Cover Sheet (NOAA Form 76-35A)

NOAA FORM 76-35A

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL OCEAN SERVICE

Data Acquisition and Processing Report

Type of Survey HYDROGRAPHIC

Field No OPR-A366-KR-17

Registry No. H13011, H13012, H13013, & H13014

LOCALITY

State Maine

General Locality East Penobscot Bay

Sublocality Covers the regions of Isle Au Haut Bay, Deer Island Thorofare, Vicinity of Swans Island, and Eggemoggin Reach.

2017

CHIEF OF PARTY

Dean Moyles

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DATE

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Title Sheet (NOAA Form 77-28)

<table>
<tr><td>NOAA FORM 77-28
(11-72)
U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

HYDROGRAPHIC TITLE SHEET</td><td>REGISTER NO.

H13011, H13012, H13013 & H13014</td></tr>
<tr><td>INSTRUCTIONS – The Hydrographic Sheet should be accompanied by this form, filled in as completely as possible, when the sheet is forwarded to the Office</td><td>FIELD NO.</td></tr>
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Scale 1:10,000 Date of Survey LiDAR 06/26/2017 – 07/04/2017 MBES 07/03/2017 – 10/07/2017

Instructions dated May, 2017 Project No. OPR-A366-KR-17

Vessel R/V Theory (1217549), R/V Westerly (1231991), De Havilland DC-6 Twin Otter (N94AR)

Chief of party Dean Moyles

Surveyed by Moyles, Cox, Blackbourn, Reynolds, Rokyta, Mount, Farley, Klein, Lopez et al.

Soundings taken by echo sounder, hand lead, pole Dual Head Reson 7125 (R/V Theory, Over the Stern Mount), Dual Head Reson 7125 (R/V Westerly, Over the Stern Mount), SHOALS-1000T Airborne LiDAR Bathymetry (DC-6 Twin Otter)

Graphic record scaled by Fugro Personnel

Graphic record checked by Fugro Personnel

Protracted by N/A Automated plot by N/A

Verification by

Soundings in METERS at MLLW

REMARKS: The purpose of this survey is to update existing NOS nautical charts in a high commercial traffic area.

ALL TIMES ARE RECORDED IN UTC.

FUGRO PELAGOS INC.
6100 HILLCROFT STREET
HOUSTON, TX 77081

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A – Equipment

The R/V Theory, R/V Westerly, and the De Havilland DC-6 Twin Otter N94AR acquired all sounding data for this project. The equipment list and vessel descriptions are included in Appendix I.

Sounding Equipment

The R/V Theory, 37 feet in length with a draft of 2.5 feet, was equipped with an over-the-stern pole that housed an underwater IMU and dual head Reson 7125 multibeam sonars (dual meaning two independent systems). The Reson 7125 is a dual frequency system operating at 200 and 400 kHz. The systems were operated in the Intermediate beam mode option, which forms 512 across-track beams (in 400 kHz), with a maximum swath coverage of 140°. Operating modes such as range scale, gain, power level, ping rates, etc. were a function of water depth and data quality and were noted on the survey line logs (see the Descriptive Report Separate 1).

The Reson systems and IMU were installed on a special mounting plate, where each Reson 7125 was rotated approximately 15°. The Reson systems were installed in their normal SV2 bracket, which included an SV70 probe (located in the nose cone) and were attached to the mounting plate by a flange. Refer to Appendix I for more information and graphics.

All 7125 multibeam data files were logged in the s7k format using WinFrog Multibeam (WFMB) v3.10.23. The bathy data from each Reson 7125 (records 7004/7006 & 7027) were stitched together in WFMB to create one s7k file with each ping containing 1024 beams.

The R/V Westerly, 44 feet in length with a draft of 2 feet, was equipped with an over the stern pole that housed an underwater IMU and dual head Reson 7125 multibeam sonars (dual meaning two independent systems). The Reson 7125 is a dual frequency system operating at 200 and 400 kHz. The systems were operated in the Intermediate beam mode option; which forms 512 across-track beams (in 400 kHz), with a maximum swath coverage of 140°. Operating modes such as range scale, gain, power level, ping rates, etc. were a function of water depth and data quality and were noted on the survey line logs (see the Descriptive Report Separate 1).

The Reson systems and IMU were installed on a special mounting plate, where each Reson 7125 was rotated approximately 15°. The Reson systems were installed in their normal SV2 bracket, which included an SV70 probe (located in the nose cone) and were attached to the mounting plate by a flange. Refer to Appendix I for more information and graphics.

All 7125 multibeam data files were logged in the s7k format using WFMB v3.10.23. The bathy data from each Reson 7125 (records 7004/7006 & 7027) were stitched together in WFMB to create one s7k file with each ping containing 1024 beams.

Both vessels, each equipped with dual head Reson 7125 sonars, were operated in the full rate dual head (FRDH) mode in the Reson topside.

The line orientation for all vessels was generally parallel to the coastline and bathymetric contours of the area. The line spacing was dependent on water depth and data quality, with an average line spacing of three to four times water depth. **Table 1** summarizes the sonar models and configurations used on each survey vessel.

Table 1 Vessel Sonar Summary

Vessel	R/V Theory	R/V Westerly
Mount Type	Over the Stern	Over the Stern
Sonar System	Dual Head Reson 7125 (FRDH)	Dual Head Reson 7125 (FRDH)

The De Havilland DC-6 Twin Otter aircraft had installed an Optech SHOALS-1000T Airborne LiDAR Bathymetry (ALB) system, serial number FPI-1. The SHOALS system is capable of acquiring 2500 soundings per second through the transmission of laser pulse signals from a scanning system and detecting return signals from land, sea surface, water column and seabed. The scanning (transmitting) occurs on a stabilized platform that compensates for aircraft pitch and roll. The return signals are electronically amplified and conditioned prior to being digitized and logged.

The SHOALS-1000T is comprised of two main subsystems. The Airborne System (ABS) is used to acquire raw bathymetric data, real-time inertial and Global Positioning System (GPS) data, and downward-looking digital imagery; raw data is collected and logged to solid state drives onboard the sensor in file formats native to SHOALS. The Ground Control System (GCS) is used to plan operations, calculate elevations and soundings from the raw LiDAR data, apply post-processed kinematic GPS (KGPS) positioning, apply tidal corrections, provide tools to allow the collected data to be evaluated, and export digital data for the compilation of final survey deliverables.

For OPR-A366-KR-17, the SHOALS-1000T was configured to operate at sounding spot spacing of 3 m x 3 m at 300 m survey altitude above sea level (ASL) and average speed over ground of 100 knots, which is typically used for hydrographic charting to meet IHO Order 1b specification requirements.

The airborne survey was planned with flightlines at maximum length of approximately 38 kilometers. Crosslines were planned in accordance with the guidelines set out in the Hydrographic Survey Specifications and Deliverables (HSSD) 2017. The preliminary planned lines are shown in **Figure 1**.

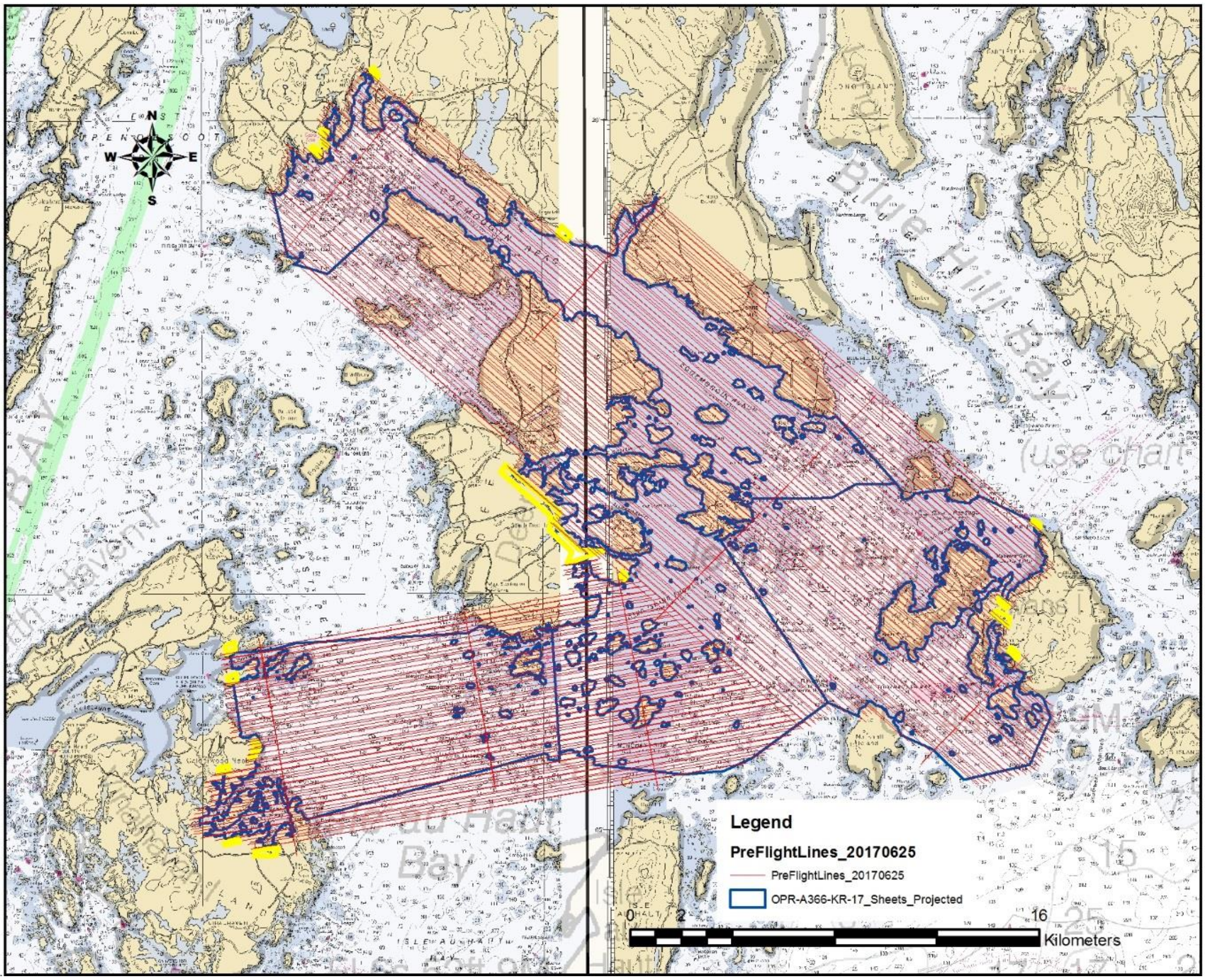


Figure 1 Overview of Preliminary airborne Flightlines and Boundaries

Backscatter Imagery

Towed SideScan Sonar (SSS) operations were not required by this contract, but the backscatter and beam imagery snippet data from all multibeam systems were logged and are stored in the s7k files. All beam imagery snippet data was logged in the 7028 record of the s7k file for the project.

To yield the best results when processing the backscatter from the dual head 7125 systems, we recommend using FMGT with Fledermaus version 7.7.8.728 (Beta).

Sound Velocity Profilers

R/V Theory and R/V Westerly were equipped with AML 1000 dbar Sound Velocity & Pressure (AML SV&P) Smart Sensors. The AML SV&P directly measures sound velocity through a time of flight calculation, and measures pressure with a temperature compensated semiconductor strain gauge at a 10Hz sample rate. The instrument has a 0.015 m/s resolution with a ± 0.05 m/s accuracy for sound velocity measurements, and a 0.01 dbar resolution and a ±0.5 m dbar accuracy for pressure.

Each vessel was equipped with two AML SVPs. The instruments were mounted within a weighted cage and deployed using a hydraulic winch that contained 350 meters of shielded Kevlar reinforced cable via a stern mounted A-Frame.

Fugro's MB Survey Tools was used to check the SV profiles graphically for spikes or other anomalies, and produce an SVP file compatible with CARIS HIPS. The WFMB acquisition package also provided quality control (QC) for surface sound velocity. This was accomplished by creating a real-time plot from the sound velocity probe at the Reson sonar head and notifying the user (via a flashing warning message) if the head sound velocity differed by more than 5 m/s from a defined reference sound velocity. This message was used as an indication that the frequency of casts may need to be increased. The reference sound velocity was determined by averaging 50 sound velocities produced at the head. The reference sound velocity was reset after each cast and when a cast was performed due to a significant deviation from the reference sound velocity.

Positioning & Attitude Equipment

The R/V Theory was equipped with an Applanix Position and Orientation System for Marine Vessels (POS/MV) V4 (underwater IMU) to calculate position and vessel attitude. Position was determined in real-time using a Trimble Zephyr L1/L2 GPS antenna, which was connected to a Trimble BD950 L1/L2 GPS card residing in the POS/MV. An Inertial Measurement Unit (IMU) provided velocity values to the POS/MV allowing it to compute an inertial position along with heading and attitude. The POS/MV was configured to accept Fugro's Marinestar G2 corrections. Marinestar is a decimeter level, phase-based service using satellite 'clock and orbit' data valid worldwide, based upon GPS L1 and L2 frequencies, and provides a horizontal accuracy of 10 cm and vertical accuracy of 15 cm.

The operational accuracy specifications for this system, as documented by the manufacturer, are as follows:

Table 2 POS/MV Specifications

POS/MV Accuracy	
Pitch and Roll	0.02°
Heading	0.02°
Heave	5% or 5-cm over 20 seconds

The R/V Westerly was equipped with an Applanix Position and Orientation System for Marine Vessels (POS/MV) V5 (underwater IMU) to calculate position and vessel attitude. Position was determined in real-time using a Trimble Zephyr L1/L2 GPS antenna, which was connected to a Trimble BD950 L1/L2 GPS card residing in the POS/MV. An Inertial Measurement Unit (IMU) provided velocity values to the POS/MV allowing it to compute an inertial position, along with heading, and attitude. The POS/MV was configured to accept Fugro's Marinestar G2 corrections. Marinestar is a decimeter-level, phase based service using satellite 'clock and orbit' data valid worldwide, based upon GPS L1 and L2 frequencies, and provides a horizontal accuracy of 10 cm and vertical accuracy of 15 cm.

The PosMvLogger and POS/MV controller software's real-time QC displays were monitored throughout the survey to ensure that the positional accuracies specified in the NOS HSSD were achieved. These include, but are not limited to, the following: GPS Status, Positional Accuracy, Receiver Status, which included Horizontal Dilution of Position (HDOP) & Precise Dilution of Position (PDOP), and Satellite Status.

The SHOALS LiDAR sensor employs an Applanix POS/AV 510 v6 to provide high accuracy 3D positioning and orientation for the sensor platform. The POS/AV is an inertial navigation system (INS) aided by high accuracy Global Navigation Satellite System (GNSS) positions. The POS/AV is comprised of an inertial measurement unit (IMU), a GNSS receiver with antenna, and a processing computer unit (PCS) producing a full inertial navigation solution.

The operational accuracy specifications for the POS/AV 510 system, as documented by the manufacturer, are presented in **Table 3**.

Table 3 POS/AV 510 Specifications

POS/AVAccuracy	
Pitch and Roll	0.005°
Heading	0.008°
Position (SmartBase PPK)	0.02 m H 0.05 m V
True Heading	0.008°

The IMU contains accelerometers and gyroscopes to measure linear acceleration and angular rates on the three axes of the reference body. The IMU measurements, position, velocity, and orientation (roll, pitch, heading), are returned to the PCS where an inertial navigator produces position and orientation data. The INS navigation solution errors that build over time are controlled by the continuous input of GNSS positioning integrated into the POS/AV. A Trimble BD690 board, coupled with a GNSS/L band high-gain antenna, and the corrections of the Marinestar G2 augmentation service produce the high-accuracy positioning observables that are integrated by the inertial navigator into position and orientation of the reference platform in real-time.

Fugro Marinestar G2 service is a real-time GPS and GLONASS Precise Point Positioning (PPP) providing refined satellite ‘clocks and orbit’ data to any GNSS receiver with a valid service subscription. Signal on the L-band with corrections is broadcasted by geo-stationary satellites. At least three of them covered the geographic region of the survey area, see **Figure 2**, and was received by the integrated GNSS/L-band antenna. Fugro uses the G2 service signal as the standard in the POS/AV embedded Marinestar receiver.

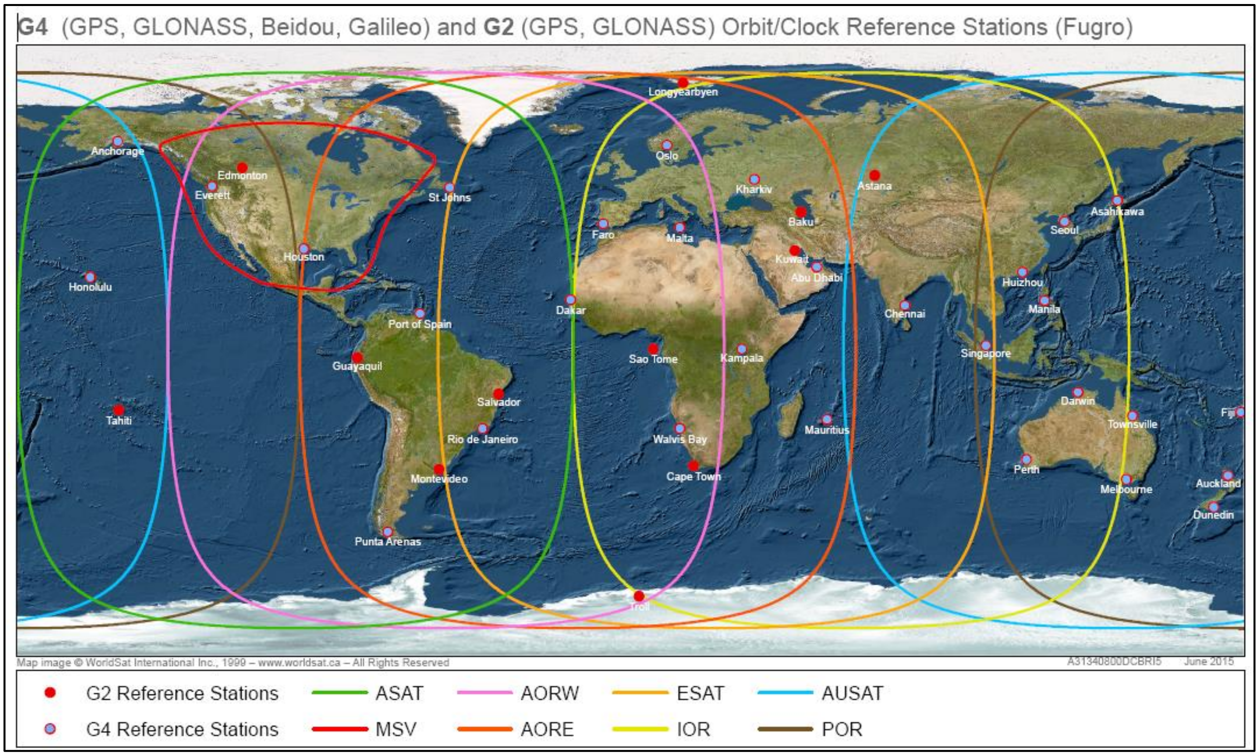


Figure 2 GNSS/IMU Positioning System

The POS/AV data streams are recorded on removable solid-state drives with high input and download data rates. The main technical specifications of the Applanix POS/AV are:

- Logging: Time tag, status, position, attitude, velocity, track and speed, dynamics, performance metrics, raw IMU data and raw GNSS data all at up to 200 Hz
- Media External: Removable 4 GB USB stick. Internal: Embedded 4 GB memory for redundant logging
- Accuracies: 0.05 – 0.3 m position, 0.005 m/s velocity, 0.005° roll/pitch, 0.008° heading and 0.10°/hr drift when post-processed

The main technical specifications of the Aero Antenna Technology AERAT1675_180 GNSS antenna are:

- Airborne Antenna – Iridium Protected
- GNSS L1 1565 – 1607 MHz frequency
- GNSS L2 1217 – 1260 MHz frequency

Processed LiDAR point positions were derived relative to the WGS84 datum (ITRF00) using a Post Processed Kinematic solution (PPK) during GNSS post-processing, which used aircraft positioning data and. Final LiDAR point positions were then reduced to MLLW using a VDatum model created for the survey area by Fugro.

