

A procedure for developing an acceptance test for airborne bathymetric lidar data application to NOAA charts in shallow waters

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U.S. DEPARTMENT OF COMMERCE National Ocean Service
Office of Coast Survey

**Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
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Coast Survey's Mission

To provide navigation products and services that ensure safe and efficient maritime commerce on America's oceans and coastal waters, and in the Great Lakes.

A procedure for developing and an acceptance test for non-hydrographic airborne bathymetric lidar data application to NOAA charts in shallow waters

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ABSTRACT

National Oceanic and Atmospheric Administration (NOAA) hydrographic data is typically acquired using sonar systems, with a small percent acquired via airborne lidar bathymetry for near-shore areas. This study investigated an integrated approach for meeting NOAA's hydrographic survey requirements for near-shore areas of NOAA charts, using the existing topographic-bathymetric lidar data from USACE's National Coastal Mapping Program (NCMP). Because these existing NCMP bathymetric lidar datasets were not collected to NOAA hydrographic surveying standards, it is unclear if, and under what circumstances, they might aid in meeting certain hydrographic surveying requirements. The NCMP's bathymetric lidar data are evaluated through a comparison to NOAA's Office of Coast Survey hydrographic data derived from acoustic surveys. As a result, it is possible to assess if NCMP's bathymetry can be used to fill in the data gap shoreward of the navigable area limit line (0 to 4 meters) and if there is potential for applying NCMP's bathymetry lidar data to near-shore areas deeper than 10 meters. Based on the study results, recommendations will be provided to NOAA for the site conditions where this data will provide the most benefit. Additionally, this analysis may allow the development of future operating procedures and workflows using other topographic-bathymetric lidar datasets to help update near-shore areas of the NOAA charts.

Key words: topographic-bathymetric lidar, airborne bathymetric lidar, hydrography, near-shore bathymetry, Integrated Ocean and Coastal Mapping

1.0 INTRODUCTION

NOAA is mandated to acquire hydrographic survey data and provide nautical charts, per the [Coast and Geodetic Act of 1947](#). Typically, 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. Hydrographic survey data are primarily acquired with sonar systems (e.g., multibeam, side scan, or singlebeam), while a small percent is acquired via airborne lidar bathymetry (ALB) for near-shore areas. Increasingly tighter budgets have resulted in a diminished ability for NOAA to acquire hydrographic data using both sonar and ALB. However, NOAA is still required to survey near-shore areas as part of the coastal mapping activities, e.g., updating nautical charts, creating hydrodynamic models, mapping habitats, and developing coastal plans. For instance, near-shore bathymetry is critical input to inundation models for storm surge and tsunamis and for understanding near-shore processes for coastal engineering purposes.

This study investigates an alternative approach to meet NOAA requirements using existing topographic-bathymetric lidar (TBL) data from the U.S. Army Corps of Engineers (USACE) [National Coastal Mapping Program](#) (NCMP) and other outside TBL mapping programs. The availability of the NCMP dataset to NOAA (via [Digital Coast](#) and direct collaboration), and the frequency with which areas are resurveyed, make these datasets the primary focus of this research (Digital Coast, 2012). However, it is important to note that the National Geodetic Survey (NGS), in collaboration with its federal and private sector partners, anticipates increasing acquisition and use of TBL data for shoreline mapping. Hence, another benefit of this study is the capability to apply the procedures developed and tested here to NGS TBL datasets in the future. This study also directly supports the provisions of the [2009 Ocean and Coastal Mapping Integration Act](#), which require coordination of federal data acquisition activities and multi-use of ocean and coastal mapping data.

2.0 MOTIVATION

The Office of Coast Survey's Hydrographic Surveys Division (HSD) ingests and verifies a small amount of outside source data for their adherence to the NOAA hydrographic survey requirements at the processing branches. HSD now faces a challenge to find creative ways to obtain more hydrographic or bathymetric data to update NOAA nautical charts, as diminished funding limits HSD's ability to sustain the same level of hydrographic contracts. HSD has historically maintained a balance of surveying areas where maritime commerce is the heaviest and most dangerous, and seafloor is highly variable over time while, at the same time, surveying near-shore areas when possible. HSD is now interested in investigating new outside source TBL data as they expect NOAA's involvement in TBL to continue to increase. Up until now, HSD has not investigated the potential use of incorporating TBL data from NCMP into NOAA nautical products. The main reason is that many existing TBL data sets have not been collected to NOAA hydrographic surveying standards (NOS, 2012) and it is not clear if, and under what circumstances, they might aid in meeting certain hydrographic surveying requirements.

The primary goal of this research is to evaluate the potential use of NCMP TBL survey data for updating the coastal portion of NOAA charts. The TBL surveys will be evaluated through a comparison to hydrography derived from NOAA acoustic surveys. As a result, it will be possible to assess whether TBL bathymetry can fill in the data gap shoreward of the navigable area limit line (NALL) (0 to 4 meters). We can also assess its potential use in deeper waters. The study will also investigate, to a lesser extent, the potential application of TBL data to near-shore areas ranging from

four to ten meters, and areas deeper than ten meters based on the TBL survey and the coastal conditions. In doing so, it will be necessary to understand the survey standards of the USACE NCMP and the other outside ALB survey programs. The resulting bathymetric products will be compared to survey standards of NOAA and other hydrographic offices, e.g., S-44 of the International Hydrographic Office (IHO, 2008). This study will develop a procedure to gather TBL survey data from federal archives (NOAA and USACE), process the laser measurements into bathymetric surfaces, and conduct statistical analysis. We will recommend the site conditions (geology, water clarity and depth) where data will provide the most benefit (quality of the final product). This will also allow the development of future operating procedures with workflows to incorporate the outside source datasets into NOAA's current workflows for updating nautical charts and other products. Some of the ALB survey programs repeat surveys every few years. The study results can help quantify the stability of coastal areas and determine how often NOAA should update their products accordingly (shoreline mapping and bathymetry).

3.0 APPLICATIONS OF TOPOGRAPHIC-BATHYMETRIC LIDAR DATA

3.1. NOAA Coast Survey Hydrographic Program

The Hydrographic Surveys Division sets the hydrographic survey priorities for the nation, using feedback from NOAA's navigation managers, federal agencies, state governments and other parts of the maritime community. Because of the enormity of NOAA's responsibility to survey 3.4 million square nautical miles, HSD uses multiple resources to acquire hydrographic data, including NOAA's Office of Marine and Aviation Operations (OMAO) hydrographic fleet, hydrographic services contracts, and the Coast Survey navigation response teams. HSD works with OMAO to obtain and schedule ship time on the hydrographic fleet, awards and manages contracts for the acquisition of hydrographic data, and instructs all the platforms acquiring hydrographic data for NOAA. HSD also processes in-house hydrographic vessel data and performs quality control on in-house, contract and outside source hydrographic and bathymetric surveys. Additionally, HSD annually updates the [*NOS Hydrographic Services Specifications and Deliverables*](#) and the [*Field Procedures Manual*](#). HSD processing branches ingest and verify outside source data for adherence to specifications, to determine if Coast Survey can use any of the data to update NOAA nautical charts and other related products.

Coast Survey is appropriated funds each year for hydrographic services contracts. For the most part, Coast Survey uses these appropriated funds to acquire hydrographic data with sonar systems, using a small percentage for acquiring near coastal hydrographic data via airborne lidar bathymetry. However, tighter budgets have resulted in a diminished ability for NOAA to acquire hydrographic data using both sonar and ALB. Because NOAA has an ongoing requirement to survey near-shore areas as part of the coastal mapping activities, e.g., updating nautical charts, creating hydrodynamic models, mapping habitats, and developing coastal plans, HSD is interested in finding collaborative means to fill in the near-coast gaps created by the loss of lidar collection.

3.2. NOAA's Coastal Mapping Program

The National Geodetic Survey's Remote Sensing Division (RSD) operates NOAA's [*Coastal Mapping Program*](#). The program provides accurate, consistent, and up-to-date national shoreline for the nation and its territories. NGS has been conducting shoreline mapping activities since 1807 (Shalowitz, 1964), and the shoreline on NOAA nautical charts is considered the nation's legal shoreline (Graham et al., 2003). The national shoreline also serves other purposes, ranging from

determination of legal boundaries to coastal management and environmental applications (White et al., 2011).

Over the past decade, NGS has worked with partners to develop, test, and refine new topographic-bathymetric lidar shoreline procedures. Tide requirements for TBL versus photogrammetric methods are not as stringent, as there is a wider window in which TBL can be acquired (Parrish, 2012). NGS typically requires one meter spot spacing for shoreline mapping lidar measurements. The measurements are cleaned of outliers, saved in LAS format (APRS, 2009), and referenced to NAD83 (current realization) (Snay and Soler, 2008). Using VDatum (Myers et al., 2007), the NAD83 ellipsoid heights of the edited TBL data are transformed to the MHW or MLLW tidal datum (White et al., 2011).

3.3. National Coastal Mapping Program

The U.S. Army Corps of Engineers developed the National Coastal Mapping Program in 2004 to support the USACE mission of managing construction and sediment, and other mandated functions, along the nation's coasts. The NCMP allows USACE to acquire high-resolution TBL data on a scheduled basis of five to seven years, using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system by the Joint Airborne Lidar Bathymetry Technical Center of Expertise. (USACE also recently began operational data acquisition with a new TBL system, known as CZMIL; however, CZMIL data was not available for testing during the time of this study.) The NCMP includes the coastal areas along the Gulf Coast (from Alabama eastward), Atlantic Coast, Great Lakes, Oregon, and California (Wozencraft and Lillycrop, 2003). The CHARTS system integrates ALB sensors, digital camera, and hyperspectral scanner on a single platform for USACE's NCMP requirements. The ALB systems are Optech SHOALS-1000T and 3000 system. USACE also contracted lidar survey work with Fugro Palegos, LADS and Woolpert. This ALB data is typically collected at a density of 5 m x 5 m spot spacing (or less) with a minimum 30-meter overlap with adjacent flight lines. The coverage area is from 0.5 kilometer inland from the shoreline to 1 km offshore, depending on turbidity. NCMP scope of work typically requires vertical positions accurate to ± 15 centimeter and horizontal positions accurate to ± 1.5 meters. Cross lines are required every 25 miles or more alongshore, to ensure 90% of all planned lines are crossed by a cross line for quality assurance and quality control (USACE NCMP, 2012). The acquired ALB data is referenced to NAD83 with NAD83 ellipsoid heights (see methodology section for more information on transformations). NCMP assesses the quality of the acquire data by looking at the differences calculated between the overlapping lines, cross lines and adjoining dataset. NCMP identifies systematic errors, and determines if the remaining errors have a normal distribution. It also ensures that the differences between a digital elevation model and ground truth data are unbiased and within ± 15 centimeter root mean square error (RMSE) within flat areas and ± 30 cm in sloped areas (NCMP, 2012; Guenther, 2001). The RMSE is calculated as:

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (Z_{ref,i} - Z_{check,i})^2 \right]^{1/2} \quad (1)$$

Where $Z_{ref,i}$ is the vertical coordinate of the i^{th} check point in the dataset, $Z_{check,i}$ is the vertical coordinate of the i^{th} check point in the independent source of higher accuracy, and N is the number of points being checked (FDGC, 1998).

3.4. Datasets of Opportunity: RIEGL USA and EAARL

Although the study will focus mainly on datasets from NCMP, there are other ALB datasets that are (or are anticipated to be) available for NOAA's use. The Remote Sensing Division is currently evaluating the capabilities of the new RIEGL VQ-820-G TBL and the USGS EAARL-B system to assess their ability to support Coastal Mapping Program requirements and the multi-use goals of NOAA's Integrated Ocean and Coastal Mapping program. NGS is also evaluating the capability of both systems to acquire bathymetric survey data landward of the NALL line and in other areas too dangerous for hydrographic survey launch operations. NGS is currently assessing both systems over test sites (the RIEGL system in Florida and EAARL-B in the U.S. Virgin Islands), to evaluate their potential to update shorelines and very shallow bathymetry (up to four meters) on NOAA charts.

4.0 Technical Overview of ALB

Airborne lidar bathymetry (ALB) measures the depths of moderately clear, near-shore coastal waters and lakes from a low-altitude aircraft using a scanning, pulsed laser beam (Guenther, 2001). The development of the ALB technology started in the mid-1960s (Hickman and Hogg, 1969). The heart of the system is a green laser (frequency-doubled Nd:YAG). The laser transmits pulsed laser beams that penetrate coastal waters. Laser reflections from the water surface and the seafloor are used to calculate the water depths. As ALB uses different principles and has different strengths and weaknesses than acoustic (i.e., sonar) systems, the two technologies are generally more complementary than competing. Mapping in waters deeper than 10 meters is generally more suitable for acoustic systems. Shallow waters of depths less than 15 meters – that include areas dangerous for ship surveying – are generally more suitable for aerial surveys. In addition, ALB can survey over land, producing a seamless elevation map of the topography and bathymetry of the region. ALB surveys can be a cost-effective, safe and rapid tool to acquire coastal bathymetry, e.g., monitoring coral reefs, determining degradation in shallow river channels, and establishing extents of coastal vegetation (Guenther, 2001).

