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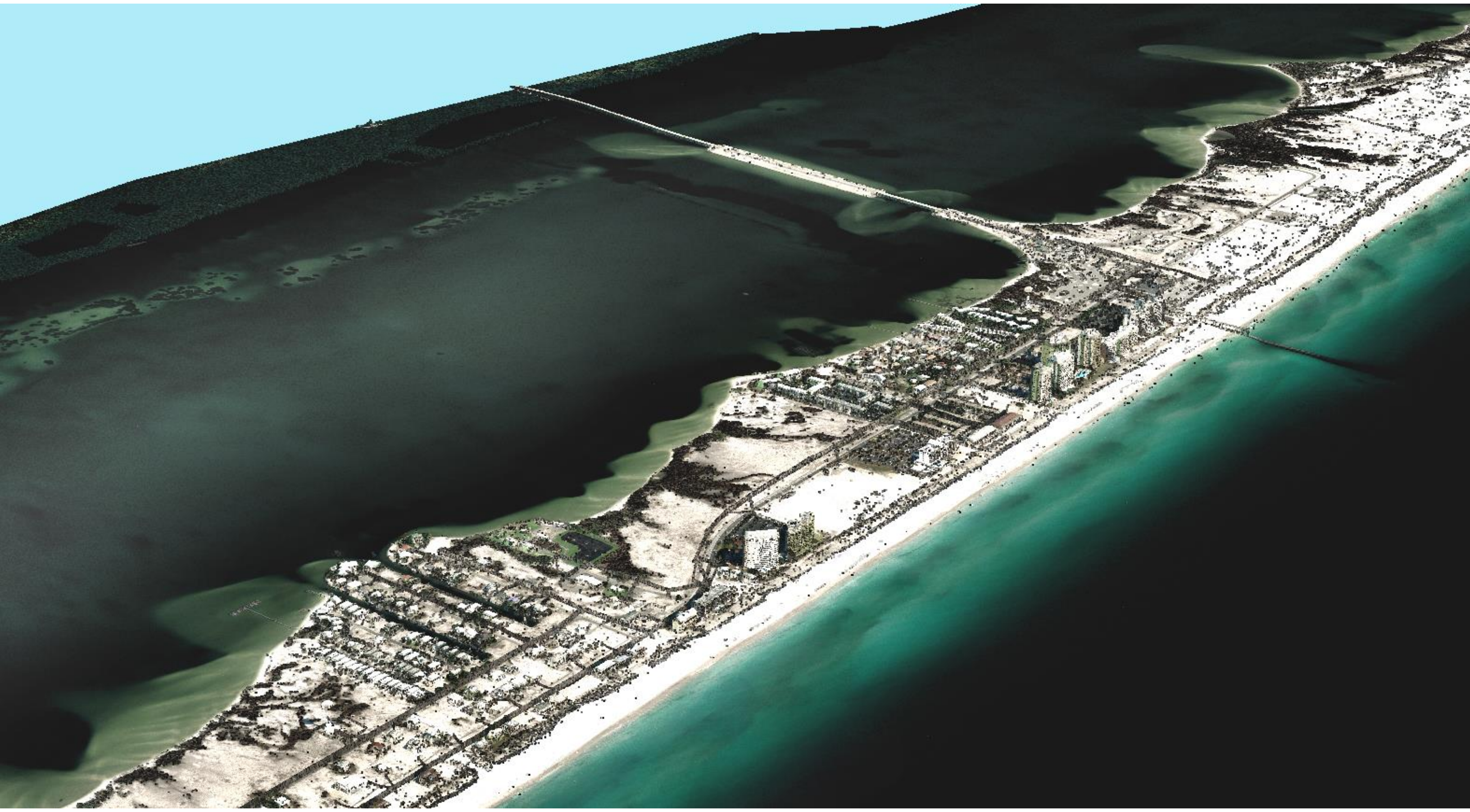

USGS Gulf Coast Islands

Topobathymetric LiDAR Technical Data Report

USGS Contract G16PC00016, Task Order 140G0219G0002

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Cover Photo: A view looking shoreward over the Gulf Islands AOI, created from the gridded bare earth model colored by elevation, overlaid with the above ground lidar returns colored using NAIP imagery.

INTRODUCTION

This photo was taken by QSI acquisition staff and shows a scenic view of the Gulf Coast Islands project area in late October 2018.

In October 2018, Quantum Spatial (QSI) was contracted by the United States Geological Survey (USGS) to collect high resolution topobathymetric Light Detection and Ranging (LiDAR) data in the winter of 2018 for the USGS Gulf Coast sites in the Gulf of Mexico. The USGS Gulf Coast project area covers approximately 174 square miles and is comprised of three main areas of interest; Chandeleur Island, Dauphin Island, and the Gulf Islands off the coast of Louisiana, Alabama, and Florida, respectively. Traditional near-infrared (NIR) LiDAR was fully integrated with green wavelength (bathymetric) LiDAR in order to provide a seamless topobathymetric LiDAR dataset. Data were collected to aid USGS in assessing the topobathymetric surface of the study area to support modeling, coastal landscape and ecosystem analysis, and hazard assessment.

This report accompanies the delivered topobathymetric LiDAR data and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR accuracy, depth penetration, and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to USGS is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the USGS Gulf Coast site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
USGS Gulf Coast	108,221	116,502	10/27/18 – 10/31/18, 11/03/18	Topobathymetric LiDAR

Deliverable Products

Table 2: Products delivered to USGS for the USGS Gulf Coast sites

	USGS Gulf Coast LiDAR Products Projection: UTM Zone 16 North Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12B) Units: Meters	USGS Gulf Coast LiDAR Products Projection: UTM Zone 16 North Horizontal Datum: NAD83 (2011) Vertical Datum: GRS80 (Ellipsoidal) Units: Meters
Topobathymetric LiDAR		
Points	LAS v 1.4, PDRF 6 • All Classified Returns LAS v 1.4 PDRF9 • Uncalibrated Flightline Swaths • Waveform data (*.wdp)	LAS v 1.4, PDRF 6 • All Classified Returns
Rasters	1.0 Meter GeoTiffs • Clipped Topobathymetric Bare Earth Digital Elevation Model (DEM) • Interpolated Topobathymetric Bare Earth Digital Elevation Model (DEM) • Hydroflattened Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM) • Green Sensor Intensity Images • NIR Sensor Intensity Images	
Vectors	Shapefiles (*.shp) • Area of Interest • LiDAR & DEM Tile Index • Ground Control Points • Ground Check Points • Ground Survey Base Stations • Data Extents for Classified LAS and all Derived Rasters • Bathymetric Coverage Shape ESRI Geodatabase (*.gdb) • LiDAR Flightline Index • Flightline Swath Extents • 3D Water's Edge Breaklines	

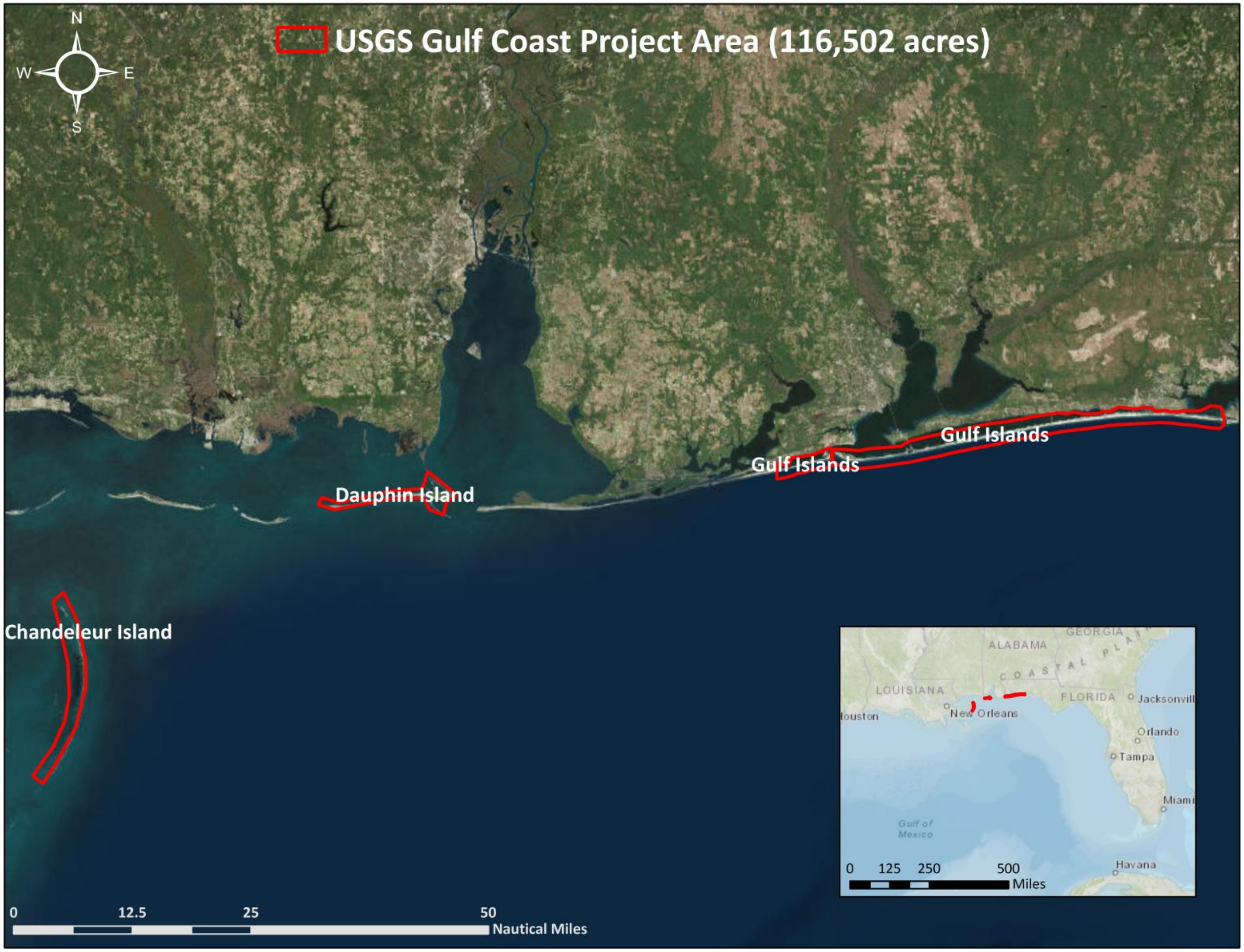
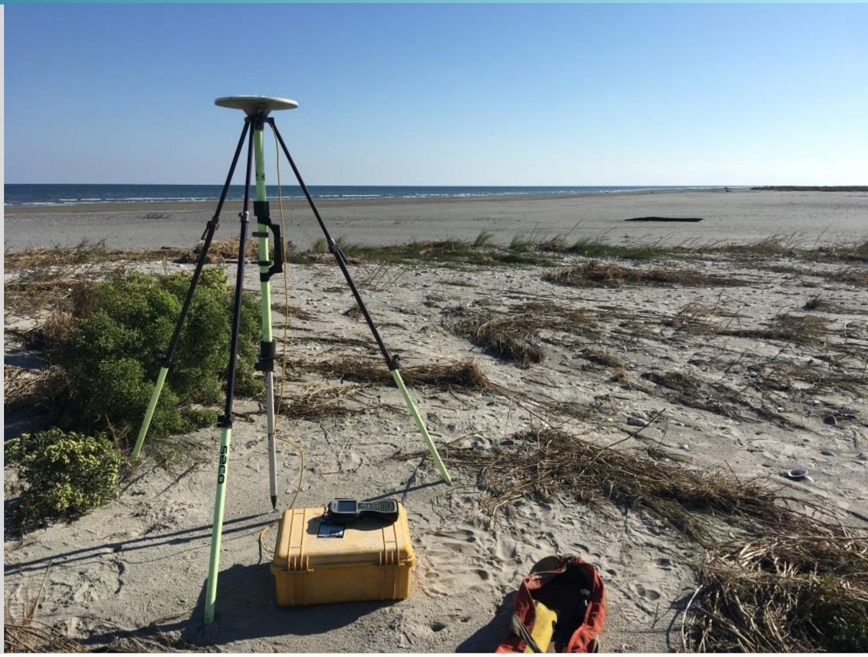


Figure 1: Location map of the USGS Gulf Coast site in the Gulf of Mexico

QSI's Ground Survey equipment set up on site in the Gulf Coast project area.



Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the USGS Gulf Coast LiDAR study area at the target point density of ≥8 points/m^2 for topographic returns, and ≥2 points/m^2 for submerged returns. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flights were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations were reviewed, including private property access, potential air space restrictions, water clarity, and tide conditions (Figure 2).

Turbidity Measurements and Secchi Depth Readings

In order to assess water clarity conditions prior to and during LiDAR collection, QSI collected turbidity measurements and secchi depth readings where feasible. Readings were collected at six locations throughout the project site between October 27th and October 31st, 2018. Turbidity observations were recorded three times to confirm measurements. The table below provides turbidity and secchi depth results per site on each day of data collection.

Table 3: Water Clarity Observations for LiDAR flights

Turbidity, Secchi Depth, and Ground Observations								
Date	**Time (UTC)**	**Latitude**	**Longitude**	**Turbidity Read 1 (NTU)**	**Turbidity Read 2 (NTU)**	**Turbidity Read 3 (NTU)**	**Secchi Depth**	**Notes**
10/27	14:00	30°19'11.96"N	87°14'26.76"W	1.55	1.27	1.10	N/A (bottom visible)	Breezy, shallow sand bar on inland side of island. No current, choppy water.
10/27	14:30	30°19'4.80"N	87°14'26.39"W	3.90	3.77	2.83	N/A (bottom visible)	Same location on island just on the gulf side. Hard to get accurate sample with waves crashing kicking up sediment.
10/28	14:00	30°23'1.87"N	86°51'49.12"W	1.56	1.89	1.52	2.75 m	Boat ramp with light traffic, none during collection. Slight breeze, calm seas, warm temps, clear water!
10/29	09:30	30°24'2.10"N	86°35'33.36"W	1.93	2.62	2.43	2.25 m	Calm water at a quiet boat ramp. Algae/sediment visible in water but still appears pretty clear. Can see to bottom in deeper areas.
10/30	12:30	29°52'16.47"N	88°49'43.50"W	3.95	3.81	3.85	~2.0 m to bottom	Very shallow island water and very clear to bottom.
10/31	11:30	30°15'0.39"N	88° 4'35.44"W	12.2	12.6	13.2	~0.6 m to bottom	Small protected dock inlet that has very murky water. Boat traffic during collection as well. Not optimal, I will note that the water all around Dauphin Island is pretty brown.

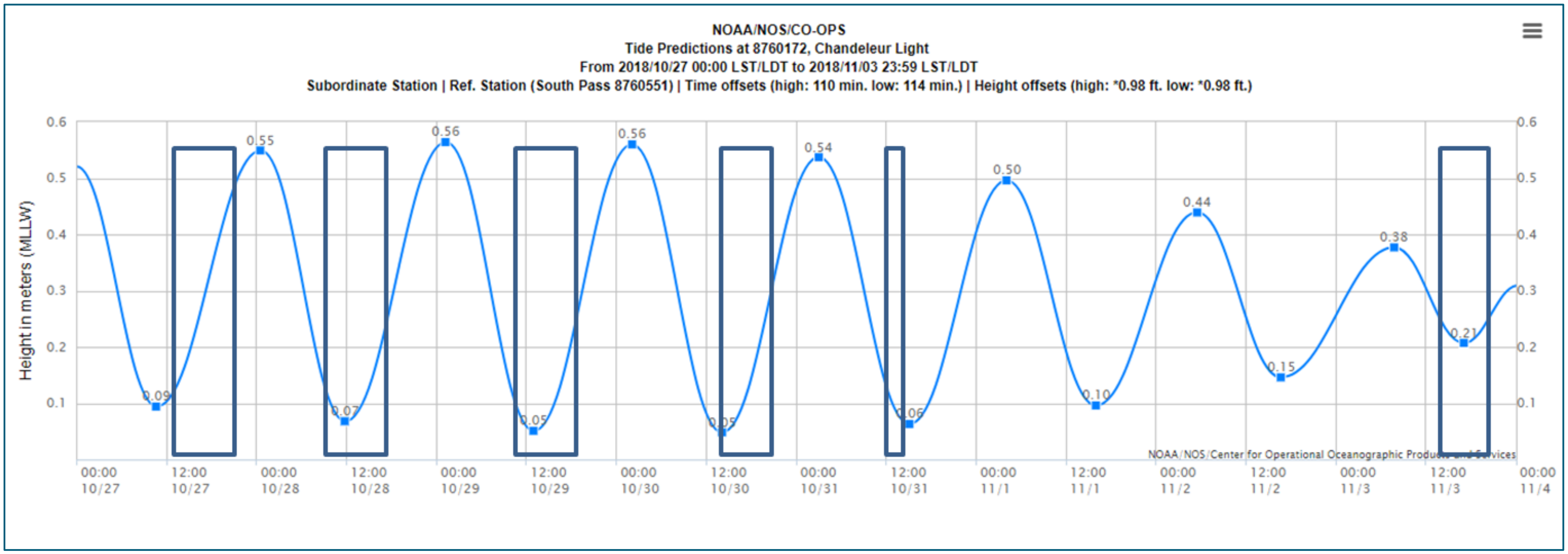


Figure 2: NOAA Tide Predictions at Chandeleur Light; LiDAR flight times are outlined in dark blue

These photos taken by QSI acquisition staff display water clarity conditions at varying locations within the USGS Gulf Coast project area, observed at the time of LiDAR acquisition.

These photos taken by QSI acquisition staff display water clarity conditions at varying locations within the USGS Gulf Coast project area, observed at the time of LiDAR acquisition.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Riegl VQ-880-G green laser system mounted in a Cessna Caravan. The Riegl VQ-880-G boasts a higher repetition pulse rate (up to 550 kHz), higher scanning speed, small laser footprint, and wide field of view which allow for seamless collection of high resolution data of both topographic and bathymetric surfaces. The recorded waveform enables range measurements for all discernible targets for a given pulse. The typical number of returns digitized from a single pulse range from 1 to 15 for the USGS Gulf Coast project area. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset. Table 4 summarizes the settings used to yield an average pulse density of ≥8 points/m^2 for topographic returns, and ≥2 points/m^2 for submerged returns, over the USGS Gulf Coast project area.

Table 4: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications		
Acquisition Dates	10/27/18 – 10/31/18, 11/03/18	10/27/18 – 10/31/18, 11/03/18
Aircraft Used	Cessna Caravan	Cessna Caravan
Sensor	Riegl	Riegl
Laser	VQ-880-G	VQ-880G-IR
Maximum Returns	Unlimited	Unlimited
Resolution/Density	Average 8 pulses/m^2	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m	0.35 m
Survey Altitude (AGL)	400 m	400 m
Survey speed	110 knots	110 knots
Field of View	40º	40º
Mirror Scan Rate	80 lines per second	80 lines per second
Target Pulse Rate	550 kHz	245 kHz
Pulse Length	1.5 ns	3.0 ns
Laser Pulse Footprint Diameter	80 cm	80 cm
Central Wavelength	532 nm	1064 nm
Pulse Mode	Single Pulse in Air (SPiA)	Single Pulse in Air (SPiA)
Beam Divergence	2 mrad	0.2 mrad
Swath Width	291 m	291 m
Swath Overlap	50%	50%
Intensity	16-bit	16-bit
Accuracy	RMSEZ (Non-Vegetated) ≤ 10 cm NVA (95% Confidence Level) ≤ 19.6 cm VVA (95th Percentile) ≤ 30cm	

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

This photo taken during flight by QSI's sensor operator shows an aerial view of one of the Gulf Islands off the coast of Florida.

Ground Survey

Ground control surveys were conducted to support the airborne acquisition. Post-Processed RTX (PP-RTX) technology was used to geospatially correct the aircraft positional coordinate data, while ground survey points were collected to perform final positional corrections to the LiDAR point cloud, and to perform quality assurance checks on final LiDAR data.

Base Stations

Base stations were used for collection of ground survey points using real time kinematic (RTK), post-processed kinematic (PPK), and fast static (FS) survey techniques. Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized three Trimble VRS Now Real Time Network (RTN) base stations and established one new monument for the USGS Gulf Coast LiDAR project (Table 5, Figure 3). New monumentation was set using a six-inch PK nail with a reference washer. QSI's Professional Land Surveyor and Mapper, Steven J. Hyde (LAPLS #5002, ALPLS #24548 & FLPSM #6436) oversaw and certified the ground survey.

Table 5: Base station positions for the USGS Gulf Coast acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Base ID	Latitude	Longitude	Ellipsoid (meters)	Type
CHANDELEUR_NAIL	29° 52' 20.94938"	-88° 49' 47.54563"	-24.822	QSI RTK Base
ALDI	30° 14' 56.98768"	-88° 04' 40.68810"	-17.920	Trimble VRS Now
DSTN	30° 23' 19.66213"	-86° 27' 53.72763"	-14.512	Trimble VRS Now
FLPL	30° 24' 19.87644"	-87° 13' 18.42641"	-13.247	Trimble VRS Now

QSI utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency by the base station. During post-processing, the static GNSS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS) to verify and update record positions as needed to align with the National Spatial Reference System (NSRS).

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[1] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 6.

[1] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Table 6: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.020 m

For the USGS Gulf Coast LiDAR project, the monument coordinates contributed no more than 2.8 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK) and fast-static (FS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. See Table 7 for QSI ground survey equipment information.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 3).

Table 7: QSI ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R8	Integrated Antenna	TRM_R8_GNSS	Rover

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the LiDAR derived ground models across land cover classes (Table 8, see LiDAR Accuracy Assessments, page 24).