Following all dynamic and static GPS data processing with Applanix POSPac MMS 7.1, the following quality factors were assessed to determine if the final GPS solutions adhered to the project accuracy specifications:

- Dilution of Precision – PDOP, HDOP, and VDOP
- Position Accuracy – RMS for Easting, Northing and Height
- Float / Fixed Ambiguity Status – ambiguity status for each epoch
- Number of Satellites

<u>Imagery Equipment</u>

The SHOALS system incorporates an Allied Prosilica GX3300 down-look camera (**Figure 3**) configured to acquire RGB image frames at a rate of 1 Hz with an image size of 3296 x 2472 resolution and a potential image resolution (ground sample distance, variable with altitude) of 0.19 m. The camera employs a high-quality 8-megapixel OnSemi KAI-08051 sensor and APO-XenoPlan lens that provides superior image quality and low noise. This combination provides sharp imagery under a variety of lighting conditions.

Figure 3 Prosilica GX3300 Camera

The camera and lens system have been metrically calibrated using a rigorous camera model that explains the mapping between the 3D coordinates and the image coordinates. This distortion model was first introduced by Brown in 1966 and is called the Plumb Bob model (radial polynomial + thin prism).
During calibration the best fit model of the following are determined:

- Focal length: The focal length in pixels
- Principal point: The principal point coordinates
- Skew coefficient: The skew coefficient defining the angle between the x and y pixel axes.
- Distortions: The image distortion coefficients (radial and tangential distortions).

Figure 4 illustrates the results of the distortion calibration. The resultant model is used as the correction inputs for ortho-rectification on the composite mosaic.

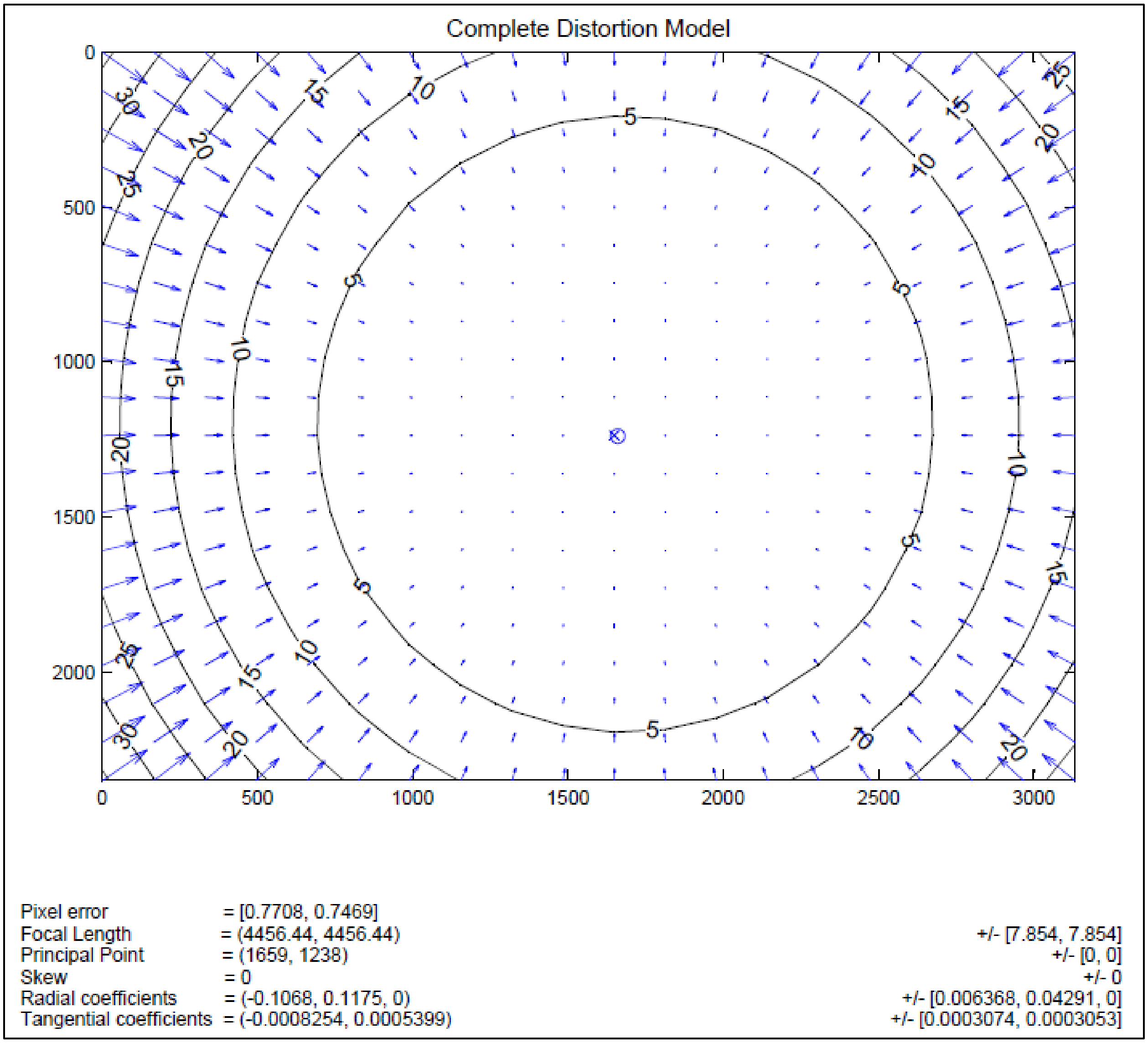


Figure 4 Sample Camera Lens Calibration Results

Once installed on the aircraft, the camera underwent a boresight calibration to eliminate misalignments between the POS/AV and the camera reference point. The procedure involves the analysis of reciprocal lines' imagery and the adjustment of pitch, roll, and heading angle correctors that would align the images to the reference targets on the ground. The angle adjustments sequence iterates for as many times necessary to reduce horizontal misalignment of features to less than 0.5 m 1σ.

Raw digital images were exported with the SHOALS-GCS processing software, which also created the external orientation (EO) image index file that includes the aircraft position and orientation information for each image. The images and EO parameters were input into ERDAS (Leica Photogrammetry Suite) LPS software to generate the ortho-rectified images with the aid of a preliminary Digital Elevation Model (DEM) derived from the LiDAR elevation data. See **Figure 5** for a sample picture from the SHOALS camera. The rectified images were output at 0.3 m resolution. Spatial accuracy of the rectified imagery has been reported to be within ±2 m at 95 %

c.l. when compared to ground control points (GCP) or to high resolution features depicted by other topographic features (< 1 m in horizontal dimensions).

Figure 5 Sample Picture from SHOALS Camera

<u>Static Draft Measurement</u>

Static draft was measured from a tab on the stern of the vessel directly above the IMU and sonar mount and then the correction to the common reference point (IMU) was applied. Refer to the offset diagrams Appendix I for additional information.

<u>Bottom Sampling</u>

The R/V Theory and R/V Westerly were equipped with a 2.4L Van Veen Grab bottom sampler and 100 meters of line. The sampler was hand deployed, and retrieved via a davit that was installed on the port side of the vessel. All samples were discarded after the sample information was recorded.

Software

MBES Acquisition

All raw multibeam data was collected with WFMB v3.10.23. WFMB ran on a Windows 7 PC with a quad-core Intel processor. Data from the Reson 7125 sonars were logged in the s7k file format. The s7k files contain all multibeam bathymetry, position, attitude, heading, and UTC time stamp data required by CARIS to process the soundings. A separate WFMB module (PosMVLogger) on the same PC logged all raw POS/MV data for the post-processing of vessel positions in Applanix POSPac MMS software. WFMB also provided a coverage display for real-time QC and data coverage estimation.

WFMB offers the following display windows for operators to monitor data quality:

1. Devices: The Devices window shows the operator which hardware is attached to the PC. It also allows the operator to configure the devices, determine whether they are functioning properly, and to view received data.

2. Graphic: The Graphics window shows navigation information in plan view. This includes vessel position, survey lines, background vector plots, and raster charts.

3. Vehicle: The Vehicle window can be configured to show any tabular navigation information required. Typically, this window displays position, time, line name, heading, HDOP, speed over ground, distance to start of line, distance to end of line, and distance off line. Many other data items are selectable.

4. Calculation: The Calculations window is used to look at specific data items in tabular or graphical format. Operators look here to view the status of the GPS satellite constellation and position solutions, real-time SV, tidal values, etc.

5. MBES Coverage Map: The Coverage Map provides a real-time graphical representation of the multibeam data. This allows the user to make judgments and corrections to the data collection procedure based on current conditions.
6. MBES QC View: The QC View contains four configurable windows for real-time display of any of the following: 2D or 3D multibeam data, snippets, pseudo sidescan, or backscatter amplitude. In addition to this, it contains a surface sound speed utility that is configurable for real-time SV monitoring at the sonar head.

Applanix POS/MV V4 and V5 controller software was used to monitor the POS/MV systems. The software has various displays that allow the operator to check real-time position, attitude and heading accuracies, and GPS status. POS/MV configuration and calibration, when necessary, was also done using this program.

Fugro’s PosMvLogger v2.0 was used to provide uninterrupted logging of all Inertial Motion Unit (IMU), dual frequency GPS, and diagnostic data. Additionally, the Delayed Heave data applied in post-processing was collected concurrently in the same file. The program also provided real-time QC and alarms for excessive HDOP, PDOP, and DGPS outages.

Fugro's MB Survey Tools v3.1.15 was used to aid in file administration and reporting during data acquisition. This program created a daily file that contained survey line, SVP, and static draft records. These logs were stored digitally in a database format and later used to create the log sheets in PDF format located in the Descriptive Report Separate 1.

CARIS Onboard was used to increase efficiency with the daily processing effort. This program ran during data acquisition; converting lines, and applying SVP and Total Propagated Uncertainty (TPU) values. A daily DTM was also updated as each line was processed. The CARIS Onboard daily project was copied to the server at the end of each shift along with the raw data.

Fugro's Back2Base software is a package that facilitated the transfer of large data sets from the survey location back to the Fugro datacenter. Back2Base was used to send the daily CARIS Onboard projects to our San Diego datacenter where processing operations took place.

LiDAR Acquisition

Line planning for the project was done using SHOALS GCS v6.32 software package; this suite contains a planning module called MAPS which is capable of importing a vector file of the project boundary as well as shoreline and other information. MAPS allows the user to quickly and easily adjust blocks of planned lines to ensure maximum efficiency, which is attained during flight while maintaining the standard of survey requirements outlined in the Project Instructions. MAPS creates the mission flight plan files that are loaded in the SHOALS Airborne System.

The SHOALS Airborne System Operator GUI v1.2 controls the LiDAR sensor operation, the collection of raw data and monitors quality indicators, such as PDOP, laser power, satellites tracked, and error messages in real-time during flight. The Airborne System Operator software is installed on a ruggedized laptop well-suited for the airborne environment. In addition to the interface used by the operator, the software outputs navigation and track guidance information to the flight crew via a separate pilot console that mounts on the dashboard of the aircraft.

SHOALS Airborne System also controls the boot up of the POS/AV system and monitor its status from the Airborne Operators laptop display.

Fugro's LiDAR Survey Tools v1.03.06 was used to aid in file administration and reporting during data acquisition. These logs were stored digitally in a database format and later used to create the log sheets in PDF format located in the Descriptive Report Separate 1.

MBES Processing

All lines were converted with CARIS Onboard v1.2 during data acquisition.

All Soundings were processed using CARIS HIPS v9.1.9. HIPS converted the s7k files to HIPS format, corrected soundings for sound velocity, motion, tide, dynamic draft, and vessel offset, and was used to examine and reject noisy soundings. HIPS also produced the final Bathymetry Associated with Statistical Error (BASE) surfaces.

CARIS HIPS and SIPS v9.1.9 with Caris_Support_Files_5_4 was used to generate the S-57 Feature Files.

ESRI ArcMap v10.3 was used for survey planning, reviewing coverage plots, creating infills & crosslines, and creating graphics.

MB Survey Tools v3.1.15 was used to extract Delayed Heave from POS files and put data into a text format acceptable to the CARIS Generic Data Parser. This was only needed when the CARIS Load Delayed Heave routine in HIPS failed to import. MB Survey Tools v3.1.15 allowed processors to track changes and add comments while processing. MB Survey Tools was also used to process all sound velocity profiles and to convert them into a CARIS format.

A complete list of software and versions used on this project is included in Appendix I.

LiDAR Processing

The general data flow between the subsystems and tools is illustrated in **Figure 6**.

Applanix POSPac MMS 7.1 was used for the post-processing of airborne GPS data (PPK). A SmartBase network was created using downloaded Continually Operating Reference Station (CORS) data, this network was then processed with the airborne POS data to calculate the positioning trajectory in a Smooth Best Estimated Trajectory (SBET) solution file that is used by the SHOALS software in the next stage.

SHOALS GCS v6.32 was used to process SHOALS sensor data once data was securely copied to the field server. GCS converts raw INH data first into ABH and INH files during download. Auto-processing routines creates Hydrographic Output Files (HOF) format data containing the point clouds, and is able to apply filters on the data based on predetermined parameter values. It is also at this stage that the KGPS trajectory positioning is applied to estimate elevation and soundings referenced to the working ellipsoid.

HOF files are taken to QPS Fledermaus v7.3.3c for the main editing and visualization of point clouds. PFM data structures are built via SHOALS GCS using Fledermaus. PFM allow for visualization and editing or the source HOF files, working in conjunction with GCS to allow for reprocessing in soundings if parameters need to be adjusted.

All soundings from the HOF files were imported into CARIS HIPS v9.1.9. HIPS converted the HOF data to HIPS HDCS format, applied TPU and reduced data to MLLW using a VDatum separation model. HIPS also produced the final BASE surfaces.

NOAA's VDatum v3.6 was used to transform data from the ellipsoid datum to MLLW using a separation model.

CARIS HIPS and SIPS v9.1.9 with Caris_Support_Files_5_5 was used to generate the S-57 Feature Files.

ESRI ArcMap v10.3 was used for survey planning, reviewing coverage plots, creating re-flight & crosslines, and creating graphics.

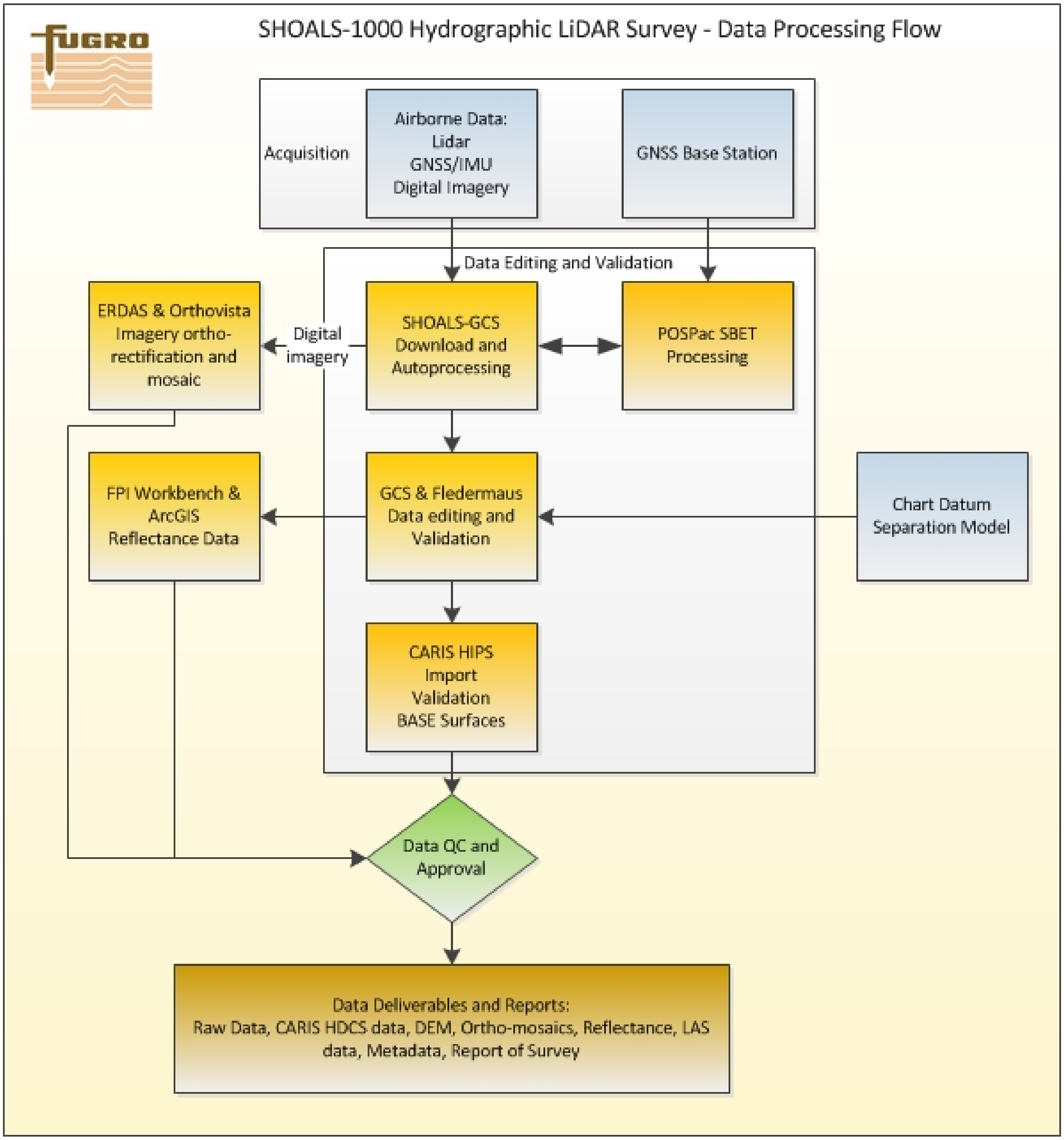


Figure 6 General Data Flow within FPI ALB System

LiDAR Survey Tools v1.03.06 was used for data management and logging. Airborne logs, processing tasks and daily project information was tracked using this Fugro-created software.

Workbench, another Fugro software package, was used at various stages. Version 6.01.04 was used for data validation tasks during acquisition and again during the deliverables stage in order to facilitate creation of ortho mosaics.

<u>Digital Imagery Processing</u>

The SHOALS camera collected digital imagery at 1 Hz and logged alongside the raw LiDAR data. These images were extracted from raw format using Fugro Workbench tools; this included extracting the precise camera position and orientation as determined by the post-processed KGPS solution creating an image index. Workbench translated this information through rotation matrices into the exterior orientation (EO) parameters that referenced the sensor's frame to the project's coordinate referenced system.

All extracted images and EO parameters were input in ERDAS LPS v 9.3 photogrammetric software to generate the ortho-rectified images with the aid of a bare earth DEM obtained from USGS National Elevation Dataset (NED).

Ortho-rectified images were processed into tiled mosaics using Trimble's Orthovista v7.0.3 software, applying automated seamlines, feature detection, and tonal color balancing. Final mosaics were produced in 8-bit RGB geoTIFF format at 0.3 meter resolution. A sample of the final ortho mosaic product can be found in **Figure 7**.

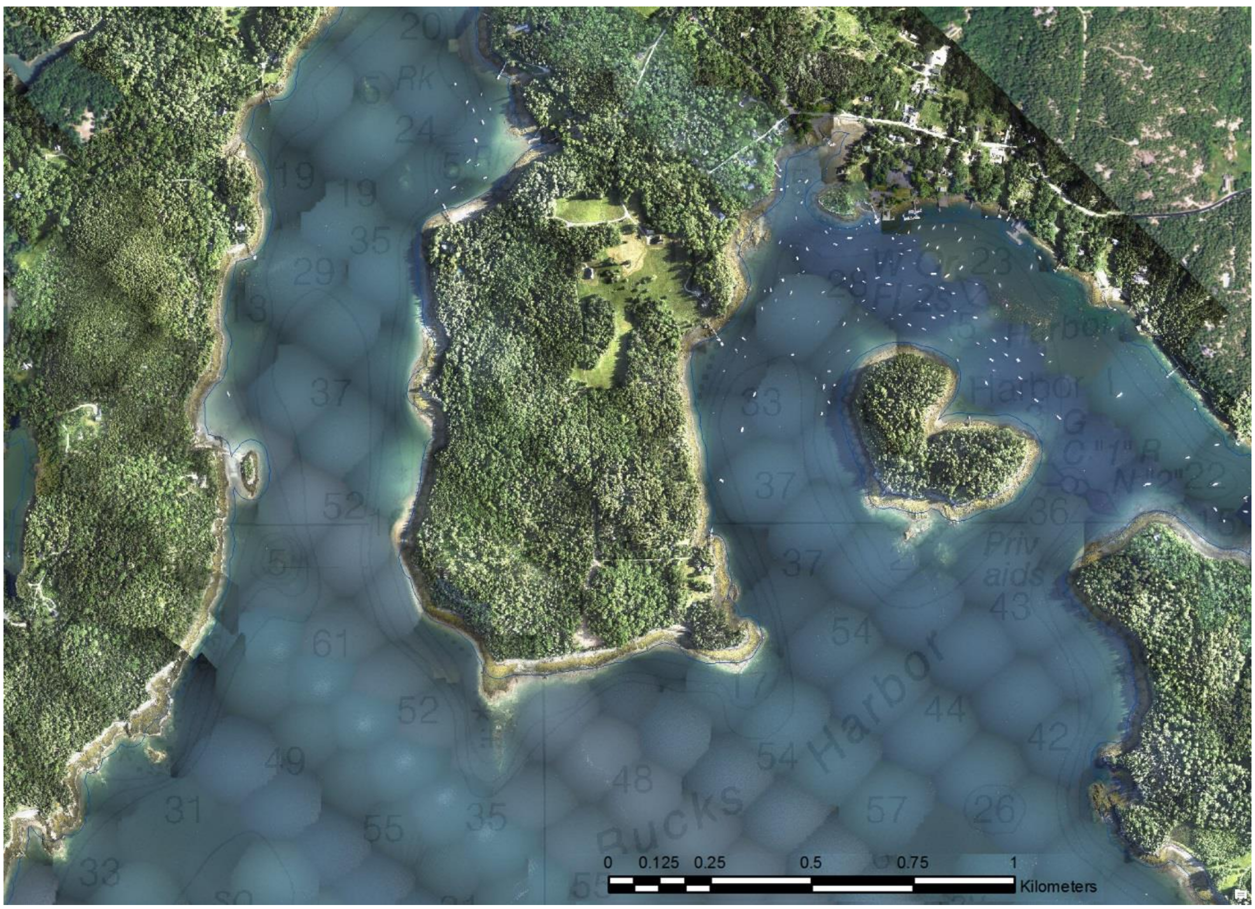


Figure 7 Sample Image from Final Ortho mosaic Product

A complete list of software and versions used on this project is included in Appendix I.