A typical ALB system includes a laser ranging unit, a scanner (moving mirror), recording unit (detector and digitizer), and integrated GPS and inertial measurement unit (IMU) position and orientation. The ranging unit defines the pulse repetition frequency, the energy of the laser pulse and the beam divergence (which, in turn, defines the laser footprint at the water surface for a given flying height). The scanner defines the pattern of the laser pulses and, together with the pulse repetition frequency, the density of the laser measurements on the water surface. The entire sequence of events from the interaction of the pulse with the water surface to the interaction with the water bottom is logged by the recording unit as a waveform. The waveform represents the received intensity (digital number) relative to time (in nanoseconds) (Pe'eri and Philpot, 2007). The waveforms are the raw ALB observations used for processing. The IMU sensor and the GPS receiver measure the attitude and position of the survey aircraft and reference the ALB measurements (Balstavias, 1999).

The ALB system uses a green laser pulse because light at green wavelengths (500-565 nanometers) has a high transmittance through the water column compared to light at other wavelengths in coastal waters. ALB depth measurements are based on time differences of events occurring along the path of the laser beam. The ranging unit transmits a pulse that is directed from the system to the water using a scanner. The angle of incidence depends on the ALB system and attitude of the

aircraft, and can range from 0 to 25 degrees in typical survey conditions. (Some systems are designed to maintain a nearly constant angle of incidence at the water’s surface, while others are not.) Depending on the laser beam’s angle of incidence and the sea-state conditions, up to 4% of the laser energy is reflected back and may be sensed by the detection unit as the “surface return” in the waveform (Guenther, 2007; Pe’eri and Philpot, 2007). The remaining portion of the green laser pulse is refracted into the water column, where scattering from entrained microscopic particulates causes it to spread into a cone of continuously increasing angle. A small fraction of the transmitted energy in the water column, whose magnitude exponentially decreases with depth, becomes incident upon the bottom. Depending on the bottom composition, ~4-15% of the laser beam energy is reflected back into the water column. Scattering and absorption again attenuate and stretch the pulse as it passes back to the surface where much of the remainder is refracted into the air and may be sensed by the detection unit as the “bottom return” in the waveform (Guenther, 2007; Pe’eri et al., 2011). The path of the ALB in the water is measured by determining the time difference between detection of the water surface (i.e., surface return) and the water bottom (i.e., bottom return). The time difference (t) is multiplied by the speed (c) and divided by two (two-way travel time). The water depth (D) is determined correcting ray-path geometry by calculating the angle of incident (γ) using information from the scanner, IMU and the GPS (h).

$$D = \frac{1}{2} * c * t \quad (2)$$

The resulting product from an ALB survey is a point cloud. The pattern points and their spot spacing (distance between one point and its neighbor) depend on the scanner used in the ALB system and the speed of the aircraft. The scanner patterns (Figure 1) typically can be classified as: line scanning, rectangular or “zig-zag” scanning (e.g., USGS EAARL and LADS-MKIII), arc scanning (e.g., Optech SHOALS-3000 and AHAB HawkEye2), and circular scanning (e.g., Optech CZMIL). The point cloud is the initial geo-referenced data product (sometimes referred to as a “level 1 data product”) from an ALB system. The coordinates of each point represent a point on the land, water surface, or seafloor from which a laser pulse was reflected. One can assess the type of scanning motion in a particular ALB system by looking at the point cloud.

Additionally, the spot spacing is a function of the angular scan rate of scanner, the pulse repetition frequency, altitude of the aircraft and the speed of the aircraft. The area of the footprint is a function of beam divergence of the laser (the beam’s angle of expansion), angle of incidence (γ) in radians, and the height of the aircraft (h).

$$A_L \approx h\gamma \quad (3)$$

In the past decade, two types of ALB systems have been developed: 1) broad-beam ALB systems that have a large beam divergence (more than 10 mrad) with a typical footprint size of 2 to 4 m on the water surface; and 2) narrow-beam ALB systems that have a small beam divergence (less than 5 mrad) with a typical footprint size of less than 1 m on the water surface. Broad-beam ALB systems can be used in shallow-water areas and can typically acquire depth measurement data at the IHO order 1b. The Order 1b IHO standard does not require a full sea floor search or the ability to detect obstructions, as in Order 1a. This study will only focus on data acquired from broad-beam ALB systems that are used in USACE’s National Coastal Mapping Program, NCMP.

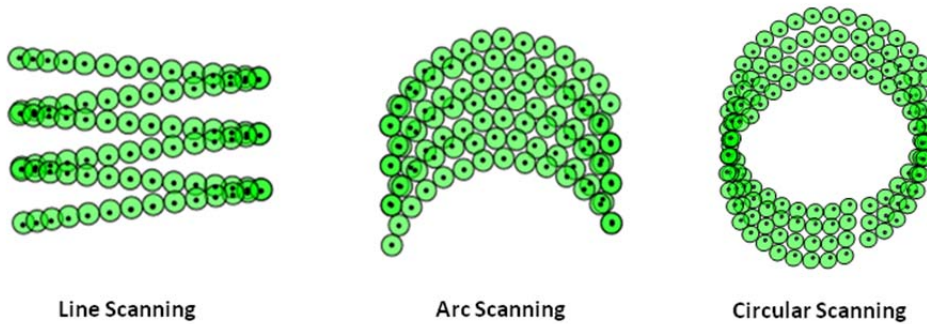


Figure 1. Scanning patterns: line scanning, arc scanning and circular scanning (Pe’eri, 2012)

In addition to the hardware configuration, ALB system measurements are also dependent on several different environmental factors. The key environmental factor limiting bottom detection is water clarity. Water clarity is a function of suspended particulates, colored dissolved organic matter (CDOM) and bubbles, which all vary spatially and temporally. As an example, runoff due to rain will cause the water to be turbid close to the coast and clearer in deeper waters. The performance of an ALB survey is typically defined in Secchi disk depths (visual property) or depth of extinction (a radiometric property that is a function of the diffuse attenuation coefficient). The depth of extinction is defined by the equation below, where K is the diffuse attenuation coefficient.

$$Z_{ext} = -1/K \quad (4)$$

Other environmental factors affecting ALB surveys are sea-surface conditions, the seafloor (e.g. roughness, slope, mineral composition, and presence of aquatic vegetation), and atmospheric conditions.

5.0 Methodology / Research Approach

Many of the NCMP lidar datasets include both topographic and bathymetric data, although some contain topographic data only. Based on Coast Survey’s interests in TBL data below the tidal zone, the focus of this project is only on the NCMP bathymetric lidar data. The project presents a statistical comparison between the NCMP bathymetric lidar and Coast Survey (OCS) acoustic (multibeam) surveys. The purpose of the comparison is to evaluate the distribution of the NCMP lidar survey for a given survey site and determine if NCMP lidar survey can be compiled with the Coast Survey multibeam data to create a seamless shallow-bathymetry digital elevation model (DEM). The NCMP lidar survey will be considered useful for NOAA hydrographic operations if it shows a good agreement (generally within IHO S-4 order 1b standards) with the reference OCS multibeam. The agreement between reference and test datasets were investigated as a function of depth.

The statistical analysis in this project consists of several steps:

- 1) determining the bathymetric lidar density (i.e. number of laser measurements per meter) by analyzing one or two flight lines;
- 2) identifying gaps in the lidar dataset for calculating the maximum depth of the ALB penetration;
- 3) calculating the depth difference between the NCMP lidar and the OCS multibeam datasets;

- 4) plotting a histogram for each study site to show the depth difference frequency of the entire lidar dataset; and
- 5) creating a scatter plot for each study site to show the difference between the two datasets as a function of depth.

One of the goals of this project is to evaluate the lidar datasets over different locations and seafloor types because bathymetric lidar responds differently to varying environmental factors and conditions. An additional criterion was that the NCMP bathymetric lidar and OCS multibeam datasets for these selected areas also had a significant overlap.

The analysis tools used in this project included a combination of commercial off-the-shelf software, ArcMap and MapInfo, and also the LAStools freeware (product from the University of North Carolina). ArcMap is the primary software used throughout the project with the Spatial Analyst and 3D-analyst modules for statistical analysis of the different datasets. At a minimum, ArcMap can perform the steps outlined in this report; one terabyte of storage space satisfied storage space needs. MapInfo was used to convert the OCS survey outlines to shape files, and LAStools was used to convert the lidar LAS files (JALBTCX archives the NCMP lidar data in LAS format) into ACSII for use in ArcMap.

5.1. Study Sites

Several sites were investigated as potential study sites along the East, Gulf and West Coasts (Figure 2). However, only four sites were found to satisfy our criteria of different seafloor compositions and a large overlap between the NCMP lidar and OCS multibeam datasets (Table 1). In addition, the potential to compile datasets that were collected over a large time period (six year difference) was investigated in Pensacola, FL. These areas were also selected based on their stability with respect to seasonal changes, with the exception of Pensacola. This will be important when doing the statistical analysis, as the data was acquired anywhere from a year to four years apart.

Table 1. The seafloor characteristics and the survey data information of the study site investigated in the project.

Study Area	Seafloor Type/Characteristics	NCMP			OCS		
		Spacing (m)	Coverage	Year	Spacing(m)	Coverage	Year
1Fort Lauderdale, FL	Sandy and Hard bottom Coral	4x4	200%	2012	4x4	100%	2009
Port Everglades, FL	Sandy and Hard bottom Coral	4x4	100%	2009	0.5x0.5,1x1	100%	2008
Kittery, ME	Fine sand with rock outcrop	5x5	100%	2007	0.5x0.5,1x1	100%	2006
Pensacola, FL	Sand	3x3, 5x5 ²	100%	2010, 2004	1x1,2x2 ³	100% ⁴	2009

¹ NCMP Lidar/OCS lidar instead of OCS multibeam

² Two NCMP lidar datasets were analyzed 2010 (3x3) and 2004 (5x5)

³ 2x2 for depths less than 20 meters and 1x1 over shoals and channel

⁴ 200% side scan and "skunk strip" bathymetry



Figure 2. Map showing the locations of the study sites.

The Fort Lauderdale NCMP dataset was acquired for calibration purposes, which was the reason for 200% coverage compared to the typical 100% over the other NCMP datasets. Additionally, the NCMP lidar data for Fort Lauderdale overlapped with lidar from an OCS hydrographic services contract. The NCMP lidar Fort Lauderdale data were acquired with the SHOALS-3000 system and the OCS lidar data were acquired by Tenix LADS, Inc. with the LADS MK-II Airborne System. A SHOALS-1000T system was used to acquire data over Port Everglades, Kittery and Pensacola 2004 survey at 1 kHz by the USACE, and the Pensacola, FL 2010 lidar dataset was acquired using the AHAB HawkEye system at 1 kHz with a sampling rate of 4 kHz by USACE contractors (Woolpert, Inc.).

In terms of the different TBL systems mentioned above, all the lidar systems were flown at about the same altitudes, nominally 250-500 meters; typically optimized based on survey requirements. The swath widths for all lidar data were therefore also similar, nominally 100 to 330 meters, and also optimized based on survey requirements.

It should be noted that the definition of coverage differs between NMCP and OCS. In NMCP, a 100% overlap refers to no gaps in the survey lines, independent of the bottom detection coverage, where typically there is 30 m overlap on each side of the 300 m swath. In OCS surveys, the definition of 100% coverage for any survey system is that it must adhere to the 100% bathymetric bottom coverage methods (Object Detection and Complete Coverage) stated in section 5.2.2 of the HSSD (NOS, 2012). For multibeam surveys (Order 1a), OCS's requirements are more stringent due to the need to resolve significant features measuring at least 1 m x 1 m x 1 m in waters up to 20 meters, and a cube measuring 5% of the depth in waters greater than 20 meters (IHO, 2008). Hydrographers must set line spacing for multibeam object detection coverage such that the grid resolutions thresholds are as defined in Table 2 or stricter to prevent gaps in object detection coverage.

Table 2. Example of grid resolution thresholds for 100% coverage as defined by OCS.

Depth Range (m)	Resolution (m)
0-20	0.5
19-40	1

For complete multibeam coverage, for example, all significant features measuring 2 m x 2 m horizontally, and 1 m vertically in waters up to 20 meters must be detected and included in the gridded bathymetry. The requirements for complete coverage require hydrographers to set line spacing such that the grid resolutions thresholds are as follows (or stricter) to prevent gaps in complete multibeam coverage:

Table 3. Grid resolution threshold example to prevent gaps in complete multibeam coverage

Depth Range (m)	Resolution (m)
0-20	1
18-40	2

Since this project goal does not include object detection, the analysis is simplified to identify the bathymetric difference between two datasets and determine if the NCMP lidar data was consistent with the OCS multibeam data for generating a seamless bathymetric surface.

