https://doi.org/10.7289/V5/TM-NOS-CS-36

NOAA Technical Memorandum NOS CS 36

INTEGRATION OF U.S. ARMY CORPS OF ENGINEERS AIRBORNE LIDAR BATHYMETRY (ALB) SURVEY DATA INTO NOAA'S PROCESSING WORKFLOW

Silver Spring, Maryland
June 2016

noaa **National Oceanic and Atmospheric Administration**

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Hydrographic Surveys Division

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The Office of Coast Survey (OCS) is the Nation's only official chartmaker. As the oldest United States scientific organization, dating from 1807, this office has a long history. Today it promotes safe navigation by managing the National Oceanic and Atmospheric Administration's (NOAA) nautical chart and oceanographic data collection and information programs.

There are four components of OCS:

> The Coast Survey Development Laboratory develops new and efficient techniques to accomplish Coast Survey missions and to produce new and improved products and services for the maritime community and other coastal users.
>
> The Marine Chart Division acquires marine navigational data to construct and maintain nautical charts, Coast Pilots, and related marine products for the United States.
>
> The Hydrographic Surveys Division directs programs for ship and shore-based hydrographic survey units and conducts general hydrographic survey operations.
>
> The Navigational Services Division is the focal point for Coast Survey customer service activities, concentrating predominately on charting issues, fast-response hydrographic surveys, and Coast Pilot updates.

https://doi.org/10.7289/V5/TM-NOS-CS-36

NOAA Technical Memorandum NOS CS 36

INTEGRATION OF U.S. ARMY CORPS OF ENGINEERS AIRBORNE LIDAR BATHYMETRY (ALB) SURVEY DATA INTO NOAA'S PROCESSING WORKFLOW

Joshua D. Witmer, Gretchen A. Imahori and Michael L. Aslasken Jr., NOAA, National Geodetic Survey, Remote Sensing Division

Michael O. Gonsalves and Eric E. Berkowitz, NOAA, Office of Coast Survey, Hydrographic Surveys Division

Shachak Pe'eri, Center for Coastal and Ocean Mapping/Joint Hydrographic Center, NOAA and the University of New Hampshire

June 2016

noaa National Oceanic and Atmospheric Administration

U. S. DEPARTMENT OF COMMERCE Penny Pritzker, Secretary	National Oceanic and Atmospheric Administration Dr. Kathryn D. Sullivan, Under Secretary	National Ocean Service Dr. Russell Callender, Acting Assistant Administrator

Office of Coast Survey Rear Admiral Gerd F. Glang	Hydrographic Survey Division Captain Eric W. Berkowitz

`

NOTICE

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Technical Memorandum CS-32 assessed the use of existing U.S. Army Corps of Engineers' (USACE's) National Coastal Mapping Program (NCMP) Airborne Lidar Bathymetry (ALB) data for hydrographic purposes. The conclusions of the study were positive about the potential use of USACE ALB data to fill in data gaps in coastal bathymetry (nearshore areas that are low priority for hydrographic surveys). This Technical Memorandum outlines USACE's current ALB processing workflow, provides a recommended workflow for data obtained from USACE by Coast Survey for use in NOAA products and offers a first step in estimating an ALB survey uncertainty value. In addition, the uncertainty components for the workflow procedure are identified and evaluated (separately and as a final product). A first-order approximation of the horizontal and vertical uncertainty components for the ALB survey data set as a whole were calculated. The two main values used to calculate the survey uncertainty are the empirical uncertainty values, calculated from calibration sites that are used at the beginning of every survey season, and VDATUM uncertainty maps.

1. INTRODUCTION

NOAA is mandated to acquire hydrographic survey data and provide nautical charts per the Coast and Geodetic Act of 1947. As stated in the Technical Memorandum NOS CS 32 (Imahori et al., 2013), NOAA uses a combination of in-house and contracting resources to acquire hydrographic survey data around the coasts of the U.S. and its territories, mostly using sonar systems (e.g. echosounder multibeam, side scan or echosounder singlebeam). In recent years, NOAA has been working to integrate outside source datasets to fulfill the Integrated Ocean and Coastal Mandate and better support charting needs. For example, coastal bathymetry areas such as the New Jersey coast were in urgent need of updated surveys following the devastating damage from Hurricane/ Post- Tropical Cyclone Sandy. Work conducted at the Office of Coast Survey (OCS) is helping mitigate charting needs for areas that have not been surveyed in 80 years or more (Kinney at al., 2015). In addition to NOAA, the navigable waters of the United States are also under the USACE jurisdiction that includes all ocean and coastal waters within a zone of three nautical miles seaward from the coastline (see 33 CFR 329.12 - .14 for more details). With an abundance of freely available survey data, NOAA is first evaluating federally certified data to update charting products before evaluating and certifying public data collected by state-level departments and private surveys (e.g., research surveys or town-level contracts).

In NOS CS-32, USACE's ALB downloaded from Office of Coast Management's Digital Coast was empirically compared to hydrographic surveys (ALB and acoustic). The next step is the development of a workflow with a direct path from the USACE's Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) to NOAA's OCS for charting purposes. In order for the USACE ALB surveys to be used to update charts, the data should be integrated into current data processing procedures. OCS quality control needs to be conducted to clearly identify and evaluate each step of the USACE ALB workflow procedure. In addition to the depth value, an uncertainty of the horizontal and vertical components of the survey data should be provided to OCS. The goal of this work is to provide recommendations and metadata for successful integration and use as a template that can be expanded for publicly-available survey data.

2. MOTIVATION

The motivation of this research is to provide a clear description of USACE ALB workflow that can be integrated into NOAA's Hydrographic Survey Division's compiling procedures. This description of the products with an uncertainty value will be comparable to traditional Coast Survey hydrographic datasets. In order for the USACE ALB surveys to be used in NOAA's hydrographic products, some additional processing steps need to be added or modified (e.g., gridding technique and vertical referencing). Also, the use of grid format is proposed as cost-efficient format and as an alternative to a point cloud dataset deliverable in a LAS format.

3. USACE ALB DATA

3.1 BACKGROUND

Originally, the USACE's National Coastal Mapping Program (NCMP) was developed in 2004 to support the USACE's missions, such as: navigation, flood risk management, environmental restoration, emergency management, as well as other mandated functions along the Nation's coasts. The NCMP allows the USACE to acquire high-resolution ALB data on a scheduled basis of 5-7 years by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX). The NCMP includes the coastal areas along the Gulf Coast, Atlantic Coast, Great Lakes, West Coast, and Hawaii. Until recently (2014), NCMP ALB data are typically collected at a density of 5m X 5m spot spacing (or denser) with a minimum of 25 percent overlap with adjacent flight lines. The coverage area is from 0.5 km inland from the shoreline to 1 km offshore or laser extinction, whichever occurs first. NCMP scope of work typically requires vertical positions accurate to +/-15 cm and horizontal positions accurate to +/-1.5 m. Some of the processing steps for data acquisition have been modified and new survey standards have been defined with the use of the recently purchased Optech Coastal Zone Mapping and Imaging Lidar (CZMIL) system. However, the USACE has kept its product suite in the same format in order to avoid any changes in the workflow to current application of the end users and to be able conduct change detection studies. In addition to the NCMP, the USACE conducts other types of ALB surveys that have different survey specification than that of the NCMP. The term USACE ALB survey will be used to refer to all these surveys (NCMP and the less routine surveys) because both undergo the same acquisition and processing procedures.

3.2 CALIBRATION

Immediately following system installation in the aircraft, calibration flights are conducted to verify the system's overall operability; refine lever arms values; solve for the scanner angle origin (SAO) offset; solve for the roll, pitch, and timing/range offset for each of CZMIL's seven shallow channels; and derive the bathymetric bias look up table (LUT) coefficients for the central shallow and deep channels. First, a topographic alignment is performed at the Stennis International Airport and JALBTCX facility in Kiln, MS. The flight line pattern is shown in Figure 1. Each line is flown multiple times in opposing directions and at different altitudes. The topographic calibration consists of two flights to solve for the boresight parameters followed by one validation flight to confirm the parameters.