B – Quality Control

MBES

Error estimates for all MBES survey sensors were entered in the CARIS Hips Vessel File (HVF). Additionally, measured uncertainty values were applied to the data where possible. These measured values included delayed heave RMS from the raw POS/MV files, positioning and attitude uncertainties from the Applanix POSPac MMS RMS files, and calculated surface sound velocity values. These error estimates were used in CARIS to calculate the TPU at the 95% confidence level for the horizontal and vertical components of each individual sounding.

The values that were entered in the CARIS HVF for the survey sensors are the specified manufacturer accuracy values and were downloaded from the CARIS website **http://www.caris.com/tpu/**. The following is a breakdown and explanation on the manufacturer and Fugro derived values used in the error model:

- Navigation – A value of 0.10 m was entered for the positional accuracy. This value was selected since all positions were post-processed, with X, Y, and standard deviation values better than 0.10 m.
- Gyro/Heading – Vessel was equipped with a (POS/MV) 320 V4 and had a baseline < 4 m, therefore, a value of 0.020 was entered in the HVF as per manufacturer specifications.
- Heave – The heave percentage of amplitude was set to 5% and the Heave was set to 0.05 m, as per manufacturer specifications.
- Pitch and Roll - As per the manufacturer accuracy values, both were set to 0.02 degrees.
- Timing – All data were time-stamped when created (not when logged) using a single clock/epoch (Pelagos Precise Timing method). Position, attitude (including True Heave), and heading were all time-stamped in the POS/MV. A ZDA+1 PPS string was also sent to the Reson 7125 processor, yielding timing accuracies on the order of 1 millisecond. Therefore, a timing error of 0.001 seconds was entered for all sensors on all vessels.
- All vessel and sensor offsets were derived via conventional survey techniques (total station), while the vessel was dry docked. The results yielded standard deviations of 0.005 m to 0.010 m, vessel and survey dependent.
- Vessel speed – set to 0.10 m/s since a POS/MV with a 50 Hz output rate was in use.
- Loading – estimated vessel loading error set to 0.05 m. This was the best estimate of how the measured static draft changed through the survey day.
- Draft – it was estimated that draft could be measured to within 0.01 m to 0.03 m; therefore values in this range were entered.
- Tide error was computed and set by the TCARI GUI provided by NOAA.
- Sound Speed Values were determined in MB Survey Tools, via the SVP Statistics utility. This utility calculated the Mean, Variance, Standard Deviation, and Min/Max values at a user-specified depth interval. A separate value was also taken from the manufacturers specifications.
- MRU Align Standard Deviation for the Gyro and Roll/Pitch were set to 0.10° since this is the estimated misalignment between the IMU and the vessel reference frame.

The calculated vertical and horizontal error or TPU values were then used to create finalized CUBE (Combined Uncertainty Bathymetry Estimator) surfaces; only soundings meeting or exceeding project accuracy specifications were included in this process.

An overview of the data processing flow follows:

During Acquisition the s7k files collected by WFMB were processed by CARIS Onboard. CARIS Onboard converted the s7k files, applied a predicted tide, SVP corrected, applied TPU values, and added lines to a daily CUBE surface. This whole process was automated and ran in the background during data collection.

Once the data arrived at the field office, a review was done to confirm all lines collected had been processed by CARIS Onboard. Once this was complete, both the Preliminary Tide and Delayed Heave data were applied to all lines.

The CARIS Onboard projects were then copied to Back2Base to be compressed and sent to our processing center in San Diego for the main processing efforts to be done.

In order for the s7k files to be collected by WFMB and used by CARIS, they must be converted to HDCS format using the CARIS ResonPDS converter routine. Prior to the files being converted, vessel offsets, patch test calibration values, TPU values, and static draft were entered into the HVF.

Once converted, the Preliminary Tide, Dynamic Draft, and Delayed Heave data were loaded into each line and the line was SVP corrected in CARIS HIPS. Prior to sound speed correction, the dynamic draft was loaded into each line via the load Delta draft routine. The TPU was then computed for each sounding and attitude. Bathymetry data for each individual line were examined for noise as well as to ensure the completeness and correctness of the data set.

The data was filtered using a time nadir depth, beam numbers, and a Reson quality flag filter (**Table 4**). The times nadir depth filter rejected all soundings falling from a specified cross distance from nadir, which based on the nadir water depth. The beam numbers; filter soundings based on a specified beam number that is entered in the field. The Reson quality flag filter rejected soundings based on the collinearity and brightness of each ping. Note that "rejected" does not mean the sounding was deleted – it was instead flagged as bad, so not be included in subsequent processing such as surface creation. Data flagged as rejected contained valid data but were flagged to remove noise and to speed the processing flow. Valid data were manually reaccepted into the data set occasionally during line and subset editing as required.

Table 4 Reson Quality Flags

Quality Flag	Brightness	Collinearity
0	Failed	Failed
1	Pass	Failed
2	Failed	Pass
3	Pass	Pass

Multiple CARIS filter files were used during the project. The most utilized filters are shown in **Table 5**. The processor selected the appropriate filter file based on a brief review of the data for environmental noise and bottom topography. Filter settings were sometimes modified based on data quality, but all filter settings used were noted on each corresponding line log found in the Descriptive Report Separate 1.

Table 5 CARIS Filter File Definitions

File name	X Nadir Depth	Beam Numbers	Quality Flag
4.0XWD_Beams400-600_01	4.0 times nadir depth	400-600	0&1
4.5XWD_Beams400-600_01	4.5 times nadir depth	400-600	0&1
5.0XWD_Beams400-600_01	5.0 times nadir depth	400-600	0&1

Because of the high accuracies realized from using Fugro's Marinestar G2 corrections, there was no need to post-process any of the positioning data.

CUBE surfaces were then created at each required resolution for the Sheet or Block (**Table 6**). Each CUBE resolution surface was then finalized using the depth thresholds for that specific resolution. The finalized CUBE surfaces were used for subset cleaning so only the surface relating to the specific resolutions' depth range would be reviewed. CUBE parameters were derived from NOS HSSD April 2017. The following depth threshold and CUBE parameter settings were used on this project.

Table 6 CUBE Surface Parameters

Surface Resolution	Depth Range	IHO S-44 Specification	Surface Creation				Disambiguation			
			Estimate Offset	Capture Distance Scale	Capture Distance Minimum	Horizontal Error Scalar	Method	Density Strength Limit	Locale Strength Maximum	Locale Search Radius
1m	0-20m	Order 1a	4	0.50%	0.71m	1.96	Density & Local	2	2.5	1 pixel
2m	18-40m	Order 1a	4	0.50%	1.41m	1.96	Density & Local	2	2.5	1 pixel
4m	36-80m	Order 1a	4	0.50%	2.83m	1.96	Density & Local	2	2.5	1 pixel
8m	72-160m	Order 1a	4	0.50%	5.66m	1.96	Density & Local	2	2.5	1 pixel
16m	144-320m	Order 1a	4	0.50%	11.31m	1.96	Density & Local	2	2.5	1 pixel

Deviations from these thresholds, if any, are detailed in the appropriate Descriptive Report.

Subsets Tiles (to track areas examined) were created in CARIS HIPS. Adjacent lines of data were examined to identify tidal busts, sound velocity and roll errors, as well as to reject any remaining noise in the data set that adversely affected the CUBE surface.

While examining the data in subset mode, soundings were designated wherever the CUBE surface did not adequately depict the shoalest point of a feature. Soundings were designated when they met or exceeded the criteria for designation set forth in the Specifications and Deliverables. Designation ensured that soundings were carried through to the finalized BASE surface.

A statistical analysis of the sounding data was conducted via the CARIS Quality Control Report (QCR) routine. Crosslines were run in each survey and compared with CUBE surfaces created from the mainscheme lines. The IHO S-44 criteria for an Order 1a survey, as specified in the Project Letter, were used in the CARIS QCR comparison on a beam by beam basis. Quality Control results are found in Separate 4 of each survey's Descriptive Report directory.

CARIS HIPS and SIPS v9.1.9 with Caris_Support_Files_5_4 was used to produce the S-57 final feature file (FFF). Seabed Area (SBDARE) polygon objects were picked from areas with obvious rocky bottom topography from the BASE surfaces. Meta-Coverage (M_COV) and Meta-Quality (M_QUAL) objects were defined as required using the extents of the multibeam BASE surfaces. All additional features that could not be depicted in the CARIS BASE surfaces, such as rocks and bottom samples, were logged in the S-57 assigned feature file.

In preparation for shoreline verification, the project composite source file (CSF.000) was copied and cropped it to include only items contained on the specific survey. This cropped file was then saved as a HOB file named HXXXXX_FFF.hob. Edits were then saved to this HOB file. De-confliction of the composite source shoreline was conducted only on items assigned while conducting shoreline verification.

Primary and secondary flagged features are correlated using the NOAA custom attributes prkyid (Primary Key ID).

Investigation methods and results are described in CARIS HIPS under the S-57 attributes acronym "remrks". Specific recommendations are described under the S-57 attributes acronym "recomd".

Features that do not exist or were determined to be a duplicate were given a "delete" value in the "descrp" attribute. Features that were positioned incorrectly were also given the "delete" value in the "descrp" attribute, and a new feature with a "new" value in the "descrp" attribute was added in its correct location. The "primsec" field was used to distinguish deleted features from newly positioned features. For survey H13011, most of the assigned features were verified or identified in the LiDAR bathy data or ortho-mosaic. These items were labelled with "LiDAR investigations" in the "Special Feature Type" attribute. The TECSOU field was populated with the "found by multi-beam attribute" for any feature verified by multibeam.

To determine the VALSOU or ELEVAT for features investigated by LiDAR, the National VDatum software developed by NOAA was used to reduce LiDAR data to MLLW. LiDAR data was then clipped to the extents of each of the survey priorities and overlaid with Fugro-acquired ortho-imagery and assigned CSF features. The LiDAR grid was then used to determine the VALSOU attribute using the height or depth on the actual features and not the height or depth of the corresponding assigned CSF features. In order to determine which features should be considered islets, a difference surface corresponding to mean high water (MHW) was created for all survey priorities. Islet elevations were derived by taking the difference between the highest SHOALS topo point and the MHW grid. See the NOS HSSD 2017, Appendix F. WATLEV Attribution encoding guidelines were used for determining points above and below MHW.

Riegl data was acquired simultaneously with the SHOALS dataset during the LiDAR reconnaissance survey for the 2017 survey. This data was used to help verify the assigned features along with the SHOALS data and Ortho-Imagery. The Riegl dataset is broken into two classes or layers: a class zero; which is data above the water surface at the time of collection, and class twenty-six; which is data below the water surface at the time of collection. Both classes were reduced to MLLW using a VDatum grid in the same manner as the SHOALS data set. The Riegl data were only cleaned in areas the Riegl was used as the source for the new VALSOU attribute in UWTROC and Obstruction features. Due to the multiple classes the VALSOU could have been taken from either the class zero or class twenty-six. These features (features derived from the Riegl) are specifically labeled in the office notes and contain, but were not limited to the following phrases: "DS – Riegl" or "DS - Riegl - Rock not seen in SHOALS data", etc. Riegl data provided a more detailed reference for feature attribution, particularly in extremely shallow areas. Where possible, SHOALS data was given priority, except in situations where it was determined that the SHOALS system was not the best source for the feature development, either due to a positional or water level difference with the original feature, or because it was determined that the SHOALS data was not the best source of the least depth. These situations are clearly marked in the office notes.

Assigned seabed areas were updated to follow the Zero contour as created from the SHOALS LiDAR surface. Riegl data was used to assist this function, particularly in the very shallow near shore tidal areas.

All shoreline data was submitted in the edited FFF in S-57 format (.000). The SORDAT and SORIND fields were filled in for any objects added or modified in the FFF.

LiDAR

All acquired bathymetric LiDAR data went through an in-field *preliminary* review to assure that adequate coverage had been obtained and that there were no gaps between flight lines or errors in the data before the flight crew departed the project site.

Following each mission, the flight data was run through a complete iteration of processing to ensure that it was complete, uncorrupted, and that the project area has been covered adequately.

GCS and Fledermaus were used to make an initial assessment of data quality. Data Analyst review of the point cloud coverage and associated waveform information for each point allowed to characterize the general environmental conditions and the resulting soundings. An example of a SHOALS waveform is shown below in **Figure 8**.

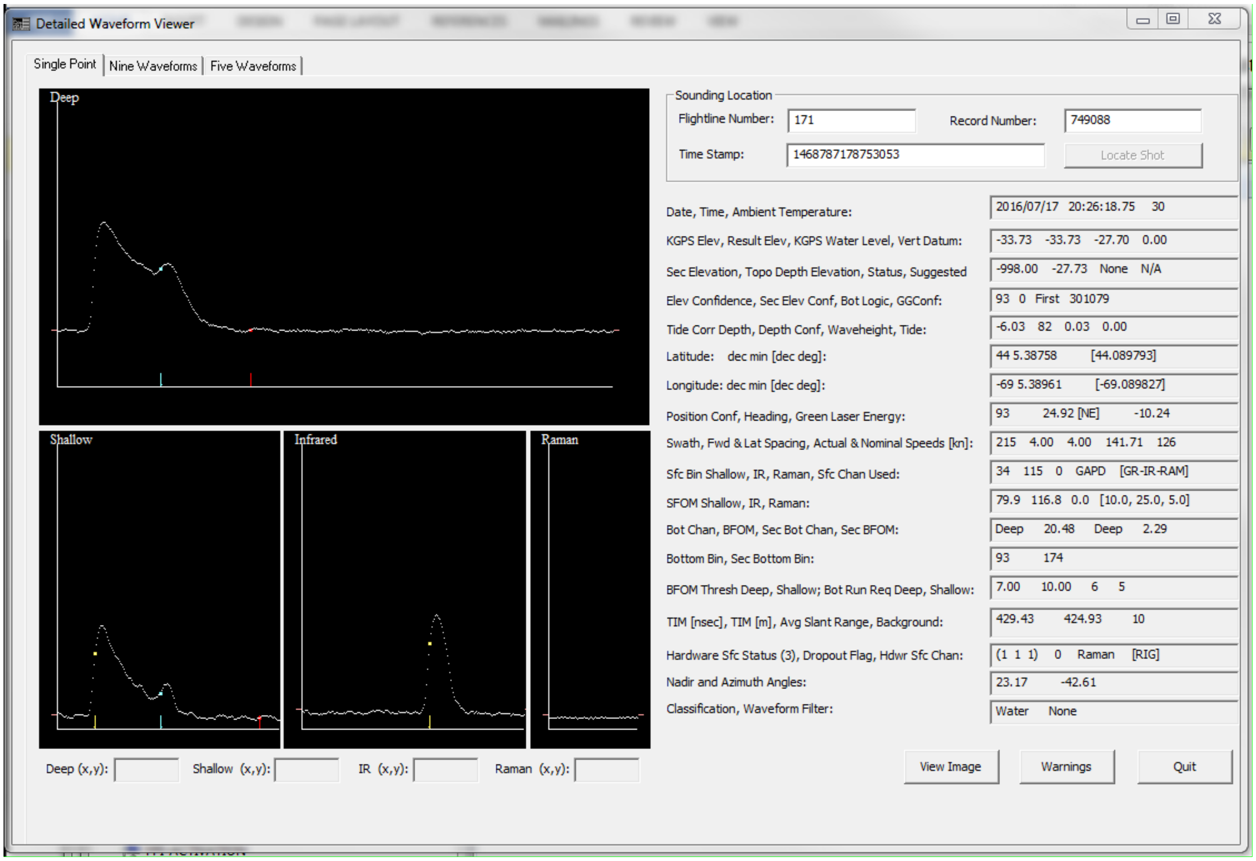


Figure 8 SHOALS GCS Waveform Window

For this project, SmartBase KGPS solutions using a CORS network were used for the 3D positioning of LiDAR soundings and elevations. Detailed information about this network can be found in the Horizontal and Vertical Control Report (HVCR).

In general, the best possible KGPS solution would present a small separation difference between forward and reverse solutions when combined, ideally <0.10 m RMS and remain fixed throughout the flight period.

The auto-processing operation (AP) is the core of the GCS software. The AP algorithms incorporate the defined calibration parameters, the optimal environmental settings selection, and the KGPS solution. The AP routines contain a waveform analysis algorithm that detects and selects water surface and bottom returns from the raw data. In KGPS mode, raw LiDAR depths are referenced as absolute ellipsoidal heights.

For this project, sea surface detection method (surface logic) was set as GIR (Green, Infrared, Raman). This means the surface detection occurred using the green receiver channel. If no green surface was found then the IR receiver channel would be used, and then the raman receiver channel as last resource. The bottom detection mode always used the green channel in the first pulse logic, which takes depth hits that could be flagged as potential targets into account.

As part of the QC process, point clouds, waveforms and metadata analysis on a point by point level was reviewed to better determine the quality of the data (refer to **Figure 9**). Also during this phase the downward looking imagery was viewed and used to correlate shallow and drying features in the LiDAR data (refer to **Figure 10**).

