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NOAA Morro Bay, California

Topobathymetric LiDAR with Sonar Integration Technical Data Report

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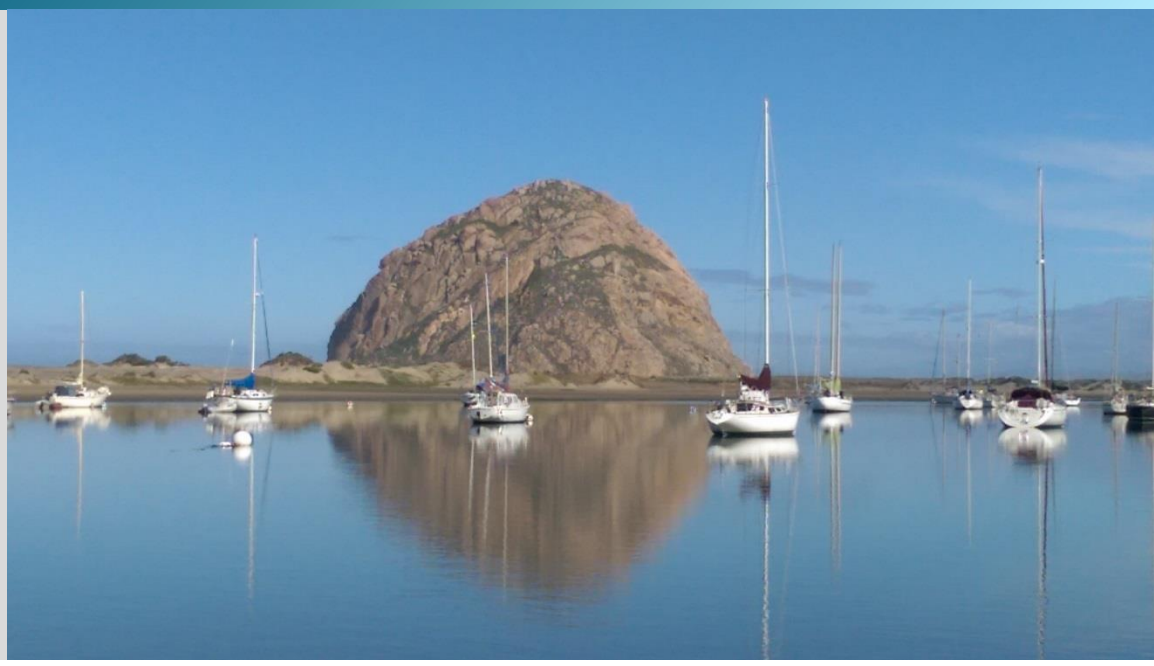
Cover Photo: A view looking over Morro Bay Estuary. The image was created from the LiDAR bare earth model overlain with aerial imagery.

INTRODUCTION

This image shows a scenic view of sailboats in front of Morro Rock in the Morro Bay project area.



In May 2019, Quantum Spatial (QSI) was contracted by National Oceanic and Atmospheric Administration Office of Coastal Management (NOAA) to collect topobathymetric Light Detection and Ranging (LiDAR) data in the spring of 2019 for the NOAA Morro Bay site in San Luis Obispo County, California. The NOAA Morro Bay area of interest (AOI) covers approximately 4,215 acres over Morro Bay, including the Morro Bay Estuary and roughly 3.6 miles of coastline. The project design included collection of traditional near-infrared (NIR) LiDAR fully integrated with green wavelength (bathymetric) LiDAR as well as the collection of Sonar data by Merkel & Associates to provide bathymetric surface modeling in areas lacking LiDAR coverage. Integration of these two complimentary sensors was used in order to provide a complete physical model of Morro Bay. Data was collected to aid NOAA in assessing the channel morphology and topobathymetric surface of the study area to support the Morro Bay National Estuary Program in habitat restoration and management.

This report accompanies the delivered integrated topobathymetric LiDAR and Sonar dataset and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR and Sonar accuracy, depth penetration, and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to NOAA is shown in Table 2, and the project extent is shown in Figure 1. A project report provided by Merkel and Associates specific to the Sonar acquisition and processing can be found in Appendix B.

Table 1: Acquisition dates, acreage, and data types collected on the NOAA Morro Bay site

Project Site	Contracted Acres	Acquisition Dates	Data Type
NOAA Morro Bay, California	3,593	May 22, 2019	High Resolution Topobathymetric LiDAR
		June 17 – 19, 2019	Acoustic Bathymetric Sonar

Deliverable Products

Table 2: Products delivered to NOAA for the NOAA Morro Bay site

Morro Bay, California LiDAR Products	
Projection: UTM Zone 10 North **Horizontal Datum: NAD83 (2011)** **Vertical Datum: GRS80 Ellipsoidal Heights** **Units: Meters**	**Projection: UTM Zone 10 North** **Horizontal Datum: NAD83 (2011)** **Vertical Datum: NAVD88 (GEOID12B)** **Units: Meters**
Points	LAS v 1.4 • All Classified Returns
Rasters	1.0 Meter GeoTiff • Topobathymetric Bare Earth Digital Elevation Model (DEM)
Vectors	Shapefiles (*.shp) • Buffered Project Boundary • LiDAR Tile Index • LiDAR/Sonar Coverage Areas • Bathymetric Coverage Shape • Water's Edge Breaklines ESRI File Geodatabase (*.gdb) • Ground Survey Points and Monument Locations • Flightline Index

Figure 1: Location map of the NOAA Morro Bay site in California.

ACQUISITION

QSI's Cessna Caravan

Planning

In preparation for LiDAR data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the NOAA Morro Bay LiDAR study area at the target combined point density of ≥8 points/m^2. 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 flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. Flight times were chosen for optimal tide conditions (Table 3 and Figure 2). In addition, logistical considerations including private property access, potential air space restrictions, and water clarity were reviewed.

Environmental Conditions: Turbidity and Secchi Depth Readings

In order to assess water clarity conditions prior to and during LiDAR collection, QSI collected turbidity measurements, secchi depth readings, and wind speed and direction measurements. Readings were collected at six locations throughout the project site between May 21nd, 2019 and May 22nd, 2019. Turbidity and wind observations were recorded twice to confirm measurements. The table below provides turbidity and secchi depth results per site on each day of data collection as applicable.

Table 3: Water Clarity Observations for LiDAR flights

Turbidity, Secchi Depth, and Wind Speed Observations							
Point ID	**Secchi Reading Time and Date**	**Longitude**	**Latitude**	**Turbidity**	**Wind Conditions**	**Secchi Depth (m)**	**LiDAR Mapped Depth (m)**
1	7:45 AM, May 21	-119.14632	35.36569	11.5	1 MPH S	1	NA
2	9:45 AM, May 21	-119.14807	35.35976	9.5	7.5 MPH W	1	NA
3	10:15 AM, May 21	-119.14949	35.35737	8	9 MPH WSW	1	NA
1	8:45 AM, May 22	-119.14632	35.36569	8.5	Calm	1	1.653
2	9:00 AM, May 22	-119.14807	35.35976	10.3	Calm	1	1.643
3	9:15 AM, May 22	-119.14949	35.35737	7.5	1 MPH S	1	2.134

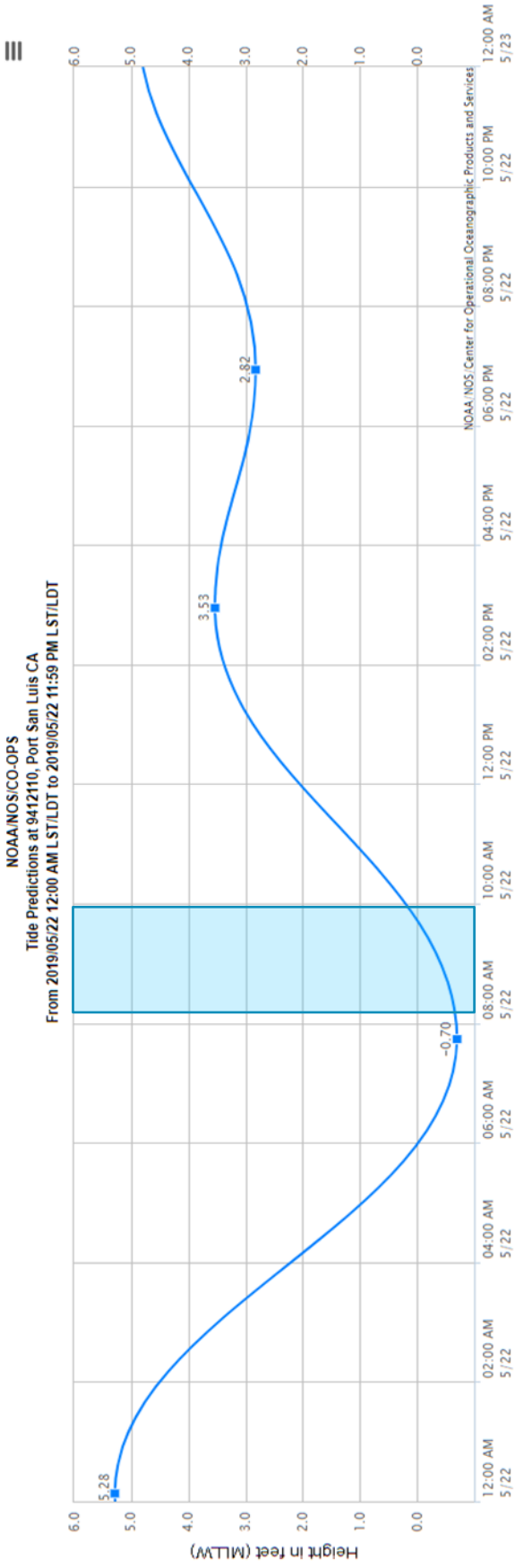


Figure 2: Tide Predictions at 9412110, Port San Luis CA during the time of LiDAR acquisition

These photos were taken by QSI's ground survey team and display water clarity conditions within Morro Bay on May 21 and May 22, 2019, near the time of LiDAR acquisition.

Airborne Survey

LiDAR

The LiDAR survey was accomplished using a Riegl VQ-880-G-II green laser system mounted in a Cessna Caravan 208B. The Riegl VQ-880-G-II boasts a high repetition pulse rate (up to 550 kHz), high scanning speed, small laser footprint, wide field of view, and integrated green and NIR wavelength lasers which allows for seamless collection of high-resolution topographic and bathymetric surface data. The green wavelength (Λ=532 nm) laser is capable of collecting high resolution topography data, as well as penetrating the water surface with minimal spectral absorption by water. The integrated NIR laser (Λ=1064 nm) adds additional topography data and aids in water surface modeling. The recorded waveform enables range measurements for all discernible targets for a given pulse. 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 pulses/m^2 over the NOAA Morro Bay project area.

Table 4: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications		
Acquisition Dates	May 22, 2019	May 22, 2019
Aircraft Used	Cessna 208NR	Cessna 208NR
Sensor	Riegl	Riegl
Laser	VQ-880-GII	VQ-880GII-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	140 knots	140 knots
Field of View	40°	40°
Mirror Scan Rate	80 Lines per Second	Uniform Point Spacing
Target Pulse Rate	200 kHz	200 kHz
Pulse Length	1.5 ns	3 ns
Laser Pulse Footprint Diameter	28 cm	8 cm
Central Wavelength	532 nm	1064 nm
Pulse Mode	Multiple Times Around (MTA)	Multiple Times Around (MTA)
Beam Divergence	0.7 mrad	0.2 mrad
Swath Width	291 m	291 m
Swath Overlap	30%	30%
Intensity	16-bit	16-bit
Accuracy	$RMSE_Z \leq 15$ cm	$RMSE_Z \leq 15$ cm

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.

Ground Survey

Ground control surveys, including monumentation, and ground survey points (GSPs), were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data.

Existing NGS Monument

QSI-Established Monument

Base Station

Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized three existing monuments and established one new monument for the NOAA Morro Bay LiDAR project (Table 5, Figure 3). New monumentation was set using 5/8” x 30” rebar topped with stamped 2 ½ " aluminum caps. QSI’s professional land surveyor, Evon Silvia (CAPLS#9401) oversaw and certified the ground survey.

Table 5: Monument positions for the NOAA Morro Bay acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
FV1162	35°22'16.61"N	120°51'27.03"W	4.659
MB_10	35°22'20.59"N	120°51'37.93"W	4.864
MB_9R	35°22'19.80"N	120°51'34.81"W	5.077
MORRO_01	35°22'20.27"N	120°51'34.35"W	4.852

QSI utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency for each 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[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS/.

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.[2] 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.

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 NOAA Morro Bay 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 R10	Integrated Antenna	TRMR10	Rover

