Mapping Shoreline Position Using Airborne Laser Altimetry

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ABSTRACT


This paper examines the feasibility of using LIDAR surveys to update existing historical shoreline data sets by comparing contour shorelines and the high water line (HWL) at eight study locations in North and South Carolina. The analysis was based on airborne LIDAR topography and orthoimagery collected simultaneously during June 2000. The popular method of digitizing the wet-dry line from orthoimagery was used to measure the HWL. Contour shorelines were derived by using the previous high tide (HW), the mean high water datum (MHW), and the mean higher high water datum (MHHW) of nearby tide gauges. A method was developed to quantitatively compare the positions of the HWL and the contour shorelines in a GIS. The mean high water and mean higher high water contour shoreline positions were the best match to the high water line at 7 of 8 locations, and differed by less than 5.4 meters from the digitized high water line positions. This difference is well within the errors associated with past methods for measuring shoreline position. Therefore, it is deemed practical to use LIDAR data to estimate the HWL.

ADDITIONAL INDEX WORDS: LIDAR, shoreline change, high water line, historical shoreline mapping.

INTRODUCTION

The ability to map shoreline position through time is critical in calculating beach erosion or accretion rates. Comparing shoreline positions over long periods (~100 years) yields more accurate trends than when a shorter time series is used (CROWELL et al., 1997; GALGANO et al., 1998; DOUGLAS et al., 1998). The shoreline data set must have a common indicator to allow for comparison of positional changes through time, because shorelines are often derived from various sources such as historical maps, aerial photographs, and field GPS surveys.

The high water line (HWL) is the most often used shoreline indicator as depicted on historical maps and interpreted in the field or from aerial photographs. The high water line is defined as the intersection of land with the water surface at high tide (HICKS et al., 2000). In the field, the HWL is often identified as the wet/dry sand boundary following high tide, which is created by the furthest extent of the rising water on a beach face (PAJAK and LEATHERMAN, 2002; ZHANG et al., 2002). For this reason, this paper considers the HWL and wet-dry line to be the same shoreline feature, and this feature will be referred to as the HWL. It is important to continue to measure the HWL or a compatible indicator such as a topo-

graphic contour so that changes in shoreline position can be detected through trend analysis.

Various techniques have been used to determine the HWL including conventional surveying, aerial photography, and GPS. Aerial photography is an often-used method for measuring shoreline position, but errors in shoreline position are estimated to be 6.1 m (CROWELL et al., 1991). While techniques have improved through the years, measuring the HWL continues to be prohibitively time and labor intensive. A recent advance in coastal surveying is airborne LIDAR (Light Detection and Ranging). Airborne LIDAR is an active remote sensing technology that is capable of producing extremely dense and accurate elevation measurements for large areas in a short amount of time (IRISH and WHITE, 1998; BAITSAVAS, 1999; KRAHILL et al., 2000). Unfortunately, the HWL is not a topographic feature, and thus there is no simple relationship between LIDAR elevations and the position of the HWL.

One approach for utilizing LIDAR elevations to determine shoreline position is to project tide levels onto a LIDAR derived digital elevation model (DEM). The resulting elevation contour can be used as an approximation for the position of the shoreline. A similar approach was taken by STOCKDON et al. (2002), who estimated shoreline positions by locating the intersection of a user specified datum on beach slopes derived from LIDAR point measurements. Unfortunately, they did not quantify the difference between the calculated shoreline
with the HWL obtained from conventional methods. Therefore, it is unknown whether their estimated shoreline is consistent with the historical shoreline record, and thus, it is unclear whether these measurements can be used in long term shoreline trend analysis.

The first objective of this paper is to present a simple method for deriving a shoreline contour from LIDAR measurements based on local tide levels. The technique is implemented in a GIS that allows for rapid and accurate estimates of shoreline position over large areas. The second objective is to examine the feasibility of using contour shorelines from LIDAR measurements to approximate the HWL by quantifying the difference between contour shorelines and the HWL interpolated and digitized from coincident orthoimagery.

**STUDY AREA AND DATA**

The beaches of North and South Carolina reflect a wide variety of shoreline environments. In North Carolina and northern South Carolina, the beaches are microtidal, whereas the beaches of southern South Carolina are mesotidal. In addition, the cuspat eform shape of the Outer Banks allows for varied wave energies, and the mix of private and publicly owned oceanfront properties provides a range of anthropogenic-influenced environments. Therefore, the beaches of these states present an excellent natural laboratory for studying shoreline change.

