Quantifying rapid changes in coastal topography using modern mapping techniques and GIS

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ABSTRACT

Innovative methodology based on a combination of Real Time Kinematic GPS (RTK-GPS), lidar, and open source GIS was developed to gain a better understanding of rapid changes in coastal topography. Improved spatial interpolation techniques were implemented to produce detailed topographic surfaces from lidar and RTK-GPS data. The methodology is demonstrated for two North Carolina areas: Jockey's Ridge State Park, and Bald Head Island. The Jockey's Ridge study quantifies recent dune movement and identifies areas of elevation loss and rapid horizontal migration that are threatening existing infrastructure. The Bald Head Island study examines pre- and post-nourishment beach evolution. The dynamics of beach topography, its geometric properties and estimates of eroded and deposited sand volumes were determined by combining lidar elevation data (1997-2000) with quarterly RTK-GPS measurements. Spatio-temporal analysis confirms the relative stability of the central “pivot point” beach section and reveals that the beach changes its shape from convex east of the pivot point, to concave to the west of it in 1997-98 and reversed shapes in year 2000. The pivot point also divides the beach into two sections that exhibit markedly different responses to nourishment. Although the entire length of nourished beach retreated, the analysis reveals that the western section lost all nourished sand offshore, whereas in the east section, significant sand volume was pushed up onto the beach, creating potential for recovery.

Key Terms: digital elevation model, beach erosion, sand dune, lidar, Kinematic GPS, topographic analysis

INTRODUCTION

Over the past decade, the standard 30m USGS Digital Elevation Model (DEM) has been successfully used for a wide range of earth science applications. However, its resolution and accuracy were not sufficient for representation of many coastal low-relief landscapes with features (e.g., beach dunes, berms, scarps) that require one order of magnitude higher resolution for adequate digital representation (1-3 m, Woolard and Colby, 2002). Acquiring such data for larger areas at short time intervals (one year and less) using traditional ground based surveys or photogrammetry would be prohibitively time consuming and expensive. Therefore, monitoring of coastal change has until recently been 2-D, focusing on shoreline evolution (that could be extracted from aerial photography) supported by a limited set of shore perpendicular profiles. Neither the 30m DEMs generated at time intervals of decades nor 2-D shoreline and profile mapping can fully capture the rapid coastal changes caused by natural processes or human intervention. For example, identification of protective beach dune loss, assessment of moved sand volumes, or evolution of nourished beaches are changes that can influence the design of large coastal management projects (often costing millions of dollars). Accurate data and a better understanding of coastal topographic change can significantly improve the success rate of such coastal engineering projects.

Recent development of Real Time Kinematic GPS (RTK-GPS) and Light Detection and Ranging (lidar) technologies have dramatically changed the efficiency of 3-D mapping and made repeated high resolution measurements of topography feasible for large areas (for example, an airborne lidar typically acquires millions of x,y,z points with 1-3m spacing per hour). Highly automated data acquisition requires processing, analysis, and visualization of massive volumes of georeferenced data, often acquired within different computational environments and formats. GIS is a natural choice for integration and analysis of this type of data; however, a traditional cartography oriented 2-D GIS approach is not sufficient (Raper, 1999). Recent developments of modular and extendable proprietary GIS tools, as well as emergence of Open Source GIS (Neteler and Mitasova, 2002), have created an opportunity to extend the range of GIS applications to new areas, including oceanography and coastal studies. Advanced 3-D GIS tools substantially increase efficiency in data processing and provide the capabilities to gain new insights into geospatial aspects of complex coastal systems. GIS is becoming an important tool in several areas of coastal research and management, such as monitoring, analysis and risk assessment, prediction of impacts using modeling and simulations, as well as in planning and decision support (NOAA, 2000; Wright and Bartlett, 1999).

To explore the new possibilities for assessment of rapid coastal change we have developed a methodology for 3-D analysis of coastal topography evolution based on existing high resolution lidar-based elevation data combined with low cost, on-ground RTK-GPS surveys. The value of such analysis is illustrated by applications to coastal North Carolina sites that face significant management challenges.

METHODS

High resolution elevation data were acquired for two North Carolina locations: a) the sand dune field at Jockey's Ridge State Park and b) a beach on Bald Head Island (Figure 1). Both areas have highly dynamic topography and display complex interactions between natural processes and human impacts. In the first case, the rate of dune field movement had been underestimated when the State Park was established in 1974 (Jude et al., 2000). As a result, the subsequent migration of dunes outside the park boundaries has posed significant management challenge. The second area, the south shore of Bald Head island, has been experiencing chronic beach erosion and serious concerns have been raised about the impacts of a recent navigation channel dredging project in the adjacent Cape Fear river. To assess the evolution of these two areas and evaluate effectiveness of implemented management strategies, a GIS database was established and a procedure developed for integration of the relevant spatio-temporal data to support continued analysis of on-going changes. The methodology involves data acquisition, preprocessing (including georeferencing, projection, and rectification typically performed within the surveying systems), importation into a GIS, transformation to a common raster data model, and finally, spatial and spatio-temporal analysis and visualization.