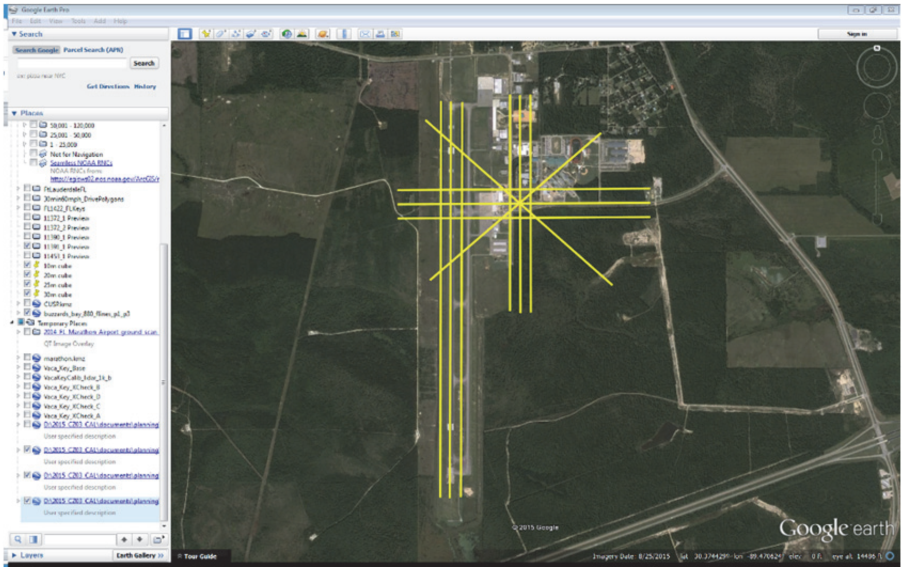

Figure 1. Stennis/JALBTCX topo lidar calibration site (Kiln, MS)

The datasets collected from these calibration flights are compared to several ground truth datasets collected at the Stennis Airport and JALBTCX facility. The ground truth data at this calibration site includes mobile terrestrial lidar collected over the Stennis runway with an Optech Lynx Mobile Mapper (range precision of 5 mm at 1 sigma) in October of 2011. Using the terrestrial laser scanner, two scan lines were collected down the runway, having a combined point density of 571 pts/m^2. These two scans vertically agree within -0.00042 m to another ground truth dataset of 20 ground points measured on the runway with a Trimble R8 Real Time Kinematic (RTK) receiver, referenced to NOAA's National Geodetic Survey (NGS) published control monument BH2999. In addition, a Trimble VX DR Plus spatial station was used to collect points along the pitched roof of the JALBTCX facility. These points are also established from the NGS published control monument BH2999.

The airport runway and taxiway is used as a flat terrain surface to help solve the scanner angle origin, roll, pitch, and timing/range offsets. The runway numbering, lettering, or other markings may also be used for comparison by viewing the lidar return intensity of each flight line. Once the offsets were identified, each channel is manually adjusted in Opetch's HydroFusion processing software to correct for these biases. The lines are then reprocessed in HydroFusion with the new values examined and further adjustments made. The point cloud from the ALB survey lines is compared to a reference 0.25 m grid surface that was collected using the Optech Lynx laser scanner. This iterative process for correcting the biases continues until the offset deviation could not be further adjusted.

Other prominent features, such as the pitched roof of the JALBTCX facility, are used to further verify these calibration parameters. The pitched roof ground truth dataset collected with the Trimble VX DR Plus spatial station is used for comparison. Figure 2 shows an example of a point cloud collected in June 6, 2013 over the JALBTCX facility, where the red vertical line drawn over the pitch roof is the location of the cross section shown in Figure 2 (bottom). The statistical results in this example using 1,934,065 points (from all 7 channels) provided a mean difference of 0.00 m ± 0.07 m (2 sigma).

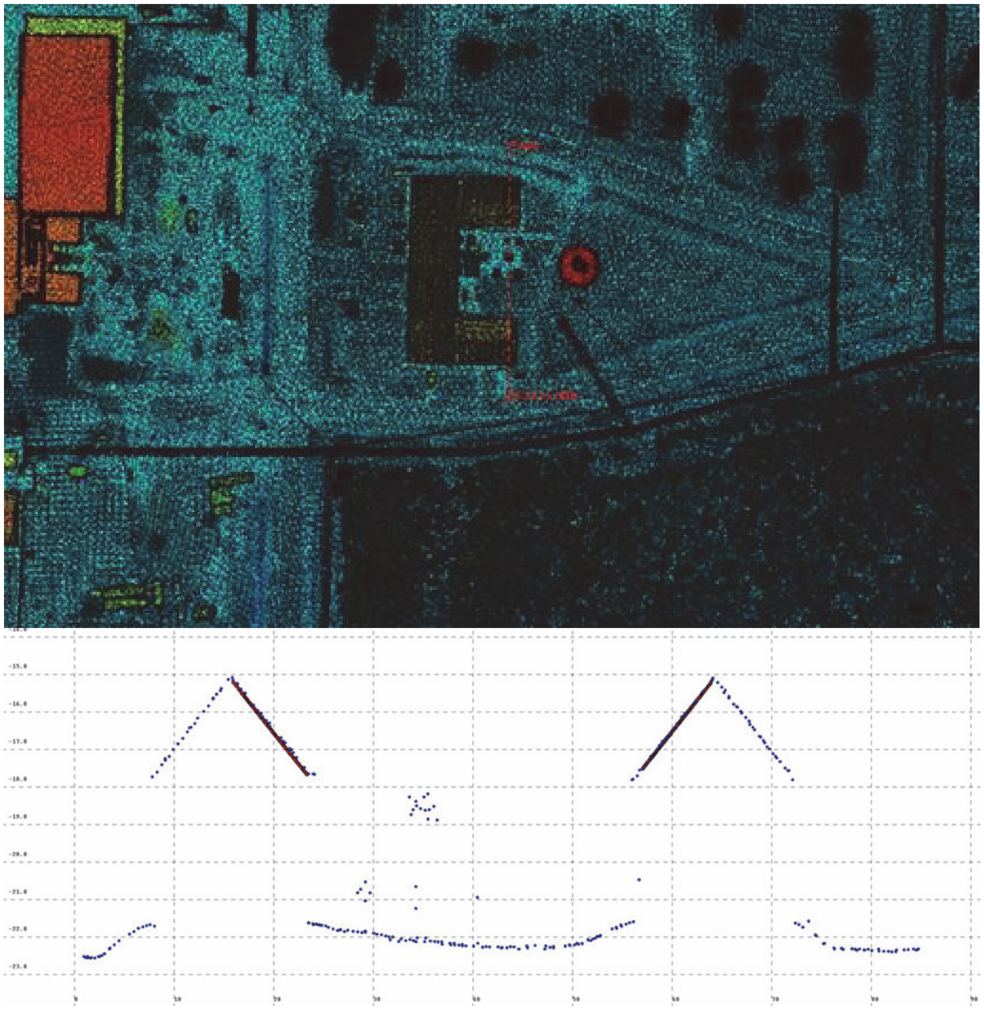

Figure 2. (Top) CZMIL point cloud of JALBTCX facility (Kiln, MS). (Bottom) Cross section view of JALBTCX pitch roof.

After a geometric calibration over land, a bathymetric alignment is performed using the CZMIL deep channel. It should be noted that CZMIL deep channel cannot undergo a geometric calibration over land because of the intensity of the laser pulse causing receiver saturation. Therefore, the lidar system undergoes a manual calibration process, separate from the topographic alignment, to solve for CZMIL's deep channel roll, pitch, and timing/range offsets, as well as the bathymetric bias LUT coefficient. This process involves two calibration flights to solve for parameters and one validation flight to confirm parameters. Two survey sites (Fort Lauderdale, FL and Marathon, FL) that have been previous surveyed are used as calibration sites (Figure 3).

