East Texas and Western Louisiana Coastal Erosion Study

Robert A. Morton and William A. White

Annual Report
(July 1, 1991 - June 30, 1992)

Prepared for the U.S. Geological Survey
under Contract No. 14-08-0001-A0912

Bureau of Economic Geology
The University of Texas at Austin
Austin, Texas 78713-7508

1992

CONTENTS

ANNUAL REPORT

East Texas and Western Louisiana Coastal Erosion Study

Bureau of Economic Geology
The University of Texas at Austin

July 1, 1991 to June 30, 1992

The following brief report summarizes the major accomplishments achieved during the first year of study of coastal erosion and wetlands loss along the southeastern Texas coast.

Work Element 1: Coastal Erosion Analysis

Objectives of this work element were to: establish a computerized database of historical shoreline positions (1882–1982), update the database using the most recent shoreline information, analyze historical trends in the context of the regional geologic framework and human modifications, synthesize the physical and habitat characteristics of different shoreline types, establish a network of field monitoring sites for surveying coastal changes, and eventually prepare an atlas of shoreline changes suitable for coastal planning and resource management.

Task 1: Shoreline Mapping. Shorelines spanning the time period from the 1860s to 1974 and covering the Gulf shoreline between Sabine Pass and Rollover Pass were digitized and entered into ARC-INFO. These shorelines were previously mapped by the Bureau of Economic Geology (BEG) and compiled onto USGS topographic maps (1:24,000 scale).

Next we tested digitizing shorelines directly from air photo mosaics and compared the results with digitizing the same shorelines optically transferred from the mosaics to topographic base maps. We prepared a plan for testing accuracy of previously mapped shorelines in rapidly eroding and relatively stable areas and completed the first phase of the test, which was to determine the error associated with computing magnitudes of change after digitization versus manual measurements. Test results indicated that computation of shoreline movement after digitization provides results that are comparable to original hand measurements and results are within the original error range determined for the hand computation techniques (microrule and hand calculator).

The second phase of the experiment was designed to test the accuracy of digitized shoreline positions. This work involved digitizing the original shoreline positions either presented on topographic maps (smooth sheets) or interpreted on aerial photographs. The initial effort involved digitizing the 1800s shoreline in the study area and comparing its Geographic Information System (GIS) generated position with the optically transferred position on the 7.5-minute quadrangle. We compared surveying control points (bench marks) on available 7.5-minute quadrangles with those appearing on the 1800s maps and determined that only one station between Sabine Pass and Rollover Pass appears on both maps. Next we examined old publications in University archives and determined that latitude and longitude positions of triangulation stations on 1800s maps had not been corrected for NAD 27. A joint letter with the Louisiana Geological Survey was sent to the National Ocean Service (NOS) requesting latitude and longitude positions of triangulation stations on 1800s maps corrected for NAD 27. Although receipt of the letter has been acknowledged by NOS, the request has not been processed. We also received and reviewed a USGS Open-File report (Digital Shoreline Mapping System [DSMS] User's Guide Version 1.0). This report describes a procedure for computer rectification of aerial photographs. Because ARC-INFO has limited capabilities to handle air photos, it will be necessary to use an additional routine such as DSMS if we digitize from the photographs rather than after they have been optically transferred to a stable base.

The Texas Highway Department, Texas General Land Office, Texas Natural Resources Information System, and U.S. Fish and Wildlife Service were contacted regarding recent low-altitude aerial photographic missions of the southeast Texas coast. Acquisition and mapping of the most recent shoreline was deferred because a greater emphasis was placed on digitizing the 1930s and 1960s shorelines for the entire study area to support the bathymetric analysis being conducted by Jeff List and Mark Hansen in St. Petersburg.