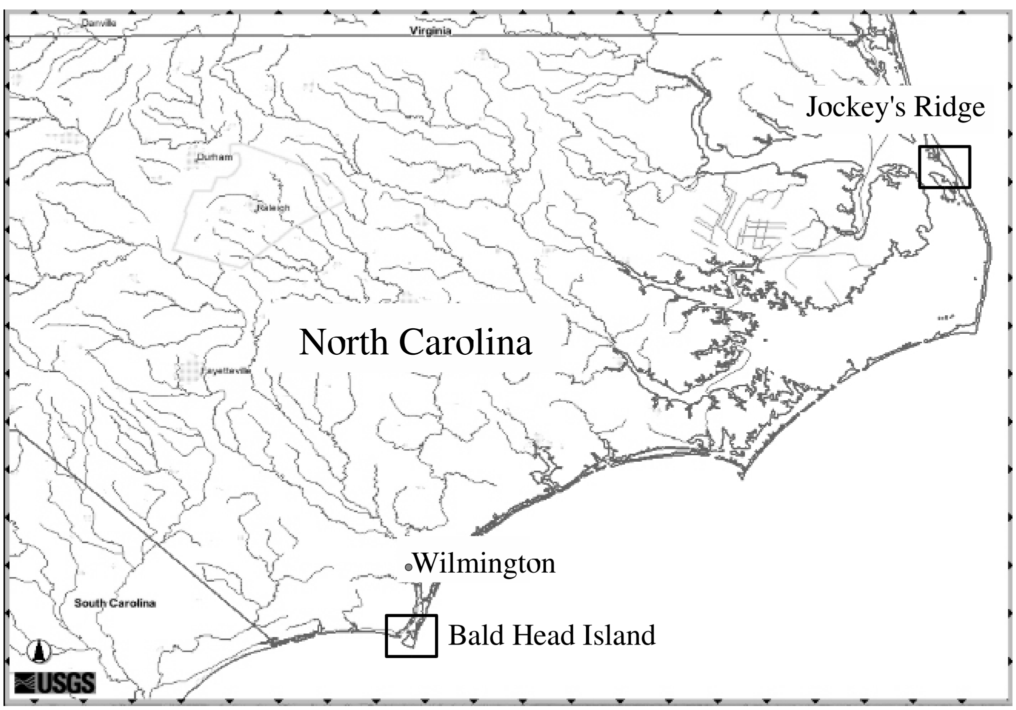

Figure 1. Location of the study areas on the Outer Banks of North Carolina.

Data acquisition

Assessment of rapid topographic change was based on elevation data acquired by lidar and RTK-GPS. Lidar surveys of the North Carolina coast were performed for the Airborne Lidar Assessment of Coastal Erosion (ALACE) project during the years 1997, 1998, 1999, 2000 (NOAA Coastal Services Center, 2002; Stockdon et al., 2002). The Airborne Topographic Mapper II (ATM-II) system was used to sample topography from 700m altitude, which generates 200-300m meter wide overlapping swaths with elevation measured every 1-3 meters (for technical details see NOAA and USGS, 2002). Reported vertical accuracy in open areas is 15 cm (for detailed analysis of accuracy for quantifying beach changes see Sallenger et al., 2003). The results of the lidar surveys are dense "point clouds" of *x,y,z* data without classification (e.g., for breaklines or structures) and with significant oversampling in the overlapping areas. The data from the project are available for download from Lidar DAta Retrieval Tool (LDART) web site (LDART, 2002). Unfortunately, the ALACE program ended systematic annual mapping in 2000 and now contracs with the private sector based on coastal management needs, so only limited high resolution elevation data are available after 2000 .

RTK-GPS has been employed to capture the continuing topographic changes in our study areas. This technique, with a reported 10cm vertical accuracy, provides less detailed DEM, but it is much easier to deploy. RTK-GPS has been applied for 2-D shoreline mapping for several years (e.g., List and Farris, 1999) and methodology has been developed for cost effective, rapid 3-D beach monitoring (for technical details see Morton et al., 1999; Freeman, et al. 2003; Bernstein et al., 2003). For the Jockey's Ridge dune field only dune crests and peaks were surveyed on foot, due to the restrictions of vehicle movement within the park. On the Bald Head Island beach, elevations were automatically sampled at 3-6 m intervals along the path of the all-terrain vehicle used in the surveys. While the density of along-path data was comparable to that for lidar, for practical reasons of time and cost, the distance between paths was at least a magnitude larger than the along-path resolution (20-30 m for shore-parallel paths and 200-300 m for shore-perpendicular paths). This spatial anisotropy in data acquisition presented challenges for analysis that required modification of spatial interpolation method. The issue of optimal beach sampling pattern for RTK GPS continues to be studied and some preliminary results were reported by Bernstein et al. (2003).

By comparison to data obtained by traditional surveys or manual digitization, which typically include only a relatively small number of carefully selected and labeled points, data collection using modern, highly automated surveying technologies presents a number of challenges for processing:

- data sets are massive with oversampling and noise,
- coverage may be anisotropic (RTK- GPS) and/or heterogeneous with gaps,
- lidar data have no attributes except elevation, so objects, features and breaklines must be identified during post-processing, often using the reflectance or imagery data
- mapping is very efficient (on the order of 10^3 points/hour for RTK-GPS and 10^6 points/hour for lidar), therefore it can be repeated at selected time intervals (e.g. annually) leading to time series of elevation surfaces that require solid support for processing of spatio-temporal data.

To meet these challenges, GIS tools should be capable of handling massive data sets and elevation surfaces need to be represented by a digital data model that supports integration and comparison of data with different sampling patterns. Although a Triangular Irregular Network (TIN) data model is commonly used for representation of elevation surfaces, each data sampling has a different TIN structure, which makes it difficult to achieve a consistency needed for comparison of temporal series of data. Therefore, grid representation based on the high accuracy spatial approximation method described below, was selected as a more appropriate data model for GIS data analysis and visualization. Open Source GRASS GIS (Neteler and Mitasova, 2002) was used as a GIS environment, because of its unique spatial interpolation, topographic analysis, 3D visualization tools, and easy handling of large data sets. The possibility to modify the code to fulfill the needs of a new application also contributed to this selection.

Spatial approximation and topographic analysis by RST

Computation of high resolution DEMs from lidar and kinematic GPS data was performed by the function called Regularized Spline with Tension and Smoothing (RST, Mitasova and Mitas, 1993; Mitas and Mitasova, 1999). The method was specially designed to meet the requirements for topographic analysis by allowing simultaneous computation of slope and curvatures based on derivatives of the RST function (Mitasova and Hofierka, 1993). Several studies have demonstrated its high accuracy (e.g., Mitasova and Mitas, 1993; McCauley, 1995; Hofierka et al., 2002). The quad-tree based segmentation procedure ensures the continuity of the resulting surface and, at the same time, makes the computation efficient for large data sets (Mitasova et al., 1995). Comparison of this method in terms of its design, properties, and applications with other spatial interpolation methods (such TIN-based methods and kriging) is discussed in Mitas and Mitasova (1999). The equations for the interpolation function and its partial derivatives, as well as equations used for the computation of slope, aspect and curvatures, can be found in Neteler and Mitasova (2002).