[2] 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

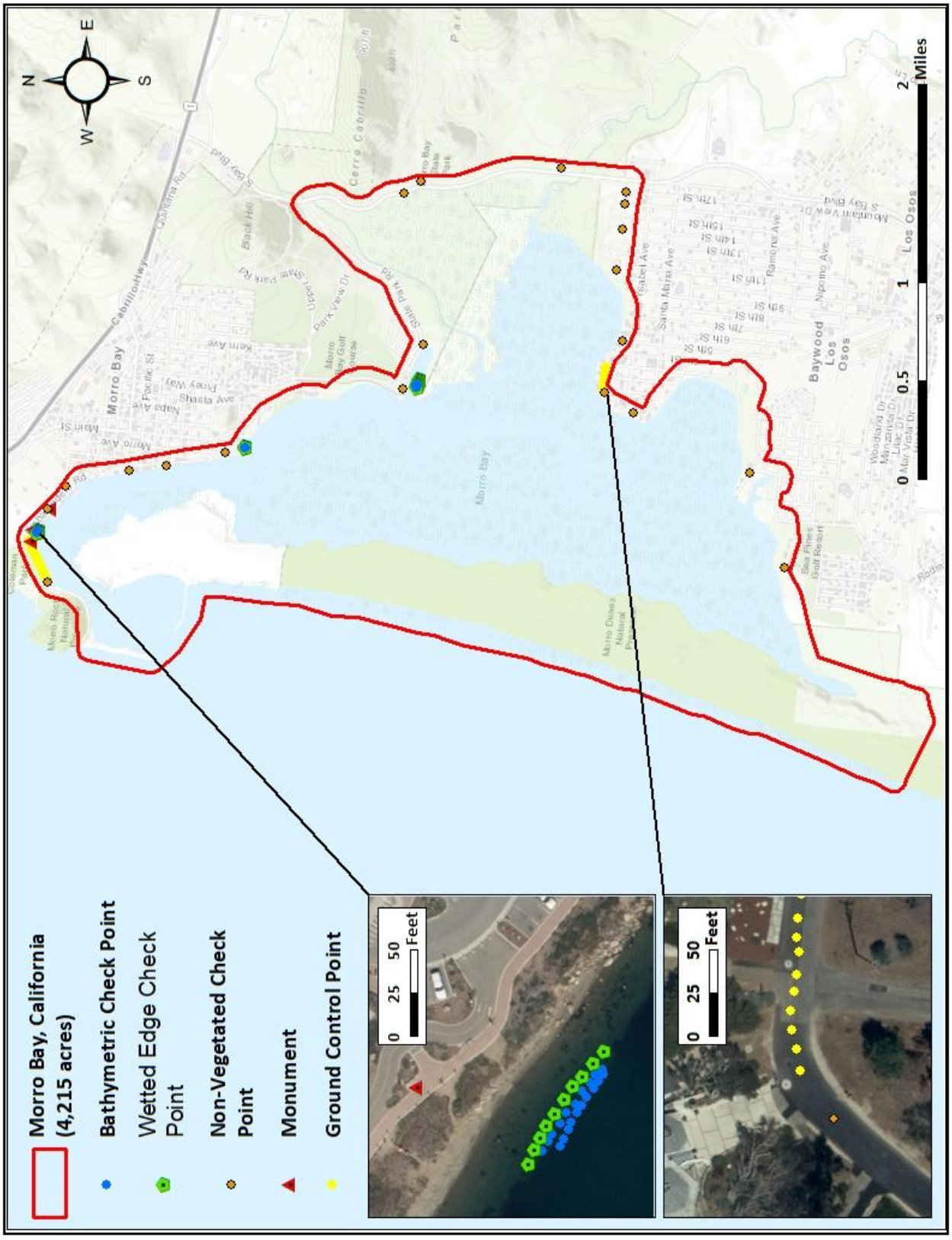
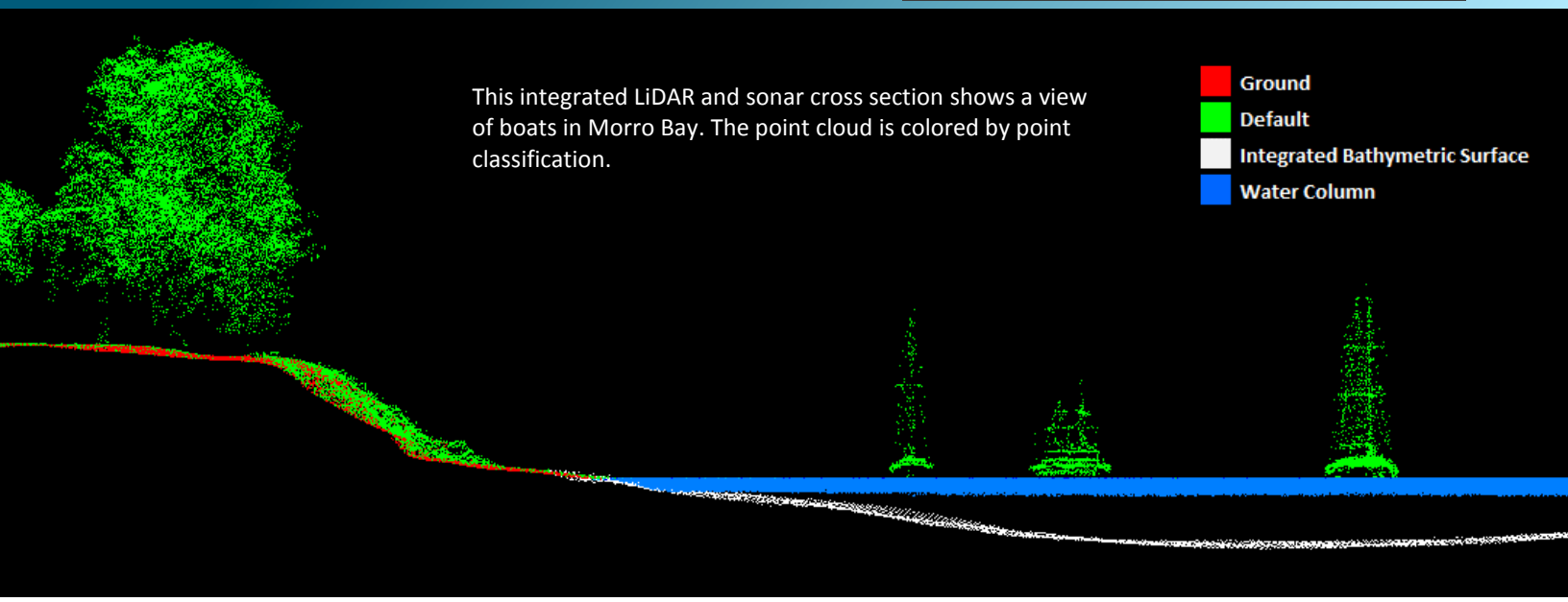


Figure 3: Ground survey location map



This integrated LiDAR and sonar cross section shows a view of boats in Morro Bay. The point cloud is colored by point classification.

Topobathymetric LiDAR Data

Upon completion of the LiDAR 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 including refraction of green laser returns through water, sensor and data calibration for optimal relative and absolute accuracy, LiDAR point classification (Table 8), and sonar integration. Details on refraction and sonar integration are provided below and a brief description of all processing tasks is shown in Table 9. Processing tasks specific to the sonar data can be found in Appendix B.

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. QSI has developed proprietary software (Las Monkey) to perform this processing based on Snell's law. The first step is to develop a water surface model (WSM) from the NIR lidar water surface returns. The water surface model used for refraction is generated using NIR points within the breaklines defining the water's edge. Points are filtered and edited to obtain the most accurate representation of the water surface and are used to create a water surface model TIN. A TIN model is preferable to a raster based water surface model to obtain the most accurate angle of incidence during refraction.

Once the WSM is generated, the Las Monkey refraction software then intersects the partially submerged green pulses with the WSM to determine the angle of incidence with the water surface and the submerged component of the pulse vector. This provides the information necessary to correct the position of underwater points by adjusting the submerged vector length and orientation.

Sonar Integration

Upon receipt from Merkel, QSI imported the multi-beam sonar into the existing bathymetric LIDAR using Bentley Microstation and Terrasolid software. Sonar-derived data was assigned a point source ID of 9, and a user byte of 2. The goal of the integration was to provide seamless, full bathymetric surface coverage; however, the temporal difference between acquisition timeframes must be considered during surface creation. LiDAR data for the NOAA Morro Bay project area was collected May 22nd of 2019 at low tide, while Sonar collection occurred June 17-19 at higher tides. Surface deviations between the two technologies occurred due to variable environmental factors such as tidal sediments, water clarity, turbidity, and bottom surface reflectivity.

As a general rule, sonar data was prioritized in deeper areas of the channel while LiDAR data was prioritized in shallower areas of the channel including all areas not submerged during the LiDAR collection. As the LiDAR laser approaches the laser's extinction point bathymetric surface profiles and point density degrade thus the prioritization of sonar data in these areas. Conversely side-scan sonar does better when water depths are greater than 1m as areas shallower than this are prone to increased noise making the LiDAR data more reliable in these areas.

Within the Morro Bay site there was one notable area of significant temporal change. The sand spit at the mouth of the bay displayed a difference as great as 5 meters from the LiDAR survey (Figure 4). Despite this area being collected at true ground during the LiDAR survey, the sonar data was used in this area being the most temporally recent data and collected at high tide with high confidence in the surface. All data from either sensor that was not used in topobathymetric and ground model creation is still preserved in the point cloud as Ignored Ground/Bathymetry (class 20).

Figure 4: A cross section of the sand spit near the mouth of the bay. A result of temporal and environmental variations, a surface deviation of up to 5 meters is observed in the detected bathymetric depths between the LiDAR and sonar datasets.

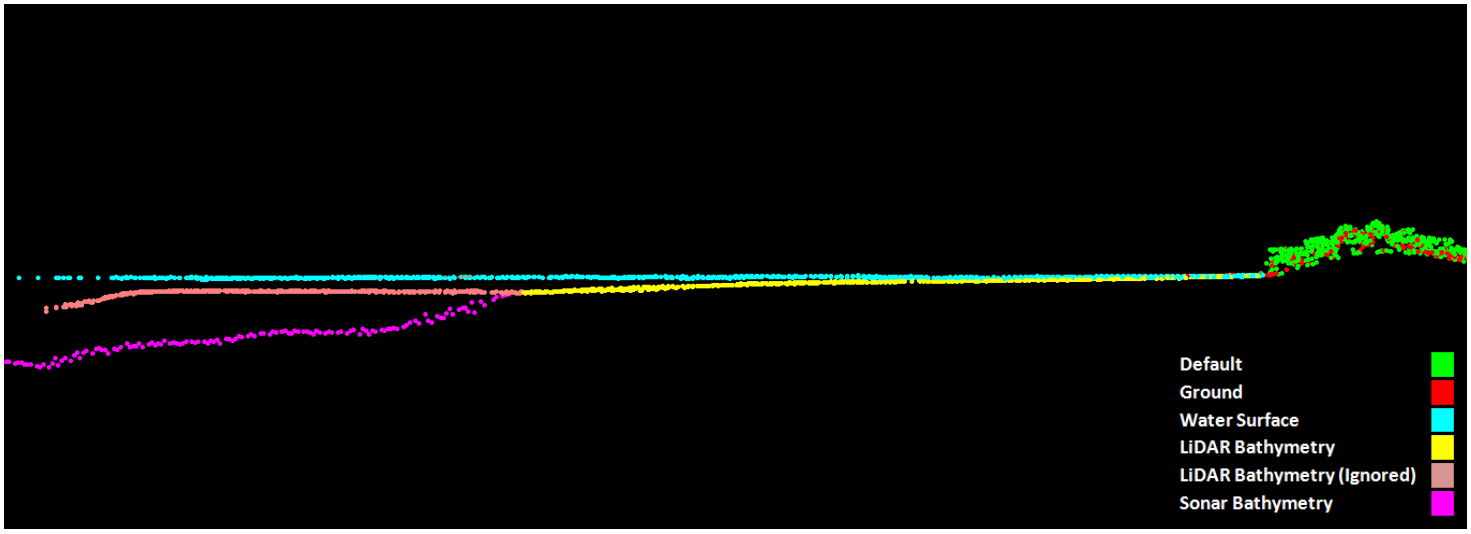


Table 8: ASPRS LAS classification standards applied to the NOAA Morro Bay dataset

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, identified using the overlap flag
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
9	Water	NIR laser returns that are determined to be water using automated and manual cleaning algorithms
18	High Noise	High Points (Outliers)
20	Ignored Ground/Bathymetry	Points ignored for seamless model creation during the lidar/sonar integration
40	Bathymetric Bottom	Bathymetric points 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	Green laser returns that are determined to be water using automated and manual cleaning algorithms.

Table 9: LiDAR processing workflow

LiDAR Processing Step	Software Used	Processor
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.8.2	QSI
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.19	QSI
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.19	QSI
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.19 RiProcess v1.8.5	QSI
Generate water surface models and apply refraction correction to all subsurface returns.	Las Monkey 2.4 (QSI proprietary software)	QSI
Classify resulting data to ground and other client designated ASPRS classifications (Table 8). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19 TerraModeler v.19	QSI
Identify LiDAR bathymetric void areas to target for sonar collection	Las Monkey 2.4 (QSI proprietary software) ArcMap v. 10.3.1	QSI
*Collect sonar. Process and edit raw track lines to remove any noise. Evaluate data for visual anomalies and perform quality assurance checks.	SEA Grid Processor	M&A
Import multibeam Sonar data into LiDAR point cloud and further classify the data to eliminate temporal artifacts as feasible and create a more seamless surface	TerraScan v.18 TerraModeler v.18	QSI
Generate bare earth models as triangulated surfaces. Export all surface models as GeoTIFFs at a 1 meter pixel resolution.	Las Product Creator 3.0 (QSI proprietary software) ArcMap v. 10.3.1	QSI

*See Appendix B for detailed explanation of sonar acquisition and processing

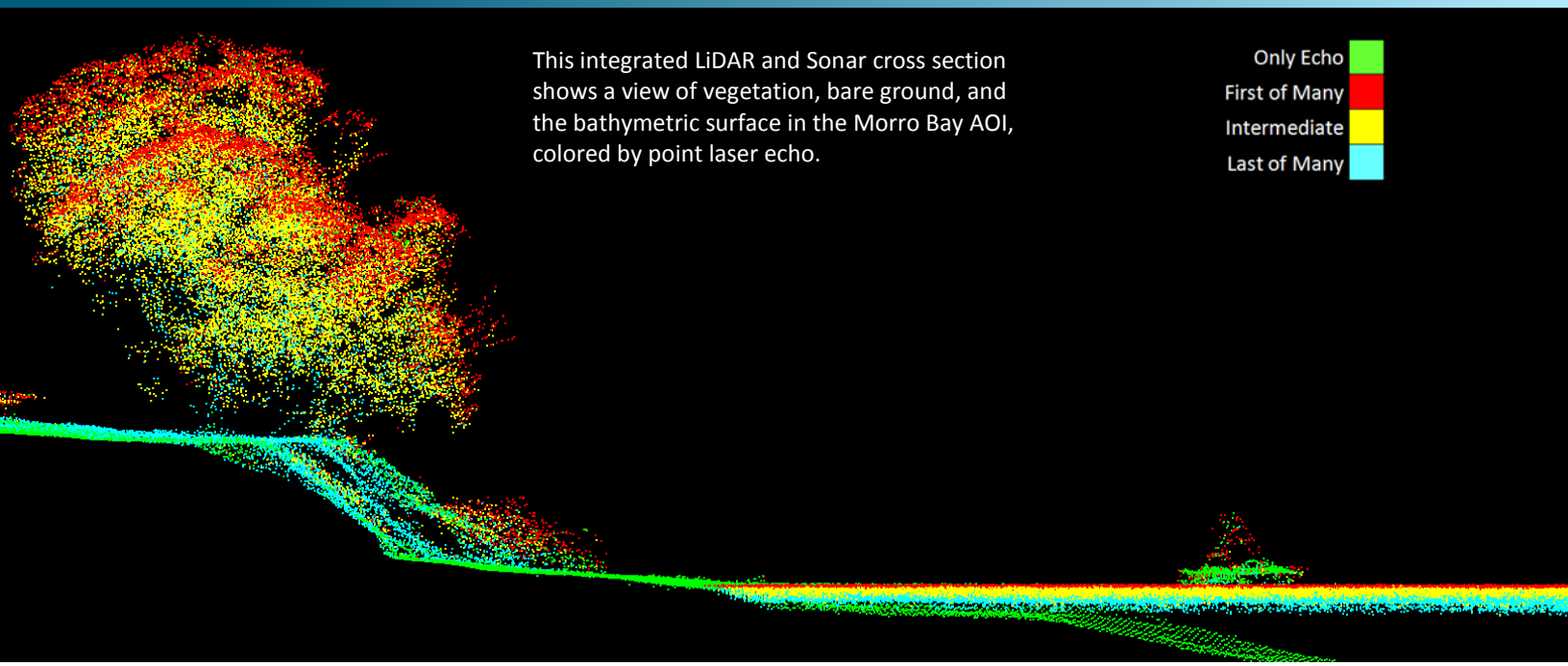
Integration Derived Products

Because hydrographic laser scanners and multi beam sonar must penetrate the water surface and water column to map submerged topography, this affects how the data should be processed and presented in derived products from the integrated point cloud.

Topobathymetric DEMs

Bathymetric bottom returns from lidar can be limited by depth, water clarity, and bottom surface reflectivity. Water clarity and turbidity affects 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. Although 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 bathymetric bottom returns in turbid or non-reflective areas. Similarly, sonar data can lack returns due to dense aquatic vegetation such as eelgrass.

As a result, creating digital elevation models (DEMs) presents a challenge with respect to interpolation of areas with no returns. Traditional 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 with 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.



This integrated LiDAR and Sonar cross section shows a view of vegetation, bare ground, and the bathymetric surface in the Morro Bay AOI, colored by point laser echo.

Bathymetric LiDAR

In order to determine the capability and effectiveness of the bathymetric LiDAR, several parameters were considered; depth penetrations below the water surface, bathymetric return density, and spatial accuracy.

Mapped Bathymetry and Integrated Coverage

The combination of lidar and sonar proved to be complimentary technologies for the Morrow Bay site with LiDAR sensor mapping the shallow and near-shore areas of the site and the sonar system mapping deeper areas beyond the LiDAR's penetration capabilities. Nevertheless, some areas lacking coverage due to a number of uncontrollable factors including dense vegetation, near shore surf/whitewater do exists. A polygon layer was created to delineate areas where bathymetry was and was not successfully mapped.

This shapefile was used to control the extent of the delivered clipped topo-bathymetric 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. A bathymetric coverage of 87.47% was calculated for the integrated dataset. Additionally, bathymetric coverage for the LiDAR and sonar datasets was calculated separately. The sonar bathymetric coverage was calculated at 45.00% and the LiDAR bathymetric coverage was calculated at 42.48%.