5.2. Procedure Outline

Downloading datasets

The NCMP JALBTCX lidar coverage map for the 2005-2007 NCMP surveys is available on the [JALBTCX website](#). This viewer is useful for getting a quick look on the success of ALB bottom detection before ordering datasets (Figure 3). When zooming into the area of interest, a low resolution DTM of the area surveyed will appear and it will be easy to discern if there is bathymetric lidar or only topographic. The cleaned and processed NCMP datasets (vice raw point cloud data) can be downloaded from the [NOAA Digital Coast Website](#) (Figure 4) or through the NOAA/NGS/RSD who works closely with the USACE JALBTCX and can aid in retrieving the NMCP bathymetric lidar datasets. Procedures describing how to download the NCMP bathymetric lidar data are provided in Appendix I.

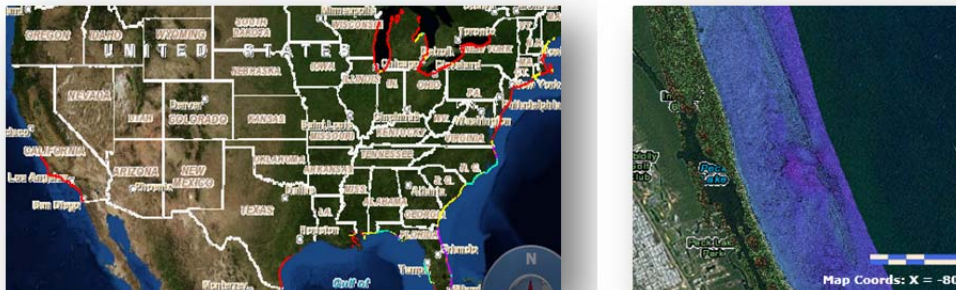


Figure 3. (left) The 2005-2007 NCMP coverage map. (right) Zoom in on the coastal area near Great Pocket, FL.

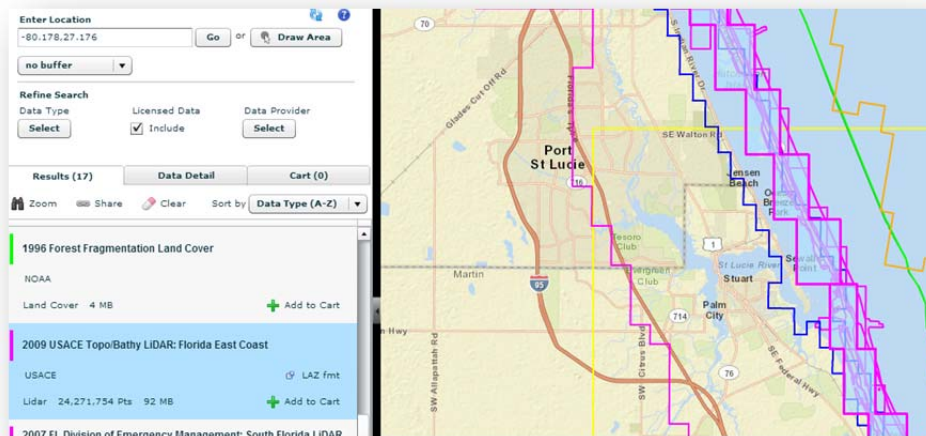


Figure 4. A screen capture from the Digital Coast website querying lidar datasets near Palm City, FL.

The OCS multibeam data were downloaded from NOAA’s [National Geophysical Data Center](#) (NGDC) shown in Figure 5. Since there is a lag in time from acquisition of the OCS survey to being placed on NGDC, Surdex files (completed OCS hydrographic survey outlines) were also investigated to determine if any new surveys would be available for this study.

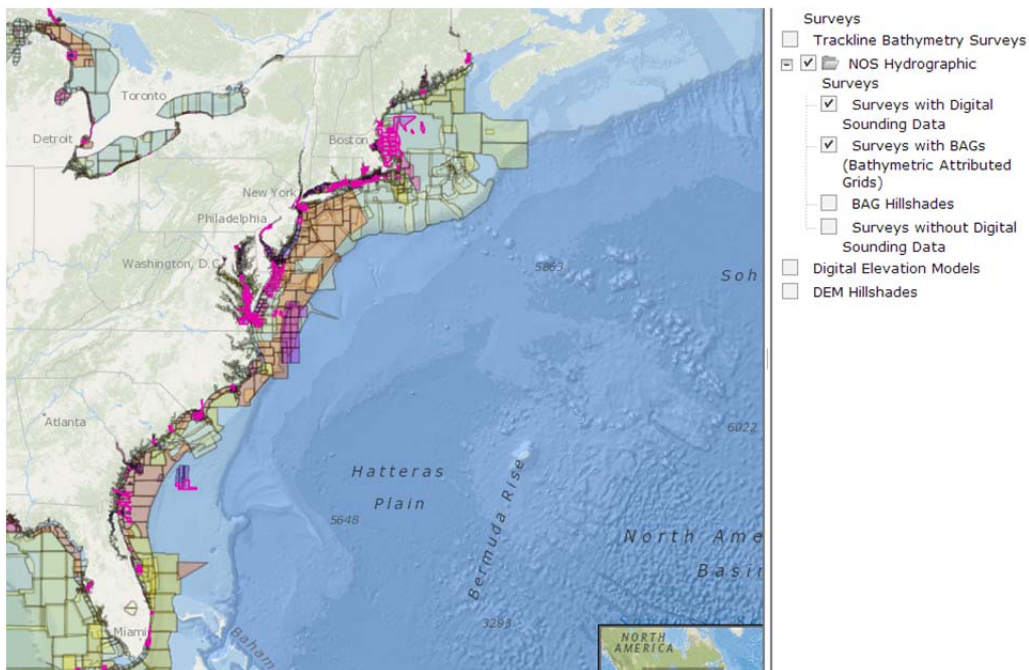


Figure 5. A screen capture from the NGDC website querying OCS hydrographic datasets.

Data Format

Typically, the NCMP lidar datasets are acquired in a propriety binary format. JALBTCX archives the NCMP lidar data in LAS format. The archived NCMP bathymetric lidar data can be downloaded in two different formats: ASCII text and binary LAS. It is possible to get the data in either format regardless of whether it is downloaded from Digital Coast or from NMCP directly. (More information

on LAS files can be found in Appendix A.) NCMP lidar data were generated in LAS format. However, it cannot be read directly into ArcMap without translation into another format such as ASCII. LASTools, a free-software, is able to transform LAS files into ASCII. LASTools can be used either as a stand-alone software for batch processing or as a module within ArcMap for single-file processing.

Datum Transformations

The NCMP lidar datasets in the JALBTCX archive are referenced to NAD83 with geographic coordinates (i.e., latitude, longitude) and NAD83 ellipsoid heights. When the NCMP lidar data is sent to NOAA for the Digital Coast archive, the data was transformed to orthometric heights using Geoid 2003. As a result, the NCMP data was horizontally referenced to NAD83 and vertically referenced to NAVD88. Digital Coast can then perform datum transformations and/or map projections (e.g., project in UTM), based on the options specified by the user. For this study, the lidar data was projected and downloaded from Digital Coast in UTM NAD83.

For NCMP lidar data that was received directly from JALBTCX, the data was projected from geographic coordinates into UTM in ArcMap. The diagram in Figure 6 shows the flow of NCMP lidar data transformed when downloading data from Digital Coast (H: horizontal and V: vertical). (More information on Coordinate Systems and Datums is in Appendices B and C.)

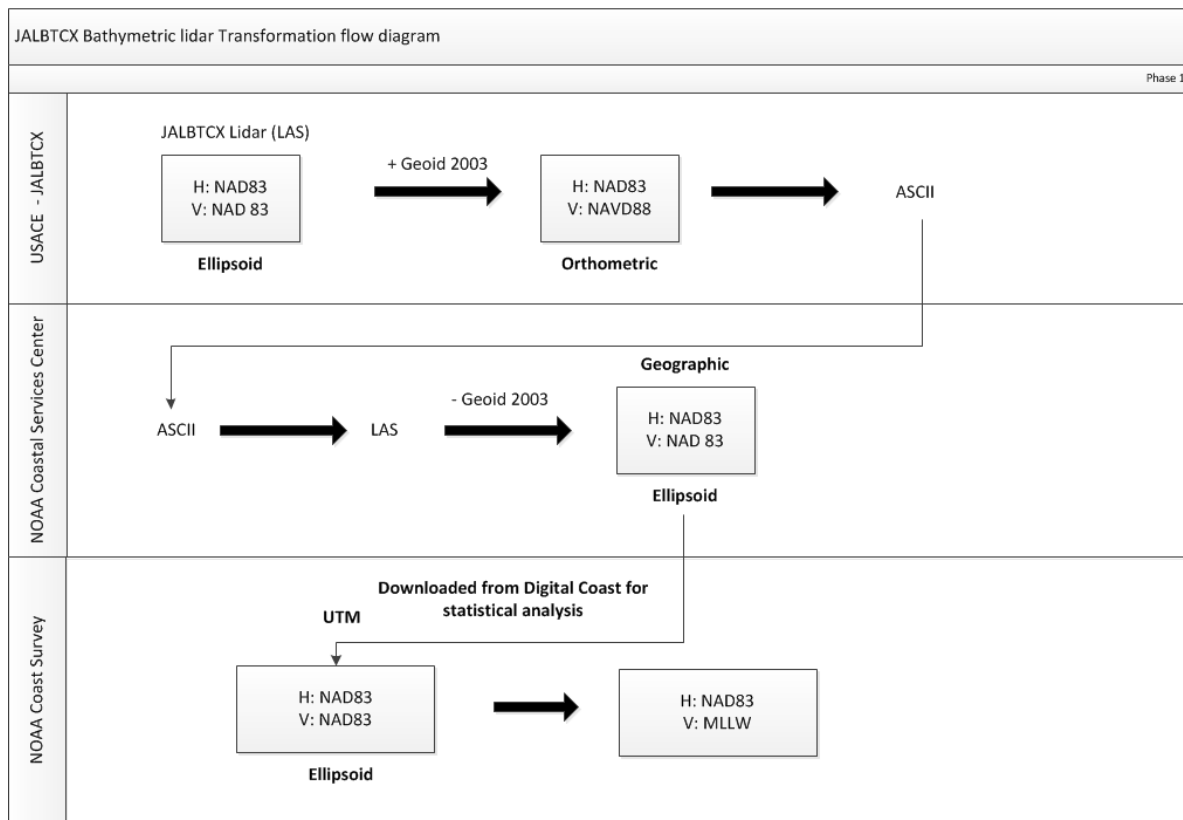


Figure 6. Transformation flow diagram of NCMP lidar data from JALBTCX archives (USACE – JALBTCX), through Digital Coast (NOAA Coastal Services Center) to OCS (NOAA Coast Survey). In the final step, the user can specify the desired horizontal and vertical datums in Digital Coast.

5.2.2 ArcMap Processing

In order to do the statistical analysis for this study, the Spatial Analyst and 3-D Analyst extension modules in ArcMap had to be installed. Then the group layer coordinate system was set to NAD83 UTM in ArcMap and the NOAA chart was brought in and projected in NAD83 UTM. (More information can be found in the NCMP and Acoustic data processing manual in Appendix I.)

Spot spacing and density maps

The NCMP lidar data and OCS multibeam data were brought into ArcMap and made into event and shapefiles, with the OCS multibeam data projected from geographic to UTM (NAD83) coordinates. Depending on the data source and size, some survey lines were all in one file while others had multiple lines which needed to be merged (where the lidar and multibeam overlapped). Clipping data were necessary for lidar datasets that included topographic data, and for multibeam and lidar which extended beyond the areas of overlap to ensure the data were manageable.

A calculation of the density of the laser measurements for a small area on one flight line without gaps (see equation 1) is then made to determine the laser measurement spacing (Figure 7). Using the Calculate Distance Band from Neighbor band tool (Spatial statistics toolbox) it is possible to calculate the minimum, maximum, and average distance to a specified number of neighbors. In this study, 4 neighbors were selected, i.e., this tool creates a list of distances between every feature and its 4th nearest neighbor (ESRI, 2012). In the example shown in Figure 7 (bottom images), the average distance is rounded to 5 m (i.e., the spacing between each laser measurements is about 5m).