The RST function imitates a behavior of a thin flexible sheet forced to pass through or close to the data points. Its tension parameter (Franke, 1985; Mitas and Mitasova, 1999; Hutchinson, 1989) tunes the sheet properties between that of a stiff thin plate (leading to a very smooth surface) and an elastic membrane (leading to a rough surface with extreme in each data point). The tension parameter is scale dependent and can be generalized to a tensor which enables modeling of anisotropy (Mitasova and Mitas, 1993), a feature that was especially important for modeling beach morphology based on RTK-GPS survey. The RST method also supports smoothing of noisy data using spatially variable smoothing parameter that controls the deviations between the resulting surface and given data points. The smoothing and tension parameters can be selected empirically or by minimization of the predictive error estimated by a cross-validation procedure (Mitasova et al., 1995; Hofierka et al., 2002).

Processing point data from lidar

For lower resolution analysis, with the size of grid cells larger than the distances between points (5m and more), simple gridding methods such as averaging, provided directly by the LDART web site (LDART, 2002), are sufficient. For example, the difference between the sand volume loss estimated from a 5m resolution gridded DEM and from a 2m resolution interpolated DEM was only 3% of the estimated volume (Mitasova et al., 2003). However, for analysis of active areas where it was important to identify the features having characteristic lengths close to the spatial sampling interval, the RST spatial approximation provided superior results as illustrated by Figure 2. While simple gridding at 5m resolution provided adequate representation of the overall shape of the dune, the 1m resolution DEM computed by the RST method revealed fences partially buried in the sand and allowed us to identify the sharp dune crests and slip-faces. For the beach survey, interpolated surfaces captured features that are important indicators of beach stability (e.g.,berms) or active erosion (scarps). To reduce the impact of noise, present in the lidar measurements, a small, empirically selected value of smoothing was used.

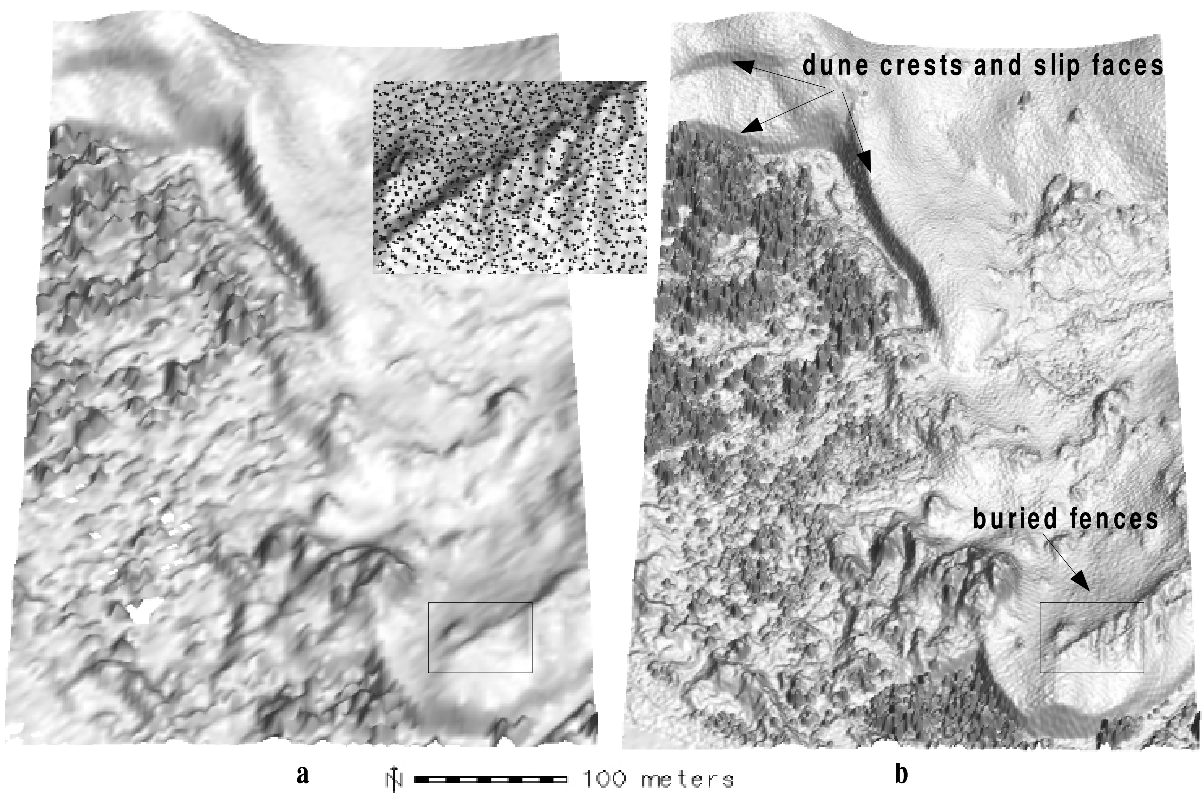

Figure 2. Gridding lidar data for Jockey's Ridge: a) assigning points to 5m grid, the highest resolution that creates a continuous surface, b) approximating to 1m grid using RST leads to a DEM that reveals buried fences and provides crisp representation of dune crests without the need to define breaklines.

Processing RTK-GPS data

Gridding techniques for data obtained by traverse sampling using various interpolation methods were evaluated by McCauley (1995) in the context of RTK-GPS mapping of agricultural fields. This study demonstrated that the results obtained by the RST function and nearest neighbor method were better than the results from inverse distance weight interpolation and kriging. Compared to a typical agricultural field, the traversing and gridding of coastal topography poses specific challenges due to terrain anisotropy caused by wind- and wave-generated sediment-transport processes. While lidar data provide sufficient sampling density to capture the anisotropic beach features, obtaining adequate representation with RTK-GPS was more difficult. Approximation at resolutions similar to the distances between the traverse paths (30m grid cell size and more) was straightforward, however, smaller features mapped along the paths were lost. To capture at least some of this detail by using higher resolutions (5m grid cell size and smaller), approximation with anisotropy was used (Figure 3). The isotropic approximation resulted in a surface with artificial waves (undershoots and overshoots between the shore-perpendicular profiles as shown by the unrealistic pattern of contours in Figure 3b), the introduction of anisotropy in the direction of long-shore profiles removed the artificial features and lead to a typical, relatively straight beach topography (Figure 3c). Similarly as for kriging, anisotropy was applied as a rescaling factor in a given direction. The direction was estimated within the GIS as a direction of the longshore profile, but it can be

also measured in the field or estimated by geostatistical analysis. In the current RST implementation, anisotropy is spatially uniform, so areas with different anisotropy need to be split into subsections. This was not necessary for our study area but for more general applications support for continuously variable anisotropy needs to be added to RST to make the application to curved shoreline areas more efficient.