LiDAR Point Density

First Return Point Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2. 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 average first-return density of the NOAA Morro Bay LiDAR project was 18.61 points/m^2 (Table 10). The statistical and spatial distributions of all first return densities per 100 m x 100 m cell are portrayed in Figure 5 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 NOAA Morro Bay project was 4.97 points/m^2 (Table 10). The statistical and spatial distributions ground classified and bathymetric bottom return densities per 100 m x 100 m cell are portrayed in Figure 6 and Figure 7.

Additionally, for the NOAA Morro Bay project, density values of only LiDAR bathymetric bottom returns were calculated for areas containing at least one LiDAR bathymetric bottom return. Areas lacking LiDAR bathymetric returns were not considered in calculating an average density value. Within the successfully mapped area, a bathymetric bottom return density of 3.34 points/m^2 was achieved.

Table 10: Average LiDAR point densities

Density Type	Point Density
First Returns	18.61 points/m^2
Ground and Bathymetric Bottom Classified Returns	4.97 points/m^2
LiDAR Bathymetric Bottom Classified Returns	3.34 points/m^2

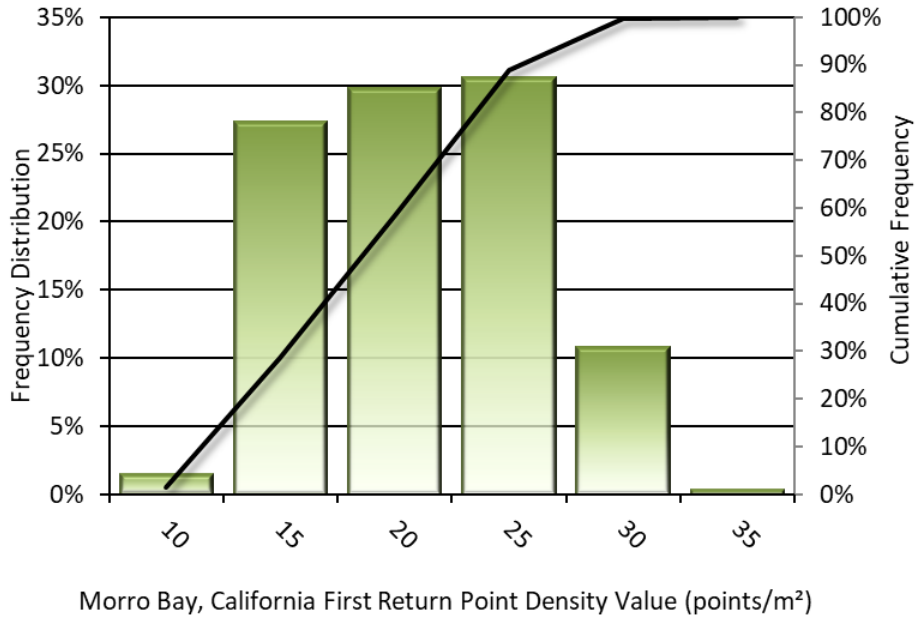


Figure 5: Frequency distribution of first return densities per 100 x 100 m cell

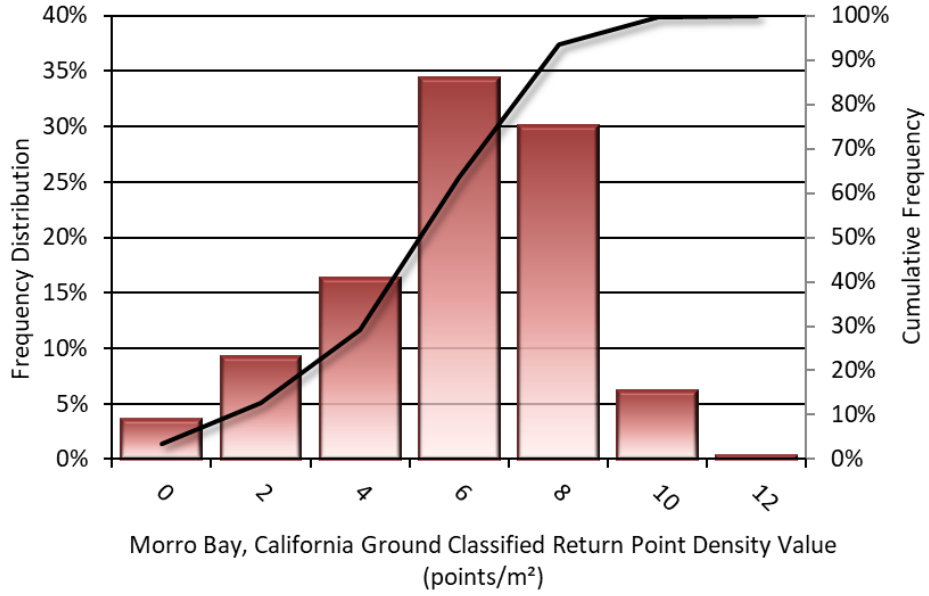


Figure 6: Frequency distribution of ground and bathymetric bottom classified return densities per 100 x 100 m cell

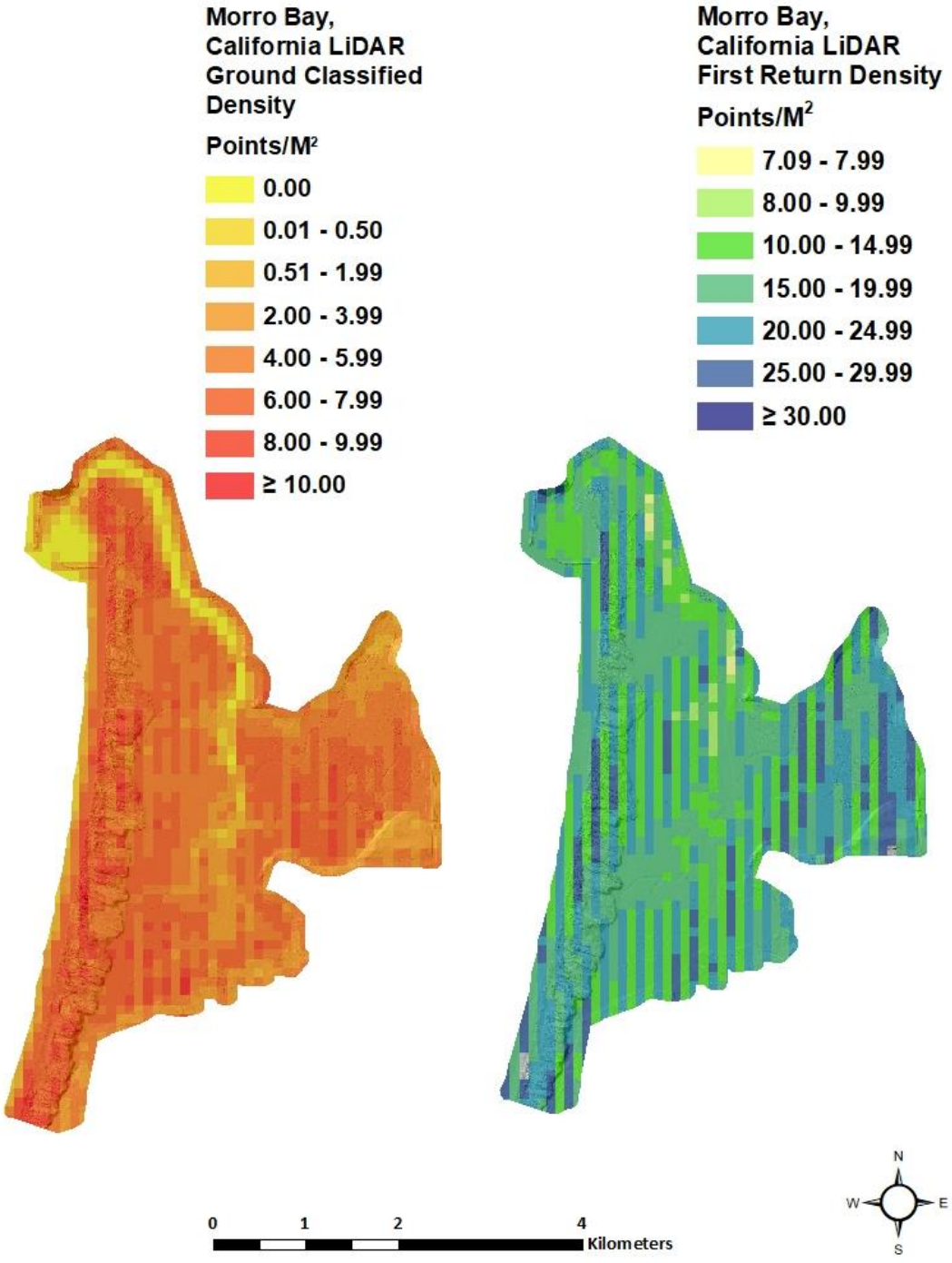


Figure 7: First return and ground and bathymetric bottom density map for the NOAA Morro Bay site (100 m x 100 m cells)

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[3]. 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 11.

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 NOAA Morro Bay survey, 20 ground check points were withheld from the calibration and post-processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.035 meters, as compared to the unclassified LAS and 0.052 meters against the bare earth DEM, with 95% confidence (Figure 9 and 10).

QSI also assessed absolute accuracy using 162 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 11 and Figure 10.

[3] 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.

Table 11: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to Unclassified LAS	NVA, as compared to Bare Earth DEM	Ground Control Points
Sample	20 points	20 points	162 points
95% Confidence (1.96*RMSE)	0.035 m	0.052 m	0.043 m
Average	0.000 m	0.015 m	0.001 m
Median	0.005 m	0.014 m	-0.007 m
RMSE	0.018 m	0.027 m	0.022 m
Standard Deviation (1σ)	0.018 m	0.023 m	0.022 m

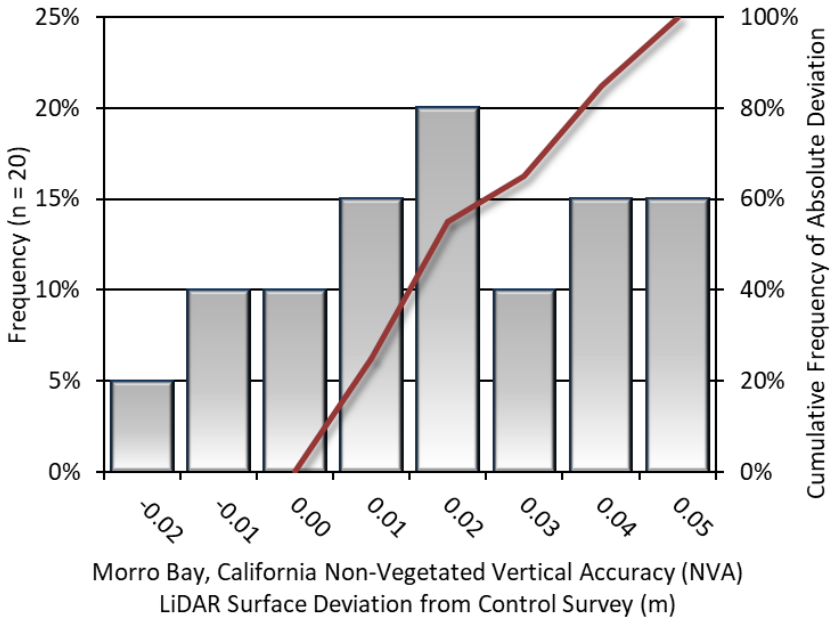


Figure 8: Frequency histogram for unclassified LAS deviation from ground check point values

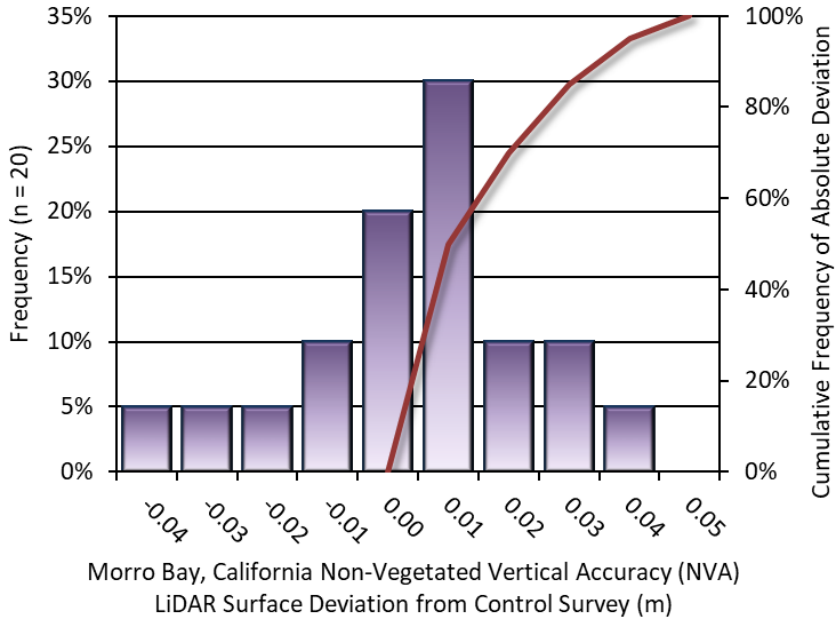


Figure 9: Frequency histogram for LiDAR bare earth DEM deviation from ground check point values

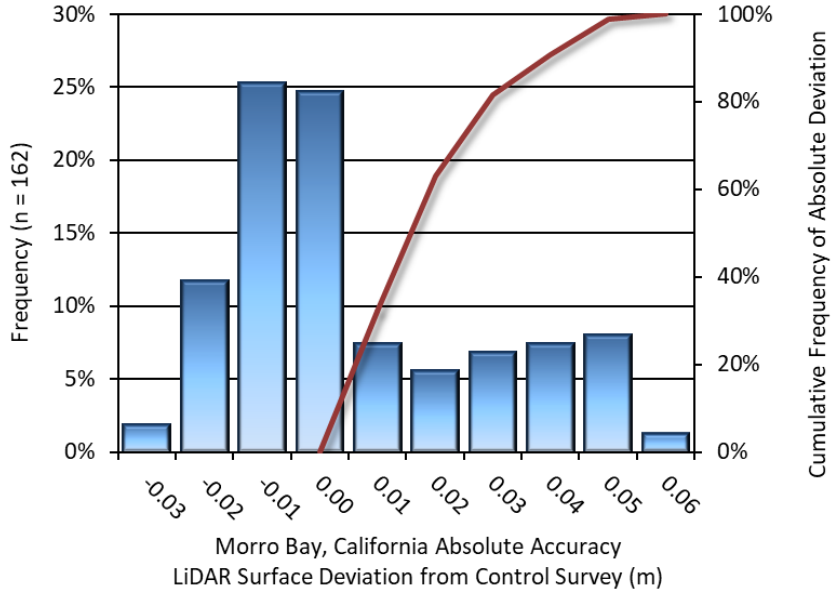


Figure 10: Frequency histogram for LiDAR surface deviation ground control point values

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. Assessment of 81 submerged bathymetric check points resulted in a vertical accuracy of 0.101 meters, while assessment of 30 wetted edge check points resulted in a vertical accuracy of 0.058 meters, evaluated at 95% confidence interval (Figure 11, Figure 12).

