

Airborne Laser Mapping of Assateague National Seashore Beach

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Abstract

Results are presented from topographic surveys of the Assateague Island National Seashore using an airborne scanning laser altimeter and kinematic Global Positioning System (GPS) technology. The instrument used was the Airborne Topographic Mapper (ATM), developed by the NASA Arctic Ice Mapping (AIM) group from the Goddard Space Flight Center's Wallops Flight Facility. In November, 1995, and again in May, 1996, these topographic surveys were flown as a functionality check prior to conducting missions to measure the elevation of extensive sections of the Greenland Ice Sheet as part of NASA's Global Climate Change program. Differences between overlapping portions of both surveys are compared for quality control. An independent assessment of the accuracy of the ATM survey is provided by comparison to surface surveys which were conducted using standard techniques. The goal of these projects is to make these measurements to an accuracy of ± 10 cm. Differences between the fall 1995 and 1996 surveys provides an assessment of net changes in the beach morphology over an annual cycle.

Introduction

Beaches are one of the most dynamic geologic (sedimentary) features on Earth. Fluxes in beach morphology occur over a wide spectrum of time scales ranging from periods of hours associated with diurnal tides and storm events to years and decades in response to longer term erosional trends. On a geological scale, beaches follow gross changes in sea level during periods of glaciation and glacial retreat. However, anthropogenic activities, especially during the past century, have created a situation where erosion of beaches has severe economic consequences. Thirty of the nation's 50 states have coastlines on the Atlantic or Pacific Oceans, the Gulf of Mexico, or the Great Lakes. These 30 states contain approximately 85 percent of the nation's population, and about half of this population resides within the coastal zone (Leatherman and Dean, 1991).

The U.S. coastline is more than 20,000 kilometers in length. Remote sensing offers the only possibility for produc-

ing a time series of elevation surveys of sufficient density to permit these valuable resources to be monitored. Airborne scanning laser altimetry currently offers a strong potential to provide such accurate, detailed, and comprehensive surveys. Annual surveys could be repeated to facilitate an understanding of long-term erosional trends or gauge effects of dredging, beach replenishment, and erosion control structures such as groins. Regional surveys could be conducted following the passage of major storms such as hurricanes and northeasters to quantify the resulting erosion/deposition and permit rapid identification of beach areas which are at risk due to the removal of sand from protective dunes. Survey input could be used by the National Flood Insurance Program (NFIP) of the Federal Emergency Management Agency to make decisions on property coverage regulations. NFIP currently offers flood insurance protection to ~1,200 coastal communities amounting to 1.4 million policies and over \$120 billion in coverage. The survey of beaches along the entire expanse of the U.S. coast could be accomplished with a modest number of airborne scanning laser altimeters. A comprehensive review of available commercial airborne scanning laser altimeters were given by Flood and Gutelius (1997), and academic researchers have used the technology to study changes in beaches caused by tropical storms and hurricanes (Carter and Shrestha, 1997). Additionally, the federal government operates several such sensors both for research and operational applications (Krabill *et al.*, 1995; Lillycrop *et al.*, 1996).

General Discussion

As a demonstration of the application of airborne remote sensing for beach monitoring, the northern portion of Assateague Island has been topographically mapped using an airborne scanning laser altimeter combined with kinematic Global Positioning System (GPS) technology. The site, shown in Figure 1, was initially surveyed with the NASA Airborne Topographic Mapper (ATM) in November, 1995, to evaluate the sensor for use in the Arctic Ice Mapping (AIM) Project (Krabill *et al.*, 1996), a NASA Earth Science program that monitors changes in the height of the large ice sheet that covers most of Greenland. The ATM group, based at Goddard Space Flight Center's Wallops Flight Facility (WFF), has been gathering baseline elevation measurements in surveys regionally distributed over the Greenland ice sheet in annual field deployments between 1993 and 1998. Assateague Island was selected as a test site because of its proximity to WFF and because the beach sand has a

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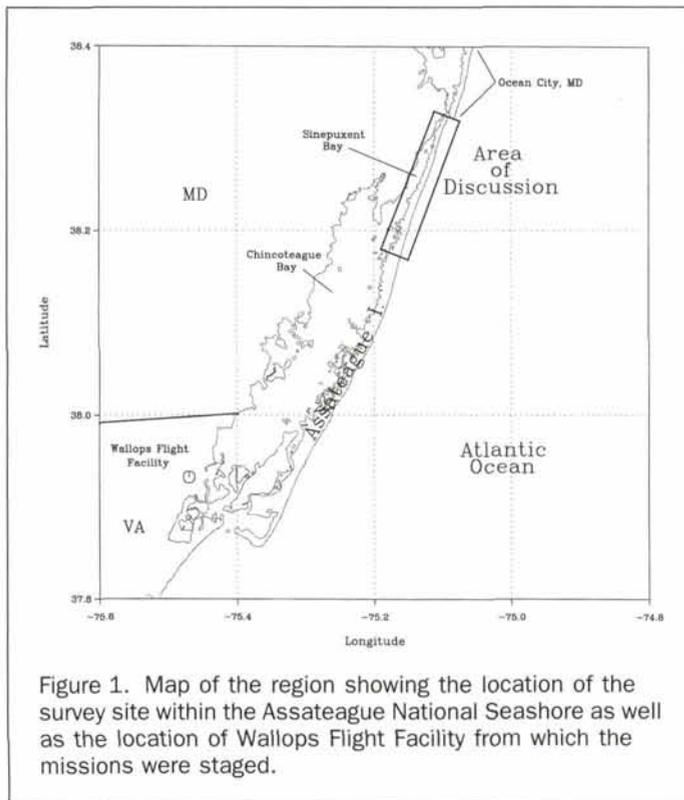