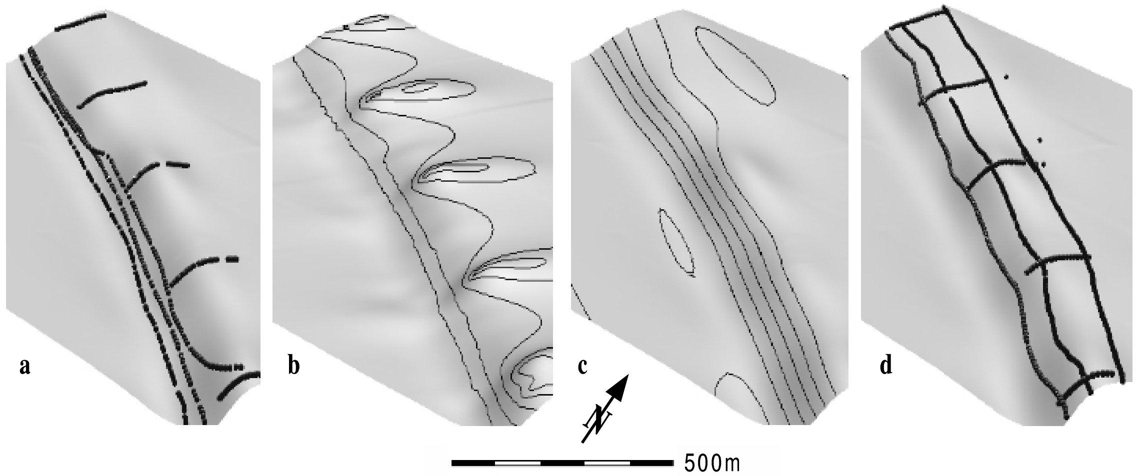

Figure 3. Interpolation of RTK-GPS data by RST: a) traditional survey pattern used in 2001: shoreline and cross-shore profiles; b) approximation of a DEM from traditional survey pattern using RST without anisotropy, c) more realistic beach representation is achieved from the same data by using RST with anisotropy; d) survey pattern, better suited for computation of DEM, used for 2002 and 2003 measurements but anisotropy is still needed to avoid artifacts.

Analysis of topographic change

Identification and quantification of changes in topography was performed within GIS using standard GIS tools, such as map algebra and spatial query combined with interactive 3-D visualization. In the first application, migration of the dune field and change in elevation at selected locations was estimated using spatial query and distance function applied to the combination of interpolated lidar-based DEM and RTK-GPS traverse data. The assessment of recent change in elevation and sand volumes for the Bald Head Island beach was based on computation of first- and second-order differences between the interpolated surfaces using map algebra. The differences were used to estimate spatial distribution and total amounts of sand volume loss and gain and to identify erosion acceleration.

RESULTS

Integration of modern surveying data from lidar and RTK-GPS allowed us to perform spatio-temporal analysis of monitored coastal areas at high spatial and temporal resolutions, quantify the observed changes and gain unique insights into ongoing coastal processes.

Dunes at Jockeys Ridge State Park

Jockey's Ridge, the largest active sand dune field on the US east coast, lies within a 400 acre state park on the North Carolina Outer Banks (Figure 1, Figure 4). Encroachment of the dunes toward a road and homes on the southern border of the park has been a continuing land management problem. Judge et al. (2000) compared the dune topography based on contour maps and photogrammetric data produced in 1950, 1974 and 1995. This work demonstrated a long term trend of southward dune migration, a lowering of the highest dune elevations (especially the main ridge), and concomitant sand volume increase at lower elevations. In recent years, sand fencing was installed on the south dune to slow its migration.

To quantify the rate of horizontal and vertical movement of Jockey's Ridge after the installation of fences, the existing lidar data, acquired as part of the ALACE program, were combined with our RTK-GPS surveys. Because the ALACE program focused on a relatively narrow strip of the coastal topography and did not extend to the Jockey's Ridge area, only a single survey was performed upon the park's request in 1999. With a focus on dune migration, the RTK-GPS survey was conducted along dune crests - linear topographic features that are easy to identify in the field and that are good indicators of the dune movement (Figure 4).

