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Remote Sensing of Barrier Island Morphology: Evaluation of Photogrammetry-derived Digital Terrain Models

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ABSTRACT

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This study evaluates the use of detailed, highly accurate digital terrain models (DTMs) in the study of coastal processes. DTMs are digital cartographic representations of the continuous surface of the ground by a large number of selected points with known X, Y, and Z coordinates. Advances in Geographic Information Systems (GIS) and terrain modeling software allow these models to be easily manipulated for analysis of coastal morphology. The DTMs in this study were derived using high-accuracy photogrammetric techniques.

We compare 101 ground-surveyed beach and dune profiles and profiles derived by interpolation of a terrain model of the area. The model is found to be sufficiently accurate to measure changes in the dune field. Aerial surveys currently cost 1.5 times more than ground surveys. Examples of the spatial richness of the DTMs are also presented, including one application in coastal hazard mitigation.

ADDITIONAL INDEX WORDS: *Dune mapping, beach mapping, digital photogrammetry, digital terrain model, beach profiles.*

INTRODUCTION

Low altitude aerial photography is a primary data source used in the study of barrier island morphology and shoreline change (*e.g.*, LANGFELDER *et al.*, 1970; DOLAN *et al.*, 1978; CROWELL *et al.*, 1991). Photogrammetric techniques for processing controlled vertical aerial photography have been used since World War II to produce highly accurate topographic maps, compliant with National Mapping Accuracy Standards (SLAMA *et al.*, 1980). However, many aerial photo sets, both recent and historic, lack ground control placed at the time of the photography, making the three-dimensional processing of these data difficult, if not impossible. Researchers have therefore focused much attention on various geo-referencing techniques to rectify uncontrolled modern and historic photography with respect to the horizontal plane (X-Y or top view) (*e.g.*, THIELER and DANFORTH, 1994). Although this type of rectification has been useful in identifying horizontal change of landforms, including inlet migration, shoreline erosion, and storm overwash fans (*e.g.*, FISHER and SIMPSON, 1979; WEBB *et al.*, 1989; DAVIDSON-ARNOTT and FISHER, 1992), it is unable to capture vertical changes.

Traditionally, when elevation data were needed, shore perpendicular transects were surveyed using traditional techniques at a specified interval along the shoreline. Coastal engineers have measured beach and dune change mostly by interpolation of these ground-surveyed transects. Profile change has long been used as a measure of dune erosion and is used almost exclusively in current storm-induced beach and dune erosion models (*e.g.*, ZHENG and DEAN, 1997; WISE *et al.*, 1996; KRIEBEL, 1990). Because of cost and time factors, these profiles are typically widely spaced, and thus have limited accuracy for volume change calculations.

For this reason, researchers are investigating new techniques designed to provide detailed spatial coverage of elevation differences. Techniques with application along coastal regions include softcopy photogrammetry using low-altitude aerial photography, (OVERTON and FISHER, 1996), small-format aerial mapping with softcopy techniques (HAPKE and RICHMOND, 2000), and LIDAR (LIght Detection And Ranging) (see KRABILL *et al.*, 2000; BROCK *et al.*, 1999; CARTER and SHRESTHA, 1997). These investigations indicate a high degree of spatial variability in coastal changes and the techniques show promise in improving the quality of coastal morphologic data. However, little published work demonstrates their accuracy in coastal areas, often due to a lack of data for comparisons.

Softcopy photogrammetry is the term used to describe the photogrammetric work flow in a completely digital environ-

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ment (GREVE, 1996). Ground-controlled aerial photography is processed into digital orthophotos and elevation models using standard photogrammetric techniques. In an orthophoto, the positional displacement due to terrain relief and camera distortion is removed to create a scaled map. Orthophotos are generated from stereo pairs of aerial photos, using standard techniques based on camera attributes, altitude, aircraft attitude and ground control. When a photogrammetrist creates a digital orthophoto, he or she must collect digital terrain model (DTM) points (WELCH, 1989). The DTM is a digital cartographic representation of the continuous ground surface by a large number of selected points and breaklines with known X, Y, and Z coordinates. A DTM differs from a digital elevation model (DEM) in that the known points can be non-uniformly spaced, and breaklines are used, providing more accuracy in areas of sudden topographic change. The term DEM generally refers to a digital cartographic representation of land elevation at regularly spaced intervals in the X and Y directions (easting and northing or longitude and latitude). Contour maps can be generated by interpolation from this collection of points, yielding a spatially continuous model of the coastal topography. Depending on the grid size used for the DTM collection phase and the detail in the model, these types of remotely sensed data can have the advantage of providing much greater spatial detail than practical with ground surveys.

Softcopy photogrammetric techniques and DTMs are being used in a number of coastal applications, and represent advances in our ability to analyze coastal morphology. The digital processing of DTMs has promoted the development of terrain modeling software tools that allow the user to quickly and easily quantify topographical features and change. For perspective, contrast the ease in which volume change can now be calculated by subtracting two DTMs with previous work done using a mirror stereoscope and parallax bar to measure topographic changes in migrating dunes (HENNIGAR, 1980).

Digital processing has also promoted investigations that attempt to re-create historical topography from archived aerial photography. BROWN and ARBOGAST (1999) describe a project using digital photogrammetry, archived photography, and DTMs to analyze historic changes in a large coastal Michigan dune field. OVERTON *et al.* (1996) used aerial photographs dating to 1955 combined with GPS surveyed ground control to reconstruct the terrain of a North Carolina barrier island beach. These data were compared with 1992 topography and used to calculate long-term erosion rates for the area. The use of a DTM-derived contour position instead of a photo-identifiable wet-dry line for shoreline position has been examined as well (OVERTON and FISHER, 1996). The DTM is a common format for elevation data; DTMs derived from softcopy photogrammetry can be used in conjunction with data sets developed using other techniques, such as LIDAR or ground surveys.

DTMs can also be derived using existing contour maps. A normal workflow in photogrammetry includes collection of DTM data directly from a stereo model of the aerial imagery. Often contour lines are interpolated using these data and plotted on the orthophotos as final mapping products. (Original DTM points and breaklines may or may not be plotted on the contour maps, depending on the intended use.) In the absence of the original DTM data points and breaklines, DTMs can be re-created from the contour lines using digital terrain modeling software. However, these re-sampled data do not capture the original point elevations and have characteristic features that reveal their indirect source (GUTH, 1999).

This study evaluates the use of re-sampled digital terrain models in the study of coastal topographic change. Dune and beach profile data extracted from these DTMs developed from aerial photography are compared with ground survey data at 101 transects in Dare County, North Carolina. Dune characteristics and cross sectional areas from heel to toe are compared as well as horizontal position of various shoreface contours. An error analysis of the remotely sensed profiles is presented with respect to a variety of parameters. The remotely sensed topography is sufficiently accurate to quantify dune areas and dune characteristics such as peak elevation. The comparison of shoreface characteristics, however, reveals differences on some profiles; greater disparity was found closer to the ocean. A comparison of volumes calculated using interpolation of ground survey transects and the topographic surface of the DTM between one set of transects is presented to illustrate the spatial richness of the DTM data, and we give one typical application of these data for hazard mitigation.

DIGITAL TERRAIN MODEL ACCURACY

The theoretical accuracy of DTMs produced using photogrammetric techniques is dependent upon aircraft height during the aerial survey. The relationship between contour accuracy and flying height is as follows:

$$\mathrm{CI} = \frac{\mathrm{H}}{\text{C-factor}}, \qquad (1)$$

where CI is the contour interval, H is the flying height, and the C-factor is a constant property of the photogrammetric equipment (for high accuracy softcopy or analytic photogrammetry $C \cong 2000$) (SLAMA *et al.*, 1980; LIGHT, 1999).

