Utilization of LIDAR and NOAA's Vertical Datum Transformation Tool (VDatum) for Shoreline Delineation

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***Abstract*- The National Oceanic and Atmospheric Administration (NOAA), an organization of the U.S. Department of Commerce, is mandated to map the United States' coastal boundary, defining the nation's legal shoreline. This paper presents a new methodology for extraction of shorelines from lidar data. The methodology incorporates NOAA's vertical datum transformation tool (VDatum) for transforming lidar data to a specified tidally-based datum for shoreline extraction. The VDatum utility comprises geoid models, fields representing departures of an orthometric datum from local mean sea level, and hydrodynamic models portraying tidal regimes for accurate demarcation of coastal lines. The procedure presented here minimizes the variability and subjectivity that have plagued more traditional shoreline delineation techniques. The semi-automated routine allows for consistent, non-interpreted shorelines to be derived, providing significant advantages over proxies such as the high water line, beach scarps, and dune lines. This technique is invariant to coastline type, and has provided good results for a range of margins, such as a sandy or rocky. Additional advantages include the ability to derive multiple tidally-based shorelines from a single dataset and greater flexibility in data acquisition. Perhaps most importantly, the lidar data can be collected in a manner to support a variety of Integrated Ocean and Coastal Mapping (IOCM) applications, including nautical charting, storm surge/tsunami modeling, coral reef mapping, ecosystem monitoring, and coastal mapping.**

I. Introduction

The intersection of the oceans and land is a margin of continuous change. Shoreline positions vary in response to several factors, and the movement of the shoreline can vary dramatically or negligibly in no uniform pattern at temporal scales of daily, seasonally, and decadal. The appropriate methodology for defining the shoreline has been a challenging and divisive topic. There are numerous definitions of shoreline currently in use by various federal, state, local, and private organizations. These varying demarcations form the basis for determination of territorial, legal, and management boundaries. A methodology for determining a consistent shoreline that minimizes variability due to the delineation procedure, as opposed to changes in morphology, is needed.

A great emphasis has been placed on the techniques and considerations involved for mapping shorelines and the accuracies associated with performing such projects. A comparison and overview of past and present shoreline mapping techniques is provided in [1], [2], [3]. Varying techniques using aerial photography for shoreline extraction have been demonstrated, which include point measurements [4], Orthogonal Grid Mapping System [5], Stereo Zoom Transfer Scope [6], Metric Mapping [1], and Softcopy Photogrammetry [7]. Although the progression of shoreline mapping techniques and advancement in technology over the last several decades has led to an improvement in the accuracy with which shoreline can be geo-located, the issue of where exactly to delineate the shoreline remains. This has led to the identification of several shoreline indicators, which have been heavily discussed and debated in the literature [3], [8], [9], [10], [11]. Suggested proxies have included vegetation lines, dune lines, dune toes, bluff or cliff lines, beach scarps, berm crest, the High Water Line (HWL), and coastal structures such as seawalls or bulkheads. Errors associated with shoreline mapping techniques that have been identified and quantified are attributed to the processing of the imagery, the selection and interpretation of the proxy, and the digitization or compilation of the line [3], [8], [9]. With the multitude of techniques and definitions currently in use by the various agencies charged with shoreline delineation, a routine that maximizes consistency and minimizes interpretation is needed.

The National Geodetic Survey (NGS), a line office of the National Ocean Service (NOS) within the National Oceanic and Atmospheric Administration (NOAA) has the responsibility to conduct remote sensing surveys of coastal regions of the United States and its territories for demarcating the nation's legal coastline. The shoreline data generated through these surveys are incorporated onto nautical charts to facilitate safe marine transportation and navigation. Currently, NGS extracts and attributes shoreline from tide-coordinated stereo photography in a softcopy environment. Tide/time windows are established for tide-coordinated photography based on tolerances recognized in NOS guidelines for Mean

High Water (MHW) and Mean Lower Low Water (MLLW). This leads to instances where the exact interface of land and water does not match perfectly with the mean high water tidal datum during the acquisition of imagery. Therefore, the majority of NOS shoreline is digitized by visually interpreting a mean high water tidal datum vector in a stereoscopic environment.

