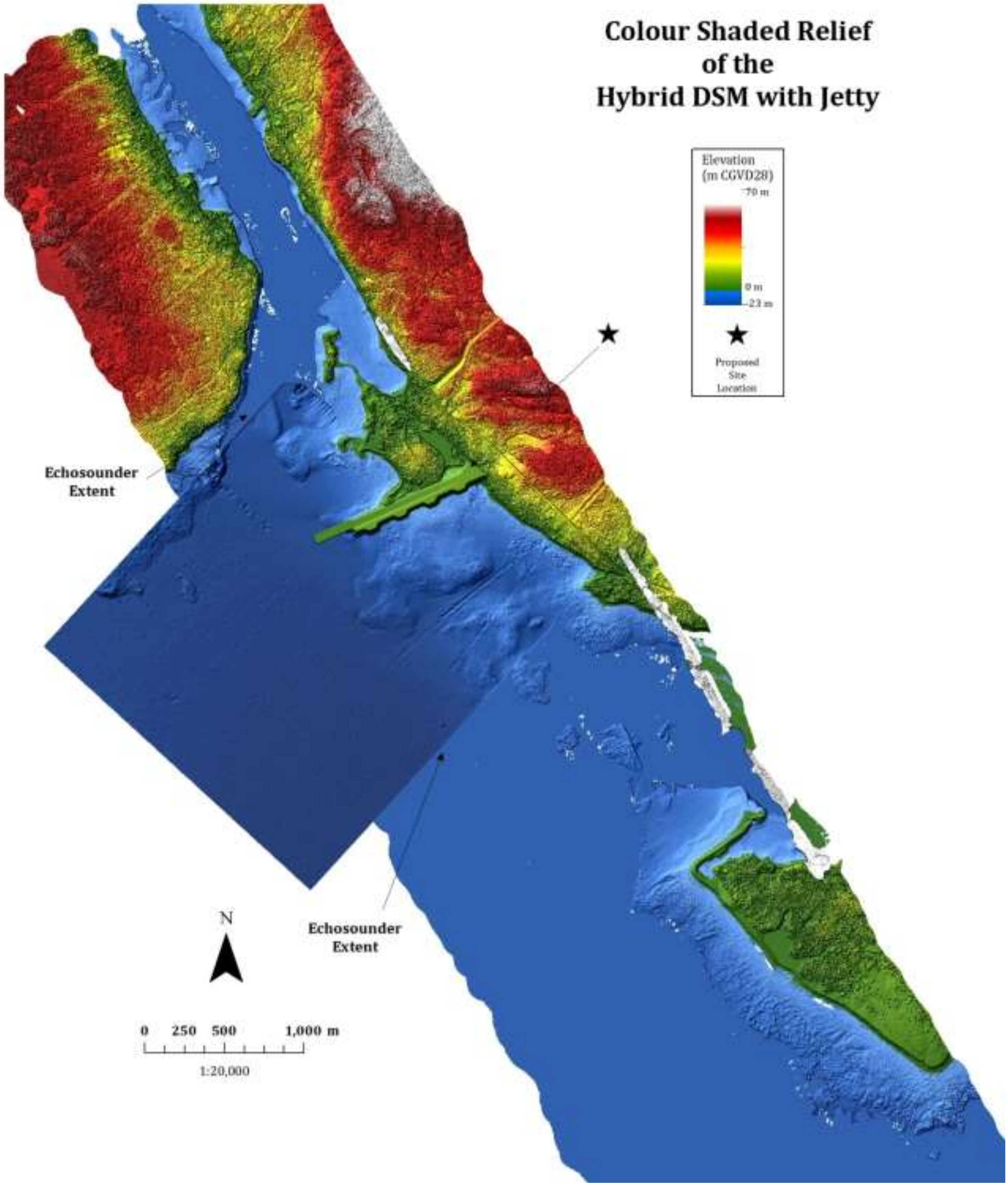


Figure 33. The colour-shaded relief of the hybrid lidar-echosounder DEM with the superimposed wharf and jetty structure.