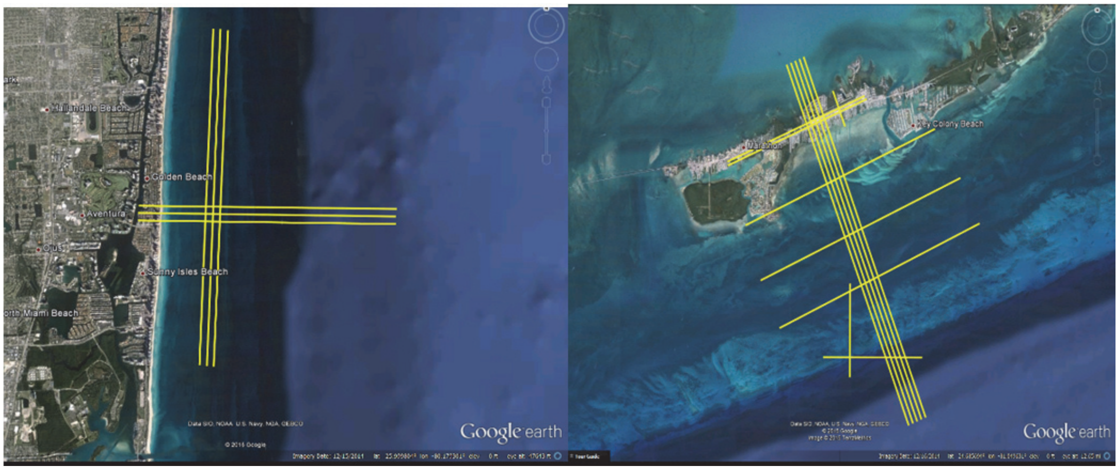

Figure 3. Bathymetric calibration sites: (Left) Fort Lauderdale, FL and (Right) Marathon, FL (Vaca Key).

A Compact Hydrographic Airborne Rapid Total Survey (CHARTS) (SHOALS-3000, 3 kHz bathymetric sensor) ALB survey is used as reference dataset at the Fort Lauderdale, FL calibration site. The survey data were collected between June 23, 2005 to July 6, 2005 over an area larger than 56 km^2, including 51 million records with over 200% coverage of more than 85% of the area, with penetration through the water column to approximately 30 meters depth. The survey data were gridded into a 2 meter surface. The calibration bathymetric adjustments excluded depths shallower than 5 meters because of changes in the bottom caused by coastal processes (e.g., wave action). Figure 4 shows a cross section view of these two surfaces from approximately 5 to 30 meters water depth.

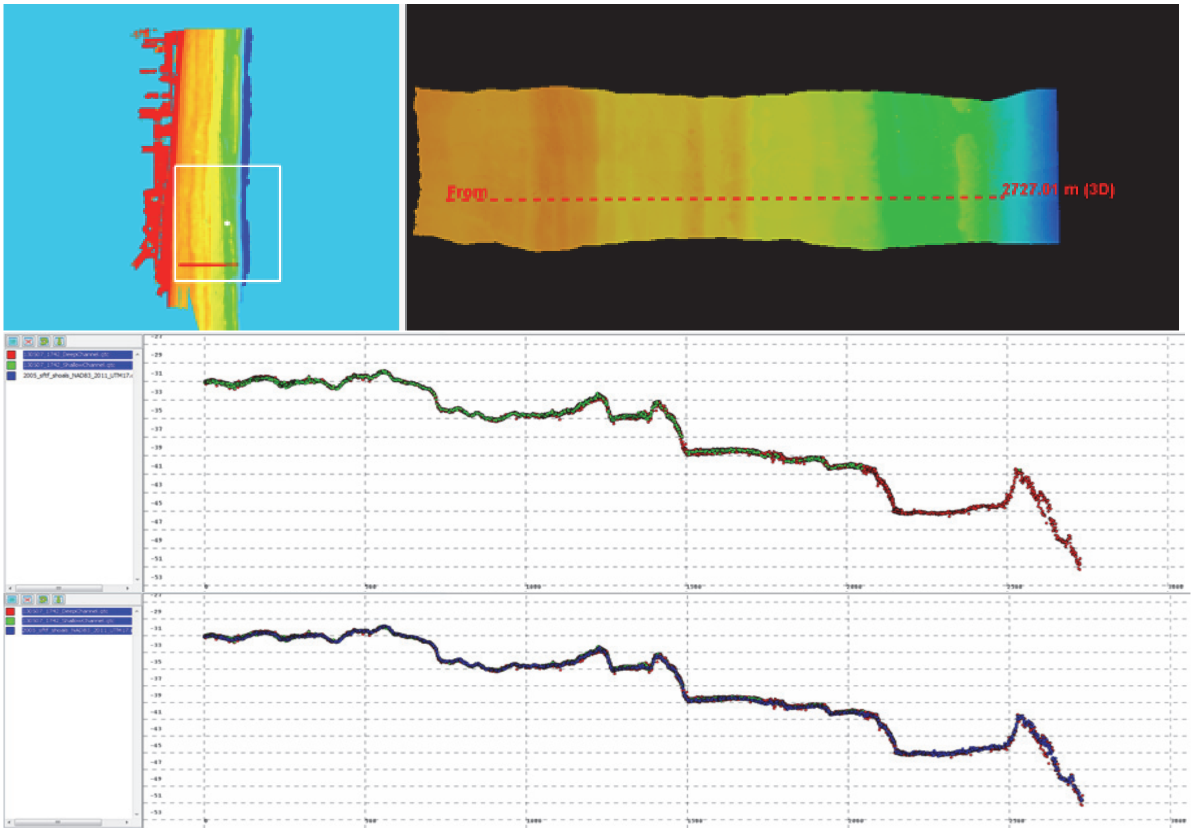

Figure 4. Cross section profile of CZMIL vs. CHARTS lidar over the Fort Lauderdale, FL calibration site (May 7, 2013). The green profile represents the CZMIL shallow channel returns, the red profile represents CZMIL deep channel returns, and blue profile represents the CHARTS returns.

The comparison results between the CZMIL surveys (2013) to the CHARTS surveys (2005) over the Fort Lauderdale calibration site provided a mean difference of 0.01 m ± 0.35 m (2 sigma) for the deep channel and a mean difference of 0.01 m ± 0.22 m (2 sigma) for the shallow channel (Figure 5). The average point density of one flight (May 7, 2013) was 0.74 pts/m^2 across the 5 - 30 meter depth range.

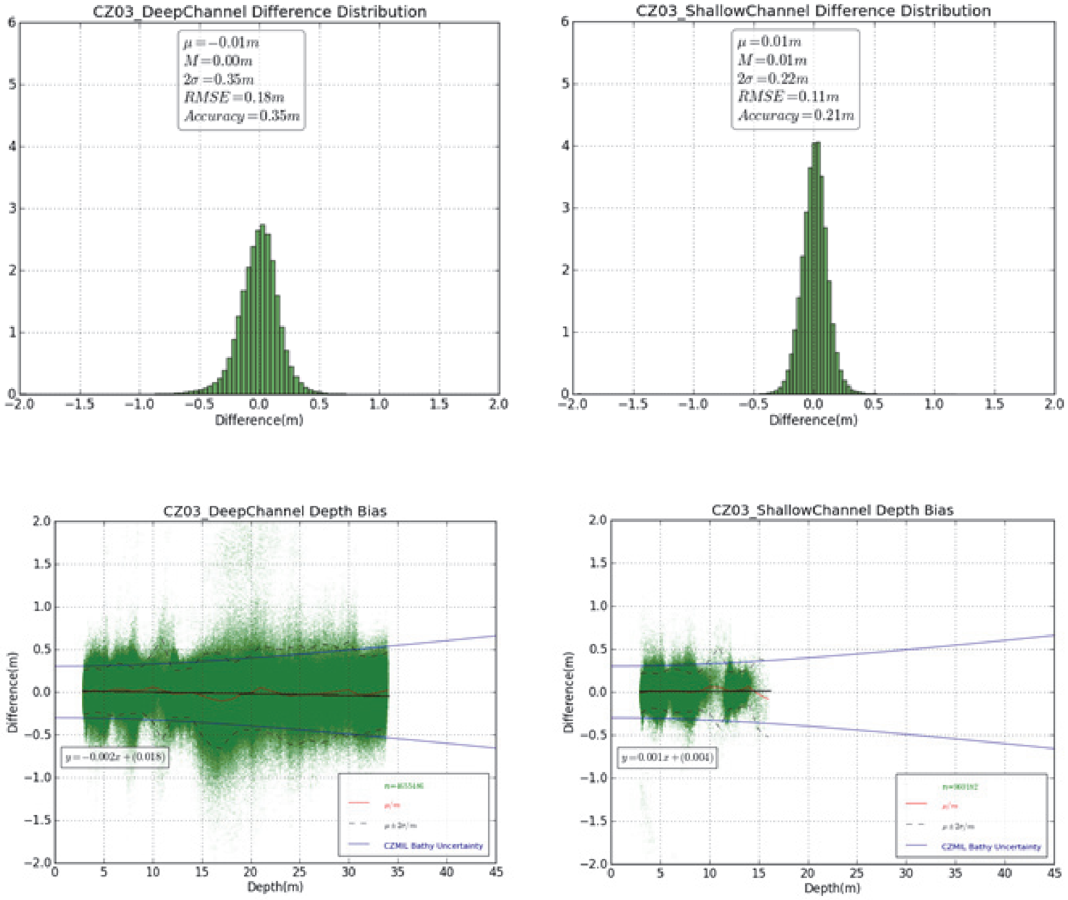

Figure 5. Histogram and scatter plot results between CZMIL-03 and CHARTS surveys over Fort Lauderdale, FL.