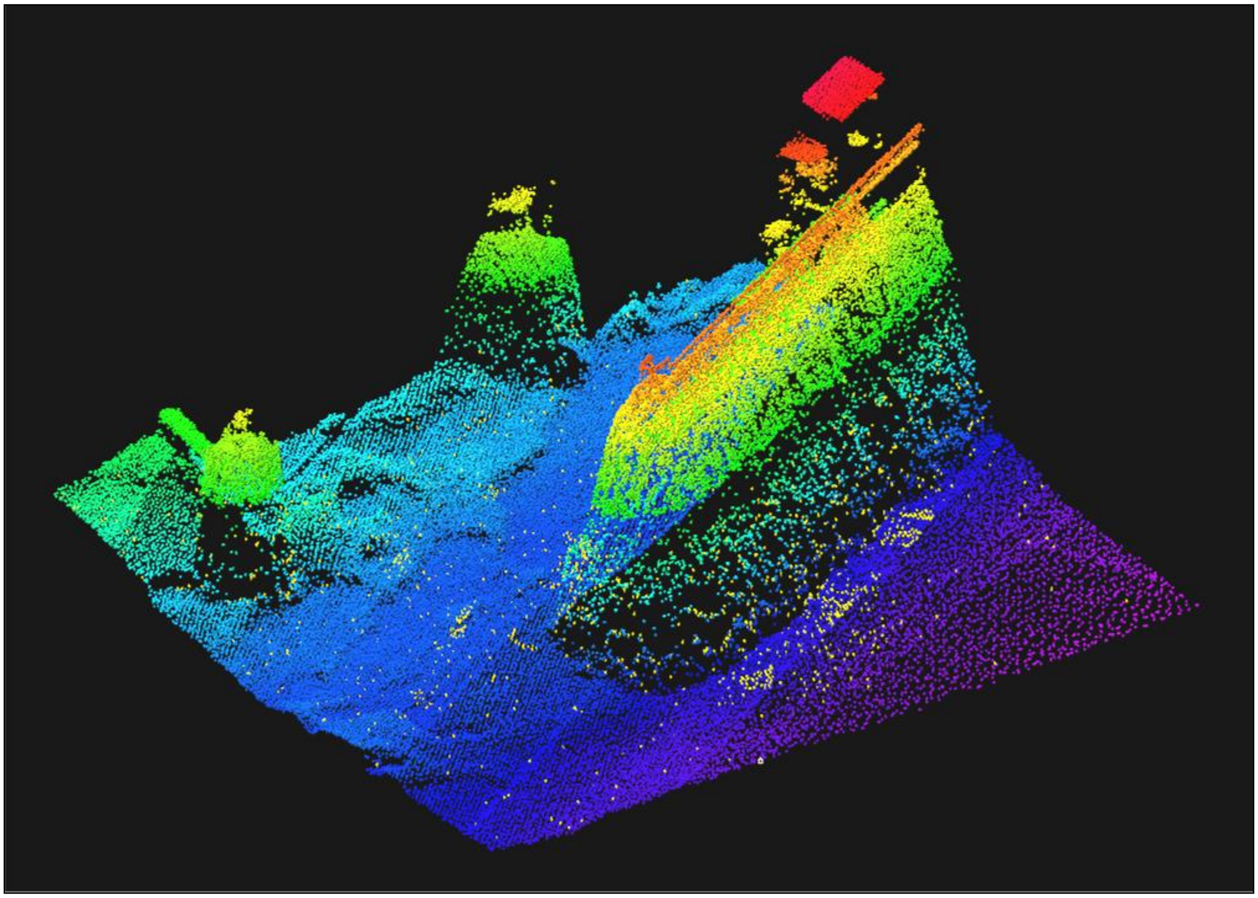


Figure 9 Example of Individual Soundings in 3D Editor

In Fledermaus 3D Editor, erroneous soundings were deleted and shoal soundings verified. Once rendered, the individual datasets were combined with other adjacent data sets for overlap comparisons, cross check comparisons, and continuity checks. The Lead Hydrographer reviewed these larger areas of data to ensure validity and for re-flights plans.

Processing tools are also available in the 3D Editor interface to enhance the sounding quality outcome based on the Data Analyst's assessments to LiDAR soundings. Such tools include, but were not limited to:

- Shallow water algorithm (SWA): recovery of very shallow depths (<1.5 m)
- Depth swaps: false bottom depth swapped in favor of valid bottom picks.
- False land: removal of false land hits caused by high energy returns (e.g. white water).

In large part, manual editing was used to remove gross fliers, obvious anomalies generally caused by poor water clarity and other non-bathymetric returns such as vegetation, boats and other floating objects.

Figure 10 Digital Image Viewer

Laser Power Timing Tests

Each flight during the course of the project collected at least one laser power timing test (LPTT). During this test, the laser is directed through a fiber optic cable of fixed, known length and the timing measured to confirm proper operation of the system. These data were analyzed, see **Figure 11** for an example of the output, and logged after each flight using the GCS software to ensure data was within acceptable thresholds. Results were tracked in LiDAR Survey Tools.

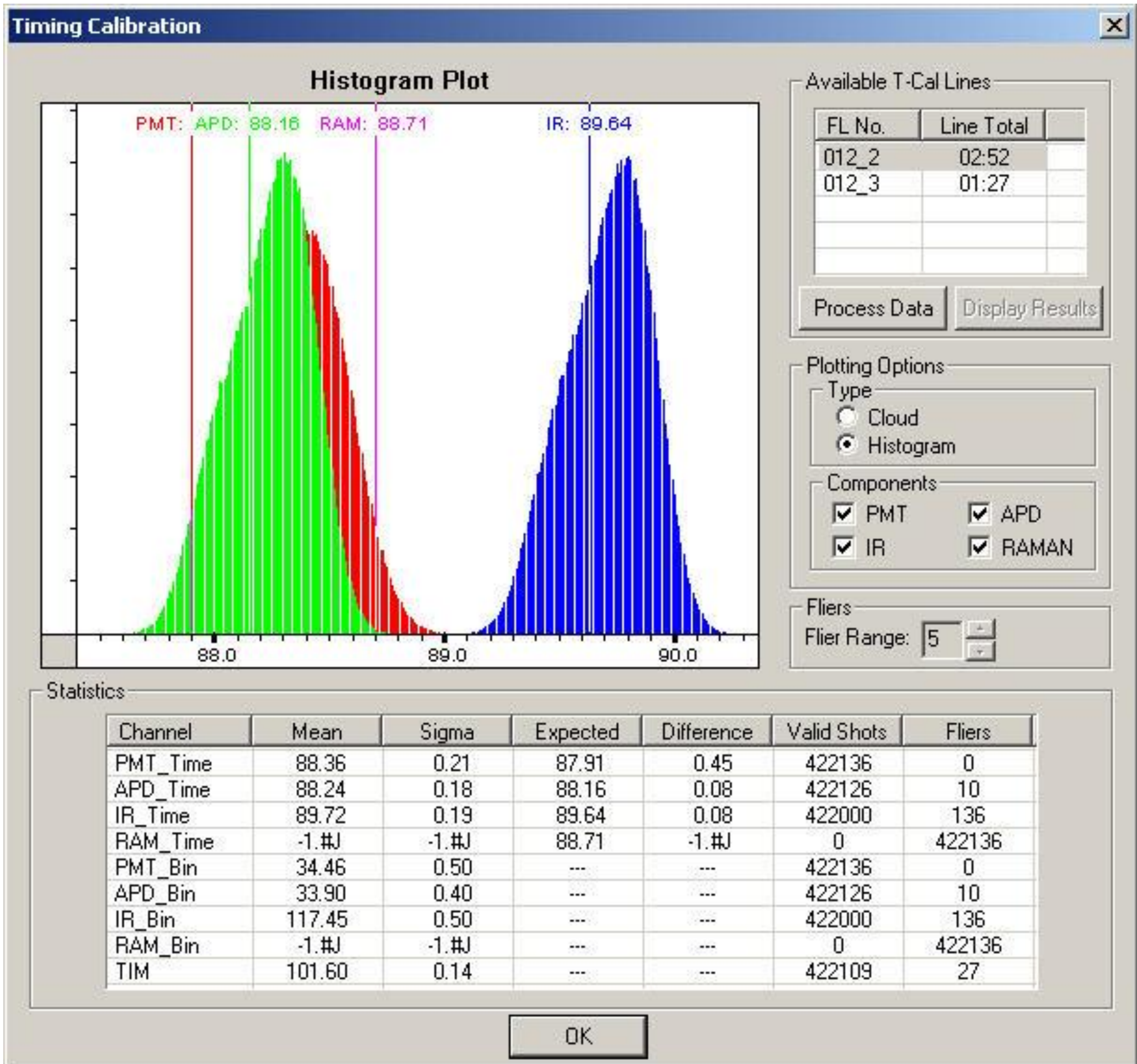


Figure 11 Example of Laser Power Timing Test Result

Data Validation

During the field acquisition period, all data were inspected for coverage and overall quality at the field office. Preliminary field processing was conducted to ensure LiDAR measurements, imagery data, and positioning control met the project's quality requirements. Field processing also served to refine mission planning, particularly when external factors such as environmental and weather conditions impacted the daily operations.

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

- SHOALS data auto-processing with KGPS
- Creation of ortho-mosaic imagery

- Soundings editing and validation
- Soundings QC and approval
- Soundings import in to CARIS HIPS
    - Application of TPU
    - Reduction to survey datum
    - Creation of BASE Surfaces
- Deliverables QC and Approval
- Final Reports

The Lead Hydrographer and Senior Data Analysts performed the final QC of data at various stages during data processing (single flight dataset editing, combined dataset editing, following CARIS import, etc.). Recurrent data editing/QC cycles had to be implemented to maximize editing best practice and minimize involuntary oversight.

Lidar was inspected in Subsets mode in CARIS HIPS. Adjacent lines of data were examined to identify vertical busts, false bottom returns, as well as to reject any remaining noise in the data set.

While examining the data in subset mode, soundings were designated wherever the Uncertainty BASE surface depiction the shoalest point of a feature. Soundings were designated when they met or exceeded the criteria for designation set forth in the Specifications and Deliverables. Designation ensured that soundings were carried through to the finalized BASE surface.

A statistical analysis of the sounding data was conducted via the CARIS Quality Control Report (QCR) routine. Crosslines were run in each survey and compared with Uncertainty BASE surfaces created from the main scheme lines. The IHO S-44 criteria for an Order 1b survey, as specified in the Project Letter, were used in the CARIS QCR comparison on a beam by beam basis. Quality Control results are found in Separate 4 of each survey's Descriptive Report directory.

Approval

All quality controlled data was imported into CARIS HIPS final approval by the Lead Hydrographer. A BASE Surface for each registered sheet was created and the following items were checked for correctness/completeness against the shoalest layer:

- All applicable flight lines were exported.
- Horizontal and vertical TPU was assigned correctly.
- Data range of minimum and maximum depth values were within project bounds.
- The BASE Surface completely covers the NOAA sheet limits.
- There were no unexplained gaps in the final coverage.
- A standard deviation surface was reviewed to ensure all data meets the accuracy specifications.

Data Management

Water Clarity

The greatest contributor to depth performance, seabed coverage and data quality with a LiDAR system is water clarity. In order to address this concern, Fugro conducted water clarity assessments across the project area, from the planning phase through the final flight, using a number of different techniques.

Water Clarity Assessment - Remotely Sensed Data

During the planning phase of the project, remotely sensed data was used to estimate the expected water clarity conditions for the East Penobscot Bay project area and the likely depth penetration of the SHOALS-1000T. The diffuse attenuation coefficient estimated with MODIS satellite sensor (**Figure 12**) attempts to correlate to water turbidity of the water column at the green-blue visible wavelength. Spatial analysis of temporal satellite imagery data allowed to estimate the average monthly diffuse attenuation coefficient for the survey area and determine the expected average water depth of LiDAR soundings (**Figure 13**).

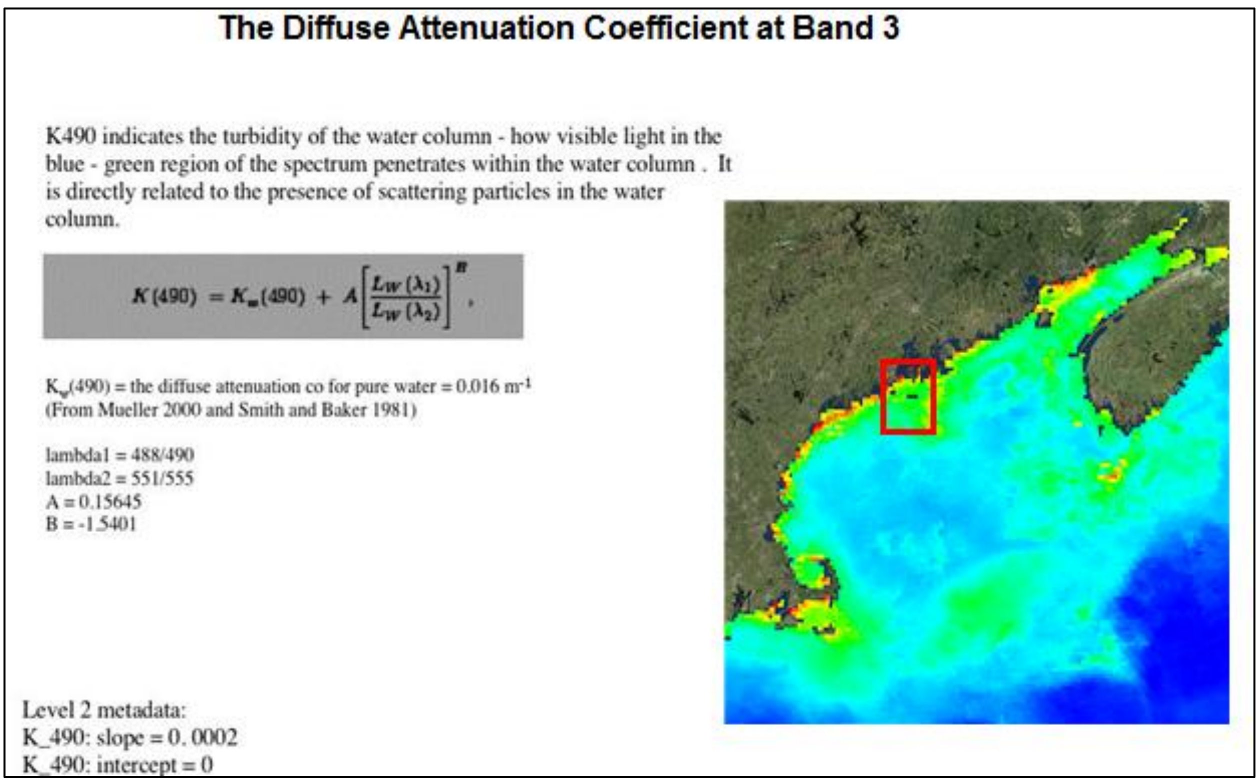
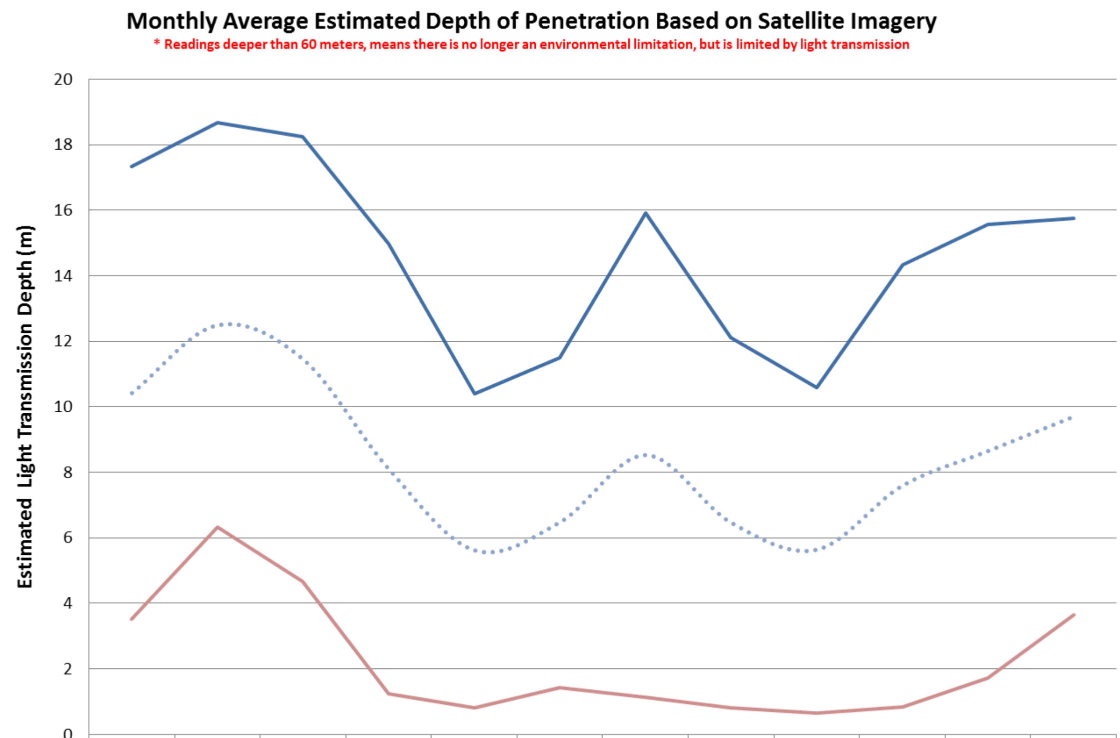


Figure 12 Diffuse Attenuation Coefficient K490 estimation

The graphic below suggested that average sounding measurements for the survey area would be around 6 to 8 meters, contingent to spatial variability, water surface and bottom type conditions.



	January	February	March	April	May	June	July	August	September	October	November	December
Average Min	3.5	6.3	4.7	1.2	0.8	1.4	1.1	0.8	0.7	0.8	1.7	3.6
Average	10.4	12.5	11.5	8.1	5.6	6.5	8.5	6.5	5.6	7.6	8.6	9.7
Average Max	17.3	18.7	18.3	15.0	10.4	11.5	15.9	12.1	10.6	14.3	15.6	15.8

Figure 13 Depth Penetration Estimates from Survey Area

Water Clarity Assessment

From the start of the mission flights on 26 June 2017, Fugro staff undertook water quality assessments along the survey sub-areas. Conditions were documented in many photos and water clarity was, on the whole, found to be relatively poor. Water was seen to be clear in the very shallow depths (likely under four meters) and murky in deeper waters; plumes of sediment swirling around shallow areas near the shoreline and islands were also identified and determined to be in detriment for LiDAR performance (**Figure 14**).

In general, water clarity in the East Penobscot Bay survey area was less than ideal for ALB acquisition. Due to the short duration of the collection period waiting to see improvement over time was not possible.

Since water clarity had a negative impact on coverage within the three to eight-meter depth range, flights were conducted during low tide period in order to maximize water depth detection relative to chart datum.

Figure 14 Aerial Reconnaissance Photograph During Mission Flights

Total Propagated Uncertainty

Fugro has developed methodology to determine vertical and horizontal uncertainty (TPU) for the SHOALS sensor using spatial variance from direct observation of surveyed data, as is laid out in Lockhart et al, 2008[1]. Data collected over a reference bathymetric area within or near the survey area was used to produce the statistical analysis for vertical TPU estimations (**Figure 15**).

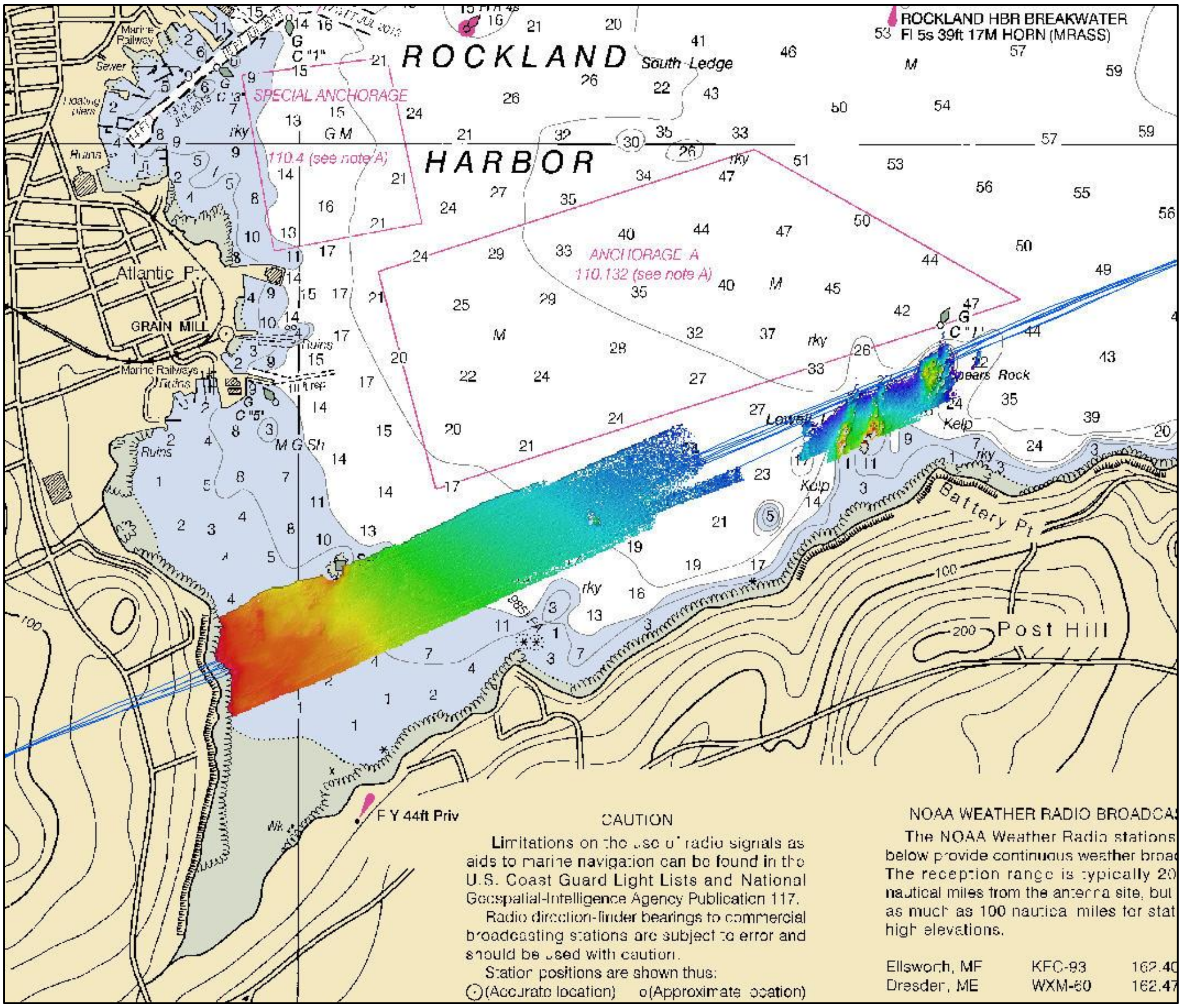


Figure 15 Reference Bathymetric Area for Vertical TPU Analysis

A total of eight lines flown on three different mission flights were evaluated for the vTPU analysis. The regression of vertical depth variances (standard deviation) at cell nodes were recorded for stepped depth intervals (referenced to ellipsoidal heights) in order to estimate the LiDAR measurement uncertainty with post-processed SmartBase SBET solution applied (**Figure 16**).