Although reliable, this method of shoreline extraction is time-consuming and the placement of the shoreline is subject to human interpretation. A primary research focus at NGS is investigation of remote sensing technologies and processing/analysis techniques that will increase efficiency in the Coastal Mapping Program (CMP). The goals of these research initiatives include gaining flexibility over weather and tidal constraints and providing data that can benefit multiple users supporting a variety of projects and programs. One technology that NGS has investigated and that shows considerable promise for mapping of the coastal environment is light detection and ranging (lidar). Several recent studies illustrate the usefulness of lidar technology in the coastal environment [12], [13], [14], [15].

II. Analysis

A. *Study Areas*

Seven project sites were selected for this research to represent differing coastal environments: Oregon Inlet, North Carolina; Fort Desoto Park, Florida; Pensacola, Florida; Marathon, Florida; Key Largo, Florida; San Diego, California; and Morro Bay, California. The Oregon Inlet site is a highly-dynamic east coast environment with an ever-changing barrier island spit, and a terminal groin on the south side of the inlet. Fort Desoto Park and Pensacola are characterized as low energy sandy beach environments. The Fort Desoto Park and Pensacola shoreline contain sandy beaches as well as alongshore features such as piers, seawalls, and vegetated lines. The two sites in the Florida Keys, Marathon and Key Largo, do not have shoreline present, but were acquired to explore the usefulness of lidar sensors for additional mapping applications. The San Diego site is representative of a highly-dynamic west coast sandy beach environment with jetties at the entrance of San Diego Bay. The Morro Bay project site is another highly dynamic west coast site that includes sandy beaches, rocky shorelines, jetties, and breakwaters.

B. *Dataset*

Three different lidar sensors were utilized during this research for the collection of elevation information at the study sites. An Optech Airborne Laser Topographic Mapper (ALTM) 2050 lidar system was utilized to collect data for Oregon Inlet, Fort Desoto Park, and Morro Bay. The Optech ALTM 2050 lidar sensor collects data at a pulse repetition frequency (PRF) of 50 kHz using a 1064 nm Nd:YAG laser. This sensor allowed for the collection of dense, highly accurate elevation information over the project site with a 1 x 1 m point spacing. An Optech Scanning Hydrographic Operational Airborne Lidar (SHOALS)-1000T operated by Fugro Pelagos captured data for the San Diego project site. The SHOALS-1000T can operate in either topographic or hydrographic mode, but not concurrently. The hydrographic mode allows for data collection at a PRF of 1 kHz using both 1064 and 532 nm lasers. SHOALS collects data in topographic mode at a PRF of 10 kHz utilizing only a 1064 nm laser. The bathymetric data were collected at a 4 x 4 m sounding density, while the topographic data was collected at a 2 x 1 m spot density. The third lidar sensor, the National Aeronautical and Space Administration (NASA) Experimental Advanced Airborne Research Lidar (EAARL), was utilized to collect the Pensacola, Fort Desoto Park, and Florida Keys project sites. The EAARL is a cross-cutting environmental sensor operating with a 532 nm laser and a small pulse width of 1.2 nanoseconds (ns). The maximum PRF is 5 kHz, but it is varied along the swath to provide a consistent sampling density. The unique design of the EAARL allows for the simultaneous collection of environmental signals such as bare earth, vegetation, sandy beaches, and submerged topography in a single scan.

Tidal stage is an important consideration in extraction of shorelines from topographic lidar. Water levels at the collection sites were monitored at NOAA tide gauges for the topographic collects during 2003 and 2004. The tidal stage was determined to be below the MHW tidal datum for the areas of interest for shoreline extraction. San Diego was collected during the period of April 10-18, 2004 by Fugro Pelagos using the SHOALS 1000-T. Lidar data were collected in hydrographic mode during high water and in topographic mode at low water to maximize the overlap of the data at the land/water interface. Due to the unique design of the EAARL system, tide coordination was not considered in response to small tidal ranges at the project sites during data collections in the spring of 2006.