Table 12: Bathymetric Vertical Accuracy for the NOAA Morro Bay Project

Bathymetric Vertical Accuracy (BVA)		
	Submerged Bathymetric Check Points	**Wetted Edge Bathymetric Check Points**
Sample	81 points	30 points
95% Confidence (1.96*RMSE)	0.101 m	0.058 m
Average Dz	0.012 m	0.016 m
Median	0.005 m	0.015 m
RMSE	0.052 m	0.030 m
Standard Deviation (1σ)	0.051 m	0.026 m

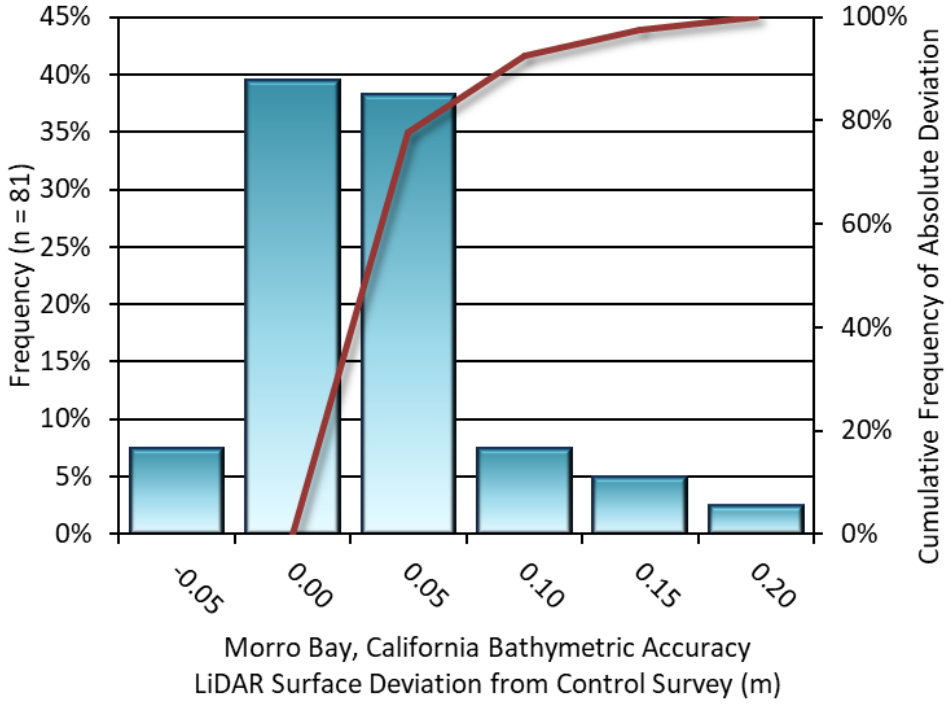


Figure 11: Frequency histogram for LiDAR surface deviation from submerged check point values

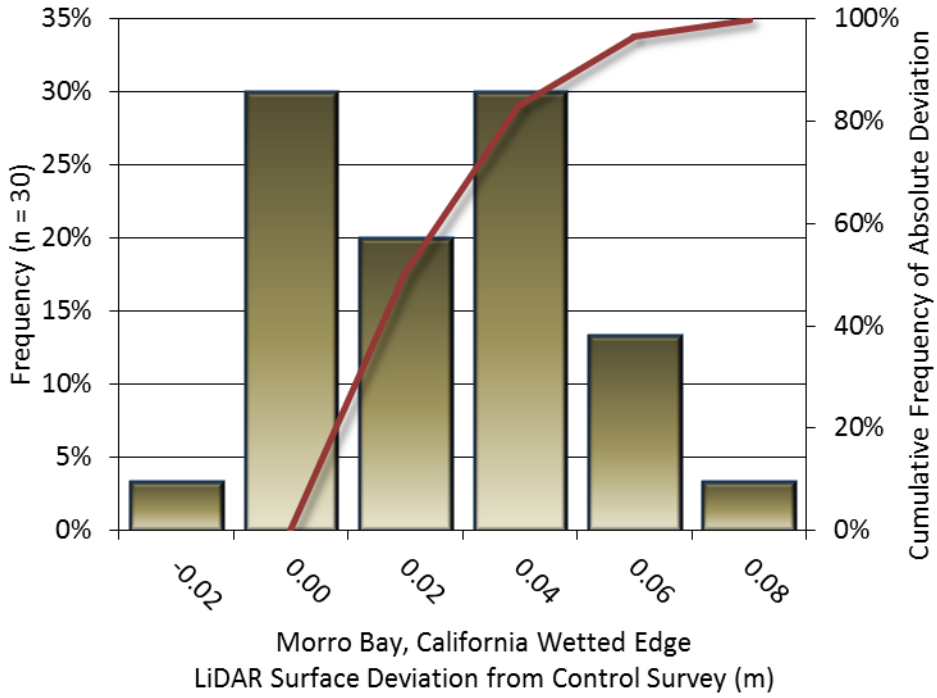


Figure 12: Frequency histogram for LiDAR surface deviation from wetted edge check point values

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. The average (mean) line to line relative vertical accuracy for the NOAA Morro Bay LiDAR project was 0.025 meters (Table 13, Figure 13).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	54 flight line surfaces
Average	0.025 m
Median	0.025 m
RMSE	0.029 m
Standard Deviation (1σ)	0.011 m
1.96σ	0.021 m

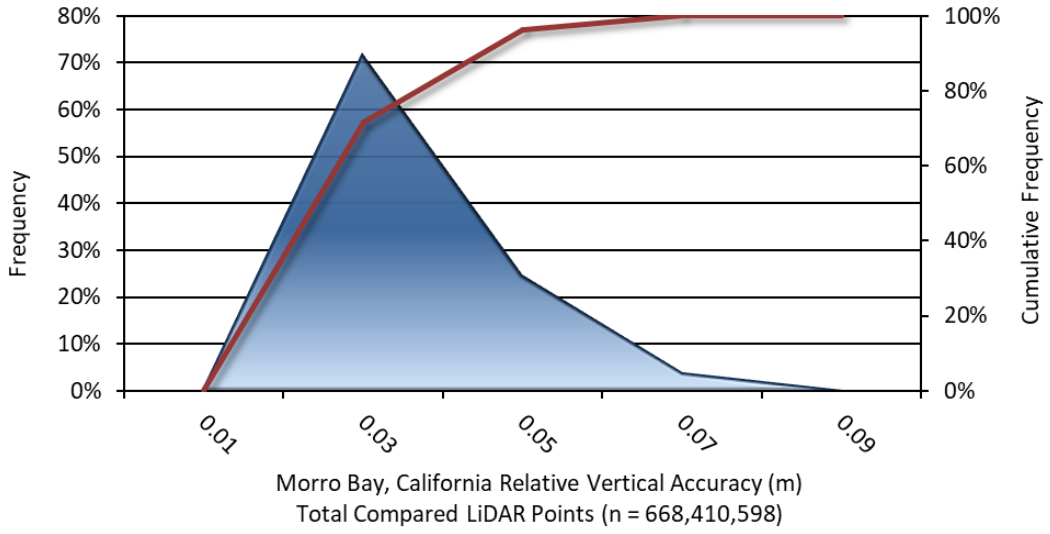


Figure 13: Frequency plot for relative vertical accuracy between flight lines

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the NOAA Morro Bay project as described in this report.

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

Ashley Daigle Sep 18, 2019

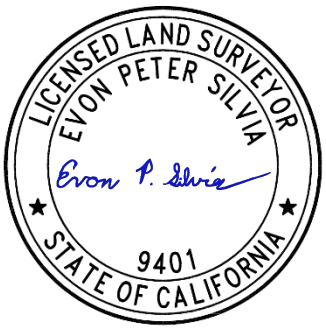
Ashley Daigle
Project Manager
Quantum Spatial, Inc.

I, Evon P. Silvia, PLS, being duly registered as a Professional Land Surveyor in and by the state of California, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between May 20 and 22, 2019.

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".

Evon P. Silvia Sep 18, 2019

Evon P. Silvia, PLS
Quantum Spatial, Inc.
Corvallis, OR 97330



Signed: Sep 18, 2019

Figure 14: View looking at the beach at Morro Bay. The image was created from the LiDAR bare earth model overlaid with the above-ground point cloud.

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 ±30° from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

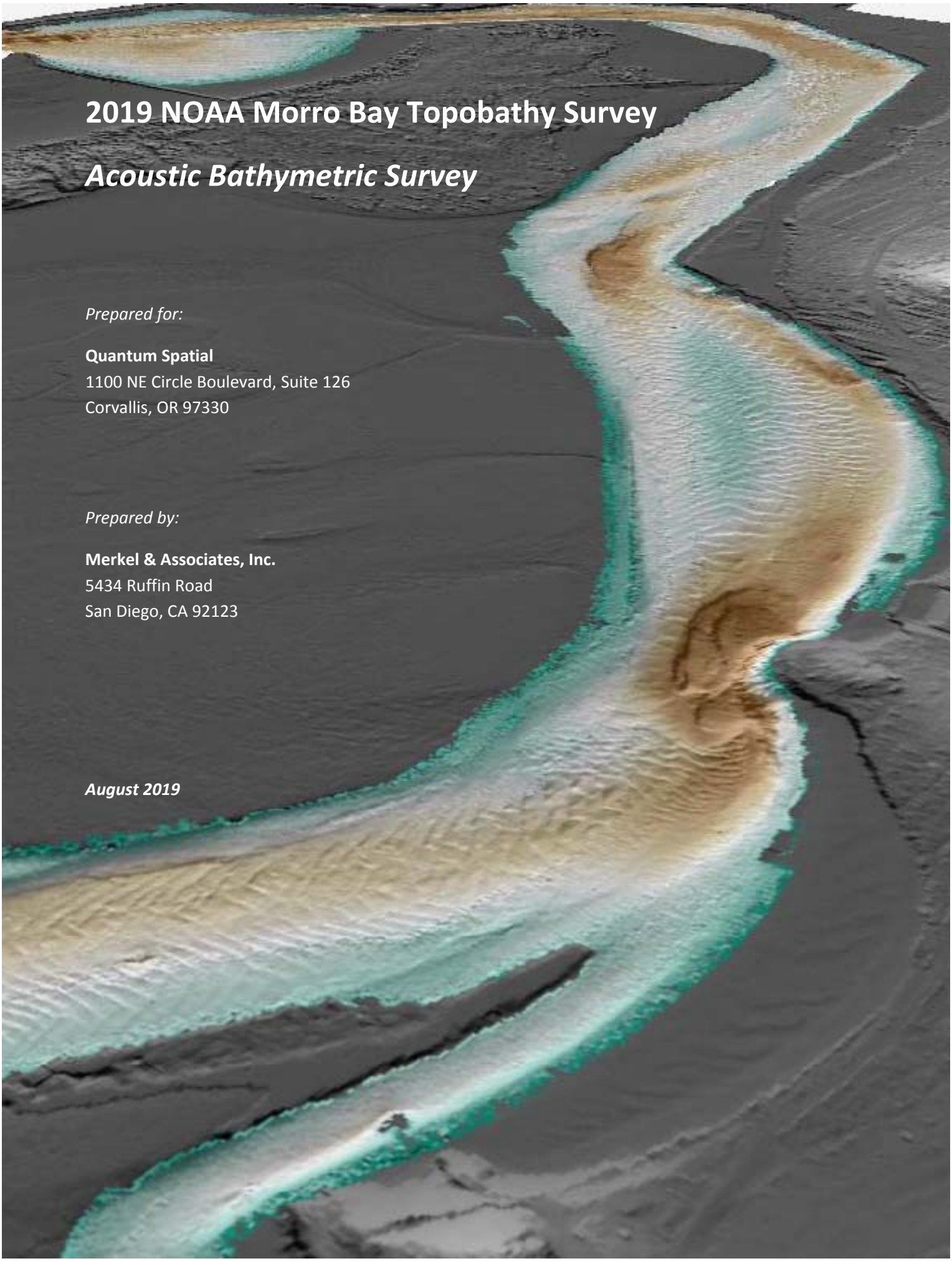
Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs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

Appendix B – Merkel and Associates Sonar Report



2019 NOAA Morro Bay Topobathy Survey

Acoustic Bathymetric Survey

Prepared for:

Quantum Spatial
1100 NE Circle Boulevard, Suite 126
Corvallis, OR 97330

Prepared by:

Merkel & Associates, Inc.
5434 Ruffin Road
San Diego, CA 92123

August 2019

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Background

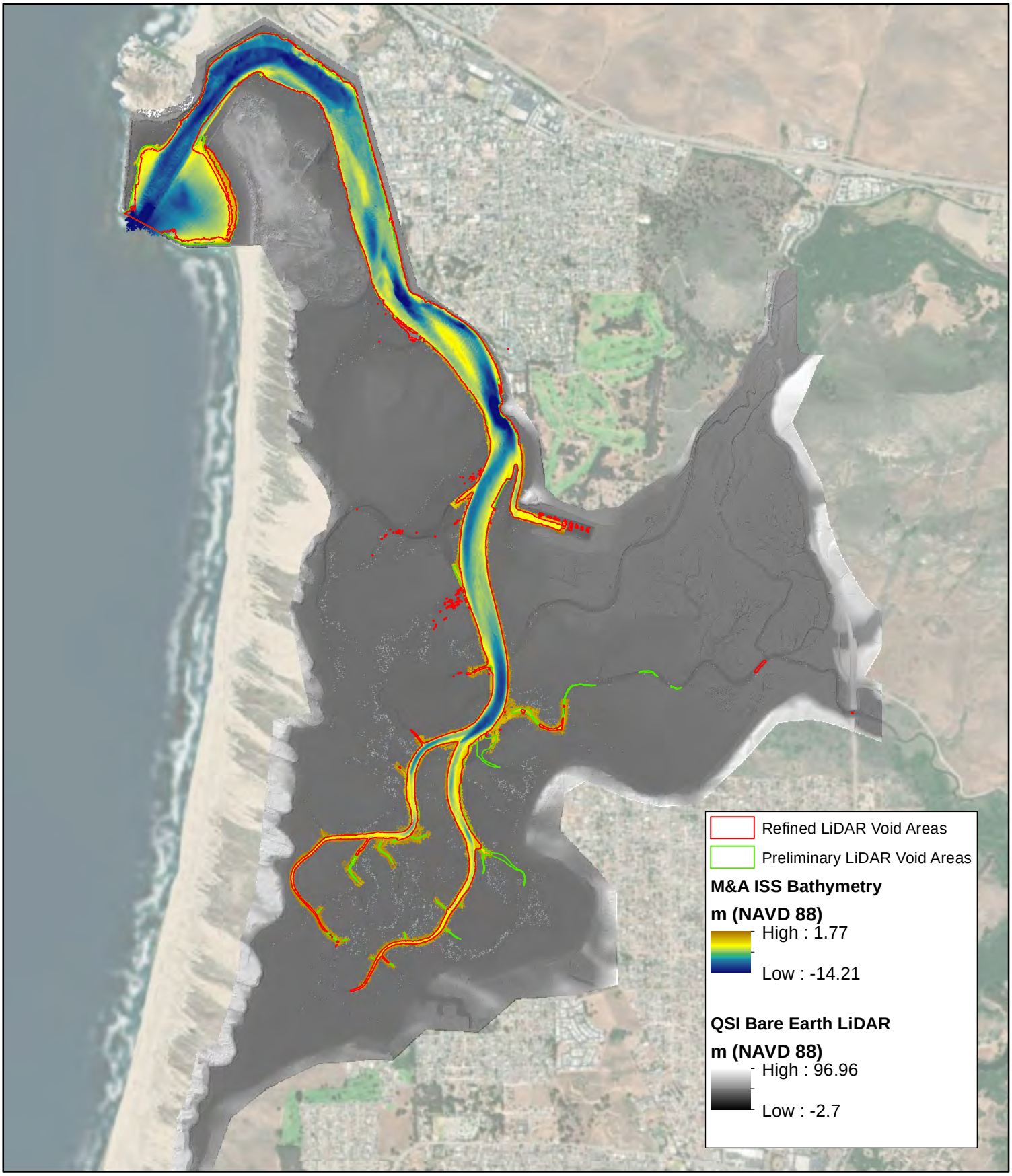
In May 2019, Merkel and Associates (M&A) was contracted by Quantum Spatial (QSI) to collect subtidal bathymetry data for integration with aerial light, detection, and ranging (LiDAR) topographic data, with the ultimate goal of producing a seamless topographic-bathymetric (hereafter, topobathy) digital elevation model (DEM) of Morro Bay, California. The underlying goal in developing this topobathy DEM was to provide an updated physical model of Morro Bay capable of supporting circulation and sediment transport modeling within the estuary by the Morro Bay National Estuary Program (MBNEP) and its partners. The topobathy DEM addresses temporal changes that have occurred since previous surveys were conducted and resolves remaining data gaps in areas of the subtidal channel network that have not been previously surveyed.