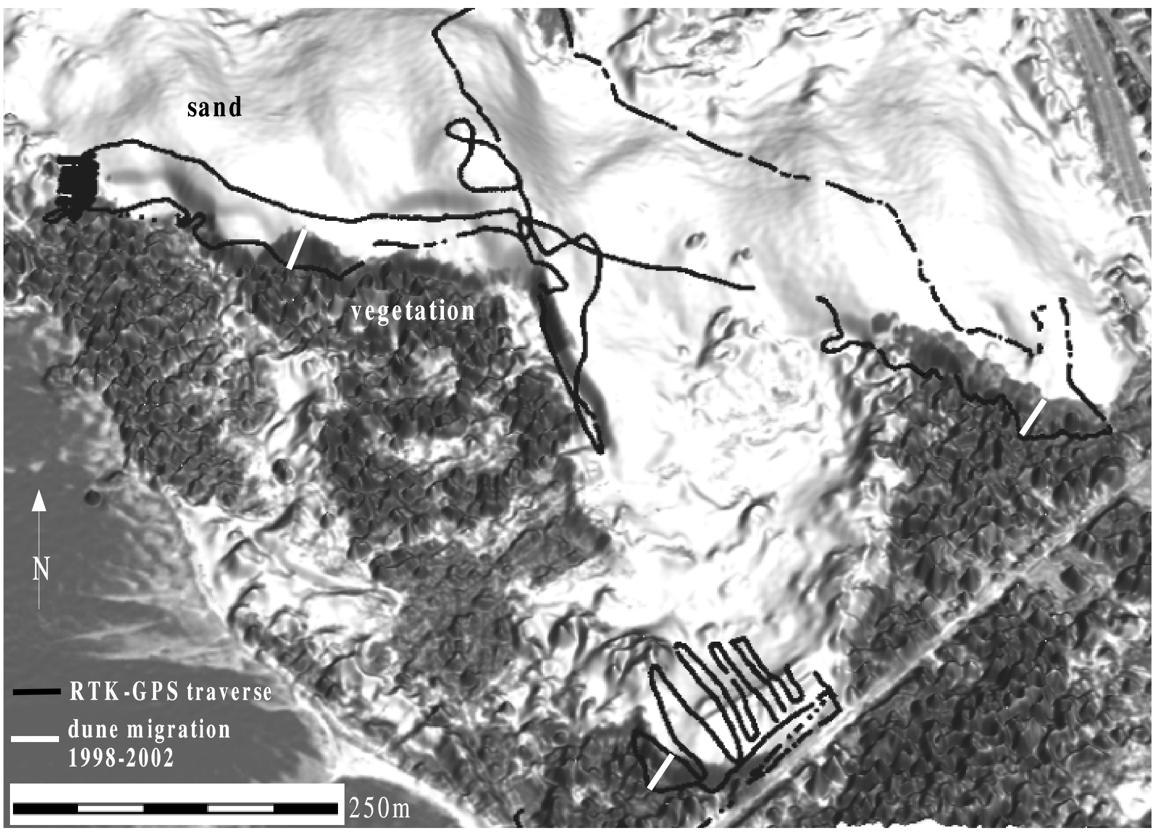

Figure 4 Jockey's Ridge dune field: 3D view of 1999 lidar-based DEM with digital orthophoto draped over the surface. The 2002 RTK-GPS survey traverse (black line), runs in several locations inside the areas covered by vegetation in 1998 (dark gray).

The RTK-GPS traverse data collected in the winter of 2002 were compared with the 1m resolution DEM approximated by RST using the 1999 lidar data. The high resolution was necessary for representation of dune crests as sharp edges and for estimation of their location with horizontal precision of 1m. To identify the exact locations of dune crests and slip faces, profile curvatures of the elevation surface were computed simultaneously with approximation. The curvature analysis was performed at 1m resolution at three different levels of detail which were determined by the tension and smoothing parameters (Figure 5). Based on visual inspection, the surface with tension=400 provided the most useful result (Figure 5b). Higher tension captured the lidar noise pattern (Figure 5a); lower tension smoothed-out the crests but it provided clear delineation of the main dune shoulders (Figure 5c). Because the density of lidar data was so high, the sharp edges of dune crests were captured without the need to define them as breaklines.

In addition to the lidar and RTK-GPS data, an infrared orthophoto (IR-DOQQ) at 1m resolution was available for 1998. This image was used to assess horizontal dune movement in those areas where the dune has migrated onto pre-existing vegetation. The length and orientation of maximum horizontal dune movement were measured perpendicularly to the three main dune crests (Table 1). Vertical change was computed along the RTK-GPS paths by transforming the RTK-GPS traverse to a 1m resolution raster representation and then computing the difference between the 1999 lidar DEM and 2002 RTK-GPS elevations using map algebra. The maximum elevation changes are reported in Table 1. The comparison of the 1998-1999-2002 horizontal dune crests locations shows that all dune crests have moved in the south/south-west direction between 20m to 40m, thus threatening the road and homes along the south boundary of the park.

After installation of fences, the primary direction of the south dune movement has shifted towards the west. The differences in 1999-2002 elevations indicate that the dune is flattening, loosing over 2m at its highest point (Table 1). Gains in elevation more than 2m were observed in lower elevation areas where protection fences were installed, proving their effectiveness in trapping sand. However, the most significant increase in elevation (over 4m) was observed in low elevation areas that were overtaken by migrating dune crests. These changes are in general agreement with the analysis by Judge at al. (2000) however, the loss of elevation on the main ridge seems to be accelerating.

Table 1 Maximum vertical and horizontal dune change in [m] at different sections.

location	horizontal change 98-99	horizontal change 99-02	migrationd irection	vertical change 99-02	elevation 1999	elevation 2002
main dune peak	-	-	-	**-2.1**	25.7	23.6
main dune crest A	-	45	S	3.9	14.3	18.2
main dune crest B	10	18	S	4	6.5	10.5
south dune peak	-	-	-	**-3.0**	10.8	7.8
south dune crest	7	21	SW	4.7	1.4	6.1
south dune fence C	-	-	-	1.7	3.6	5.3
south dune fence D	-	-	-	2.8	7.2	10
east dune near peak	-	-	-	**-1.7**	15.3	13.6
east dune crest	16	25	SW	3	1.7	3.7

The quantitative assessment of dune movement made possible through the use of state-of-the-art mapping technologies and integrated GIS analysis has provided new insight into the short-term evolution of the Jockey's Ridge sand dune field. Through detailed spatial analysis, areas of relative dune stability were located, areas and direction of active dune translation requiring land management intervention were identified, and rates of change over the time intervals 1998-1999-2002 were quantified.