C. *Methods*

The lidar point cloud, a mass assortment of lidar returns in 3D space, was cleaned by removing lidar points that struck objects, such as birds along the beach and any other erroneous lidar returns, as seen in Fig. 1. These returns can add significant error when extracting shoreline vectors. Concurrent aerial imagery was used in determining whether or not a laser return needed to be removed before surface generation. The lidar data were acquired referenced to the North American Datum 1983 (NAD83). To extract a non-interpreted consistent shoreline relative to a tidal datum, a vertical datum based on a tidally-derived surface, the lidar point data need to be vertically transformed. MHW and MLLW were chosen as the tidal datums for extraction in this research. MHW is the shoreline proxy represented on NOAA nautical charts. This tidal datum is defined as the average of all the high water heights observed over the National Tidal

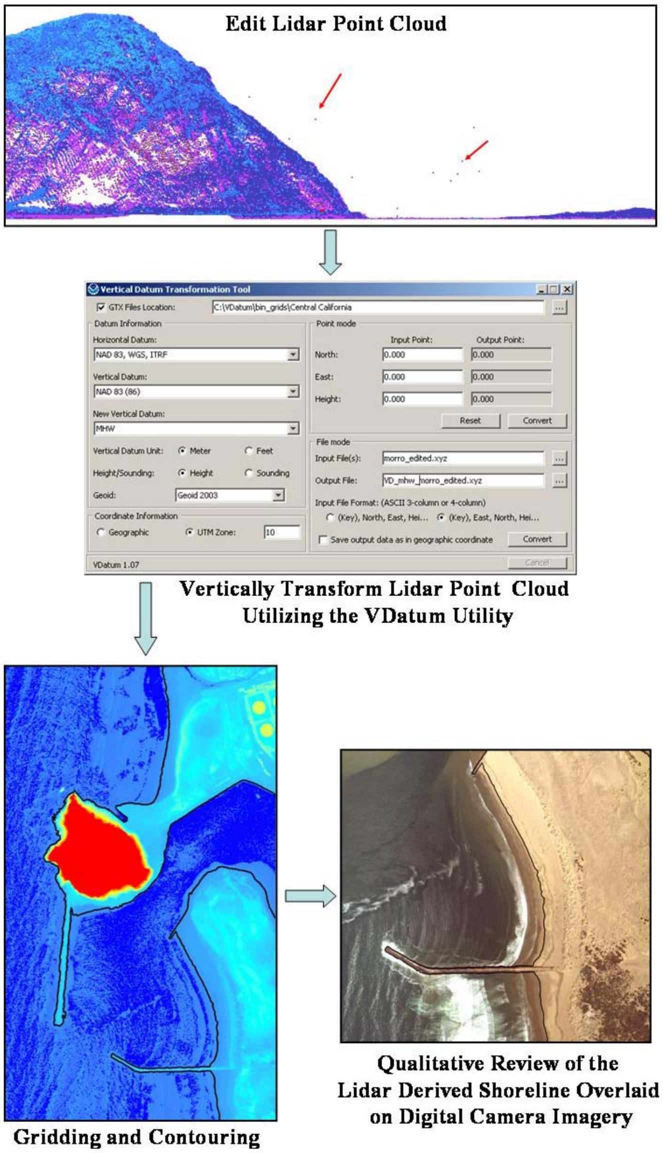

Figure 1. Outline of methodology for extracting tidally datum based lidar shorelines with the assistance of VDatum.

Datum Epoch (NTDE) [16]. MLLW is defined as the arithmetic mean of the lower low water heights of the tide observed over the NTDE. The NTDE is a specific 19-year period that spans the longest periodic tidal variations resulting from astronomical tide-producing forces. This span of 19-years helps average out the long term seasonal meteorological, hydrologic, and oceanographic fluctuations.