The flying height H is related to the scale of the photography and the camera parameters as:

$$\mathrm{S} = \frac{f}{\mathrm{H}}, \qquad (2)$$

where S is the photo scale, f is the focal length of the camera (for a typical aerial survey camera, $f = 153$ mm), and H is the flying height (SLAMA *et al.*, 1980). These relationships give an indication of the best possible vertical contour accuracy of a DTM, assuming that the ground control accuracy is better than the contour accuracy indicated. If the ground control is not surveyed with a high-accuracy GPS or other precise system, it becomes the limiting factor. If the control accuracy is not limiting, however, the theoretical horizontal accuracy of a photogrammetry-derived DTM is approximately twice as good as the vertical accuracy. HUISING and VAESSEN (1997) note that in bare areas of low relief, such as beaches, a lack of texture in the aerial photos may result in an increase in

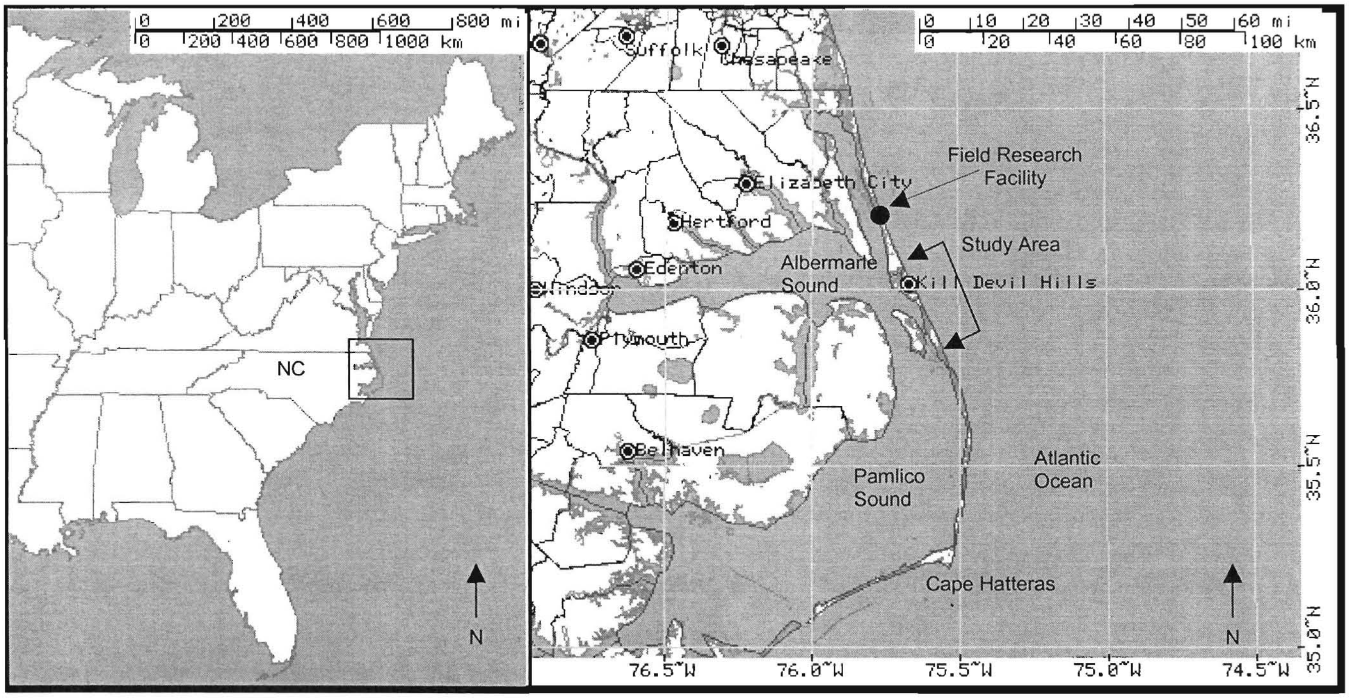

Figure 1. Location map of study area. The study area spans approximately 30 km.

error over the standard contour accuracy. We are especially concerned about this source of error, since we know that ground control panels were not set on the beach face for the current data set.

The DTMs examined in this study were derived from an aerial survey flown at 1220 m (4000 ft) above mean ground surface (for a photo scale of 1:8000). From equations (1) and (2), theoretical contour accuracy is 0.6 m (2 ft) and horizontal accuracy is 0.3 m (1 ft).

METHODOLOGY

Study Area and Data

The data discussed here were collected in Dare County, North Carolina (Figure 1). The U. S. Army Corps of Engineers (USACE) provided the data used. The data include a series of 101 ground surveyed beach profiles, 31 digital contour maps with 0.6 m (2 ft) contour intervals, and 31 digital orthophoto maps developed using photogrammetric techniques. Both the ground and aerial surveys cover an approximately 32 km (20 mile) section of the coast. Transect lines are spaced at approximately 305 m (1000 ft).

Ground Survey

Technicians performed the ground survey over a 22-day period from 11 July 1994 through 1 August 1994 using a Topcon 301 Total Station. The survey was conducted to Second Order Class II accuracy, indicating a horizontal control survey closure standard ratio of 1:20,000 and a vertical survey closure standard of

$$\text{vpoc} = 0.35M^{1/2} \quad (3)$$

where M is the distance in miles and the vertical point of closure (vpoc) is in feet. Typical survey length was about 91 m (300 ft) or 183 m total (600 ft) for closure, the horizontal accuracy is estimated as 0.009 m (0.03 ft), and the vertical accuracy as 0.004 m (0.012 ft) (DENNIS, 1999).

A baseline was established along the west right-of-way of the beachfront highway (NC Highway 12) using eleven North Carolina Geodetic Survey markers as reference. Profiles were surveyed along this baseline at 305 m (1000 ft) intervals. Depending on the location of the road, the profiles may include one or two beachfront lots, and in a few locations no lots were included as the road runs right next to the dune. Survey data extend into the surf zone to approximately 1.5 m below NAVD 88 (low-tide wading depth).

Aerial Survey

The aerial survey used to develop the contour maps and orthophotos was conducted February 25, 1995. Control to georeference the photography consisted of 90 targets distributed throughout the study area. The presence of the water surface on the photography limits the terrain model to approximately 0.6 m elevation above NAVD 88 (the upper swash zone).

We should note that a six-month difference exists in the timing of the ground and aerial surveys. These data were not collected with this particular study in mind but were generously made available when we expressed an interest in the comparison. Obviously it would be preferable for a comparison to have conducted temporally coincident surveys. Storms

