AIRBORNE BATHYMETRIC LIDAR FOR HYDROGRAPHIC CHARTING IN MAINE, USA

SURVEY IN THE VICINITY OF BLUE HILL BAY, MAINE

REPORT OF SURVEY

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ABBREVIATIONS

ABS	SHOALS-1000T Airborne System component
ALB	Airborne LiDAR Bathymetry
c.l.	Confidence Level
CRP	Common Reference Point
CSC	NOAA Coastal Services Center
DAVIS	Download, Auto Processing, and Visualization Software
GCS	SHOALS Ground Control System
GNSS	Global Navigation Satellite System
GRS80	Geodetic Reference System of 1980
Hz	Hertz
IHO	International Hydrographic Organization
IMU	Inertial Measurement Unit
IR	Infrared
ITRF08	International Terrestrial Reference Frame of 2008
kHz	Kilohertz
MLLW	Mean Lower Lowe Water
LPTT	Laser Power Timing Test
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
OCS	NOAA Office of Coast Survey
PDOP	Position Dilution of Precision
PFM	Fledermaus 3D Grid Surface Processing File Format
POS AV	Position Orientation System, Airborne Vehicle (Applanix)
QL2B	Quality Level Two, Bathymetry
SHOALS	Scanning Hydrographic Operational Airborne LiDAR Survey
SWA	Shallow Water Algorithm
UTM	Universal Transverse Mercator
WGS84	World Geodetic System of 1984

1. INTRODUCTION AND SCOPE OF WORK

1.1 GENERAL

Fugro was contracted in July 2017 by the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (CSC) to conduct an Airborne LiDAR Bathymetry (ALB) survey in the vicinities of Blue Hill Bay in Maine, and to deliver fully processed and verified hydrographic survey data.

The scope of this project was to collect bathymetric lidar data to the extent specified in the provided project boundary shapefile (Figure 1.1), approximately from the 0 meter to the 10 meter contours (Mean Lower Low Water datum - MLLW), as water clarity allowed it. The survey area, totaling 27.7 km^2, is located southwest of Blue Hill Bay. This report of survey describes the field activities and processing efforts for ALB data collected on this area.

The ALB survey was conducted with the SHOALS-1000T and VQ-820-G lidar systems in a concurrent acquisition. The SHOALS system, with a high power laser, provided the better probability for deep sounding detections at a reduced point density (about 0.15 pts/m^2); whilst the VQ-820-Q provided high density coverage (up to 8.5 pts/m^2) but at reduced depth detection. Specification sheets for SHOALS and VQ-820-G systems can be found in Appendix A.

Airborne lidar acquisition operations took place on June 29th, July 2nd and July 5th 2017, during the ongoing survey project OPR-A366-KR-17 for NOAA Office of Coast Survey (OCS).

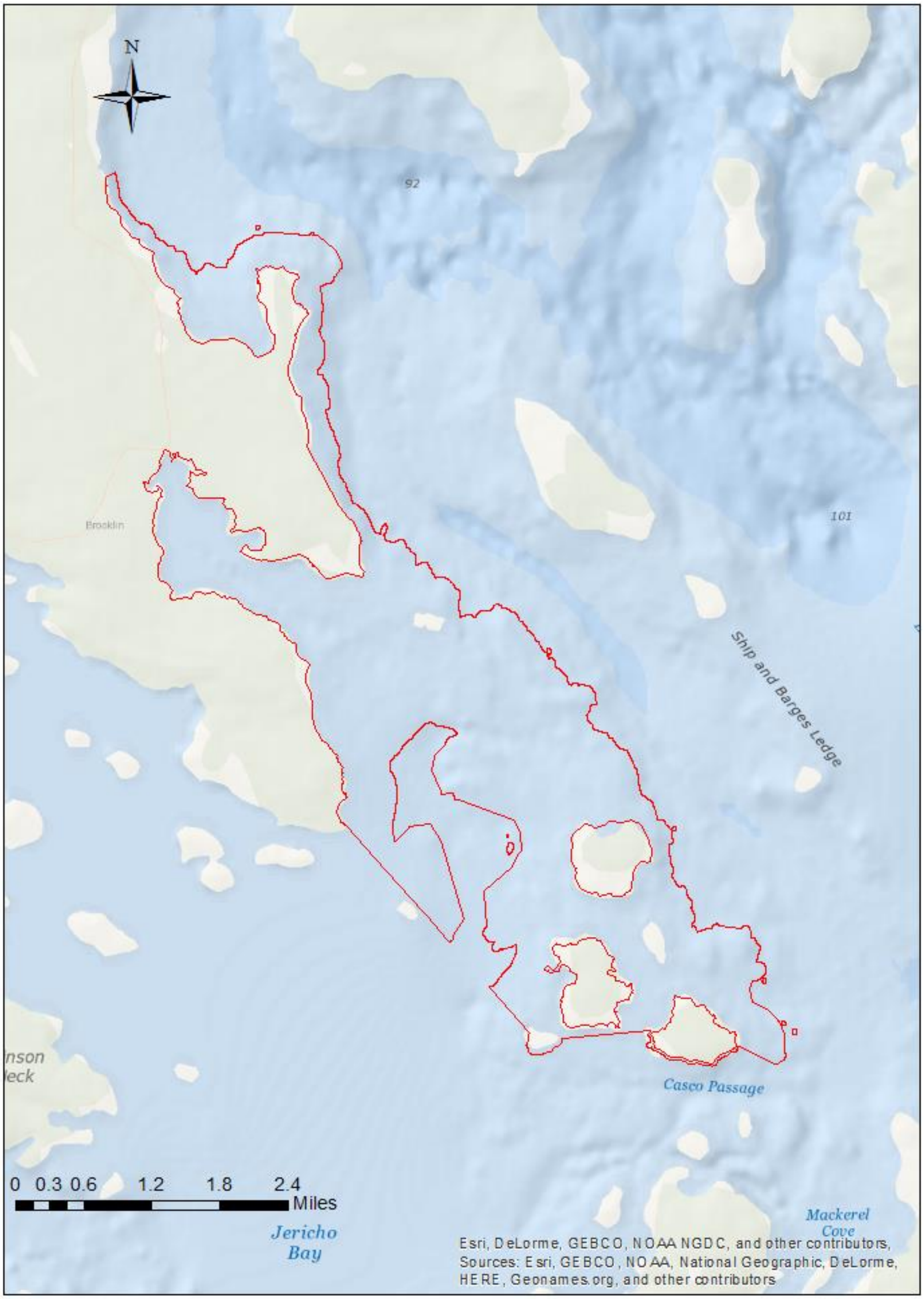


Figure 1.1 Survey Area. Red polygon denotes project boundary

1.2 SURVEY SPECIFICATIONS

The ALB survey was planned to achieve Quality Level 2 specifications for bathymetry (QL2B) specification for category of survey coverage and accuracy, as described in the Draft National Coastal Mapping Strategy 1.0 document:

- QL2B Bathymetric Lidar
  - Vertical accuracy a=0.3, b=0.013 d=depth as in $\pm\sqrt{\boldsymbol{a}^2 + (\boldsymbol{b}\ \boldsymbol{x}\ \boldsymbol{d})^2}$
  - Nominal pulse spacing ≤0.7 m
  - Point density ≥2.0 m

Fugro utilized the SHOALS and VQ-820-G lidar systems in a single acquisition platform. VQ-820-G would meet QL2B specification in both point density and vertical accuracy down to laser extinction depth. SHOALS data would not meet QL2B in point density and have a reduced probability to meet vertical accuracy. Therefore, accuracy results would be circumscribed to meet International Hydrographic Organization (IHO) SP-44 Order 1 specifications, where a= 0.5 m and b = 0.013

Sensor	SHOALS	VQ-820-G
Nominal pulse spacing (m)	2 x 3	0.3 x 0.4
Point density (pts/m^2)	0.15	8.5
Accuracy specification	IHO Order 1	QL2B

Lines were flown at 400 m altitude at 100 kts speed-over-ground with approximately 46 m of sidelap. Airborne Operator assessments included reconnaissance of areas for water turbidity issues, and wind direction/strength affecting survey parameters. Missions were timed with low time periods to increase depth range, however, reflight lines were flown without the tide preference observed.

