Multiple Applications of Bathymetric LIDAR

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Abstract

This paper will examine the multiple applications of Airborne Lidar Bathymetry (ALB) within one agency, NOAA, and the advantages of deriving multidisciplinary datasets from one survey source. Advancements in ALB technology have allowed surveyors to examine the littoral zone in greater detail by complementing traditional bathymetric data (xyz) with topographic heights, digital imagery and bottom reflectance data. NOAA's focus for lidar applications has mainly centered on nautical charting, but the high demand for ancillary near shore data, along with the high cost of data acquisition in shallow water, has driven significant technological advancements. Some of the factors in compiling a quality survey dataset that can be used across multiple disciplines include project planning, exchange formats, datum and dissemination of information. The concept of "surveying once for multiple uses" across disciplines such as nautical charting, shoreline mapping, seabed classification, habitat mapping, fisheries and inundation modeling is a challenging endeavor but is ultimately the most efficient and cost effective way to survey.

Introduction

ALB systems were first developed in the 1960s to collect ocean depth data to serve nautical charting applications (Guenther, G.C., 1985). Today, bathymetric data is still typically the primary deliverable of an ALB survey. This being said, more and more focus is being placed on enhancing bathymetric datasets with complimentary data that can be collected during an ALB survey. By collecting and extracting additional datasets the number of potential applications and end users can be increased, thereby increasing the effectiveness of each flight. Firstly, by adding sensors to the survey platform, such as a topographic lidar, multispectral/hyperspectral sensor and digital camera additional datasets can be acquired and processed separate from the bathymetry. The second method for creating complimentary datasets is by additional processing of the raw lidar waveforms to extract information other than bathymetry. By doing this, information such as seabed relative reflectance can be gathered.

The following describes the datasets collected by the Laser Airborne Depth Sounder (LADS) Mk II system and how the data is being used within NOAA. Lidar supports NOAA's commitment to Integrated Ocean and Coastal Mapping where one data collection simultaneously supports multiple mission requirements.

The LADS Mk II System

The LADS Mk II System commenced commercial contract operations in 1998. The system has undergone several hardware and software upgrades over the years to enable enhanced acquisition and processing of data. The system in its current state includes a 1kHz Nd: YAG laser mounted on a stabilized platform inside a DeHavilland Dash-8 200 series aircraft. The laser produces IR energy at a wavelength of 1064nm which is frequency doubled via an optical coupler to produce green-blue laser pulses at a wavelength of 532nm. A single laser pulse is emitted with 5mJ energy and a pulse width of 5ns. By the time the laser pulse reaches the sea surface its illumination footprint is approximately 2.5m in diameter. The emitted energy and illumination footprint are regulated by eye safety standards. Returned energy from the air, water surface, water column and seafloor is captured back at the airborne platform by a green receiver. The returned energy is digitized into a waveform.

Figure 1a: Tenix LADS deHavilland Dash 8 200 Series bathymetric lidar survey platform. 1b: LADS MkII lidar system

Also mounted on the aircraft in 2007 is a Redlake MegaPlus II ES 2020 digital camera. Images are taken at one-second intervals with 1600x1200 pixels and a 2-megapixel interline-transfer camera head and controller. The collected images are compiled into a georeferenced mosaic at completion of a survey.

Figure 2: An example of imagery captured during survey operations around Craig, AK. Inset: The Redlake MegaPlus II ES 2020 digital camera

Bathymetric Data for Nautical Charting

Tenix LADS has been contracted by NOAA since 2001 to provide bathymetry acquisition services with the stated purpose of providing NOAA with modern, accurate hydrographic survey data with which to update the nautical charts.

Depths can be collected to a maximum of 70m in clear water while elevations can be collected from the water/land interface up to 50m. Survey altitudes are available from 1,200 to 2,200ft (366 to 671m) at 200ft increments at ground speeds of between 140 and 210kts. Swath widths, dependant on scanning pattern but independent of the aircraft operating height, range between 50 and 288m. There are several scanning patterns that can be used depending on the application; 2x2, 2.5x2.5 and 3x3m patterns are typically used for investigations or where maximum data density is required. For these patterns swath width is relatively narrow. The 4x4m pattern provides a compromise between data density and swath width. The 5x5m and 6x6m scanning patterns allow for greatest survey efficiency with wide swath widths and high survey speeds. These patterns are typically used for reconnaissance surveys or for where general bathymetry is required. Another method for increasing data density other than by using the smaller scanning patterns is to illuminate a seabed more than once. This 200% coverage is advantageous as data can be collected during different environmental conditions. For example, flying the same survey line during different tidal stages and on different days will often result in increased coverage resulting in fewer gaps and higher density data, especially inshore. This technique is particularly useful in areas of complex coastline, kelp, breaking waves and surf.