[1] Lockhart, C., D. Lockhart, J. Martinez, 2008. *Comparing LIDAR and Acoustic Bathymetry Using Total Propagated Uncertainty (TPU) and the Combined Uncertainty and Bathymetry Estimator (CUBE) Algorithm*, ILMF 2008. http://www.fugro-pelagos.com/papers.asp

These values and the regression curve adjusted to them was considered the total vertical uncertainty (1-σ) for the SHOALS depth measurements.

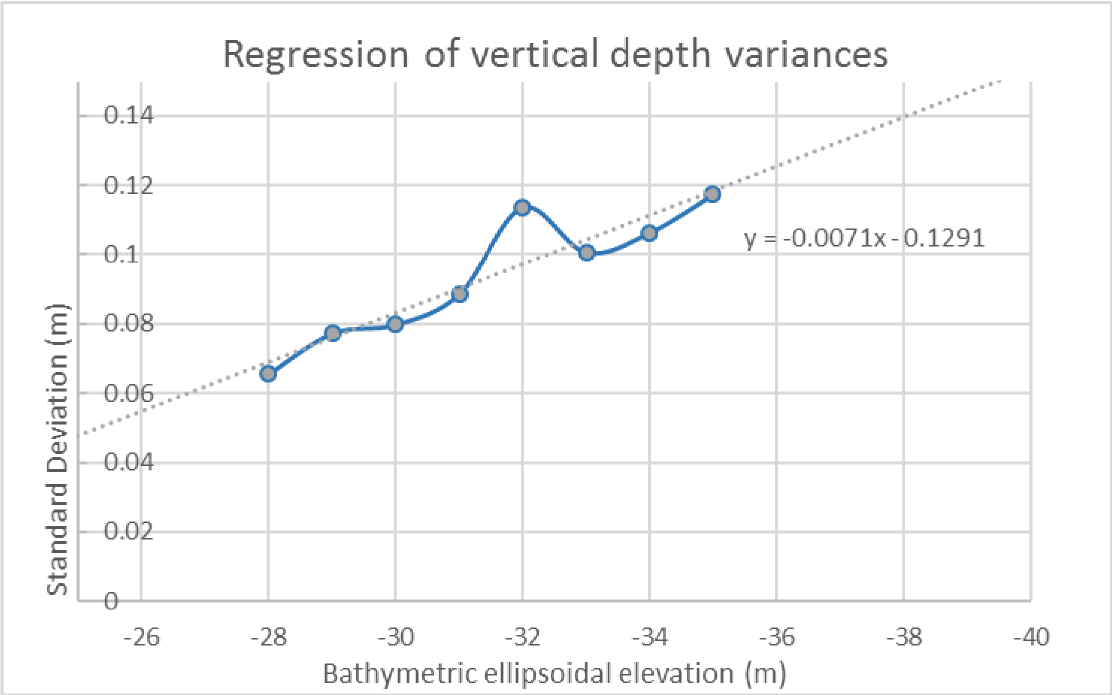


Figure 16 Regression of Vertical Depth Variances for SHOALS Data

Since VDatum was used to reduce depths to chart datum, the uncertainty value associated to this conversion process was added to the SHOALS vertical uncertainty model, in the form:

$$TPU_v = \sqrt{Lidar_U^{\ 2} + VDatum_U^{\ 2}}$$

The estimated VDatum uncertainty for the Maine region is estimated to be 0.134 m (1-σ), therefore, the final vTPU look up table by depth range to be applied to LiDAR data is shown in **Table 7**.

Table 7 Vertical TPU by Depth (meters)

Depth	LiDAR u	VDatum u	vTPU (1-σ)	vTPU (2-σ)
-200	0.045	0.134	0.141	0.277
-2.0	0.055	0.134	0.145	0.284
-1.0	0.062	0.134	0.148	0.290
0.0	0.069	0.134	0.151	0.296
2.0	0.076	0.134	0.154	0.302
4.0	0.087	0.134	0.160	0.313
6.0	0.105	0.134	0.170	0.333
9.0	0.122	0.134	0.181	0.356
11.0	0.140	0.134	0.194	0.380

14.0	0.158	0.134	0.207	0.406
16.0	0.175	0.134	0.221	0.433

The horizontal TPU had previously been estimated using dynamic positioning checks over ground truth targets (usually corners of buildings). The standard deviation of the mean difference between the observed and surveyed check point positions was determined to be 2.295 meters at 1 sigma. And 4.499 m at (2-sigma).

The final TPU look-up table used for assigning vertical and horizontal TPU each LiDAR depth shown in **Table 8**.

Table 8 Final LiDAR TPU Lookup Table at 2-σ

Depth	vTPU	hTPU
-200	0.277	4.499
-2	0.284	4.499
-1	0.290	4.499
0	0.296	4.499
2	0.302	4.499
4	0.313	4.499
6	0.333	4.499
9	0.356	4.499
11	0.380	4.499
14	0.406	4.499
16	0.433	4.499

C – Corrections to Soundings

Sound Velocity Profiles

Sound velocity casts were normally performed every two to three hours on the R/V Theory and R/V Westerly. For each cast, the probes were held at the surface for one to two minutes to achieve temperature equilibrium. The probes were then lowered and raised at a rate of 1 m/s. Between casts, the sound velocity sensors were stored in fresh water to minimize salt-water corrosion and to hold them at an ambient water temperature.

Fugro's MB Survey Tools software was used to check the profiles graphically for spikes or other anomalies, and to produce an SVP file compatible with CARIS HIPS. The WFMB acquisition package also provided QC for surface sound velocity. This was accomplished by creating a real-time plot from the sound velocity probe at the Reson sonar head and notifying the user (via a flashing warning message) if the head sound velocity differed by more than 5m/s from a defined reference sound velocity. This alarm was used as an indication that the frequency of casts may need to be increased. This reference sound velocity was determined by averaging 50 sound velocities produced at the head. The reference sound velocity was reset after each cast and also reset when a cast was performed due to a significant deviation from the reference sound velocity.

Refer to Appendix IV for SVP Calibration Reports.

Settlement Curves

Squat-settlement tests were performed on all vessels to obtain dynamic draft correctors.

The squat-settlement tests were performed by first establishing a 1000-meter line in the direction of the current. The survey vessel sat static at one end of the line for five minutes logging L1/L2 GPS data with the G2 correction. The line was first run at lowest possible engine RPM, then rerun heading the opposite direction at the same RPM, stopping at the end of the line to obtain an additional five minutes of static L1/L2 GPS data. This pattern was repeated for additional lines at incrementing vessel RPMs.

All measurements were corrected for heave, pitch, roll, and reduced to the vessel's common reference point (CRP). Static measurements observed at the end of each line set were used to compute a tide curve for tidal corrections. The settlement curve of dynamic draft correctors was computed via MB Survey Tools directly from the processed PosMV file (SBET). Since the squat and settlement curve was based on the vessel RPMs and not the vessel speed, the results were not entered into the CARIS HVFs. Instead, MBTools was used to create and export these values, which were applied in CARIS using the Load Delta Draft routine prior to sound speed correction.

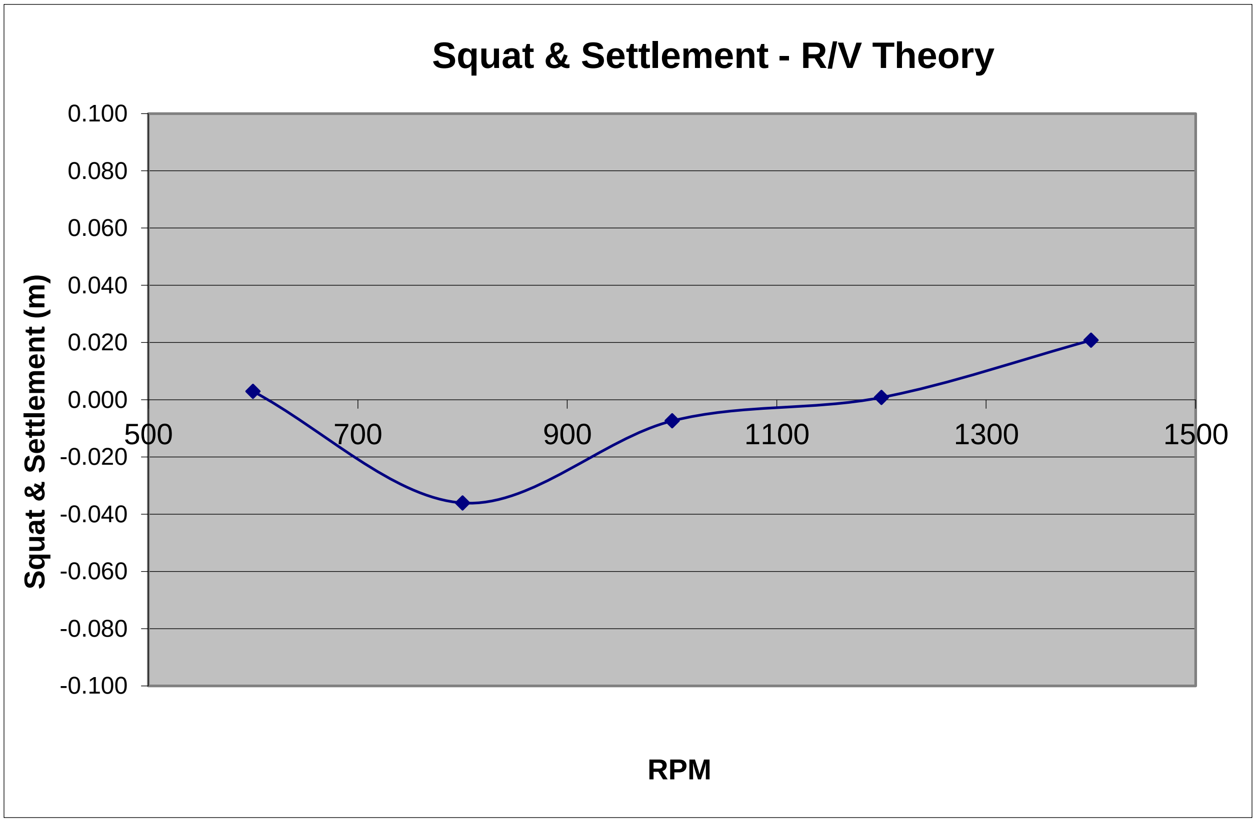


Figure 17 R/V Theory **Dynamic Draft**

Table 9 R/V Theory **Squat Settlement Results**

R/V Theory **DYNAMIC DRAFT CORRECTORS**		
Speed (kts)	**RPM**	**Settlement**
2.7	600	0.003
3.2	700	-0.017
3.6	800	-0.036
4.0	900	-0.022
4.4	1000	-0.007
4.7	1100	-0.003
5.0	1200	0.001
5.4	1300	0.011
5.7	1400	0.021

The squat settlement test for the R/V Theory was conducted on August 16, 2017 (Julian Day 228).

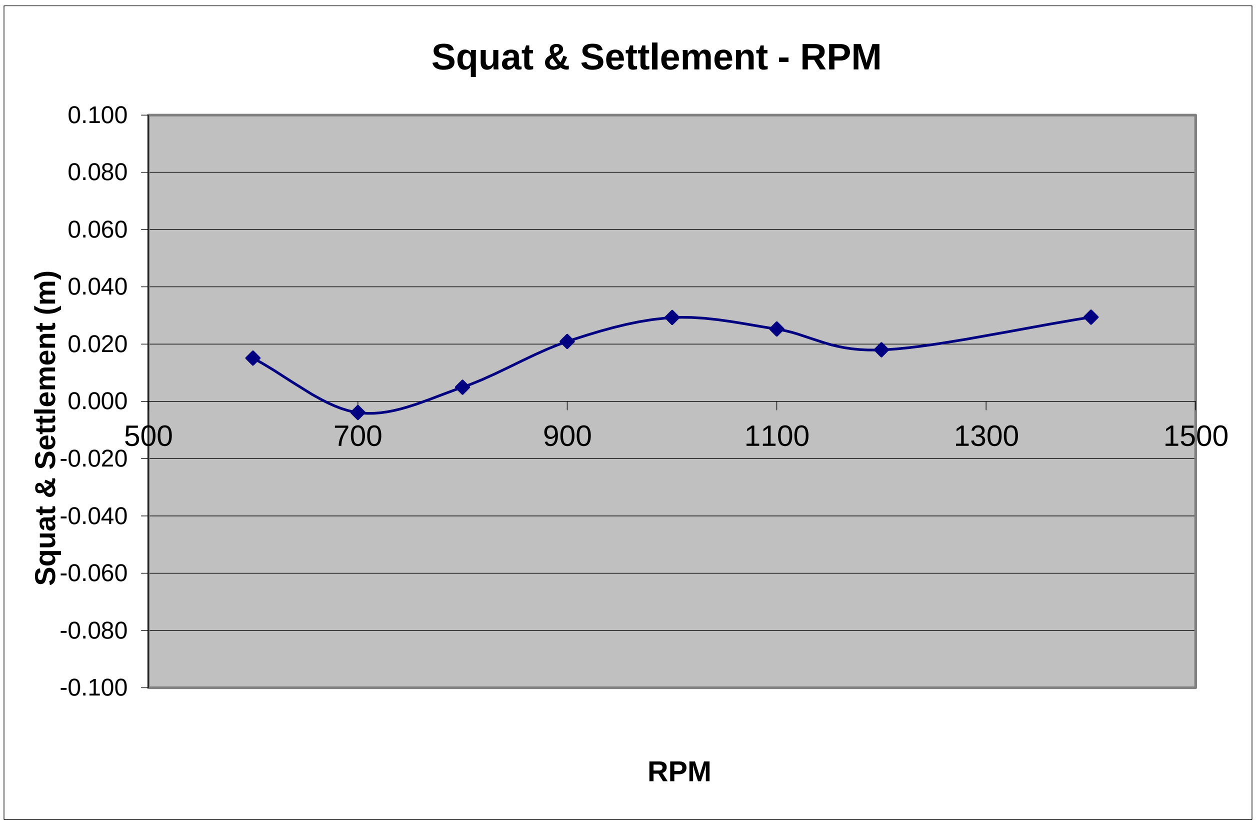


Figure 18 R/V Westerly Dynamic Draft

Table 10 R/V Westerly Squat Settlement Results

R/V Westerly DYNAMIC DRAFT CORRECTORS		
Speed (kts)	**RPM**	**Settlement**
3.6	600	0.015
3.9	700	-0.004
4.5	800	0.005
4.9	900	0.021
5.4	1000	0.029
5.8	1100	0.025
6.0	1200	0.018
6.7	1400	0.029

The squat settlement test for the R/V Westerly was conducted on Sept 1, 2016 (Julian Day 245). The R/V Westerly was used on the 2016 survey, since it had the exact setup and equipment, only a verification settlement test was required. This was conducted on July 2, 2017 (Julian Day 185), the result compared within +/- 0.005m.

Static Draft

Static draft was measured from a point on the stern of the vessel beside the pole. The tables below show the static draft values measured for all vessels (**Table 11**).

Table 11 Draft Measurements for the R/V Theory **(Dual 7125)**

DRAFT #	JULIAN DAY	DATE (UTC)	TIME (UTC)	DEPTH (m)
1	192	7/11/2017	11:20:47	-0.56
2	193	7/12/2017	10:48:04	-0.55
3	194	7/13/2017	10:10:51	-0.56
4	195	7/14/2017	11:58:02	-0.55
5	195	7/14/2017	22:27:25	-0.53
6	196	7/15/2017	10:53:48	-0.53
7	197	7/16/2017	10:28:57	-0.54
8	198	7/17/2017	10:25:49	-0.54
9	199	7/18/2017	10:27:21	-0.53
10	200	7/19/2017	10:25:41	-0.54
11	201	7/20/2017	10:54:57	-0.55
12	202	7/21/2017	10:19:19	-0.56
13	203	7/22/2017	10:37:07	-0.54
14	204	7/23/2017	10:03:19	-0.54
15	205	7/24/2017	11:15:42	-0.54
16	206	7/25/2017	10:33:01	-0.55
17	207	7/26/2017	10:07:34	-0.54
18	208	7/27/2017	10:11:06	-0.54
19	209	7/28/2017	10:11:14	-0.54

DRAFT #	JULIAN DAY	DATE (UTC)	TIME (UTC)	DEPTH (m)
20	209	7/28/2017	10:41:49	-0.55
21	211	7/30/2017	10:12:12	-0.54
22	212	7/31/2017	10:08:04	-0.53
23	213	8/1/2017	10:31:53	-0.55
24	214	8/2/2017	10:19:48	-0.54
25	215	8/3/2017	10:01:04	-0.54
26	216	8/4/2017	10:05:56	-0.53
27	217	8/5/2017	10:40:10	-0.55
28	218	8/6/2017	10:10:46	-0.55
29	219	8/7/2017	10:06:14	-0.54
30	220	8/8/2017	10:11:28	-0.53
31	221	8/9/2017	10:48:58	-0.56
32	222	8/10/2017	12:41:14	-0.55
33	223	8/11/2017	10:09:21	-0.54
34	224	8/12/2017	10:03:48	-0.54
35	225	8/13/2017	11:58:49	-0.56
36	226	8/14/2017	10:06:16	-0.55
37	227	8/15/2017	10:28:48	-0.53
38	228	8/16/2017	10:26:24	-0.53
39	228	8/16/2017	13:34:36	-0.53
40	229	8/17/2017	10:02:26	-0.53
41	230	8/18/2017	10:36:36	-0.55
42	231	8/19/2017	10:20:35	-0.55
43	232	8/20/2017	9:57:56	-0.54
44	233	8/21/2017	10:02:54	-0.54
45	234	8/22/2017	10:35:45	-0.56
46	235	8/23/2017	10:29:14	-0.55
47	236	8/24/2017	10:22:45	-0.54
48	237	8/25/2017	10:11:15	-0.53
49	238	8/26/2017	10:56:30	-0.56
50	239	8/27/2017	10:23:34	-0.55
51	240	8/28/2017	10:18:57	-0.53
52	241	8/29/2017	10:48:16	-0.55
53	242	8/30/2017	11:21:28	-0.55
54	243	8/31/2017	10:20:11	-0.55
55	244	9/1/2017	10:09:10	-0.54
56	245	9/2/2017	10:27:59	-0.54
57	246	9/3/2017	10:25:51	-0.56
58	247	9/4/2017	10:30:43	-0.55
59	248	9/5/2017	10:27:44	-0.54
60	249	9/6/2017	10:12:02	-0.55

DRAFT #	JULIAN DAY	DATE (UTC)	TIME (UTC)	DEPTH (m)
61	250	9/7/2017	10:37:45	-0.55
62	251	9/8/2017	10:32:06	-0.54
63	252	9/9/2017	10:14:37	-0.54
64	253	9/10/2017	10:18:42	-0.55
65	254	9/11/2017	10:12:28	-0.55
66	255	9/12/2017	10:10:54	-0.54
67	256	9/13/2017	10:25:59	-0.55
68	257	9/14/2017	10:12:46	-0.55
69	258	9/15/2017	12:08:50	-0.54
70	259	9/16/2017	10:08:03	-0.54
71	260	9/17/2017	10:23:05	-0.55
72	261	9/18/2017	10:15:36	-0.55
73	262	9/19/2017	10:45:59	-0.54
74	263	9/20/2017	10:42:49	-0.54
75	264	9/21/2017	10:52:13	-0.56
76	265	9/22/2017	10:32:08	-0.56
77	266	9/23/2017	11:03:05	-0.55
78	267	9/24/2017	10:46:12	-0.56
79	268	9/25/2017	11:08:16	-0.56
80	269	9/26/2017	11:06:06	-0.55
81	270	9/27/2017	11:43:20	-0.56
82	271	9/28/2017	14:35:46	-0.55