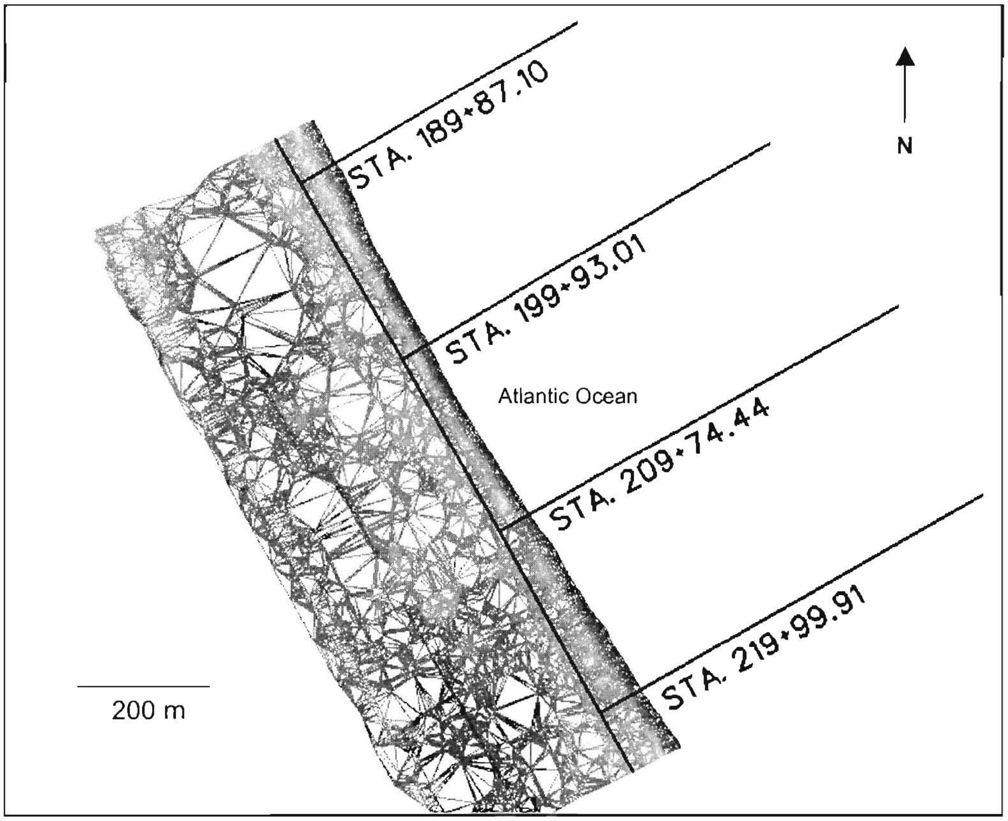

Figure 2. Triangulated Irregular Network (TIN) and profile transects along 1 km of the study area.

during this six-month interval may have caused significant alteration of landforms on the beach and dune. However, the time scales of significant change in the dune field should be larger than six months, depending on the severity of storms. Errors resulting from the non-synoptic data collection should be smaller than those due to mapping error. This is in contrast to the active shoreface, which has smaller time scales for change and where the effects of both the sources of error should be apparent.

Methods

The original DTMs developed as part of the photogrammetry process were not available for this analysis. Digital contour maps (0.6 m interval) originally created from those DTMs were, however. These contour maps were imported into a terrain modeling software package and converted to new DTMs. While the original DTM points were expected to have a vertical accuracy greater than the contour accuracy of 0.6 m (2 ft), the re-created DTMs were limited to this accuracy. In addition to the loss of accuracy provided by the original DTM points, GUTH (1999) has observed a disproportionate concentration of points at contour elevations when DTMs are built using this method. Furthermore, the re-sampled DTM lacks the maximum or minimum elevation points that necessarily exist within concentric contours.

We compared the series of ground surveyed beach profiles with profiles generated at corresponding locations using the re-created DTMs. The USACE provided the elevation data for each ground-surveyed profile, as well as a computer design file mapping the locations of the profile transects. Image files of the orthophoto maps were also used for reference. Geographic Information Systems (GIS) software was used to merge the data sets.

We used each re-created DTM design file to generate a Triangulated Irregular Network (TIN) (Figure 2). The TIN consists of a series of non-overlapping triangles connecting points of known elevation. The terrain modeling software algorithm linearly interpolates elevations along the edges of the triangles. Where points are the most dense, the original contours were closely spaced—in this case on the beach and dune. The triangles in that area are smaller and tighter. To extract the profile elevations, we referenced the computer file mapping the locations of the ground surveyed transects to the TIN file so that the lines representing the profile transects overlaid the TIN. The transects were then projected onto the triangulated surface. In the projection algorithm, an elevation point is generated wherever a transect line intersects a triangle. These elevation points may be actual DTM points (corners of triangles) or, more likely, they may be points along which the elevation has been interpolated between two DTM points (edges of triangles).

We first compared the data using a qualitative inspection of plots of both profiles for each transect. Additional analyses were conducted to quantify the differences between the two sets of profiles as discussed in the following section.

RESULTS AND DISCUSSION

Both sets of profiles were plotted and examined qualitatively for characteristics including general shape, height and location of dune peak, dune heel and toe elevation and position, and shoreface contour position. Some matched nearly perfectly, most corresponded closely (see Figure 3), and some had marked differences. A number of measures were developed to quantify the accuracy of the DTM derived profiles. These were: 1) comparison of dune peak elevation (maximum Z); 2) comparison of horizontal position of shoreface contours (X location of a given Z); 3) comparison of elevation values for fixed points along the transect (Z of a given X); and 4) comparison of cross-sectional area of the dune from heel to toe. Plots of the results are presented and discussed below.

Qualitative Inspection

A visual inspection of the profile patterns shows close correspondence of the two profiles from the baseline to the dune. Figure 3 shows six comparisons typical of the data set. At many transects, a clear difference from the ground surveyed (August) to the DTM-derived (February) is apparent on the beach face (Figure 4). We are not certain whether this difference is due to normal beach processes occurring during the six-month time interval between the surveys or to an increase in mapping error on the bare, low-relief beach.

It is hypothesized that the discrepancy between the DTM derived and ground surveyed profiles on the beach face is due largely to the six-month time difference between the ground and aerial surveys. During the winter of 1994–1995, 13 storms impacted the study area, including a brush with Hurricane Gordon. The USACE Field Research Facility (FRF) in Duck, North Carolina (see Figure 1) observed these winter storm events (USACE, 1999). The FRF is located approximately 10 km north of the study area and experiences similar weather and wave conditions. Each event represents an interval in which the significant wave height at the end of the FRF research pier exceeded 2 m. This typically stormy winter period is expected to have caused erosion on the beach face, and to bias the DTM data along the shoreface toward lower elevations.

Dune Peak Elevation Comparison

The maximum elevation of the profile, or dune peak, was extracted for each transect and compared. No consideration was given to the horizontal position of the maximum elevation in this analysis. The Figure 5 histogram presents the number of transects with absolute values of the difference between the profile elevations. The cumulative percentage plot in the figure shows clearly that 80% of the transects have a difference in the profile maximum elevation value of less than 0.6 m (2 ft), which is within the theoretical vertical contour accuracy of the DTM as discussed above. This indicates that the majority of the DTM-derived profiles captured the peak elevation of the dune within the known mapping accuracy. The rest of the profiles had some larger discrepancy.

Shoreface Contour Comparison

The results obtained from the dune peak comparison support the idea that the discrepancy between the surveys on the beach face was the result of normal winter erosion rather than mapping error. Presumably, at most transects erosion would not affect the dune peak. The horizontal positions of given shoreface contours, 0.6 m (2 ft), 1.2 m (4 ft), 2.4 m (8 ft) and 3.0 m (10 ft), were examined to identify any erosive trend. A computer program was written to find a given elevation's most seaward position for both sets of profile data. The position of the DTM derived profile was subtracted from that of the ground surveyed profile. Therefore, a positive difference in position indicates that the DTM contour was landward of the ground-surveyed contour, and a negative value indicates that it was seaward.

Figure 6 shows histograms of the difference in horizontal position of the shoreface contours and fit with a Gaussian distribution. All mean differences are positive, generally indicating net erosion (DTM landward of ground survey). The lower contour [0.6 m (2 ft), 1.2 m (4 ft), 1.8 m (6 ft)] difference values are more positive, and generally larger in absolute value than those of the upper contours [2.4 m (8 ft), 3.3 m (10 ft)]. In addition, the lower contours show a larger standard deviation. While these differences may be due to mapping error, it is probable that the six-month interval and the number of storms occurring in this interval contributed significantly to the profile differences. It follows that seasonal variation would affect the lower contours more than the upper contours, due to the lower slopes and proximity to swash or wave impact.