Figure 1. Map of the region showing the location of the survey site within the Assateague National Seashore as well as the location of Wallops Flight Facility from which the missions were staged.

reflectivity similar to that encountered over the Arctic glaciers. In addition, the National Park Service conducts a semiannual series of profile surveys across the beach from benchmarks located landward of the dune line. This provides a reasonably good source of supporting surface observations when airborne tests are conducted concurrently with the ground survey. The airborne surveys will also be valuable to the National Park Service and the U.S. Army Corps of Engineers, which are about to begin a beach replenishment project within the site.

The initial survey was undertaken in November 1995, primarily to verify recent enhancements to the ATM-I sensor. A second survey of the northern portion of the island was conducted in May 1996, during calibration tests that preceded a Greenland deployment. These two missions were conducted with ATM-I operated on the NASA P-3B four-engine turboprop aircraft. A third survey was conducted in October 1996, with a new version of the sensor, the ATM-II mounted in a two-engine NOAA Twin Otter aircraft. This survey was performed as part of a joint program with NOAA's Coastal Services Center designed to explore the potential utility of using an airborne scanning laser altimeter combined with kinematic GPS technology developed for the AIM Project to gather rapid and highly accurate topographic maps of beaches. The joint NASA/NOAA program is focused on establishing techniques and standards that will permit airborne scanning laser altimeters, some of which are beginning to appear in the private sector, to be used to regularly monitor long-term erosion/deposition trends and the response of beaches to major storm events.

Instrumentation

Sensors within the ATM program are continually evolving, with improvements resulting periodically in new sensors. These improvements are largely focused on reduction in sensor size and weight, and enhancements such as increase in scanner rotation and data capture rates. The basic accuracy of the sensor and signal-to-noise aspects have remained about the same

Thus, only ATM-II, the latest version of ATM used in the fall 1996 survey discussed in this paper, will be described in detail.

A photograph of the ATM-II mounted on the NOAA Twin Otter is shown in Plate 1. The ATM-II was operated with a Spectra Physics TFR laser transmitter which provides a 7-nsec wide, 250-micro-joule pulse at a frequency-doubled wavelength of 523 nm in the blue-green spectral region. The laser transmitter can operate at pulse rates from 2 to 10 KHz, but was operated at 3 KHz for the beach surveys because of a degradation in transmitter performance observed at progressively higher pulse repetition rates. The laser system, which includes a separate cooling unit, weighs approximately 45 Kg and requires approximately 15 amps of aircraft power at 115 volts. The transmitted laser pulse is reflected to the Earth's surface using a small folding mirror mounted on the back of the secondary mirror of a 9-cm diameter Newtonian reflector telescope which views the laser footprint on the Earth's surface. The co-axial transmit and receive path facilitates changing altitude above the topographic target without the need to realign the transmitter and receiver optics. The transmitted laser pulse and receiver field-of-view (FOV) are directed Earthward by a nutating scan mirror assembly which is mounted directly in front of the telescope. The scan mirror, which is rotated at 20 Hz, is made from a section of 15-cm diameter round aluminum stock machined to a specific off-nadir angle. A scan mirror with an off-nadir angle of 15° was used for the ATM-II beach mapping survey, producing an elliptical scan pattern with a swath width equal to approximately 50 percent of the ~700 m aircraft altitude. (A 10° off-nadir scan mirror was used on the ATM-I surveys which were flown primarily to test the instrumentation for use in the AIM project where the wider swath width was not a strong consideration.) The ATM-II receiver is composed of the Newtonian reflector telescope, a single photomultiplier tube (PMT), and various other low-cost, off-the-shelf optical components. The 2.1-milliradian FOV of the system is established by the thickness of a fiber optic cable situated at the focal plane of the telescope. The fiber transmits the reflected laser pulse to a photomultiplier assembly which consists of a lens, a narrow band filter, and the PMT.



The major components of the data acquisition system are a 133-MHz Pentium PC and a Computer Automated Measurement and Control (CAMAC) interface card cage. A time-interval counter located within the CAMAC unit measures the elapsed time between the transmitted laser pulse and the reflected return from the ground target in resolution cells of 156 picoseconds, yielding a precision of 2.3 cm. The receiver power supply, pulse digitizers, inertial navigation interface, and pulse amplifiers are also located within the CAMAC unit. The aircraft pitch, roll, and heading are acquired from a Laser Ring-Gyro Inertial Navigation Unit (both Litton and Honeywell units have been utilized). The positioning information from a survey grade GPS receiver (Ashtech Z-12) is captured by a separate PC.