Sounding Density (m)	**Swath Width (m)**	**Line Spacing 100% Coverage (m)**	**Line Spacing 200% Coverage (m)**	**Survey Speed m/sec (knts)**
6x6	288	250	125	108 (210)
5x5	240	200	100	90 (175)
4x4	192	170	85	72 (140)
4ax4a	150	120	60	90 (175)
3x3	100	80	40	77 (150)
2.5x2.5	80	70	35	72 (140)
2x2	50	40	20	72 (140)

Table 1 – Scanning patterns

After each flight, the raw collected data is processed and depths can be determined using algorithms that analyze each waveform. Processed waveforms are further validated to remove fliers and other erroneous depths from the dataset.

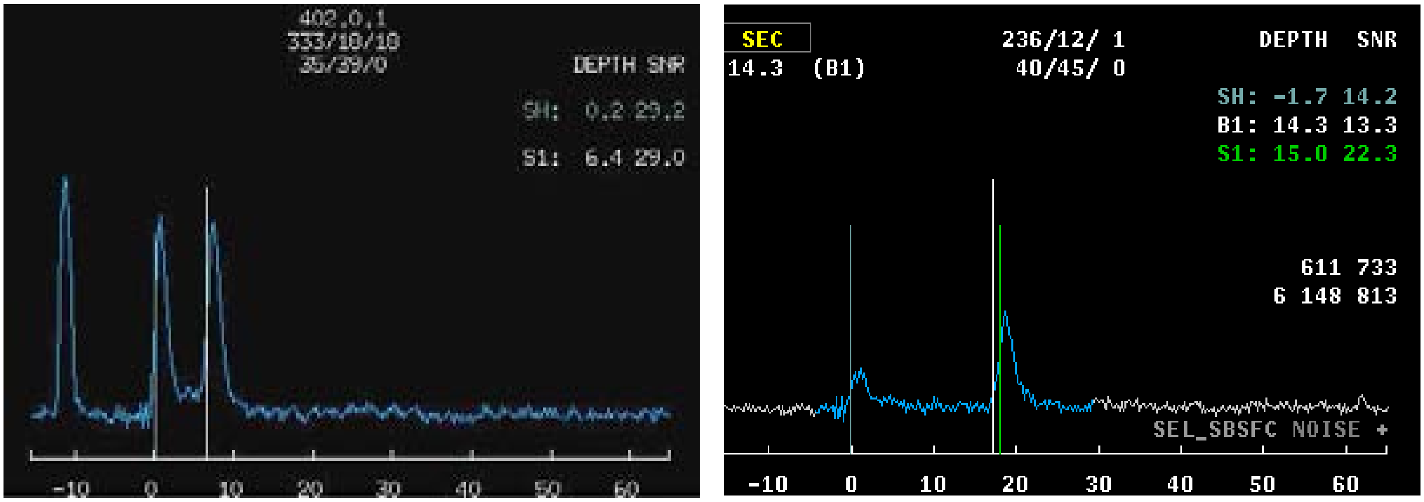

Figure 3a: Example of a composite LADS waveform displaying surface return from the infrared receiver and the water surface, water column backscatter, return from the seafloor and system and sun noise from the Green Receiver. 3b: Example of a waveform that has detected the presence of a bottom feature as displayed by the "bump" on the leading edge of the seafloor return. This object was confirmed on multiple survey lines.