To test this hypothesis, we examined topographic data collected at the USACE FRF during the 1994–1995 season. The FRF is located approximately 10 km north of the northernmost transect examined in this work; beach and dune response seen in our survey area should be consistent with what is seen at the FRF. Data collected as part of a routine profile data collection program (see USACE, 1999) on July 29, 1994, and January 25, 1995, were chosen for analysis and comparison to the data in our study area. The difference in horizontal position of the profile at six elevations is computed and plotted in Figure 7. These survey data provide an extremely detailed view of the alongshore variation in profile response. Calculating the spatial average of the response over this 1000 m yields similar results to our study: the lower elevations (on the beach face) varied the most with an average of about 5 m while the higher elevations (the dune face) varied the least, about 1 m. The standard deviation of the FRF data also decreases with elevation. Taking advantage of the spatial detail available in this data set, we also note the wide range of response within the 1000 m sample of shoreline. At the 0.6 m, 1.0 m and 1.2 m contours, the change in position varied from approximately 20 m of erosion to 15 m of accretion. At the higher contours, (2.4 m and 3.3 m) the change was much smaller, ranging from 5 m of accretion to 5 m of erosion. The differences in the comparison between

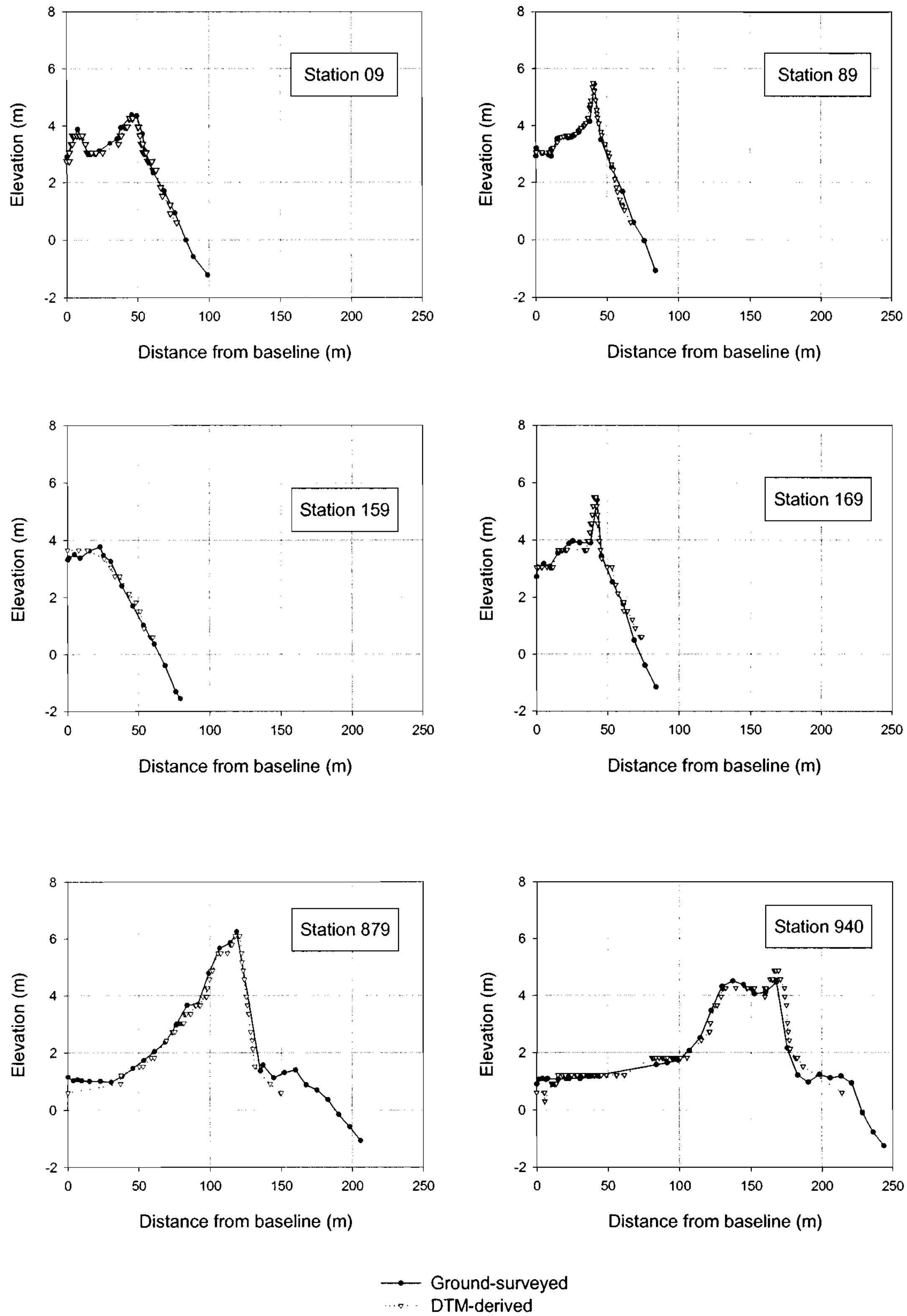

Figure 3. Representative profile comparisons. Note: Ground survey predated DTM survey by approximately 6 months.