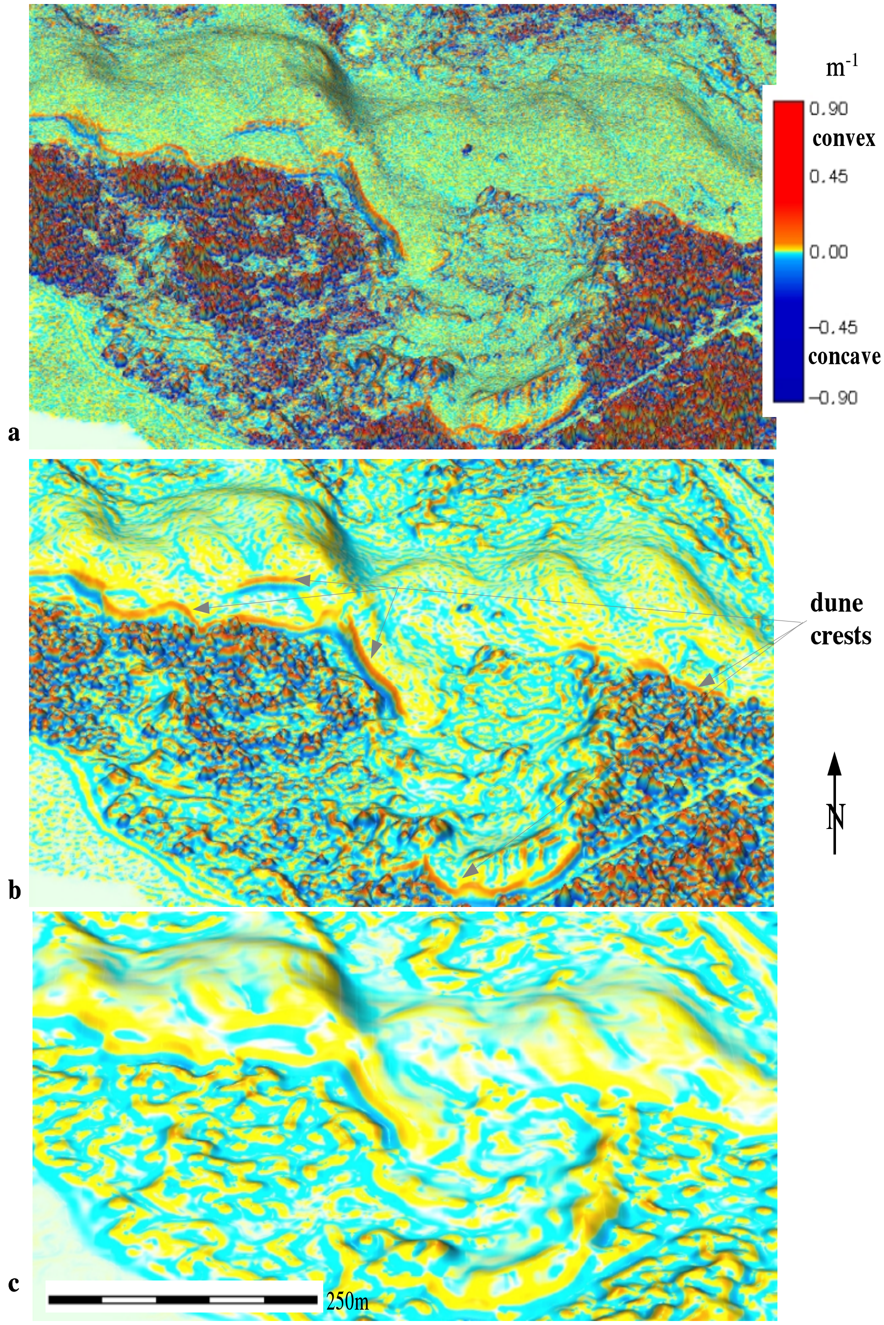

Figure 5. Profile curvature computed at 1m resolution at different levels of detail controlled by tension and smoothing parameters: a) high tension/low smoothing (800/0.05) captures the noise, b) moderate tension/smoothing (400/0.5) clearly captures the dune crests and slip-faces and smooths out the noise, c) low tension/high smoothing (200/5) extracts only the main shoulders and valleys.

Bald Head Island

The barrier island study area near the mouth of the Cape Fear river displays complex interactions between anthropogenic activities and natural processes. In 2000, the US Army Corps of Engineers (USACE) has started one of its largest coastal dredging project in this area, the Wilmington harbor navigation channel re-alignment and deepening (Figure 6) in year 2000 (US Army Corps of Engineers, 2003).

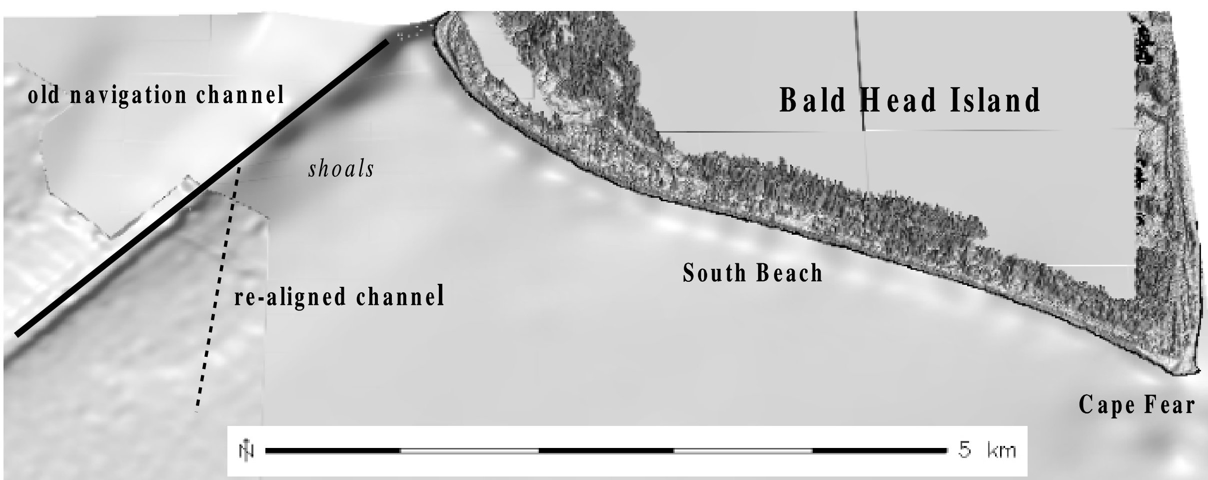

Figure 6. Model of August 2000 topography (lidar) and bathymetry, including the pre-dredging location of the channel at the Bald Head Island. Bathymetry data are courtesy USACE Field Research Facility at Duck, NC (http://www.frf.usace.army.mil/).

The impact of this engineering project on the neighboring beaches has been a major concern (Cleary et al. XXX), and in response to these concerns, some of the dredged material has been placed on the adjacent beaches of Bald Head Island and Oak island that were most likely to be impacted by the project. Quantification of short-term spatial change in this dynamic environment before and after the project is crucial for understanding the beach response to the substantial modifications in nearby bathymetry and for finding sustainable management solutions.