To perform the necessary transformations, NOAA's vertical datum transformation tool (VDatum) was utilized (Fig. 1). VDatum is a software tool developed for transformation of elevation data between vertical datums. VDatum currently supports 29 vertical datums that can be placed into three categories: ellipsoidal (realized through space-borne systems), orthometric (defined relative to a geopotential surface, and realized concurrently through geodetic leveling), and tidal (based on a tidally-derived surface). The lidar data points were then processed through VDatum. This involved transforming the data from ellipsoidal NAD 83 heights to orthometric North American Vertical Datum 1988 (NAVD 88) heights using GEOID03. GEOID03 is known as a "hybrid" geoid model. The predominant structure of such a model is a gravimetric model, attempting to model one equipotential surface which best fits mean sea level. However, overlaying this gravimetric field is data which represents deviations of NAD 83 ellipsoidal heights and NAVD 88 heights from the purely gravimetric signal. Thus GEOID03 is not purely a geoid model as much as it is a model to transform between NAD 83 ellipsoidal heights and NAVD 88 orthometric heights [17]. The lidar data were converted to a tidal datum by taking into account local mean sea level departures from NAVD 88 and utilizing models that simulate tidal ranges.

Local mean sea level departures from a global mean sea level can be attributed to prevailing winds, currents, atmospheric pressure, temperature, and salinity. Local variations between a mean sea-level surface and the NAVD 88 reference surface were compensated for through a value calibrating approach of fitting tide model results to tidal benchmarks leveled in NAVD 88. The spatial variability of tidal ranges differs from mean sea level at different geographic locations. The complex nature of the tidal ranges from place to place is a function of the location on the earth, shape of the coastline, hydrography of the coastal margin, winds, salinity, and river discharge. To account for the geographically varying tidal ranges, tidal datum transformation fields are generated by numerical hydrodynamic circulation models. These modeled fields are forced for calibration purposes with coastal water levels, inputs from rivers, winds, water and air temperature, and coastal salinity [18]. The hydrodynamic models are then corrected by interpolating errors at tide gauges by utilizing the tidal constituent and residual interpolation (TCARI) method to produce a more accurate field [19].

The lidar point data, now referenced to MHW, were then interpolated to a regular grid to create a digital elevation model (DEM). Delaunay triangulation with planar interpolation was employed for the gridding of these data sets. This was performed by first creating a Triangular Irregular Network (TIN) from the lidar point data utilizing an excursion filter. This filter limits the length of a triangle side in the surface being created. The maximum sample excursion value for this research was set at two times the resolution of the grid being generated. In areas beyond the range of the excursion value in any direction of a lidar return where another lidar return cannot be found, a null value is assigned to the corresponding grid. A regular grid is then populated through the extraction of elevation information for each grid cell from the corresponding TIN using planar interpolation. With the lidar DEM referenced vertically to MHW, zero represents the MHW tidal datum. Therefore, this allows for a contour to be extracted at the zero elevation of the DEM, representative of the MHW shoreline. ESRI's Spatial Analyst contouring algorithm was employed for this task. A qualitative assessment of the derived shoreline vector is performed by overlaying the vector on the concurrently-collected digital camera imagery.

III. Discussion

Upon visual examination, it was determined that the lidar derived MHW shoreline vector agreed well with the horizontal position of the concurrent digital aerial imagery. Extracting shorelines utilizing the method depicted in this research from highly accurate lidar data has several advantages over traditional methods. Shorelines from a lidar derived DEM that has been accurately referenced to a tidal datum provides a routine that maximizes consistency with a minimal amount of interpretation. This semi-automated technique for delineating coastal boundaries is possible with the assistance of a vertical datum transformation utility, such as VDatum. The analyst does not need to make judgments on the correct portion of the beach face for delineation. The shoreline is extracted based on accurate elevation information obtained during transformations, regardless of geographical location within the extent of the vertical datum utility.

Derived shorelines based on a tidal datum provide a consistent proxy when compared to others such as the HWL, dune lines, and beach scarps. Since tidal datum shorelines are based on elevation information computed from nineteen years of tidal data over the span of a National Tidal Datum Epoch, no interpretation of the dataset is needed. This leads to consistency that cannot be achieved when trying to delineate shorelines based on other proxies. The HWL shoreline can change daily based on differences in tidal heights and wave setup. The dune line proxy also has its pitfalls. If the coastal system does not have a dune system or has just recently experienced a storm event where the dune line was destroyed, the placement of the shoreline becomes highly subjective. A proxy such as a beach scarp can also cause inconsistencies. Some beaches have several beach scarps making delineation of the shoreline subjective in such areas. Beaches that have experienced grooming practices or are rocky margins might not have a scarp from which to define the vector. Although the morphology may vary, as with any shoreline proxy, the elevation information that defines a tidal datum shoreline remains constant over a National Tidal Datum Epoch.