Table 8: Land Cover Types and Descriptions

<table>
<tr><th>Land cover type</th><th>Land cover code</th><th>Example</th><th>Description</th><th>Accuracy Assessment Type</th></tr>
<tr><td>Tall Grass</td><td>TALL_GRASS</td><td>
</td><td>Herbaceous grasslands in advanced stages of growth</td><td>VVA</td></tr>
<tr><td>Shrub</td><td>SHRUB</td><td>
</td><td>Forested areas dominated by deciduous species</td><td>VVA</td></tr>
<tr><td>Bare Earth</td><td>BARE, BE</td><td>
</td><td>Areas of bare earth surface</td><td>NVA</td></tr>
<tr><td>Urban</td><td>URBAN</td><td>
</td><td>Areas dominated by urban development, including parks</td><td>NVA</td></tr>
</table>

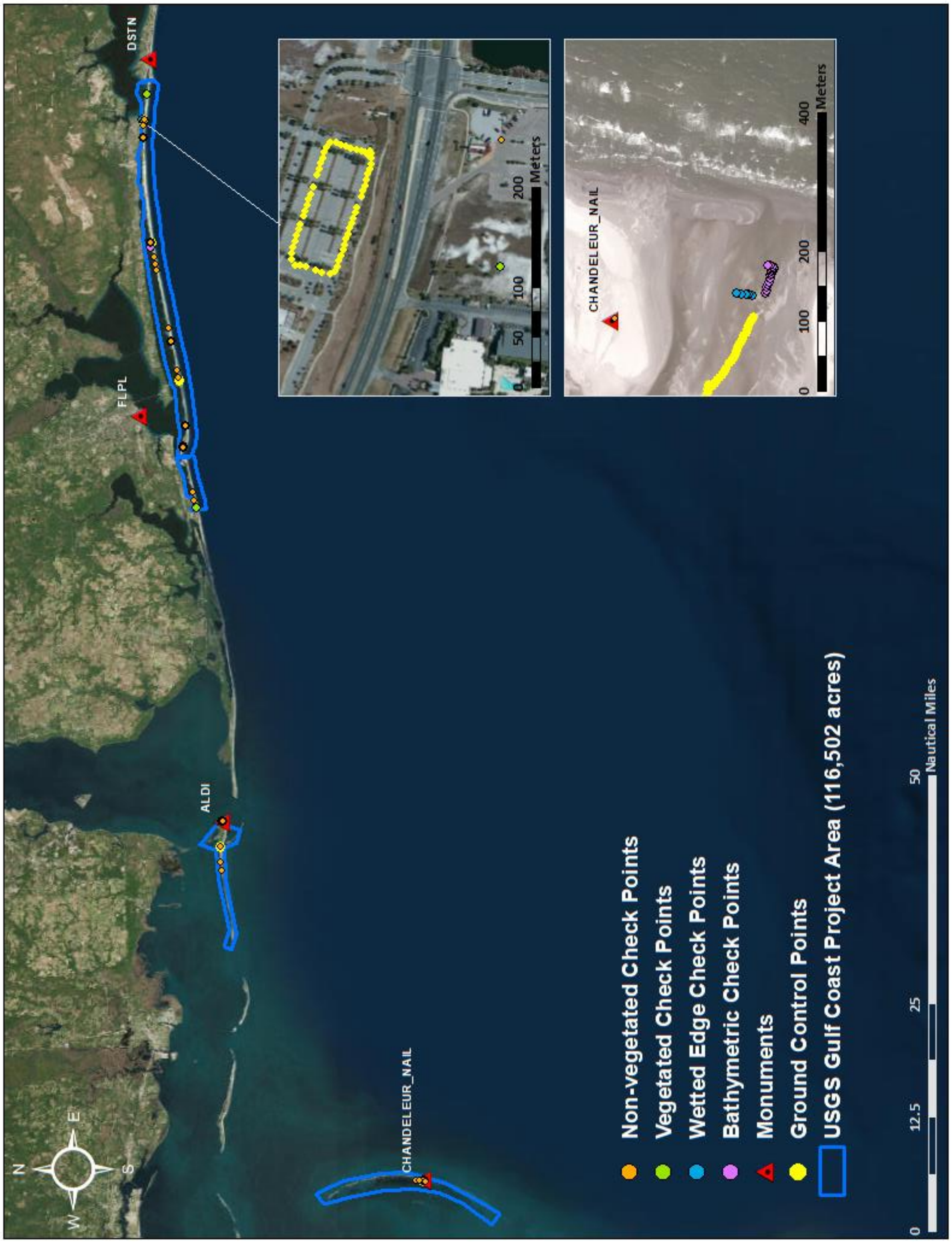
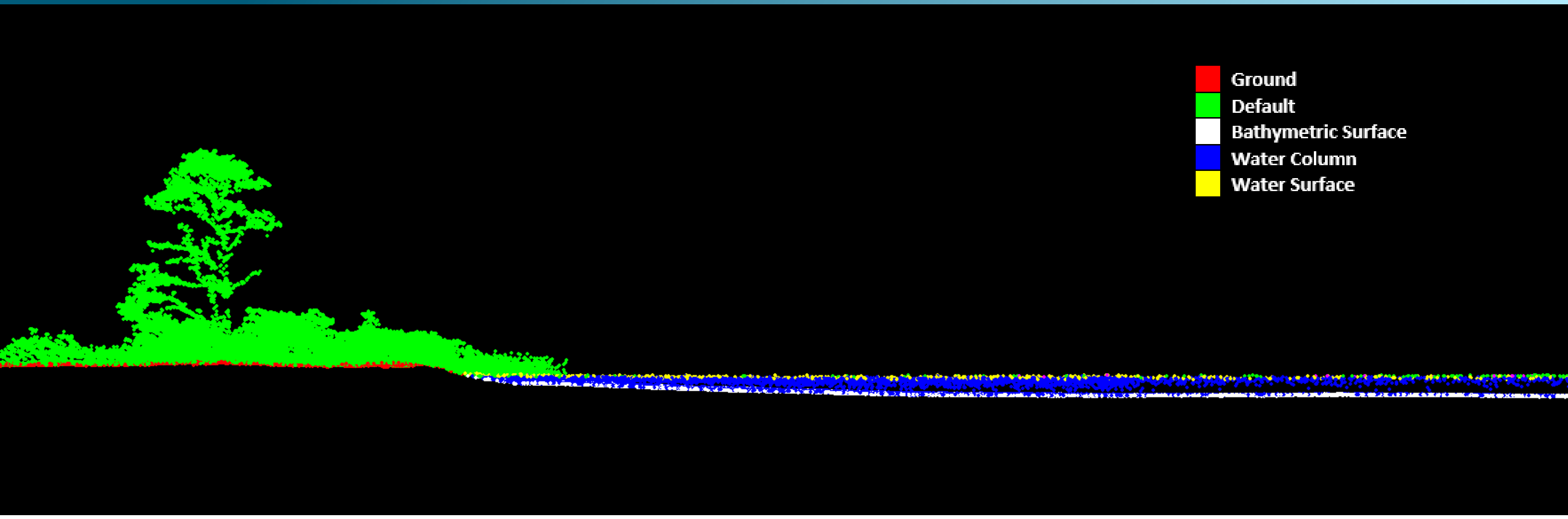


Figure 3: Ground survey location map



Topobathymetric LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 9).

Riegl's RiProcess software was used to facilitate bathymetric return processing. Once bathymetric points were differentiated, they were spatially corrected for refraction through the water column based on the angle of incidence of the laser. QSI refracted water column points using Riegl's RiHydro tools. The resulting point cloud data were classified using both manual and automated techniques. Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 10.

Table 9: ASPRS LAS classification standards applied to the USGS Gulf Coast dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-O	Overlap/Edge Clip	Flightline edge clip
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7	Noise	Laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the ground surface. Flagged as withheld
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms

Classification Number	Classification Name	Classification Description
17	Bridge	Bridge decks
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation
40	Bathymetric Bottom	Refracted Riegl sensor returns that fall within the water's edge breakline which characterize the submerged topography.
41	Water Surface	Green laser returns that are determined to be water surface points using automated and manual cleaning algorithms.
45	Water Column	Refracted Riegl sensor returns that are determined to be water using automated and manual cleaning algorithms.

Table 10: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.3
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	RiProcess v1.8.5 TerraMatch v.18
Apply refraction correction to all subsurface returns.	RiProcess v1.8.5
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.18
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.18 RiProcess v1.8.5
Classify resulting data to ground and other client designated ASPRS classifications (Table 9). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.18 TerraModeler v.18
Generate bare earth models as triangulated surfaces. Export all surface models as GeoTIFFs at a 1 meter pixel resolution.	TerraScan v.18 TerraModeler v.18 ArcMap v. 10.3.1
Export intensity images as GeoTIFFs at a 0.5 meter pixel resolution.	ArcMap v. 10.3.1 Las Product Creator 3.0 (QSI proprietary software)

Bathymetric Refraction

Green LiDAR pulses that enter the water column must have their position corrected for refraction of the light beam as it passes through the water and its resulting decreased speed. The refraction processing is done using RiHydro tools which a component running within Riegl's RiProcess software. The first step is to develop a water surface model (WSM) from the LiDAR water surface returns. The water surface models used for refraction are generated using elevation information derived from the NIR channel to inform where the green water surface level is located, and then water surface points are classified for both the forward and reverse look directions of the green scanner. Points are filtered and edited to obtain the most accurate representation of the water surface and are used to create a water surface model for each flight line and look direction. Water surface classification and modeling is processed on each flight line to accommodate local water level changes due to tide and wave action. The water surface model created is raster based with an associated surface normal vector to obtain the most accurate angle of incidence during refraction.

LiDAR Derived Products

Because hydrographic laser scanners penetrate the water surface to map submerged topography, this affects how the data should be processed and presented in derived products from the LiDAR point cloud. The following discusses certain derived products that vary from the NIR LiDAR specification and delivery format.

Topobathymetric DEMs

Bathymetric bottom returns can be limited by depth, water clarity, and bottom surface reflectivity. Water clarity and turbidity affect the depth penetration capability of the green wavelength laser with returning laser energy diminishing by scattering throughout the water column. Additionally, the bottom surface must be reflective enough to return remaining laser energy back to the sensor at a detectable level. While the predicted depth penetration range of the Riegl VQ-880-G sensor is 1.5 Secchi depths on brightly reflective surfaces, it is not unexpected to have no bathymetric bottom returns in turbid or non-reflective areas.