The South Beach of Bald Head Island has been a major focus of the monitoring efforts. Analysis of historical maps (Cleary et al., 1989) has shown rotation of the South Beach shoreline around relatively stable central pivot point area (Figure 7). The counterclockwise rotation accompanied by growth of the west section of the beach (over 800m) was reversed in 1960s when Wilmington harbor channel was deepened to 12m and, in some places, reached bedrock. While the study by Cleary et al. (1989), based on maps and aerial photographs, provided insight into the long term 2-D evolution of shoreline, the available data could not be used to assess changes in the beach morphology or to estimate the volume of eroded sand. The lidar ATM surveys (NOAA-USGS, 2002) performed in 1997, 1998, 1999, and 2000 provided excellent data for assessment of the “pre-project” beach evolution including the impacts of two major hurricanes (Bonnie in 1998 and Floyd in 1999). After the completion of the nourishment project in summer 2001, ongoing quarterly RTK-GPS surveys have provided less detailed, but adequate representation of beach evolution.

To quantify the pre-nourishment topographic change the annual lidar elevation data were approximated to 2m resolution grids by RST. Because the lidar survey extends to the sea, as well as beyond the beach into vegetated and developed areas, a mask was created that restricts the analysis only to the 4.5km long and between 120m to 70m wide open beach covering an area of 36ha. The difference between the 1997 and 2000 elevation surfaces within this area indicates that the beach sand loss was around 375,000 m^3, of which about 15% was transported landward over the beach dune, increasing the elevation up to 1.5m in some areas; the remainder was lost offshore. Temporal distribution of erosion was relatively steady between 120,000 -

160,000 m^3 annually, while sand gains due to accretion and overwash varied between 24,000 - 42,000 m^3 per year. Both erosion and accretion rates were spatially variable and their distribution had significant impact on the cross-shore beach shape. Lidar data from 1997 define a wide, convex beach with well-developed berms in the west section of the studied area and a concave shape with a steep scarp in the east (Figure 7). The shape of the beach transforms smoothly from convex to concave along the relatively stable pivot point area (Figure 7). By 2000, after two major hurricanes, the scarp at the east end had eroded completely, changing the east section beach shape to uniform with low slope. By comparison, rapid erosion of the berms in the west section changed the beach shape there from convex to concave with a well-defined scarp. Second order differences show accelerating erosion at the foot of the beach scarp and deceleration on the lower part of beach with gentler slopes. This indicates that the scarps may be accelerating erosion due to their steep slope in absence of any significant wind sand transport to fill the concave areas at the foot of the scarp and lower the slope. However, currently there are almost no data showing the change of beach geometry due to the sand transport by wind.

The beach was nourished with sand dredged from the re-aligned channel in the spring and summer of 2001, changing its shape to convex along the entire length of the beach (Figure 7). Based on the RTK-GPS survey performed in December 2001, the nourished beach quickly gained a shape distribution similar to the one observed in 2000. The May 2002 data indicate that the intense erosion observed before nourishment had continued in the west section, close to the area with most significant changes in bathymetry. The differences between the December 2001, May 2002, and September 2002 data show that the sand volume loss continued at an increased rate and that nourishment did not have a substantial impact on the pattern of erosion process (Figure 7). The end of the east beach section close to Cape Fear was extending, following the trend observed in 2000, and this trend had been enhanced by the beach nourishment. The central part of the beach, around the pivot point, has been relatively stable both before and after the nourishment (Figure 7). The RTK-GPS survey conducted after tropical storm Gustav in September 2002 produced a particularly interesting observation. While comparison based solely on 2-D shoreline position shows retreat along the entire length of the beach (Figure 7), 3-D analysis reveals different behavior for the east and west sections. The west section lost most of its new sand within a year of nourishment and, in some areas, erosion has moved the beach inland beyond the 2000 pre-nourishment surface. By contrast, a substantial portion of sand in the east section was pushed up onto the beach, increasing elevation in some areas up to 0.6 m, creating conditions for partial beach recovery.

This analysis indicates that, under the current conditions, the west section of the beach will only be sustained through frequent nourishment or relocation of the deepend channel. A better understanding of nearshore processes and new nourishment approaches may be necessary to return the beach to self-sustaining dynamic equilibrium.

CONCLUSIONS

The analysis of rapid topographic change at two different locations on the North Carolina coast demonstrate that the integration of modern mapping techniques and well-designed geospatial modeling and analysis tools can provide new insights into the short term evolution of coastal landscapes by quantifying topographic change at high levels of spatial and temporal detail. Such results can provide important information for land management decision making as well as methodologies and tools that can be applied to other coastal regions.