Cross check lines for verifying and evaluating the accuracy and reliability of surveyed depths were planned in addition of production lines. The analysis of the cross check lines provided confirmation of the meeting of accuracy requirements (see Section 4).

1.3 PROJECT DATUM

Coordinate system for all finalized data was referenced to the North American Datum 1983 (NAD83 2011)), Universal Transverse Mercator (UTM) Zone 19 North. Vertical reference was set to the North American Vertical Datum (NAVD88) using GEOID12b model in meters.

Table 1-1 presents the geodetic details of project datum and projection parameters.

Table 1-1 Project Geodetic and Projection Parameters

Positioning System Geodetic Parameters	
Datum:	ITRF08
Spheroid:	GRS80
Semi major axis:	a = 6 378 137.000 m
Inverse Flattening:	$^{1}/_{f}$ = 298.257222101
Project Datum Geodetic Parameters	
Datum:	NAD83 (2011)
Spheroid:	GRS80
Semi major axis:	a = 6 378 137.000 m
Inverse Flattening:	$^{1}/_{f}$ = 298.257222101
Local Projection Parameters	
Map Projection:	Universal Transverse Mercator
Grid System:	UTM Zone 19N
Central Meridian:	69° W
Latitude of Origin:	0° 00’ 00”
False Easting:	500 000 m
False Northing:	0 m
Scale factor on C.M.:	0.9996
Units:	Meters
Project Vertical Datum	
Datum:	NAVD88 – GEOID12b

1.4 AIRBORNE PLATFORM

A De Havilland DC-6 Twin Otter aircraft, tail number N94AR, (Figure 1.2) had installed both lidar sensors, SHOALS, s/n FPI-1, and RIEGL VQ-820-G s/n S9998923, integrated to operate simultaneously. Technical specifications for the aircraft are located in Table 1-2.

Figure 1.2 De Havilland DC-6 Twin Otter N94AR with lidar sensor onboard

Table 1-2 Aircraft Technical Specifications

Characteristics	De Havilland DC-6 Twin Otter
Registration Number	N94AR
Owner	Twin Otter International
Wing Span	19.8 m
Length	15.8 m
Gross Weight (Empty)	5,670 kg
Allowable Load	2,000-3, 150 kg
Engines	PT6A-27
Cabin space	10.87 cubic meters
Maximum sensor power	300 Amp @ 28 VDC or 8400 Watt

1.4.1 AIRCRAFT MOBILIZATION

The airborne components of the SHOALS-1000T consist of two separate modules. The laser and camera sources are contained in a single housing bolted to a flange above the aircraft camera door. An equipment rack, containing the system cooler and power supplies was installed aft of the laser. The system is controlled through a laptop by the Airborne Operator and a separate pilot console provides navigation and track guidance information to the flight crew. Figure 1.3 shows the ALB systems installed in the aircraft. SHOALS and RIEGL VQ-820-G systems specifications can be found in Appendix A.

Figure 1.3 ALB System Installation in N94AR

1.4.1.1 OFFSET MEASUREMENTS AND LEVER ARMS

The only offset measurements required during the installation of SHOALS and VQ-820-G sensors are the ones from the POS AV IMU reference point to the GNSS antenna. The IMU is completely enclosed within the laser housing of the SHOALS sensor and has fixed measurements to the laser scanning mirrors, therefore, physical measurements are made to a common reference point (CRP) on the exterior of the SHOALS sensor. Offsets are measured using a total station, establishing a base line along the port side of the aircraft. Ranges and bearings are measured from the total station to the CRP on the top of the SHOALS housing. Additional measurements were made to the sides and top of the housing to determine its orientation. A final measurement was made to the center of the POS AV GNSS antenna.

Installation design drawings were used to extend the lever arms from the CRP to the IMU. Similarly, the designed mounting plate that accommodates both SHOALS and VQ-820-G was used to determine the lever arms from IMU to the VQ-820-Q scanner center point.

A summary of the offset measurements made during system mobilization are presented in Figure 1.4 and complete log can be found in Appendix B. The lever arms from the IMU to the VQ-820-G scanner are illustrated in Figure 1.5.

RESULTS

SENSOR REFERENCE POINT to GPS ANTENNA		SET 1		SET 2		SET 3		SET 4	
	X	1.272	REJECT DATA ☐	1.271	REJECT DATA ☐	1.271	REJECT DATA ☐	1.272	REJECT DATA ☐
	Y	0.345		0.348		0.349		0.347	
	Z	-1.028		-1.023		-1.029		-1.027	

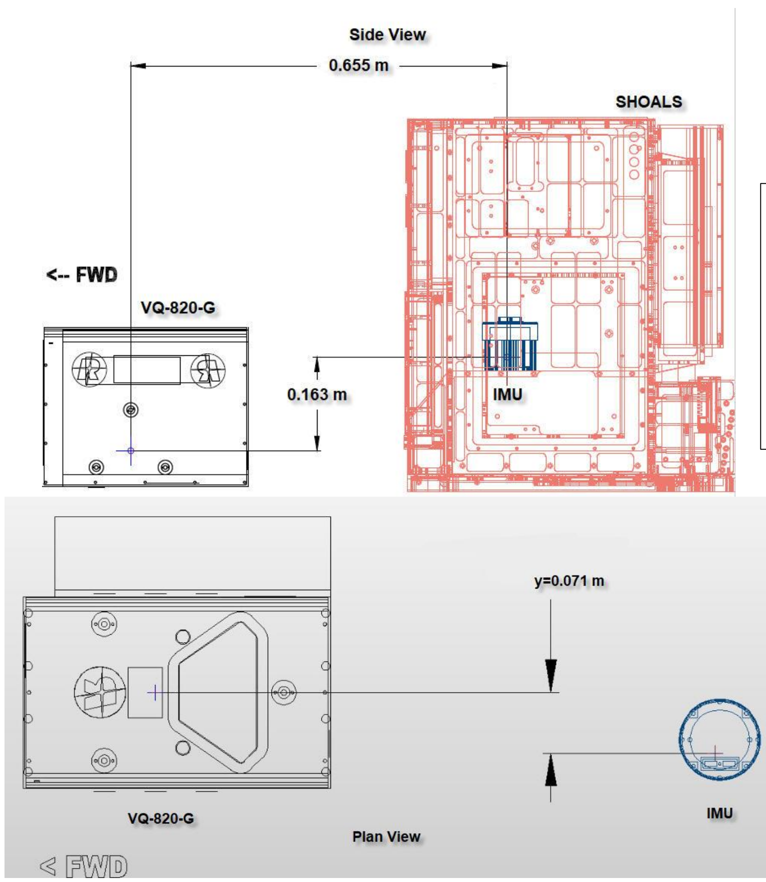
TAPE MEASUREMENT (SENSOR REF to GPS ANTENNA)	
X	n/a
Y	n/a
Z	n/a

IMU to SENSOR REFERENCE		SENSOR REF to GPS ANTENNA	
X	0.073	X	1.272
Y	-0.230	Y	0.347
Z	-0.415	Z	-1.027

IMU to GPS ANTENNA		
	X	1.345
	Y	0.117
	Z	-1.372

Checked By: M. Blackbourn

Figure 1.4 SHOALS Offsets Measurements and IMU-to-GNSS antenna lever arms



IMU to Scanner
X 0.655 m
Y 0.071 m
Z 0.163 m

Figure 1.5 VQ-820-G Lever Arms from IMU-to-Scanner

1.4.2 LIDAR CALIBRATION

The SHOALS system is regularly verified for valid calibration parameters to ensure that vertical and horizontal accuracies are maintained throughout the operational service of the system. The system was fully geometrically calibrated in June 23rd 2017 and parameters derivation completed shortly thereafter. A completed report documenting the calibration results is included in Appendix B (20170623 FPI-1 SHOALS Calibration Report r0 External.pdf).

A boresight alignment was performed on RIEGL VQ-820-G system, following the manufacturers best practice procedures and instructions for installation and data processing. The boresight results from flights conducted on June 23rd 2017 indicate the system was within expected tolerances for angular misalignments and vertical accuracy. A completed report documenting the calibration results is included in Appendix B (20170623 RIEGL VQ-820-G Calibration Report r0 External.pdf).