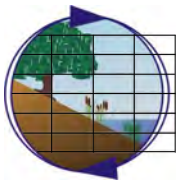
Survey Location and Timing

Swath acoustic bathymetric surveys were completed throughout the deeper portions of Morro Bay and along the shallow margins of the bay where LiDAR based surveys reached their limit of applicability. Surveys were guided by a preliminary void boundary provided by QSI to identify areas where LiDAR was not likely to provide suitable data to support bathymetric mapping (Figure 1). The preliminary void area was approximately 352.6 acres.

The surveys were conducted over a total area of 419.7 acres of the bay, including the preliminary void map and overlap areas with the LiDAR coverage. Surveys were completed from June 17 - 19, 2019 using both day and night high tides to make best use of the spring tides to garner greater depth of water over the tidal flats.

Following completion of the vessel based surveys, the LiDAR void boundary was refined slightly resulting in a reduction of some areas of void space, thus expanding overlap, but also resulting in the addition of some minor areas where coverage by LiDAR data could not be achieved. In particular, these included a small gap of approximately 1,342 m^2 near the Los Osos Marsh, some extensions of previously identified gaps along small channels on the marsh flats, eelgrass blanks in the data, and gaps in coverage beneath the State Park Marina docks. In some cases, the acoustic survey data covered the extensions beyond the preliminary void map, while in other cases the added voids fell outside of collected acoustic survey data, or constraints encountered by the LiDAR data collection were also encountered during acoustic surveys. The most prevalent constraint was dense eelgrass that obscured the bottom in some area. The final void map totaled 343.6 acres. When considering the added void area beyond coverage and the removal of uninterpretable data, principally within dense eelgrass, the acoustic data collection provided comprehensive field data over 98.95% of the void area.





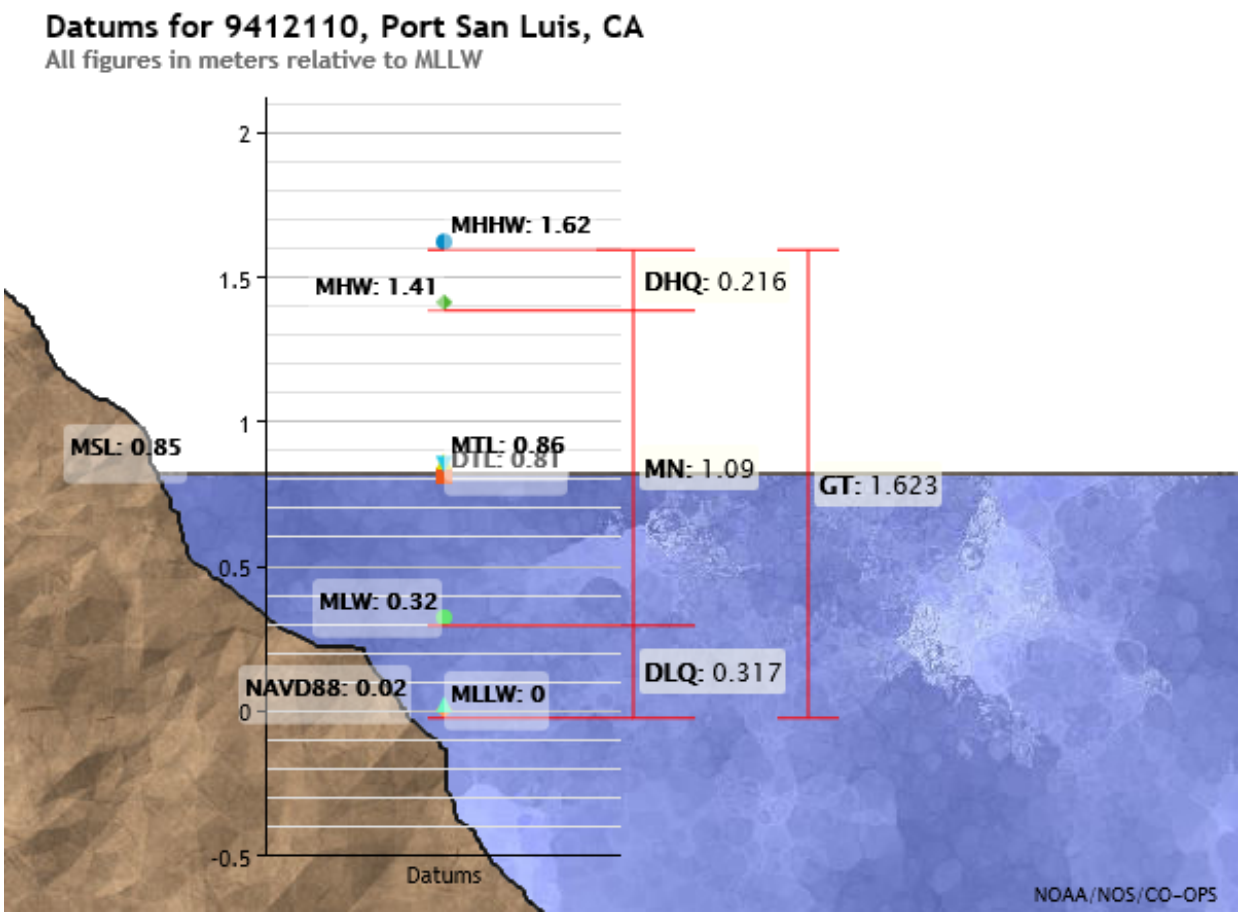
Morro Bay ISS Bathymetry Coverage - June 2019

Morro Bay Topobathy DEM Project

Figure 1

Survey Control

Survey reference control was derived from the existing U.S. Army Corps of Engineers (USACE) established benchmark 2298 C 1978 NOS. The benchmark is a 3.5-inch brass disk located on a center island in Embarcadero Street near the Harbor District offices (35˚22’16.5634”; 120°51’26.9807”). This benchmark is a 3rd order benchmark verified in June 2006 with an elevation of 4.698 m Mean Lower Low Water (MLLW) epoch 83-01 (Appendix 1). The benchmark is tied to a number of other benchmarks around the northern portion of Morro Bay and the USACE updated the tie-in sheet in November 2019 after they set an additional 3rd order 3.5-inch brass disk benchmark, MB-9R set on a walkway near Coleman Beach in October 2009. Vertical control for the benchmarks is from Port San Luis. The tidal datum correction between MLLW and North American Vertical Datum of 1988 (NAVD88) was taken to be NAVD88 equals 0.024 m above MLLW based on the NOAA Port San Luis California tide Station 9412110.



Tidal data equivalencies at the tidal reference station of NOAA Stn. 9412110, Port San Luis, CA.

RTK correction was derived from the California Real Time Network UNAVCO Plate Boundary Observatory (PBO) Station P523 (Station Los Osos CS2006) located at Los Osos, California (35.304˚

Lat.; -120.860˚ Long.). At the most extreme northerly end of the survey area, the horizontal error is increased to 17.5 mm and the vertical error is increased to 35 mm based on the maximum distance from the RTK base.

For the bathymetric products of this survey, the horizontal datum is to be NAD83 (2011) – GRS 1980 Spheroid with a vertical datum of NAVD88 (Geoid 12B). The horizontal projection is UTM Zone 10N and both the horizontal and vertical units are in meters.

Survey Methods

Acoustic bathymetric surveys were conducted using vessel-based interferometric sidescan sonar (ISS) survey methods. The vessel was the M&A survey vessel, Ocean King I, a 24-foot welded aluminum vessel manufactured by Weldcraft. The boat is outfitted with an integrated survey system suitable for completing a variety of acoustic and video surveys. The vessel was custom constructed to isolate survey electronics from noise associated with vessel electronics and radio frequency (RF) interference. Survey equipment specifications sheets are provided in Appendix 2.

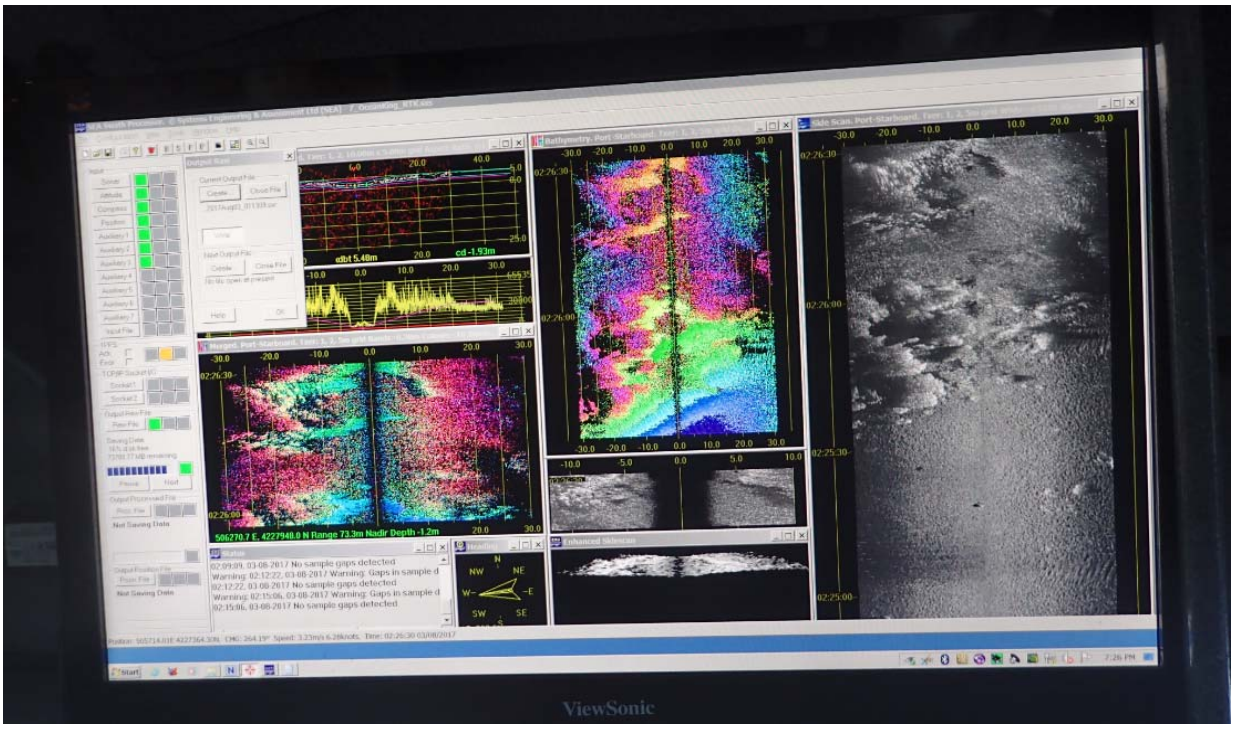
The survey equipment for the project work was an interferometric sidescan sonar system manufactured by Systems Engineering & Assessment, Ltd (SEA). The system used was a SEA SWATHplus-H sonar operating at 468kHz on two channels, port and starboard. The across track resolution for the system is 1 cm and the system has an azimuth beam width of 0.55˚. The transmit pulse length for the sonar is variable between 4.3µs up to 250µs. The system has a maximum operating range of 80 meters per channel and was operated at 31 meters per channel throughout the present survey.

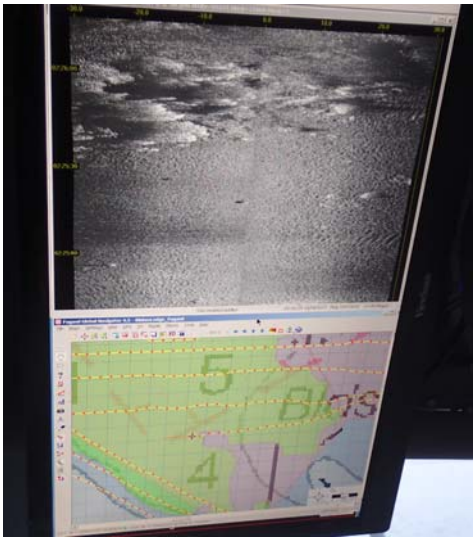
M&A survey vessel Ocean King I in Morro Bay

Speed of sound correction was provided by a Valeport mini SVP sound velocity profiler. The system has an operating range between 1375 and 1900 meters per second (m/s) and an accuracy of ±0.02 m/s. Motion control correction for the vessel pitch and roll was provided by a Ship Motion Control (SMC) SMC-108 inertial motion unit (IMU). The dynamic accuracy for pitch and roll is ±0.03˚ root-mean square (rms).

Vessel positioning, horizontal and vertical, as well as heading, heave and yaw were provided by a dual antenna Hemisphere VS330 real time kinematic (RTK) global positioning system (GPS). The system used L1/L2 band, GLONASS and GPS signals at a 20 Hz update rate. The RTK positional accuracy capabilities of the equipment were 10 mm plus 1 part per million ppm horizontal and 20 mm plus 2ppm vertical based on the distance between the receiver and the RTK base station. Heading accuracy is 0.05˚ rms.

Data integration from the survey sensors is handled by an on-board computer that collects survey data files, provides navigation and coverage tracking data to the survey crew and provides information and alarms for sensor operational status and variance from normal operating parameters.





Two monitors display survey data including system, status, signal to noise data, bathymetry, sidescan reflectance data, GPS including RTK and satellite counts, navigation charts and tracklines, and survey coverage. An additional multifunction marine unit is used to monitor engine status, serve navigation charts, display radar data, and provide a singlebeam fathometer to support vessel operations at night and in very shallow water. A

The permanent integration of the system components on the ridged vessel framework limits sources of equipment calibration error. Nevertheless, as an element of the survey a patch test was performed to identify instrument alignment issues allowing for adjustment of offsets and calculation of residual biases influenced by the dynamics of the survey vessel, alignment of the instruments, and positional latency. Calculation of the horizontal and vertical offsets between each of the sensors is followed by a series of field-based measurements known as patch tests wherein survey swaths are navigated in overlapping patterns at multiple speeds in order to identify instrument alignment and timing error. These are then corrected for by fine tuning of offsets applied to the collection files. Results of the patch test are used to calculate a pitch, roll and heading offset and navigation latency. Additional calibration measures are performed including comparison of nadir depths with lead line soundings and sound velocity profiles.

Surveys were conducted at an along track vessel speed of 0.5 to 4.5 knots with slower speeds traveled within the constrained developed areas and shallow waters and faster speeds occurring in deeper portions of the bay. Surveys were conducted across multiple tides taking advantage of the higher tides to complete the shallow water surveys and the lower tides to conduct surveys in deep water.