Task 2: Geomorphic Characterization. This task involved field investigations between Sabine Pass and Rollover Pass. Beach profile sites were reoccupied and observations made that allowed an initial classification of shoreline characteristics including physical characteristics of the beach (morphology, composition, slope, width, dune development, substrates, stabilization projects) as well as shoreline stability determined from the preceding erosion analysis. A digital base map of the entire east Texas study area was created in ARC-INFO (GIS) and used to map geomorphic characteristics of the Gulf shoreline between Sabine Pass and Rollover Pass.

Work Element 2: Regional Geologic Framework

Objectives of this work element were to begin investigating the geologic origin and evolution of the principal coastal subenvironments, establish a chronostratigraphic framework for the coastal systems and construct relative sea-level curves for the reconstruction of Holocene coastal evolution. This task will also provide data on the physical characteristics and natural habitats of the various shoreline types in the context of shoreline stability.

Task 1: Stratigraphic Analysis. The study area encompasses a chenier plain, deltaic headlands, progradational barriers, retrogradational barriers, tidal inlets, lagoons, estuaries, and the inner continental shelf. We plan to use vibracores, faunal assemblages, isotopic dates, and seismic surveys to investigate the late Quaternary and Holocene stratigraphy of these diverse environments. These data, and others generated in the western Louisiana project, will be used to construct cross sections illustrating the various coastal and nonmarine facies and to construct a detailed sea-level curve for the late Holocene and Modern time periods. Results of these investigations will provide a basis for predicting future magnitudes and rates of land loss.

Subtask 1: Data Inventory and Compilation. We began compiling maps, cross sections, and reports as well as basic data such as isotopic dates, foundation borings, and core descriptions for Sabine Lake and the chenier plain of southeastern Texas. The surficial and shallow subsurface data are being used to construct subregional cross sections showing the distribution of sedimentary facies, sequence boundaries, and age relationships. This preliminary investigation will provide the basis for systematic collection of vibracores during subsequent phases of the investigation. An overflight and field reconnaissance of western Louisiana and eastern Texas were conducted to observe the diversity of shoreline types, processes, and regional geology of the study area. Shallow subsurface data (foundation borings, cross sections, seismic profiles) was compiled for the southeastern Texas Coast from available industry and government sources. Lithologic logs of selected borings constructed and stratigraphic cross sections were prepared that illustrate the composite entrenched valleys of the Sabine and Trinity fluvial systems and characteristics of the Holocene valley fill.

Subtask 2: Field Studies. A reconnaissance field survey of the McFadden Wildlife Refuge was completed and 7 vibracores were obtained from the marsh, tidal channel, and beach environments. These vibracores constitute the first in a series of strike and dip transects that will be used to reconstruct the depositional history of the area. Also, one deep core and a fixed piston core were collected for age dating and to support wetlands studies being conducted by Don Cahoon (U.S. Fish and Wildlife Service), Denise Reed (LUMCON), and John Day (LSU). Also, a work plan was developed for obtaining precise elevations, shallow subsurface lithologies, and age dates for the entrenched valley fill of Sabine Lake and the chenier plain of southeastern Texas.

Work Element 3: Coastal Processes

Understanding coastal processes is the key to understanding coastal erosion and predicting future changes. Therefore, this work element involves numerous tasks that address the quantification of basin energy, sediment motion, and the forcing functions that drive the coastal system. Objectives of this work element are to evaluate relative sea level rise on geological and historical time scales, provide a basis for assessing wave and current energy as well as sediment transport, assess climatic and meteorological influences on coastal processes, evaluate the impacts of storms on shoreline stability and instantaneous erosion potential, and begin quantification of coastal sediment budget.

Task 1: Relative Sea-Level Rise and Subsidence. Sea level is perhaps the single most important variable with regard to coastal erosion and planning for future development of the coast. An analysis of relative sea level will involve acquiring tidal data at selected gauges with long-term records and releveling surveys from the NOAA. This task will focus on the major factors causing relative rise in sea level within the study area and the recent acceleration in the rate of sea-level rise. A request was submitted to NOS inquiring about the availability of digitized hourly readings at tide gages in Texas. The request has been received but not processed by NOS.