Following the calibration, a system verification flight was conducted on June 23rd 2017 in the vicinity of Grand Junction, Colorado. The verification analysis was conducted right after and included the following tests:

- Data alignment over a peaked-roof building and over a flat water surface to verify angular alignment

- Topographic elevations comparison vs. reference ground truth to verify vertical accuracy within specification

The results of the above analysis demonstrated that the system was within the accepted calibration parameters recommended by the manufacturer.

2. MOBILIZATION AND DATA ACQUISITION

After verification of calibration results, the aircraft transited to Penobscot Bay, Maine to commence survey activities in Jun 24th, 2017 for NOAA OCS survey. Operations in Maine were based out of Knox County Regional Airport (RKD), Maine. Fugro personnel arrived at the survey site on June 25th, 2017. The field office was set up and operational logistics such as hangar space, fueling, amendments to mission plans commenced. On June 29th, July 2nd and July 5th, data for Blue Hill Bay project was acquired.

2.1.1 POSITIONING AND ORIENTATION

Aircraft positioning was determined in real time using and Applanix POS AV 510 v6 system aided with Starfix DGNSS differential corrections. The POS AV is a full inertial navigation system integrating GNSS positioning with IMU data streams to estimate accurate position and orientation (roll, pitch, and heading). The POS AV data is also used during acquisition to maintain a consistent laser scan pattern as the aircraft pitches and rolls in flight.

2.1.2 LIDAR SYSTEMS

The SHOALS acquired bathymetric and topographic data at a rate of 2.5 kHz through the transmission of infrared laser (1064 nm) with a frequency doubled green wavelength (532 nm) in a single beam. The infrared wavelength is used to detect the water surface and does not penetrate the air/water interface. The green wavelength penetrates through the water and detects the seafloor up to 2.5 times Secchi disk depths. The scanning (transmitting) occurs on a stabilized platform that compensates for aircraft pitch and roll. The return signals are electronically amplified and conditioned prior to being digitized and logged. Background theory on bathymetric LiDAR can be found in Guenther, et al., 2000 (Appendix A).

The RIEGL VQ-820-G provides high resolution data, up to 10 pts / m^2 over land and shallow water to 1 Secchi disk depths. Riegl VQ-820-G uses a laser at 532 nm at a high scan rate, selectable up to 520 kHz, that penetrates the water surface to detect shallow seafloor returns. The VQ-820-G system acquires highly dense point data to approximately 10 m water depth in very clear water conditions. Technical datasheet can be found in Appendix A (10_DataSheet_VQ-820-G_05-04-2012_PRELIMINARY).

Data received by the airborne systems were continually monitored for data quality during acquisition operations. Display windows show coverage and information about the system status. In addition, center waveforms at five Hz were shown. All of this information allowed the airborne operator to assess the quality of data being collected.

2.2 GROUND CONTROL

Positioning was post-processed relative to the NAD83 (2011) datum using Applanix POSPac MMS SmartBase engine. POSPac SmartBase has been optimized for large changes in altitude by the rover, and extended to work with multiple CORS reference stations separated over very large distances. POSPac SmartBase processes the raw GNSS observations from a network of 4 to 50 reference stations to compute the atmospheric, clock and orbital errors within the network. These are used to correct for the errors at the location of the POS AV GNSS receiver at each epoch, as it moves throughout the network.

The SmartBase network of NGS CORS stations is shown in Figure 2.1. The primary and control station used for the network was MEOW. Network stations as well as the primary and control were held for the duration of ALB acquisition.

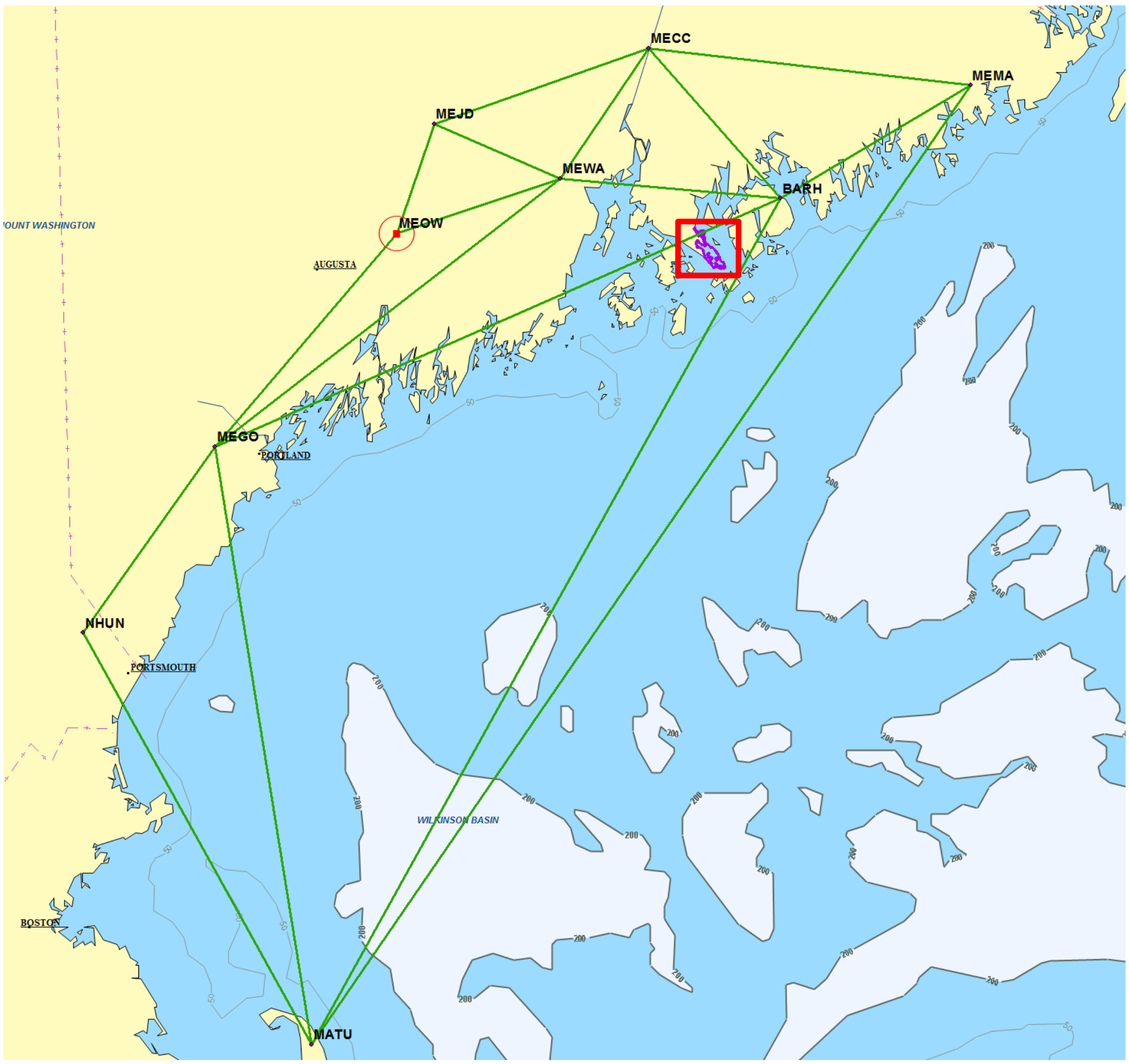


Figure 2.1 SmartBase CORS Network in reference to the survey area (red box)

2.3 PERSONNEL

The following Table 2-1 lists Fugro personnel involved in the project.

Table 2-1 Project Personnel

Team	Function
Mark MacDonald	Operations Manager
Trisha Mouton	Project Manager
Mila Cox	Lead Hydrographer
Juan Lopez	Data Analyst
David Dietzler	Data Analyst / Airborne Operator

2.4 CHALLENGES ENCOUNTERED

Challenges encountered on this survey were of both environmental and technical nature. The sensor system performed according to specifications and within the accuracies verified before the survey was performed. Table 2-2 describes the standard environmental operational limits for an ALB survey.