In 2014, a new calibration site was established in Marathon, FL (Vaca Key) in order to conduct a comparison between the CZMIL to a reference dataset that was collected using acoustic methods. The goal is that this location may serve as both a topographic and bathymetric calibration site. A topographic survey was conducted over small areas on the NE and SW end of the Florida Keys Marathon International Airport (MTH) using Trimble VX DR Plus spatial station. NOAA's NGS collected approximately 30 RTK ground control points with a Trimble R8 Global Navigation Satellite System (GNSS) receiver spread across Vaca Key and NAVOCEANO's Fleet Survey Team (FST) collected multibeam and side scan sonar over a small designated area SSE of Vaca Key, FL. Currently, it is planned that Marathon site will replace Fort Lauderdale site in future calibration procedures. The transition will depend on future activities of USACE and involvement of its JALBTCX partners. It should also be noted that these calibration procedures can be applied for other lidar sensors.

3.3 SURVEY

As mentioned above, typical surveys for the NCMP extend along the coastline from the waterline inland 500 meters (topography) and offshore 1,000 meters or to laser extinction (bathymetry). Lidar data is acquired at 400 meter altitude, 140 knots (speed over ground), and

25% overlap between adjacent flight lines. During survey acquisition flights, the aircraft is kept to a bank angle less than 20° at all times in order to maintain GPS lock to satellites. The maximum baseline between the survey aircraft and the nearest base station or CORS is kept to a minimum (i.e., 45 km or less), so that the uncertainties associated with the trajectory file are minimized. Data are not collected with Position Dilution of Precision (PDOP) value greater than 3. Once the survey platform arrives at the project area, a verification flight line is collected over the runway of the airport where the aircraft is based. This verification flight line is recollected whenever the ALB system undergoes maintenance or if other data issues are discovered. If needed, the verification flight lines are processed separately and compared to previous and/or subsequent flight lines over the same area. This comparison allows the field survey team to better monitor and assess the system's operability, as well as minimize any malfunctions which may otherwise go unnoticed until the survey platform has departed the project area. Cross check lines are collected as an additional means to verify system performance and data quality. Typically, a minimum of one cross line is collected per survey block, with maximum of 20 km alongshore distance between cross lines. The typical CZMIL operating parameters for USACE ALB projects are listed in Table 1:

Table 1. CZMIL Operating Parameters

Inland coverage:	500 meters
Offshore coverage:	1,000 meters (or to laser extinction)
Flying altitude:	400 meters
Speed over ground:	140 knots
Overlap:	25 %
Bank angle:	less than 20°
GPS baseline:	less than 45 km
PDOP:	less than 3

3.4 PROCESSING

3.4.1 FIELD PROCESSING

After the ALB survey is collected, the field survey crew conducts initial data processing and reviews the data using Pure File Magic - Area Based Editor ('PFMABE' or just 'ABE') software for data coverage and to ensure there were no potential system issues. It should be noted that field processing is only used to assess system operability, survey coverage, and create preliminary data products used for project tracking. All survey data is reprocessed and edited in the JALBTCX office for the creation of final products and deliverables.

3.4.2 TRAJECTORY PROCESSING

GNSS data collected with the base stations setup by the field unit are converted to RINEX format and submitted to NGS' Online Positioning User Service (OPUS) for a processed solution of the station's coordinates. In cases where CORS stations are utilized, the associated RINEX data is downloaded from NGS website along with the published station coordinates for post processing. The aircraft trajectory is then processed alongside the base station data using Applanix POSPac software. This is accomplished by importing the base station RINEX data into POSPac. Then, the OPUS and/or published station coordinates are entered for that station in POSPac's Coordinate Manger. Finally, either In-Fusion Single Base Station Processing mode or In-Fusion Multi-Single-Base Processing mode is used to process the aircraft trajectory. The quality of the POSPac Smoothed Best Estimate of Trajectory (SBET) solution is assessed by reviewing the accompanying message logs and processing plots.

3.4.3 LIDAR PROCESSING

Native lidar data is not generally in a format accessible to most Geographic Information Systems (GIS). Specialized in-house and commercial surface analysis software packages are needed. For lidar data collected with the CZMIL sensor suite, Optech's HydroFusion software is used to process the raw/native lidar data. HydroFusion combines the raw lidar data with calibration information and the processed trajectory from POSPac to produce an accurately georeferenced lidar point cloud. The user selects a subset of data from the flight to generate a water surface model. HydroFusion then uses this water surface model to complete the initial classification of each point as either topographic or hydrographic. HydroFusion scrutinizes the waveform of each lidar return to correct each hydrographic point for refraction.

3.5 LIDAR EDITING

After the raw lidar data has been processed, the .cpf files (product of HydroFusion processing) are imported into ABE for reviewing and cleaning the point cloud data. By running several filters available in ABE and by performing manual editing techniques, erroneous points (a.k.a. 'flyers' or 'noise') are removed from the dataset. ABE allows for the associated waveform and imagery to be viewed alongside each lidar point, assisting the data processor during manual editing.

Steps for manual editing included:

- Remove any remaining topographic laser data on the water surface
- Remove any remaining noise from the bathymetric dataset, such as data on the water surface
- Review all of the bathymetric data
- Review areas of sparse data at depth extinction limits or over dark seafloor to ensure no valid data exists
- Clean shoreline data to remove any remaining waves or water
- Review inland water areas (such as, small rivers and channels) to ensure water surface points are removed

The edited or ‘cleaned’ dataset are then converted from .cpf files into LAS files (NAD83 geographic coordinates and ellipsoid height).

3.6 DATUM CONVERSION

Using NOAA’s VDatum tool, the LAS files are then transformed from NAD83 ellipsoid heights to NAVD88 orthometric heights using the latest published geoid model. The final product’s accompanying metadata files should be referenced for the specific geoid model used. For more information about NOAA’s VDatum tool and an estimation of vertical uncertainties in using VDatum, refer to: http://vdatum.noaa.gov/welcome.html.

3.7 FINAL PRODUCTS/ DELIVERABLES

Once the lidar dataset has been processed, edited, and transformed to the desired datum, final products and deliverables are made using GeoCue, Quick Terrain Modeler, and ArcGIS software packages. The product suite includes:

Coverage shapefiles: created within ESRI ArcMap showing the extents of lidar coverage and where gaps may exist.

1 & 5 meter Grids: Quick Terrain Modeler (QTM) is used to convert LAS to ASC. ESRI ArcMap is used to convert ASC to TIF format using the ASCII to Raster conversion tool. The grids are horizontally referenced to NAD83 geographic coordinates and vertically referenced to NAVD88 orthometric heights. The elevation value assigned to each node point is calculated as the average elevation value for that grid cell.

Bare Earth Grids: Bare earth classification (*.tif) is conducted using GeoCue’s TerraSlave. The grids are horizontally referenced to NAD83 geographic coordinates and vertically referenced to NAVD88 orthometric heights.

5 meter Grid RGB: A color image format (*.tif) with shaded relief is generated from the 5m Grid DEM to show coverage extents and elevation.

NAVD88 Zero Contour: A zero contour referenced to NAVD88 is generated from the 5m Grid DEM characterizing the USACE’s defined shoreline.

RGB Imagery: Typical RGB products have a ground resolution of 0.20m.