Tidally-derived shorelines are a demarcation that can be utilized on coastlines that are sandy, rocky, or have undergone anthropogenic influences such as jetties, seawalls, and groins. Fig. 2 illustrates lidar derived tidal datum based shorelines for several of theses differing coastline types. The elevation information that characterizes a specific tidal datum allows for consistent extraction of a vector, regardless of the shoreline type. Shoreline delineation in heavily vegetated coastal margins, such as mangroves in Fig. 2 (c) and wetland areas have been extracted as apparent shorelines. This is the current method for shoreline compilation from stereo imagery of these areas for nautical charting. The removal of vegetation returns for determination of the ground surface for delineating the extent at which a tidal stage reaches in these spots is currently being investigated. It should be noted that delineation of alongshore features such as the pier in Fig. 2 (e) and in port areas have shown to be difficult in response to the presence of boats and the capture of laser returns underneath the pier surface. The delineation for such features was improved by utilizing the concurrent aerial imagery to edit the vector, with the assistance of the lidar-derived shoreline as a guide.

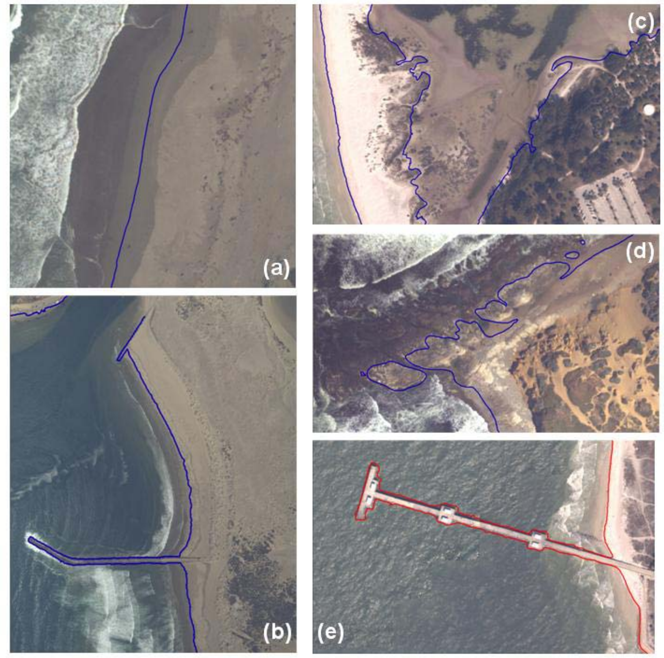

Figure 2. Tidal datum lidar derived shorelines at various coastal margins: (a) sandy beach, (b) sandy beach, jetty, and breakwater, (c) sandy beach and vegetated lines, (d) rocky coastline, (e) sandy beach, pier and seawall.

Tide coordination was an important aspect when planning for the topographic lidar collects. In response to the water surface being above the MLLW tidal datum for the topographic lidar collects, only the MHW shoreline was able to be extracted. An advantage of utilizing lidar data coordinated with specific tide windows is the extraction of multiple shorelines from the same dataset. When lidar is acquired at a water level below the MLLW tidal datum, several tidal datum shorelines such as MLLW, Mean Sea Level (MSL), and MHW could, in theory, be extracted by simply vertically referencing the data to the tidal datum of choice. The coordination of such an effort to obtain the MLLW shoreline has been difficult. In order to extract both MHW and MLLW shorelines, several factors need to coincide. These include acquiring topographic lidar, during a spring low tide, minimal wave activity, and having either no wind or an offshore wind. This issue has led NOAA to investigate other options for lidar derived shoreline extraction.