Calibration

Two types of calibrations are necessary for the topographic mapping system. The first is to develop a correction to the laser range determination. The ATM-II sensor uses a leading edge discriminator in timing the laser range measurement. It must be calibrated for a systematic error in range, which consists of a fixed part, or "zero-set," and a part related to the amplitude of the received laser pulse (sometimes referred to as "range walk"). During pre-mission and post-mission ground calibrations, the outgoing laser beam is directed horizontally by means of a folding mirror to a flat target board. Range measurements are then recorded while modulating the strength of the laser beam exiting the aircraft, which effectively produces a wide variation in the amplitude of the received laser signal. The distance between the scan mirror and the horizontal target board is measured both with a steel tape and independently with an electronic range finder. A correction table used in post-flight processing is developed from this ground calibration.

The second type of calibration is designed to determine the angular mounting biases of the ATM sensor relative to the inertial navigation system (INS) from which the aircraft attitude (roll, pitch, and heading) are determined. The roll and pitch orientation of the ATM scanner platform relative to the INS reference system must be determined to somewhat better than 0.1° because, for an aircraft altitude of 700 meters and an off-nadir angle of 15° , a 0.1° mounting error would introduce a height error of 32 cm and a horizontal displacement error of 131 cm. The relative orientation between the ATM platform and the INS reference can be determined by flying over either a flat surface such as a water body or a known reference surface. These observed ranges are then compared with those computed on the basis of the determined position of the aircraft GPS antenna, the measured position of the scanner mirror relative to the GPS antenna in the aircraft (INS) coordinate system, the INS attitude measurements, and a model of the scanner measurement system. This calibration technique is possible because of the geometry of a conical scanner. A large aircraft parking apron at Wallops Flight Facility, which has been densely surveyed, served as the reference surface for the three ATM surveys of Assateague National Seashore discussed in this paper. It may be noted that these mounting biases can include small day-to-day variations in INS pitch, roll, and heading zero set. Nonetheless, the ATM mounting biases are generally stable enough during a particular aircraft installation for a single set of numbers to be utilized for an entire campaign.

INS pitch and roll uncertainties are generally considered the limiting factor in ATM survey accuracy and are thus a primary source of concern. The observed variations in mounting biases show, however, that the variations seldom reach a level of 0.1° and are within 0.05° most of the time. Attempts have been made to monitor the variations in INS errors through the use of GPS attitude estimates using several GPS antennas on board the aircraft. In general, these attitude estimates have been found to be less accurate than the INS estimates, due to measurement noise, multipath effects, and structural flexure of the aircraft.

Navigation

The capability to precisely follow specific flight lines is an important facet in this activity, both to insure that data are collected over desired sites, as well as to insure repeating measurements for change detection. Aircraft inertial navigation systems are not sufficiently accurate to ensure that flights are precisely navigated along prescribed routes because of drift in their position estimates determined through accelerometers. Consequently, a navigation system based upon real-time GPS information was developed by the ATM group (Wright and Swift, 1996). Associated software utilizes real-time positional output from the on-board GPS receiver, which can supply data to an autopilot and provide the pilots with a real-time visual display of the flight line and the current offset from desired track. This system has enabled the pilot to maintain the aircraft within 30 to 50 m of the desired flight track during missions lasting several hours and covering 100 to 200 kilometers of beach.

Aircraft Trajectory Determination

In order to measure topography to the desired accuracy of 10 cm, the vertical location of the GPS antenna mounted on the aircraft must be known to ~ 5 cm, and the horizontal location should be on the same order. This goal was achieved using kinematic GPS techniques (Krabill and Martin, 1987), which use the difference in the GPS dual frequency carrier-phase-derived ranges from a mobile receiver in the aircraft and a fixed receiver located over a precisely known benchmark at Wallops Flight Facility. Throughout the flights, the bank angle of the aircraft was kept below 10° to avoid loss of carrier phase lock on the airborne GPS receiver. GPS data sets were obtained with the aircraft parked close to the fixed receiver for about 45 minutes both before and after each survey flight. These stationary data sets are used to resolve ambiguities in carrier phase for each frequency between the fixed and mobile receivers for subsequent application during the processing of the in-flight data. Additionally, the local meteorological conditions (pressure, temperature, and humidity) were recorded for subsequent application during post-mission processing. These data are combined with a precise ephemeris of the GPS constellation into a point-to-point range difference solution for the trajectory of the aircraft. Because of the relatively low noise in the phase data, no filtering or smoothing is required. The use of a precise *post facto* ephemeris is required for operations in which the baseline between the aircraft and the fixed receiver exceeds 30 to 40 km, and is recommended for all operations. These are available from several sources on the internet within 2 to 10 days.