For more details on each product/deliverable, please refer to the accompanying metadata notes of each product.

4. ALB DATA COMPILATION (NOAA)

4.1 USACE'S ALB SURVEYS

In 2015, the USACE adopted the quality level (QL) survey standards (Table 2; Figure 6) as defined in the National Coastal Mapping Strategy (NCMS), which was developed by the Interagency Working Group on Ocean and Coastal Mapping (IWG-OCM). These QLs are specified in terms of vertical uncertainty or accuracy, point density, and equivalent nominal point spacing. The bathymetric QLs defined by IWG-OCM in the NCMS are derived from a combination of the topographic QLs, as defined by the U.S. Geological Survey (USGS) 3D Elevation Program (3DEP) (Dewberry, 2012; Snyder, 2012), and the IHO S-44 Minimum Standards for Hydrographic Surveys at water depths greater than 20 m (IHO, 2008). Since adoption of the QL survey standards, the USACE NCMP's strives to collect and deliver ALB products that meet or exceed QL3 (this exceeds Order 1b and NOS HSSD). It is important to note the NCMS QL survey standards include a point density requirement, which is not specified in the IHO survey standards but is in the NOS HSSD and is noted in Table 3). Also, the NCMS bathymetric QL survey standards do not specify feature detection requirements, as in the IHO order 1b survey standards (Table 3). Because IHO defines the total vertical uncertainty (TVU) in terms of a 95 percent confidence level (1.96 sigma for a normal distribution), the NCMS bathymetric QLs also follow this practice. Whereas, the 3DEP topographic QL standards are defined in terms of RMSE 1 sigma values. NOS HSSD was used as guidelines for point (sounding) density as IHO S-44 does not provide details on this property.

Table 2. Quality level definitions for bathymetric lidar surveys, where *D* is the water depth in meters. These definitions are applicable for areas submerged at the time of survey.

Bathy Lidar Quality Level	Source	Vertical accuracy coefficients a, b as in $\sqrt{A^2+(B*D)^2}$	Nominal Pulse Spacing (m)	Point Density (pt/m^2)	MB Point Density (pt/m^2)	Example Applications
QL0	Bathymetric Lidar	0.25, 0.0075	0.7	2.0	5.0	Detailed site surveys requiring the highest accuracy and highest resolution seafloor definition; dredging and inshore engineering surveys; high-resolution surveys of ports and harbors.
QL1	Bathymetric Lidar	0.25, 0.0075	2.0	0.25		
QL2	Bathymetric Lidar	0.30, 0.0130	0.7	2.0		Charting surveys; regional sediment management. General bathymetric mapping; coastal science and management applications. Change analysis; deep water surveys, environmental.
QL3	Bathymetric Lidar	0.30, 0.0130	2.0	0.25		
QL4	Bathymetric Lidar	0.50, 0.0130	5.0	0.04	0.25	Recon/planning; all general applications not requiring higher resolution and accuracy.

Table 3. TVU Coefficient values for the different IHO orders (IHO, 2008) up to 40 m.

IHO order	A	B	Minimum Point Density based on the NOS HSSD (pt/m^2)	Feature detection
Special	0.25	0.0075	20.0 for MBES	Cubic features > 1 m
1a	0.5	0.013	5.0 for MBES	Cubic features > 2 m
1b	0.5	0.013	0.11 for ALB	Not Applicable
2	1.0	0.023	Not Applicable	Not Applicable

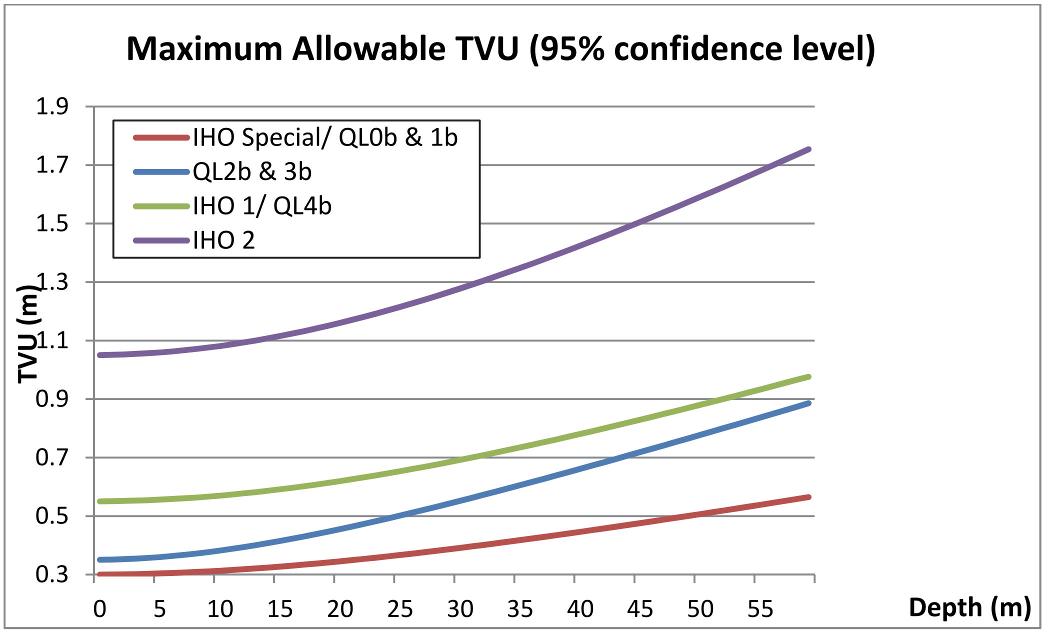

Figure 6. IHO S-44 and NCMS Quality Level (QL) maximum allowable Total Vertical Uncertainty (TVU)

4.2 USACE TO NOAA WORKFLOW

USACE surveys are typically not tidally referenced. In order to compile USACE ALB survey data with NOAA surveys for providing a seamless charting product, the vertical coordinate system of the ALB dataset needs to be converted from North American Vertical Datum 1988 (NAVD88) to Mean Lower Low Water (MLLW). A similar situation may also occur with the horizontal system, where one dataset uses geographic units (i.e., longitude and latitude) and the other dataset is projected using northing and easting coordinates. Figure 7 illustrated the three steps that are required to transform the USACE ALB survey data (geographic horizontal system and an ellipsoidal North American Datum 1983 (NAD83) vertical system) to the chart datum used in NOAA products (Universal Transverse Mercator (UTM) projected horizontal system and a tidal MLLW vertical system). The transformation is conducted using NOAA's VDatum transformation tool (White, 2007). It is important to note that currently the first step in the transformation uses GEOID12A that will be replaced soon by GEOID15 and VDatum will be updated accordingly (estimate date: 2016).

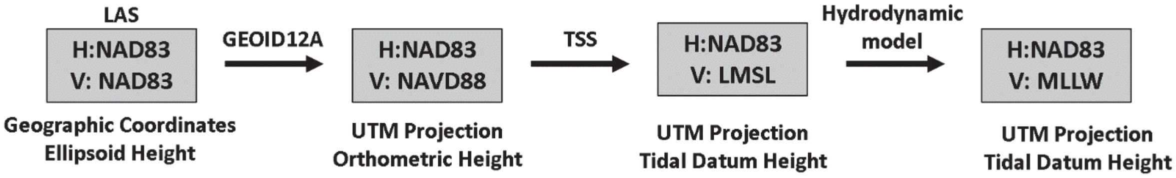

Figure 7. Transformation flow diagram of NCMP lidar data from USACE archives (USACE – JALBTCX), to NOAA's OCS all managed using VDatum. LMSL – Local Mean Sea Level; TSS – Topography of the Sea Surface.

Another important point in the work flow is the data format. Additional software is required for surface analysis by NOAA or for further processing of the referenced point cloud data (e.g., ArcGIS, Global Mapper, CARIS, Fledermaus, and AutoCad Map). In order to load the data into these software packages, the laser measurements need to be converted from a proprietary format (i.e., a file structure intended for internal processing and is not open to the public) into a conventional exchangeable binary format. The most commonly used deliverable format of ALB data are LAS format files. These files are binary and contain a specific structure that is defined by the American Society for Photogrammetry and Remote Sensing (ASPRS, 2008). Documentation for the LAS format is publically available allowing vendors and customers to export and import the data between different software. To date, ASPRS has published a fourth revision of the LAS format specification (LAS 1.4) since its initial version 1.0 release (ASPRS, 2013). However, it is important to verify that the LAS versions of ALB data sets provided by the USACE match the current version available in the lidar processing software. There is the possibility that import and export LAS files are in different LAS versions that may modify the data or will not be able to load into the processing software.