In June 2000, Florida International University collected over 850 km of coincident LIDAR measurements and orthoimagery along the coasts of North and South Carolina. Eight study areas with shorelines ranging between 1.6 and 3.2 km were selected to represent different beach types with a range of slopes and tidal conditions (Figure 1, Table 1). Beaches studied in North Carolina include Duck, Cape Hatteras north, Cape Hatteras south, Portsmouth Island, and Wrightsville Beach. Crescent Beach, Fripp Island north, and Fripp Island south were the beaches studied in South Carolina.

Data were collected over a four-day period. The dates and times of each flight were carefully planned to coincide with a minimum tidal range (e.g. neap tide), low tide, and favorable

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Beach Slope</th>
<th>Tidal Conditions</th>
<th>Tidal Stage</th>
<th>MHW Elevation</th>
<th>Wave Height</th>
<th>Coastline Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duck</td>
<td>1:12</td>
<td>Micro-tidal</td>
<td>Low</td>
<td>-0.04 m</td>
<td>1.29 m</td>
<td>2.1 km</td>
</tr>
<tr>
<td>Cape Hatteras North</td>
<td>1:7</td>
<td>Micro-tidal</td>
<td>Low</td>
<td>0.11 m</td>
<td>1.10 m</td>
<td>2.1 km</td>
</tr>
<tr>
<td>Cape Hatteras South</td>
<td>1:13</td>
<td>Micro-tidal</td>
<td>Low-Mid</td>
<td>0.11 m</td>
<td>1.13 m</td>
<td>3.2 km</td>
</tr>
<tr>
<td>Portsmouth Island</td>
<td>1:17</td>
<td>Micro-tidal</td>
<td>Low-Mid</td>
<td>0.11 m</td>
<td>1.13 m</td>
<td>3.2 km</td>
</tr>
<tr>
<td>Wrightsville Beach</td>
<td>1:19</td>
<td>Micro-tidal</td>
<td>Low</td>
<td>0.13 m</td>
<td>1.25 m</td>
<td>2.4 km</td>
</tr>
<tr>
<td>Crescent Beach</td>
<td>1:18</td>
<td>Meso-tidal</td>
<td>Mid</td>
<td>0.48 m</td>
<td>0.75 m</td>
<td>1.6 km</td>
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<tr>
<td>Fripp Island North</td>
<td>1:26</td>
<td>Meso-tidal</td>
<td>Mid</td>
<td>0.78 m</td>
<td>0.71 m</td>
<td>1.6 km</td>
</tr>
<tr>
<td>Fripp Island South</td>
<td>1:3*</td>
<td>Meso-tidal</td>
<td>Mid</td>
<td>0.76 m</td>
<td>0.71 m</td>
<td>1.6 km</td>
</tr>
</tbody>
</table>

*D Bouldered shoreline
wave conditions. Tidal stage ranged between low and mean tide level (Table 1). Wave conditions were generally light with significant wave heights less than 1.3 m. These conditions were pre-selected to ensure that the shoreline positions were not biased by anomalous wave or tidal conditions.

LIDAR data were collected with an Optech 1210 ALTM system and orthoimagery were collected with a Kodak 420 digital camera system. Both systems were mounted in a Cessna 337 twin-engine aircraft that was flown at a speed of 200 km/hr and an altitude of 500 m.

The Optech 1210 system utilizes a near-infrared (1.1 μm) laser scanner, an Inertial Measurement Unit (IMU) to provide aircraft orientation information, and a data processing and collection unit. With a laser pulse rate of 10 kHz, a field of view (FOV) of 32 degrees, and a scan rate of 15 Hz, the LIDAR system yielded a swath of 286 m, and a laser footprint diameter of 0.13 m (Figure 2). Measurements were spaced 0.86 m along each scan line, with scan lines spaced 3.70 m apart at the edges of each swath. The coast was flown twice in opposite directions for redundancy and to maximize data density. These parameters resulted in an average data density of approximately one point per square meter. The aircraft trajectory of each flight was determined from GPS phase measurements collected in the plane and at several ground stations using the algorithm of MAHER and LUCAS (1989). The vertical and horizontal accuracy of the LIDAR measurements for this system are estimated to be about 10 cm and 20 cm, respectively (SHRESTHA et al., 1999). These accuracy estimates are based on ideal flight and surface conditions and actual errors for some beach surveys may be higher.