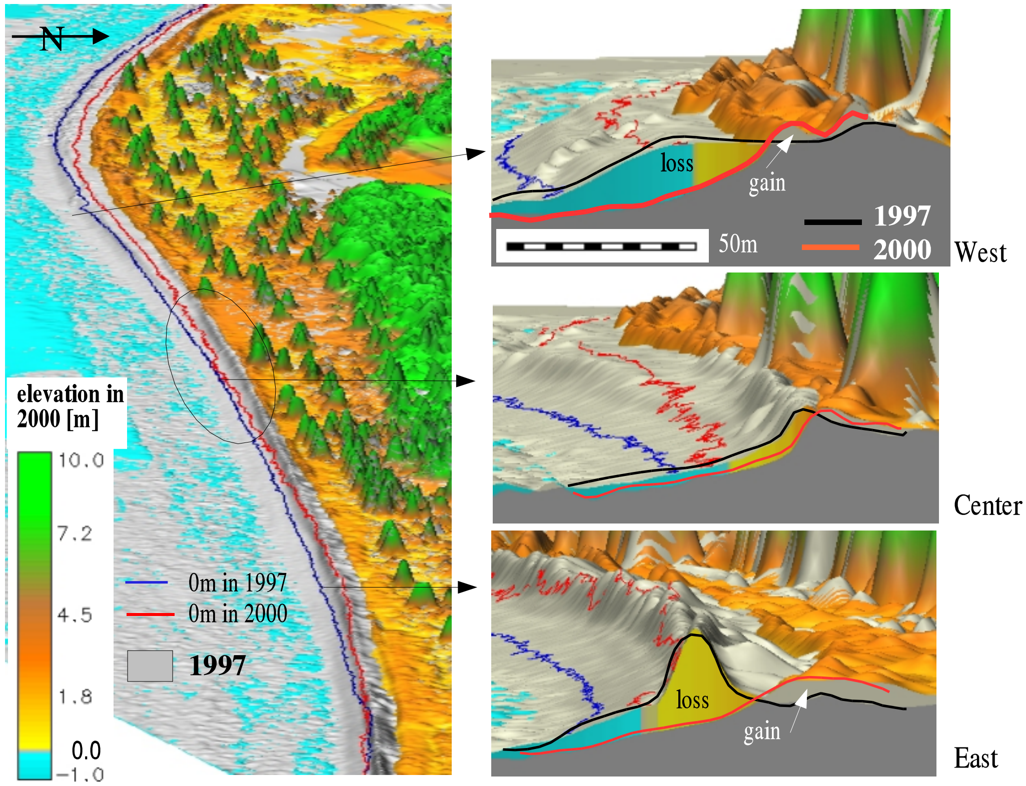

Figure 7. Overlay of lidar-based 1997 and 2000 elevation surfaces, visualized using multiple surfaces and cutting planes. Detail shows change in the west (convex to concave), central (relatively stable) and east (concave to convex) crossections.

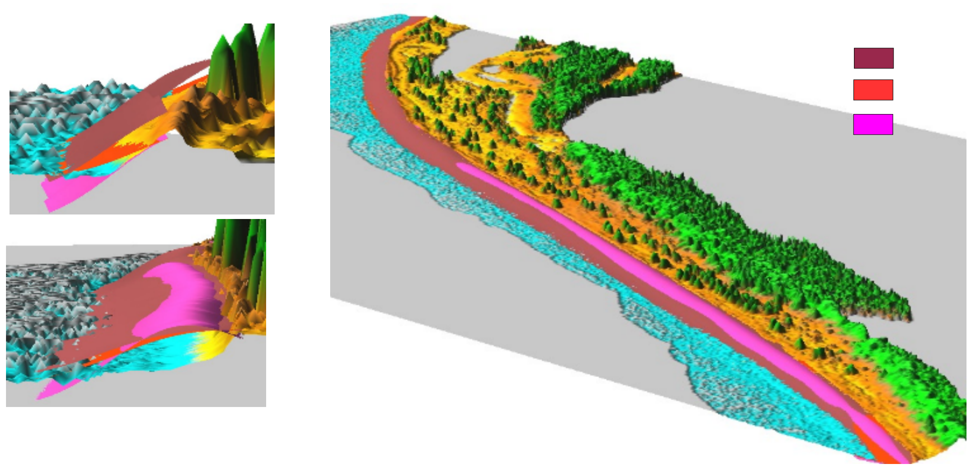

Figure 8. Overlayed lidar-based 2000 elevation surface and RTK-GPS-based Dec. 2001, May and September 2002 surfaces. Crossections show complete erosion of nourished beach in the west section and erosion accompanied by redistribution of sand on the beach in the central and east sections.

Application of our methodology to the Jockey's Ridge sand dune field has confirmed the long term trend of dune erosion and migration with possible acceleration of this process in recent years. The main ridge has lost almost half of its elevation since 1950 and the horizontal movement of crests continues at rates 20-40m per year. The recent placement of downwind fences has been effective in trapping sand, however, the impact is limited to the lower elevation areas. The ongoing study of this area will be further enhanced by the recent release of North Carolina floodplain mapping elevation data obtained by a different type of lidar. This new data will allow us to compare the spatial pattern and volumes of erosion and accretion after the installation of fences with those reported in a study by Jude et al. (2000).

The RTK-GPS surveys allowed us to study Bald Head Island South beach as a complex, continuous surface, analyze its geometry, and quantify the beach response to changes in bathymetry and nourishment. Using 3-D visualization of multiple surfaces it was possible to detect important aspects of beach evolution, such as change in the beach shape and the different fate of transported sand in the east and west sections of the beach. The study provided important information for coastal management related to effectiveness of beach nourishment and possibilities for improving beach stability.

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FIGURE CAPTIONS

Figure 1. Location of the study areas on the Outer Banks of North Carolina.

Figure 2. Gridding lidar data for Jockey's Ridge: a) assigning points to 5m grid, the highest resolution that creates a continuous surface, b) approximating to 1m grid using RST leads to a DEM that reveals buried fences and provides crisp representation of dune crests without the need to define breaklines.

Figure 3. Interpolation of RTK-GPS data by RST: a) traditional survey pattern used in 2001: shoreline and cross-shore profiles; b) approximation of a DEM from traditional survey pattern using RST without anisotropy, c) more realistic beach representation is achieved from the same data by using RST with anisotropy; d) survey pattern, better suited for computation of DEM, used for 2002 and 2003 measurements however, anisotropy is still needed to avoid artifacts..

Figure 4 Jockey's Ridge dune field: 3D view of 1999 lidar-based DEM with digital orthophoto draped over the surface. The 2002 RTK-GPS survey traverse (black line), runs in several locations inside the areas covered by vegetation in 1998 (dark gray).

Figure 5. Profile curvature computed at 1m resolution at different levels of detail controlled by tension and smoothing parameters: a) high tension/low smoothing (800/0.05) captures the noise, b) moderate tension/smoothing (400/0.5) clearly captures the dune crests and slip-faces and smooths out the noise, c) low tension/high smoothing (200/5) extracts only the main shoulders and valleys.

Figure 6. Model of August 2000 topography (lidar) and bathymetry, including the pre-dredging location of the channel at the Bald Head Island. Bathymetry data are courtesy USACE Field Research Facility at

Duck, NC (http://www.frf.usace.army.mil/).

Figure 7. Overlay of lidar based 1997 and 2000 elevation surfaces, visualized using multiple surfaces and cutting planes. Detail shows change in the west (convex to concave), central (relatively stable) and east (concave to convex) crossections.

Figure 8. Overlayed lidar-based 2000 elevation surface and RTK-GPS-based Dec. 2001, May and September 2002 surfaces. Crossections show complete erosion of nourished beach in the west section and erosion accompanied by redistribution of sand on the beach in the central and east sections.