Reference Conversion

The ATM survey results are computed within the International Terrestrial Reference Frame, or ITRF, coordinates referenced to the WGS-84 ellipsoid, because this is the coordinate system used to express the precise orbital positions of the GPS satellites. However, the National Park Service's beach profile surveys were determined using NAD83 UTM horizontal coordinates and orthometric height (referenced to mean sea level, MSL). Thus, it was necessary to transform the results into a common coordinate system before comparisons could be made.

First, the ATM aircraft trajectories (and, thus, the laser survey results) were re-referenced to the NAD83 system using the published coordinate transformation. Next, the UTM horizontal coordinates of the National Park Service's beach profiles were converted to NAD83 coordinate system using the Blue Marble Geographics "Geographic Calculator" commercial software package. Then, the height of the geoid was computed at each beach profile location using the National Geodetic Survey's GEOID93 geoid model. The geoid height added to the orthometric height yielded beach profile height referenced to the ellipsoid. The ATM survey results and the NPS beach profiles were then directly comparable.

Regional Setting

The mapped portion of the Assateague Island National Seashore is located on the northern portion of Assateague Island which stretches from Ocean City Inlet south 58 km to Chincoteague Inlet. Historically, this long continuous barrier island was known as Assateague Spit, the southern extent of Fenwick Island which begins at the Bethany Beach, Delaware headland located approximately 16 km north of Ocean City Inlet. The inlet at Ocean City resulted from a breach of Fenwick Island during a 1933 hurricane and has been maintained as a permanent inlet by jetties which were completed in 1935. The net annual littoral drift along Fenwick and Assateague islands is to the south, although it can reverse for short periods. Prior to the breach in 1933, the landward migration of northern Assateague Spit has been estimated at approximately 2 m/yr (Underwood and Hiland, 1995). Since the construction of the jetties, the southerly sand transport has been interrupted. This has resulted in wider beaches immediately north of the inlet and the formation of an ebb shoal seaward of the inlet, as well as erosion of Assateague to the south of the inlet, where landward beach migration has been estimated to exceed 12.2 m/yr (Leatherman, 1979). The accelerated erosion on northern Assateague Island has resulted in decreased width of the barrier island and lowering of dunes, permitting frequent overwash of the beach across the full width of the island. The northern part of the island is now extremely narrow, averaging 120 to 215 m in width (Leatherman, 1984). More recent observations reported by Underwood and Anders (1989) suggest that ebb shoal growth may have slowed due to natural bypass of sediments around the inlet, resulting in a reduction of the rate of shoreline migration along the northern portion of Assateague Island. They suggest patterns of deposition observed along the northernmost portion of the island are evidence of the natural bypass around the ebb shoal.

Results

The surveys conducted with the ATM-I sensor in November 1995, and with ATM-II in October 1996, provide complete coverage of the northern portion of Assateague Island. The May 1996 survey, flown as part of the pre-mission calibration preceding the AIM Greenland deployment, consisted of just two passes that did not cover the beach face except for a relatively small portion of the site. This spring survey set is included in this paper primarily because it was conducted within a few days of a National Park Service ground profile survey, while the fall flights were several weeks later than the ground surveys.

Color composites of the fall 1995 and 1996 surveys are shown in Plates 2 and 3, respectively. Each figure contains three contiguous panels arranged from south to north with the bottom of the left panel being the southern-most point. The individual laser spot elevation measurements were averaged into 5-meter-square pixels. These (5 m)² cells are shown as small dots color coded according to elevation with cells containing no data appearing white. The labeled grey lines spanning the island at fairly regular intervals correspond to the locations of ground surveys taken by the National Park Service which will be discussed later. The fall, 1995 survey in Plate 2 is a composite of five parallel passes, three acquired from an altitude of ~400 m and two from ~700 m while the fall 1996 survey in Plate 3 was developed from four parallel passes, all flown at an altitude of ~700 m. The panels provide a good visual indication of the coverage density resulting from the ATM scan. A significant amount of detail can be seen to correspond between the two surveys. These include the parking lot and high dune area near the bottom of the left panel, fossil depositional features on the bay side of the barrier island from historic dune overwash in the middle and right panels, and the distribution of dunes at the northern tip of the island near the top of the right panel.

Note also the terminus of the causeway at the entrance to the island near the top of the left panel in the 1995 survey (Plate 2), which had more coverage of the western side of the island than did the 1996 survey. The large amount of missing data in the water on both sides of the island in the 1995 survey is a result of low laser backscatter from the water surface which can be quite variable depending on wind/wave conditions at the time of the flight.