One such investigation, has been to utilize the capability to collect both topographic and bathymetric lidar from the same sensor such as the SHOALS 1000-T. Fugro Pelagos collected bathymetric data for the San Diego project site at a high stage of tide and the topographic portion at a lower tide stage, minimizing the data gaps at the land water interface. This procedure allowed for a consistent topographic/bathymetric DEM to be created, permitting the extraction of both MHW and MLLW tidal datum shorelines as seen in Fig. 3 (a). Although this method can produce the two shorelines of interest, it entails planning the bathymetric acquisition at a higher tide and the topographic collect at a lower tide.

The EAARL system with cross environment surveying capabilities was employed to determine if simultaneous collection of topographic and bathymetric lidar was possible without the cumbersome need of tide coordination. Therefore, in simulating no preplanning of water level heights, the Pensacola data set was flown approximately half way between high and low tide, while Fort Desoto Park was flown at high tide. The unique design of the EAARL laser with a narrow pulse width and small beam divergence, allowed for the capture of highly detailed topographic and bathymetric data of the swash zone and near shore region within the same scan. This capability permitted easy extraction of both the MHW and MLLW shorelines as seen in Fig. 3 (b), without the need to collect lidar in two differing acquisition modes such as the SHOALS. The EAARL sensor allowed for the extraction of the challenging MLLW shoreline without tide coordination at the Fort Desoto Park project site, where before with the topographic lidar, only the MHW shoreline could be extracted.

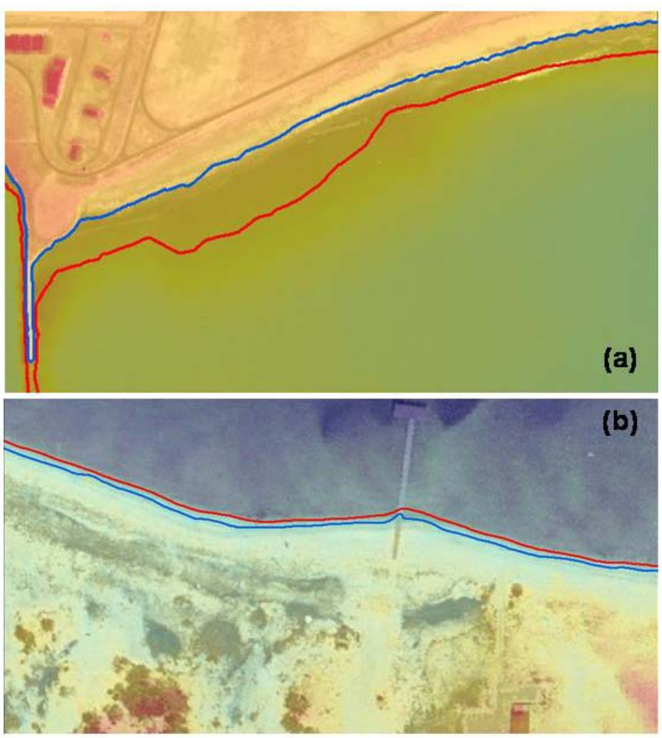

Figure 3. MHW (blue) and MLLW (red) shorelines extracted from a single dataset: (a) SHOALS 1000-T dataset in San Diego, (b) EAARL dataset in Pensacola.

It should be noted that for the EAARL data collects, the tidal range between the tidal datums of interest were very small. The tidal range between MHW and MLLW based on NOAA tide gauge data in the Pensacola vicinity is approximately 37 cm and 55 cm at Fort Desoto Park. In areas where the tidal range is large and is greater than the depth of laser extinction, coordination of the tide to an acceptable level would need to be considered for the capture of MLLW during the survey. Another consideration is that both the SHOALS and EAARL bathymetric capabilities are dependent on water clarity. Therefore this technology will not work in all geographical areas, all the time.