As a result, creating digital elevation models (DEMs) presents a challenge with respect to interpolation of areas with no returns. Topographic DEMs are "unclipped", meaning areas lacking ground returns are interpolated from neighboring ground returns (or breaklines in the case of hydro-flattening), with the assumption that the interpolation is close to reality. In bathymetric modeling, these assumptions are prone to error because a lack of bathymetric returns can indicate a change in elevation that the laser can no longer map due to increased depths; the resulting void areas may suggest greater depths, rather than similar elevations from neighboring bathymetric bottom returns. Therefore, QSI created a water polygon of bathymetric coverage to delineate areas with successfully mapped bathymetry. This shapefile was used to control the extent of the delivered clipped topobathymetric model to avoid false triangulation (interpolation from TIN'ing) across areas in the water with no bathymetric returns. QSI provided topobathymetric bare earth models in two formats: one with void areas clipped out, and one that is fully interpolated across voids.

It must also be noted that the interpolated topobathymetric bare earth model does not extend completely to the buffered project boundary in some areas. Due to the nature of the project site, and the extinction of bathymetric bottom returns with increasing depth, interpolation from neighboring ground or bathymetric classified returns was limited to a maximum distance of ≤1000 meters. In order to adequately display the extent to which the interpolated topobathymetric bare earth model covers, QSI provided a polygon shapefile of the full raster model extent. A corresponding extent shapefile was created for each raster model included in the data delivery.

Hydroflattening and Water's Edge Breaklines

The ocean surrounding the USGS Gulf Coast site and other water bodies within the project area were flattened to a consistent water level. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres, all streams and rivers that are nominally wider than 30 meters, all waters bordering the project, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were developed using an algorithm which weights LiDAR-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary.

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered LiDAR returns to create the final breaklines. Ocean and lakes were assigned a consistent elevation for an entire polygon. Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3D water edge breaklines resulting in the final hydroflattened model (Figure 4).

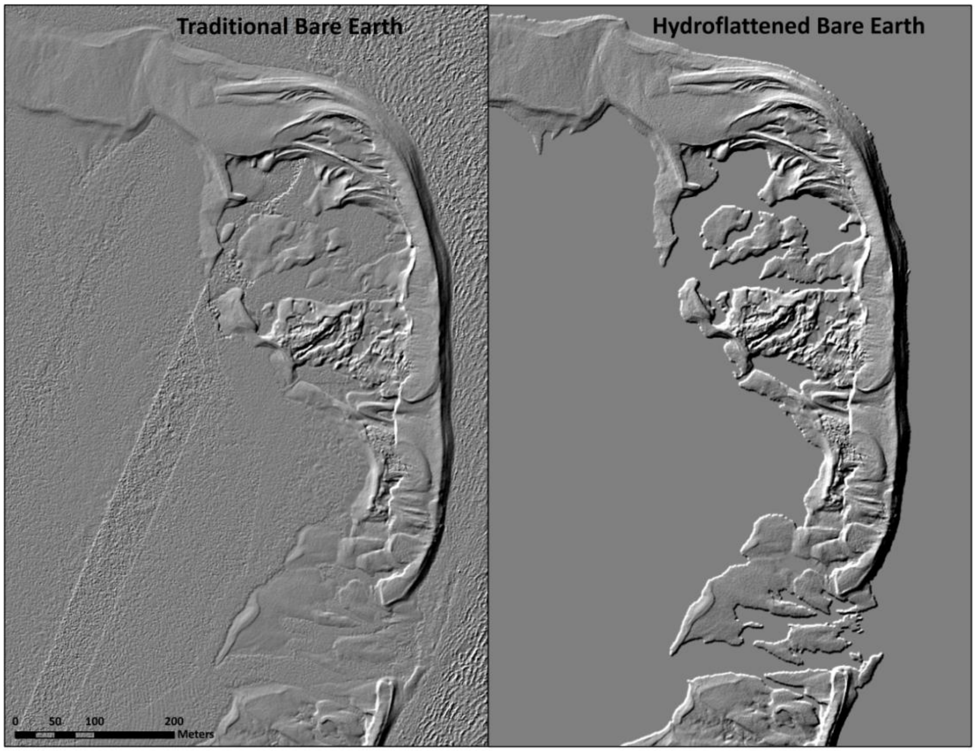
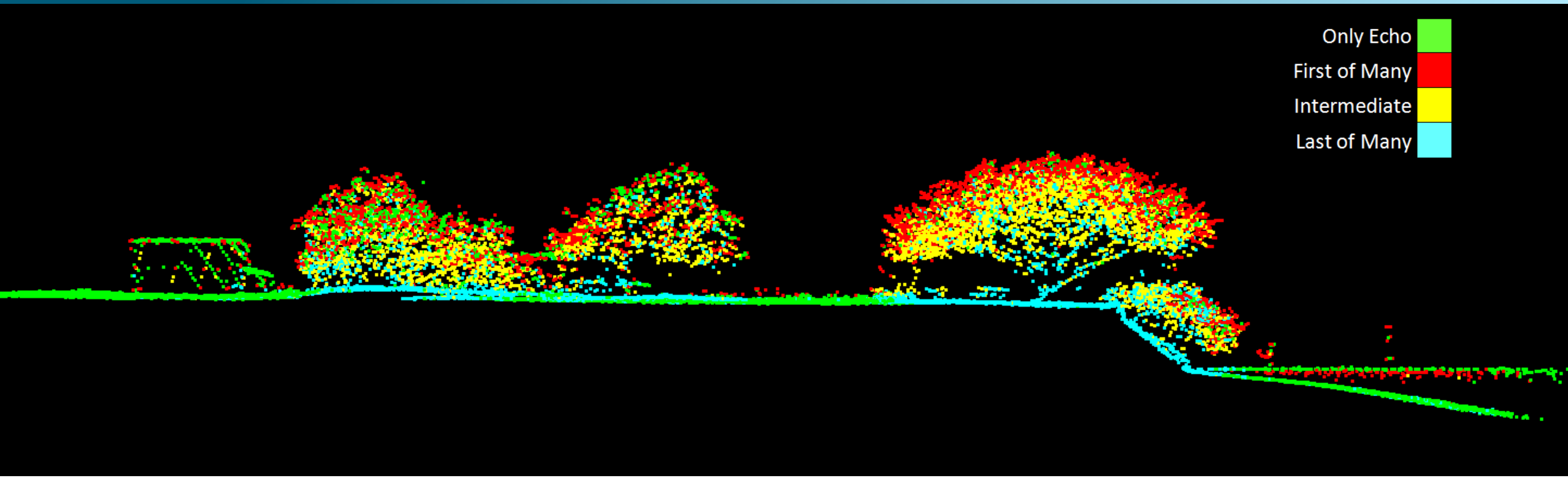


Figure 4: Example of hydroflattening in the USGS Gulf Coast LiDAR dataset



Bathymetric LiDAR Assessment

An underlying principle for collecting hydrographic LiDAR data is to survey near-shore areas that can be difficult to collect with other methods, such as multi-beam sonar, particularly over large areas. In order to determine the capability and effectiveness of the bathymetric LiDAR survey, several parameters were considered; depth penetrations below the water surface, bathymetric return density, and spatial accuracy.

Mapped Bathymetry

In order to assist in evaluating performance results of the sensor, a polygon layer was created to delineate areas where bathymetry was successfully mapped. This shapefile was used to control the extent of the delivered clipped topobathymetric model and to avoid false triangulation across areas in the water with no returns. Insufficiently mapped areas were identified by triangulating bathymetric bottom points with an edge length maximum of 4.56 meters. This ensured all areas of no returns (> 9 m^2), were identified as data voids. In total, approximately 38.48% of water areas were mapped with bathymetric bottom points. Bathymetric coverage per project site is provided in Table 11 below.

Table 11: Percent Bathymetric Coverage by AOI

Area of Interest	% Covered
Chandeleur Island	71.72%
Dauphin Island	32.14%
Gulf Islands	28.05%

Depth Penetration

The specified depth penetration range of the Riegl VQ-880-G sensor is 1.5 secchi depths; therefore, bathymetry data below 1.5 secchi depths at the time of acquisition is not to be expected. Due to the nature of the project area, QSI had limited access to deep enough waters to collect true secchi depth readings from which to compare bathymetric bottom returns. Every effort was made to collect these readings; however, out of the secchi depths collected, only one was in an area which visible extinction before the bottom was noted. Thus, the average secchi depth result of 1.9 meters is a measurement prone to error. In order to evaluate depth results, QSI created a depth raster by subtracting the water surface model (WSM) from the topobathymetric bare earth digital elevation model (DEM). From this depth raster model, a maximum depth of 10.1 meters was identified within the USGS Gulf Islands project area (Figure 5).

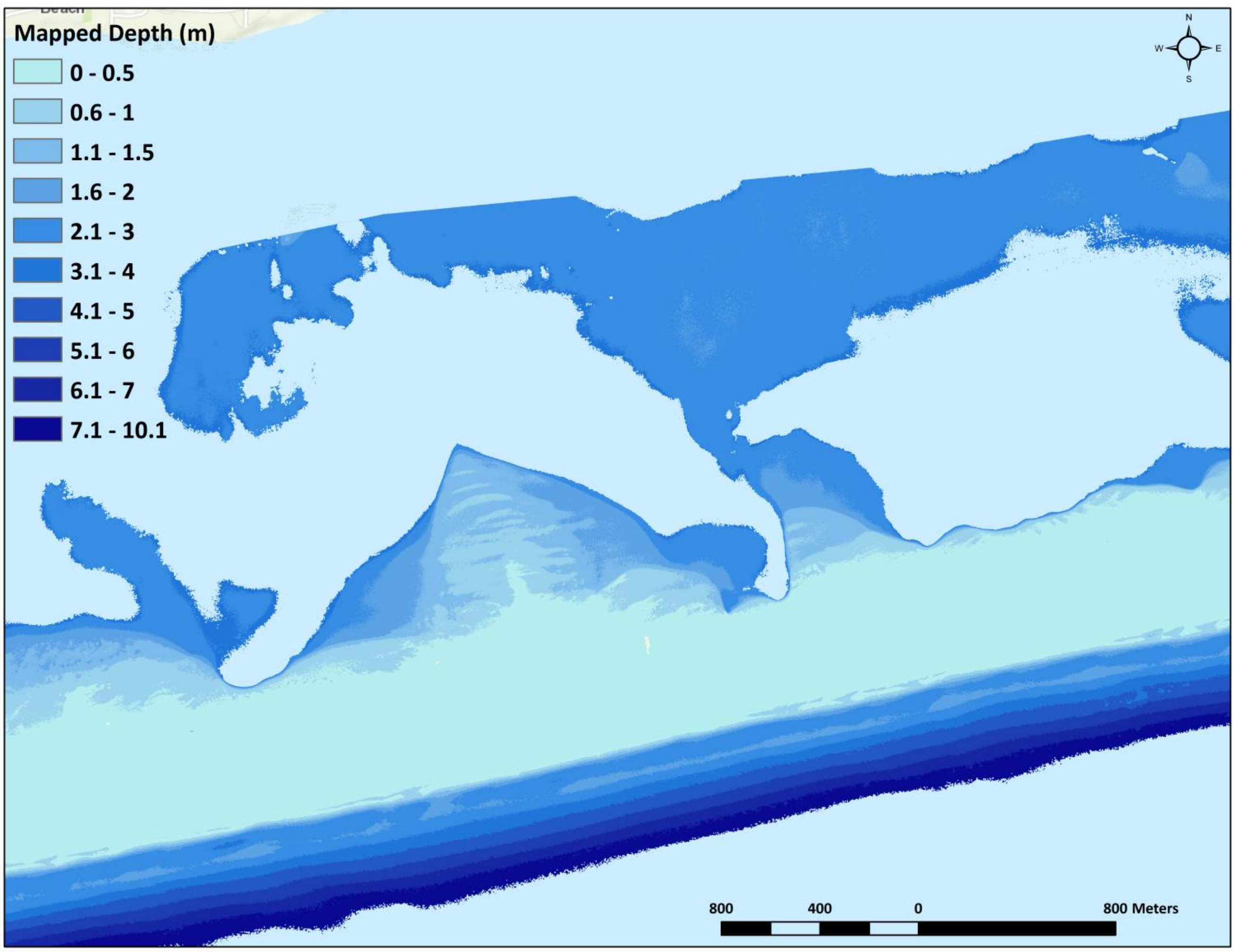


Figure 5: Sampled area of depth results within the Gulf Islands AOI

LiDAR Point Density

First Return Point Density

The acquisition parameters were designed to acquire an average first-return density of ≥8 points/m^2 for topographic returns, and ≥2 points/m^2 for submerged returns over the USGS Gulf Coast project area. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser.