Task 2: Sediment Transport. This task will examine seasonal beach and nearshore profiles as a first approximation of time-averaged sediment transport as determined from post-Alicia beach profile data on Galveston Island. During the first year of study, preliminary field experiments were being designed to measure the frequency and duration of sediment movement, as well as the response of sandy and muddy substrates to similar levels of wave and current energy.

Task 3: Sediment Budget. This task will evaluate the primary sediment sources (updrift erosion and fluvial sediment supply) and the principal sinks (accretion, washover, dune construction, and offshore deposition). Some additional losses occur at tidal inlets and some unknown quantity is trapped in the deep-draft navigation channels. Material periodically dredged from the ship channels deserves further evaluation as a potential source of beach nourishment material. During the first year of study we compiled available erosion and bathymetric analyses, beach profiles, sediment transport analyses, stream discharge records, and vibracore descriptions for the area of interest.

Task 4: Storm Impacts. This task will involve the reconstruction of storm impacts from historical records and the development of models to predict the response of each shoreline type to storms having variable characteristics. Monitoring of beach profiles before and after a major storm will also provide a quantitative measure of beach changes and allow for calculations of mass sediment transfer. During the first year of study we conducted a field experiment to test the concept of using GPS techniques to monitor nearshore changes in elevation and sediment volume. Conventional beach surveys at Galveston Island State Park were conducted by the BEG and the GPS surveys were jointly conducted by the BEG and the University of Texas Applied Research Laboratories. State-of-the-art GPS equipment (3 multichannel receivers, tripods, range poles, mounting brackets) was provided by the

Texas Highway Department. Differential GPS surveying techniques were used to conduct rapid static (stop-and-go) and kinematic surveys. All surveys closed within a few millimeters. Each technique was replicated during the second day of data collection to test repeatability for different satellite geometries. We prepared plots and tables showing GPS repeatability and compared them with the theodolite surveys. We also developed techniques for contouring GPS data, comparing two-dimensional surfaces, and calculating volumetric differences between the surfaces. Preliminary results indicate that a combination of stop-and-go and kinematic techniques will allow rapid, relatively low cost, and reliable beach surveying that is independent of bench marks and still provides absolute three-dimensional positions. A report summarizing the field and laboratory techniques and results of the GPS surveys was completed and is attached as an addendum.

Work Element 4: Prediction of Future Coastal Response

Simple time-averaged linear methods of estimating future rates of shoreline movement are inappropriate for most future predictions of shoreline position. Objectives of this work element are to improve rate of change estimates, develop conceptual models that synthesize coastal changes on both geological and historical time scales, and develop quantitative models that improve our predictions of shoreline changes and coastal inundation.

Task 1: Mathematical Analysis of Rates of Change. We began to evaluate available software that performs time series analysis and designed a procedure within ARC/INFO to generate shore-normal transects at user specified intervals, determine distances between consecutive shorelines at those transects, calculate rates of change, and transfer data to ASCII files. This subroutine will be used to generate data sets that will be statistically analyzed in order to develop better predictive models of shoreline movement.

We reviewed several unpublished methods of predicting shoreline movement (Dolan and Fenster, University of Virginia) and coastal submergence. A summary of those techniques that emphasizes the assumptions underlying each technique is also attached as an addendum.

Work Element 5: Technology Transfer

The technology transfer work element provides for the timely reporting of project results and makes the interpretations and conclusions available to users as needed. It also establishes a repository to preserve raw data and materials that would be a significant source of information for future studies.

Task 1: Geographic Information System. Development of a coastal GIS for Texas data was begun that initially focused on digitizing shorelines, preparing a digital base map as well as initiating an inventory of basic data including shot point locations of offshore seismic data.

Task 2: Reporting and Data Dissemination. This task included preparation of a detailed planning document for the five-year program and four quarterly reports as well as participation in several meetings between the principal investigators and coordination with other states in the Gulf of Mexico program.