An additional goal of the project was to examine the acceptability of the data collected to support other projects, programs, and agencies needs. A primary objective in NOAA is to develop operational procedures to support Integrated Ocean and Coastal Mapping (IOCM). This effort is to efficiently and cost-effectively collect and distribute data meeting a variety of coastal mapping needs across NOAA and the rest of the Federal Government. The purpose of such an endeavor is to decrease the duplication of mapping efforts along this margin, through acquiring data once and having several groups utilize the data for their needs. The topographic lidar collected for this research can easily be utilized by others for such coastal issues and applications as shoreline change, monitoring beach volumetric changes, sediment budget calculations, flood risk analysis, and habitat mapping. The utilization of data from lidar sensors capable of collecting bathymetric and topographic data can be instrumental for nautical charting (Fig. 4) in areas that have been determined hazardous utilizing other technologies. These areas include the shallow, wave prone near shore and shallow reef areas where hydrographic boats cannot safely operate. These hazardous areas where data gaps have been so prevalent in the past, if collected with lidar are significant for supporting storm surge and tsunami modeling efforts. This same data collected over the reefs can be utilized for mapping rugosity, habitat structure and cover, and for ecosystem management. Therefore, the lidar sensors utilized in this research can be utilized through an IOCM effort to increase both the quantity and quality of information about the coastal environment.

IV. Summary

A routine for the extraction of shoreline vectors from lidar data that minimizes variability introduced from the delineation procedure has been demonstrated. This is accomplished through the use of a vertical datum transformation tool for converting lidar data to a tidally-based datum. Lidar datasets collected at numerous project sites have provided detailed tidal datum shorelines. The methodology presented here for demarcating shorelines permits non-interpreted coastal lines that are advantageous over other suggested proxies, is invariant to coastline type, and can provide multiple shoreline extraction from a single dataset. Perhaps most importantly,

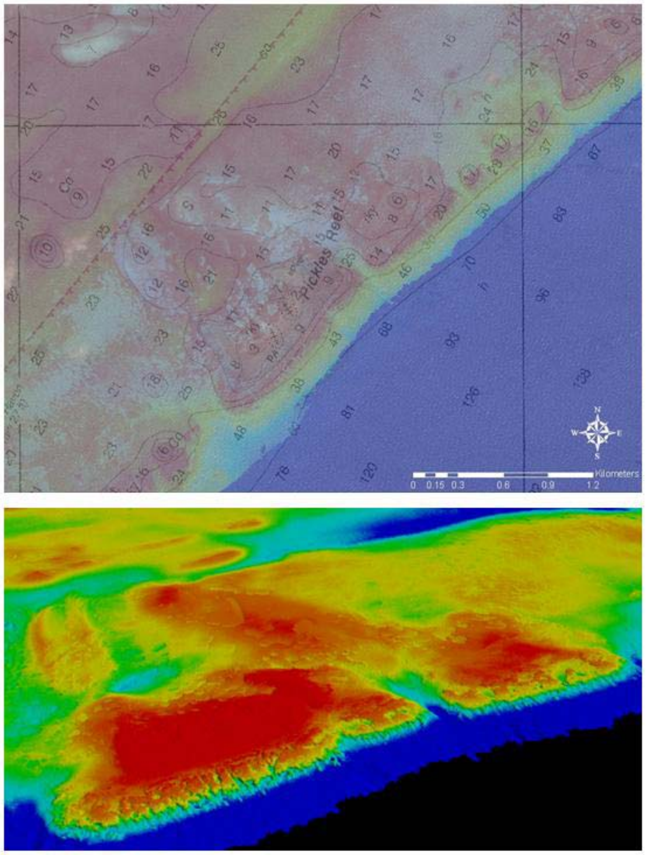

Figure 4. EAARL datasets demonstrating the benefit of lidar to a variety of users, projects, programs, and agencies through an integrated ocean and coastal mapping approach. Pickles Reef off the island off of Marathon, Fl (a) nadir and (b) oblique view.

the lidar data acquired for such efforts can be collected in a manner to assist a variety of users, supporting several projects, programs, and agencies through an integrated ocean and coastal mapping approach.

It should be noted however that the VDatum tool is only available for a limited number of areas within the continental United States. An effort is currently underway to populate a nationwide VDatum for the U.S. Several issues still remain and need to be further investigated when using lidar data for obtaining tidally-based coastal lines. Assessment of the absolute error of the derived shoreline in relation to that of a ground truth shoreline captured during the acquisition of lidar has not been demonstrated and was beyond the scope of this particular project. Also, the acceptability of shorelines for piers and port areas derived from lidar, needs to be further refined. Work is currently being conducted by NOAA to address these issues.