Table 12 Draft Measurements for the R/V Westerly (Dual 7125)

DRAFT #	JULIAN DAY	DATE (UTC)	TIME (UTC)	DEPTH (m)
1	182	7/1/2017	16:44:00	-0.67
2	183	7/2/2017	13:23:09	-0.65
3	184	7/3/2017	10:48:31	-0.64
4	186	7/5/2017	10:52:35	-0.66
5	188	7/7/2017	10:53:04	-0.63
6	189	7/8/2017	10:37:52	-0.63
7	190	7/9/2017	10:22:17	-0.63
8	191	7/10/2017	10:59:40	-0.63
9	192	7/11/2017	10:22:33	-0.63
10	193	7/12/2017	10:18:06	-0.64
11	194	7/13/2017	10:38:25	-0.64
12	195	7/14/2017	10:16:22	-0.64
13	196	7/15/2017	10:37:15	-0.64
14	198	7/17/2017	14:49:42	-0.64

DRAFT #	JULIAN DAY	DATE (UTC)	TIME (UTC)	DEPTH (m)
15	199	7/18/2017	10:35:42	-0.64
16	200	7/19/2017	11:15:19	-0.64
17	201	7/20/2017	11:00:19	-0.65
18	202	7/21/2017	10:58:58	-0.64
19	203	7/22/2017	10:39:42	-0.63
20	204	7/23/2017	10:05:24	-0.64
21	205	7/24/2017	10:48:34	-0.64
22	206	7/25/2017	10:18:37	-0.64
23	207	7/26/2017	10:31:45	-0.64
24	208	7/27/2017	10:24:20	-0.64
25	209	7/28/2017	10:55:08	-0.64
26	210	7/29/2017	10:30:58	-0.65
27	211	7/30/2017	10:28:43	-0.65
28	212	7/31/2017	10:18:03	-0.65
29	213	8/1/2017	10:31:01	-0.65
30	215	8/3/2017	10:25:46	-0.65
31	216	8/4/2017	10:22:11	-0.64
32	217	8/5/2017	10:35:19	-0.65
33	218	8/6/2017	10:19:34	-0.64
34	219	8/7/2017	14:13:39	-0.64
35	222	8/10/2017	10:33:16	-0.63
36	223	8/11/2017	10:30:57	-0.65
37	224	8/12/2017	10:17:20	-0.64
38	225	8/13/2017	10:16:30	-0.64
39	226	8/14/2017	11:32:32	-0.64
40	227	8/15/2017	10:07:44	-0.64
41	228	8/16/2017	10:51:45	-0.64
42	229	8/17/2017	10:13:44	-0.64
43	230	8/18/2017	10:10:05	-0.64
44	231	8/19/2017	10:02:57	-0.64
45	232	8/20/2017	10:00:27	-0.63
46	233	8/21/2017	10:14:10	-0.63
47	234	8/22/2017	10:23:11	-0.63
48	235	8/23/2017	10:16:57	-0.65
49	236	8/24/2017	10:24:05	-0.64
50	237	8/25/2017	10:08:53	-0.65
51	238	8/26/2017	10:20:29	-0.65
52	239	8/27/2017	10:11:35	-0.64
53	240	8/28/2017	10:08:14	-0.63
54	241	8/29/2017	10:24:11	-0.64
55	242	8/30/2017	10:25:41	-0.64

DRAFT #	JULIAN DAY	DATE (UTC)	TIME (UTC)	DEPTH (m)
56	243	8/31/2017	10:40:34	-0.64
57	244	9/1/2017	10:36:52	-0.64
58	245	9/2/2017	10:46:52	-0.64
59	246	9/3/2017	10:50:10	-0.63
60	247	9/4/2017	10:39:26	-0.64
61	248	9/5/2017	10:40:42	-0.64
62	249	9/6/2017	10:45:02	-0.63
63	250	9/7/2017	10:59:49	-0.63
64	251	9/8/2017	10:45:24	-0.64
65	252	9/9/2017	10:44:41	-0.64
66	253	9/10/2017	10:43:29	-0.64
67	254	9/11/2017	10:50:10	-0.64
68	255	9/12/2017	10:34:27	-0.64
69	256	9/13/2017	10:50:33	-0.64
70	257	9/14/2017	10:34:20	-0.64
71	258	9/15/2017	10:55:44	-0.64
72	259	9/16/2017	10:45:34	-0.64
73	260	9/17/2017	10:40:50	-0.64
74	261	9/18/2017	10:41:11	-0.63
75	262	9/19/2017	10:40:46	-0.63
76	263	9/20/2017	11:20:45	-0.63
77	264	9/21/2017	10:56:44	-0.63
78	265	9/22/2017	10:48:23	-0.63
79	266	9/23/2017	10:53:21	-0.64
80	267	9/24/2017	10:58:23	-0.64
81	268	9/25/2017	11:35:03	-0.64
82	269	9/26/2017	11:30:38	-0.64
83	270	9/27/2017	12:09:53	-0.63
84	271	9/28/2017	15:03:19	-0.63
85	272	9/29/2017	10:43:29	-0.63
86	279	10/6/2017	18:17:41	-0.63
87	280	10/7/2017	12:44:11	-0.63

Tides

During field operations, the Theory and Westerly sounding data were initially reduced to MLLW using a combination of preliminary and verified tidal data from gauges 8413320 (Bar Harbor, ME) and 8418150 (Portland, ME) using the TCARI GUI (version 16.8) and merged in CARIS HIPS. These stations are owned and operated by NOAA's National Ocean Service (NOS) through the Center for Operational Oceanographic Products and Services (CO-OPS). Preliminary and verified tidal data was assembled by CO-OPS and accessed through NOAA's Tides&Currents website (*http://tidesandcurrents.noaa.gov/*). These unverified tides were used in the field for preliminary processing only.

On October 26, 2017, notification that the preliminary TCARI grid is accepted as the final grid for survey project OPR-A366-KR-2017 was acquired from CO-OPS and applied to all sounding data using the TCARI GUI (version 16.8) and merged in CARIS HIPS. Verified tidal data were used for all final CUBE Surfaces, soundings, and S-57 Feature files.

LiDAR vertical control for OPR-A366-KR-17 was GPS-derived. POS files logged during data acquisition on each flight were post-processed using Applanix POSPac SmartBase routine to create an SBET file. Following creation, the SmartBase SBETs were then applied to the data in SHOALS GCS, replacing the real-time GPS navigation position with a post-processed GPS position. The separation model was created with NOAA's VDatum v3.6. This model also allowed for topographic data to be referenced to MLLW through the use of DTM-derived interpolation.

Data was referenced to the WGS84 (ITRF00) datum with the KGPS trajectory solution processed with POSPac SmartBase (ASB) routine using a network of CORS stations, with station ID MEOW, as primary control. The LiDAR data was maintained on the ellipsoid during processing.

LiDAR elevations on the ellipsoid were eventually reduced to soundings on MLLW in CARIS using a separation model grid created in VDatum v3.6. Topographic heights detected by LiDAR were also related to MLLW through the same method. The model was applied to the data, using the compute GPS tides utility, and then merged.

For additional information, refer OPR-A366-KR-17 HVCR.

Vessel Attitude: Heading, Heave, Pitch, and Roll

Vessel heading and dynamic motion were measured by the Applanix (POS/MV) V4 on R/V Theory and Applanix (POS/MV) V5 on the R/V Westerly. The system calculated heading by inversing between two Trimble GPS-generated antenna positions. An accelerometer block (the IMU), which measured vessel attitude, was mounted directly above the multibeam transducer.

Calibrations

Multibeam

For all vessel and sonar configurations, patch tests were conducted to identify alignment errors (timing, pitch, heading, and roll) between the motion sensor and the multibeam transducer(s). Patch test calibration values used to correct all soundings for the survey are shown in **Table 13**.

Table 13 Patch Test Results Summary

Patch Test Results						
Vessel	**Patch Test Day**	**MB Sonar**	**Timing Error**	**Pitch Offset**	**Roll Offset**	**Azimuth Offset**
R/V Theory	2017-191	Port 7125 400 kHz	0.000	1.100	14.950	0.900
	2017-191	Stbd 7125 400 kHz	0.000	0.900	-14.550	0.400
R/V Westerly	2017-181	Port 7125 400 kHz	0.000	-0.950	16.650	0.000
	2017-181	Stbd 7125 400 kHz	0.000	-0.700	-15.000	-0.350
	2017-187	Port 7125 400 kHz	0.000	-1.650	16.300	0.600
	2017-187	Stbd 7125 400 kHz	0.000	-1.600	-14.900	-0.550

Notes:

- Patch Test Day represents the Julian day the actual test was conducted. May be pre- or post-dated in CARIS HVF to cover lines run before or after patch test.

- Several CARIS HIPS Vessel files (HVF) were used throughout the project; some for calibration purposes (which include PORT or STBD in file name) and others for the project’s main line scheme and crosslines. For example, the CARIS HVF named “2Westerly_PORT_7125_7027_Record_400kHz” was used to compute the patch test results for the port 400kHz 7125 system on the R/V Westerly using the 7027 bathy record. HVF “1 Theory_PORT_7125_7027Record_400kHz” was used to compute the patch test results for the port 400kHz 7125 system on the R/V Theory using the 7027 bathy record.

- The Installations Parameters 7030 record was implemented into the acquisition workflow. The 7030 record is the installation parameter of the sonar, which includes the transmit and receiver offsets. Most of the information stored in the 7030 record is not used by CARIS. To fully utilize the 7027 record in a dual head setup, the 7030 record was essential and written to the raw s7k files during data collection. During the conversion process, if the 7030 record was present in the s7k file, CARIS wrote an “InstallationParameter.XML’’ file to the line directory. The HVF was set up in such a way that the sonars’ receiver offsets were input under SV1 (Port receiver offsets) and SV2 (STBD receiver offsets) and the transmitter offsets were read from the 7030 record by CARIS.

Aircraft Offset Survey

The only offset measurement required during system mobilization was from the POS/AV Inertial Measurement Unit (IMU) to the POS/AV GPS antenna. The IMU is completely enclosed within the laser housing. The offsets from the IMU to the common measuring point (CMP) on the outside of the housing are known constants.

Offsets were measured using a total station establishing a base line along the port side of the aircraft. Ranges and bearings are measured from the total station to the CMP on the top of the laser housing. Additional measurements are made to the sides and top of the housing to determine its orientation. A final measurement is made to the center of the POS/AV GPS antenna. The IMU to POS/AV GPS offsets are calculated using the known IMU to CMP offsets. A summary of the offset measurements made during system mobilization are presented in **Figure 19** below. The offsets from the IMU to the POS/AV GPS antenna are entered into the POS/AV console prior to survey.

RESULTS

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

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

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

IMU to GPS ANTENNA		
	X	1.345
	Y	0.117
	Z	-1.372

Checked By: M. Blackbourn

Figure 19 SHOALS Sensor Offsets

SHOALS Sensor Calibration

A full geometric calibration was carried out in June 2017 in Grand Junction, CO in preparation for the survey operations in Maine. This rigorous procedure involves several stages intended to characterize the system parameters to allow raw, uncorrected data to be transformed into calibrated data.

Calibration data used is collected over a variety of environments outlined below.

- Bathymetric lines over a flat, calm surface
- Opposing flight lines over pitched roof buildings – both parallel and perpendicular to the flight path. Additionally, lines that are offset from the peak are collected to capture the edges of the swath.
- Lines of varying altitudes over a topographic ground truth surface – both centered and offset to capture all areas of the swath.
- Bathymetric data over a previously collected MBES ground truth surface. This data should include data in the 8 to 13-meter range.

An overview of the calibration process is detailed below.

The first step is the angular calibration, a minimum of two lines of approximately five-minute duration are collected over a flat, calm body of water. These lines are downloaded and auto-processed in SHOALS GCS, after which they are loaded into an Optech calibration Utility, AutoCalib. This utility analyzes the line data and determines a set of angular offset equations that generate offset values to flatten the water surface when applied to data.

Following the derivation of angular equations, the offset values are further refined using the lines flown on the pitched roof building(s). These lines are examined and reprocessed with different values iteratively until all passes are found to align the building peak with minimal offset from one another.

Once angular values are finalized, the residual vertical error of the system is addressed. This portion uses the topographic ground truth lines and involves comparing the observed elevations to a previously surveyed ground truth surface. Small offset values are then derived for each altitude to correct any existing vertical topographic bias in the system.

The final step derives the remaining bias values using the bathymetric data collected. Bias values for the deep green channel are automatically calculated by SHOALS GCS during the auto-process stage. Apriori depth values are calculated by comparing the data collected by the LiDAR to the bathymetric ground truth surface.

Derived offset values are then used to populate a file referred to as the system parameters file, which is loaded into the mission plans used for flights. Values are again verified before auto-processing to ensure resulting data will be fully calibrated.

D – Approval Sheet

Approval Sheet

For

H13011, H13012, H13013 & H13014

As Chief of Party, Field operations for this hydrographic survey were conducted under my direct supervision, with frequent personal checks of progress and adequacy. I have reviewed the attached survey data and reports.

All field sheets, this Data Acquisition and Processing Report, and all accompanying records and data are approved. All records are forwarded for final review and processing to the Processing Branch.

The survey data meets or exceeds requirements as set forth in the NOS Hydrographic Surveys and Specifications Deliverables Manual, Standing and Letter Instructions, and all HSD Technical Directives. These data are adequate to supersede charted data in their common areas. This survey is complete and no additional work is required.

Approved and forwarded,

Dean Moyles, (ACSM Cert. No. 226)
Senior Hydrographer
Fugro
May 1, 2018

X Moyles, Dean

Digitally signed by Moyles, Dean
DN: dc=com, dc=fugro, l=america, ou=fpi, ou=people_fpi, 0.9.2342.19200300.100.1.1=moylesd, cn=Moyles, Dean, email=dmoyles@fugro.com
Date: 2018.05.01 14:06:59 -02'30'

Dean Moyles (ACSM Cert. No. 226)
Senior Hydrographer

Appendix I – Vessel Reports

<u>R/V Theory</u>

The R/V Theory **(Figure 20),** is owned and operated by Theory Marine and accommodated a survey crew for day operations and acquisition hardware. Dual Reson SeaBat 7125 multibeam sonars were installed on an over the side pole mount on the stern. The Reson systems and IMU were installed on a special mounting plate, where each Reson 7125 was rotated approximately 15 degrees. The Reson systems were installed in their normal SV2 bracket which included an SV70 probe (located in the nose cone) and were attached to the mounting plate by a flange. The inertial measurement unit (IMU) for the POS/MV was an underwater unit that was installed directly above the Reson 7125s (**Figure 21**).

All 7125 multibeam data files were logged in the s7k format using WFMB v3.10.23 The bathy data from each Reson 7125 (records 7027) were stitched together in WFMB to create one s7k file with each ping containing 1024 beams.

Table 14 Vessel Specifications (R/V Theory**)**

SURVEY VESSEL R/V Theory	
Owner	Theory Marine Services
Official Number	1217549
Length	38’
Breadth	13.5’
Max Draft	2.5’
BHP Main Engines	500 HP (Cummins QSC 8.3 liter x 2)
Propulsión	Hamilton 322 Jet Drive x 2
Fresh Water Capacity	30 Gallons
Fuel Capacity	600 Gallons

Figure 20 R/V Theory

Figure 21 R/V Theory Dual 7125 with Underwater IMU

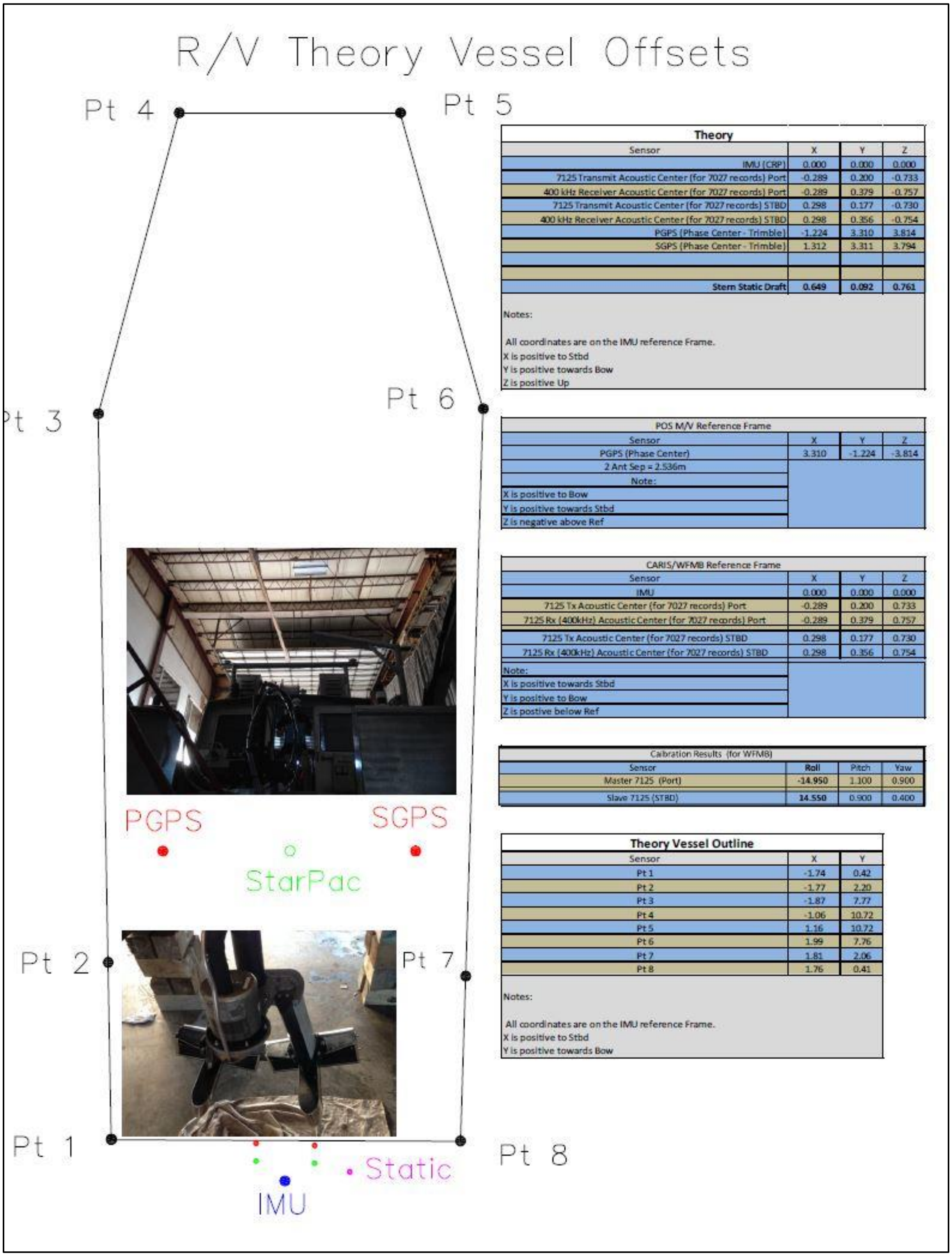
Figure 22. R/V Theory Dual 7125 mount with Underwater IMU

Two Trimble L1/L2 antennas were mounted above and forward from the sonar. Offset 2.536 meters port-starboard from each other, the L1/L2 antennas provided GPS data to the POS/MV for position, attitude, and heading computations. The port side antenna functioned as the POS/MV master antenna, the starboard side antenna functioned as the POS/MV secondary.

The AML Smart probes were deployed from the stern using a hydraulic winch.

A Draft measurement point was located on the stern alongside the pole. The Draft measurement point being located so close to the CRP (IMU) and Reson 7125 allowed us to obtain a precise static draft measurement.

Offset values for the CRP to the sonar and waterline were applied to the data in CARIS HIPS as specified in the HIPS vessel file (HVF). Offsets between the GPS antennas and the CRP were applied internally by the POS/MV by entering a GPS lever arm offset. Note that the HVF does not contain navigation offsets, because the position provided by the POS/MV is already corrected to the CRP. Vessel offsets used are shown in the offset diagram (**Figure 23**).