Table 2-2 Environmental Operational Limits for an ALB survey

Restriction	Limitation	
Cloud Ceiling	>500 m	
Precipitation	Data are not collected during periods of heavy rainfall.	
Wind Speed	Head Wind	< 40 kts / 74 km/h
	Tail Wind	< 20 kts / 37 km/h
	Cross Wind	< 40 kts / 74 km/h
WMO Sea State	1 – 4	
Aircraft Cabin Temperature	5 - 40ºC (system will shut off automatically at the maximum limit and data collection will stop)	
Topography	Land elevations more than 200 m in the flight path vicinity	

2.4.1 ENVIRONMENTAL

Water turbidity caused by wind and tide currents was a common factor affecting the water surface and bottom detection capabilities of the system. These limitations were accounted for in the initial assessment of survey and affected the final data validation. The water conditions in survey area at this time of the year did not seem to have improvements during the fast-paced airborne acquisition.

Atmospheric conditions were free of fog and low cloud conditions and consider optimal.

2.4.2 TECHNICAL

Both, SHOALS and VQ-820-G lidar systems worked without concern throughout the entirety of the project. No failures or malfunctions were observed.

Reflight missions where planned to fill-in gaps between scanned swaths and a full flight was dedicated to reattempt line re-acquisition were poor results were observed on previous flights.

2.5 SUMMARY OF SURVEY ACTIVITIES

The following is a summary of daily activities during the field phase of the project. Details were extract from the Daily Project Reports (Table 2-3).

Table 2-3 Daily Summary

Date	Daily Summary
29 June 2017	Successful flight collected 23 lines in Survey Area. Takeoff delayed slightly by RIEGL POS issues - discussion with betterment determined this was common when POS signal is split and supplied to both RIEGL and SHOALS. Data backlog underway in the office with coverage creation remaining a focus.
2 July 2017	Load Mission Plan for Reflight. Not much data in polygons—maybe too deep. Some decent Areas. 45 planned reflight lines collected.
5 July 2017	Load Mission Plan, Some glint, but not nearly as bad as it was this morning. @7 Production Lines collected, 3 Crosslines.

3. DATA PROCESSING

During the field acquisition period, all data were initially checked for coverage and quality at the temporary field office. These initial steps ensured that no time was spent on trying to process data which did not meet Fugro's standards.

At the conclusion of field operations, the survey data package was transferred to the Fugro Datacenter in San Diego where final processing and product assembly took place. The data processing flow is summarized in Figure 3.1.

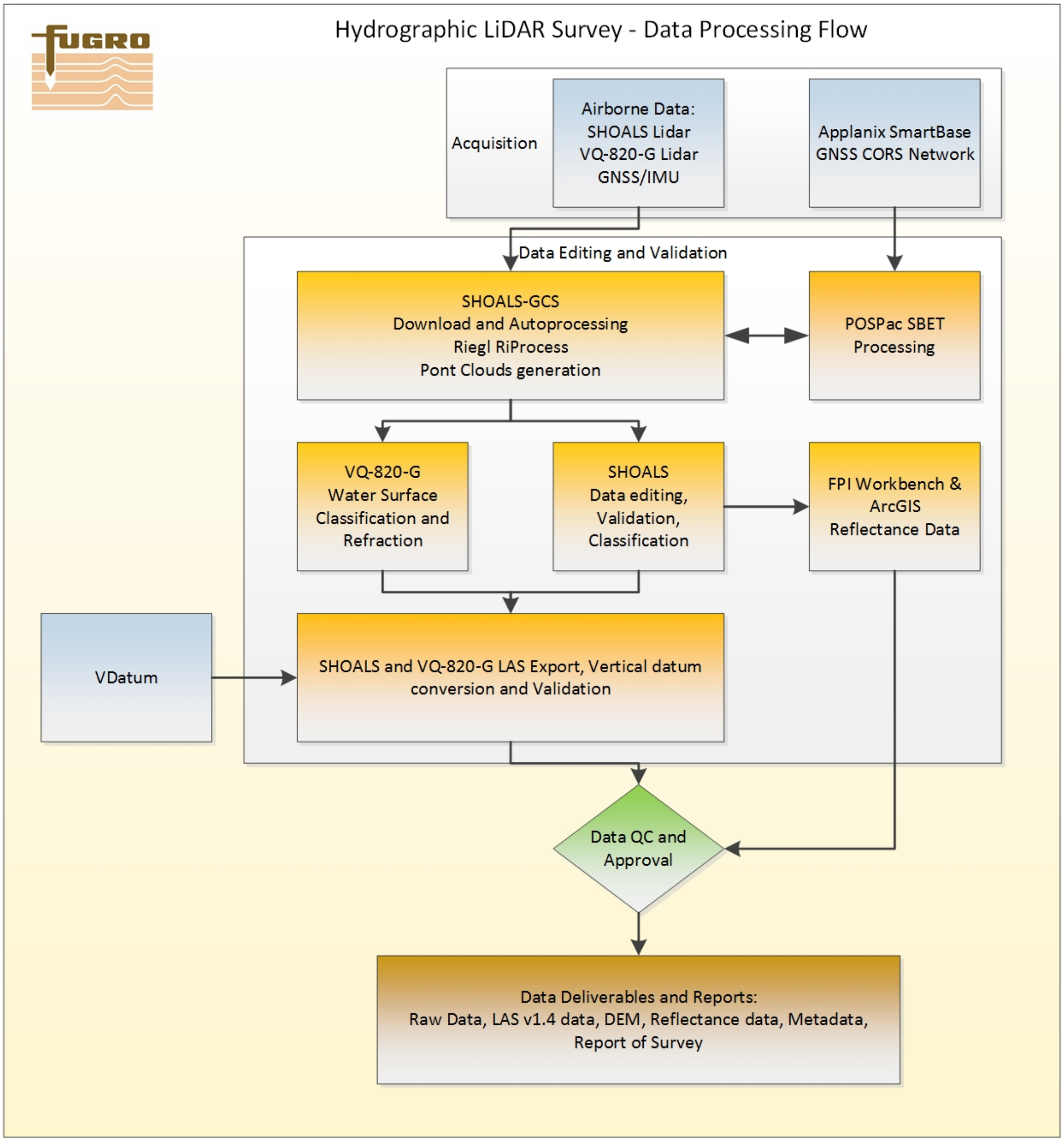


Figure 3.1 LiDAR Data Processing Flowchart

3.1 SHOALS PROCESSING

All SHOALS data was processed using the Optech SHOALS Ground Control System v6.32 (GCS) on Windows 7 workstations. GCS includes links to QPS Fledermaus v 7.7 software for data visualization and 3D editing. The GCS DAViS module (Download, Auto-processing and Visualization Software) was used to download raw SHOALS sensor data, auto-process waveforms with specialized algorithms for surface/bottom detection and depth determination, perform waveform analysis for reflectance generation, and make an initial assessment of data quality.

3.1.1 AUTO PROCESSING

The Auto Processing routine contains a waveform analysis algorithm that detects and selects surface and bottom returns from the raw data. Land returns are also characterized from the bathymetric laser and classified as such.

The Auto Processing algorithms obtained inputs from the raw data and calculated a height, position and confidence for each laser pulse. This process, using the default environmental parameters, also performed an automated first cleaning of the data, rejecting poor land and seafloor detections. Questionable soundings were flagged as suspect, with associated warning information, so that further investigation by the Data Analysts could take place during data visualization and editing.

In addition to the hardware values, some default environmental parameters were also set relative to assumed water quality conditions of the survey area. Surface detection method (surface logic) was set as Green-Infrared. This prompted the surface detection algorithms to use the Green channel initially. If no Green surface pick was found, then the IR channel would be used. The bottom detection mode can be set to either strongest pulse logic or first pulse bottom logic. In the case of hydrographic surveys such as this, the first pulse bottom logic is used to increase the bottom object detection capability of the SHOALS system. Data was then imported into a Fledermaus project in PFM file format to allow data inspection and editing in a 3D environment.