LADS hydrographic surveys for NOAA meet International Hydrographic (IHO) Order 1 depth and position accuracy standards as nautical charting is the primary application. To meet these nautical charting standards the survey area is typically illuminated using the 4x4 scanning pattern at 200% coverage. Special care is undertaken to ensure that maximum coverage is obtained and shoalest depths are represented. To achieve these goals all areas are illuminated at least twice, with inshore lines flown during the extreme of both high and low tides. As lidar typically has difficulty extracting data in the surf zone (0 to 0.5m depth relative to the water level during collection), flying at high and low tide in a region that has a tide range of 1m or more, will allow for full coverage within these areas. For areas such as Alaska, where Tenix conducts the majority of its work for NOAA, flying during extremely low tide also exposes many rocks in kelp that might not otherwise be captured, as laser pulses will not penetrate most thick kelp beds.

Upon completion of data collection, the depth data is "cleaned" using in-house software to remove outliers and erroneous data points. NOAA requires that data is delivered using the Bathymetric Attributed Grid (BAG) format as developed by the Open Navigation Surface Working Group. The BAG is more or less a set of co-located grids that store bathymetry and associated uncertainty along with metadata. One feature of the BAG is that changes to the grid can be made and tracked to ensure the surface meets safety of navigation needs (Brennan R.T. et al, 2005). Typically for a NOAA lidar survey the BAG will be delivered at a resolution of 3m. The BAG stores a weighted mean, mean, deep and shoal layer. Also, the shoal point of significant features are selected and stored in the BAG. An S-57 file is also delivered that contains rocks created from the designated soundings in the BAG, coastline, and cultural features from which NOAA's existing ENC's can be updated.

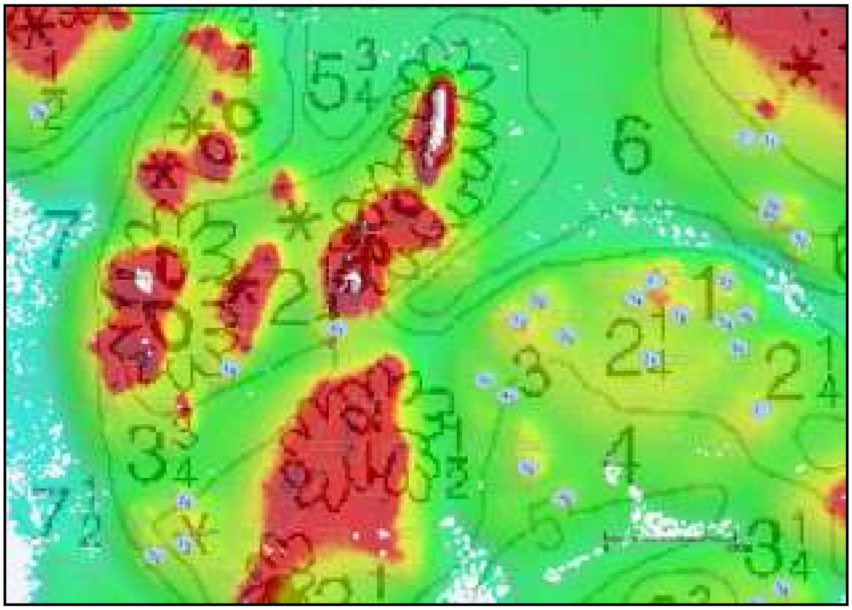

Figure 4: Deliverables for a NOAA nautical charting survey include a BAG surface and an S-57 Feature file. This example comes from West of Prince of Wales Island, AK, delivered in 2007. On the above image the BAG and S-57 feature file are overlayed on the NOAA chart.

Lidar surveys have demonstrated several advantages over traditional hydrographic surveying techniques, particularly in complex nearshore areas. The lidar data is provided to the NOAA field units conducting deep water junctioning to increase efficiency with respect to acquiring bathymetry and feature delineation. This reduces overall survey time in the generally hazardous nearshore areas.

Habitat Mapping Using Relative Reflectance Data

The LADS system determines the water depth from the time between the surface and bottom reflections. The reflectivity algorithm determines the relative reflectivity of the seabed using a simple energy summation for each sounding. The transmitted energy is recorded during the survey and the received energy can be found by integrating the bottom pulse in the green waveform. The energy losses along the path of the beam are estimated using models of the physical phenomena, such as light scattering through the water column and diffuse reflection from the sea bottom. Energy is also lost as a result of the receiver field of view and filters that may be used during acquisition. When all losses are properly accounted for and transmitted and received energies are known, the amount of energy absorbed by the sea bottom is calculated and hence the reflectivity can be determined. (Collins, B., 2007)

$$\textit{energy absorbed} = \textit{energy transmitted} - \textit{energy received} - \textit{path losses}$$