Plate 4 is a color composite of the difference between the 1995 and 1996 fall passes from Plates 2 and 3, respectively. The difference plot was developed by subtracting the elevation of the cells from the 1995 survey from the elevation of the corresponding cells from the 1996 survey. The differences are shown as small squares color coded according to magnitude with negative values (net loss) shown in cooler (bluer) colors and positive values (net gain) shown in warmer (yellow-red) hues. The most obvious feature in the Plate 4 difference plot is the erosion indicated by the band of blue which extends along the beach face over much of the surveyed area and is especially prominent in the middle panel. This area of highest erosion is the section of the survey area with the lowest dunes as can be seen in Plates 2 and 3. The National Park Service personnel were not surprised by the net loss in this region of the island. They stated that this section of beach, especially around profile location G, is frequently completely overwashed during twice-monthly spring tides, resulting in considerable shifts in the distribution of sand. A section of net accretion can be seen near the north end of the island in the right panel between survey locations A and B. Underwood and Anders (1989) suggest that a natural sand bypass formed around the Ocean City Inlet ebb shoal serves as the sediment source for observed accretion near the north end of the island.

Figures 2 to 4 are plots comparing the three airborne surveys to the National Park Service ground profiles that are most closely associated in time. The ATM surveys are shown plotted as small grey "dots" with the large "plus" symbols indicating the location of individual ground-survey-determined beach elevation points. The ATM survey points were determined by extracting all of the remotely sensed laser spot elevations falling within a 2.5-m distance on either side of the ground survey profile. Reasonable agreement between the ATM elevations and the spot elevations determined with the "total station" survey instrument can be seen in all of the profiles except along the beach face adjacent to the ocean and on the western end of the profiles in the vegetated region flanking the lagoon. The overall agreement is best in Figure 3 where the ATM May 1996 survey was compared to a ground survey taken within a week of the airborne survey. However, the extent of the May 1996 airborne survey coverage was limited (as previously discussed) and consequently offers much less opportunity to compare with the ground surveys, especially in the critical area of the beach face. The fall 1995 survey in Figure 2 shows differences in the beach face at several stations between the September ground survey and the November ATM survey. An increase in excess of one meter can be seen at profile location C located in the region where net accumulation was seen in the composite of the differences between the 1995 and 1996 fall surveys in Plate 4.

The largest differences between the airborne and ground measurements are evident in Figure 4 where the October 1996 ATM survey is compared with ground measurements taken over a two-week period during the preceding month, resulting in a two- to four-week temporal separation between the airborne and ground measurements. The section of beach with the largest change is centered near profile location G where the beach corresponding to the top of the low-lying dune structure in the September ground survey can be seen to be some 2 m lower at the time of the October ATM survey. The horizontal displacement of the high point of the beach was more than 60 m between the two surveys. The erosion of the beach face can also

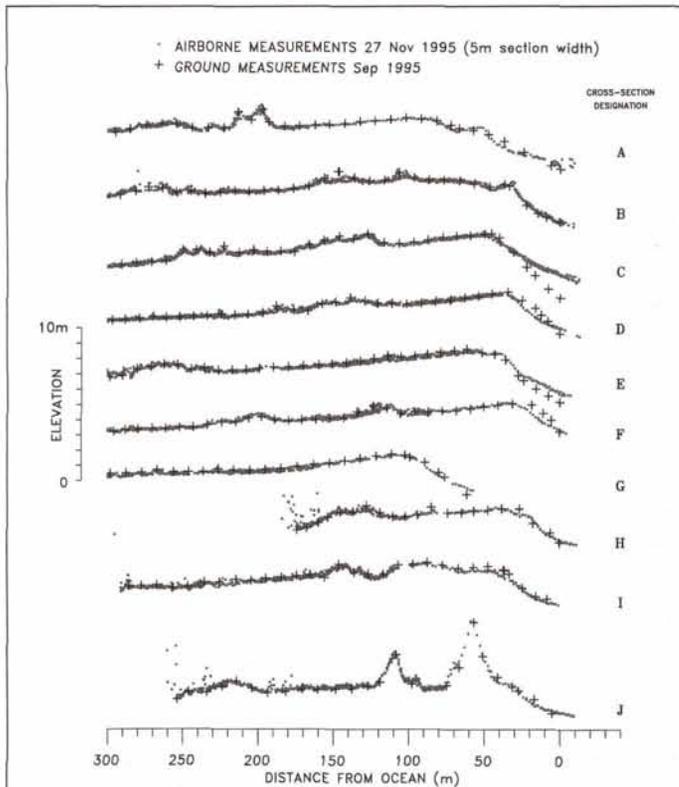


Figure 2. A set of profile plots comparing the September 1995 beach surveys performed by the National Park Service (+ 's) with laser spot elevations obtained with the ATM-I during the November 1995 airborne survey (small grey dots). The letter designation to the right of each profile corresponds to the grey bar in Plate 2 with the same letter designation. The profiles are in reasonable agreement except along the beach face (right-most portion of profiles).