First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The cumulative average first-return density of the USGS Gulf Coast LiDAR project was 31.86 points/m^2 (Table 12). The statistical distributions of all first return densities per 100 m x 100 m cell are portrayed in Figure 6 and Figure 7.

Bathymetric and Ground Classified Point Densities

The density of ground classified LiDAR returns and bathymetric bottom returns were also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may have penetrated the canopy, resulting in lower ground density. Similarly, the density of bathymetric bottom returns was influenced by turbidity, depth, and bottom surface reflectivity. In turbid areas, fewer pulses may have penetrated the water surface, resulting in lower bathymetric density.

The ground and bathymetric bottom classified density of LiDAR data for the USGS Gulf Coast project was 7.82 points/m^2(Table 12). The statistical and spatial distributions ground classified and bathymetric bottom return densities per 100 m x 100 m cell are portrayed in Figure 8 and Figure 9.

Additionally, for the USGS Gulf Coast project, density values of only bathymetric bottom returns were calculated. Bathymetric bottom density is calculated for areas containing at least one bathymetric bottom return; areas lacking bathymetric returns (voids) were not considered in calculating an average density value. Within the successfully mapped area, a bathymetric bottom return density of 14.68 points/m^2 was achieved. A bathymetric bottom point density of 5.65 points/m^2 was achieved within the entire water's edge breakline.

Table 12: Average LiDAR point densities

Density Type	Point Density
Cumulative First Returns	31.86 points/m^2
Ground and Bathymetric Bottom Classified Returns	7.82 points/m^2
Bathymetric Bottom Classified Returns	14.68 points/m^2

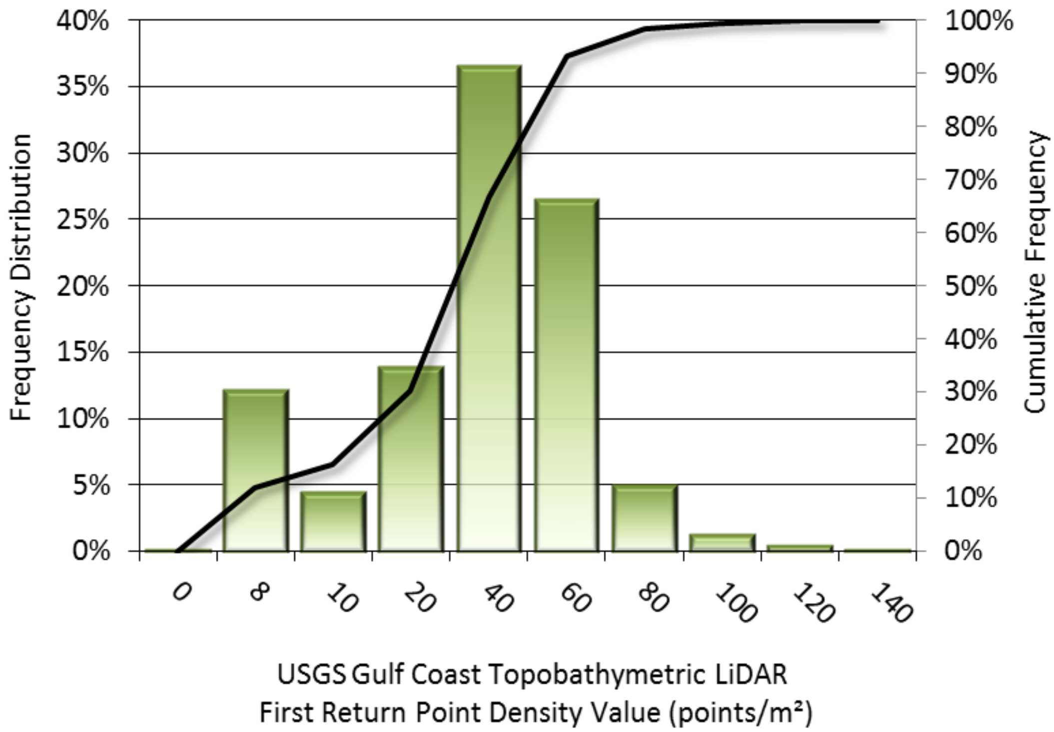


Figure 6: Frequency distribution of cumulative first return densities per 100 x 100 m cell

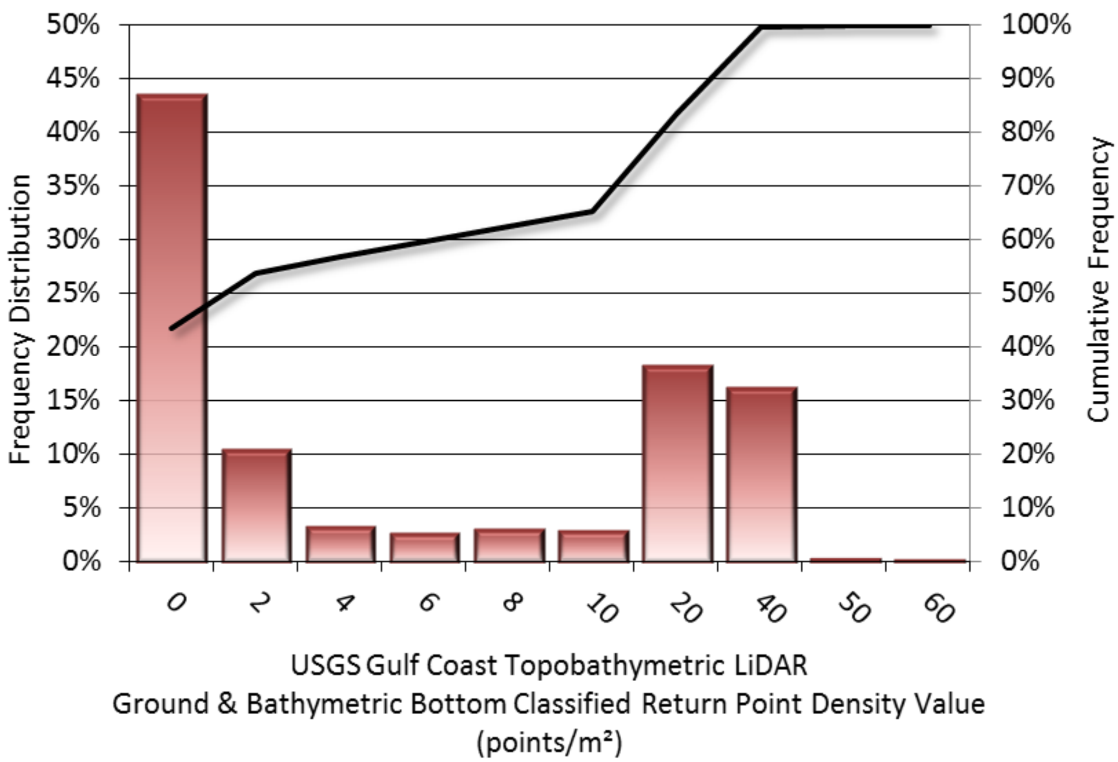


Figure 7: Frequency distribution of ground and bathymetric bottom classified return densities per 100 x 100 m cell

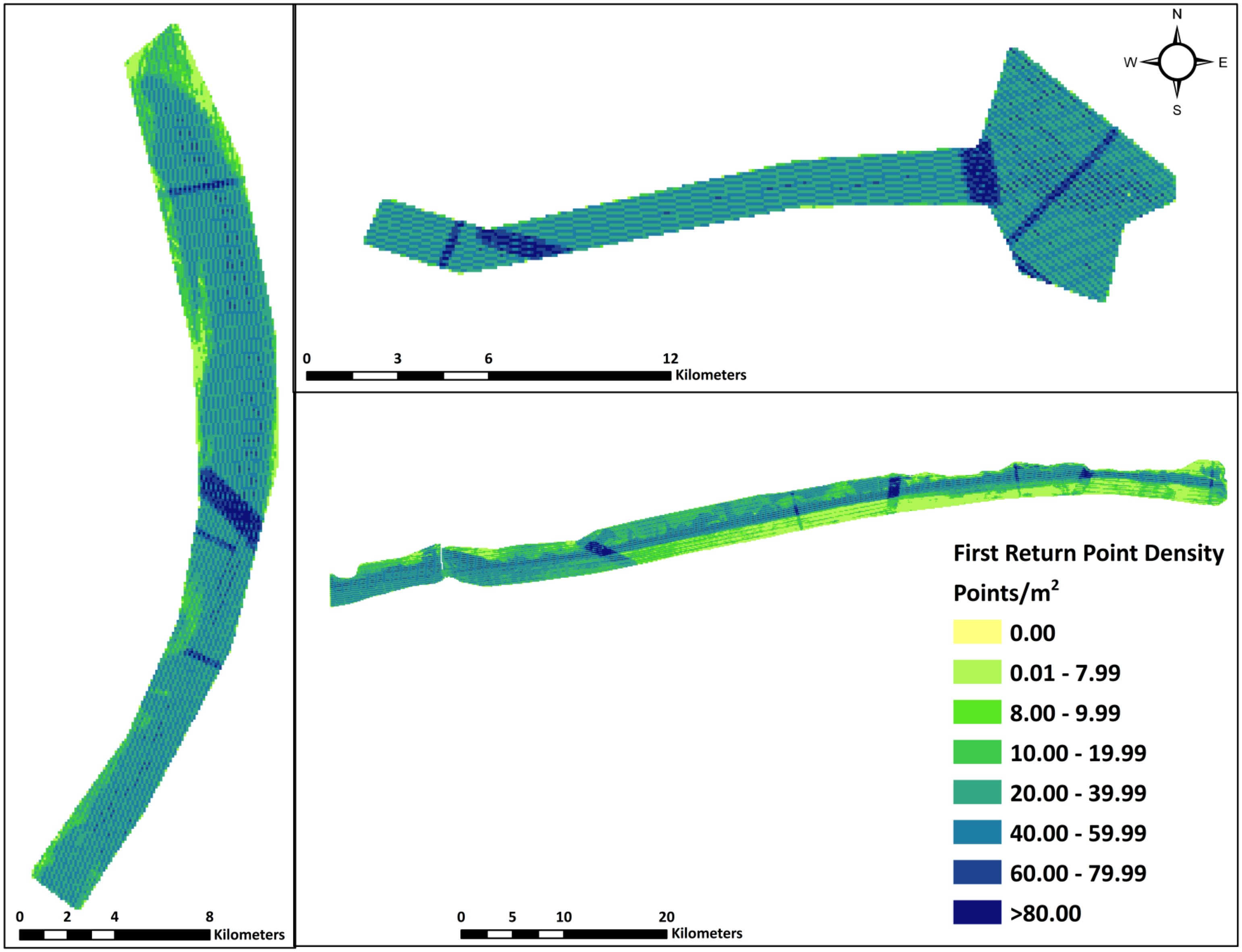


Figure 8: First return density map for the USGS Gulf Coast site (100 m x 100 m cells)