3.1.2 DATA VISUALIZATION & EDITING

Data visualization and editing was done using QPS Fledermaus v 7.7. Fledermaus displays a gridded and shaded 3D surface (PFM) of each project block (Figure 3.2).

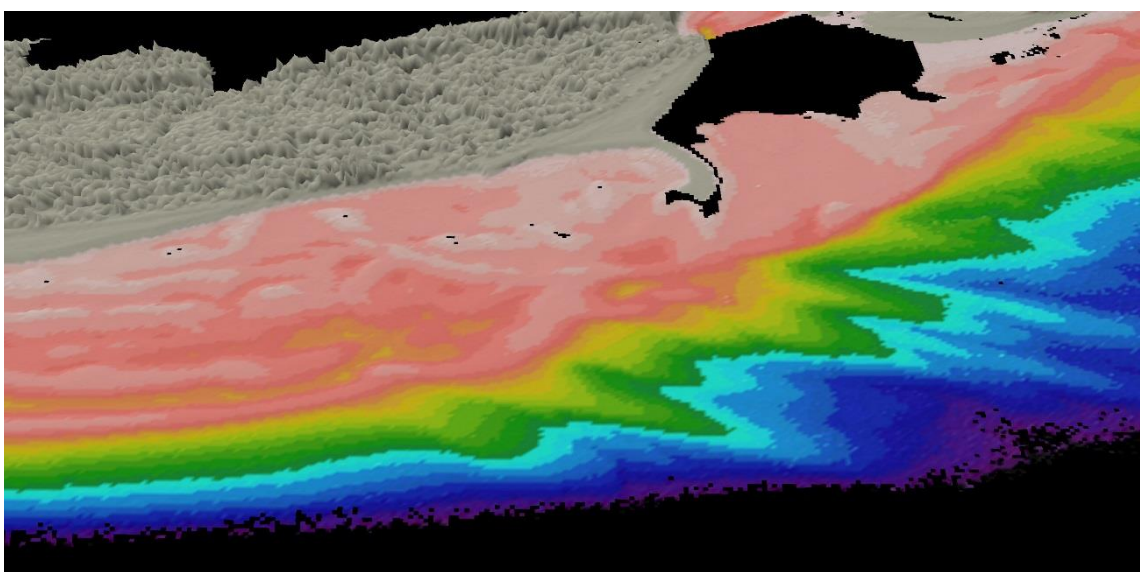


Figure 3.2 Fledermaus PFM Surface View

Smaller sections are then reviewed using the 3D area-based editor. The 3D Editor opens up a smaller subset of data, displaying individual sounding point clouds in 3D (Figure 3.3).

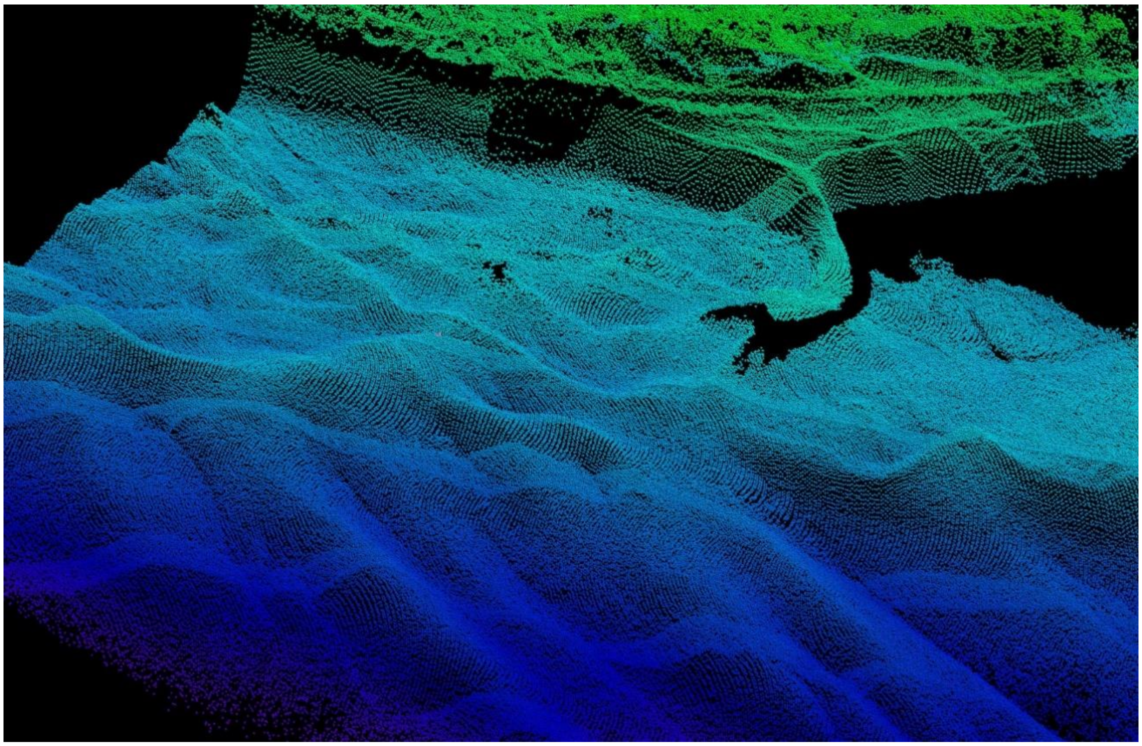


Figure 3.3 Fledermaus 3D Editor Lidar Point Cloud

Spot depths with erroneous elevations (gross fliers) were manually rejected. Other data of uncertain quality requiring more examination were reviewed using the waveform window, which displays shallow and deep channel bottom selections, and green, IR, surface picks (Figure 3.4).

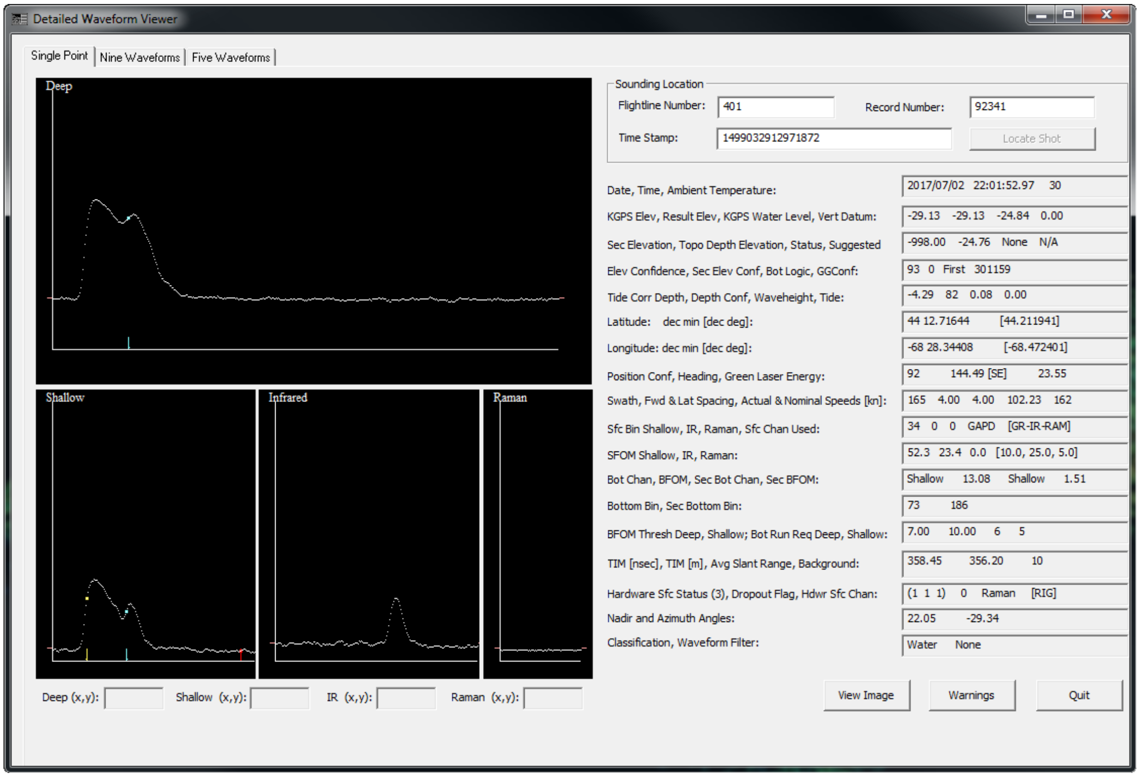


Figure 3.4 Waveform Viewer

Other metadata such as confidence values and laser shot warnings are also incorporated into the waveform viewer. Additionally, the down look camera image associated with the laser pulse can also be displayed (Figure 3.5).