Survey vessel tracklines (June 17-19, 2019)

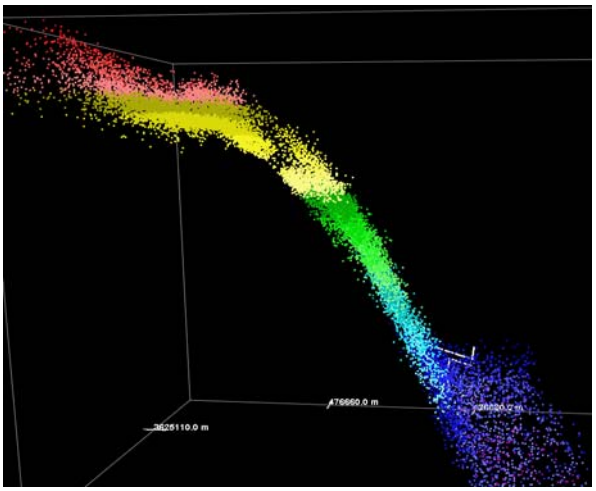
In general, the survey vessel traveled along parallel tracklines spaced to provide nadir gap overlap between adjacent tracks. For sidescan sonar surveys, ideal water depths are greater than 1 meter of clearance between the transducer head and the seafloor. Depths shallower than this tend to suffer from increased hull noise due to multipath reflectance and also suffer from reduced range in areas with eelgrass or other features that extend off the bottom. As a result, this creates severely limited survey windows in very shallow waters, increased noise at swath margins and a necessity for tighter line spacing in extreme shallows such as in the southern end of the bay along small tidal channels than in deeper portions of the bay along the main channel and in the northern portions of the bay. In the south bay where small

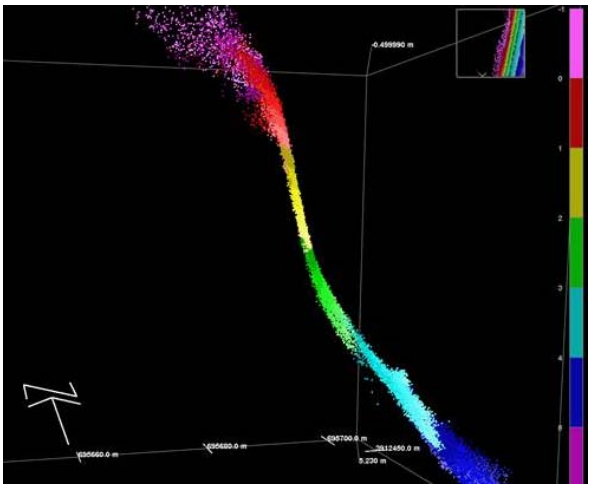
and sometimes circuitous channels occur, multiple survey paths at different angles were navigated to garner coverage in the bottoms of channels, especially in deep narrow channels at bends where the bottom may be obscured from multiple angles.

Data Processing

Bathymetric data collected by interferometry consists of dense point clouds of individual measured returns defining the elevation of the bottom at any given position within the survey swath. Each point is an individual measurement of a reflected return at a given position in an x,y,z coordinate space. In relatively simple environments with hard bottoms the returned point cloud is tightly clustered along the true surface of the bottom. However, in more complex environments point clouds are more diffuse and may represent a variety of surfaces and false surfaces from which sound is reflected. This creates artifacts that must be cleaned in order to reduce error around the true surface. After cleaning, the residual points are flattened by binning the points into singular values representing the mean of all remaining points within a defined grid area.

To clean data, multiple single swaths were imported collectively into the SEA Grid Processor Gridding and Visualization Application© in order to create a composite point cloud for an area of the bay. The data were then subjected to standard deviation and de-spiking filters to remove outliers and minimize noise in the data. Manual cleaning was then conducted by applying a vertical exaggeration to the point cloud in order to separate the cloud in order to help illuminate areas of wide variance. A strip editing feature was used to incrementally move through the point cloud data in a multi-axis three dimensional viewer that allowed pivoting each segment of the point cloud in a manner that allowed for observation and deletion of erroneous points. The result is a cleaned file wherein artifacts of spurious returns are reduced by removing excess points that do not cluster along the bottom surface. In some cases eelgrass formed a solid wall with no points in the point cloud representing the actual bottom within the eelgrass beds. In such areas, all points in the point cloud were removed thus leading to voids in the processed surface. Upon

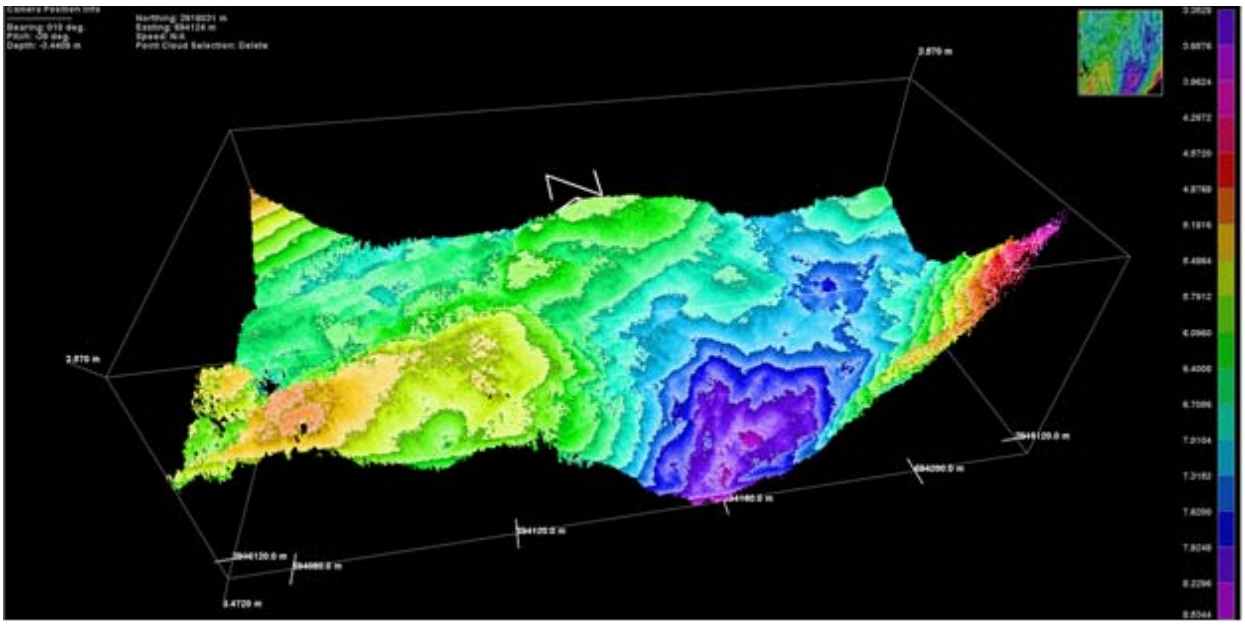




Uncleaned point-clouds displayed in 3D at half density within SEA Grid Processor. Note the nadir gap crossing near the top of slope in upper image.

completion of cleaning, the individual grid mosaics were flattened to a single layer wherein each of the defined grids, in the case of the present bathymetric survey, 0.5 meter x 0.5 meter grids, were represented by a single value that was the mean of all points within the grid. After processing files into flattened grids, the grids were then merged together by averaging the values within the grids such that a single grid of the surveyed area of the bay was produced.

Data file sizes are exceptionally large as dense point clouds and are simplified through the process as spurious points are deleted and files are reduced to grids and ultimately text files to develop grid based raster bathymetry. Because of file size constraints only a small portion of the bay can be managed in the SEA Grid Processor, although a small area may include several million points at the commencement of cleaning. As the data are simplified the survey area that can be managed in the software increases substantially. At the final product level, the grid was collapsed to a 1m pixel resolution thus allowing the entire Morro Bay survey area to be contained in two SEA Grid Processor files.

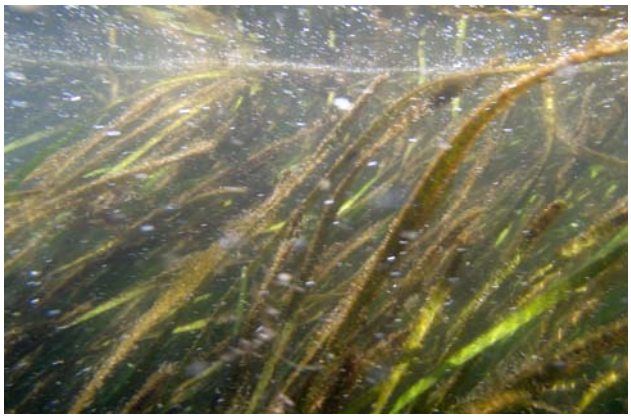


A segment of complex bottom near Coleman Beach during the point cloud cleaning process.

The final processed output meets and exceeds the International Hydrographic Organization (IHO) standards for Special Order surveys. The collected bathymetry was delivered to Quantum Spatial electronically as a zipped folder containing .txt files to be merged with the LiDAR data into a seamless composite 1m resolution topobathy DEM in ESRI Grid format.

Survey Limitations

The Morro Bay acoustic bathymetric survey was performed with generally few data collection and processing issues and the data collected and delivered is believed to provide the most comprehensive subtidal data set ever prepared for Morro Bay. Further, the integration of these data with the QSI LiDAR data provides the best comprehensive topobathy ever produced for Morro Bay. However, a few issues are of note in that they have both influenced the presence of data gaps and they might be avoidable or reduced in the future if this exercise is conducted again within Morro Bay and the lessons learned may be applicable elsewhere in other similar systems. First, eelgrass in Morro Bay, especially in northern Morro Bay can be extremely tall and extremely dense. At Coleman Beach, some of the eelgrass can be over 2 meters tall. This eelgrass impeded efforts to obtain bathymetry representing the bottom within the developed beds. As a result, gaps exist in the data where dense eelgrass beds occur. This issue may have been reduced had surveys been conducted during winter months when eelgrass is generally more sparse and it would be expected that penetration of the bed by sonar would have improved coverage. An alternative would have been the integration of single-beam sonar surveys across the eelgrass beds in order to develop profiles of the bottom that could be used to control an interpolated infilling of the data gaps.



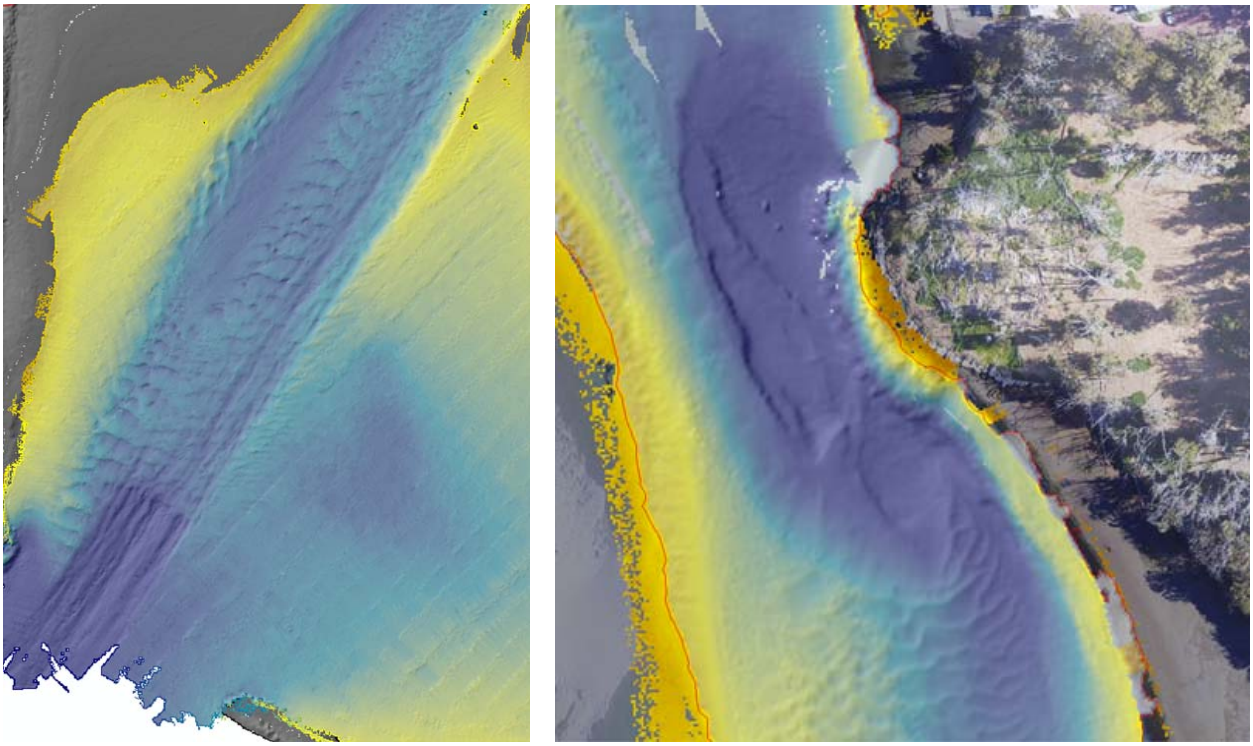
Photographs showing eelgrass on the surface of Morro Bay at a moderate low tide and also depicting the density of eelgrass subsurface. The eelgrass is of an adequate density ahd length to severely limit sonar penetration from sidescan equipment. Singlebeam sonar may be used to develop linear profile data that could be used for interpolated infill of bottom contours within the eelgrass beds.

A second issue that was encountered was that the summer timing of the survey meant that the survey corresponded to intensive waterside use of the Embarcadero docks and piers. In some cases, vessels were stacked three deep with adjacent vessel to vessel side-tying being common. This practice highly restricted access within the developed waters and on several occasions the widths of vessels on piers combined with the piers themselves did not allow complete swath coverage from one side of the pier to the next. This resulted in small gaps being missed within the more urbanized waters.

Conclusions

The acoustic sonar bathymetric survey conducted in Morro Bay in June 2019 was successful in providing necessary support to the LiDAR surveys in completion of a single and complete topobathy survey of the bay at a high resolution suitable to support hydrodynamic modeling and change analyses investigations. The joint LiDAR and acoustic bathymetric products were prepared efficiently capitalizing on the strengths of both technologies within area where they were best suited. Further, the overlap of data from the differing sources allowed for improvements to the topobathy DEM by leveraging comparisons of each to identify areas of agreement and disagreement to further enhance the accuracy of the product.

In addition to providing a valuable tool for numeric analyses, the data quality and resolution of the survey grid also provides a uniquely valuable tool for exploring some of the system energetics by examination of the bedform patterns of the bay that have been generated by water movement and dredging. Most uniquely, the northern channel of Morro Bay was dredged by the hopper dredge Yaquina less than a month prior to completion of the topobathy survey. As a result, it is possible to view changes in bedform within areas just recently disturbed by dredging and garner an appreciation of the extent of sand movement within the main channel over a very short period of time.



Major bedform scour features in Morro Bay located at the outer breakwater jaws (left) and at the bedrock constriction of Fairbanks Point in mid bay (right). Other areas exhibit greater or lesser degress of sediment wave topology that conveys much about current velocities in the area.

Appendix 1.