4.3 QUALITY CONTROL

Currently, OCS' Hydrographic Surveys Division (HSD) ALB datasets undergo a Survey Acceptance Review (SAR) (Miller, et al., 2011). In-house hydrographers and contractors working under HSD task orders must acquire, process and submit hydrographic survey data (including any ALB) according to requirements stated in the NOS Hydrographic Survey Specifications and Deliverables (HSSD). The SAR is a quality control check to ensure the required NOS HSSD steps are followed (e.g. including an S-57 feature file and BAG) and it identifies systematic errors and major /significant deficiencies which would prohibit the survey from being used to update the nautical chart, as well as determine the data's fitness for its intended use (OCS, 2016).

Looking at the most recent hydrographic contract for ALB data (H12606) and specifically noting the following steps after the contractor manually edited the LAS files from noise, the remaining steps of the contractor to create the BAG product and other required deliverables are listed below:

- Remove topographic (topo) laser data
- Review bathymetric (bathy) data to ensure no potential objects were missed

- Review areas of sparse data at depth extinction limits or over dark seafloor to ensure no valid data exists
- Review inland water areas such as small rivers and channels to ensure what surface points are removed
- Classify any points required for S-57 generation such as piling, buoys and bridges
- Exported S-57 points to ASCII XYZ files
- Calculate average offset between MLLW and MHW for each area
- Withhold classes: unclassified, topo ground and topo water surface, high noise, bathy land
- Kept classes: ground, rejected during editing, S-57 feature information, bathy water surface, derived water surface
- Transform the data to the tidal datum (MLLW)
- Clip the data to the VDatum spatial extents
- Load MLLW and MHW las files with accepted data (only) into Fledermaus to create MLLW and MHW surfaces and create a difference surface between the two.
- Use the MHW surface to generate the MHW shoreline and export in DXF format for use in the S-57 generation
- Load las files into Fledermaus to generate PFM CUBE surfaces using kept classes mentioned above
- Calculate TVU and THU
- Flag depths greater than half the allowable error
- Regenerate CUBE surface – shoalest hypothesis selected
- Apply feature depths to CUBE surface
- Export CUBE surface to BAG format
- Convert BAG data to .csar format using SAFE FME software and a *.csar surface due to datum issues between the CARIS shifts and the BAG surface by up to 2 meters if opened with other data
- Import .csar surfaces into CARIS Bathy DataBASE and finalized, clipping the average MHW height for each area.

USACE NCMP acquire ALB data per their own internal mapping requirements but they do not meet all of the NOS HSSD requirements. As stated in NOS CS-32, JALBTCX archives the NCMP lidar data in LAS. All the steps listed above (or similar steps) would have to be done by HSD, with the exception of the removal of sparse data which has already been done by USACE, to meet the NOS HSSD requirements.

Some initial assessments made by HSD with the help of the Joint Hydrographic Center (JHC) and the Marine Chart Division (MCD), lead HSD to conclude they have limited resources to ingest, efficiently and within their current workflow, the USACE NCMP LAS files. LAS processing (point cloud data) and lidar editing of the waveform will require HSD to purchase additional software (such as, LP360 or those mentioned in the list above as well as section 3.4.3 and 3.5) and personnel and will also require a maintenance contract (with possible updates of the LAS version). Additionally, HSD concluded that the USACE NMCP ALB data would have to be reviewed in a different fashion from HSD multibeam surveys. For example, while some objects such as pilings, buoys a bridges may be identified in lidar (especially, with the aid of imagery flow on or about the same time), HSD may want to determine which object classes are lidar ‘friendly’ so the processing branches are not spending an inordinate amount of time on S-57 attribution.

After discussion between MCD and HSD under OCS, JHC and the Remote Sensing Division (RSD) under the National Geodetic Survey, it was agreed that USACE is an authorized federal data source and the use of the ALB data collected by JALBTCX that are specifically intend for navigational use do not need a rigorous data review. The USACE NCMP ALB already goes through its own quality control and review process (as described in section 3). Also, RSD’s JALBTCX Liaison noted that USACE NCMP data is also available in GeoTiff format, a digital elevation model provided in a grid format; 1m and 5m. JHC looked into in the grid format and found that the file size of a grid file is smaller than the LAS files of the same project. The ALB grid files can be easily ingested into multiple COTS that OCS and RSD already own, thus giving HSD the ability to take in numerous datasets available from JALBTCX. Also, the repeated surveys of the USACE are gridded to the same geographic cells in order to reduce gridding errors.

MCD and JHC suggested that a Category of Zone of Confidence (CATZOC) letter stated by OCS’ Nautical Chart Manual be considered to denote the cartographic quality of the USACE and RSD ALB. In general, all USACE ALB data would be expected to be CATZOC B, where a full area search (is) not achieved and uncharted features, hazardous to surface navigation are not expected but may exist. This does not mean that ALB will not show features but lidar experts agree that ALB will not be able to resolve all objects required by the NOS HSSD as with full coverage HSD multibeam surveys. The main purpose in using lidar in shallow waters (0-4m) is to update depths and cover areas where NOAA will not likely survey because acquiring multibeam is too dangerous or simply inefficient and not cost effective.

5. UNCERTAINTY CALCULATIONS

Based on the USACE ALB collection and processing described in the previous sections, the key properties that contribute to the vertical uncertainty are: 1) uncertainty related to the ALB system (as reported by the manufacturer), σ_{ALB}; 2) uncertainty related to the positioning, σ_{GPS}, and orientation, σ_{IMU}; 3) uncertainty related to the geometric calibration (boresight calibration), σ_{cal}; and 4) uncertainty related to VDatum, σ_{VD}.

Geometric calibrations for ALB systems are typically self-consistent, i.e. they do not require an external reference dataset. In contrast to standard calibration in photogrammetry, it is practically impossible to establish a direct correspondence between two point-cloud datasets in overlapping lidar calibration strips (Gonsalves, 2010a). A comparison between two calibration strips provides the 3D offset parameters that describe an affine transformation. The seven parameters that are required to define the geometric relationship between the point cloud in one strip to point cloud include three for the translation vector between the strips $(X_T, Y_T, Z_T)^T$, three for the rotation matrix for the co-alignment between the strips, $R_{\Omega,\Phi,\mathrm{K}}$, and a scale factor, S:

$$\begin{bmatrix} x_{q_i'} \\ y_{q_i'} \\ z_{q_i'} \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + S \times R_{(\Omega,\Phi,\mathrm{K})} \begin{bmatrix} x_{q_i} \\ y_{q_i} \\ z_{q_i} \end{bmatrix} \qquad \textbf{(1)}$$

Geometric calibration serves as a validation test for the measured offsets, it is required for aerial surveying in order to measure the lever-arm (position) offsets between a survey system to the GPS and IMU systems. Geometric calibration for ALB is similar to that of topographic lidar, which includes pairs of survey lines are under the same survey conditions with a bias in one survey parameter between the lines (El-Sheimy, Valeo, and Habib 2005; Habib, 2009; Habib et al., 2010). The main difference between an underwater calibration procedure and a calibration over land is that potential errors related to the water surface and the water column (e.g., glint, refraction, and attenuation) are absent and prominent linear features (e.g., buildings with slope roofs) are more abundant (Habib, 2009; Gonsalves, 2010b).

As mentioned in Section 3, the geometric calibration used by USACE includes two survey lines in opposing directions and are used to evaluate the attitude of the vessel, where roll and yaw are evaluated over any bottom profile, and pitch is evaluated over a sloping bottom. It is important to note that yaw evaluation requires the survey lines to completely overlap. Once the survey lines are acquired, carefully chosen subsets of the soundings are examined to systematically determine each calibration value. The lever-arm offsets are calculated using the Applanix POSPac Package. In addition, the ALB data requires a vertical transformation from an orthometric to a tidal datum for hydrographic processing. In general, the national horizontal and vertical uncertainties transforming from ITRFxx or WGS84 (the native datum collected by a GPS) ellipsoidal coordinate frame to NAD83 and NAVD88 is about 2 cm and 5 cm, respectively. RSD provides site specific calculations of the uncertainties that are dependent on the quality of the shoreline and the density of the control measurements. For more information please refer to: http://vdatum.noaa.gov/docs/est_uncertainties.html.