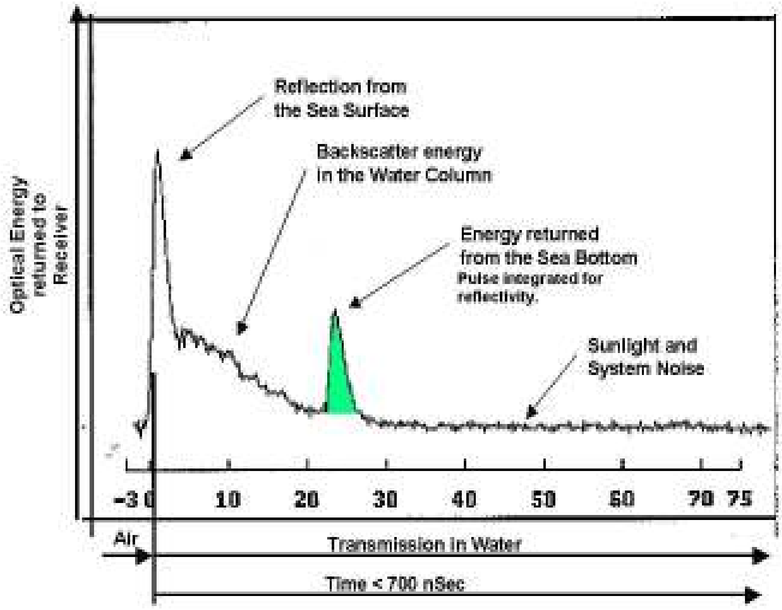

Figure 5: To extract reflectance from the LADS waveform, integration of the area of the seafloor pulse is necessary as well as the determination of transmitted energy and the modelling of energy losses between the transmission and reception of the lidar pulse (Image from Collins, 2007).

Upon calculation of relative reflectance values, outliers are removed from the dataset. Lidar pulses returned from land or shallow water (<2.0m depth) are also removed from the reflectance dataset. Data is exported in XYZ (where Z is reflectance) format to an ascii text file. The reflectivity value that is calculated by the LADS algorithms is considered relative. By treating the data as relative, the model is less sensitive to absolute values of water clarity, sea surface conditions and sensor operating parameters. Relative reflectivity data is a measure of the reflectance of the seabed in a single wavelength (green/blue 532nm). The numerical values for the relative reflectivity are scaled logarithmically to an 8-bit integer range 0 – 255 ensuring maximum contrast between areas of differing reflectance values. The absolute reflectivity has not been calculated. If the same area was surveyed under different conditions with a different sensor the variations in reflectivity would match but the absolute values would not.

At this stage, the reflectance data can be used to visually identify areas of high and low reflectance by taking the XYZ data and creating a gridded or TIN surface. Although this is a simple method for approaching the data, information can be gained by observing general trends in the dataset. Simple inferences can be made concerning an area of similar reflectance such as whether it is a hard or soft bottom. This is often confirmed by ground truthing.

In 2006 Tenix LADS, Inc. acquired data for a joint ongoing project with the National Centers for Coastal Ocean Science (NCCOS), National Weather Service, National Geophysical Data Center, and Office of Coast Survey on a shallow-water coral ecosystems digital mapping project in southwest Puerto Rico (Battista, T., 2008). Tenix collected 265 square nautical miles from -20 meters (topographic) down to 50 meters (depth). The spatial resolution of the bathymetric surface was 4 meters and the spatial resolution of the reflectivity surface was 5 meters. (*Seafloor Charactorization of the U.S. Caribbean-2006 Lidar Bathymetry and Reflectivity website)*.