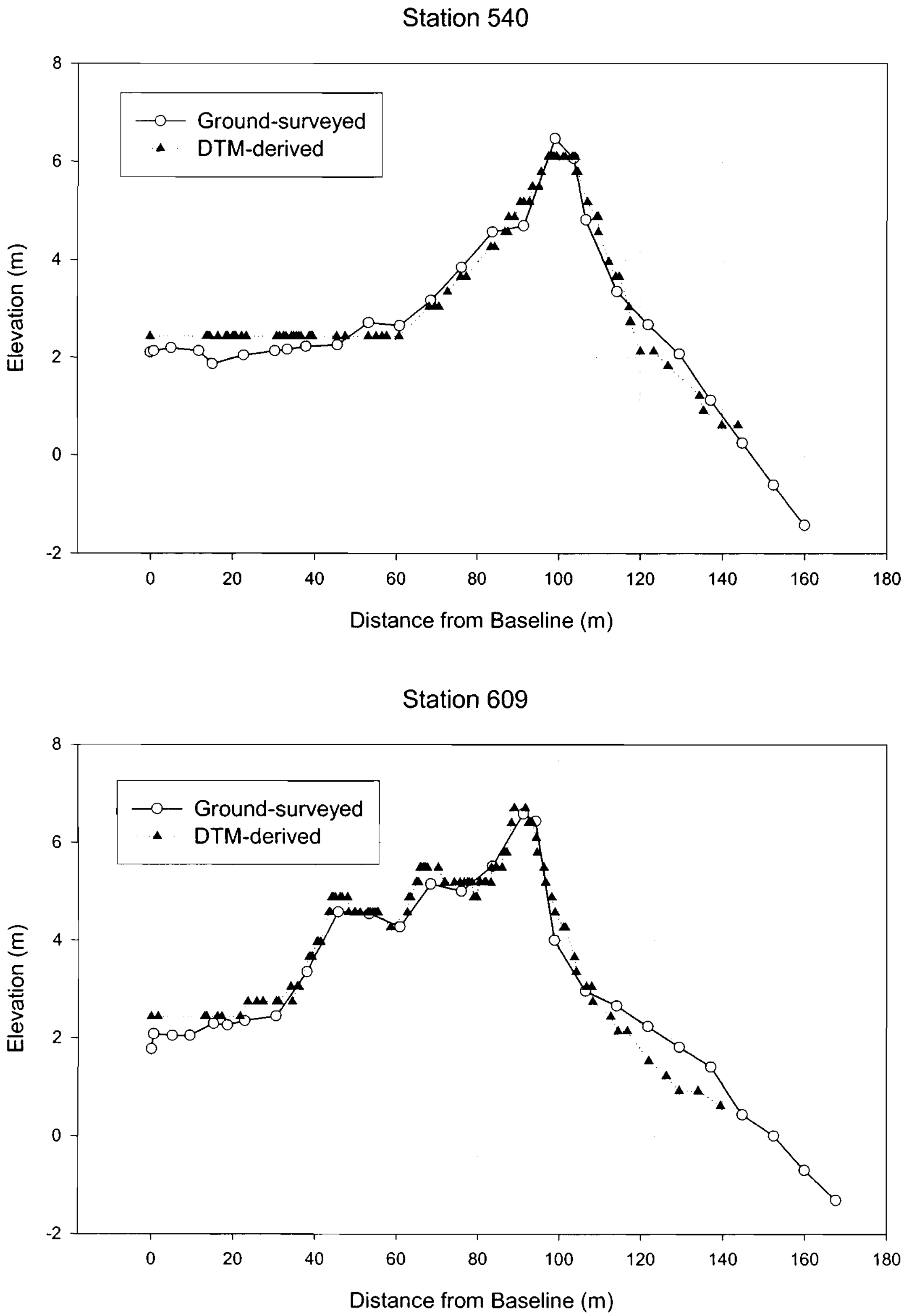

Figure 4. Representative profiles with differences on the beach face.

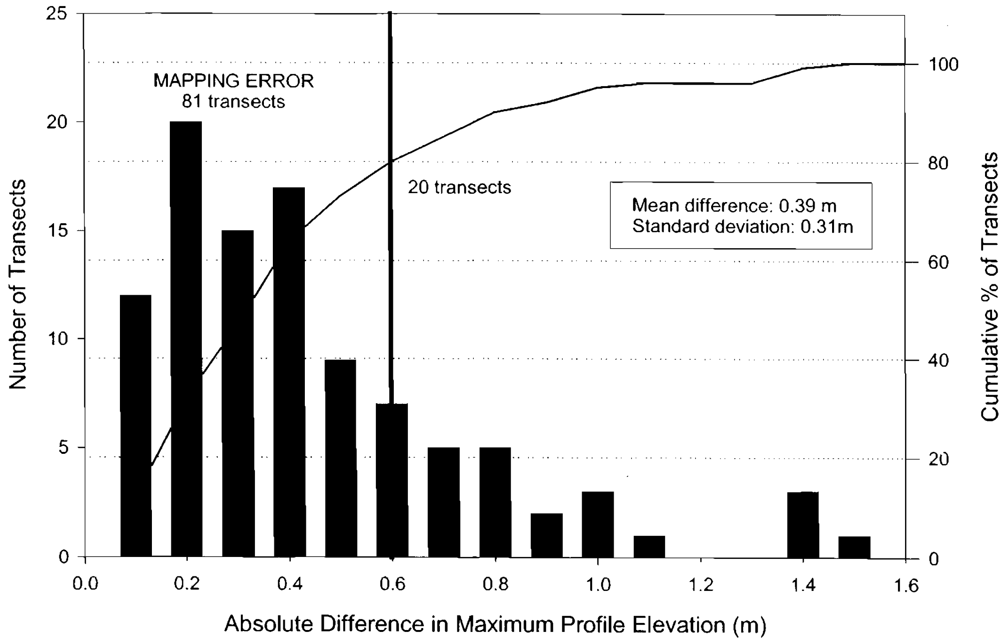

Figure 5. Comparison of difference in maximum profile elevation between ground survey and DTM at 101 transects. The vertical line at 0.6 m denotes the theoretical accuracy of the DTM data.

the DTM data derived from contours and the ground surveys conducted six months earlier are well within the known mapping error and the contour change observed in independent measurements.

Interpolated Profile Elevation Comparison

To quantify the agreement of the two surveys throughout the entire profile, we devised an interpolation scheme to compare profile at given horizontal positions. Horizontal profile length (the smaller of the DTM derived or ground surveyed) was found, and six distinct locations on the profile were identified (as measured from the baseline). These were: baseline intersection (at the beachfront road), 20% of maximum length, 40% of maximum length, 60% of maximum length, 80% of maximum length (typically approximately at the dune), and maximum length (the 0.6 m (2 ft) shoreface contour). At each of these locations, both profile elevations were found using linear interpolation and compared. Figure 8 shows a cumulative percentage of the stations at which the absolute value of the difference in elevation is less than the value varying along the x-axis. It is clear that over the majority of the profile the elevation difference is within the accuracy of the DTM (0.6 m); however, at the maximum profile length there is a much greater error. This result is consistent with the shoreface contour comparison, which indicated that at lower shoreface contours differences in profile elevations were much greater.

Area Comparison

A comparison between the volume of sand per unit length of dune (or area under the profile) calculated using the DTM points and calculated using the ground surveyed points provides an additional measure of the accuracy of the DTM derived profiles. First, the 101 profiles were screened to determine the presence of a dune. Some of the profiles cut through walkways, between houses, and in areas where dunes were absent. Fourteen profiles were eliminated from the set because of these factors. Using the ground surveyed profiles, we then identified the position of the dune toe (seaward extent of the dune) and the dune heel (landward extent of the dune). A qualitative assessment of the change in slope of the profile was used to locate the heel and the toe. An example is shown in Figure 9 (a). Finally, the area under the profile from the dune heel to the dune toe was computed using a trapezoidal rule for both profiles. The areas are compared in Figure 9 (b) along a line that represents perfect agreement.

The DTM derived profiles are well correlated to the ground surveyed data with a fit of DTM = 0.94 * GS and an R2 value of 0.96. This analysis indicates that the DTM profiles underestimate the dune area by approximately 6% on average. We attribute the profiles' differences in part to loss of sand from the dune face due to the winter storms (note, Figure 7, that the average shift in the FRF data at the 3 m contour is 1 m) and to the loss of peak elevation points in the re-sampled DTM. In addition, the profiles that had the greatest error were also profiles that possibly had mapping error (grade underestimated at steep dune faces near footpaths) or human intervention (bulldozing or beach scraping) as determined by examining the orthophotos.

In summary, the profiles generated from the DTM prove to be sufficient for characterizing the volume per unit length under the dune profile. Given that the DTM data are essen-