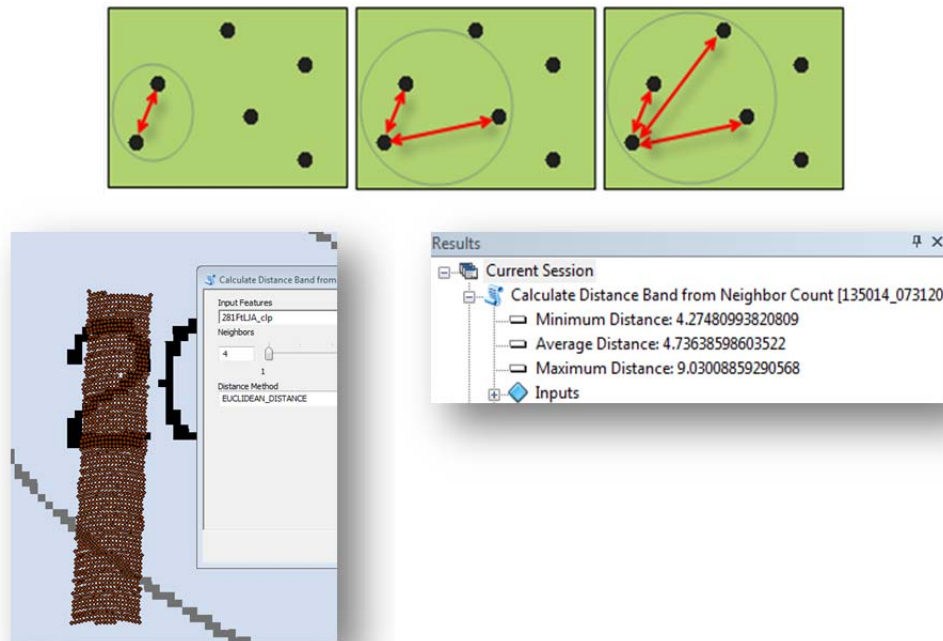


Figure 7. (top) A schematic illustration for calculating the spot spacing to nearest neighbor, two nearest neighbors and the three nearest neighbors, respectively (ESRI, 2012).

(bottom left) A small area showing no gaps is selected.

(bottom right) ArcMap provides statistical results on the spot spacing.

In addition to spot spacing, a point density calculation is performed on the entire dataset, and a density map (i.e., a raster map showing the number of laser measurements per grid cell) is output. Figure 8 is a density map of a NCMP dataset, where the green and blue lines indicate a greater number of laser measurements. Due to the large number of soundings, and because the focus of the study is to quantify the level of agreement between the NCMP lidar and the OCS multibeam data, spot spacing and density maps were not calculated/generated for the OCS multibeam data.

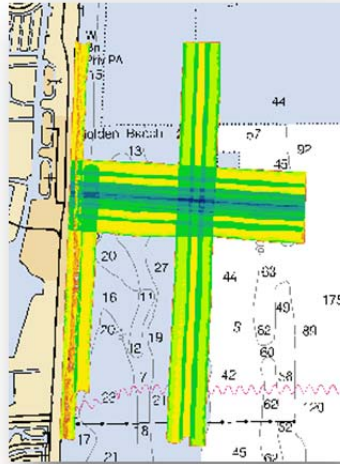


Figure 8. An example of a density map of a NCMP dataset, where the green and blue lines indicate denser laser measurements.

Gridding the data

The next step requires generating a grid surface from the lidar and multibeam datasets. Based on the density maps, a mask was created to include only areas that pass a density threshold (minimum of 2 laser measurements per cell). A Spline interpolation was selected for creating a surface from the point cloud (however, there might situations in which a Kriging interpolation may be more appropriate). It is also important to note that the reason that the Inverse Distance Weighted gridding was not used is because of its interpolation over gaps. There are several tools that can be used for the spatial analysis of the gridded surfaces that include difference maps between the surfaces and statistical calculations, such as mean, standard deviation, histograms and scatter plots. It should be also noted that in ArcMap processing, the two NCMP lidar and OCS multibeam grids must be at the same grid resolution. As a result, the OCS multibeam was gridded based on the NCMP lidar data because it is at a lower resolution, i.e., a grid surface with a resolution of 10 m x 10 m will be generated for a point spacing of 5 m.

Statistical Analysis Tools

The spline grids and raster calculator in ArcMap were then used for the statistical analysis of the two data sets by creating a difference map. This allows us to see if there was a major bias. Typically, a bias of up to 0.2 m between the NMCP lidar and multibeam data was reasonable, as there are several factors that could cause a slight elevation bias in one or both of the datasets. A difference greater than 0.2m may be an indication that there is a datum issue or a bias due to temporal differences. The latter (i.e., a bias due to temporal differences) could be the result of seasonal bathymetric changes, longer term trends (shoaling or deepening), and/or storm effects.

A histogram (Figure 9) was created for each study area to investigate the distribution of differences between the two surfaces. The histogram shows the depth difference frequency between the NCMP lidar and the OCS multibeam (reference) dataset. The mean of the initial histograms has an offset because the lidar data was referenced to the ellipsoid and not to Mean Lower Low Water (MLLW), like the OCS multibeam data. The VDatum tool was used to determine the offset and adjust the histogram.

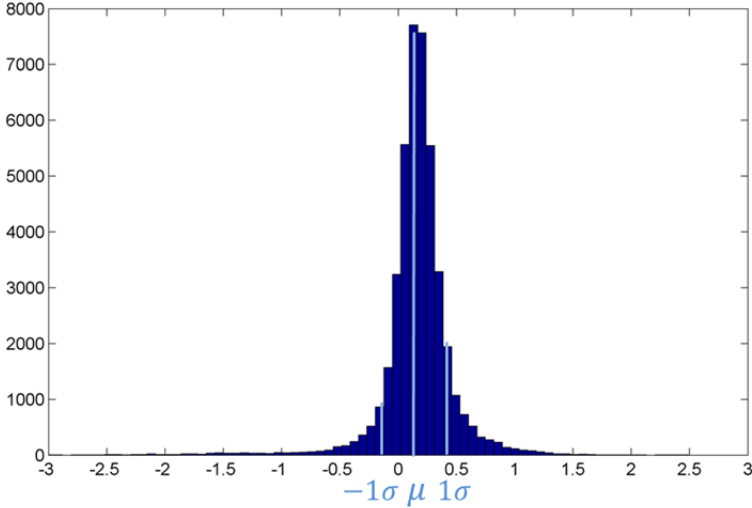


Figure 9. Example histogram

In this histogram, we are able to see the pattern of the data distribution where the highest peak indicates the most frequent value at about 0 m.

A scatter plot (Figure 10) was created to show difference between the NCMP lidar and the OCS multibeam echosounder (MBES) dataset as a function of depth. The example scatter plot below shows that there is no correlation between depth and depth difference (i.e., difference between the NCMP lidar data and OCM MBES data). More importantly, it shows how consistent the datasets are from 5 to 15 meters and that there is little difference (less than 0.2 m) between these two datasets.

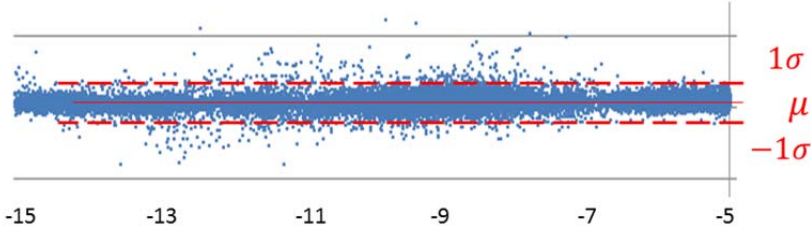


Figure 10. Scatter plot example

Detailed steps for statistically analyzing and comparing NCMP lidar and OCS MBES data were outlined in the NCMP and Acoustic Data Processing Manual in Appendix I.

6.0 Results

6.1 Fort Lauderdale, Florida

The bottom type of Ft. Lauderdale is characterized as white coral sand and a coral hard bottom, which is ideal for ALB surveying. This site was chosen first because it enabled comparison of two lidar surveys: an ALB survey collected in 2012 according to the USACE NCMP standards (5 m x 5 m or 4 m x 4 m spot spacing with 100% overlap) and an ALB survey collected in 2009 according to OCS survey requirements (3 m x 3 m spot spacing with 200% overlap). This helped give us an idea of a ballpark difference overall for two similar type systems before comparing the statistical differences between the NCMP lidar and OCS MBES datasets. The NCMP lidar density map (Figure 11, top left) shows a range of 0.05 to 0.3 laser measurements per square meter for a nominal spot spacing of 4 m x 4 m. A greater number of laser measurements are typically within the overlapping flight lines, while the sparsest laser measurements are near the shoreline. One reason for the low density values near the shoreline may be due to coastal process (e.g., waves and suspended material) that may reduce the laser's ability to successfully measure the seafloor depth. Another, slightly more technical, reason is that the convolution of the laser pulse (with a pulse width of a few nanoseconds for the primary systems discussed in this report) with the water surface can obscure the bottom return in very shallow water areas (< ~1 m) near the shoreline. The difference map (Figure 11, top right) shows a uniform difference of about zero to one meters between the NCMP lidar and the OCS lidar survey data. The overall mean and standard deviation (1σ) are 0.17 m and 0.32 m, respectively. Originally the mean value identified a datum issue. At that time the difference was one to two meters.) The vertical datum was calculated as NAD-83 (CORS96) instead of ITRF2000 (1997.0), which resulted in a 1.61 m difference. After applying the correct datum, the mean was reduced to 0.17 m, which is a very good result between two ALB surveys that are four years apart. The histogram plot (Figure 11, bottom left) confirms these results by showing that there is a slightly positive bias around 0.17 m. An investigation of depth difference measurements as a function of depth in the scatter plot (Figure 11, bottom right) shows a sub-meter difference between the datasets from 3 m up to 20 m. At depths shallower than 3 m, the depth difference increases to ± 1.0 m.

Fort Lauderdale: 2012 NCMP lidar and 2009 OCS lidar comparison

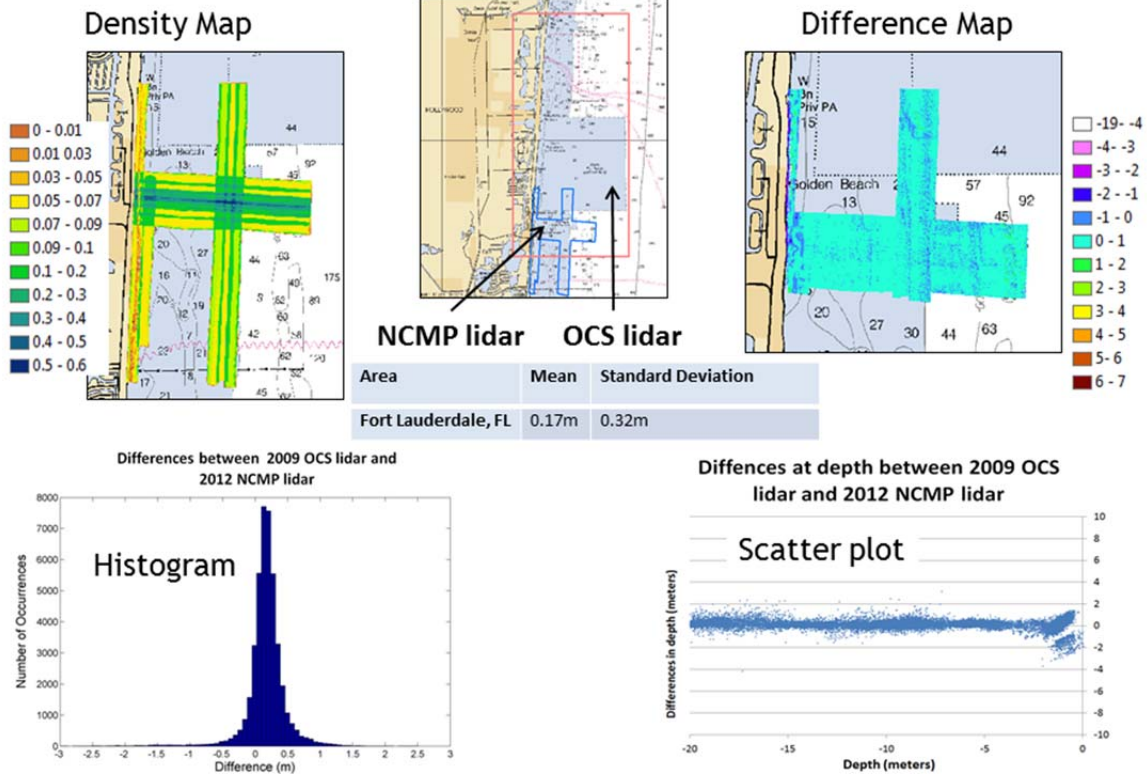


Figure 11. Comparison results from the Ft. Lauderdale calibration site: (top left) NCMP lidar density map; (top center) coverage of the NCMP ALB survey (in blue) and the OCS ALB survey (in red); (top right) difference map between the NCMP and the OCS datasets; (bottom left) histogram plot of the depth differences; and (bottom right) the scatter plot of the depth differences).

6.2 Port Everglades, Florida

Port Everglades study site has similar bottom type characteristics to the Fort Lauderdale calibration site. In the Port Everglades study site, the NCMP lidar data that were collected in 2009 was compared to the OCS MBES survey that was collected in 2008. The NCMP lidar density map (Figure 12, top left) shows a range of 0.05 to 0.2 laser measurements per square meter for a nominal spot spacing of 4 m x 4 m. The laser measurement distribution seems to be relatively uniform along the coast. The densest laser measurement distribution is in the inlet, where it seems that the survey lines have more than 100% overlap. The difference map (Figure 12, top right) shows a uniform difference of less than 1 m between the NCMP lidar and the OCS MBES datasets. The overall mean and standard deviation (1σ) are 0.54 m and 0.27 m, respectively. The histogram plot (Figure 12, bottom left) shows that the majority of the depth difference measurements between the OCS MBES and NCMP lidar datasets are between -0.5 m to + 1 m, where a positive value indicates that NCMP laser measurements are shallower than OCS MBES soundings. The scatter plot (Figure 12, bottom right) shows that the effective depth range for comparison between datasets is from 3 m to 14 m that have a typical depth difference of up to 1 m in water depth greater than 7 m and a depth difference of up to 1.5 m in water shallower than 7 m. It seems the Coast Survey did not survey in

depths shallower of 3 m. This is likely because MBES was not/could not be acquired. Typically, Coast Survey does not require hydrographers (whether contractors or NOAA FTEs) to acquire MBES data inside the 4 meter curve because of the increased time it takes to work in near-shore areas and the sometimes dangerous conditions linked to those areas. As a result, the number of depth measurements below 3 m is too small for a comparison.