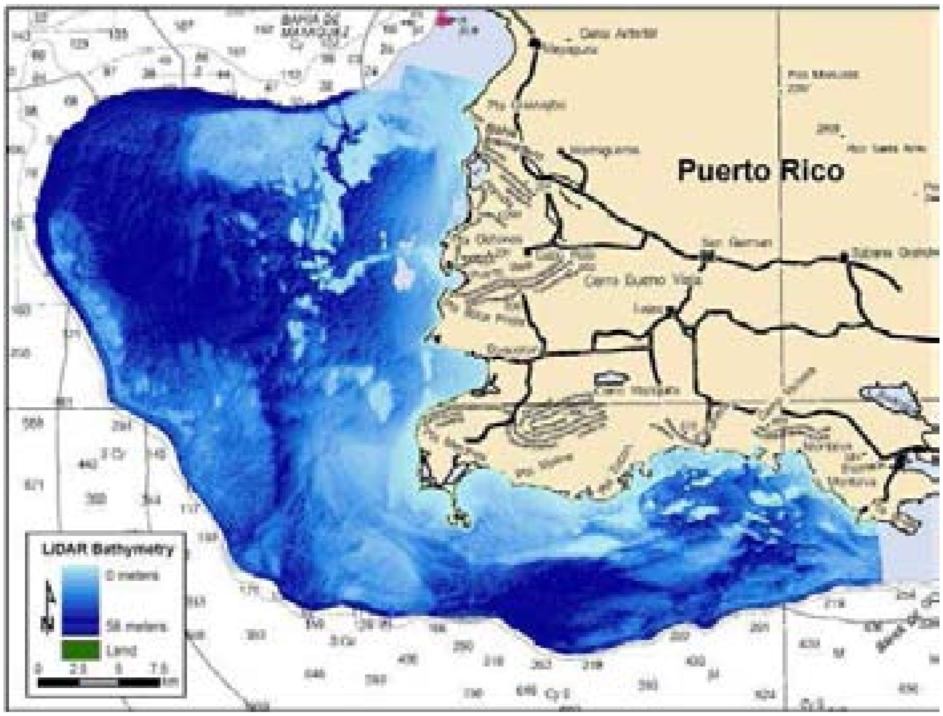

Figure 6: A bathymetric surface of the West coast of Puerto Rico from lidar data collected in 2006. Darker blue represents deeper water. Image created by Center for Coastal Monitoring and Assesment, NOS, NOAA.

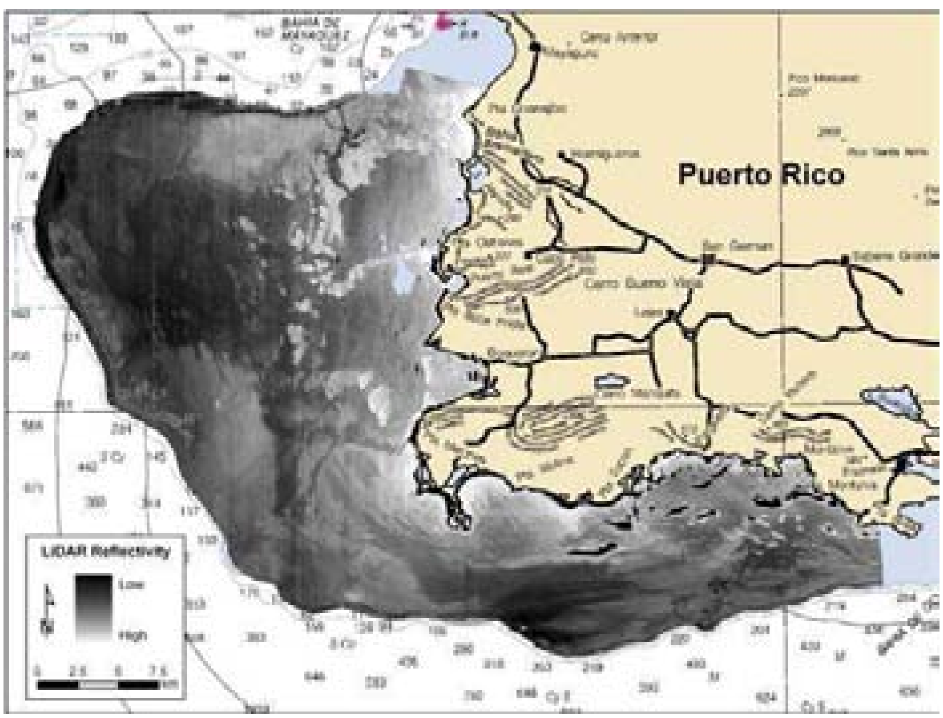

Figure 7: A relative reflectivity surface of the West coast of Puerto Rico extracted from lidar data collected in 2006. Darker grey represents lower relative reflectance. Image created by Center for Coastal Monitoring and Assessment, NOS, NOAA.