Currently, JALBTCX is conducting a full geometric calibration (topographic and bathymetric) every time they install the ALB system back into the aircraft to calculate the boresight angles. Assuming that these geometric calibrations are conducted at the same altitude that the ALB surveys are conducted, then it is possible to use the empirically-calculated uncertainty, σ_{emp}. A topographic calibration includes the uncertainty related to the positioning, orientation and boresight calibration together. A bathymetric geometric calibration will also include the uncertainty caused by the environment. It is also possible to assume as a first-order approximation that the water clarity affects the penetration depth of the lidar system but the measurement uncertainty does not increase. Thus, if the uncertainties of all key properties can be approximated as Gaussian with corresponding values of standard deviation that are independent from each other, then TVU can be calculated as the root sum of squares:

$$\sigma_{\mathrm{TVU}} = \sqrt{\sigma_{\mathrm{emp}}{}^{2} + \sigma_{\mathrm{VD}}{}^{2}} \qquad \textbf{(2)}$$

6. DISCUSSION

Based on OCS discussions with JHC and RSD, the Chief of HSD designed a general workflow for ingesting ALB data coming from RSD and USACE JALBTCX (Figure 8). Given the amount of ALB data that RSD has collected over the years to support NOAA's National shoreline mission, OCS considers RSD the NOAA lidar experts. Additionally, RSD has a JALBTCX Liaison that works closely with JALBTCX personnel and USACE NCMP data. The premise of the workflow is to have RSD's JALBTCX liaison work with JALBTCX to deliver the 1m and 5m GeoTiffs to NOAA's Digital Coast along with the LAS files for accessibility in the long term. In the short term, RSD's JALBTCX liaison could request USACE NCMP ALB data (i.e. GeoTiffs, metadata, coverage shapefiles, etc.) from JALBTCX per OCS priorities then transform the GeoTiffs to a tidal datum (MLLW) and create ArcGIS GRIDS, generate a report similar to RSD's DR-DAPR (with additional information about the laser's extinction depth, global uncertainty, and boresight) and create a delivery package for HSD (with a .shp to show coverage area) to do a quick review. RSD is also the developer of VDatum and maintains this transformation software so this is something RSD could do quickly and can assure OCS that it was done correctly. The ALB grid survey will be provided over the same grid locations that the current JALBTCX grids are produced (i.e., the RSD grid will snap to the JALBTCX grids). In order to provide a more seamless product, current ALB will be compiled with ALB data from the past 5 years. Thus, the grid will contain less gaps.

The Chief of HSD plans to create a small team to specifically deal with reviewing NOAA and USACE ALB data as CATZOC B. This team will import the ArcGIS GRIDS into Caris, extract depths (i.e., Smooth-sheet Soundings) and depth contours and submit this data to the processing branch for compilation to an HCell. In areas where there is overlap between USACE NCMP ALB data with RSD ALB data, RSD will do its best to submit both surveys in HSD approved delivery packages. The benefit of having both dataset is to provide the best coverage available.

The advantage of this workflow is that it helps OCS update in a timely manner nearshore areas on NOAA Nautical Charts that were last surveyed around the 1920's and are not currently considered navigationally significant. The proposed workflow is integrated without reducing the quality assessment that needs to be considered when applying data to NOAA charts. As NOAA builds this data into their workflow, we also need to ensure that the focal point is data centric (vice product centric). In addition, the use of a bathy database from which to create products should be considered as future direction.

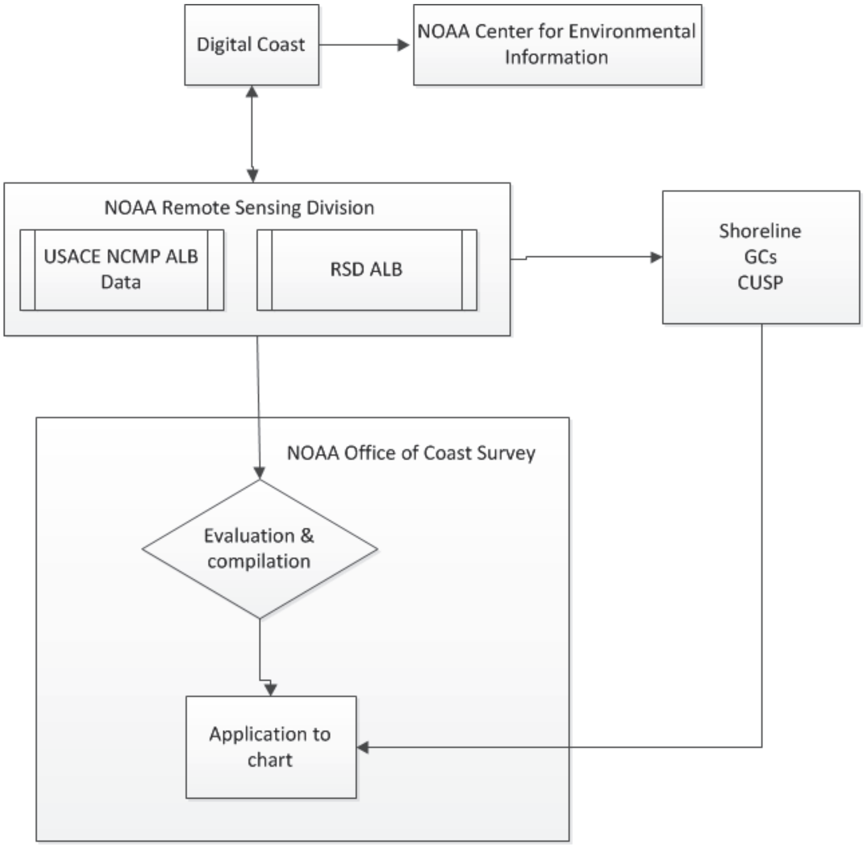

Figure 8. General flow diagram of NCMP lidar data through NGS to OCS.

7. RECOMMENDATIONS

Based on the information collected in this study, the main recommendations are as follows:

1. Workflow

Currently, USACE JALBTCX is delivering hard drives with the ALB data to Office of Coastal Management (OCM) for uploading into Digital Coast website. Based on previous communication between RSD's JALBTCX Laision (Josh Witmer) and OCM, the grids and polygons can be shared through a File Transfer Protocol (FTP) site or by sending a physical copy to NGS. RSD will require a sharing permission to see the update notices from USACE to OCM, which is typically conducted by updating an Excel Spreadsheet. This will allow RSD to know about the new projects sent to OCM and update OCS.

2. Product suite for deliverables

The structure of the current delivery product suite from the USACE seems to be suitable for the integration into Coast survey. However, the following steps in the procedure need to be modified:

Gridding format – The 1-m and 5-m grids should be gridded using a shoal-biased direct grid. In order to load the grids into CARIS, the grid format should be ERSI GRID.

Vertical referencing – The grids should be vertically referenced to MLLW.

Uncertainty evaluation – A periodical report after every full Boresight calibration (with an empirical comparison) should be delivered to OCS.

This bathymetry data with an uncertainty value and a coverage polygon can be easily imported into the current production procedures.

3. HSD ALB review team

In order to validate all the USACE ALB datasets from the past 15 to 20 year and ingest it into HSD pipelines, a new review procedure should be developed. Otherwise, more resources (personnel and computers) would be needed. Tools described in the approved NOS CS-32 can be used for quality control and as alternative to the Survey Acceptance Review (SAR). These tools will conduct a statistical comparison between the USACE ALB data and available OCS acoustic (multibeam) surveys or USACE ALB surveys from previous years (one comparison site per project area). The purpose of the comparison is to quantify the ALB surveys and provide a recommendation for further processing or rejection of the data. The statistical analysis consists of several steps: 1) identifying gaps in the lidar dataset for calculating the maximum depth of the ALB penetration, 2) calculating the depth difference between the USACE lidar and a reference datasets, 3) plotting a histogram for each study site to show the depth difference frequency of the entire lidar dataset and, 4) creating a scatter plot for each study site to show the difference between the two datasets as a function of depth. All the tools can be used in an ArcMap environment and require Spatial Analyst and 3D-analyst modules. Please refer to NOS CS-32 (Imahori, et al., 2013) for a step-by-step description of the tools.