Port Everglades: 2009 NCMP lidar and 2008 OCS MBES comparison

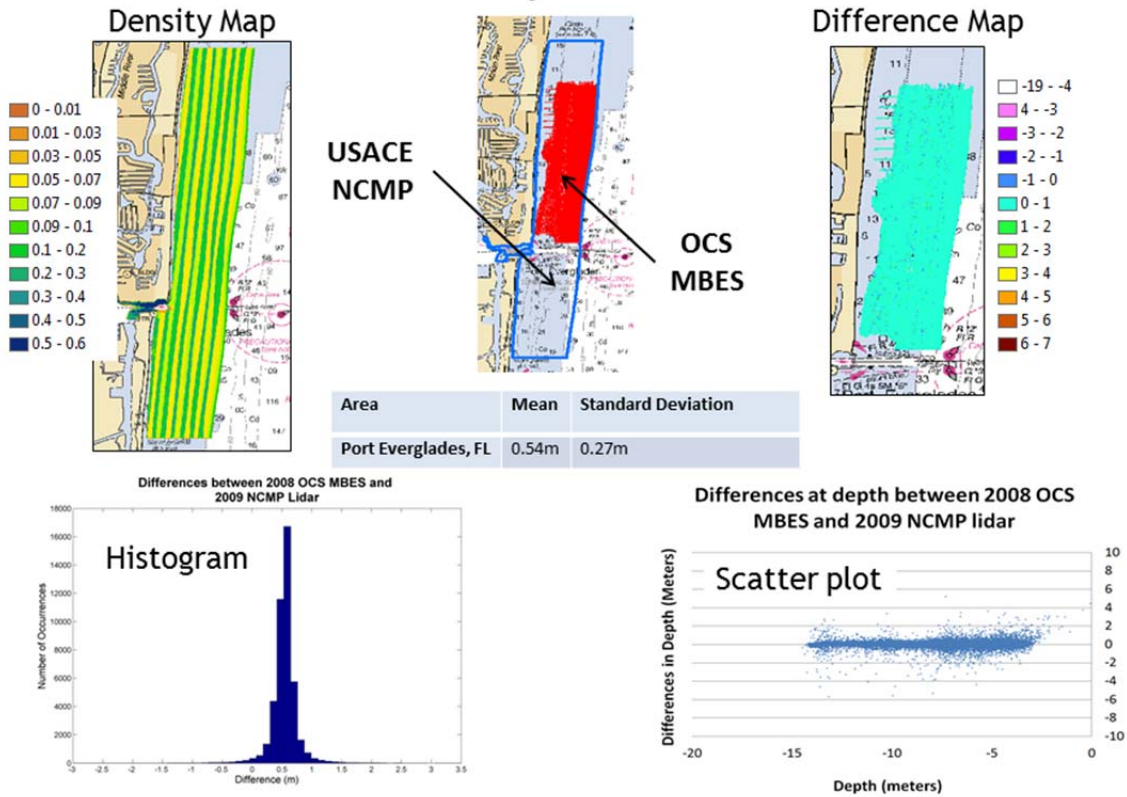


Figure 12. Comparison results from the Port Everglades, FL study site: (top left) NCMP lidar density map; (top center) coverage of the NCMP ALB survey (in blue) and the OCS ALB survey (in red); (top right) difference map between the NCMP and the OCS datasets; (bottom left) histogram plot of the depth differences; and (bottom right) the scatter plot of the depth differences.

6.3 Kittery, Maine

The bottom type characteristics of the Kittery, ME study site are a mix of sand, gravel, rocks and rocky outcrops. The NCMP lidar dataset that was collected in 2007 was compared to the OCS MBES survey that was collected in 2006. The NCMP lidar density map (Figure 13, top left) shows a range of 0.01 to 0.1 laser measurements per square meter for a nominal spot spacing of 5 m x 5 m. Although there are many gaps in the survey, the laser measurement distribution seems to be relatively uniform along the coast in areas that the NCMP was able to detect the bottom. The difference map (Figure 13, top right) in the areas that the ALB system was able to detect the bottom, the difference distribution was uniform with values less than 1 m between the NCMP lidar and the OCS MBES

datasets. The overall mean and standard deviation (1σ) are 0.17 m and 0.39 m, respectively. Although the standard deviation is about 0.1 m higher than the results from the studies in southeast Florida, these results are still considered reasonable. The histogram plot (Figure 13, bottom left) shows that the majority of the depth difference measurements between the OCS MBES and NCMP lidar datasets are between ± 1 m, where a positive value indicates that NCMP laser measurements are shallower than OCS MBES soundings. The scatter plot (Figure 13, bottom right) shows that the effective depth range for comparison between datasets is from 3 m to 13 m that have a uniform depth difference distribution that ranges up to 1.5 m. Similar to Port Everglades, it seems Coast Survey did not survey in depths shallower of 3 m so, again, the number of depth measurements below 3 m is too small for a comparison.

Kittery: 2007 NCMP lidar and 2006 OCS MBES comparison

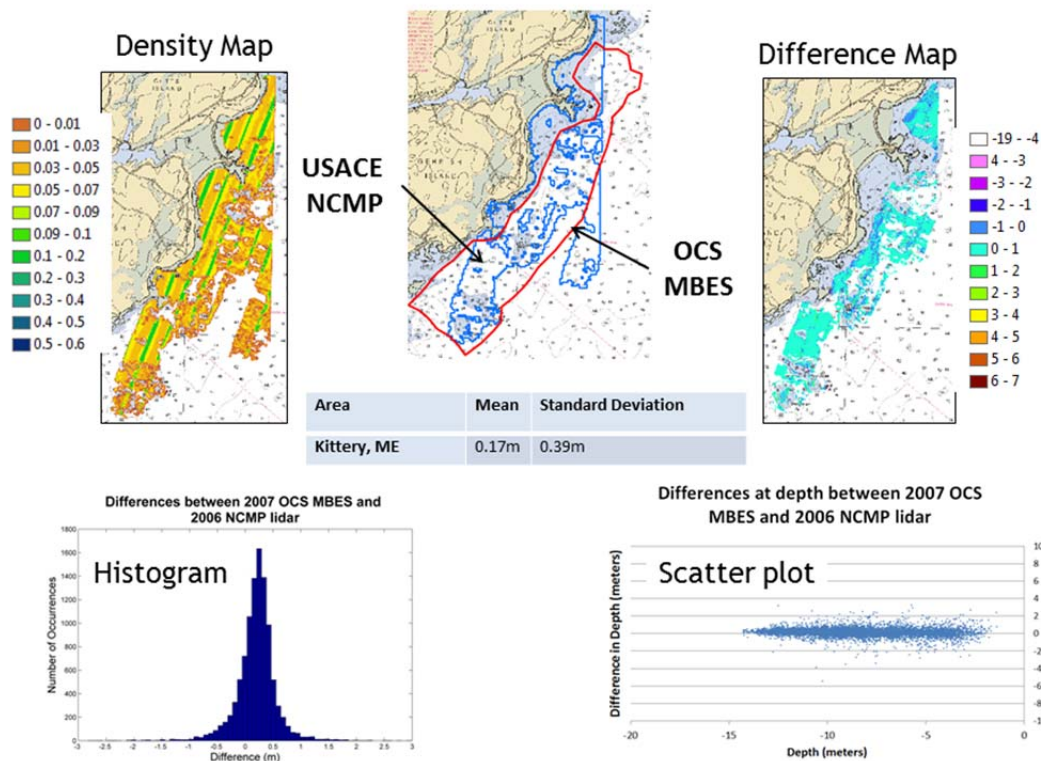


Figure 13. Comparison results from the Kittery, ME study site: (top left) NCMP lidar density map; (top center) coverage of the NCMP ALB survey (in blue) and the OCS ALB survey (in red); (top right) difference map between the NCMP and the OCS datasets; (bottom left) histogram plot of the depth differences; and (bottom right) the scatter plot of the depth differences.

6.4 Pensacola, Florida

The Pensacola study site contains a tidal inlet in a sandy environment. In this site, two NCMP lidar datasets from 2004 (Figure 14) and 2010 (Figure 15) were used to investigate and compare datasets that were collected one year and five years apart. The 2010 NCMP lidar dataset was collected using the AHAB HawkEye 2 system by USACE contractors. Changes in the bathymetry are noticeable in a visual comparison between the OCS dataset that was acquired in 2009 to the bathymetry generated from the 2004 NCMP lidar dataset. The seafloor in the Pensacola study site seems to vary even over the span of one year. The study results show a larger difference range value between the NCMP and

OCS datasets compared to the results in other study sites. The 2004 NCMP lidar density map (Figure 14, top left) shows a range of 0.01 to 0.07 laser measurements per square meter for a nominal spot spacing of 5 m x 5 m, whereas the 2010 NCMP lidar density map (Figure 15, top left) shows a range of 0.1 to 0.5 laser measurements per square meter for a nominal spot spacing of 3 m x 3 m. The main gap in the 2004 NCMP datasets in the center and along the left side of the channel in both density maps are most likely due to turbidity issues from wave action. The 2010 NCMP coverage shows more gaps than the 2004 map, which may be related to tidal stage (flood versus ebb) or rough sea state conditions. An investigation of the difference maps shows that the seafloor bathymetry changes as the time between the NCMP and the OCS datasets increases. The 2010 difference map (Figure 15, top right) shows a more uniform sub-meter difference between the NCMP lidar and the OCS survey data, where only the northeast bank of the inlet shows depth differences larger than 1 m. The 2004 NCMP difference map (Figure 14, top right) shows more variability in the difference map, where depth differences greater than 1 m are observed also at the mouth of the inlet. The overall standard deviation (1σ) values in both NCMP datasets are higher compared to the other study sites with a mean of 0.12 m and 0.57 m and a standard deviation of 0.94 m and 1.72 for the 2010 and 2004 NCMP datasets, respectively. The histogram and scatter plots confirm the observations in the difference maps. The 2010 NCMP shows histogram (Figure 15, bottom left) shows a narrower histogram than the 2004 NCMP histogram (Figure 15, bottom left). The 2010 NCMP shows histogram (Figure 15, bottom right) shows that the effective depth range for comparison between datasets is from 3 m to 13 m, where depth difference distribution ranges up to 2 m. The 2004 NCMP shows histogram (Figure 14, bottom left) shows that the effective depth range for comparison between datasets is from 2 m to 17 m, where depth difference distribution ranges up to 4 m. Similar to Port Everglades study site, there does not seem to be depths from the Coast Survey survey shallower than 3 m. As a result, the number of depth measurements below 3 m is too small for a comparison.

Pensacola: 2004 NCMP lidar and 2009 OCS MBES comparison

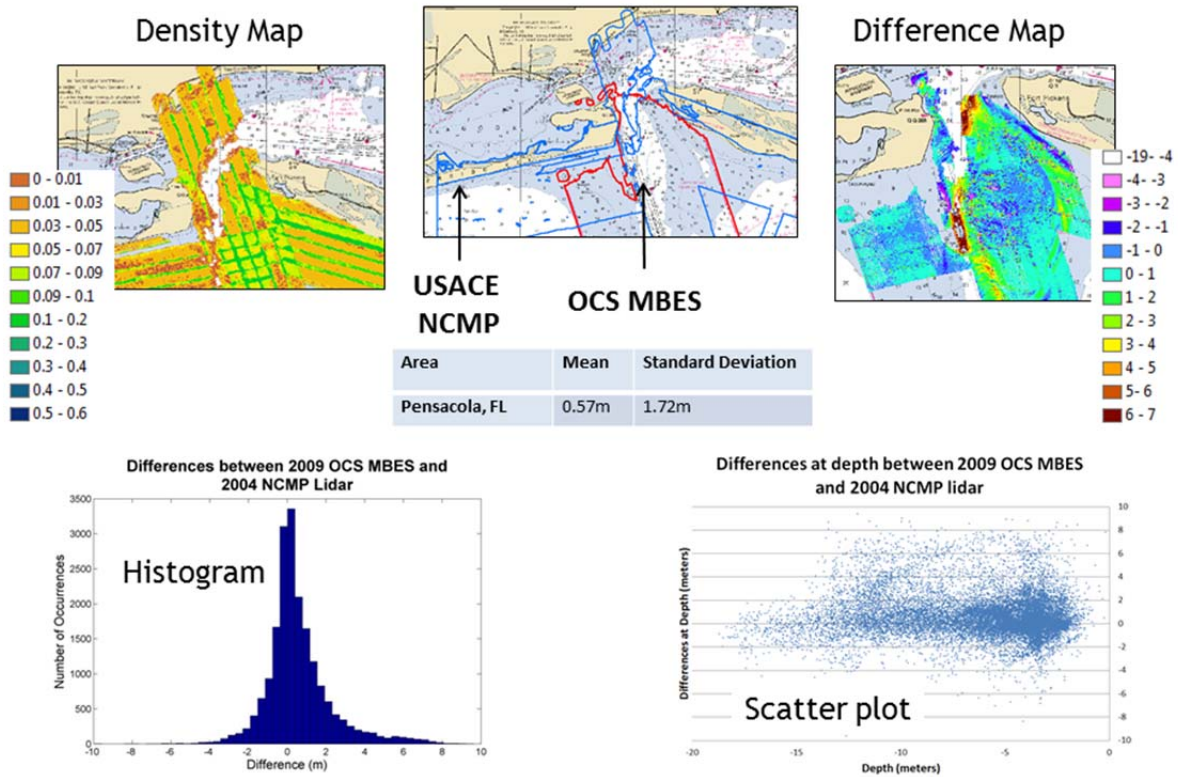


Figure 14. Comparison results from the Pensacola study site (NCMP 2004): (top left) NCMP lidar density map; (top center) coverage of the NCMP ALB survey (in blue) and the OCS ALB survey (in red); (top right) difference map between the NCMP and the OCS datasets; (bottom left) histogram plot of the depth differences; and (bottom right) the scatter plot of the depth differences.