10 Appendix C: Detailed Schematic of Proposed Wharf provided by Pieridae Energy

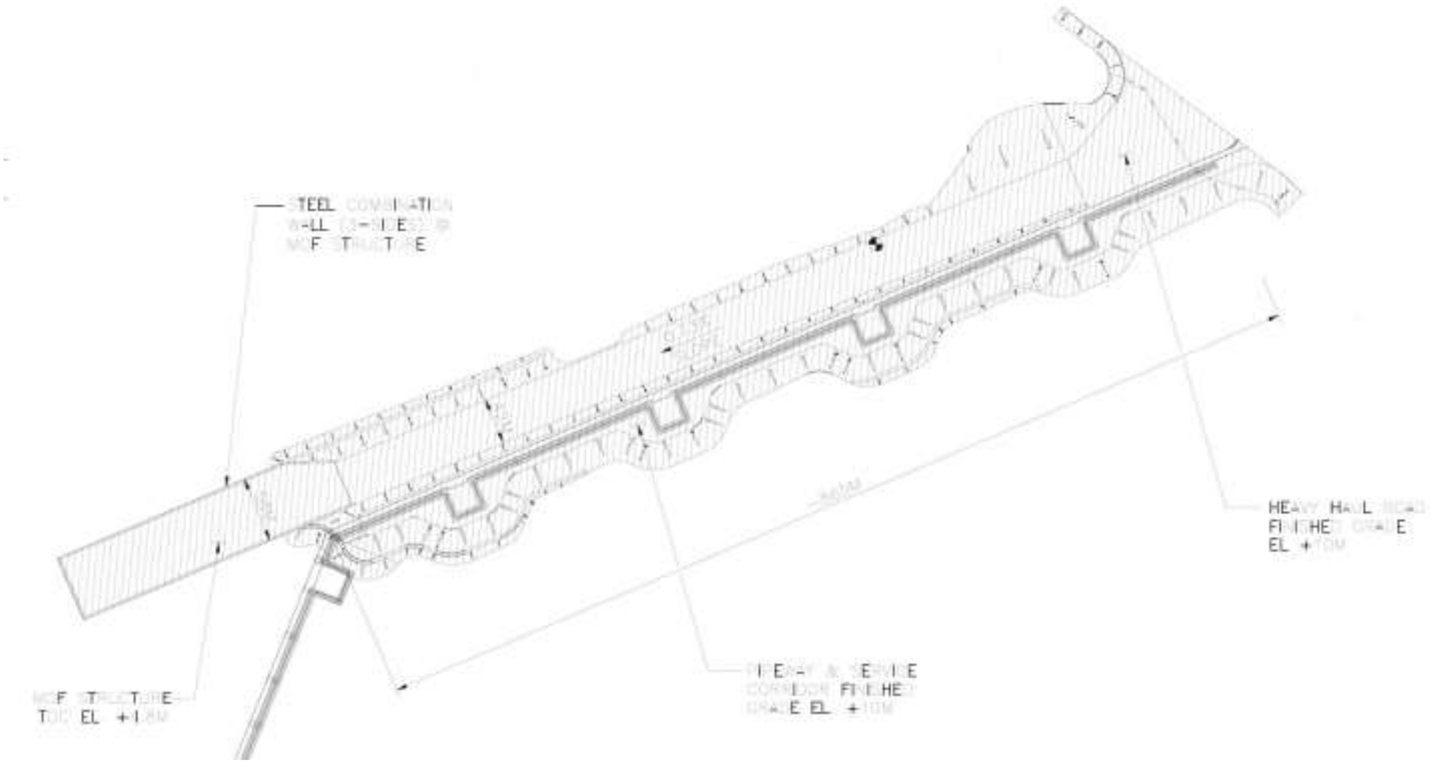


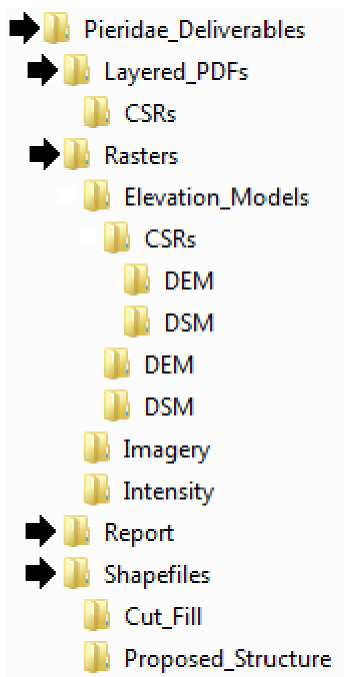
Figure 34. The overall plan of the wharf and jetty structure provided by Pieridae Energy.

11 Appendix D: Deliverable Dictionary

11.1 Overview

A total 5.38 GB of data collected from the bathymetric lidar campaign, in addition to analysis products and hybrid elevation models, has been provided along with this document for submission. Data included in the submission is in accordance with the deliverables as proposed.