Survey Control Monuments

COUNTRY:	TYPE OF MARK:	STATION:	
U.S.A.	3 ½" Brass Disc	2298 C	
LOCALITY:	STAMPING ON MARK:	AGENCY (CAST IN MARKS)	ELEVATION:
Morro Bay, California	2298 C 1978	NOS	4.698 M
LATITUDE:	LONGITUDE:	DATUM:	DATUM:
35° 22' 16.5634" N	120° 51' 26.9807" W	NAD 83 epoch 2004.0	MLLW epoch 83-01
(NORTHING)	(EASTING)	GRID AND ZONE:	EST. BY (AGENCY):
711 267.076 M	1 740 368.270 M	CA Zone V	USACE from Port San Luis
(NORTHING)	(EASTING)	GRID AND ZONE:	DATE: / ORDER:
2 333 548.73 FT	5 709 858.23 FT	CA Zone V	June 06 / 3rd

TO OBTAIN GRID AZ. ~~(ADD)~~(SUB) TO THE GEODETIC AZIMUTH

TO OBTAIN GRID AZ. (ADD)(SUB) TO THE GEODETIC AZIMUTH

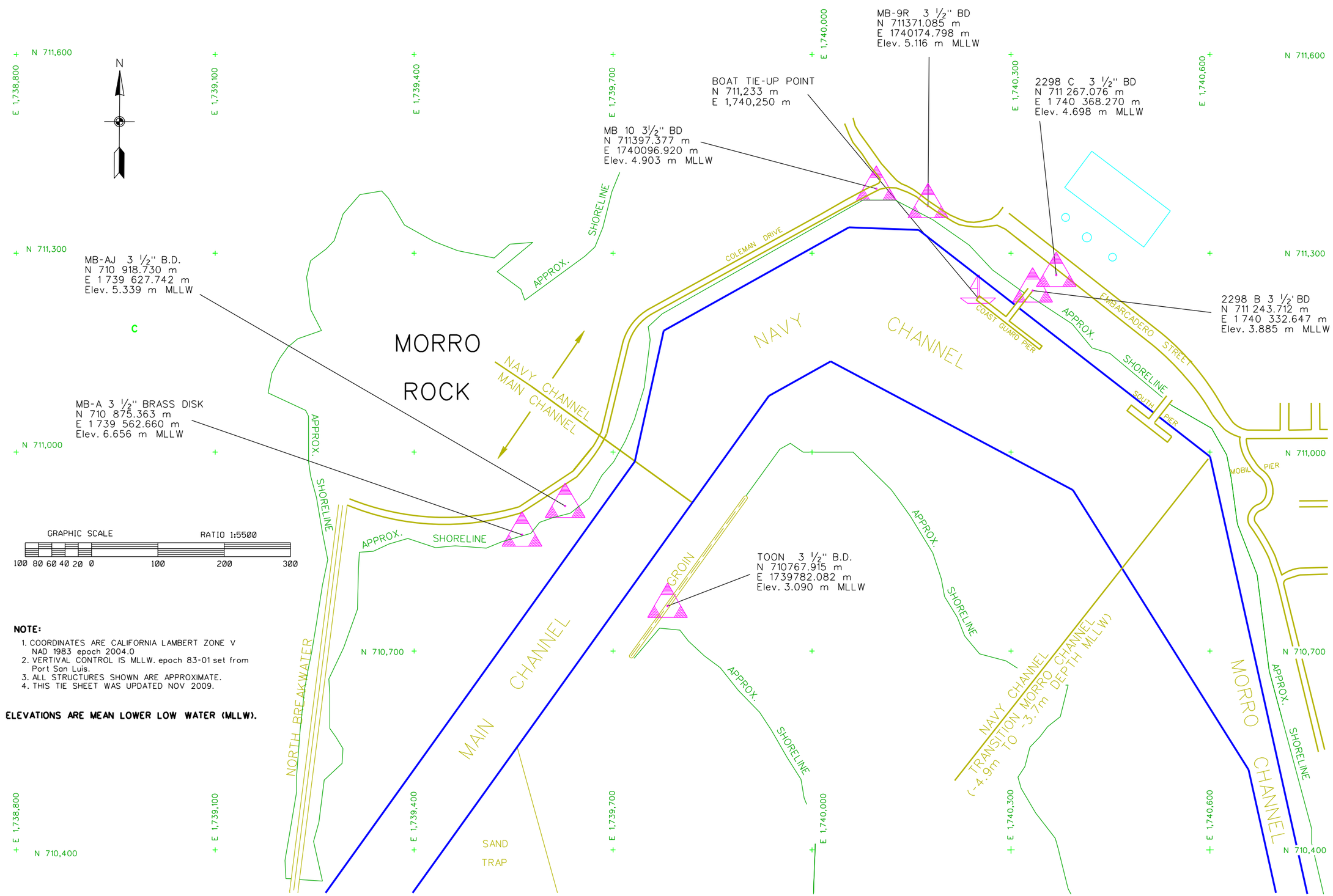
OBJECT	AZIMUTH OR DIRECTION (GEODETIC)(GRID)(MAGNETIC)	BACK AZIMUTH	GEODETIC DIST. (METERS)(FEET)	GRID DIST. (METERS)(FEET)

THE STATION IS LOCATED NEAR: MORRO BAY (CITY), SAN LUIS OBISPO (COUNTY), CALIFORNIA (STATE).

TO REACH THIS STATION: from Hwy. 1 exit Morro Bay Blvd., continue west to Main St. Turn north on Main St. and travel 0.2 mi. to Beach St. Turn west on Beach St. and travel 0.2 mi. to Embarcadero St. Turn north on Embarcadero St. and travel 0.3 mi to the Harbor Patrol office.

THIS STATION IS LOCATED: set flush in the concrete median of Embarcadero Street at the entrance to the North T Pier and just northwest of the last planting area in the median.

THIS STATION IS A: 3 ½" Brass Disc.



NOTE:

1. COORDINATES ARE CALIFORNIA LAMBERT ZONE V NAD 1983 epoch 2004.0
2. VERTIVAL CONTROL IS MLLW. epoch 83-01 set from Port San Luis.
3. ALL STRUCTURES SHOWN ARE APPROXIMATE.
4. THIS TIE SHEET WAS UPDATED NOV 2009.

ELEVATIONS ARE MEAN LOWER LOW WATER (MLLW).

US Army Corps of Engineers
Los Angeles District

Rev.	Date	Description	Rev.	Date	Description	Rev.
			New monuments set	Nov 09		

Designed by: | Date: | Rev.
Dwn by: RKS | Ckd by: | Design file no. |
Reviewed by: | Drawing code:
Submitted by: Chief, Arch. Branch | File name: Plot date: Plot scale:

US ARMY CORPS OF ENGINEERS
LOS ANGELES DISTRICT
SURVEY/ MAPPING SECTION

NAVIGATION IMPROVEMENT INFORMATION

MORRO BAY HARBOR
TIE SHEET
ELECTRONIC/ GPS SURVEY

Sheet reference number:

Sheet 1 of 1

Appendix 2.

Bathymetric Survey Equipment

SWATH*plus*

A low cost, high performance bathymetry and sidescan system, suitable for use on dedicated survey vessels and vessels of opportunity.

"SWATHplus gives exceptional productivity in shallow water whilst meeting our client's stringent accuracy requirements. The low capital cost, reliability and robustness make them our swath bathymetry system of choice for many applications." - GEMS Survey.

"Operating swath of the bathymetric system ranged from 15 to 20 times water depth in depths less than 15 m." - US Geological Survey (USGS).

SWATH*plus* is an interferometric, wide-swath sonar system for surveying underwater surfaces, providing co-registered, high-density bathymetric data and seafloor imagery. Processed data outputs include digital terrain models and sidescan quality seafloor images. It is equally well suited for use at sea, inland waterways and on lakes.

Why SWATH*plus*?

- wide swath width in shallow water or low altitude
- co-registered high-quality bathymetry and seafloor imagery
- high data count gives high special resolution up to the swath edge
- low cost of ownership compared with most beamforming multibeams
- lightweight, compact, lower power requirement and highly portable - facilitates simple and rapid deployment
- reduced survey effort and data turn-around times
- data exportable to industry-standard applications, such as CARIS
- meets tight international data standards, such as IHO survey requirements

Applications

- shallow water hydrographic surveys
- navigational charting
- environmental monitoring
- dredging operations
- river, harbour, lake and dam management
- marine archaeology
- wreck location
- pipeline and cable routeing survey and inspection
- hull inspection
- harbour security

Email us for more information

Datasheet for SWATHplus (English PDF)

Datasheet for SWATHplus (Portuguese PDF)

Datasheet for SWATHplus (Spanish PDF)

Aerospace
- MEMS/SiREUS

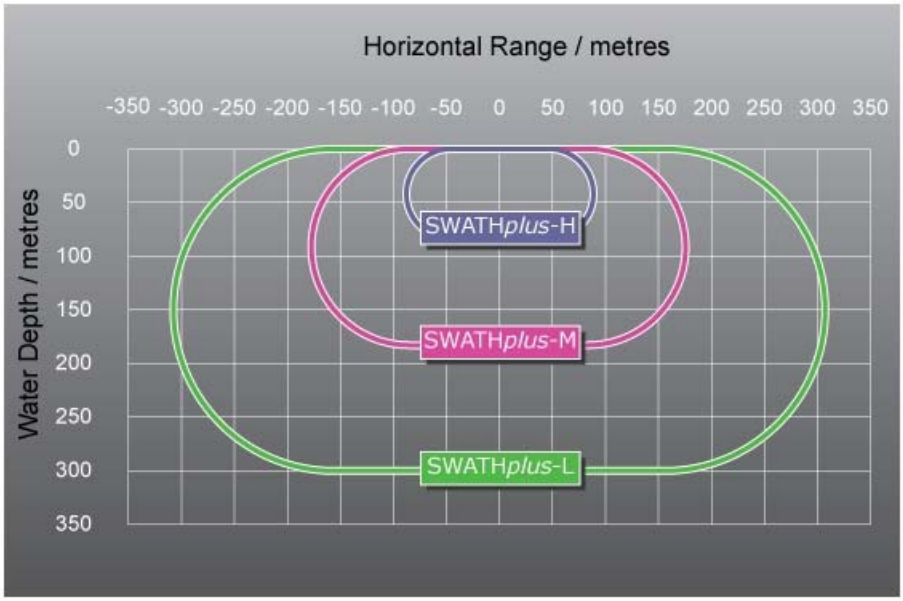
Defence
- Mobile Data Node
- Network Interface Unit
- VIBRAtrak
- Brahan-SAR

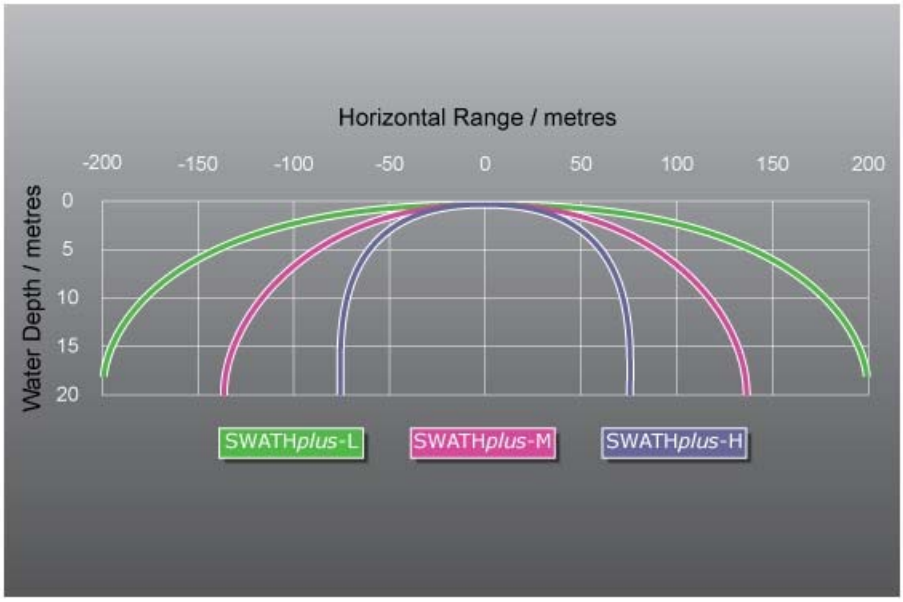
Transport
- ROADflow

Simulation
- DECKsim
- CSF

Communications
- Mobile Data Node

- military rapid environmental assessment





Presentation

- Download the SWATHplus presentation (Powerpoint 1.42mb)

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A company incorporated in England and Wales No: 2430846

Telephone: +44 1373 852 000 | Fax: +44 1373 831 133 | Email: info@sea.co.uk

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SWATHplus Specifications

SWATH*plus* - Wide Swath Bathymetry & Sidescan

A low cost, high performance bathymetry and sidescan system, suitable for a portable or fixed hull installation.

SWATH*plus* is a pole or hull-mounted swath bathymetry survey sonar that can achieve swath widths of over 12 times the water depth. Fully flexible and very compact, a pole mounted SWATH*plus* can be used from almost any vessel of opportunity, for surveying in water depths between zero and 300 metres.

SWATH*plus* is easily integrated into a survey suite, and produces a uniquely high data density and resolution at an accuracy that meets the requirements of hydrographic applications. It also provides integrated bathymetry and sidescan imaging from the same sonar system, with a variety of real time displays and processing options. Operating in Microsoft Windows and with full on line help/manual, the system is easy to operate and robust.

During the survey the sonar stores all raw data output from the transducers while the real time displays allow processing and QA. Data processing abilities include swath generation with speed of sound profile and motion correction, swath gridding and fairsheet plots. Final data sets consist of correct positional xyz and a (amplitude) data. These xyza DTMs can be interrogated, viewed, exchanged and printed by SWATH*plus* software and third party charting and DTM display software. Processing may be carried out on the survey workstation or another PC running Microsoft Windows XP or Vista

Specifications

SWATH*plus* is available in three frequency versions, 117 kHz and 234 kHz and 468 kHz. The system accuracy of both versions exceeds the latest IHO specifications, as set out in IHO Standards for Hydrographic Surveys, Special Publication 44.

Performance Parameters*

	SWATH*plus*-L	**SWATH*plus*-M**	**SWATH*plus*-H**
Sonar Frequency	117 kHz	234 kHz	468 kHz
Recommended Depth to*	300m	100m	50m
Maximum Swath Width	600m	300m	100m
Swath Width*	Up to 15 times depth, up to maximum swath width(typically 7-12 times, depending on water conditions and bottom type)		

Aerospace
- MEMS/SiREUS

Defence
- Mobile Data Node
- Network Interface Unit
- VIBRAtrak
- Brahan-SAR

Transport
- ROADflow

Simulation
- DECKsim
- CSF

Communications
- Mobile Data Node

Azimuth	1.7°	1.1°	1.1°
Resolution Across Track	5cm	2cm	1cm
Transmit Pulse Length	17µs to 1 ms	8.5 µs to 500 µs	4.3 µs to 250 µs

Dimensions*

Transducer	Height (mm)	Width (mm)	Depth (mm)	Weight in Air (kg)	Weight in Water (kg)
SWATHplus-L	235	550	90	13	1.6
SWATHplus-M	160	350	60	6	0.9
SWATHplus-H	100	215	42	1	0.1

*Parameters are given for guidance only and may vary according to survey conditions. All specifications subject to change without notice.

Technical Specification

Universal Mounting System

- Permits bow or side mounting
- Readily deployed on vessel of opportunity

System Transducers

- Compact and lightweight system
- 3 frequency options 468 kHz, 234 kHz and 117 kHz

Transducer Interface Unit

- Real time sonar data acquisition to PC
- 2 SWATH*plus* transducer connectors: MIL-C-26482
- 2 USB connections to PC computer
- 2 signal ground connections: screw terminal
- Sync port; supports trigger pulse output to echosounders
- 1 Pulse Per Second port for precise timing: BNC
- 230 V mains in: IEC connector 100-240 V AC mains, < 20 W
- Size 120 mm H x 290 mm W x 285 mm D

System Computer and Software

SWATH*plus* interfaces to high performance Laptop or Desktop PC running Microsoft Windows XP and Vista Laptop may be supplied or user selected for best utilisation of off-the-shelf interface solutions to suit survey system requirements.

Head Office Address: SEA, Beckington Castle, 17 Castle Corner, Beckington, Frome, Somerset BA11 6TA United Kingdom
A company incorporated in England and Wales No: 2430846

Telephone: +44 1373 852 000 | Fax: +44 1373 831 133 | Email: info@sea.co.uk

Vector™ VS330 GNSS Receiver

Professional Positioning and Heading Receiver

key features

- Athena™ RTK, Atlas® L-band, Beacon and SBAS capable
- Extremely accurate heading with baselines up 50 m
- Multi-frequency GPS/GLONASS/BeiDou RTK capable
- Automatic antenna baseline survey
- Maintain heading and position lock when more of the sky is blocked
- Runs Athena core GNSS engine offering improved initialization times, robustness in difficult environments, performance over long baselines and under scintillation
- Integrated gyro and tilt sensors help deliver fast start-up times and provide heading updates during temporary loss of satellites

atlas

Experience the Vector VS330 with our powerful Athena GNSS core engine technology. The Vector VS330 supports precise marine, dynamic positioning, and land applications that require RTK positioning and precise heading performance.

The Vector VS330 utilizes all of the innovations in Hemisphere GNSS' Eclipse™ Vector technology. Our optimized Eclipse Vector technology brings a series of new features to the Vector VS330 including heave, pitch, and roll output, and more robust positioning and heading performance.