Pensacola: 2010 NCMP lidar and 2009 OCS MBES comparison

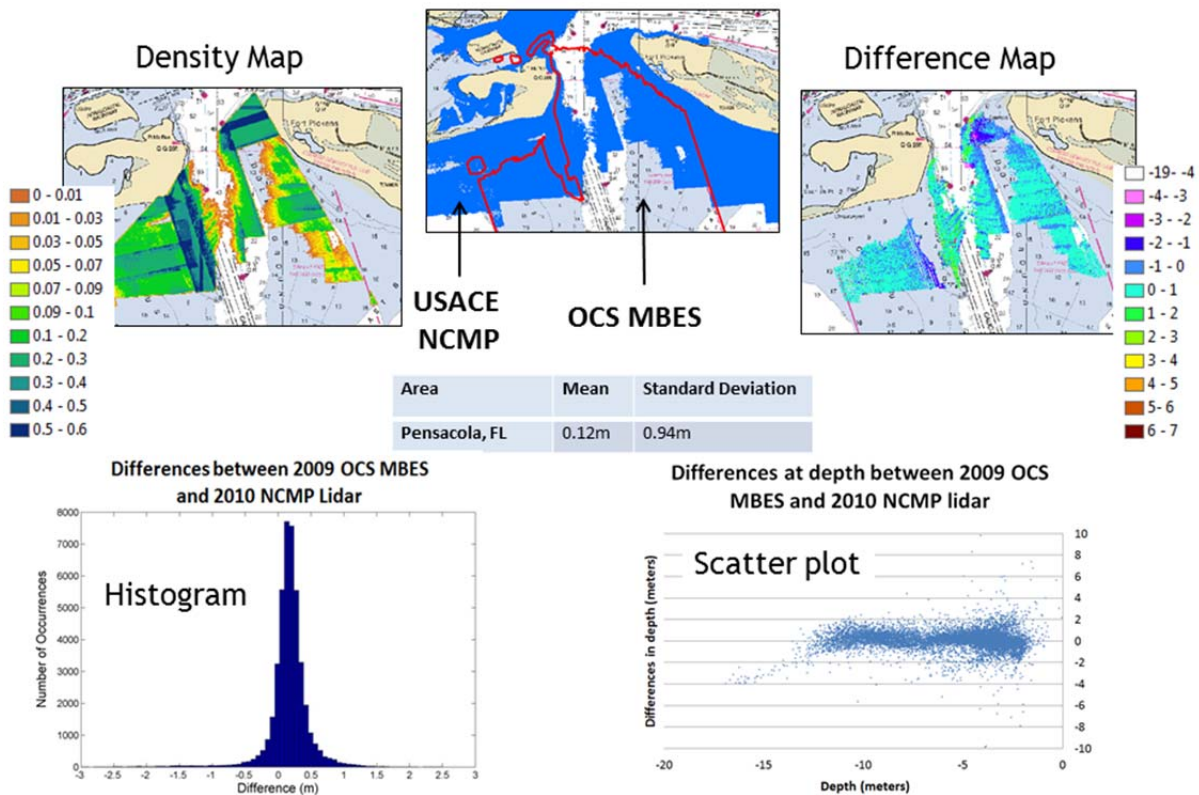


Figure 15. Comparison results from the Pensacola study site (NCMP 2010): (top left) NCMP lidar density map; (top center) coverage of the NCMP ALB survey (in blue) and the OCS ALB survey (in red); (top right) difference map between the NCMP and the OCS datasets; (bottom left) histogram plot of the depth differences; and (bottom right) the scatter plot of the depth differences.

6.5 Statistical Analysis Overview

Table 4 summarizes the overall mean and standard deviation (1σ) of the depth difference between the NCMP datasets and the reference dataset. Based on the scatter plots, of their standard deviations (Figure 16) and the mean differences for each study area (Figure 17) as a function of depth were generated. The mean results for all sites indicate that the datum transformations were successful. The standard deviation results indicate that the study sites were reasonably stable between surveys (with the possible exception of Pensacola); NCMP datasets are consistent with the OCS MBES datasets up to 0.4 m. This is the only study site that had a very active seafloor (i.e., sandy area near tidal inlets) thus the period between the surveys was an important factor for the comparison. Even after only one year, the standard deviation was close to 1.0 m. The reason for this large standard deviation is most likely environmental (turbidity and change of the seafloor).

Table 4. The overall mean and standard deviation (1σ) of the depth difference between the NCMP datasets and the reference dataset.

Areas	Mean	Standard Deviation
Fort Lauderdale, FL	0.17 m	0.32 m
Port Everglades, FL	0.54 m	0.27 m
Kittery, ME	0.17 m	0.39 m
Pensacola, FL (2004)	0.57 m	1.72 m
Pensacola, FL (2010)	0.12 m	0.94 m

It is important to note that all of the means are positive (Table 4), which may therefore indicate that the NMCP ABL data are always slightly deep-biased with respect to the MBES data. Possible causes could stem from the NOAA MBES processing that may lead to slight shoal bias or a small systematic error (bias) introduced in datum transformations.

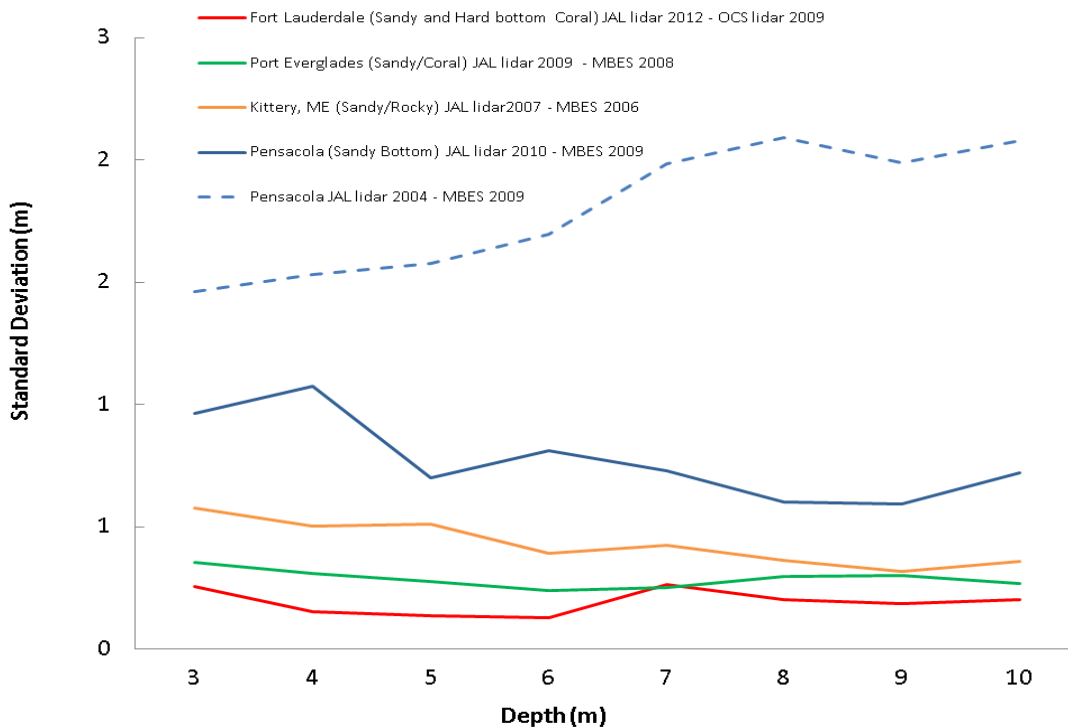


Figure 16. Plot of the standard deviation for each study area as a function of depth.

Note that as opposed to a root mean square error (RMSE), we are going to refer here to a RMS difference (RMSD), as the differences observed between the two datasets in our comparisons may reflect additional factors beyond error in the test data (e.g., seafloor changes between acquisition dates and uncertainty in the reference bathymetry). RMSD is calculated as:

$$\text{RMSD} = \left[\frac{1}{N} \sum_{i=1}^N (Z_{ref,i} - Z_{check,i})^2 \right]^{1/2} \quad (4)$$

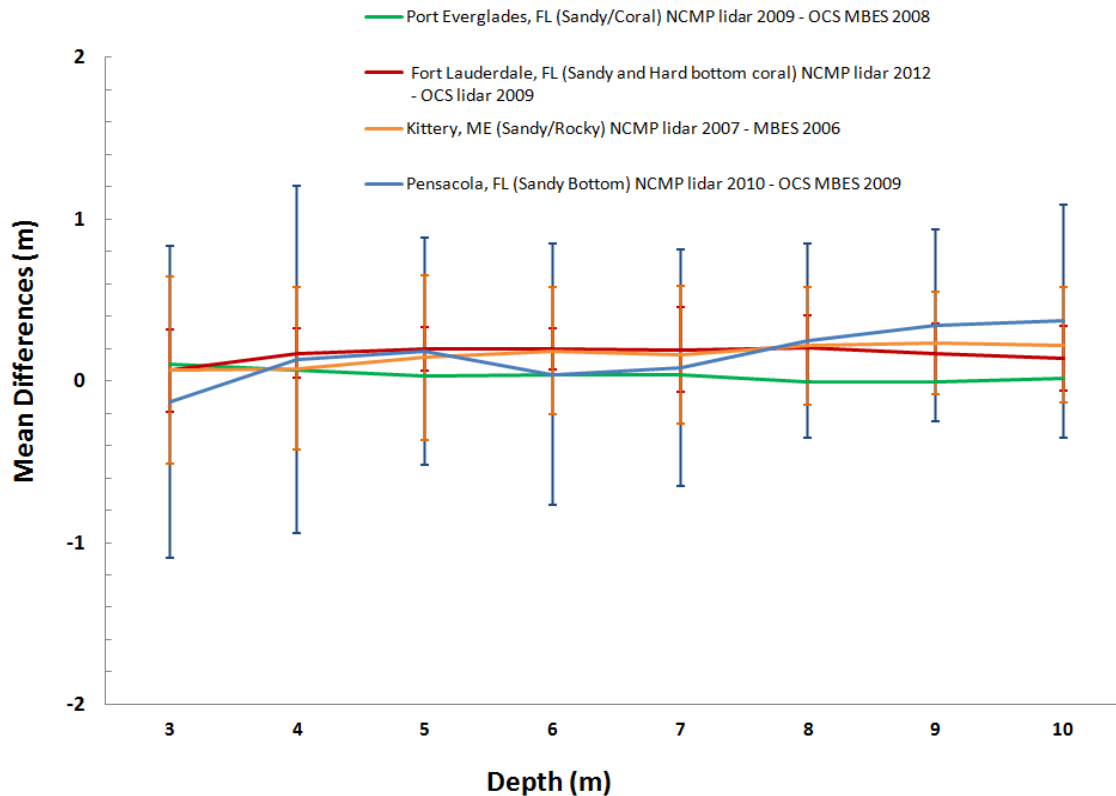


Figure 17. Plot of the mean differences (with error bars) for each study area as a function of depth.

This plot above also shows the anomalous nature of that Pensacola 2004 lidar and 2009 MBES data comparison. These data were problematic due to the large temporal separation and bottom instability. It should also be noted that there should be at least 1000 measurements between 2 and 10 meters. Both Pensacola datasets have less than 1000 measurements, which may be due to turbidity issues. It is very likely that much of the data were discarded during processing and “cleaning,” which may explain why there is a downward trend between 2 to 3 meters.