ADDENDUM 1: PREDICTIVE COASTAL EROSION AND SUBMERGENCE MODELS: A SUMMARY OF TECHNIQUES AND ASSUMPTIONS

Robert A. Morton
Bureau of Economic Geology
The University of Texas at Austin

Introduction

Now that coastal erosion and land loss have been identified as important scientific and social issues, questions are being asked about how much land will be lost in the future, where will the shoreline be at some particular time, which communities will be threatened by land loss, and how much land will be flooded if sea level continues to rise. To answer these questions, several methods (models) have been developed that project shoreline positions based on assumptions regarding past shoreline changes and estimated rates of future sea-level rise. It should be remembered that all the predictive models are hampered because they are unable to anticipate significant changes in the factors that cause or control shoreline movement and therefore their forecasts may not be very accurate. Despite the uncertainties involved in the model results, planners want to have at least some basis for making decisions that will influence future use and development of the coast.

Models that estimate future land loss can be either qualitative or quantitative. Non-quantitative predictions of coastal evolution and future shoreline positions are based on a general understanding of how nearshore environments respond to changing oceanic conditions. Geological and historical evidence clearly demonstrate that a rapid rise in sea level will cause narrowing of barrier islands, accelerate migration of transgressive barriers, replace fresh and brackish water marshes with saltwater marshes, convert uplands to wetlands, enlarge flood plains, and increase the area that would be inundated by storms of historical record.

Quantitative predictions of future coastal erosion and land loss rely on *statistical models*, *geometric models*, or *deterministic models*. Despite the common goal of all these models, they are based on completely different assumptions and input data. Statistical models do not attempt to understand the causes of shoreline change. Instead, they depend on empirical data representing interactions of the important contributing factors for a sufficiently long period of time so that reliable projections can be made on the basis of historical records. Geometric models emphasize how beach slopes and shapes control profile evolution in response to increased water levels. Deterministic (numerical) models simulate sequences of events expressed as equations that represent observed physical conditions and processes. Even the deterministic models rely on statistical data such as wave characteristics, average beach profiles, and average sizes of beach sand.

A critical element employed in both geometric and deterministic models is the concept of equilibrium nearshore profiles. This engineering concept, which has been presented in several different forms, suggests that concave offshore profiles are geomorphic expressions of textural parameters (grain size, fall velocity) and wave-energy dissipation (Dean, 1991; Bodge, 1992). Recent investigations of equilibrium profiles have revealed that a single mathematical expression does not adequately depict all profiles or even averages of profile classes (Bodge, 1992).

Statistical Models

Simple statistical models (means, standard deviations, regression analysis) are used to reduce long-term historical shoreline movement to a single value (rate of movement) that is extrapolated to estimate future shoreline positions. Dolan et al. (1991) summarized the most common linear analyses of shoreline movement and described the advantages and disadvantages of each technique.

Computer graphics programs can convert shoreline dates and positions to scatter diagrams (figs. 3-5) and also generate regression curves and equations representing the best statistical fit for the polynomial selected. When used properly, the least-squares equations are particularly helpful because they can be used to estimate a future shoreline position when the date (year 2100) or elapsed time (next 100 yrs) is specified.

If reversals in shoreline movement cannot be explained, then the mathematical analyses and prediction of future positions are of little value. None of the linear time-averaging techniques used to analyze historical shoreline movement and to calculate rates of change are appropriate if actual trend reversals occur during the period of record (fig. 5). Simple statistical tests can be used to identify anomalous data but they should not be viewed as a substitute for specific knowledge of shoreline behavior at a particular site.

Rates of shoreline change are generally reported as single values without the benefit of standard deviations or error bars indicating the uncertainty of projected shoreline positions. Furthermore, errors associated with the predicted rates of change are magnified by at least 10 times and as much as 60 times when they are used to define projected erosion zones (National Research Council, 1990). Therefore, minimizing the uncertainty of these predictors should be a primary objective of coastal research.