The Vector VS330 receiver, with its display and user interface, can be conveniently installed near the operator. The two antennas are mounted separately with a user-determined separation to meet the desired heading accuracy. The fully-subscribed Vector VS330 uses Atlas L-band, Beacon, and SBAS for differential positioning. Our firmware allows the VS330 to smoothly transition between DGNSS systems.

Hemisphere®

precision@hgnss.com
www.hgnss.com

Vector VS330 GNSS Receiver

GNSS Receiver Specifications

Receiver Type:	Vector GNSS L1/L2 RTK Receiver
Signals Received:	GPS, GLONASS, BeiDou, and Atlas
Channels:	540
GPS Sensitivity:	-142 dBm
SBAS Tracking:	3-channel, parallel tracking
Update Rate:	10 Hz standard, 20 Hz optional
Timing (1PPS) Accuracy:	20 ns
Rate of Turn:	100˚/s maximum
Compass Safe Distance:	30 cm (with enclosure)[5]
Cold Start:	60 s (no almanac or RTC)
Warm Start:	20 s typical (almanac and RTC)
Hot Start:	5 s typical (almanac, RTC and position)
Heading Fix:	20 s typical (valid position)
Maximum Speed:	1,850 mph (999 kts)
Maximum Altitude:	18,288 m (60,000 ft)
Differential Options:	SBAS, Beacon, External RTCM, Atlas L-band and Athena RTK

Positioning and Heading Accuracy

RMS:	Horizontal	Vertical
Single Point [1]:	1.2 m	2.5 m
SBAS (WAAS) [1]:	0.3 m	0.6 m
Code Differential GNSS [1]:	0.3 m	0.6 m
L-Band [2]:	0.08m	0.16 m
RTK [1, 3]:	10 mm + 1 ppm	20 mm + 2 ppm
Heading Accuracy:	0.2˚ rms @ 0.5 m antenna separation 0.1˚ rms @ 1.0 m antenna separation 0.05˚ rms @ 2.0 m antenna separation 0.02˚ rms @ 5.0 m antenna separation	
Pitch/Roll Accuracy (RMS):	1˚	
Heave Accuracy (RMS):	30 cm (DGPS) [5],10 cm (RTK) [1,3]	

Beacon Receiver Specifications

Channels:	2-channel, parallel tracking
Frequency Range:	283.5 to 325 kHz
Operating Modes:	Manual, Automatic, and Database
Compliance:	IEC 61108-4 beacon standard

L-Band Receiver Specifications

Receiver Type:	Single Channel
Channels:	1530 to 1560 MHz
Sensitivity:	-130 dBm
Channel Spacing:	5 kHz
Satellite Selection:	Manual or Automatic
Reacquisition Time:	15 sec (typical)

Communications

Serial Ports:	2 full-duplex RS232, 1 half-duplex RS422 port
USB Ports:	1 USB-A
Baud Rates:	4800 - 115200
Correction I/O Protocol:	RTCM SC-104, L-Dif™ [6], RTCM v2 (DGPS), RTCM v3 (RTK), CMR (RTK), CMR+ (RTK) [3]
Data I/O Protocol:	NMEA 0183, Hemisphere GNSS binary [6]
Timing Output:	1 PPS (CMOS, active high, rising edge sync, 10 kΩ, 10 pF load)

Power

Input Voltage:	8-36 VDC
Power Consumption:	5.3 W nominal (GPS L1/L2 + GLONASS L1/L2) 7 W nominal (GPS L1/L2 + GLONASS L1/L2 + BeiDou B1/B2 + L-band)
Current Consumption:	0.44 A nominal (GPS L1/L2 + GLONASS L1/L2) 0.51 A nominal (GPS L1/L2 + GLONASS L1/L2 + BeiDou B1/B2 + L-band)
Power Isolation:	500 V
Reverse Polarity Protection:	Yes
Antenna Voltage:	5 VDC maximum 60mA
Antenna Short Circuit Protection:	Yes
Antenna Gain Input Range:	10 to 40 dB
Antenna Input Impedance:	50 Ω

Environmental

Operating Temperature:	-30°C to + 70°C (-22°F to + 158°F)
Storage Temperature:	-40°C to + 85°C (-40°F to + 185°F)
Humidity:	95% non-condensing
Mechanical Shock:	EP455 Section 5.14.1 Operational (when mounted in an enclosure with screw mounting holes utilized) EP455
Vibration:	Section 5.15.1 Random
EMC:	CE (IEC 60945 Emissions and Immunity) FCC Part 15, Subpart B CISPR22
Enclosure:	IP66 (IEC 60529)

Mechanical

Dimensions:	20.2 L x 12.0 W x 7.5 H (cm) 8.0 L x 4.7 W x3.0 H (in)
Weight:	~1.1 kg (~2.5 lbs.)
Status Indications (LED):	Power, Primary and Secondary GPS lock, Differential lock, DGPS position, Heading, RTK lock, L-band DGNSS lock
Power Switch:	Front panel soft switch
Power/Data Connector:	9-pin ODU metal circular
Power Connector:	2-pin ODU metal circular
Data Connector:	DB9 (sealed)
Antenna Connectors:	2 TNC (female)

Aiding Devices

Gyro:	Provides heading smoothing with GNSS. Drift rate is 1˚ per minute in heading for periods up to 3 minute when loss of GNSS has occurred [4]
Tilt Sensors:	Provide pitch, roll data, assist in fast start-up and heading reacquisition

1 Depends on multipath environment, number of satellites in view, satellite geometry, no SA, and ionospheric activity.

2 Requires a subscription

3 Depends on multipath environment, number of satellites in view, satellite geometry, baseline length (for differential services), and ionospheric activity.

4 Based on a 40 second time constant

5 This is the minimum safe distance measured when the product is placed in the vicinity of the steering magnetic compass. The ISO 694 defines "vicinity" relative to the compass as within 5 m (16.4 ft) separation.

6 Hemisphere GNSS proprietary

NavtechGPS®
+1-703-256-8900 or 800-628-0885
info@NavtechGPS.com
www.NavtechGPS.com

Hemisphere®

Hemisphere GNSS, Inc.
8515 E. Anderson Drive
Scottsdale, AZ, USA 85255

Toll-Free: +1-855-203-1770
Phone: +1-480-348-6380
Fax: +1-480-270-5070
precision@hgnss.com
www.hgnss.com

miniSVS Sound Velocity Sensor

Our unique digital time of flight technology gives unmatched performance figures, with signal noise an order of magnitude better than any other sensor. The miniSVS is available in a selection of configurations and with optional pressure or temperature sensors. There are a variety of sizes to suit many applications.

miniSVS - still the most accurate sound velocity sensor in the world. Nothing else comes close.

Sound Velocity Measurement

Each sound velocity measurement is made using a single pulse of sound travelling over a known distance, so is independent of the inherent calculation errors present in all CTDs. Our unique digital signal processing technique virtually eliminates signal noise, and gives almost instantaneous response; the digital measurement is also entirely linear, giving predictable performance under all conditions.

Range:	1375 - 1900m/s	
Resolution:	0.001m/s	
Accuracy:	Dependent on sensor size	
100mm	Random noise (point to point)	±0.002m/s
	Max systematic calibration error	±0.013m/s
	Max systematic clock error	±0.002m/s
	Total max theoretical error	**±0.017m/s**
50mm	Total max theoretical error	±0.019m/s
25mm	Total max theoretical error	±0.020m/s

Acoustic Frequency: 2.5MHz

Sample Rate: Selectable, dependent on configuration

Rate	SV	SV+P	SV+T
Single Sample	•	•	•
1Hz	•	•	•
2Hz	•	•	•
4Hz	•	•	•
8Hz	•	•	•
16Hz	•	•	•
32Hz	•	•	
60Hz	•		

Optional Sensors

The miniSVS may be optionally supplied with either a pressure or temperature sensor (but not both). Data is sampled at the rates shown above

Sensor	**Pressure**	**Temperature**
Type	Strain Gauge	PRT
Range	5, 10, 50, 100 or 600 Bar	-5°C to +35°C
Resolution	0.001% range	0.001°C
Accuracy	±0.05% range	±0.01°C

Data Output

Unit has RS232 & RS485 output, selected by command code. RS232 data may be taken directly into a PC over cables up to 200m long, whereas RS485 is suitable for longer cables (up to 1000m) and allows for multiple addressed units on a single cable.

Baud Rate: 2400 - 115200 (NB. Low baud rates may limit data rate)
Protocol: 8 data bits, 1 stop bit, No parity, No flow control

Electrical

Voltage: 8 - 30vDC
Power: 0.25W (SV only), 0.35W (SV + Pressure)
Connector: Subconn MCBH6F (alternatives on request)

Data Format

Examples of data formats are:
<space>{sound_velocity}<cr><lf>
<space>{pressure}<space>{sound_velocity}<cr><lf>
<space>{temperature}<space>{sound_velocity}<cr><lf>

SV: Choose from mm/s (1510123), m/s to 3 decimal places (1510.123), or m/s to 2 decimal places (1510.12)

Pressure: If fitted, pressure is always output in dBar with 5 digits, with a decimal point, including leading zeroes if necessary. Position of the point is dependent on sensor range, e.g.

50dBar	47.123
100dBar	047.12
1000dBar	0047.1

Temperature: If fitted, temperature is output as a 5 digit number with 3 decimal places and leading zeroes, signed if negative, e.g. 21.456
02.298
-03.174

Physical

Please refer to factory for detailed dimensions if required.

Depth Rating: 6000m (Titanium), 500m (acetal)
Weight: 1kg (housed type)
Housing & Bulkhead: Titanium or acetal, as selected
Transducer Window: Polycarbonate
Sensor Legs: Carbon Composite
Reflector Plate: Titanium.

Ordering

All systems supplied with operating manual and carry case. OEM units come with a test lead, housed units with a 0.5m pigtail.

Configuration	100mm	50mm	25mm
Titanium Housed	0652004	0652005	0652006
Acetal Housed	0652045	0652046	0652047
Bulkhead OEM	0652001	0652002	0652003
Remote OEM	0652007	0652008	0652009
Titanium + Pressure	0652004-P	0652005-P	0652006-P
Titanium +Temperature	0652004-T	0652005-T	0652006-T

Datasheet Reference: miniSVS version 2b, June 2013

As part of our policy of continuing development, we reserve the right to alter at any time, without notice, all specifications, designs, prices and conditions of supply of all equipment

Valeport Limited, St. Peter's Quay Totnes, Devon, TQ9 5EW UK
t. +44 (0)1803 869292 f. +44 (0)1803 869293 e. sales@valeport.co.uk w. www.valeport.co.uk

SMC IMU-10 Range

Motion Sensors

SMC has developed its IMU-10 range of Motion Sensors to meet the requirements of the hydrographic and marine sectors. The IMU range provides high accuracy motion measurement data in dynamic environment in all areas from small hydrographic vessels to large oil rigs in all weather conditions.

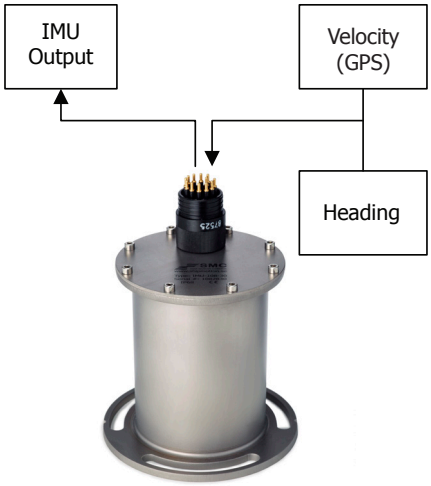
Key Specifications
- Roll & Pitch 0.03° (RMS) Dynamic Accuracy
- Heave 5 cm or 5 %
- Accelerations / Velocities
- Inputs, Velocity and Heading
- Various Industry Protocols NMEA
- 2 years warranty

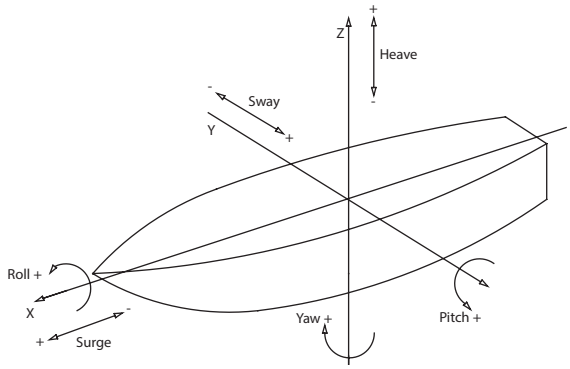
The SMC IMU uses solid state gyros and accelerometers to provide real time motion measurements with high dynamic accuracy even during accelerations. RS232 or RS422 outputs with RS232 velocity and heading inputs for aiding furing vessel turns. High quality titanium design, construction and assembly produce an IMU with an extremely high reliability in the most demanding marine environment.

Every SMC IMU is individually calibrated and tested, inside a calibration machine with a controlled temperature environment between 0 and +55 degrees Celsius.

The SMC IMU is supplied with a data distribution unit, cables and windows based software for ease of set up and configuration. The configuration software enables the user to configure the IMU parameters for the installation.

The SMC IMU is available in a variety of design and depth options.





SMC IMU Motion Sensors

Datasheet

IMU-10x-30

IMU-10x

Technical Specifications	IMU-106	IMU-107	IMU-108
Roll / Pitch	N/A	Yes	Yes
Accelerations X, Y, Z	N/A	Yes	Yes
Heave	Yes	N/A	Yes
Performance			
Angle Accuracy static	N/A	0.02º RMS	0.02º RMS
Angle Accuracy Dynamic @ ±5º simultaneous roll and pitch	N/A	0.03º RMS	0.03º RMS
Resolution Angle	N/A	0.001º	0.001º
Resolution Heave	0.01m	N/A	0.01m
Angle range Roll/Pitch	± 30º	± 30º	± 30º
Heave range	±10m	N/A	±10m
Heave Accuracy	5cm or 5%	N/A	5cm or 5%
Acceleration accuracy	N/A	0.01 m/s^2 RMS	0.01 m/s^2 RMS

Communications

IMU Configuration Software	The IMU is shipped with SMC configuration windows software allowing on site setup
Output Signal Protocol	Multiple, user selectable Output Protocols ASCII NMEA and binary
Communications Interface	Output RS422 and RS232. Analog with remote converter (optional) 2 x RS232 External inputs, (not available on all models) Velocity input formats RMC, RMA, VTG, VBV, VHW; Heading input formats HDT, HDG

Physical

Dimensions for IMU-10x (W x H)	tube Ø89, mounting plate Ø134, flange Ø110) x 127
Weight	~2 kg
Housing Material	Titanium

Environmental

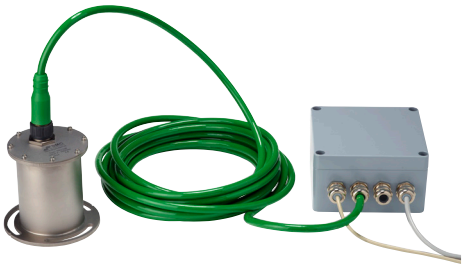
Temperature (absolute max)	0º to +55º Celsius (-10º to +65º); Storage Temperature -40º to +65º Celsius
Mounting Orientation	Vertical or Horizontal mounting (factory set)
Power requirements	12 - 30 VDC; 2 W
MTBF (computed)	50 000 hours
Depth rating	IP66 (standard); IP68 30 meter depth rated (optional)
Standard	Complies with the IEC 60945

Warranty & Support

Warranty	2-year Limited Hardware & Software Warranty
Support	Free Technical & Hardware support

Bundled Delivery

Junction Box	Multiple Input & Output Connection Case, including 10 m cable



SMC
SHIP MOTION CONTROL

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NOAA_Morro_Bay_Topobathymetric_LiDAR_Sonar_Integration_Report_V2

Final Audit Report 2019-09-18

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By:	Steven Schuetz (sschuetz@quantumspatial.com)
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