REFERENCES

[1] S.P. Leatherman, “Shoreline Mapping: A Comparison of Techniques,” *Shore and Beach*, vol. 51, pp.28-33, 1983.

[2] R.A. Morton, “Accurate Shoreline Mapping: Past, Present, and Future,” American Society of Civil Enginneers, *Coastal Sediments '91*, vol. 1, pp. 997-1010, 1991.

[3] L.J. Moore, “Shoreline Mapping Techniques,” *Journal of Coastal Research*, vol. 16, pp. 111-124, 2000.

[4] D.B. Stafford, & J. Langfelder, “Air photo Survey of Coastal Erosion,” *Photogrammetric Engineering*, vol. 37, pp. 565-575, 1971.

[5] R. Dolan, B. Hayden, & J. Heywood, “A New Photogrammetric Method for Determining Shoreline Erosion,” *Coastal Engineering*, vol. 2, pp. 21-39, 1978.

[6] J.J. Fisher & E.J. Simpson, “Washover and Tidal Sedimentation Rates as Environmental Factors in Development of a Transgressive Barrier Shoreline,” in *Barrier Islands,* Leatherman, S.P., Eds. New York: Academic Press, 1979, pp.127-148.

[7] D. Graham, M. Sault, & J. Bailey, “National Ocean Service Shoreline-Past, Present, and Future,” *Journal of Coastal Research*, vol. 38, pp. 14-32, 2003.

[8] M. Crowell, S.P, Leatherman, & M.E. Buckley, “Historical Shoreline Change: Error Analysis and Mapping Accuracy,” *Journal of Coastal Research*, vol. 7, pp. 839-852, 1991.

[9] R.A. Morton & M.F. Speed, “Evaluation of Shorelines and Legal Boundaries Controlled by Water Levels on Sandy Beaches,” *Journal of Coastal Research*, vol. 14, pp. 1373-1384, 1998.

[10] M.J. Pajak & S.P. Leatherman, “The High Water Line as Shoreline Indicator,” *Journal of Coastal Research*, vol. 18, pp. 329-337, 2002.

[11] S.P. Leatherman, “Shoreline Change Mapping and Management along the U.S. East Coast,” *Journal of Coastal Research*, vol. 38, pp. 5-13, 2003.

[12] J.C. Brock, C.W. Wright, A.H. Sallenger, W.B. Krabill, & R.N. Swift, “Basis and Methods of NASA Airborne Topographic Mapper Lidar Surveys for Coastal Studies,” *Journal of Coastal Research*, vol. 18, pp.1-13, 2002.

[13] W. Krabill, et al., “Airborne Laser Mapping of Assateague National Seashore Beach,” *Photogrammetric Engineering and Remote Sensing*, vol. 66, pp. 65-71, 2000.

[14] A.H. Sallenger, et al., “Evaluation of Airborne Topographic Lidar for Quantifying Beach Changes,” *Journal of Coastal Research*, vol. 19. pp. 125-133, 2003.

[15] S.A. White & Y. Wang, “Utilizing DEMs Derived from LIDAR Data to Analyze Morphologic Change in the North Carolina Coastline,” *Remote Sensing of Environment*, vol. 85, pp.39-47, 2003.

[16] S.D. Hicks, “Tidal Datums and Their Uses-A Summary,” *Shore and Beach*, pp.27-32, 1980.

[17] D.R. Roman, Y.M. Wang, W. Henning, & J. Hamilton, “Assesment of the New National Geoid Height Model, GEOID03,” *Proceedings of the American Congress on Surveying and Mapping*, 2004.

[18] B. Parker, “The Integration of Bathymetry, Topography and Shoreline and the Vertical Datum Transformations Behind It,” *International Hydrographic Review*, vol. 3, pp. 35-47, 2002.

[19] K.W. Hess, “Spatial Interpolation of Tidal Data in Irregularly-shaped Coastal Regions by Numerical Solution of Laplace’s Equation,” *Estuarine, Coastal and Shelf Science*, vol. 54, pp. 175-192, 2002.