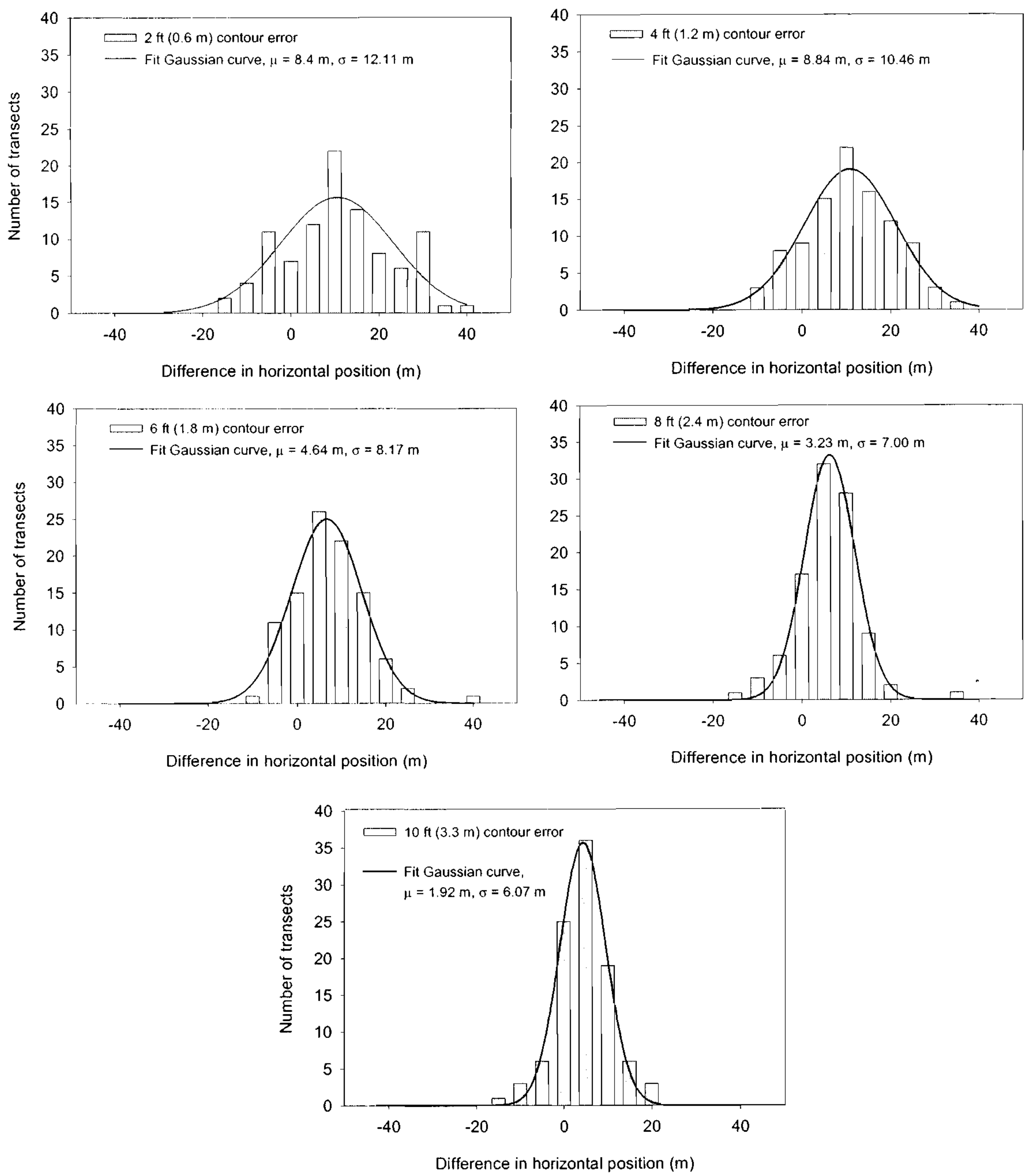

Figure 6. Error analysis of various shoreface contours with fit Gaussian distributions. The contour error decreases with proximity to the dune line, reflecting the less dynamic changes near the base of the foredune compared to the contour movements around the swash elevations.

tially continuous along the length of the beach (as opposed to the ground-surveyed profiles taken every 300 m), the DTMs provide a spatially dense data set for computing the along-shore spatial variation of dune volumes.

Spatial Resolution

Figure 10 shows a comparison of grids derived from the DTM topography (a) and a linear interpolation of the ground survey profile data (b) between transects at Stations 50 and 60. While the data at the actual transects correspond well, the variation in dune topography is not captured by linear interpolation of the ground survey. Examination of the volumes between the transects (constrained by the baseline and shoreline) calculated using the two methods reinforces this observation. Volume calculations using the DTM yield a total volume between the transects of 64510 m^3, whereas a calculation using a linear interpolation between the transects gives 71860 m^3. Due to the variation in dune elevations at

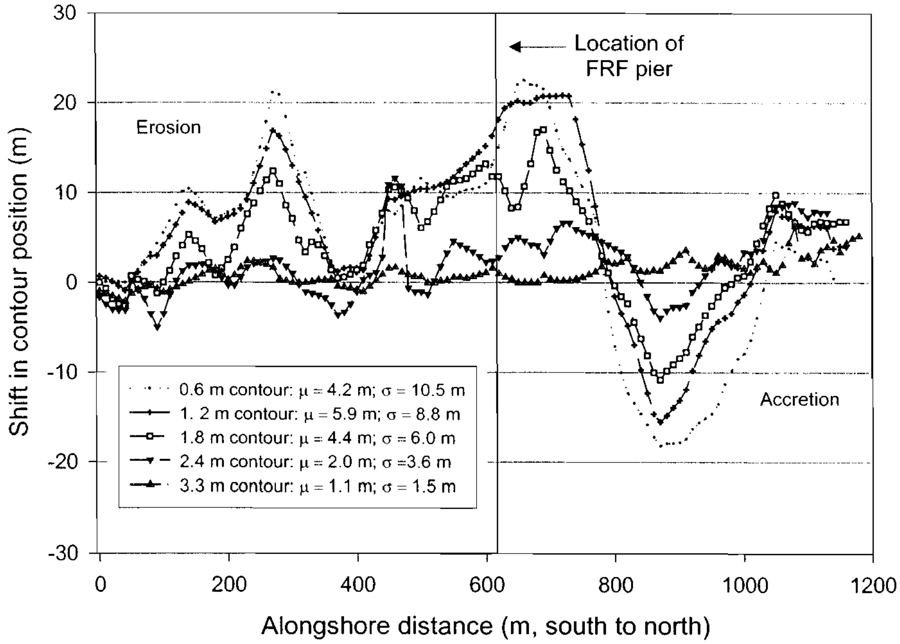

Figure 7. Comparison of contour position change at the USACE Field Research Facility in Duck, NC, about 10 km north of the study area. Survey data were collected July 29, 1994 and January 25, 1995. Note the variability in contour response at the lower elevations.

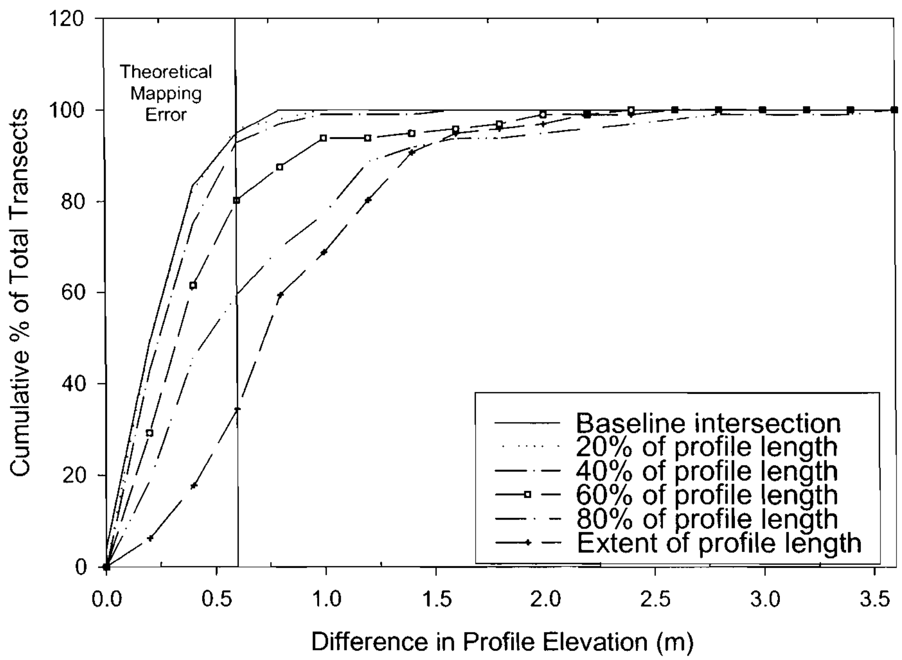

Figure 8. Profile elevation comparison at intervals along the length of the profile. The vertical line at 0.6 m denotes the theoretical accuracy of the DTM data.