For analysis purposes, the irregularly spaced LIDAR data were interpolated to a 0.5 m resolution digital elevation model (DEM). Interpolation was performed using the method of point kriging with a linear variogram and a search radius of 15 m. These DEMs were then used to generate contours used in the later analysis.

The Kodak 420 digital camera utilizes a 1012 by 1524 rectangular Charged Coupled Device (CCD) array. During the flight, images were acquired every 2.5 seconds over a FOV of 28°. Each image covers an area of 250 × 250 m and has a 25% overlap with adjacent images at each end along the flight path.

Alignment and orthorectification of the images were performed by Verimap, Inc. using proprietary software. This software utilized the same GPS trajectory and IMU measurements used for the LIDAR data. In addition, the LIDAR DEM was used to orthorectify the images. Initial processing produced perfect pixel alignment in 90% to 95% of the mosaiced imagery. Further manual processing produced a 0.5 pixel mismatch in less than 0.5% of the mosaic. The final orthomosaics were produced at 20 cm pixels. The positional errors of these orthomosaics are estimated to be within 2 pixels, or 40 cm (D. Stonehouse, personal communication, 2001).
ANALYSIS

The analysis proceeded in three steps. First, the HWL was identified and digitized by locating the tonal differences due to the wet-dry boundary on the beach surface. Then, shoreline contours were generated at elevations corresponding to tide levels measured at nearby tide gauges. Finally, the positional differences between the HWL and shoreline contours were quantified in a GIS.

Identification of the HWL using aerial photographs is well documented (Crowell et al., 1991; Pajak and Leatherman, 2002; Zhang et al., 2002). Vertical aerial photographs for each study area were imported into a GIS. The tonal differences in the sand were identified and digitized to represent the HWL (Figure 3). The digitized vectors were then converted to rasterized lines so that they can be differenced, as described below.

Shoreline contours were created by projecting measurements recorded by nearby tide gauges onto DEMs generated from the LIDAR data. The National Ocean Service (NOS) maintains a network of tide gauges throughout coastal areas of the United States. At these stations, water level measurements are recorded every six minutes with an accuracy of 1.0 cm (Gill and Schultz, 2001). These measurements are used to tabulate the high water elevation (HW) from each tidal cycle (Figure 4). In addition, NOS calculates long-term averages for each tidal station. These averages include mean high water (MHW) which is the average of all high tides observed over a 19-year period, and mean higher high water (MHHW) which is the average of the higher high water of each tidal day observed over a 19-year period (Figure 4). For each study area, tide data (HW, MHW, MHHW) from the most appropriate tide stations were used to determine the shoreline contour levels (Figure 1). The DEMs were then contoured at elevations corresponding to HW, MHW, and MHHW levels.

The horizontal differences between the HWL and contour shorelines were quantified in a GIS. The analysis proceeded in four steps (Figure 5). First, the digitized HWL and a contour shoreline were rasterized to grids at a 20 cm cell resolution (Figure 5a). In the contour grid, the pixel values were assigned a value of 1 on the contour shoreline and 0 elsewhere. Then, a buffer grid was created from the HWL grid...
Figure 4. Tide levels and datums used in this study. HW is the elevation of water during the previous high tide. MHHW is a 19 year average of high tides. MHHW is a 19 year average of the highest high tide of each tidal day. Data were reported in MLLW and converted to NAVD88 by applying NOAA-determined benchmark offsets.

Figure 5. Schematic diagram showing the methodology for comparing the distance between the HWL (solid line) and water level contour (dashed line). See text for explanation.

by calculating the Euclidian distance from each cell to the HWL (Figure 5b). In the buffer grid, distances on the seaward and landward sides of the HWL were assigned negative and positive values, respectively, in order to separate seaward and landward offsets of the contour shoreline (Figure 5c). Next, the positive/negative Euclidian distance buffer was multiplied with the contour grid (Figure 5d). This resulted in a set of rasterized lines for each water level with the raster values corresponding to the signed Euclidian distance from the HWL.

RESULTS

A longitudinal profile of the differences between the HWL and the water level contours for Portsmouth Beach is shown in Figure 6. In general, the HW contour is seaward (negative difference) of the HWL. This is expected since the HWL reflects both tide level and wave run-up. In contrast, the MHHW contour is in closer agreement with the HWL. The MHHW difference profile was not shown for clarity and falls between the HW and MHHW difference profiles.