NOAA is responsible for conserving and protecting coral reef ecosystems. A fundamental component of coral reef management is benthic habitat mapping and characterization. Traditional benthic habitat mapping techniques include optical remote sensing technologies such as aerial photography and satellite imagery. These traditional methods have been effective but do not provide bathymetric data (*Seafloor Charactorization of the U.S. Caribbean website)*. The bathymetric data assists in seafloor morphology modeling which provides additional information for habitat mapping. In contrast, lidar has the capability to collect high resolution bathymetric data over large areas. This high resolution data exposes the various surfaces and terrain necessary for habitat mapping.

The 2006 Puerto Rico survey was the first time lidar data collected at the IHO Order 1 accuracy standards from the LADS Mk II Airborne System was used in conjunction with NOAA coastal management resources for additional purposes than nautical charting. In addition to using the XYZ datasets for updating the nautical chart, the depth and reflectance data were delivered to aid in benthic habitat mapping. The habitat mapping goal of the lidar system was to discern seafloor habitat composition (e.g. feature hardness and roughness) and geomophological structure (Battista, T., 2008).

By identifying the seafloor composition and structure, scientist can link physical habitats with biological information. In general, a positive relationship between geomorphologic complexity and marine fish abundance is displayed.

Lidar depths were used to quantify the surface morphology of the reefs such as standard deviation of water depth, rugosity, slope, slope of the slope (a measure of curvature), plan curvature and fractal dimension. Field data which included visual fish surveys and *in-situ* benthic habitat surveys were performed to correlate habitat with species. The study demonstrated that *in-situ* and Lidar derived metrics (e.g. reflectance and bathymetry) can predict a wide range of fish and coral species. In addition, the Lidar data offers even more benefit than *in-situ* measurements because it provides more accurate detail across a continuous representation of the surface in a digital format (Pittman, 2008).

A second approach has also been taken in some non NOAA projects using tools developed by Quester Tangent. The dataset is further analyzed by utilizing the bathymetry and reflectance information in combination to characterize the interaction between the illuminated area of the seafloor and its vertical relief. Using methods similar to those used with sonar imagery classification, optical diversity classes can be assigned within the survey area.

The classification process starts once a reflectance gridded image has been created from the LADS relative reflectance XYZ data. The image is then broken into squares that are 9x9 pixels where one pixel is approximately the resolution of the laser footprint at the sea surface. Optical diversity classes are then assigned after an analysis based on depth, reflectance (first order characteristics), and texture which is determined by comparing a pixel to its neighbors (second order characteristic). From the optical diversity classes generated with Quester Tangent software ground truthing will lead to seabed classification.

Once the optical diversity classes have been generated using the Quester Tangent software, several of the optical diversity classes are typically grouped into fewer seabed classes that are determined based on bottom samples collected from throughout the survey area (Collins, B., 2007).

Shoreline Mapping

In the United States the national shoreline is critical to territorial limits such as the Exclusive Economic Zone and to coastal resource management. The U.S. has approximately 95,000 miles of coastline (as would be compiled from 1:80,000 scale charts). In 1998 U.S. Congress granted the National Geodetic Survey (NGS) the authority to survey and to set the standards for all information acquired for nautical charting purposes (*Remote Sensing Division Coastal Mapping Program website*).

The term "shoreline" has several different definitions according to various offices. Shoreline on a U.S. nautical chart, also called Mean High Water (MHW) represents the line of contact between the land and a selected water elevation (*Coastal Cartographic Object Attribute Source Table (C-Coast) Glossary website*). However, other federal, state and local authorities have different definitions of shoreline and base its delineation on a different vertical datum other than MHW, which may cause inconsistencies between maps and other products.
Currently NGS delineates the shoreline through stereo photogrammetry using tide-coordinated aerial photography (*Remote Sensing Division Coastal Mapping Program website*). While this is an adequate method it is not ideal because correlating the land-water interface from the imagery to an exact MHW is inexact. If an end user needs shoreline relative to a datum other than MHW, the aerial photography would need to be captured during the different tide state. In addition, the shoreline delineation process is subject to individual interpretation by the operator. Finally, aerial photography is a passive system requiring daylight for acquisition and it is easily affected by environmental factors such as clouds and haze (Morgan, 2007).