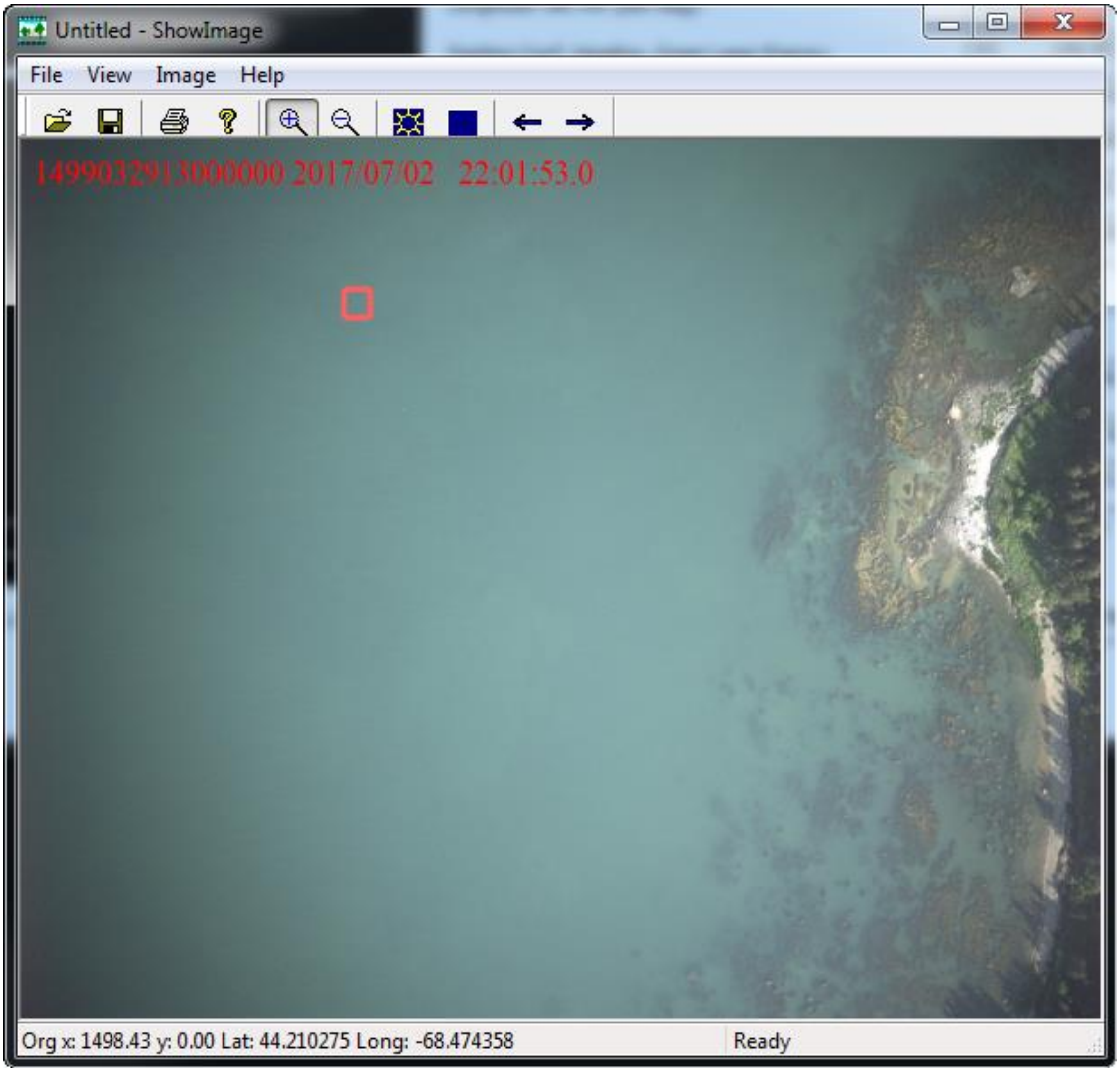


Figure 3.5 Airborne Down look Digital Imagery

Other GCS specific tools, such as swapping a sounding that was falsely recognized as land to water, were used inside Fledermaus by experienced Data Analysts. In the shallower near shore margins the Shallow Water Algorithm (SWA) for bottom detection was used to recover very shallow (less than 1.5 m) bathymetry and to allow, where valid returns permitted, a seamless join with the topographic data obtained on the specific missions that these data were collected.

Once all editing and validation had occurred, data points were exported to LAS format for final validation and preparation to deliverables products.

3.2 VQ-820-G PROCESSING

The RIEGL VQ-820-G sensor data was process using the RIEGL LMS suite of software. The bulk of the field processing was done in RiProcess v1.8.3. The post-processed SBET solutions were applied to converted raw data to produce point clouds in the project reference coordinates. The VQ-820-G data is run through a routine that classifies water surface point returns, however, the classification needs to be manually completed by the Data Analyst to verify no erroneous points are classified as water surface or to complete water surface points classification to higher accuracy.

The importance of water surface points classification accuracy is justified in the next process where the water surface points are modeled into an undulating surface representing the air-water interface to which the laser beams are refracted according to Snell's law (as the angle of incidence changes when passing different media, the position of the detected targets change). The water surface model is used as the air-to-water interface for refraction correction. The refraction correction adjusts the point position both vertically and horizontally.

After refraction correction is applied, data is exported to LAS format were it is inspected in TerraSolid software packages, TerraScan and TerraMatch, to review potential misalignments, as well as for achieved coverage. Terrascan is also used to perform complex point classification (bare ground, vegetation, buildings, utilities, and so on), however, the VQ-820-G classification was not required as per scope of work.

3.3 CONVERSION TO NAVD88 VERTICAL DATUM

As stated in Section 1.3, project vertical datum for lidar elevations is NAVD88 (GEOID12b) in meters. To perform this conversion, NOAA's VDatum Transformation tool v3.6.1, was used to perform a direct computation in both the SHOALS and VQ-820-G LAS-formatted line data. This process included all topographic and bathymetric lidar points. Figure 3.6 shows an overview of the GEOID12b geoidal undulation surface model, where a small 0.2 m gradient sweeps through the survey area East-West.