Summary statistics including minimum, maximum, mean and standard deviation were compiled at each site and for each contour in order to determine how closely each contour line corresponds to the location of the HWL (Figure 7; Table 2). The mean horizontal difference between the HWL and HW contour ranged from 1.9 m at Duck to −10.2 m at Crescent Beach. The HWL differed from the MHHW contour by only 0.6 m at Wrightsville Beach, but by as much as −9.2 m at Crescent Beach. The difference between the HWL and MHHW contour was 0.2 m at Portsmouth Island and −6.9 m at Crescent Beach. In most cases, the position of all water level contours differed from the HWL by less than 6 m. The one exception was found at Crescent Beach where the HWL differed by −10.6 m, −9.2 m, and −6.9 m from the HW con-
tour, MHW contour, and MHHW contour, respectively. However, this site appears to be anomalous. The reason for this discrepancy is discussed later in this section.

In general, there is a north to south variation in the relative offset between the water level contours and the HWL (Figure 7). At the two northernmost sites, Duck and Hatteras north, the water level contours are offset landward relative to the HWL. In contrast, at sites south of Cape Hatteras, water level contours are generally offset seaward of the HWL.

The cause for the landward offset of the two northern sites is unclear. In theory, the HW contour should always be found seaward of the HWL because the position of the wet-dry line is a function of tidal level and wave run-up. One source may be horizontal and vertical errors in the LIDAR data. For example, a negative vertical error of 0.2 m at Duck (slope 1:12) would result in a 2.4 m landward horizontal offset of the shoreline contours. Errors such as these may contribute to the landward position of the HW contour at Hatteras north and Duck locations. Vertical errors will affect gentle slope beaches more significantly. For example, at Wrightsville Beach a vertical error of 0.2 m would result in a horizontal contour offset of 3.8 m. Unfortunately, these errors are usually due to uncertainties in the aircraft trajectory that are not constant and therefore cannot be equally applied to each study location.

The largest horizontal differences were found at Crescent Beach, N.C., where the shoreline contours are offset seaward from the HWL by 5 m or more (Figure 8). This offset is probably too large to be explained by errors in the LIDAR elevations. Instead, this offset is probably due to the misidentification of the HWL on the digital orthoimagery. The sand color at Crescent Beach made it difficult to identify the HWL, and this highlights the problem with using aerial photographs for mapping shoreline position.

In addition, the beach face was characterized by ridge and

### Table 2. Differences between the High Water Line and the High Water, Mean High Water, and Mean Higher High Water contours. The mean value is the mean of the horizontal difference, range is the distance between the minimum and maximum values, and Std. is the standard deviation of the mean difference.

<table>
<thead>
<tr>
<th>Location</th>
<th>Slope</th>
<th>HW Difference</th>
<th>MHW Difference</th>
<th>MHHW Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Range</td>
<td>Std.</td>
</tr>
<tr>
<td>Duck</td>
<td>1:12</td>
<td>1.9</td>
<td>10.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Cape Hatteras North</td>
<td>1:7</td>
<td>-2.4</td>
<td>37.1</td>
<td>2.9</td>
</tr>
<tr>
<td>Cape Hatteras South</td>
<td>1:13</td>
<td>-2.6</td>
<td>9.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Portsmouth Island</td>
<td>1:17</td>
<td>-1.0</td>
<td>21.5</td>
<td>3.2</td>
</tr>
<tr>
<td>Wrightsville Beach</td>
<td>1:19</td>
<td>-10.6</td>
<td>26.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Crescent Beach</td>
<td>1:18</td>
<td>-9.6</td>
<td>4.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Fripp Island North</td>
<td>1:26</td>
<td>-1.9</td>
<td>9.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Fripp Island South</td>
<td>1.5</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

runnel morphology parallel to the shoreline (Figure 9). The ridges cause a seaward migration of the contoured shorelines despite the fact that the HWL was able to bypass the ridge by propagating up the runnel. As a result, the ridges cause locally higher negative differences (Figure 8) between the HWL and contoured shorelines and represent one limitation of using contours as shorelines.

**DISCUSSION**

This study demonstrates that water levels and tidal datums can be used to calculate contour shorelines based on LIDAR data, and the contour shorelines approximate the HWL with reasonable accuracy (Table 2). In many ways, the elevation contour is a better shoreline indicator than the HWL. The HWL must be manually digitized from aerial photographs that have been spatially corrected. The critical step when digitizing the HWL is to identify the correct HWL locations from the imagery. Usually, the HWL at yellowish sandy beaches can be identified by the change of gray or color tone on high-resolution metric-quality aerial photographs (PAJAK and LEATHERMAN, 2002). However, the tone changes caused by other features in the imagery such as debris lines, the HWLs left by high waters earlier than the most recent, and instant swash lines can occasionally smear the HWL on photographs, thus making it difficult to identify the correct HWL positions. For example, despite the fact that this study used high-resolution orthoimagery, we still had trouble identifying the HWL at the Crescent Beach location. On highly reflective beaches consisting of white sand, it is very difficult to discern the HWL from aerial photographs. In contrast, a contour shoreline calculated based on LIDAR measurements is not affected by these problems, making it a more reliable shoreline indicator.