4. Enhancing the uncertainty estimations

The uncertainty evaluation in this report is very crude and does not take many factors into account. It is important to take into account uncertainties related to the hardware components of the laser system, variation of the environmental conditions, and spatial statistics (i.e., gridding to a 1-m or 5-m surface). It is recommended to further develop the uncertainty in order to provide a more accurate global uncertainty for each survey and a full TPU uncertainty evaluation in order to process the ALB data in editing software, such as CUBE. In parallel to uncertainty estimated, it is also possible to automate the quality control and the extraction of the smooth sheet soundings using ESRI model builder tool or program in Python.

Points of Contact

For further information, please contact: Mike Aslaksen
Chief, Remote Sensing Division
National Geodetic Survey NOAA, National Ocean Service
Phone: 301-713-2663 x 160
Email: Mike.Aslaksen@noaa

Capt. Eric Berkowitz
Chief, Hydrographic Surveys Division
Office of Coast Survey NOAA, National Ocean Service
Phone: 301-713-2700 x 124
Email: Eric.W.Berkowitz@noaa.gov

Dr. Shachak Pe'eri
Research Assistant Professor
Center for Coastal and Ocean Mapping
Phone: 603-862-1892
Email: shachak@ccom.unh.edu

ACKNOWLEDGMENTS

The authors of this report would like to thank the Directors and Deputy Directors of Coast Survey (Rear Admiral Gerd Glang and Kathryn Ries) and the National Geodetic Survey (Juliana Blackwell and Brett Howe). Also, the authors would like to thank all those that provided support for this project overall; especially those that helped with processing, giving guidance and providing valuable discussions:

National Geodetic Survey
Stephen White

Joint Hydrographic Center/Center for Coastal and Ocean Mapping
Andrew Armstrong

Coast Survey
LCDR Matthew Jaskoski
John Nyberg
Mike Brown
LT Anthony Klemm
Castle 'Gene' Parker
Edward Owens

Center for Operational Oceanographic Products and Services
Stephen Gill

Joint Airborne Lidar Bathymetry Technical Center for Expertise
Chris Macon
Jennifer Wozencraft

REFERENCES

American Society for Photogrammetry and Remote Sensing (ASPRS), 2013. *LAS Specification, Version 1.4-R13*: American Society of Photogrammetry and Remote Sensing. Bethesda, MD.

ASPRS, 2008. Superseded ASPRS Lidar Data Exchange Format Standard Version 1.2. American Society for Photogrammetry and Remote Sensing (ASPRS) Standards Committee, 13p. http://www.asprs.org/a/society/committees/standards/asprs_las_format_v12.pdf

Dewberry. 2012. *Final Report of the National Enhanced Elevation Assessment*: Dewberry. Fairfax, VA, Final Report.

El-Sheimy, N., Valeo, C., & Habib, A., 2005. *Digital terrain modeling: acquisition, manipulation, and applications*. *Artech House remote sensing library*. Norwood, MA: Artech House.

Gonsalves, M. O., 2010a. *A comprehensive uncertainty analysis and method of geometric calibration for a circular scanning airborne lidar*. (S. Howden, Ed.)*ProQuest Dissertations and Theses*. The University of Southern Mississippi, Hattiesburg, MS.

Gonsalves, M. O., 2010b. Flat-bottomed world you make thoselidar swirls around: Contrasting a ship-based acoustic patch test with an automated calibration routine for a circular-scanning airborne lidar system. In *Canadian Hydrographic Conference 2010*. Quebec, QC, Canada.

Habib, A., 2009. Accuracy, quality assurance, and quality control of LiDAR data. In J. Shan & C. K. Toth (Eds.), *Topographic Laser Ranging and Scanning: Principles and Processing* (pp. 269–294). Boca Raton, FL: CRC Press.

Habib, A., Kersting, A. P., Bang, K. I., & Lee, D.-C., 2010. Alternative methodologies for the internal quality control of parallel LiDAR strips. *Geoscience and Remote Sensing, IEEE Transactions on*, *48*(1), 221–236. http://doi.org/10.1109/TGRS.2009.2026424

Imahori, G., Jeff F., Wozumi, T., Scharff, D., Pe'eri, S., Parrish, C., White, S., Jeong, I., Sellars, J., and Aslaksen, M. 2013. *A Procedure for Developing an Acceptance Test for Airborne Bathymetric Lidar Data Application to NOAA Charts Iin Shallow Waters*: National Oceanographic and Atmospheric Administration. Silver Spring, MD, NOAA Technical Memorandum NOS CS-32.

International Hydrographic Organization (IHO), 2008. *IHO Standards for Hydrographic Surveys, 5th edition.*, Monaco: International Hydrographic Bureau, 36p.

Kinney, J., Wolfskehl, S., Bruce, S., Bogonko, M., Bongiovanni, C., Armstrong, A., Nagle, E., Pe’eri, S., and Parrish, C., 2015. Update on NOAA’s IOCM Sandy Project for Charting & Habitat Mapping using Topobathymetric Lidar surveys. 16th Annual JALBTCX Airborne Coastal Mapping and Charting Workshop, Corvallis, OR.

Miller, V.S.; Mortimer, K.; Miller, J.J; Wilson, M.J.; Wyllie, K., 2011. The Port of Norfolk Project. *In: Proceedings of the US Hydrographic Conference (Tampa, FL).*

National Ocean Service (NOS), 2015. National Ocean Service Hydrographic Surveys Specifications and Deliverables (2015 Edition). Retrieved from http://www.nauticalcharts.noaa.gov/hsd/specs/specs.htm

Office of Coast Survey (OCS), 2016. Hydrography. *In: Nautical Chart Manual (Vol. 1): Policies and Procedures (*Version 2016.2). Last accessed 2/19/2016.

Snyder, G. I., 2012. *National Enhanced Elevation Assessment at a Glance*: U.S.G.S., U.S. Geological Survey Fact Sheet 2012-3088.

White, S., 2007. "Utilization of Lidar and NOAA's Vertical Datum Transformation Tool (VDatum) for Shoreline Delineation." Marine Technology Society/IEEE Oceans Conference Vancouver, BC, 29 Sep - 4 Oct 2007, IEEE. doi:10.1109/OCEANS.2007.4449147.

APPENDIX A. ABBREVATIONS AND ACROYNMS

3DEP – 3D Elevation Program
ABE – Area Based Editor
ALB – Airborne Lidar Bathymetry
CATZOC – Category of Zone of Confidence
CHARTS – Compact Hydrographic Airborne Rapid Total Survey
CORS – Continually Operating Reference Station
CUBE – Combined Uncertainty and Bathymetric Estimator
CZMIL – Coastal Zone Mapping and Imaging Lidar
HSD – Hydrographic Surveys Division
HSSD – Hydrographic Survey Specifications and Deliverables
GNSS – Global Navigation Satellite System
IWG-OCM – Interagency Working Group on Ocean and Coastal Mapping
JALBTCX – Joint Airborne Lidar Bathymetry Center of Expertise
JHC – Joint Hydrographic Center
LUT – Look-up Table
MCD – Marine Chart Division
NCMP – National Coastal Mapping Program
NCMS – National Coastal Mapping Strategy (NCMS)
MLLW – Mean Lower Low Water
LMSL – Local Mean Sea Level
NAD83 – North American Datum 1983
NAVD88 – North American Vertical Datum 1988
OCS – Office of Coast Survey
QL – Quality Level
QTM – Quick Terrain Modeler
RSD – Remote Sensing Division
RTK – Real Time Kinematic
SAO – Scanner Angle Origin
SAR – Survey Acceptance Review
SBET – Smoothed Best Estimate of Trajectory
TSS – Topography of the Sea Surface
UTM – Universal Transverse Mercator
USACE – US Army Corps of Engineers
USGS – U.S. Geological Survey
UTM - Universal Transverse Mercator