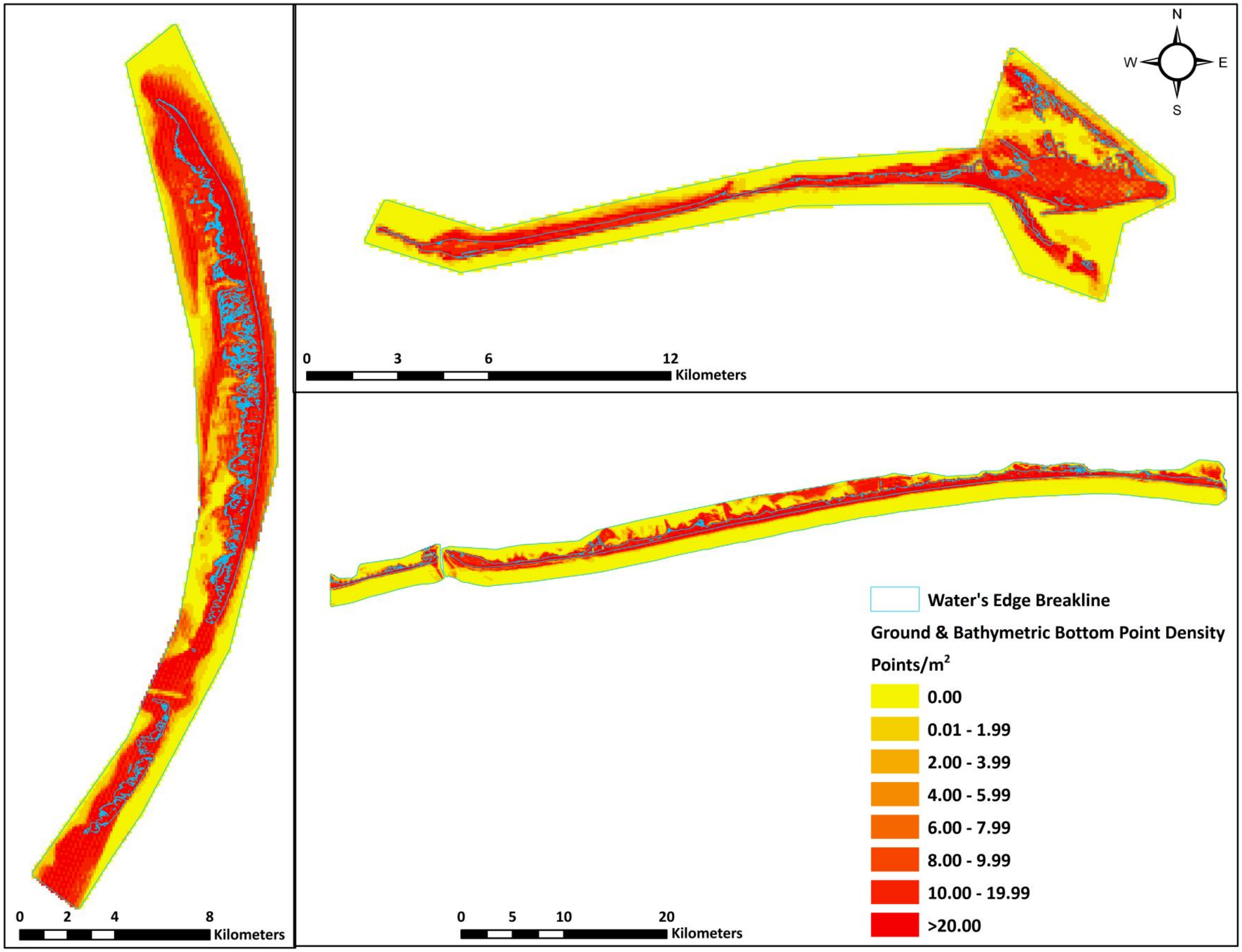


Figure 9: Ground and bathymetric bottom density map for the USGS Gulf Coast site (100 m x 100 m cells)

LiDAR Accuracy Assessments

The accuracy of the LiDAR data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

LiDAR Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[2]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the LiDAR point cloud to the triangulated surface generated by the unclassified LiDAR point cloud as well as the derived gridded bare earth DEM. NVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 13.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground check point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the USGS Gulf Coast survey, 26 ground check points were withheld from the calibration and post-processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.053 meters, as compared to the unclassified LAS and 0.046 meters against the bare earth DEM, with 95% confidence (Figure 10 and Figure 11).

QSI also assessed absolute accuracy using 320 ground control points. Although these points were used in the calibration and post-processing of the LiDAR point cloud, they still provide a good indication of the overall accuracy of the LiDAR dataset, and therefore have been provided in Table 13 and Figure 12.

Table 13: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to Unclassified LAS	NVA, as compared to Bare Earth DEM	Ground Control Points
Sample	26 points	26 points	320 points
95% Confidence (1.96*RMSE)	0.053 m	0.046 m	0.038 m
Average Dz	0.010 m	-0.004 m	0.001 m
Median	0.008 m	-0.002 m	0.000 m
RMSE	0.027 m	0.024 m	0.019 m
Standard Deviation (1σ)	0.026 m	0.024 m	0.019 m

[2] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

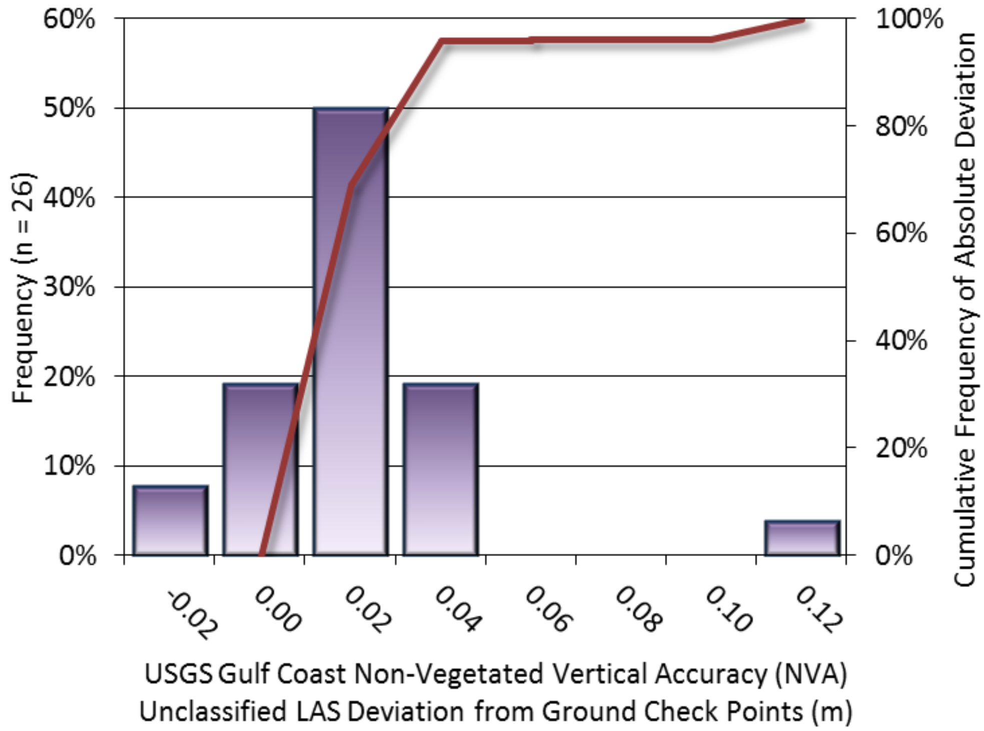


Figure 10: Frequency histogram for unclassified LAS deviation from ground check point values

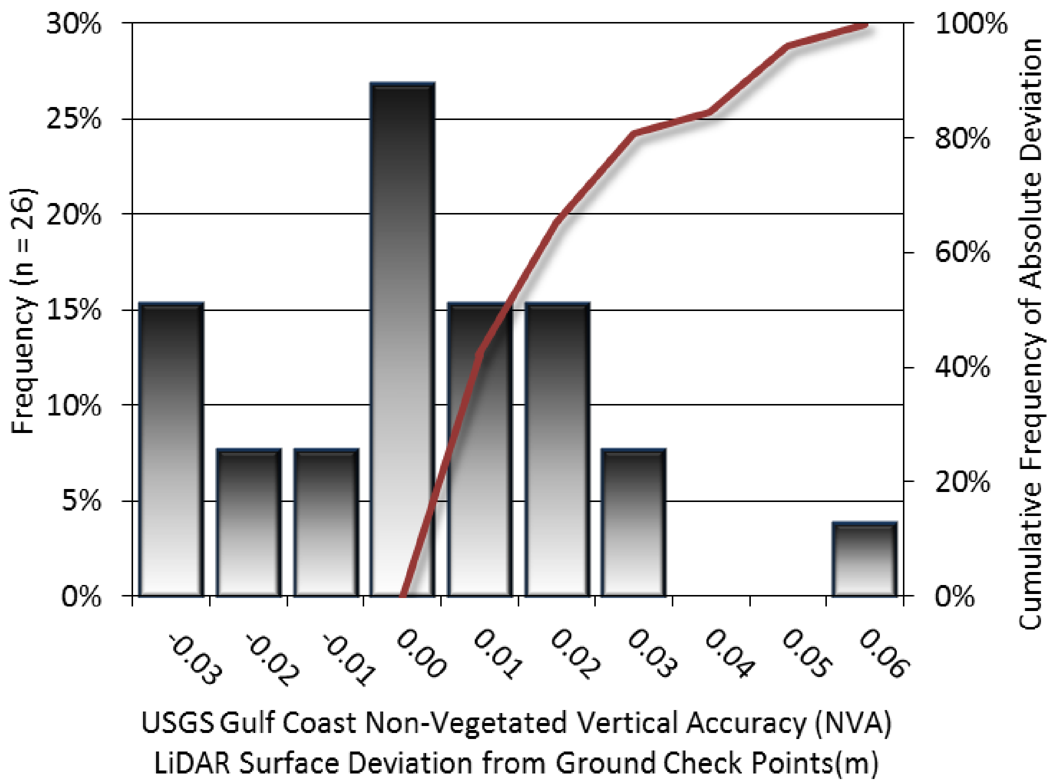


Figure 11: Frequency histogram for LiDAR bare earth DEM deviation from ground check point values