In addition, the variation of the HWL is not only caused by actual beach changes, but also influenced by tidal ranges and wave run-up at high tide. As discussed by PAJAK and LEATHERMAN (2002), there can be large variability (~ 10 m) involved when using the HWL as a shoreline indicator because of day-to-day changes in tide, wave run-up, and beach slope. These HWL changes can be larger than actual beach changes and they are extremely difficult to separate. Therefore, it is unreliable to detect the short-term beach changes by comparing the HWLs directly. By comparing the same contour shoreline from LIDAR measurements, the variability from HWL shorelines is removed. Thus, the short-term beach changes can be detected as long as the change magnitudes are larger than the position errors of LIDAR-derived contour shorelines.

HW, MHW, and MHWW contour shorelines approximate the HWL fairly well. However, the MHW and MHWW con-
tours are better surrogates for the HWL. Since MHW and MHHW are averaged datums, they do not require daily tidal data simultaneous with LIDAR surveys. MHW and MHHW are estimated using historical water level records, while HW can only be available from tide gauges that are operational during LIDAR surveys. In addition, beach changes indicated by HWs include not only actual beach changes, but also the day-to-day variation of tidal ranges. The variation of HW shoreline contours due to tidal ranges is removed by using the MHW and MHHW contours as shoreline indicators. Therefore, the shoreline positions based on MHW and MHHW contours include less "noise" and are better for long-term trend analysis.

Recent studies have applied LIDAR data to the estimation of shoreline position (Stockton et al., 2002; Sallenger et al., 2003). The accuracy of LIDAR shoreline measurements were justified by comparing locations of shorelines based on slopes derived by LIDAR and the SWASH GPS vehicle system. While these studies significantly aided coastal research by demonstrating that land-based GPS derived elevations and shoreline positions were similar to elevations and shoreline positions derived from LIDAR data, they provide no information as to whether the derived shoreline is consistent with long-term historical shoreline position databases. Here in, we demonstrated that LIDAR-derived contour shorelines are compatible with those digitized from coincident digital orthomagery, which is an often-used method for measuring shoreline position.

This study utilized GIS techniques to compare and quantify the difference between an interpreted HWL and a projected shoreline contour. The same techniques can also be used to quantify the difference between two shorelines. Past methods for measuring shoreline differences have involved extracting profiles or transects perpendicular to the shoreline. The advantage of our method is that the entire shoreline position database is analyzed, and is not biased by selection of transect locations. In addition, our method measures the closest distance from the location in question to the nearest shoreline position. From the prospect of a shoreline resident or coastal manager who is concerned that the encroaching ocean will compromise a structure, our method will provide an idea of how quickly the ocean is approaching a position despite direction. However, the use of this technique to quantify change in multiple shoreline positions is not possible if the researcher is attempting to determine a linear regression trend. Profiles and transects continue to be the best method for regression modeling.

CONCLUSIONS

This study presents a method for estimating shoreline positions by projecting tide levels on LIDAR elevations. One tidal level (HW) and two tidal datums (MHW and MHHW) were used to generate contours on DEMs derived from LIDAR. The resulting shoreline contours are consistent with a common indicator of shoreline position, the HWL, mapped from aerial photographs. At seven of eight study sites, the mean difference between position of the water level contours and the HWL was less than 6 m. With exception of Crescent Beach, S.C., the MHW and MHHW contours most closely matched the HWL with a maximum mean difference of 5.4 m. In general, the errors associated with projecting contour levels on LIDAR data are less than the 6.1 m errors associated with the digitization of the HWL off aerial photographs. Therefore, we conclude that it is feasible to use LIDAR to extend historical shoreline positional data sets.

Datum-derived contours from LIDAR surveys provide more stable shorelines than HWL measurements because they are not subject to the effect of short-term fluctuations in wave energy and water levels. This methodology can be used to update existing shoreline data sets at coasts with similar conditions to the Outer Banks of North Carolina and the South Carolina coast.

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LITERATURE CITED