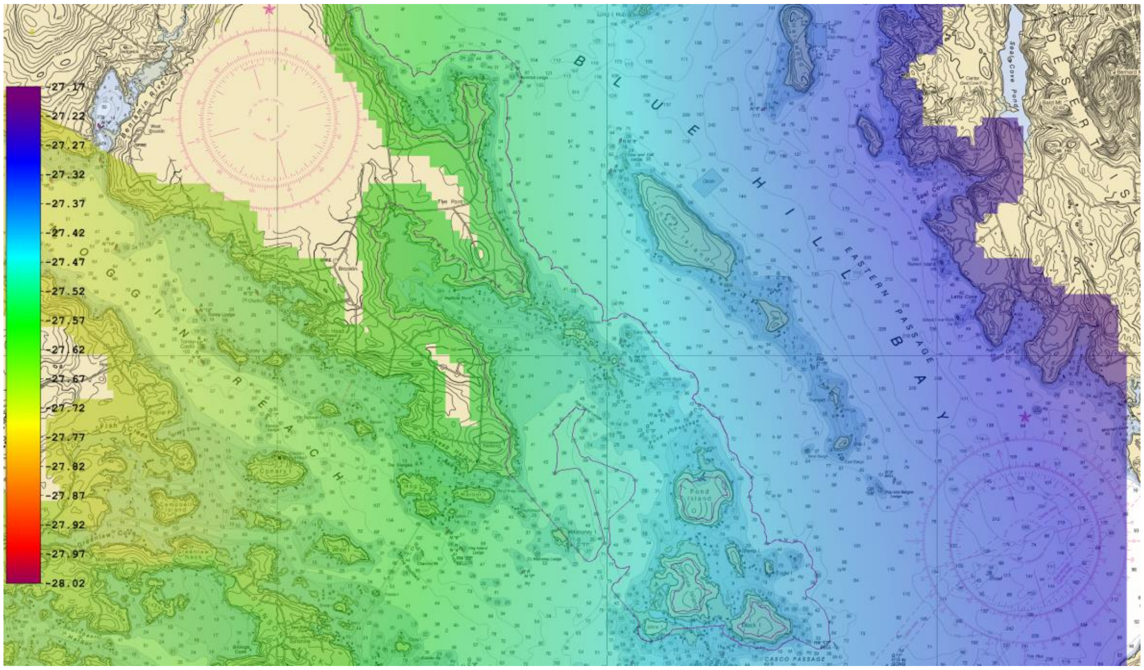


Figure 3.6 GEOID12b Geoidal Surface Model in the Survey Area

3.4 REFLECTANCE AND INTENSITY

Intensity information is stored automatically in the VQ-820-G data in LAS format and it is available as 16-bit integer values that decode as grey-scale imagery in most LAS visualization packages. Graphic in Figure 3.7 shows intensity gradient for topographic returns over an island (light color) and the surrounding water surface and bathymetric returns (dark color)

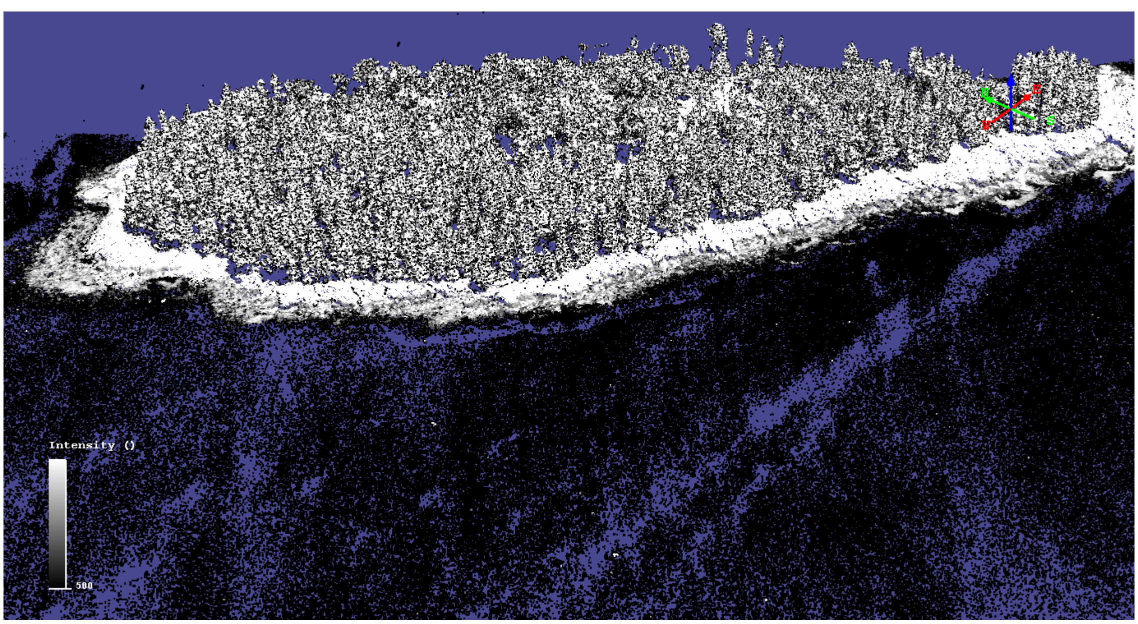


Figure 3.7 Example of Typical VQ-820-G Intensity

For SHOALS data, reflectance information has to be post-processed from the digitized waveform information of valid lidar shots. The calculation of returned laser energy power is resolved for land coverage using the inversion of a radiative transfer equation. The principle is extrapolated to bathymetry coverage with two additional variables: water depth and water clarity. Water depth is determined by the lidar depth and a correcting factor estimated empirically when same bottom type covers a large water depth range. Water clarity is estimated using the slope of the volume backscatter on waveform return, which is the signal response as the laser signal travels through the water column.

This processing yields an estimate of reflectance at each location where the depth is measured. Estimates for hydrographic and topographic coverage are produced separately due to the high variance in value between them. The produced reflectance values range from zero to 100 where zero represents absolute absorption and 100 is complete reflectance. Values are usually gridded in raster images where line-to-line and flight-to-flight data are compared for seamless reflectance coverage. An example of typical reflectance results can be seen in Figure 3.8.

SHOALS reflectance data is not embedded in the LAS format files but it is delivered as ASCII XYR files.

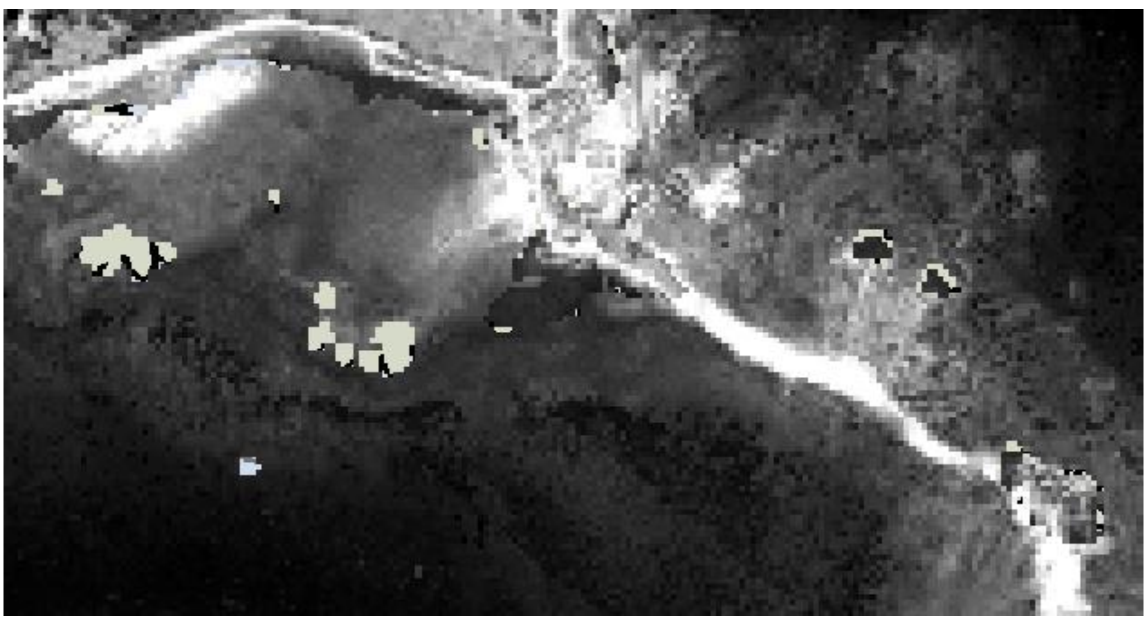


Figure 3.8 Example of Typical Reflectance Result Showing the Shoreline in Bright Tones

4. QUALITY ASSURANCE

Throughout the data acquisition and processing procedures there were numerous quality control checks performed to ensure that the lidar system was performing correctly and within specification.

The Airborne Operator continually monitored the data collected in real-time to ensure all navigation and laser system quality parameters were within acceptable tolerances. The Data Analyst continually inspected the data throughout the entire processing flow to ensure the collected data was within project accuracy specifications. These checks included:

- SHOALS timing and power tests
- Visual inspection of the overlapping lines point clouds. Point overlap over flat terrain and over pitched roof buildings assist on identifying vertical mismatches and misalignments.
- Crossline analyses. Generate statistical measures to assess relative accuracy.

4.1 CROSS CHECK LINE ANALYSIS

Crosscheck analysis is used to estimate the relative accuracy of the lidar data. It assumes the main lines and the crosslines have all the accounted random errors associated to the measurement process, thus the statistical results are equivalent to the overall accuracy of the project data. A number of crosslines spaced along the main lines are normally planned at a separation interval, however the goal is that 90% of the main scheme lines are intersected by the crosslines. The overall coverage results of ALB surveys make difficult to achieve this percentage all the times, though.