7.0 Discussion

Good agreement was found in three study sites (Fort Lauderdale, Port Everglades and Kittery) when we consider the overall data in Table 4 and Figure 16. One possibility to consider in future projects using ALB data in OCS, is to subtract off the average bias, if there is one, obtained in this study or (better option, if possible) as obtained through a project-specific comparison against overlapping sonar data. If the biases can be subtracted off, the RMS difference (which should approximately equal the standard deviation) will always be very small: < 0.4 m. This is if you disregard the Pensacola site, where we believe there may have been a lot of actual seafloor change between survey dates. Despite the small sample size (just 3 sites, if we disregard Pensacola), we believe the result show very good agreement between the ALB and MBES, especially given that actual seafloor change between survey dates could account for some of that difference even in the other 3 sites.

This study attempted a thorough investigation with datasets from different sources (i.e., different ALB and MBES) to create a NCMP evaluation procedure. The main goal of this study was to quantify the level of agreement between the NCMP lidar and OCS MBES data in terms of an RMS difference,

recognizing that there are several factors beyond the vertical uncertainty of the lidar data (e.g., actual seafloor change between the survey dates) that could contribute to the computed values. It is important to note that the study results should not be compared directly to IHO S-44 Order 1b standards. It is possible to use the values obtained in this study to compute a root means square error (RMSE) and accuracy at the 95% confidence interval for depth following the procedures and definitions in the Federal Geographic Data Committee’s National Standard for Spatial Data Accuracy, and then compare the latter value with the IHO S-44 Total Vertical Uncertainty specifications for IHO Order 1b surveys. However, the validity of the accuracy at 95% confidence level is unclear because of the following:

- 1) A large portion of the ‘error’ in the RMSE could be due to change in the seafloor between the dates of the MBES and lidar surveys, especially with a temporal offset of a few years and in areas of rapid change.
- 2) The uncertainty of the computed values will be a function of the vertical uncertainty of both the lidar data and the MBES and, while we certainly expect the latter to be much smaller, it may not be negligible.
- 3) It is not clear whether this type of empirical accuracy assessment can be equated exactly with the methods specified by IHO S-44, which states: "A statistical method, combining all uncertainty sources, for determining positioning uncertainty should be adopted."

It is also important to note that this study investigated only the current ALB systems in the NCMP surveys. A separate study should be conducted to investigate the new systems that planned to be used by the USACE (i.e., CZMIL) or by NGS RSD (e.g., EAARL-B or RIEGL).

Using an empirical analysis, the mean and standard deviation results (Figures 16 and 17) give an idea as to the data quality available from the ALB NCMP surveys. Excluding the Pensacola study site, the results from the NCMP surveys are adequate for meeting charting requirements and should be considered for NOAA hydrodynamic models. The ALB surveys provided a uniform coverage over sites with a sandy bottom. In Kittery, Maine, which has a mixed sandy and rocky bottom, there were many gaps in the datasets. Originally, the study plan was to include sites with muddy bottom (e.g., Alabama and Texas). However, an investigation of the NCMP surveys revealed that the ALB surveys were not successful in getting bottom detection. The study results also showed that the seafloor in areas close to tidal inlets is continuously changing. The amount of suspended material because of currents and wave action with the continuously changing bottom may cause problems in merging NCMP surveys with OCS surveys. Some of the turbidity issues can be reduced if the ALB surveys are conducted only on a flood stage of a tide.

Because the statistical analysis was accomplished by reducing the resolution of the OCS data to that of the NCMP lidar data, there may be some question whether the mean and standard deviation would differ greatly if the OCS data resolution remained unchanged and a point to point and grid to grid comparison was made. In the case of the Fort Lauderdale study site the results were as follows:

Fort Lauderdale, FL	Mean	Standard Deviation
Vdatum Offset	-1.6	
Point	1.73	0.27
Grid	1.75	0.19

The mean, as we expected, was slightly lower (0.13-0.15 m) for the grid and point to the mean calculated using a smoothed OCS lidar grid (0.17 m). Likewise, the standard deviations (0.27-0.19 m) were also lower as compared with the 0.32m for the coarser OCS lidar grid. It should be noted again that the NCMP lidar was deeper generally than the OCS lidar data, i.e., OCS lidar – NCMP lidar (with VDatum offset applied). Unfortunately, due to the time constraints of this project we ran out of time to do the same comparison for the other datasets.

All the plots shown in section 6 give a good idea as to the performance of the NCMP lidar systems. The surveys are adequate for HSD except for the Pensacola surveys – which are anomalies in this study – but for the others across the board the NCMP data are relatively consistent (Figure 16 and 17). The largest differences with respect to NCMP lidar data were in the depth range of 0-3m, which as previously discussed was due to lack of MBES coverage. Considering the smaller difference at the 3-10 m depth, we could just expect a similar performance of NCMP lidar even at 0-2 m had MBES been available in that area. Therefore, the NCMP should be considered as a means to successfully update Coast Survey nautical charts under the following conditions: 1) coastal areas from up to 10 m; and 2) where most seafloor types are rocky/sandy/coral areas (excluding vegetated and muddy areas). In general the majorities of the differences are close to or lower (i.e., better) than the stated accuracy of the systems.

It is important to note that the consistency between the datasets is affected by the seafloor type and the survey period. For example, sandy seafloor near tidal inlets and along-shore bars varies with time. Also the bottom detection success (bathymetry) of NCMP datasets over muddy seafloor is very low.

The NCMP evaluation procedure used in this study was created to fit within the current processing and acceptance testing workflow at OCS HSD. The analysis operations in this procedure are relatively straight forward. It would be very useful, if the operator has GIS background or had a training course using GIS software. With that said, there are a few items of which HSD and those utilizing the procedures should be aware.

Access to NCMP datasets

Although the coverage of NCMP ALB data may be shown on the JALBTCX website, it may not always be available on NOAA's Digital Coast website. There were cases where the metadata files in Digital Coast showed the availability of topographic and bathymetric dataset; however, after downloading the files and plotting the data, it was obvious that only the topographic data existed. The files were downloaded using various options (e.g., LAS, ASCII, selecting "All" for data classes or using advanced options to get the bathymetry, etc.), but still did not have any bathymetry in some cases. An example study site is the Port Everglades dataset. Digital Coast metadata stated topographic and bathymetric data were available, but only topographic data existed. An alternative that was used in the study was through communication with the NGS RSD person at JALBTCX to acquire the NCMP data.

Metadata

In some cases, such as in the Fort Lauderdale study site, the metadata files were not available with the NCMP dataset. The reason may be that the survey was conducted in January 2012 and was not yet available on Digital Coast.

Other Datasets Investigated

Other areas were investigated to find areas where NCMP lidar and OCS MBES overlapped: New Jersey, New York, North Carolina, Rhode Island, Texas, Washington, Alabama, and Florida (St. Andrews and Key West). These are still potential areas to look at in the future, but currently there is no recent NCMP lidar and OCS MBES for comparison purposes.

8.0 Recommendations

1. The procedure used in this study and detailed in Appendix I fits within the current workflow and can be used at HSD's processing branches. If accepted by OCS, it is recommended that:
 - Discussions begin to assess whether OCS would like any more research done before implementing this process (e.g., look into more sites, look into subtracting biases, ask RSD and OMAO if JALBTCX Team lead can help do more research and work with the NCMP to simplify the transformations in Figure 6, etc.).
 - Discussions begin with respect to training key personnel at processing branches.
 - Discussions begin with respect to using the NCMP lidar data for reconnaissance surveys:
 - for areas with great tidal accretion and turbidity, such as in Pensacola, which will need to be re-surveyed more often than every 5 years (or every time a new NCMP dataset is available); and
 - for the Operations Branch to get an assessment of the area and determine which areas require additional surveying with MBES after the lidar data are processed to resolve possible hazards to navigation.
2. Recommend that if Coast Survey expresses interest, this procedure be expanded for examining other ALB datasets outside (e.g., CZMIL) and inside (e.g., EAARL and RIEGL) NOAA.
 - Use the NCMP and Acoustic Data Processing Manual (in Appendix I) as a starting point.
 - Conduct a patch test to use as a reference at very high accuracy to estimate the accuracy of the systems.
 - Conduct a comparison analysis between new and older lidar systems.
 - Error uncertainty analysis: Conduct any future comparative analyses within the lens of error estimates for each system. The differences might have high precision; however, they will have little statistical meaning unless their individual and collaborative uncertainties are studied as well.
 - Investigate data from USACE and USGS that is withheld for scientific reasons.
 - Add any of these to a list for future JHC NOAA students to choose from if they are interested in the topic for research.
3. Recommend Coast Survey consider this process for possible application to hydrodynamic models.

Other recommendations related to this project

4. Recommend using RSD CUSP shoreline when updates to the national shoreline are not available, instead of using Google Earth Satellite imagery for MLLW or MHW shoreline. RSD

has a process to extract the MHW, and this process could also be used to extract the MLLW. Recommend discussing the possibility of having RSD extract the MLLW so the processing branches can use it. Also, recommend using worldview satellite imagery from NGA to aid with determining new structures or removing old structures that no longer exist on the chart. Also, recommend following up with RSD to see if the use of the terrestrial lidar scanner for determining/validating structural features is possible.

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APPENDIX A. LIDAR DATA FORMATS

There are different lidar formats: proprietary binary, LAS and ASCII. Each ALB manufacturer uses a binary format with a structure that is not open to the public, but is only for their internal uses. LAS format files are also binary files for lidar 3-dimensional point data, but they have a specific structure. The American Society for Photogrammetry and Remote Sensing (ASPRS) supports the use of LAS for lidar data because it provides an open binary format (the structure of the format is published) for vendors and customers to exchange lidar data and ideally be able to integrate the lidar data with other datasets (e.g., GPS, IMU, laser point range data). The LAS file has several different classifications (ASPRS, 2008):

ASPRS Standard LIDAR Point Classes

<i>Classification Value (bits 0:4)</i>	<i>Meaning</i>
0	Created, never classified
1	Unclassified ¹
2	Ground
3	Low Vegetation
4	Medium Vegetation
5	High Vegetation
6	Building
7	Low Point (noise)
8	Model Key-point (mass point)
9	Water
10	<i>Reserved for ASPRS Definition</i>
11	<i>Reserved for ASPRS Definition</i>
12	Overlap Points ²
13-31	<i>Reserved for ASPRS Definition</i>

Typically, the LAS files that are available in the USACE and NOAA archives, such as Digital Coast, contain point clouds that have been edited (no rejected laser measurements in the dataset). With respect to JALBTCX data, all the points in the final LAS file are all the accepted points, versus having both the rejected and accepted data included. In order to load any of the lidar data to be analyzed in ArcMap, these LAS files must be converted to another format, ASCII. Luckily this project does not require the entire dataset, as we are only interested in the water portion (classification = 9) versus the topography portion which is not needed.

There is a new LAS profile that has not yet been approved by the ASPRS which will be of interest to those using bathymetric lidar in the future (ASPRS, 2012):

Classification Value	Meaning
40	Bathymetric point (e.g., seafloor or riverbed; also known as submerged topography)
41	Water surface (e.g., sea surface from bathymetric or topographic-bathymetric lidar; distinct from Point Class 9, which is used in topographic-only lidar)
42	Derived water surface (synthetic water surface location used in computing refraction at water surface)

Classification Value	Meaning
43	Submerged object (e.g., wreck, rock, submerged piling)
44	Hydrographic object (feature of interest to a hydrographer for nautical charting purposes, e.g., aid to navigation)
45	No-bottom-found-at (bathymetric lidar point for which no detectable bottom return was received)

References:

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APPENDIX B. COORDINATE SYSTEMS

As with any geospatial analysis involving multiple datasets, use of a consistent coordinate system was a key factor in this project. We elected to reference our data horizontally to NAD 83(CORS96) and to use a Universal Transverse Mercator (UTM) projection. The rationale for these choices is described below.

While HSD uses WGS84, there were three factors that motivated our selection of NAD 83 as the datum for this study:

- 1) NAD 83 has been officially adopted as the legal horizontal datum for the United States by the federal government (NGS, 2012).
- 2) Both the NCMP lidar and OCS multibeam datasets were already referenced horizontally to NAD 83(CORS96). Therefore, keeping these data referenced to NAD 83(CORS96) reduced the number of datum transformations that needed to be performed and, hence, uncertainty (or “error”) introduced through datum transformations.
- 3) Use of WGS84 can be problematic, as many data providers do not specify which realization of WGS84 they use, which can result in position errors of over a meter.

The use of projected, as opposed to geographic, coordinates (i.e., UTM Eastings and Northings, rather than latitudes, longitudes) simplified computation of offsets between the lidar datasets and reference datasets used in the study. Units of meters were used consistently in this project.

VDatum was used for performing required vertical datum transformations, and ArcMap was used to perform horizontal datum transformations (as needed) and to project the data in UTM, using the applicable zone for each site.

References:

National Geodetic Survey (NGS), 2012. *National Geodetic Survey: Frequently Asked Questions*: <http://www.ngs.noaa.gov/faq.shtml> (last date accessed: 18 Dec 2012).