Projections of historical data are easy to make and understand but their predictive capabilities can be severely limited because (1) input data are empirical, site specific, and not broadly applicable because of morphological variability and diversity of coastal settings, (2) the analyses assume linear shoreline responses even though they may be nonlinear, (3) statistical analyses can be strongly biased by data clusters and single anomalous shoreline positions, and (4) physical processes summarized in historical shoreline change records may not adequately represent future conditions. The most severe limitation of historical projections is that they are incapable of accurately predicting future responses if some factor (sea level, sediment budget) is drastically altered. Predictions of climatic changes clearly indicate that the rate of sea-level rise will probably accelerate and other factors such as variable substrate composition, sediment influx, and storm activity could invalidate the extrapolation of even recent erosion rates.

Geometric Models

Simple submergence models, such as the one used by Daniels (1992), employ ground slopes, elevations, and projected sea levels to predict future shoreline positions. This static topographic technique, which does not account for coastal erosion or sediment transport, is used to estimate minimum areas of inundation, potential losses of wetlands caused by flooding, or transformation of wetland types. Models that assume one-dimensional passive inundation may greatly underestimate landward retreat of erodible shores as a result of sea-level rise and they ignore dynamic responses to shifting sites of deposition and erosion.

Bruun (1962, 1988) presented the first and most frequently applied geometric model that graphically relates shoreline recession to a relative rise in sea level (Figure). Most numerical models employ the Bruun Rule or a similar relationship to estimate the horizontal translation of the shoreline for a particular sea-level rise scenario. The original mathematical expression of the Bruun Rule assumes (1) an equilibrium beach profile, (2) material eroded onshore is directly deposited offshore with no gain or loss in sediment volume, (3) only cross-shore sediment transport occurs, (4) the increase in offshore profile elevation is equal to the rise in water level so that water depth remains constant, (5) the profile remains unchanged as it is shifted landward and upward, and (6) there is a point beyond which there is no active sediment transfer. The stringent closed-system requirements of an equilibrium profile, fixed closure depth, negligible alongshore transport, and conservation of mass across the same profile cannot be met at most coastal sites.

The fundamental issue involving predictive geometric models is the shape of beach and nearshore profiles for it is this parameter that determines the horizontal displacement of the shoreline relative to an incremental rise in sea level (Bruun, 1962). Pilkey and Davis (1987) found little agreement between measured recession along the North Carolina coast and those predicted by several geometric shoreline response models including the Bruun Rule. It is clear from the analysis of Pilkey and Davis (1987) that steep slopes of the shoreface are only appropriate for prediction of short-term shoreline recession (decades) whereas gentle slopes of the coastal plain are the geometries that control shoreline recession over centuries and millennia. According to the Bruun Rule, shoreline recession is 50 to 100 times the rise in relative sea level (SCOR, 1991); however evidence from the late Wisconsin/Holocene sea level history shows that shorelines actually retreated 1,500 to 2500 times the rise in sea level over broad continental shelves.

Field tests have confirmed the general validity of the Bruun Rule (Rosen, 1978; and Hands, 1983) at least along coasts where profiles could rapidly equilibrate relative to the rise in sea level. However, the Bruun Rule commonly does a poor job of predicting changes at a specific site. Dean (1990) has argued that the Bruun Rule may be a better predictor of general or average shoreline response rather than being a good predictor at a particular location. If the Bruun Rule only approximates general erosion trends, then it may have little relevance to many site specific applications. SCOR (1991) recommended using large error bars with shoreline predictions derived from the Bruun Rule as a reminder of the large uncertainty associated with the method.

Geometric models only predict maximum potential shoreline recession and therefore they are unable to accommodate such things as the time lag before equilibrium conditions are reached. Another major deficiency of most geometric models is that they fail to take into account sediment transport or its long-term equivalent, sediment budget. Everts (1985, 1987) combined continuity of mass equations (sediment budget) with the concept of equilibrium profiles to separate long-term (>20 yrs) shoreline erosion caused by sea-level rise from other effects. Using several field sites along the Atlantic coast, Everts (1987) was able to explain between 20 and 88% of the observed erosion by a rise in relative sea level whereas the remaining erosion was attributed to sand losses from the offshore profile.