The elevation difference between the points on the crosslines and the main survey lines was performed using the Crosscheck utility within the Fledermaus software suite. A surface grid was created from the main lines at approximated the nominal lidar spot spacing. The elevation of the grid surface is queried by the point data position of the crossline; the elevation difference statistics between surface and point constitute the test for accuracy evaluation. For fairness of results, predominant data analyzed was over areas with homogeneous bottom detection, smooth topo-bathymetric relief and gentle slopes.

The vertical accuracy for VQ-820-G data, as specified by Quality Level 2 specifications for bathymetry (QL2B as described in the USGS Lidar Base Specifications (Version 1.2, November 2014), is $\pm\sqrt{a^2 + (b * d)^2}$, where, a=0.3 and b=0.013, d=depth

The cross line analysis results for VQ-820-G data are presented in Table 4-1. The column on the right shows the percentage of points that are within the accuracy threshold (indicated); percentages above 95% indicate passing the accuracy test.

Table 4-1 VQ-820-G Crossline Analysis Results. QLB2.

Crossline Flight Date	Area ID	Xline No.	No. of Points	Diff Mean (m)	Diff St. Dev. (m)	Percentage of Points ±0.3 m QL2B
5-Jul-17	023_30cm	23_1	462734	-0.066	0.146	93.2
5-Jul-17	024_30cm	24_1	476913	-0.007	0.046	99.5
5-Jul-17	025_30cm	25-1	893053	-0.089	0.110	94.7

The VQ-820-G data crossline analysis was performed at locations where the main lines and crosslines intersected with relative successful bottom detections. The selected suitable areas for analysis consisted on shallow bathymetry and adjacent beach terrain. These areas have an apparent gentle slope and smooth textures that could serve for a fair vertical comparison. From the aerial imagery, however, some areas may have included submerged rocky shore that described non-flat terrain, as shown in Figure 4.1. The terrain observed over these areas may help to explain the accuracy test results: 1) that the elevated standard deviation of the point elevation differences is caused by natural terrain roughness; 2) that combined with the mean elevation difference (bias), some tests are slightly below the passing threshold; and 3) the results do not mean the vertical accuracy specification was not met.

Figure 4.1 Sample terrain in crossline comparison for VQ-820-G data coverage (purple hue inside red polygon)

For the SHOALS sensor, the crossline analysis results are shown in Table 4-2. Note that as indicated in Section 1.2 *Survey Specifications*, SHOALS data analysis was also held to IHO Order 1 standard where a = 0.5 and b = 0.013. The two accuracy standard tests, QL2B and Order1, are included in the last two columns.

Table 4-2 SHOALS Crossline Analysis Results. QL2B and IHO Order 1.

Crossline Flight Date	Area ID	Xline No.	No. of Points	Diff Mean (m)	Diff St. Dev. (m)	Percentage of Points ±0.3 m QL2B	Percentage of Points ±0.5 m Order1
5-Jul-17	023_3m	23_1	22508	-0.112	0.133	93.2	99.6
5-Jul-17	024_3m	24_1	22465	-0.103	0.147	90.9	99.3
5-Jul-17	025_3m	25-1	33145	-0.049	0.157	93.9	99.4

As in the case of the VQ-820-G crossline results, the terrain areas are not completely flat and devoid of some degree of vertical relief. Figure 4.2 below shows a sample of the terrain area where SHOALS collected valid point coverage; the red polygon demarks the coverage area analyzed by the cross line intersection. It essentially sampled a range of bathymetric features and morphology and not necessarily flat and featureless for an ideally fair vertical comparison. Even though the crossline analysis covers a comprehensive range of terrain types, the accuracy tests passed the IHO Order 1 standard with high percentage.

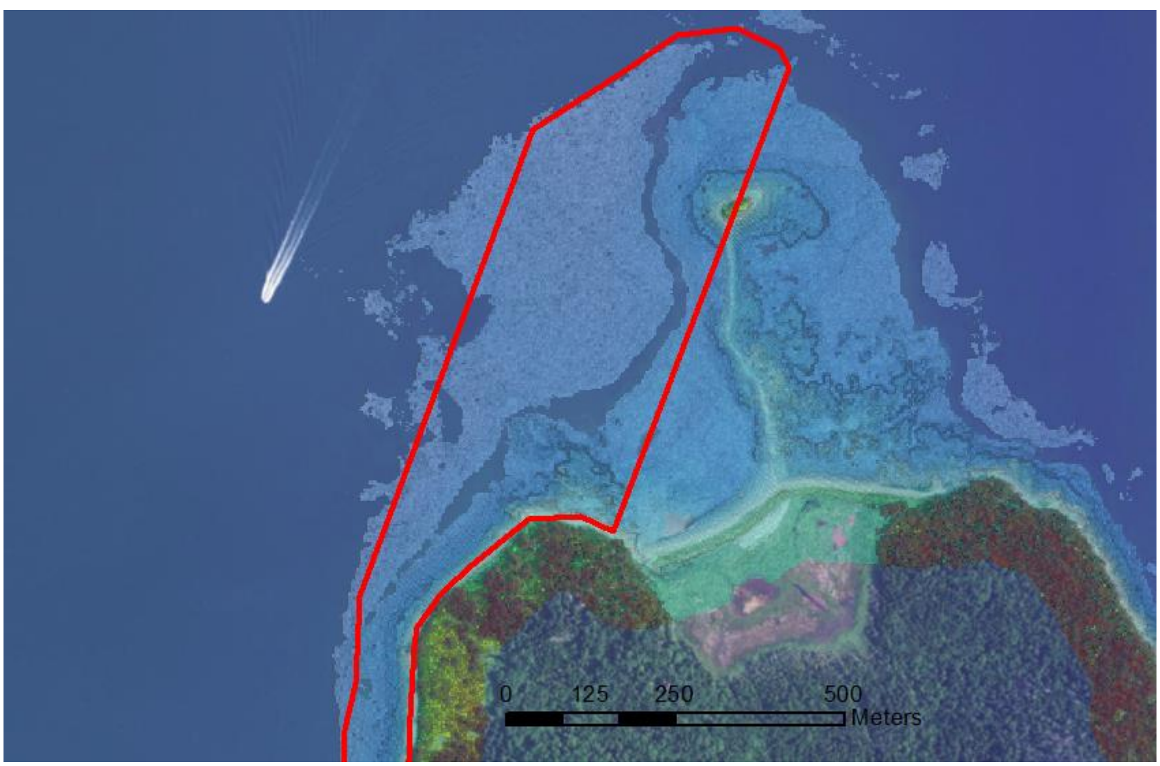


Figure 4.2 Sample terrain in crossline comparison for SHOALS data (inside red polygon)

Complete results logs for both sensors are included in Appendix C - Quality Control

5. DATA DELIVERABLES

The following are the data deliverables produced

1. This project report describing field and processing activities along with QA/QC section.
2. Raw and Post-processed data
3. Processed SHOALS Data, Classified point cloud in LAS format v1.4
4. Radiometrically calibrated reflectance X,Y,R
5. SHOALS DEMs
6. Boresighted, unclassified RIEGL point cloud in LAS format v1.4
7. Metadata for SHOALS LAS data and VQ-820-G LAS data

SHOALS Data Classes are shown in Table 5-1

Table 5-1 SHOALS LAS Classes

Team	Function
Class 0	Created, never classified (rare)
Class 1	Unclassified (Includes buildings and vegetation)
Class 7	Noise and rejected data (auto and manual rejections)
Class 40	Bathymetry
Class 42	Derived Water Surface
Class 43	Submerged object (Wreck, rock, pilings, etc)

6. APPENDICES

Contents of the Appendices of this report are documents produced digitally. Please refer to accompanying directory structure when looking for referenced information. Following is the content descriptions of each Appendix.

Appendix A – Lidar Sensor Specifications

Appendix B – Lidar Sensor Calibration Reports

Appendix C – Quality Control

- Crossline Analysis