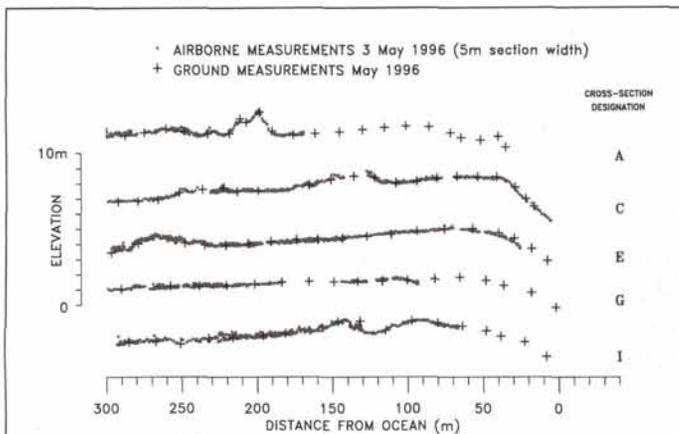


Figure 3. A set of profile plots comparing the May 1996 beach surveys performed by the National Park Service (+ 's) with laser spot elevations obtained with the ATM-I during the May 1996 airborne survey (small grey dots). The letter designation to the right of each profile corresponds to the grey bar in Plate 2 with the same letter designation. Although the profiles show reasonable agreement, the amount of coverage is limited due to the reduced amount of airborne surveying performed during the spring mission.

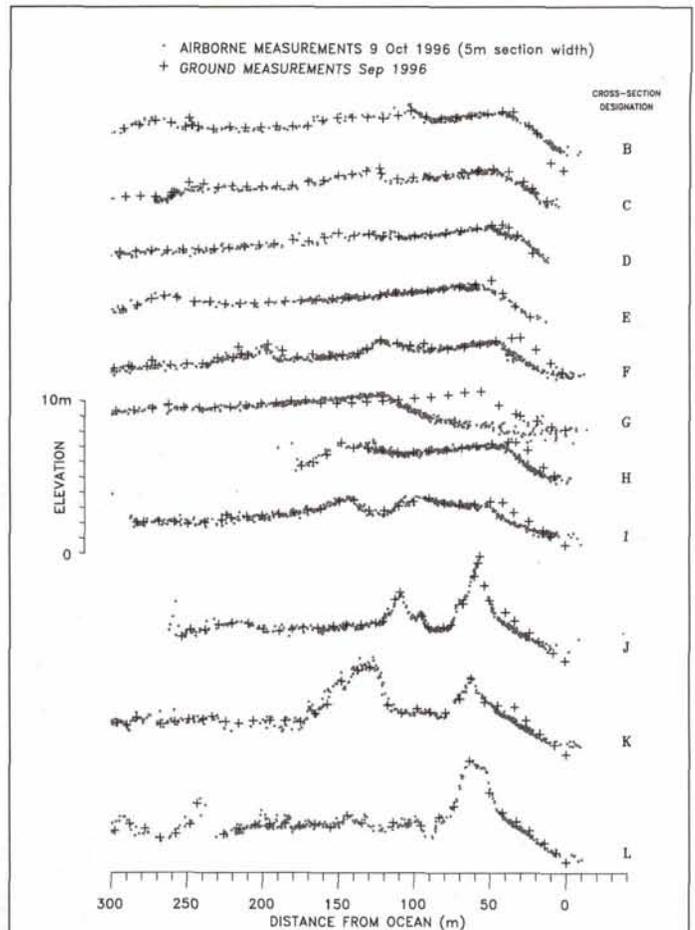


Figure 4. A set of profile plots comparing the September 1996 beach surveys performed by the National Park Service (+ 's) with laser spot elevations obtained with the ATM-II during the October 1996 airborne survey (small grey dots). The letter designation to the right of each profile corresponds to the grey bar in Plate 2 with the same letter designation. The profiles are in reasonable agreement except along the beach face (right-most portion of profiles). Considerable differences can be seen in Profiles F and G which are located along a section of the islands with low dunes and frequent overwash during spring tides.

be seen in profile locations F and H, but to a lesser degree. This area corresponds to the section of beach where National Park Service personnel have observed frequent overwash during spring tide events.

Statistical comparison of the 1995 airborne and ground surveys (Table 1 and Figure 2) provides the best indication of the accuracy of the ATM. Comparisons of the other surveys is hampered by the poor coverage in May 1996 and by the large change in the beach face during fall 1996. The comparisons were made by finding all the ATM laser measurements from the 1995 airborne survey that fall within a 1-meter radius of each ground survey measurement, then calculating the elevation differences between the ATM and ground measurements. The mean and standard deviation were computed for each cross-section. Most of the mean differences are a few centimeters and standard deviations about 10 to 20 cm. Characteristics of the topography appear to have affected some of the results: Profile G, which is in an area prone to overwash, shows a mean loss of 15 cm; and the vegetation and steep dune in profile J contribute to the large standard deviation of 49 cm.