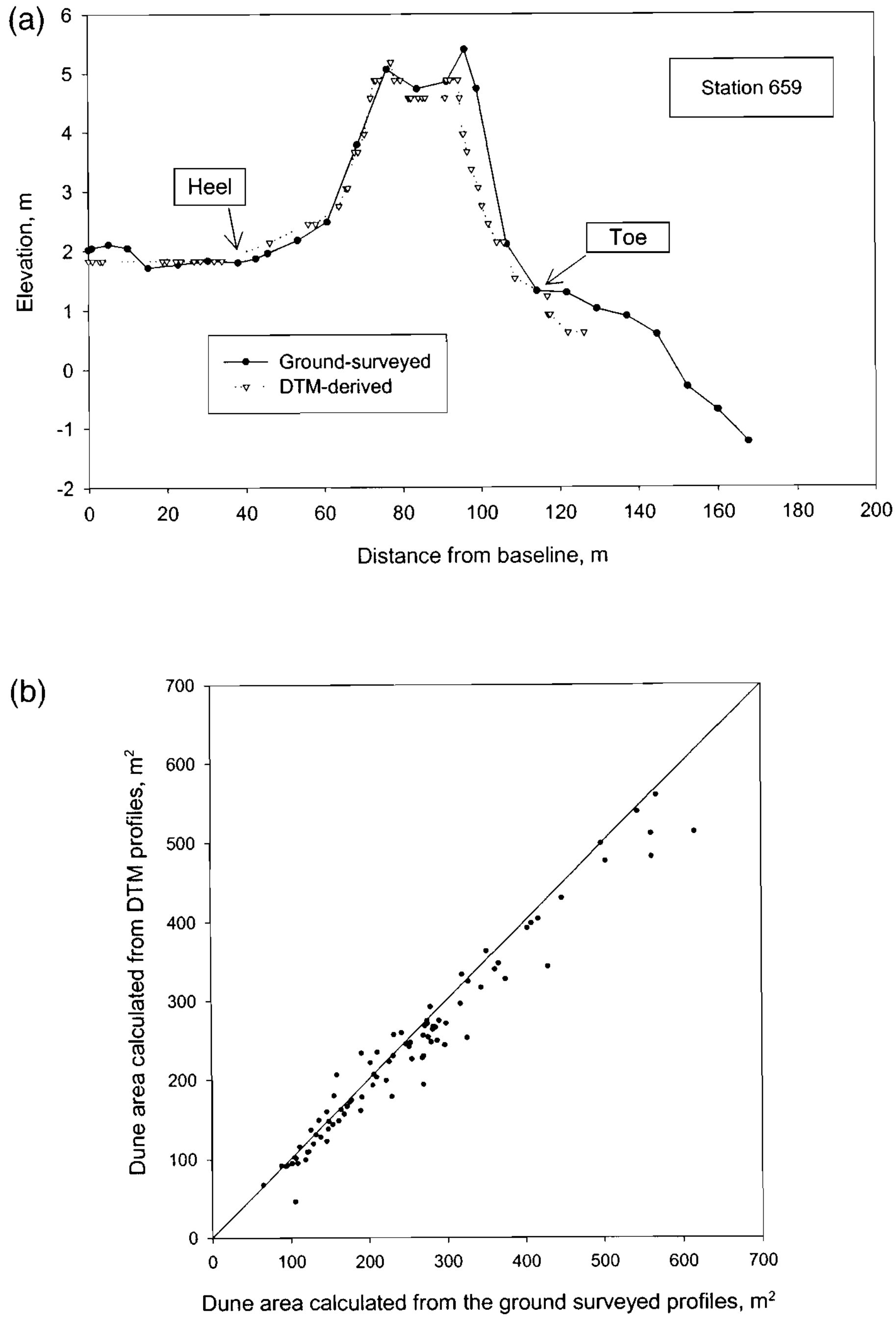

Figure 9. (a) Qualitative determination of dune heel and toe position. (b) Dune cross-sectional area comparison, plotted with a line representing perfect agreement.

this particular location, the ground survey data overpredict the volume by approximately 10 percent. Another pair of profiles could as easily under-predict the volume.

Data Applications

An example of the use of these data is presented in Figure 11. The example area includes Stations 50 and 60, used in the volume calculations. As seen in (a), the orthophoto map of an area can be displayed with an overlay of the roads and shoreline position. Hazard analysis can be performed by "flooding" the DTM with a surge of given elevation (b). In this case, we have used a surge of 3 m above NGVD, which is typical of a category III hurricane. The flooded areas can then be delineated on the computer screen as shown in (c). Finally, maps can be developed as in (d), indicating areas of flood risk.

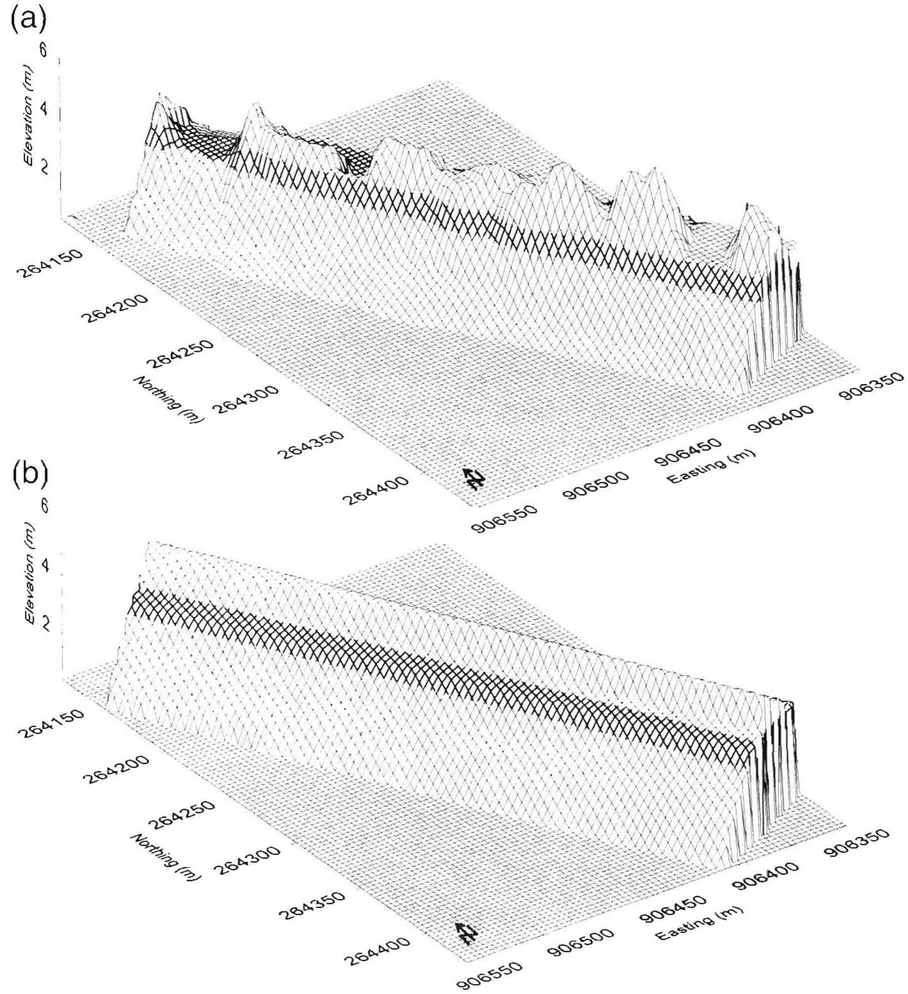

Figure 10. (a) Grid representation of the area between transects at Stations 50 and 60 as derived from DTM data. (b) Grid representation of linear interpolation of ground survey profile data between those transects. Coordinates are shown in State Plane, NAD 83, Zone 3200, meters. Elevations are referenced to NAVD 88, meters. The black band is shown for reference at elevation 3–3.6 m. Linear interpolation of profiles (b) over-predicts dune volume by approximately 10% in this example.