The data delivered in the top level directory (Pieridae_Deliverables) falls into one of four major categories: Layered_PDFs, Rasters, Report, and Shapefiles, as shown below. Details on these data follow.



11.2 Rasters

Topographic bathymetric raster data are presented as two variants; Digital Surface Model (DSM), and the hybrid Digital Elevation model (DEM). Both data variants are constructed using bathymetric laser returns; combined with infrared topo-laser returns over land features. Topographic features include all ground (fields, forest bottom, roads etc.) as well as valid non-ground land features (trees, vegetation, buildings, power lines, etc…). The DEM is built from bathymetric and all ground returns only (i.e., no trees, power lines etc… included), as well as a 2 m interpolated echosounder portion added as per Section 2.6. Similarly, the DSM is built from bathymetric returns as well as the 2 m interpolated echosounder portion, but includes all valid non-ground laser returns. The hybrid elevation and surface models include bathymetric echosounder data provided by Pieridae Energy.

All lidar derived raster datasets are delivered in a geographic .TIF raster format; each with a spatial resolution of 2 metres and suitable to be viewed in ArcGIS. Raster data is stored in the Universal Transverse Mercator projection (UTM, Zone 20N) and referenced to the North American Datum 1983 (NAD83). All raster elevation data (DEMs and DSMs) are referenced to the Canadian Geodetic Vertical datum (CGVD28, HT2) whereas the lidar reflectance raster contains relative values representative of lidar pulse return intensity. The lidar reflectance information delivered is derived from the green bathymetric channel laser of the Chiroptera II for lakebed and on ground laser pulse returns.

Shaded relief rasters of the DEM and DSM are delivered in a geographic .jp2 raster format, and greatly enhance the visualization of local terrain by providing illumination from a desired sun angle. The values in a hillshade raster are associated with integers from 0 – 255 that represent various shades of grey associated with areas of shadow and light. Each hillshade was constructed with the hypothetical light source (sun) at an azimuth of 315° and an altitude of 45°, and a vertical exaggeration of 5 times to accentuate the subtle terrain.

The 0.25 m resolution orthomosaic is delivered in georeferenced .TIF format, and similarly projected in NAD 83 UTM Zone 20N. Photos were acquired using a LEICA RCD30 CH62 NAG-D in tandum with the Chiroptera 2 lidar system.

Spectral range and filters	**λ (nm)**
Blue:	435 – 495
Green:	530 – 580
Red:	610 – 660
Near-infrared:	840 – 900

11.3 Shapefiles

All shapefiles are delivered in a geographic .SHP format, all stored in the Universal Tranverse Mercator projection (UTM, Zone 20N) and referenced to the North American Datum 1983 (NAD83). One shapefile (Proposed_Jetty_Polygon.shp) is the 2-D digitized wharf and jetty structure with each segment named in the attributes. The remaining 6 shapefiles show the results of the volumetric cut and fill analysis executed in Section 3.5. More information on each shapefile, including the full list of attributes and their meanings, is shown in Table 3.

Table 3. Full list of all delivered shapefiles and their associated attributes.

Shapefile	Information
Proposed_Jetty_Polygon.shp	The cut and fill locations and volumes for this segment of the wharf and jetty structure
10m_Landing_Cut_Fill.shp	The cut and fill locations and volumes for the 10 m Landing segment of the wharf and jetty structure
North_Bank_Cut_Fill.shp	The cut and fill locations and volumes for the North Bank segment of the wharf and jetty structure
Ramp_Cut_Fill.shp	The cut and fill locations and volumes for the Ramp segment of the wharf and jetty structure
South_Bank_Cut_Fill.shp	The cut and fill locations and volumes for the South Bank segment of the wharf and jetty structure
Wharf_Cut_Fill.shp	The cut and fill locations and volumes for the Wharf segment of the wharf and jetty structure
Whole_Jetty_Cut_Fill.shp	The cut and fill locations and total volumes for the entire wharf and jetty structure
Attribute	***Meaning***
FID	*Internal ARC attribute*
Shape	*Internal ARC attribute; polygon shapefile*
Segment	*Name of the individual segment as referred to in the report (attribute present only in Proposed_Jetty_Polygon.shp)*
Cutfill	*Either 'Cut' which is volume which must be removed or 'Fill' which is volume which must be added (attribute present only in Cut_Fill shapefiles)*
Volume_m3	*Computed volume to be cut or filled*