APPENDIX C. DATUMS

Vertical Datums

- Tidal – based on precise definitions of NOAA and are defined relative to 19-year National Tidal Datum Epoch (NTDE) s. Determined through observation at tide stations (CO-OPS, 2001)
- Orthometric – based on measurements
- Ellipsoidal – based on a mathematical model

Ellipsoidal	Orthometric	Tidal
NAD83	NAVD88	MHW
WGS84	NAVD29	LMSL
ITRFXX	EGM	MLW
		MLLW

NAD83 is a mathematical surface defined by an ellipsoid with the origin at the Earth’s mass center and NAVD88 is determined by geodetic leveling. These do not include subsidence or any other systematic errors.

Water levels

Typically, lidar is collected referenced to the ellipsoid using positioning control linked to GPS measurements on the aircraft and at a ground station. Often, the lidar data are then presented (served) relative to an orthometric datum such as NAVD88 or to a tidal datum such as MHW. Therefore, in order to perform statistical analysis, it is necessary to translate the lidar data relative to MLLW (the NOAA chart datum) so the vertical datums of the lidar and the multibeam are the same. For this research, the lidar data are translated to MLLW using the NOAA VDatum tool (<http://vdatum.noaa.gov/>)

One can determine the data’s vertical and horizontal datum by checking the metadata. If there is a water level station in the area of the two surveys, it is also helpful to look at the differences in datums for that specific location (e.g. see Port Everglades example below). (see http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Datums) .

```

Station: 8722951                                T.M.:      75 W
Name:    PORT EVERGLADES, LAKE MABEL, FL        Units:     Meters
Status:  Accepted (Aug 31 2011)

```

```

MHHW      1.417  Mean Higher-High Water
MHW       1.382  Mean High Water
NAVD88      1.245  North American Vertical Datum of 1988
MSL       0.998  Mean Sea Level
MTL       0.996  Mean Tide Level
DTL       0.989  Mean Diurnal Tide Level
MLW       0.610  Mean Low Water
MLLW      0.561  Mean Lower-Low Water
STND      0.000  Station Datum

GT        0.856  Great Diurnal Range
MN        0.771  Mean Range of Tide
DHQ       0.036  Mean Diurnal High Water Inequality
DLQ       0.049  Mean Diurnal Low Water Inequality

```

<u>HWI</u>	0.67	Greenwich High Water Interval (in Hours)
<u>LWI</u>	6.82	Greenwich Low Water Interval (in Hours)
Maximum	1.908	Highest Observed Water Level
Max Date	19731025	Highest Observed Water Level Date
Max Time	07:36	Highest Observed Water Level Time
Minimum	0.174	Lowest Observed Water Level
Min Date	19710426	Lowest Observed Water Level Date
Min Time	14:42	Lowest Observed Water Level Time

Tidal Datum Analysis Period: 10/01/1970 - 09/30/1973

To refer Water Level Heights to

NAVD88 (North American Vertical Datum of 1988), apply the values located at:

[National Geodetic Survey](#)

References:

Center for Operational Oceanographic Products and Services (CO-OPS), 2001. Tidal datums and Their Applications, Special Publication No. CO-OPS 1, NOAA/NOS/CO-OPS, February, 2001, 111pp.

APPENDIX D. VDATUM

VDatum is designed to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datums, allowing users to convert their data from different horizontal/vertical references into a common system and enabling the fusion of diverse geospatial data in desired reference levels (vdatum.noaa.gov)

Initially we assume that the datum listed in the metadata that the user provided has zero uncertainty. And for those that use an ellipsoidal coordinate frame such as ITRFxx or WGS84 we assume that this was obtained using GPS and no errors were introduced. Although a final error assessment will have to take these errors into account as well as the other VDatum transformation errors. A future report, should OCS move forward with accepting this process, should have a discussion on the mean differences between the two systems in context with the error budgets. NAD83 referenced measurements which are used for the most part in this project are accurate to about 2 cm nationally and NAVD88 to about 5 cm. For this discussion, see http://vdatum.noaa.gov/docs/est_uncertainties.html.

It is important to note that information listed in the metadata may be listed incorrectly and that knowledge regarding the datums as to which source the datasets are referenced may be incorrect. This is unfortunately not an uncommon occurrence.

Below is an abbreviated list as an example for a location near the Fort Lauderdale study site:

NAD83 (NSRS2007/CORS96/HARN) -> NAVD88 (GEOID 2009): 25.7851 m
NAD83 (NSRS2007/CORS96/HARN) -> MLLW: 26.4889 m
NAD83 (NSRS2007/CORS96/HARN) -> MHW: 26.4889 m
WGS 84(G1150)/ITRF2000 -> NAD83 (NSRS2007/CORS96/HARN): 1.6091 m
NAVD88 -> LMSL: 0.2675 m
NAVD88 -> MLLW: 0.7039 m
NAVD88 -> MHW: -0.1130 m

Once the conversions are done but there appears to be a “residual” offset that looks like one of the numbers in the table above, for example 1.58 m. This value is close to the 1.6091 m WGS84(G1150)-> NAD83 datum offset listed above, so this might be a clue that perhaps one of the input datasets that was thought to be referenced to NAD83 was actually WGS84(G1150), or vice versa. This doesn't mean that this is the answer but it should help those having trouble begin investigating.

APPENDIX E. SPECIFICATIONS OF ABL SYSTEMS

	EAARL	Hawk EYE II	Shoals 1000	Shoals 3000	LADS MKII
wavelengths	532	532, 1064	532, 1064	532, 1064	532, 1064
max depth	26 m	70 m*	50 m Kd>3.0	50 m	70 m*
min depth	30 cm	0.3 m	0.2 m	0.2 m	
altitude	300 m	200 - 400 m	h: 200 - 400 m t: 300 - 700 m	h: 300 - 400 m t: 300 - 1000 m	400 - 700 m
speed	100 knots	120 knots	125 - 180 knots	125 - 180 knots	140 - 210 knots
spot spacing	2x2	1.4x1.4 m - 3x3 m	2x2, 3x3, 4x4, 5x5	2x2, 3x3, 4x4, 5x5	2x2, 3x3, 4x4, 5x5, 6x6
swath width	240 m at 300 m	100 m at 300 (~1/3 alt)	58% altitude	75% of alt	250 m (5x5)
Vertical accuracy	3 - 5 cm	IHO Order 1 S.O. (>10)	IHO Order 1 25 cm	IHO Order 1 25 cm	IHO Order 1 cm 25
Horizontal accuracy	< 1 m	IHO Order 1 2.5 m	IHO Order 1 2.5 m	IHO Order 1 2.5 m	IHO Order 1 m 2.5
pulse rep. freq	up to 10 kHz	h: 1 kHz t: 8 kHz	h: 1 kHz t: 10 kHz	h: 3 kHz t: 20 kHz	990 Hz
scan frequency	20 Hz ² 25 Hz ²	0.3 - 7 Hz	0.3 - 7 Hz	16 Hz	18 Hz
pulse length	1.2 ns	7 ns	7 ns	6 ns	532: 5 ns 1064: 7 ns
footprint	20 cm	2.4 m	2.5 m	2 m	1.5 - 4 m
° of incidence		20	20	20	0
scanning °	45	0 - 40	0 - 40	0 - 40	27
pulse energy	0.05 mJ	3 - 5 mJ	532: 5 mJ 1064: 15 mJ	7.5 mJ	7.2 mJ total 5 mJ adjusted
scan pattern		parallel lines or arcs	circular arc	circular arc	rectangular
beam divergence	2 - 15 mrad	5-7 mrad	5.2 mrad	3 - 12 mrad	

Note: EAARL and RIEGL systems are narrow beam systems

	SHOALS 1000	CZMIL
Scanning angle/Swath angle	20° nadir angle	20° (fixed off-nadir)
Vertical accuracy	(same as horizontal?)	± 15 cm, 2 σ
Horizontal accuracy	IHO Order 1 (2.5m, 1 σ)	(3.5+0.05 depth) m, 2 σ
Pulse repetition Frequency	1000/3000	10000
Scanning Frequency	16 Hz	26 Hz
Pulse Length	7ns	2ns
Footprint on the water surface (at an altitude of 300m)	2m (at 400m)	2.5m (at 400m)
Angle of incidence	0 (± 5° roll)	0 (0° roll)
Pulse energy	3mJ	3mJ
Scan pattern	Scanning	Circular
Beam Divergence	5.2 mrad	7mrad ± 0.5mrad

See also [Specification Matrix](#) from the January 2009 JALBTCX Workshop on Common Specifications for Airborne Coastal Mapping and Charting Data.

APPENDIX F. ALB SYSTEMS USED IN USACE AND NOAA SURVEYS

Since HSD has used LADS MK II for acquiring ALB, it should be noted that USACE's NCMP has acquired ALB data with both the LADS MK II and HawkEye 2 systems according to the same USACE specifications as the surveys used in this study. One HawkEye 2 dataset (Pensacola) was investigated for this study and if HSD accepts the use of NCMP SHOALS data then it may be worth contacting USACE regarding accessing the LADS MK II that may not be readily available on Digital Coast or at RSD. The CZMIL system is currently being tested operationally and if USACE can successfully operate this system, HSD should seriously consider investigating the use of data from this system as a potential next step.

APPENDIX G. STAGES OF THE NCMP LIDAR PROJECT

This research project was set up into three stages over the course of a one year detail assignment at NGS (April 1, 2012 – March 31, 2013). Stage 1, from April 1 to June 31, is the preparation phase; stage 2, from July 1 to September 31, is preliminary processing phase and; and stage 3, from October 1 to December 31, is the final processing phase. Below is a timetable of activities during the course of these stages.

Task	Details
1. ALB theory	Learn and understand ALB theory and multiple systems
2. Identify sites	Identify sites that NCMP ALB can be junctioned with MBES data and is of importance to NOAA.
3. Acquire datasets	Obtain all ALB and multibeam data for processing through Digital Coast (NOAA/CSC) and the USACE/NCMP
4. Learn ArcMap10	Learn to process datasets using ArcMap10 and other COTS software
5. Processing datasets	<ol style="list-style-type: none"> 1. Set ArcGIS environment <ul style="list-style-type: none"> ○ Make sure you have Spatial Analyst and 3D-analyst. ○ Set coordinate system to the local UTM zone of the study site. 2. Import the background chart and the reference dataset. <ul style="list-style-type: none"> ○ Chart in order to identify the gaps. ○ MBES for junctioning with the ALB datasets. 3. Convert the LAS files into TXT (if needed) 4. Format the LAS files for ArcMap. 5. Calculate the statistical distribution of the points. 6. Identify the gaps. 7. Generate a surface from the ALB dataset and the MBES dataset. 8. Subset to the areas that overlaps between the two datasets. 9. Calculate the overlap areas between the two datasets. 10. Comparison between the two datasets: <ul style="list-style-type: none"> ○ Mean difference. ○ Standard deviation. ○ Histogram. ○ Trends. ○ Visual.
6. Briefings	Brief and update all the supervisors and project participants (Michael Aslaksen (MA), Mary Erickson (ME), Jeffery Ferguson (JF), Curt Loy (CL) Juliana Blackwell (JB) and Gerd Glang (GG)).
7. Documentation	Document procedures, meeting minutes, technical report and technical papers.
8. Mid-term report	Summary report for stage 2
9. Final report	Summary report for stage 3

Gantt Chart

	4/12	5/12	6/12	7/12	8/12	9/12	10/12	11/12	12/12
1. ALB theory	█	█							
2. Identify sites		█	█						
3. Acquire datasets			█	█					
4. Learn ArcMap10	█	█	█						
5. Processing datasets			█	█	█	█	█	█	
6. Briefings		JF/ME	CL	MA/JB	JF/GG	MA/CL	JF/JB	GG/ME	JB/GG
7. Documentation	█	█	█	█	█	█	█	█	█
8. Mid-term report						█			
9. Final report									█

APPENDIX H. ABBREVIATIONS AND ACROYNMS

ALB: airborne bathymetric lidar
APRS: American Society for Photogrammetry and Remote Sensing
DEM: digital elevation model
FGDC: Federal Geographic Data Committee
HSD: Hydrographic Services Division
HSSD: Hydrographic Services Specifications and Deliverables
IHO: International Hydrographic Office
IMU: Inertial measurement unit
JALBTCX: Joint Airborne Lidar Bathymetry Technical Center of Expertise
MBES: multibeam echosounder
MHW: mean high water
MLLW: mean low low water
NALL: navigable area limit line
NCMP: National Coastal Mapping Program
NGDC: National Geophysical Data Center
NGS: National Geodetic Survey
NOAA: National Oceanic and Atmospheric Administration
NOS: National Ocean Service
OCS: Office of Coast Survey
RMSD: root mean square difference
RMSE: root mean square error
RSD: Remote Sensing Division
TBL: topographic-bathymetric lidar
USACE: U.S. Army Corps of Engineers

APPENDIX I. NCMP AND ACOUSTIC DATA PROCESSING MANUAL

Due to the length of this document, it was made into a separate document.