Cost Comparison

The cost of the ground survey was approximately $1000 per km (or approximately $320 per profile) for the 32 km (20 mile) study area. The cost of the aerial survey, including photogrammetric processing, DTMs, and orthophoto development was approximately $1530 per km for continuous coverage (DENNIS, 1999). Profiles can be extracted from the DTM at any spacing, decreasing the per-profile cost. The cost of the aerial survey is approximately 1.5 times that of the ground survey, but the increase in the number of profiles provided by the aerial coverage more than justifies the added expense. In addition, when multiple aerial surveys are conducted at the same location, the initial cost of surveying ground control decreases proportionately.

Spatially continuous data are invaluable when attempting to quantify morphologic changes or examining coastal processes. DTM derived profiles of the backshore, dune, and upper beach can provide the alongshore continuity that is cost-prohibitive to obtain using ground survey technology. Ground surveys can capture more of the topography of the littoral zone, but do not provide the alongshore detail desirable for three dimensional studies. The degree of detail required should dictate the data collection or combination of data collection technologies used.

CONCLUSIONS

A comparison of ground surveyed and DTM derived transects indicates that the DTM data is sufficiently accurate to measure changes in the dune field. Some discrepancies in the beach face portion of the analyzed data sets may be due to winter beach erosion or mapping error. Consistent apparent erosion and independent measurements from the FRF during the winter of 1994–1995 indicate that the differences may be the result of erosion. However, further research using ground

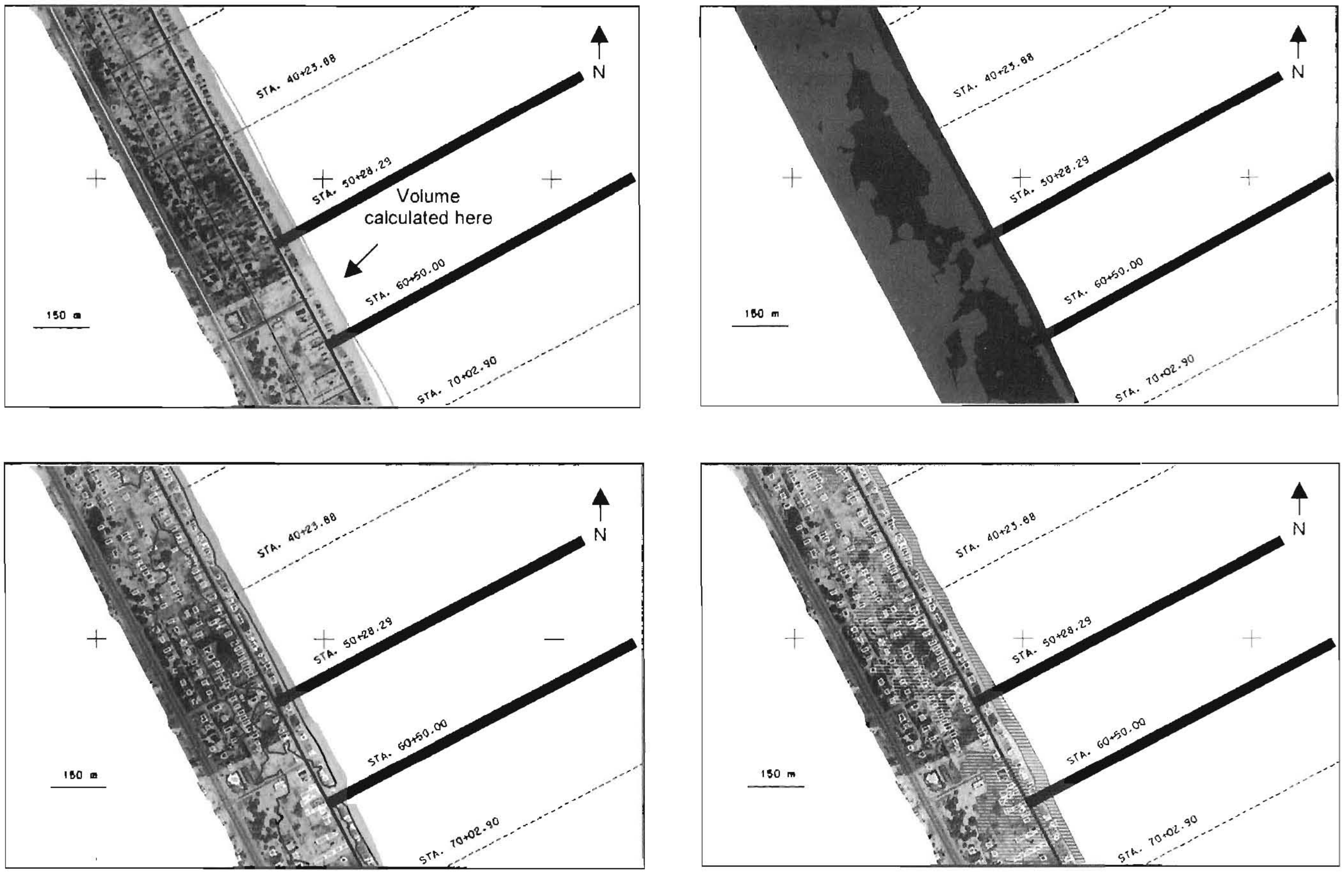

Figure 11. (a) Orthophoto with transect overlay, road, and shoreline. (b) Shaded relief image of DTM flooded with a storm surge of 3 m above NAVD. (c) Orthophoto with digitized flood areas. (d) Orthophoto with overlay indicating areas of extreme and high flood hazard. Note that, as seen in Figure 9, an interpolation of the ground survey data between transects at Stations 50 and 60 would not have identified the low-lying area just north of Station 60.

and aerial surveys during the same time span should be conducted to confirm the accuracy of photogrammetry derived DTMs on the beach face.

Costs associated with using the DTM derived profiles were compared with those of a high accuracy ground survey. Although the aerial survey is 1.5 times more expensive the increased spatial resolution may be worth the added expense, especially as attempts are made to quantify morphologic changes on the beach and dune. Additional DTM data could be generated using photogrammetric techniques, LIDAR, or ground surveys as subsequent coastal morphological changes occur. It is clear that many possibilities exist for use of spatially continuous data, and these techniques are expected to provide an invaluable contribution to coastal science and engineering.

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RESUMEN (en español)

Este proyecto avalua el uso de modelos digitales del terreno (MDTs) muy precisos en el estudio de los procesos costeros. Los MDTs son representaciones cartográficos del superficie del terreno por un gran número de puntos con coordenadas X, Y, y Z que se saben. Los avances por los programas de sistemas geográficas de información permiten que se manipulan facilmente los modelos para el analisis morfodinámico de la costa. Los MDTs se pueden crear utilizando una variedad de métodos, incluso la agrimensura, el lidar, y la fotogrametría digital. Los MDTs en este estudio se hicieron con las técnicas de la fotogrametría digital.

Una comparación se hace entre unos 101 perfiles medidos por la agrimensura y los mismos medidos por manipulación del MDT del área. El modelo se encuentra suficientemente preciso para medir los cambios en la zona de las dunas. Una comparacion de los costos de los métodos de medir indica que los costos de la fotogrametría son 1.5 veces más que los de la agrimensura tradicional. Unos ejemplos de aplicaciones de los MDTs se presentan.