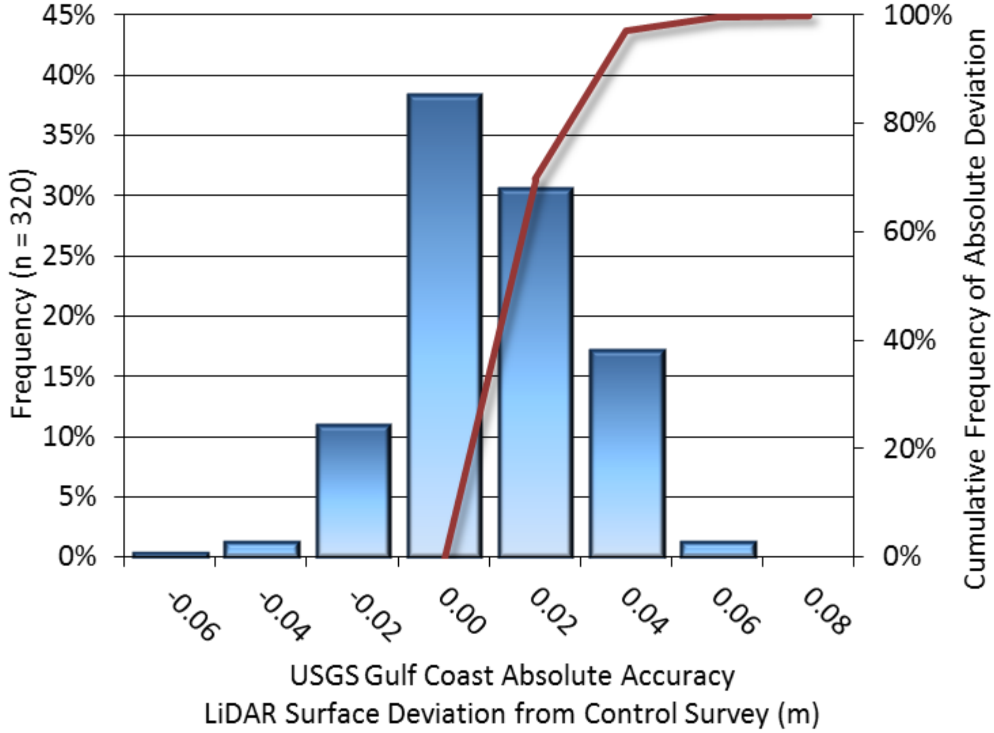


Figure 12: Frequency histogram for LiDAR surface deviation ground control point values

LiDAR Bathymetric Vertical Accuracies

Bathymetric (submerged or along the water's edge) check points were also collected in order to assess the submerged surface vertical accuracy. Bathymetric vertical accuracy was by comparing bathymetric check point data to the derived gridded topobathymetric bare earth DEM. Assessment of 66 submerged bathymetric check points resulted in a vertical accuracy of 0.093 meters, while assessment of 17 wetted edge check points resulted in a vertical accuracy of 0.090 meters, with 95% confidence (Figure 11 and Figure 14). Table 14 below displays bathymetric accuracy results and also includes summary statistics for the submerged bathymetric check points at various depth ranges.

Table 14: Bathymetric Vertical Accuracy

Bathymetric Vertical Accuracy for Check Points at Indicated Depth							
	Submerged Check Points						Wetted Edge Check Points
	0 – 0.2 m	0.3 – 0.4 m	0.5 – 0.6 m	0.7 – 0.8 m	0.9 – 1.0 m	Cumulative	
Sample	20 points	11 points	25 points	8 points	2 points	66 points	17 points
95% Confidence (1.96*RMSE)	0.075 m	0.084 m	0.087 m	0.121 m	0.190 m	0.093 m	0.090 m
Average DZ	-0.001 m	-0.003 m	-0.016 m	-0.006 m	-0.089 m	-0.010 m	-0.026 m
Median	-0.007 m	-0.002 m	-0.015 m	-0.003 m	-0.089 m	-0.011 m	-0.045 m
RMSE	0.038 m	0.043 m	0.045 m	0.062 m	0.097 m	0.047 m	0.046 m
Standard Deviation (1σ)	0.039 m	0.045 m	0.042 m	0.066 m	0.054 m	0.047 m	0.039 m

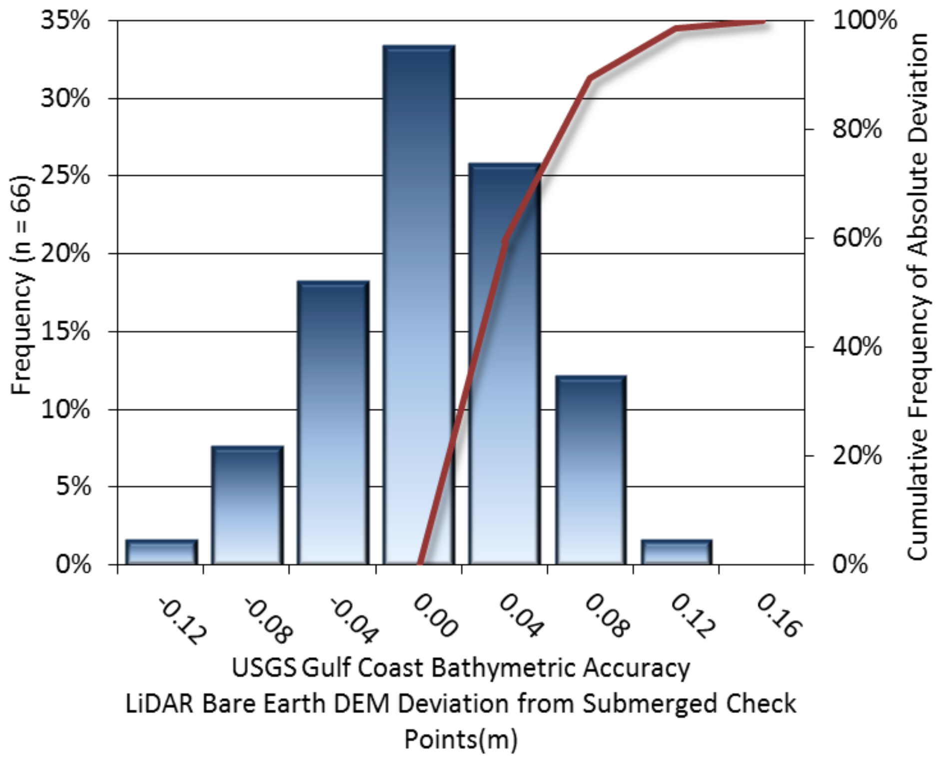


Figure 13: Frequency histogram for LiDAR bare earth DEM deviation from submerged bathymetric check point values

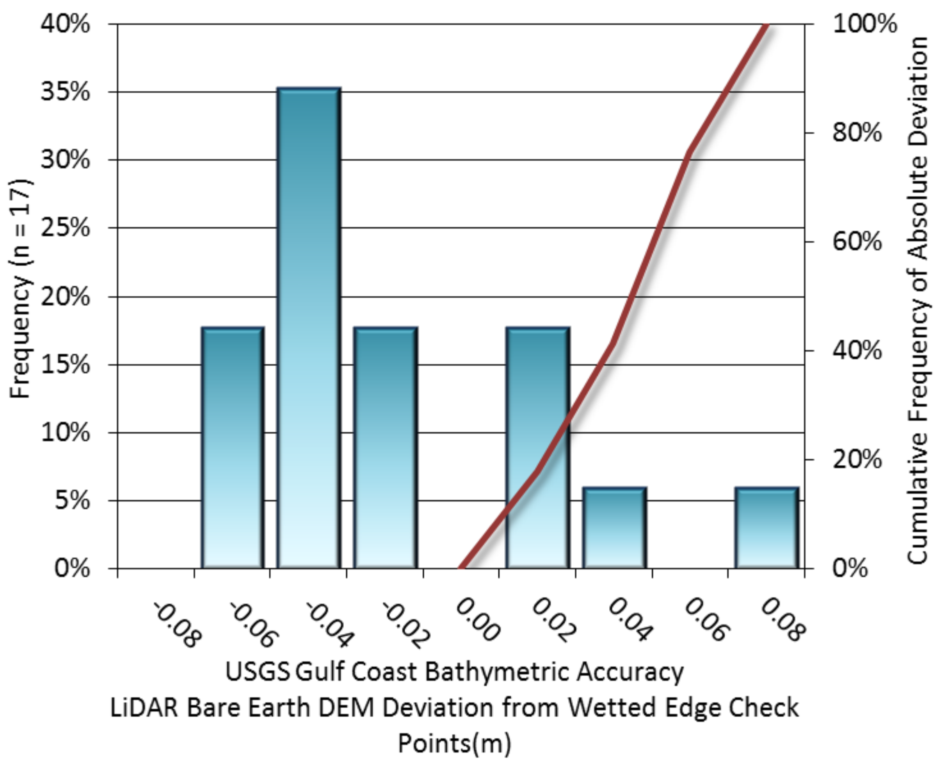


Figure 14: Frequency histogram for LiDAR bare earth DEM deviation from wetted edge check point values

LiDAR Vegetated Vertical Accuracies

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified LiDAR points. For the USGS Gulf Coast survey, 14 ground check points were collected over vegetated surfaces, with resulting vegetated vertical accuracy of 0.150 meters as compared to the bare earth DEM, evaluated at the 95th percentile (Table 15, Figure 15).