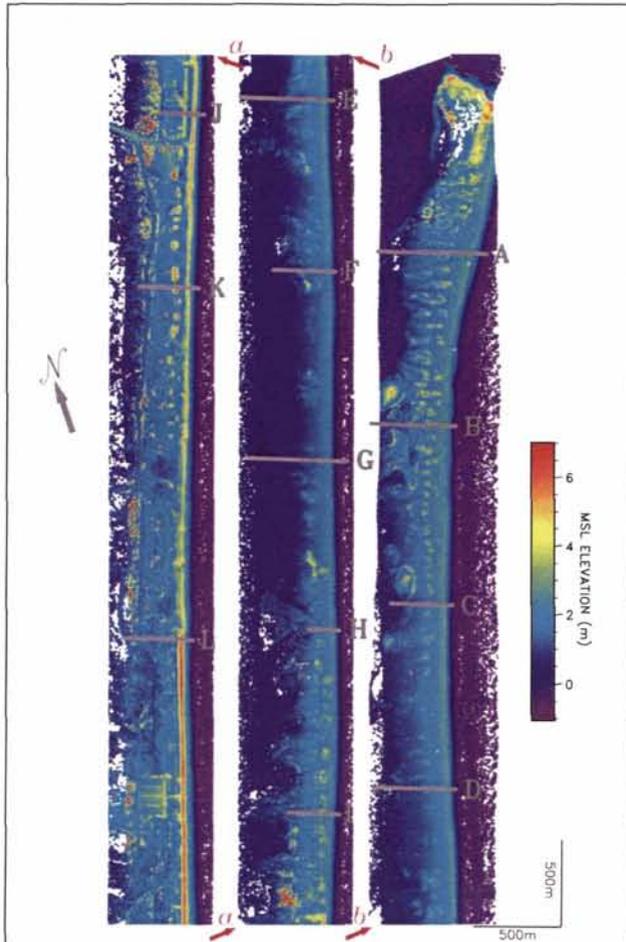


Plate 2. Color composite of the 27 November 1995 survey shown as three contiguous panels arranged from south to north, with the bottom of the left panel being the southern-most point. The individual laser spot elevation measurements were averaged into 5-meter-square pixels. These $(5\text{ m})^2$ cells are shown as small dots color coded according to elevation, with cells containing no data appearing white. (A color coded key within the figure provides the actual elevations associated with each hue.) The labeled grey lines spanning the island at fairly regular intervals correspond to the locations of ground surveys taken by the National Park Service.

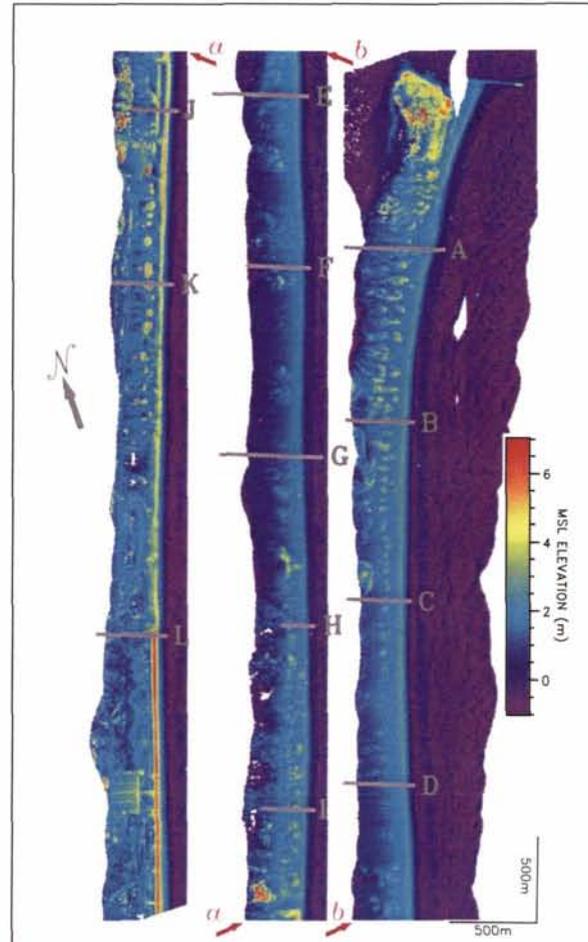


Plate 3. Color composite of the 09 October 1996 survey shown as three contiguous panels arranged from south to north, with the bottom of the left panel being the southern-most point. The individual laser spot elevation measurements were averaged into 5-meter-square pixels. These $(5\text{ m})^2$ cells are shown as small dots color coded according to elevation, with cells containing no data appearing white. (A color coded key within the figure provides the actual elevations associated with each hue.) The labeled grey lines spanning the island at fairly regular intervals correspond to the locations of ground surveys taken by the National Park Service.