Hybrid Statistical/Geometric Models

Some methods of predicting shoreline movement combine long-term rates of change, determined by statistical methods (taken as background change), with shoreline retreat predicted by the Bruun Rule (Bruun, 1962). Sea-level scenarios, such as those forecast by EPA (Titus, 1988), provide the input for estimating probable magnitudes of sea-level rise for the period of interest. An example of the hybrid method of predicting shoreline response was presented by Kana et al. (1984) in their analysis of Charleston, South Carolina.

Although most land loss models focus on shoreline erosion, one model has been specifically developed to investigate wetland changes and wetland losses as a result of predicted sea-level rise. Park et al. (1989) developed the SLAMM model (Sea Level Affecting Marshes Model) to analyze what impacts a long-term (>100 yrs) accelerated rise in sea-level would have on the composition and distribution of coastal wetlands. The model starts with initial conditions (wetland classes and elevation at a particular site) then predicts future conditions in time steps by combining geometric inundation (sea-level rise scenario) with coastal erosion (Bruun Rule). Although the model does not explicitly simulate salinity changes, it does accommodate sediment accumulation as well as inland wetland migration and conversion of biotic assemblages. Results of one study (Park et al., 1989) suggested that nearly half of the extant marshes and swamps in the contiguous U.S. would be destroyed if sea level rises 1 m during the next century.

Deterministic Models

Advanced mathematical models that can accurately predict shoreline erosion and coastal land loss are still in the formative stages of development because the coastal processes being simulated are complex and existing equations do not adequately describe the physics of sediment transport across the beach and offshore profile (LeMehaute and Soldate, 1980; SCOR, 1992). Furthermore, there is a general lack of field data (wave climate, wave-field transformation, sediment budget, offshore bathymetry) for calibrating the models. Most numerical models are designed to predict shoreline changes of limited coastal segments and for brief periods (less than a decade), and to evaluate effects of coastal structures on shoreline evolution (LeMehaute and Soldate, 1980; Kriebel and Dean, 1985, Perlin and Dean, 1985). Furthermore, most of the predictive engineering procedures are designed to simulate specific conditions (storm-induced beach erosion, bathymetric changes, structural alterations) that require basic assumptions, which may be oversimplifications. For example, some simulations assume equilibrium beach profiles that remain constant as beaches retreat, smooth unbarred shorefaces, nearshore material balance, and constant water levels (Bruun, 1962; Perlin and Dean, 1985).

Deterministic models are highly data dependent and require site-specific values for such parameters as wave climate, alongshore and cross-shore sediment transport, and sediment budget. The common lack of local oceanographic and geological data coupled with the fact that nearshore hydrodynamics are nonlinear and therefore nonadditive means that prediction confidence rapidly declines after the first few years of simulation. Subsequent simulations are further hampered by a poor understanding of nearshore physical relationships, especially the relationship of sediment transport to forcing events and profile recovery after storms that is necessary as a starting point for the next simulation. The cumulative result of this uncertainty is a probability distribution of shoreline positions with confidence bands that define an envelope of possible future shoreline positions. Verification of these models is also hampered by the need for detailed oceanographic data during the same time period as observed shoreline movement, which means a short historical record when both shoreline movement and oceanographic data were available. Deterministic models also place a heavy emphasis on intuition and extensive local experience of the user at the site being modeled so that appropriate parameters are selected and the model is given substantial guidance as the controlling routine calls the various subroutines that are used to forecast shoreline positions.

LeMehaute and Soldate (1980) documented a mathematical model that was developed to predict evolution of bluffs and shores near coastal structures on the Great Lakes. Their model, which does include sea level as a time-dependent variable, employs the concept of equilibrium profiles, and a depth of profile closure on the shoreface.