Table 15: Vegetated Vertical Accuracy for the USGS Gulf Coast Project

Vegetated Vertical Accuracy (VVA)	
Sample	14 points
Average Dz	0.070 m
Median	0.054 m
RMSE	0.084 m
Standard Deviation (1σ)	0.084 m
95th Percentile	0.150 m

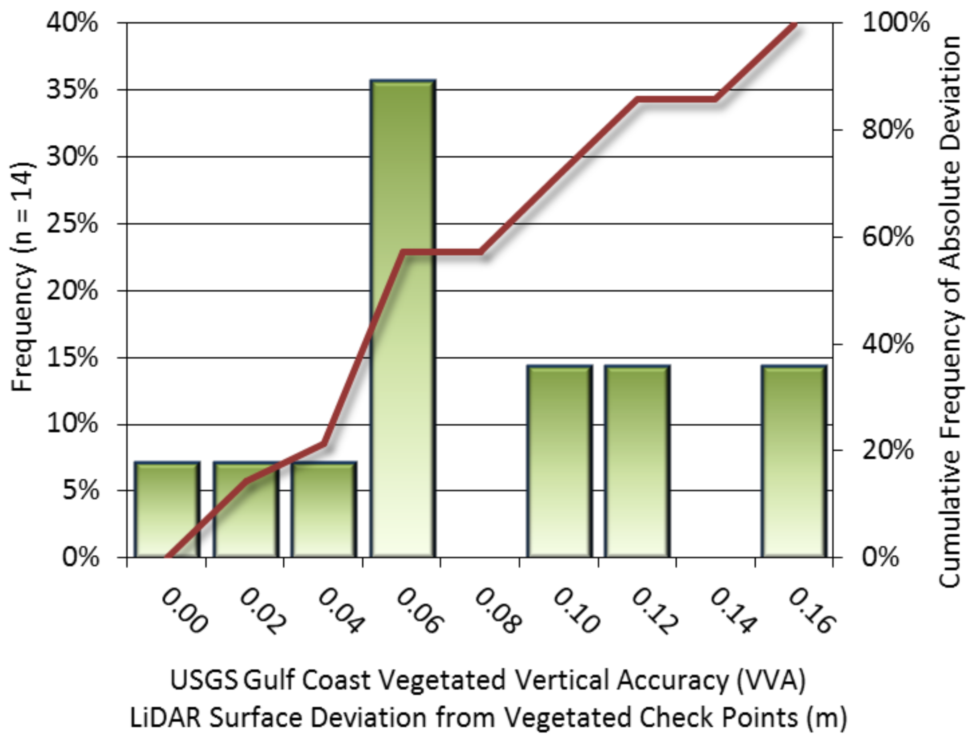


Figure 15: Frequency histogram for LiDAR surface deviation from all land cover class point values (VVA)

LiDAR Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. Due to the project area being largely over water, some lines had no ground or bathymetric bottom returns and were therefore not considered in relative accuracy analysis. The average (mean) line to line relative vertical accuracy for the USGS Gulf Coast LiDAR project was 0.028 meters (Table 16, Figure 16).

Table 16: Relative accuracy results

Relative Accuracy	
Sample	341 surfaces
Average	0.028 m
Median	0.027 m
RMSE	0.068 m
Standard Deviation (1σ)	0.050 m
1.96σ	0.097 m

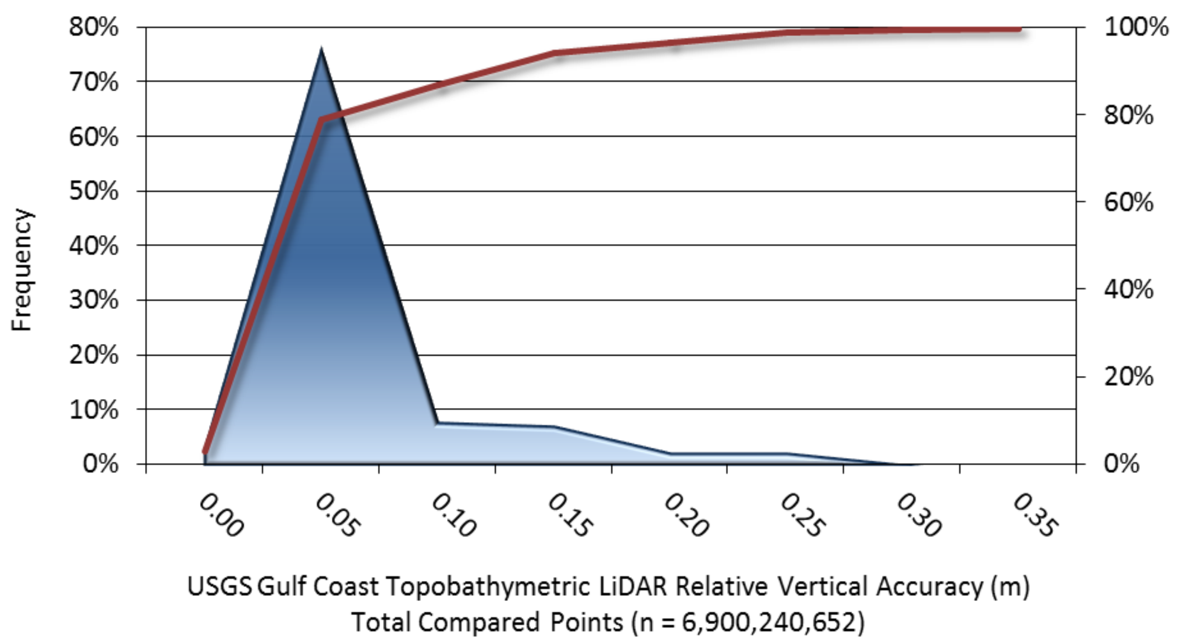


Figure 16: Frequency plot for relative vertical accuracy between flight lines

LiDAR Horizontal Accuracy

LiDAR horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS-derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component (ACCr) of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95 percent of the time. Using a flying altitude of 400 meters, an IMU error of 0.005 decimal degrees, and a GNSS positional error of 0.072 meters, the horizontal accuracy for the USGS Gulf Coast Topobathymetric LiDAR collection is 0.118 meters at the 95% confidence level (Table 17). Data from the USGS Gulf Coast Topobathymetric dataset have been tested to meet horizontal requirements at the 95% confidence level, using NSSDA reporting methods.

Table 17: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.068 m
ACC_r	0.118 m

Quantum Spatial, Inc. provided lidar services for the USGS Gulf Coast project as described in this report.

I, Steve Miller, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Jul 19, 2019

Steve Miller, PMP
Project Manager
Quantum Spatial, Inc.

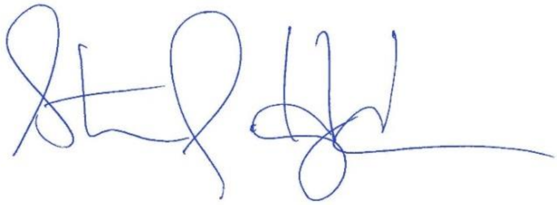
I, Steven J. Hyde, PLS, being duly registered as a Professional Land Surveyor and Mapper in and by the states of Louisiana, Alabama and Florida, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. QSI field work conducted for this report was conducted between October 25 and November 3, 2018.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

Expires: 09/30/2019

Expires: 12/31/2019

Expires: 02/28/2021



Steven J. Hyde, PLS, PSM
Quantum Spatial, Inc.
St. Petersburg, Florida 33716

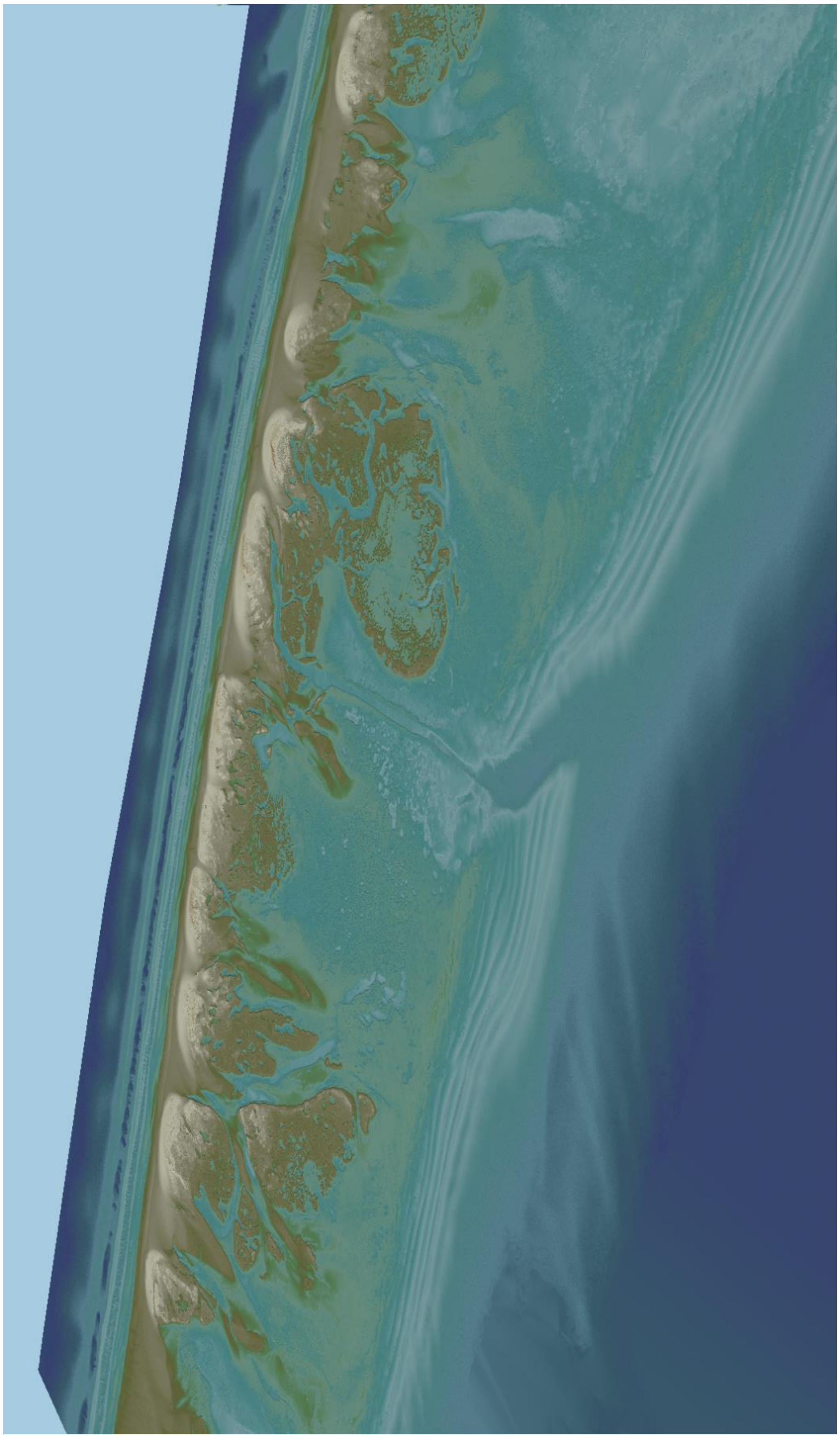


Figure 17: Looking east, this view shows the bathymetry and topography within the Chandeleur Islands. This chain of barrier islands is a part of the Breton National Wildlife Refuge and marks the eastern and outer boundary of the Chandeleur Sound. This image was created with LiDAR derived topobathymetric bare earth digital elevation model colored by elevation.

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (FVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of LiDAR data is described as the mean and standard deviation (sigma σ) of divergence of LiDAR point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of LiDAR resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echoes) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native LiDAR Density: The number of pulses emitted by the LiDAR system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

LiDAR accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±20^{o} from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.