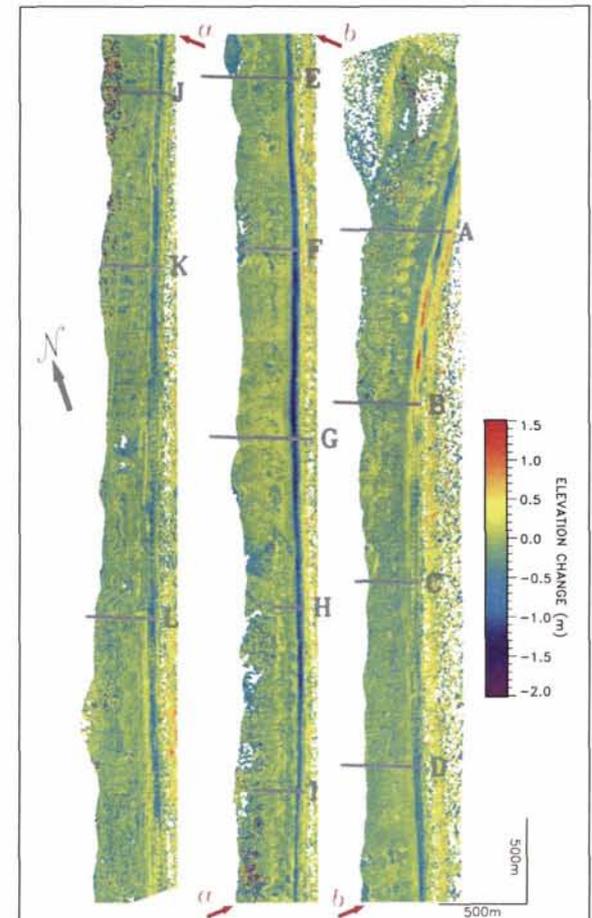


Plate 4. Color composite of the difference between the fall, 1995 and fall, 1996 surveys of northern Assateague Island. The composite is shown in contiguous panels arranged from south to north, with the bottom of the left panel being the southern-most point. The differences are shown as small squares color coded according to magnitude, with negative values (net loss) shown in cooler (bluer) colors and positive values (net gain) shown in warmer (yellow-red) hues. The actual magnitudes are provided in a key within the figure. The predominantly green areas west of the beach indicate little or no change in elevation while the blue areas near the beach face (especially in the center panel) show substantial erosion and the red sections along the northern portion of the near the top of the right panel shows some significant accretion.

TABLE 1. COMPARISON OF AIRBORNE AND GROUND SURVEYS FROM FALL 1995. ATM ELEVATION (NOV.) MINUS GROUND SURVEY ELEVATION (SEPT.) INDIVIDUAL ATM LASER MEASUREMENTS FALLING WITHIN 1 METER OF INDIVIDUAL GROUND MEASUREMENTS ARE USED TO COMPUTE THE ELEVATION DIFFERENCE. (UNITS ARE IN METERS)

cross-section	<i>N</i>	μ	σ
A	85	-0.01	0.23
B	82	-0.05	0.10
C	77	-0.03	0.34
D	74	-0.03	0.19
E	81	-0.06	0.17
F	73	-0.03	0.15
G	108	-0.15	0.07
H	37	+0.03	0.26
I	42	-0.11	0.24
J	34	+0.12	0.49

TABLE 2. COMPARISON OF ATM ELEVATION DATA OVER THE BEACH AREA OF NORTH ASSATEAGUE ISLAND. EACH OF FOUR PASSES IS COMPARED TO THE COMBINATION OF THE THREE OTHER PASSES. INDIVIDUAL COMPARISONS ARE MADE BETWEEN EACH PAIR OF LASER MEASUREMENTS THAT FALL WITHIN 1 METER OF ONE ANOTHER. (UNITS ARE IN METERS)

pass	<i>N</i>	μ	σ
1	147567	-0.023	0.156
2	74376	0.000	0.154
3	130389	-0.090	0.157
4	124530	-0.066	0.156

The consistency of the ATM measurement is indicated by a comparison (Table 2) of the four passes flown at ~700 m from October 1996. The data have been limited to the beach face between the ocean and the dune in order to separate the effects of the instrument from the effects of topography. The comparisons were made by finding all the laser measurements from one pass that fall within a 1-meter radius of any measurement from the other three passes. The unweighted means of the differences are 9 cm or less with standard deviations all about 16 cm.

Conclusions

The ATM surveys have been shown to provide high detail beach morphology which is in reasonable agreement with available contemporaneous ground-profile surveys of North Assateague Island, except in sections subject to frequent beach overwash and resultant shifts in the distribution of sand where surveys separated by even a few days could be expected to show marked changes in elevation. The ATM data have the advantage over traditional ground-survey profiles because they are continuous, permitting quantitative assessment of the extent of beach erosion/deposition. Moreover, the aerial laser survey can be accomplished quickly over wide areas. For instance, the October 1996 survey of North Assateague Island conducted with the NOAA Twin Otter is just an 18-km section out of a survey of ~100 km from the Delaware Bay to the southern end of Assateague Island. This entire survey was accomplished in approximately 3 hours. Moreover, this survey was only the initial portion of a total of 590 km of beaches surveyed in five missions over barrier islands from Delaware to South Carolina.

Several difficulties in the implementation of airborne scanning laser altimeter data for the beach mapping application have been observed. These are (1) adapting present analytical procedures and models in use by various federal, state, and local agencies to accept the higher sampling density afforded by the ATM sensor; (2) organizations requiring the data generally use local coordinate systems while the airborne laser data are expressed in the ITRF system; and (3) editing of the laser data to remove vehicles and people and other ground clutter remains problematic as does delineation of buildings and vegetation. The NASA/NOAA beach mapping project is presently addressing these issues.

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