Based on these limitations other methods such as lidar are being pursued. There are multiple methods to extract shoreline from topographic or bathymetric lidar. NGS has defined a 1m resolution requirement for shoreline delineation by lidar. Although topographic lidar systems may be able to meet this requirement, bathymetric lidar systems will not, based on the large (~2.5m) illumination footprint that is necessary to meet eye safety standards and sounding positional accuracy which is generally +/- 3 to 4 m (95% confidence). This should not preclude bathymetric lidar delineated shoreline from being useful to many potential end users and most practical applications.

Tenix delivers a shoreline product as part of its charting contract deliverables with NOAA. This shoreline is generated from acquired data across the water land interface. Each laser pulse that is assigned a depth or elevation in this nearshore zone is tide corrected which makes it possible to accurately interpolate shoreline to any vertical datum. This is very attractive to end users that may require a shoreline referenced to a datum other than MHW, which is used on NOAA's nautical charts. For example, the MLLW line can also be determined. Where data gaps may exist across the water land interface or where bare earth hits can not be captured as a result of overhanging trees or buildings, the shoreline can still be captured by heads-up digitizing using the georeferenced imagery that is collected during each flight. In many cases the LADS derived shoreline is better than the shoreline that is currently available on NOAA charts. It is an accepted practice at the Office of Coast Survey to update sections of charted MHW and MLLW lines in Alaska with the newly surveyed bathy lidar data.

Figure 8: An example of shoreline delineated using bathymetric lidar data around Craig, AK. Cultural features are also captured from the georeferenced imagery.

Tsunami Inundation Modeling

NOAA is responsible for providing tsunami warnings to the Nation (*NOAA Tsunami website*). Coastline delineation and high-resolution digital elevation models (DEMs) are a critical element in identifying coastal areas at risk of inundation in the event of a tsunami. NOAA's National Geophysical Data Center (NGDC) is building these integrated bathymetric–topographic DEMs in support of the 'Short-term Inundation Forecasting for Tsunamis' (SIFT) for the NOAA Tsunamis Warning Center and the 'Method of Splitting Tsunami' (MOST) model that is used to simulate tsunami generation, propagation and inundation (*NGDC Tsunami Inundation Gridding Project website*).

In order to create the most accurate coastal DEMs, NGDC uses data collected by numerous agencies and different instruments (Eakins, 2008, pers. comm.), such as NOS shipborne hydrographic surveys, and USACE airborne bathymetric and topographic lidar. An example is NGDC's development of high-resolution coastal DEMs for Puerto Rico (Taylor et al., 2007). These DEMs were built using NOS hydrographic surveys, multibeam swath sonar surveys, shallow-water scuba depths and bathymetric lidar collected during the ongoing joint NOAA project in southwest Puerto Rico (described above in 'Habitat Mapping Using Reflectance Data'). The reflectance and imagery data from lidar surveys are not utilized directly in building DEMs, however, they are useful in qualitative assessments of DEM accuracy (Eakins, 2008, pers. comm.).

The shoreline for the Puerto Rico project was also constructed from various sources: digitized vectors from aerial photographs, NOS shoreline (T-sheets) maps and CAD-based Standard Digital Data Exchange Format (SDDEF), and NOS nautical charts. One of the challenges of using various sources is transforming the elevation data to a common horizontal and vertical datum and in to one common file format for analysis and integration. The conversion to a common vertical datum is particularly challenging as the relationships between vertical datums must be well determined before such conversions can occur. Where available, NGDC uses

NOAA's VDatum tool, which models tidal ranges in various regions and determines the relationships with geodetic vertical datums.

Future

NOAA's mission includes conserving and managing coastal and marine resources by understanding and predicting changes in the environment. This mission will continue to be supported by technological advancements in remote sensing systems such as lidar. This will result in various applications of bathymetric lidar in the future such as hazard mitigation (e.g. flooding), shoreline delineation, coastal erosion monitoring, tsunami inundation modelling, seabed characterization and benthic habitat mapping. The ability for bathymetric lidar to survey across the land water interface and export collected data to any vertical datum makes it a useful tool that can be applied across many disciplines.

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