Theory			
Sensor	X	Y	Z
IMU (CRP)	0.000	0.000	0.000
7125 Transmit Acoustic Center (for 7027 records) Port	-0.289	0.200	-0.733
400 kHz Receiver Acoustic Center (for 7027 records) Port	-0.289	0.379	-0.757
7125 Transmit Acoustic Center (for 7027 records) STBD	0.298	0.177	-0.730
400 kHz Receiver Acoustic Center (for 7027 records) STBD	0.298	0.356	-0.754
PGPS (Phase Center - Trimble)	-1.224	3.310	3.814
SGPS (Phase Center - Trimble)	1.312	3.311	3.794
Stern Static Draft	**0.649**	**0.092**	**0.761**

Notes:

All coordinates are on the IMU reference Frame.
X is positive to Stbd
Y is positive towards Bow
Z is positive Up

POS M/V Reference Frame			
Sensor	X	Y	Z
PGPS (Phase Center)	3.310	-1.224	-3.814
2 Ant Sep = 2.536m			
Note:			
X is positive to Bow			
Y is positive towards Stbd			
Z is negative above Ref			

CARIS/WFMB Reference Frame			
Sensor	X	Y	Z
IMU	0.000	0.000	0.000
7125 Tx Acoustic Center (for 7027 records) Port	-0.289	0.200	0.733
7125 Rx (400kHz) Acoustic Center (for 7027 records) Port	-0.289	0.379	0.757
7125 Tx Acoustic Center (for 7027 records) STBD	0.298	0.177	0.730
7125 Rx (400kHz) Acoustic Center (for 7027 records) STBD	0.298	0.356	0.754
Note:			
X is positive towards Stbd			
Y is positive to Bow			
Z is postive below Ref			

Calibration Results (for WFMB)			
Sensor	**Roll**	Pitch	Yaw
Master 7125 (Port)	**-14.950**	1.100	0.900
Slave 7125 (STBD)	**14.550**	0.900	0.400

Theory Vessel Outline		
Sensor	X	Y
Pt 1	-1.74	0.42
Pt 2	-1.77	2.20
Pt 3	-1.87	7.77
Pt 4	-1.06	10.72
Pt 5	1.16	10.72
Pt 6	1.99	7.76
Pt 7	1.81	2.06
Pt 8	1.76	0.41

Notes:

All coordinates are on the IMU reference Frame.
X is positive to Stbd
Y is positive towards Bow

Figure 23 R/V Theory Offset Diagram

R/V Westerly

The R/V Westerly **(Figure 24),** is owned and operated by Zephyr Marine, accommodated a survey crew for day operations and acquisition hardware. Dual Reson SeaBat 7125 multibeam sonars were installed on an over the side pole mount located on the stern. The Reson systems and IMU were installed on a special mounting plate, where each Reson 7125 was rotated approximately 15 degrees. The Reson systems were installed in their normal SV2 bracket which included an SV70 probe (located in the nose cone) and were attached to the mounting plate by a flange. The inertial measurement unit (IMU) for the POS/MV was an underwater unit that was installed directly above the Reson 7125's (**Figure 25**).

All 7125 multibeam data files were logged in the s7k format using WFMB v3.10.23. The bathy data from each Reson 7125 (records 7004/7006, 7027) were stitched together in WFMB to create one s7k file with each ping containing 1024 beams.

Table 15 Vessel Specifications (R/V Westerly)

SURVEY VESSEL R/V Westerly	
Owner	Zephyr Marine
Official Number	1231991
Length	44'
Breadth	15.5'
Max Draft	2'
BHP Main Engines	500 HP (Cummins QSC 8.3 liter x 2)
Propulsión	Hamilton 322 Jet Drive x 2
Fresh Water Capacity	30 Gallons
Fuel Capacity	600 Gallons

Figure 24 R/V Westerly

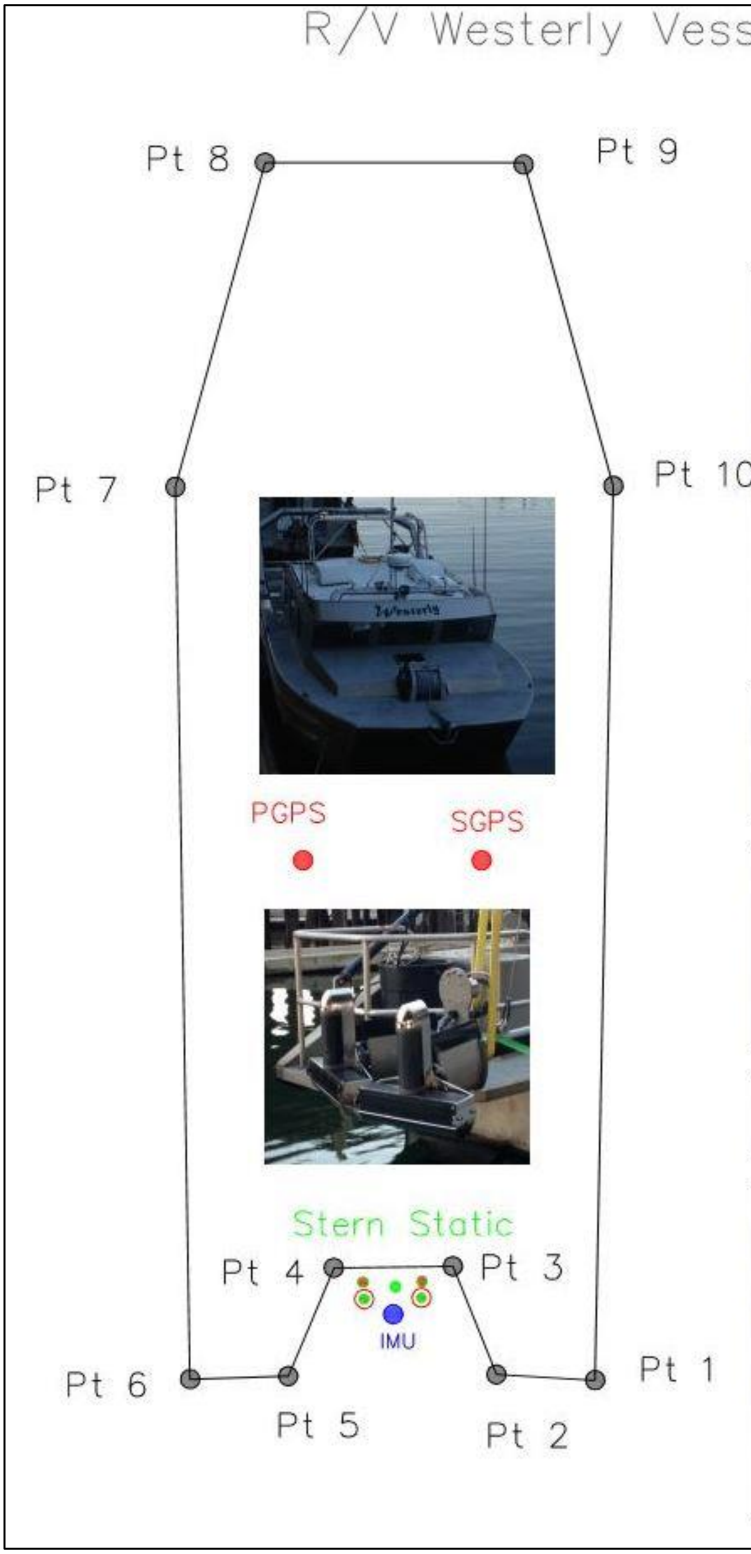
Figure 25 R/V Westerly Dual 7125 with Underwater IMU

Two Trimble L1/L2 antennas were mounted above and forward from the sonar. Offset 1.877 meters port-starboard from each other, the L1/L2 antennas provided GPS data to the POS/MV for position, attitude, and heading computations. The port side antenna functioned as the POS/MV master antenna; the starboard side antenna functioned as the POS/MV secondary.

The AML Smart probes were deployed from the stern using a hydraulic winch.

A Draft measurement point was located on the stern alongside the pole. The Draft measurement point being located so close to the CRP (IMU) and Reson 7125 allowed us to obtain a precise static draft measurement.

Offset values for the CRP to the sonar and waterline were applied to the data in CARIS HIPS as specified in the HIPS vessel file (HVF). Offsets between the GPS antennas and the CRP were applied internally by the POS/MV by entering a GPS lever arm offset. The HVF does not contain navigation offsets, because the position provided by the POS/MV is already corrected to the CRP. Vessel offsets used are shown in the offset diagram (**Figure 26**).



Westerly			
Sensor	X	Y	Z
IMU (CRP)	0.000	0.000	0.000
7125 Sonar Acoustic Center (for 7004 records) Port	-0.310	0.176	-0.688
7125 Transmit Acoustic Center (for 7027 records) Port	-0.310	0.176	-0.664
400kHz Receiver Acoustic Center (for 7027 records) Port	-0.310	0.355	-0.688
200kHz Receiver Acoustic Center (for 7027 records) Port	-0.310	0.374	-0.688
7125 Sonar Acoustic Center (for 7004 records) STBD	0.291	0.190	-0.692
7125 Transmit Acoustic Center (for 7027 records) STBD	0.291	0.190	-0.668
400 kHz Receiver Acoustic Center (for 7027 records) STBD	0.291	0.369	-0.692
200 kHz Receiver Acoustic Center (for 7027 records) STBD	0.291	0.388	-0.692
PGPS (Phase Center - Trimble)	-0.916	4.665	4.349
SGPS (Phase Center - Trimble)	0.961	4.665	4.336
Stern Static Draft	0.032	0.259	1.266

Notes:

All coordinates are on the IMU reference Frame.
X is positive to Stbd
Y is positive towards Bow
Z is positive Up

POS M/V Reference Frame			
Sensor	X	Y	Z
PGPS (Phase Center)	4.665	-0.916	-4.349
2 Ant Sep = 1.877m			
Note:			
X is positive to Bow			
Y is positive towards Stbd			
Z is negative above Ref			

CARIS/WFMB Reference Frame			
Sensor	X	Y	Z
IMU	0.000	0.000	0.000
7125 Tx Acoustic Center (for 7027 records) Port	-0.310	0.176	0.664
7125 Rx (400kHz) Acoustic Center (for 7027 records) Port	-0.310	0.355	0.688
7125 Tx Acoustic Center (for 7027 records) STBD	0.291	0.190	0.668
7125 Rx (400kHz) Acoustic Center (for 7027 records) STBD	0.291	0.369	0.692
Note:			
X is positive towards Stbd			
Y is positive to Bow			
Z is postive below Ref			

Calibration Results (for WFMB)			
Sensor	Roll	Pitch	Yaw
Master 7125 (Port)	-16.300	-1.650	0.600
Slave 7125 (STBD)	14.900	-1.600	-0.550

Westerly Vessel Outline		
Sensor	X	Y
Pt 1	2.12	-0.69
Pt 2	1.08	-0.63
Pt 3	0.63	0.50
Pt 4	-0.63	0.49
Pt 5	-1.10	-0.65
Pt 6	-2.14	-0.68
Pt 7	-2.29	8.69
Pt 8	-1.35	12.10
Pt 9	1.37	12.08
Pt 10	2.31	8.70

Notes:

All coordinates are on the IMU reference Frame.
X is positive to Stbd
Y is positive towards Bow

Figure 26 R/V Westerly Offset Diagram

De Havilland DC-6 Twin Otter

The survey platform for the SHOALS-1000T LiDAR operations was a De Havilland DC-6 Twin Otter, tail sign N94AR, owned and operated by Twin Otter International of Grand Junction, Colorado.

Figure 27 De Havilland DHC-6 Twin Otter

The Twin Otter is ideal for slower survey speeds to ensure data density, and obtaining maximum swath width and control. This aircraft and supplier have been used previously by Fugro projects with the SHOALS-1000T. Technical information relating to this aircraft can be found in **Table 16**. Fugro is able to quickly and easily mobilize this platform using specially engineered and FAA approved mounting plates.

Table 16 Aircraft Technical Specifications

AIRCRAFT	De Havilland DHC-6 Twin Otter
Registration Number	N94AR
Owner	Twin Otter International

Wing Span	19.8 m
Length	15.8 m
Gross Weight (empy	5,670 kg
Allowable load	2,000-3,150 kg
Engines	PT6A-27
Cabin space	10.87 cubic meters
Maximum sensor power	300 Amp @ 28VDC or 8400 Watt

The airborne components of the SHOALS-1000T consist of two separate modules. The laser and camera sources are contained in a single housing bolted to a flange above the aircraft camera door (**Figure 28**). An equipment rack, containing the system cooler and power supplies was installed fore of the laser. The system is controlled through a laptop by the Airborne Operator and a separate pilot console provides navigation and track guidance information to the flight crew.

Figure 28 SHOALS-1000T modules. Equipment rack (left); sensor housing (right)

The SHOALS-1000T ALB system is shown in as installed on the aircraft in **Figure 29**.

Figure 29 SHOALS Installation in DC-6 Twin Otter

Additional information relating to the operational capacities of the SHOALS-1000T and aircraft can be found below in **Table 17**.

Table 17 Aircraft and SHOALS Operating Specifications

Aircraft Type	De Havilland DHC-6 Twin Otter
Average Aircraft Endurance	4.5 hours
Aircraft Range	Up to 1000 nautical miles
Aircraft Transit Speed	170 knots
Aircraft Transit Altitude	2300 to 2900 m
Survey Altitude	300 to 500 m
Airborne System	• Independent sensor cooling • Gyro-stabilized scanner bed • Single operator console • Integrated pilot display
Operational Capability	Full day or night operation in all weather (VFR, IFR)
Airborne Survey Crew	One operator and two pilots
Bathymetric LiDAR	SHOALS-1000T, s/n FPI-1
Depth Sounding Rate	2500 kHz
Depth Range	50 m in very clear water
Topographic Range	150 m below sensor
Sounding Density	2 x 2 m, 3 x 3 m, 4 x 4 m and 5 x 5 m
Swath Width	Variable swath, up to 0.75 x altitude
Digital Imagery Capability	Allied Prosilica GX3300
Integrated Inertial System	Applanix POS/AV 510 v6
Differential Corrections	Marinestar G2 (GPS/GLONASS) service
Horizontal Accuracy	IHO Order 1b
Vertical Accuracy	IHO Order 1b
Area Coverage	50.4 km^2 per hour, 5 x 5m

Equipment

Table 18 R/V Theory **Acquisition Equipment**

Description	Serial Number
Applanix IMU LN200	64
Applanix POS/MV Processor L1/L2 (RTK)	4032
GPS Antenna L1/L2 (Primary)	1441036287
GPS Antenna L1/L2 (Secondary)	1441045035
Reson NAVISOUND SVP 70	1008130
Reson NAVISOUND SVP 70 (Spare)	1016096
Reson 71-P Processor-7125 SV2 (FP3)	18340714124
Reson 71-P Processor-7125 SV2 (FP3)	18243512030
Reson SeaBat 7125 400kHz/200Khz Projector	1612100
Reson SeaBat 7125 400kHz/200Khz Projector	3313039
Reson SeaBat 7125 Receive Array	4107007
Reson SeaBat 7125 Receive Array	4013021
Fugro Acquisition PC	BGR 602604
WinFrog Multibeam Dongle	3100441U
WinFrog Multibeam Dongle	3100442U
AML SV Plus Velocity Probe	5283
AML SV Plus Velocity Probe	5354

Table 19 R/V Westerly Acquisition Equipment

Description	Serial Number
Applanix IMU LN200	
Applanix POS/MV Processor L1/L2 (RTK)	7821
GPS Antenna L1/L2 (Primary)	1441021131
GPS Antenna L1/L2 (Secondary)	1441045154
Reson NAVISOUND SVP 70 (Primary)	4506001
Reson 71-P Processor-7125 SV2 (FP3)	18341114131
Reson 71-P Processor-7125 SV2 (FP3)	18340313024
Reson SeaBat 7125 400kHz/200Khz Projector	2710017
Reson SeaBat 7125 400kHz/200Khz Projector	1012060
Reson SeaBat 7125 Receive Array	2411051
Reson SeaBat 7125 Receive Array	4715040
Fugro Acquisition PC	BGR 602832
WinFrog Multibeam Dongle	3100443U
AML SV Plus Velocity Probe	4431
AML SV Plus Velocity Probe	5353

Table 20 LiDAR Acquisition Equipment

Description	Serial Number
SHOALS -1000T	FPI-1
Applanix POS/AV 510	6152
GPS Antenna L1/L2 (Iridium filtered)	5594
Applanix IMU LN200	407154

Software

Table 21 MBES Software List (Acquisition & Processing Center)

Software Package	Version	Service Pack	Hotfix
Fugro WinFrog Multibeam	3.10.23	N/A	N/A
Fugro MB Survey Tools	3.1.15	N/A	N/A
Fugro POSMVLogger	2	N/A	N/A
CARIS HIPS/SIPS	9.1.9	N/A	N/A
CARIS Notebook	3.1	1	2
CARIS Bathy DataBASE	4.1.17	N/A	N/A
CARIS Onboard	1.2	N/A	N/A
CARIS Easy View	4.1.16	N/A	N/A
ESRI ArcGIS	10.3	10.3	N/A
Applanix POS/MV V4 Controller	5.8.0.0	N/A	N/A
Applanix POS/MV V5 Controller	8.46	N/A	N/A
Nobeltec Tides and Currents	3.5.107	N/A	N/A
Microsoft Office	2013	N/A	N/A
Microsoft Windows (64-bit)	7 Enterprise	1	N/A
Helios Software Solutions TextPad	5.2.0	N/A	N/A
NOAA Extended Attribute Files	5.5	N/A	N/A
IrfanView	4.25	N/A	N/A
IrfanView	5.25	N/A	N/A
IrfanView	6.25	N/A	N/A
IrfanView	7.25	N/A	N/A

Table 22: LiDAR Software List (Acquisition & Processing Center)

Software Package	Version	Service Pack	Hotfix
Fugro LiDAR Survey Tools	1.03.06	N/A	N/A
SHOALS Airborne System Operator	1.2	N/A	N/A
SHOALS GCS	6.32	N/A	N/A
Optech AutoCalib	N/A	N/A	N/A
CARIS HIPS/SIPS	9.1.9	N/A	N/A
CARIS Base Editor	4.1.17	N/A	N/A
QPS Fledermaus	7.3.3c	N/A	N/A
Workbench	6.01.04	N/A	N/A
NovAtel Convert 4	3.9.0.7	N/A	N/A
ESRI ArcGIS	10.3	N/A	N/A
Applanix POS Pac MMS	7.1	N/A	N/A
NOAA’s VDatum	3.6	N/A	N/A
ERDAS LPS	9.3	N/A	N/A
OrthoVista	7.0.3	N/A	N/A
Microsoft Office	2013	N/A	N/A
Microsoft Windows (64-bit)	7 Enterprise	1	N/A
Helios Software Solutions TextPad	5.2.0	N/A	N/A

Appendix II – Echosounder Reports

Multibeam Echosounder Calibration

A patch test was completed for the MBES using seafloor topology for data to be corrected for navigation timing, pitch, azimuth, and roll offsets, which may exist between the MBES transducer and the Motion Reference Unit (MRU).

Patch tests were performed independently on each sonar and were run at various stages of survey operations to calibrate the MBES and MRU for different vessel configurations.

No adjustment was required for navigation timing error. Fugro has implemented a specific timing protocol for multibeam data acquisition. In this method, UTC time tags generated within the POS/MV are applied to all position, heading, and attitude data. The POS/MV ZDA+1 PPS (pulse per second) string is also sent to the Reson SeaBat sonar system, where the ping data are tagged. The architecture of the POS/MV ensures that there is zero latency between the position, heading, and attitude strings. The only latency possible is in the ping time. In addition, the navigation-to-ping latency will be identical to the attitude-to-ping and heading-to-ping latencies.

Navigation latency is generally difficult to measure using standard timing and patch testing techniques. However, using Fugro's timing protocol, the navigation latency will be the same as the roll latency. Fortunately, roll latencies are very easy to identify. Data with a roll timing latency will have a rippled appearance along the edge of the swath. During patch test analysis, the roll latency is adjusted until the ripple is gone. This latency value is then applied to the ping time, synchronizing it with the position, attitude, and heading data.

The pitch error adjustment was performed on sets of two coincident lines, run at the same velocity, over a conspicuous object, in opposite directions. The nadir beams from each line were compared and brought into alignment, by adjusting the pitch error value.

The azimuth error adjustment was performed on sets of two lines, run over a conspicuous topographic feature. Lines were run in opposite directions, at the same velocity with the same outer beams crossing the feature. Since the pitch error has already been identified, data from the same outer beams for each line were compared and brought into alignment, by adjusting the azimuth error value.

The roll error adjustment was performed on sets of two coincident lines, run over flat terrain, at the same velocity, in opposite directions. The pitch error and azimuth error were already identified. Data across a swath were compared for each line and brought into agreement by adjusting the roll error value.

Patch test data were then corrected using the identified values, and the process repeated to check their validity. Patch test values were obtained in CARIS HIPS calibration mode. Calculated values were then entered into the HVF so that data could be corrected during routine processing.

Multibeam Echosounder Calibration Results

Table 23 Patch Test Results for Each Vessel

Patch Test Results						
Vessel	**Patch Test Day**	**MB Sonar**	**Timing Error**	**Pitch Offset**	**Roll Offset**	**Azimuth Offset**
R/V Theory	2017-191	Port 7125 400 kHz	0.000	1.100	14.950	0.900
	2017-191	Stbd 7125 400 kHz	0.000	0.900	-14.550	0.400
R/V Westerly	2017-181	Port 7125 400 kHz	0.000	-0.950	16.650	0.000
	2017-181	Stbd 7125 400 kHz	0.000	-0.700	-15.000	-0.350
	2017-197	Port 7125 400 kHz	0.000	-1.650	16.300	0.600
	2017-197	Stbd 7125 400 kHz	0.000	-1.600	-14.900	-0.550

Notes:

- Patch Test Day represents the Julian day the actual test was conducted. May be pre- or post-dated in CARIS HVF to cover lines run before or after patch test.

- Several CARIS HIPS Vessel (HVF) files were used throughout the project; some for calibration purposes (which include PORT or STBD in file name) and others for the project's main line scheme and crosslines. For example, the CARIS HVF named "2Westerly_PORT_7125_7027_Record_400kHz" was used to compute the patch test results for the port 400kHz 7125 system on the R/V Westerly using the 7027 bathy record. HVF "1Theory_PORT_7125_7027Record_400kHz" was used to compute the patch test results for the port 400kHz 7125 system on the R/V Theory using the 7027 bathy record.

- The 7030 record was implemented into the acquisition workflow. The 7030 record is the installation parameters of the sonar, which include the transmit and receiver offsets. Most of the information stored in the 7030 record is not used by CARIS. To fully utilize the 7027 record in a dual head setup, the 7030 record was essential and written to the raw s7k files during data collection. During the conversion process, if the 7030 record was present in the s7k file, CARIS wrote an "InstallationParameter.XML'' file to the line directory. The HVF was set up in such a way that the sonars' receiver offsets were input under SV1 (Port receiver offsets) and SV2 (STBD receiver offsets) and the transmitter offsets were read from the 7030 record by CARIS. Any HVF with Dual in its name is using the 7027/7030 records. For example, "2Westerly_Dual_7125_7027_Record_400kHz" is for the dual 400kHz 7125 systems on the R/V Westerly using the 7027 bathy record and the 7030 installation parameters record.

Multibeam Bar Check

A bar check calibration of multibeam sonar systems is performed to accurately relate observed (recorded) depths to the true depth of water. Therefore, the calibration determines any error in the system's raw depth readings (as well as verifying the accuracy of the vessel offset survey).

A bar check calibration is performed by lowering a horizontal metal plate to a known depth below the waterline. Then, data at that known depth is acquired using the multibeam sonar system and processed using the CARIS HIPS and SIPS Swath Editor routine.

By processing the data in the CARIS Swath Editor routine, the vessel's equipment offsets measured during the offset survey, the sound velocity profile taken at the time of the bar check, the survey's static draft measurement procedure, and the data cleaning routine used during the survey are all applied to the data to calculate the difference between the sonar's measurement of the horizontal bar and the actual, known depth below the waterline.

Any difference in the measured depth versus the known depth can be attributed to error in the sound velocity profile, the static draft measurement procedure, the vessel offset survey, and/or the sonar system's internal capabilities.

On 16 July 2017 and 17 July 2017 respectively, hydrographers onboard the R/V Westerly and the R/V Theory performed bar check calibrations for the respective Reson 7125 multibeam sonar systems. An additional bar check was conducted for the R/V Westerly on 29 September 2017 and for the R/M Theory on 27 September 2017.

Prior to performing the bar check calibrations, accurate static draft measurements were performed. Then, a flat, metal plate was lowered to a specific depth below the waterline, using lowering lines of metal chain on both sides to have the plate horizontal.

The Reson 7125 systems were energized and data was acquired to measure the plate's depth. During data acquisition, the vessels' navigation and motion sensors, a POS/MV (v. 4) on the R/V Theory and POS/MV (v. 5) on the Westerly were also energized to record the vessels' attitude in the water at the time of measurement. Data were acquired for a period of 1-2 minutes to provide data samples large enough to calculate an average observed depth for each system.

An SVP cast was performed to create sound velocity profiles of the water column in the vicinity of the vessels.

The data was then processed in CARIS HIPS to reduce the observed depths to the waterline and compare them to the known depths of the horizontal plate. The processing procedure that was followed, parallels the standard data processing procedures as detailed in the report of survey. The static draft measurement, the vessel equipment offsets, the vessel attitude data, and the sound velocity corrections were all applied to the raw depth observations.

The data were then further processed in the CARIS HIPS Swath Editor routine.

The acquired observed plate's depths were exported from CARIS to Microsoft Excel to calculate an average observed depth over a 1-minute period for each system. The results of the bar check calibrations are detailed below.

<u>Multibeam Bar Check Results</u>

R/V Theory **Reson 7125 (2m Bar Depth)**

The image below shows a CARIS HIPS Swath Editor display screen with the horizontal plate ensonified at a depth of 2.0 meters below the waterline (the value of 2.01 meters is the average depth calculated over a 1-minute period of data acquisition).

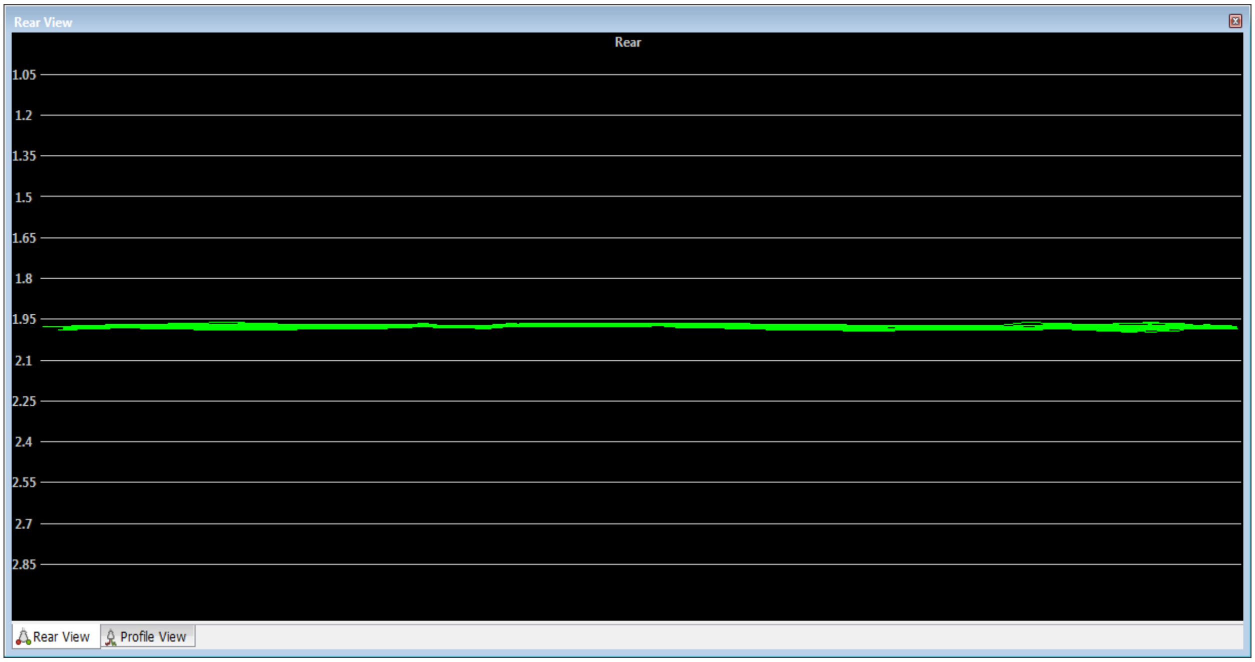


Figure 30 R/V Theory **2m Bar Check Showing the Bar Relative to Seafloor**

R/V Westerly Reson 7125 (4m Bar Depth)

The image below shows a CARIS HIPS Swath Editor display screen with the horizontal plate ensonified at a depth of 4.0 meters below the waterline (the value of 4.04 meters is the average depth calculated over a 1-minute period of data acquisition).

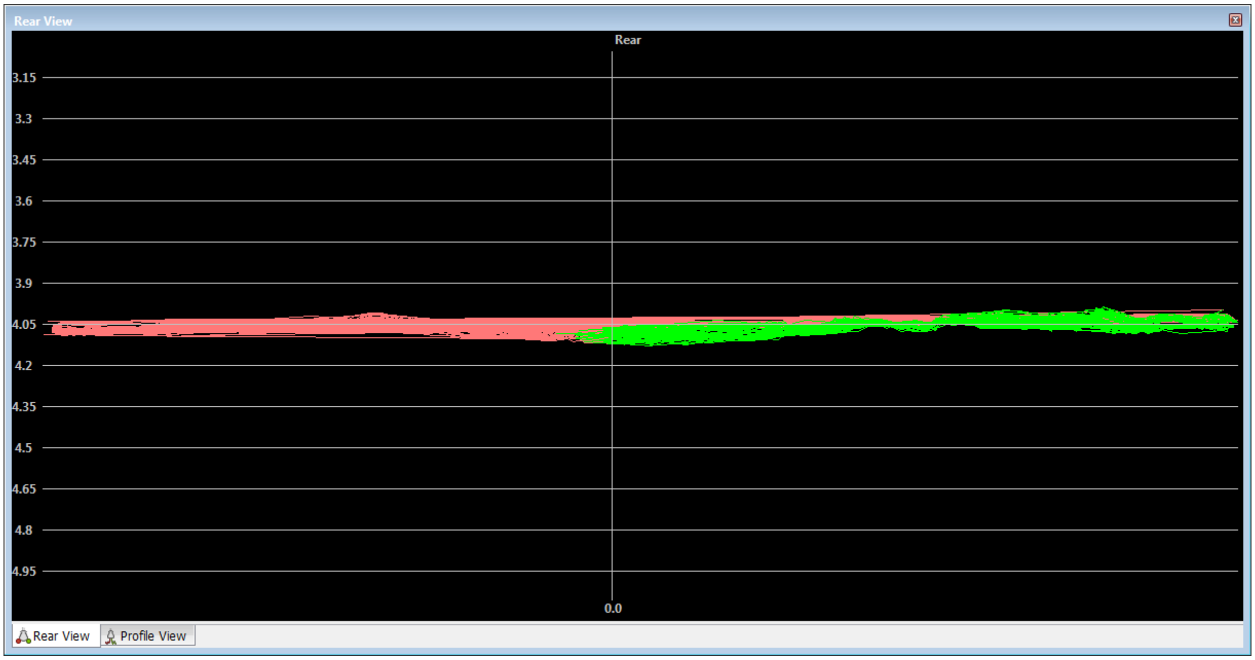


Figure 31 R/V Westerly 4m Bar Check Showing the Bar Relative to Seafloor

Multibeam Confidence Checks

Sonar system confidence checks, as outlined in Section 5.2.3.1 of the HSSD, were performed by comparing post processed depth information collected over a common area by each vessel. The confidence check results are outlined in the table below. In addition to this, checks were performed on overlapping main scheme and crossline data collected from different vessels on different days.

Multibeam Confidence Check Results

Table 24 Confidence Check Results

Surface Vessels	Mean Difference (m)	Standard Deviation (m)
Theory vs. Westerly	0.04	0.05
Westerly vs. LiDAR	+/-0.1	+/-0.3

The above results were computed from difference surfaces that were created from overlapping data collected by the R/V Theory and the R/V Westerly during field operations. See **Table 24** and **Figure 32**. The same or better results were noticed in additional checks that were performed using crossline data.

Overlapping data between the LiDAR and MBES systems was also compared and results are shown in the table above and in the images in **Figure 33** and **Error! Reference source not found.**.

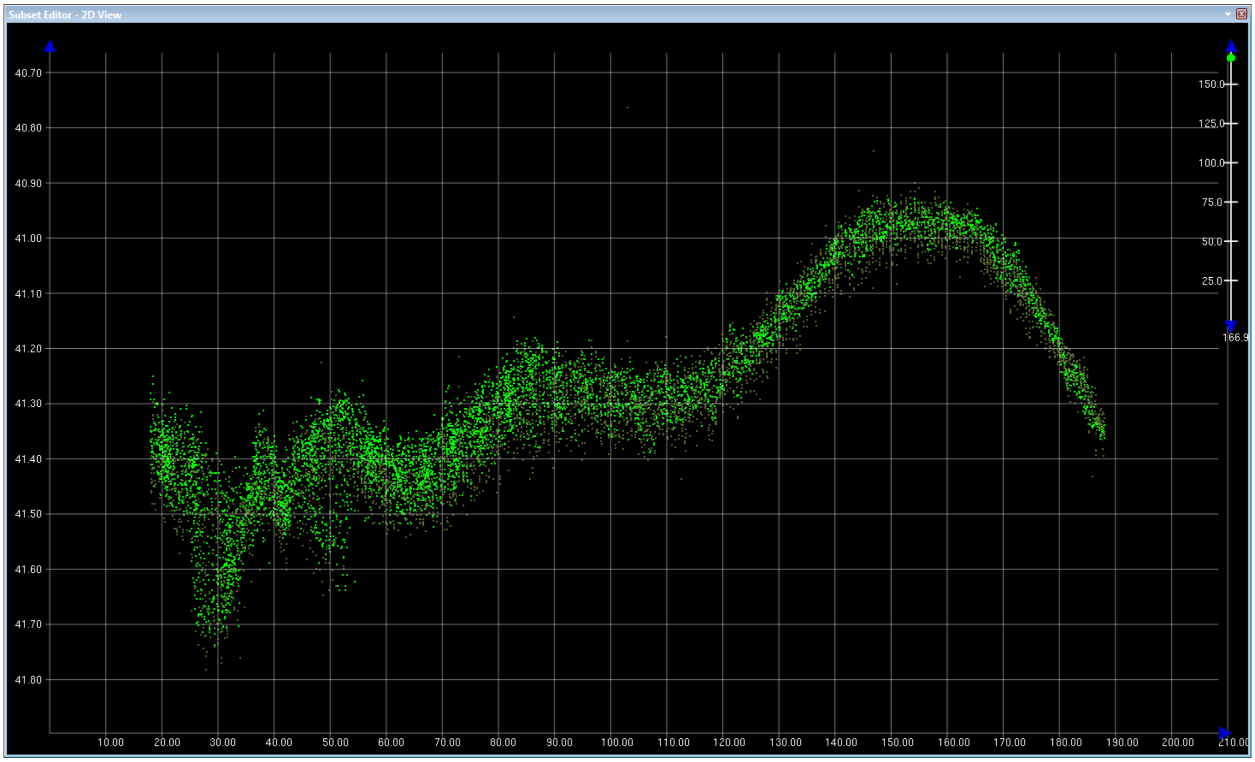


Figure 32 Theory vs Westerly Comparison

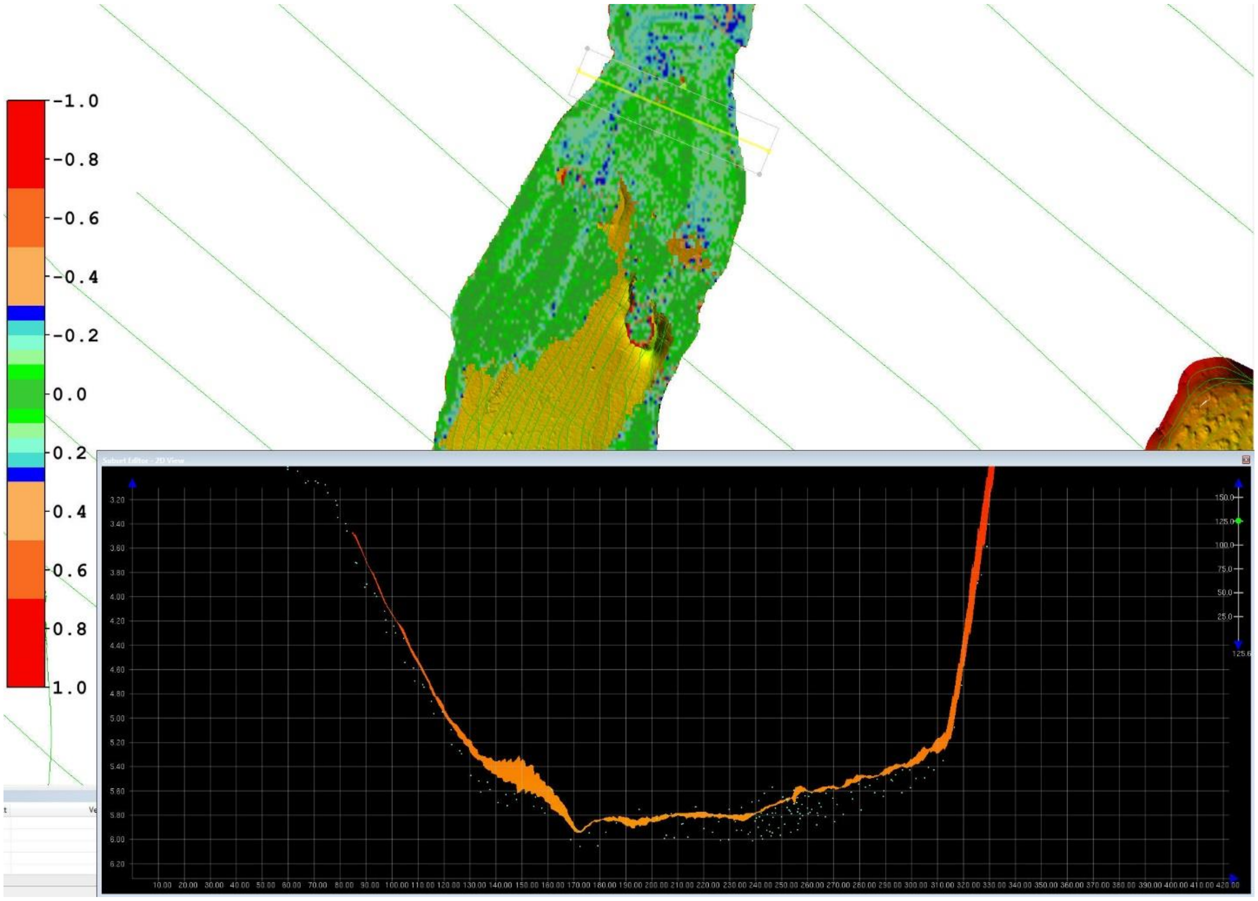


Figure 33 Westerly vs LiDAR at Orcutt Bay

Appendix III – Positioning and Attitude System Reports

GAMS Calibration

Vessel headings are measured by the Applanix POS/MV V4/V5, by way of a GPS Azimuth Measurement Subsystem (GAMS). GAMS computes a carrier-phase differential GPS position solution of a Slave antenna with respect to a Master antenna position, thereby computing the heading between the two. In order for this subsystem to provide a heading accuracy of 0.01º, the system needs to know and resolve the spatial relationship between the two antennas. During the GAMS calibration, since the offset from the IMU to the Master antenna is known (from the vessel offset survey), the location of the Slave antenna is calculated by computing the baseline between the two antennas with respect to the IMU axes.

To calibrate the heading data received from the POS/MV GAMS subsystem, the POS Viewer software is used to run the GAMS Calibration routine. First, an accurate and precise separation distance between the two GNSS antennas is entered into the POS Viewer's GAMS Parameter Setup window. Once this known offset is entered into the system, the vessel begins maneuvering with turns to port and starboard (preferably figure-eight maneuvers) to allow the system to refine its heading accuracy.

Once the heading data falls to within an allowable accuracy, the vessel ends the figure-eight maneuvers and maintains a steady course and speed. The GAMS Calibration routine is started, and the POS/MV completes the calibration. The results can be viewed in the GAMS Parameter Setup window of the POS Viewer software.

The GAMS subsystem should be calibrated only one time at the start of the survey. An additional calibration should be completed and logged any time the IMU or antennas are moved.

<u>GAMS Calibration Results</u>

The calculations give the following results:

Table 25 Vessel Heading Calibration (GAMS Calibration)

Vessel	R/V Theory	R/V Westerly
Two Antenna Separation (m)	2.533	1.876
Heading Calibration Threshold (deg)	0.5	0.5
Heading Correction (deg)	0.000	0.000
Baseline Vector X axis	0.051	0.022
Baseline Vector Y axis	2.532	1.876
Baseline Vector Z axis	0.012	0.005

Appendix IV – Sound Speed Sensor Report

All SVP Calibration Reports can be found under the Appendix_IV_(SVP_Calibrations) directory.