Kriebel and Dean (1985) formulated a procedure for estimating cross-shore sediment transport resulting from the nearly instantaneous beach and dune erosion during a storm. Although this model is based on the equilibrium profile concept it addresses the problem of maximum erosion potential not being achieved because of rapidly changing parameters during the storm. Instead it emphasizes nearshore profile adjustment that depends on the storm surge hydrograph. This model employs a generalized beach/dune profile where the onshore boundary coincides with the dune. Thus it is not applicable to overwash beaches where dunes are low or absent and surface elevations are less than the storm surge. The model has some direct application with regard to hazards zones and location of coastal construction, but it only addresses one phase of beach cyclicity and therefore is inappropriate for predicting long-term shoreline changes.

GENESIS (Generalized Model for Simulating Shoreline Change) is a one-dimensional deterministic model used to predict future positions of shorelines as a result of emplaced coastal structures (Hanson and Krause, 1989). Maximum length of shoreline and periods simulated are 100 km and 10 yrs respectively. Basic input parameters are initial shoreline position, wave statistics, beach profiles and bathymetry, boundary conditions, and configurations of engineering structures. Although GENESIS is capable of simulating longer shorelines and greater periods than most other models, it is not applicable to open-coast changes that are tidally dominated, storm induced, or caused by water-level fluctuations and its greater utility is for predicting transitions from one equilibrium state to another (Hanson and Krause, 1989).

Although some of the deterministic models incorporate future magnitudes of sea-level rise, a fully three-dimensional model has not been developed that will distinguish among different pathways of coastal evolution depending on variable rates of sediment supply and sea-level rise. For example, slow rates of sea-level rise typically allow eroding barrier islands to maintain a dune ridge that retards erosion. In contrast, rapid rates of rise cause dune breaching, washover, and eventually barrier migration. During highest rates of sea-level rise the barrier is drowned in place, overstepped, and partially preserved on the inner shelf. Furthermore, the models do not adequately provide for variable sediment textures. The extant models have been developed, tested, and verified for sandy beaches, not muddy shores, despite the fact that many eroding coasts are composed of thin sand beaches overlying fine-grained bay and estuarine deposits.

Shoreline movement and wetland changes of many coastal regions were reasonably consistent and predictable before economic development because they were primarily controlled by unaltered processes and the geologic framework. However, post-development human activities have caused large-magnitude imbalances in the natural forces. As a consequence of this induced disequilibrium, future predictions of coastal change will be more difficult to make and will require better quantification of human alterations.

References

Bodge, K. R., 1992, Representing equilibrium beach profiles with and exponential expression: Journal of Coastal Research, v. 8, p. 47-55.

Bruun, P., 1962, Sea level rise as a cause of erosion: Journal of Waterways and Harbors Division, ASCE, WW1, p. 117-133.

Bruun, P., 1988, The Bruun Rule of erosion by sea-level rise: a discussion of large-scale two- and three-dimensional usages: Journal of Coastal Research, v. 4, p. 627-648.

Daniels, R. C., 1992, Sea-level rise on the South Carolina coast: Two case studies for 2100: Journal of Coastal Research, v. 8, p. 56-70.

Dean, R. G.,1990, Beach response to sea level change, *in* LeMehaute, B., and Hanes, D. M., eds., Ocean Engineering Science: The Sea v. 9, John Wiley Inc., New York.

Dean, R. G., 1991, Equilibrium beach profiles: Characteristics and applications: Journal of Coastal Research, v. 7, p. 53-84.

Dolan, R., Fenster, M. S., and Holme, S. J., 1991, Temporal analysis of shoreline recession and accretion: Journal of Coastal Research, v. 7, p. 723-744.

Everts, C. H., 1985, Sea level rise effects on shoreline position: Journal of Waterway, Port, Coastal and Ocean Engineering, v. 111, p. 985-999.

Everts, C. H., 1987, Continental shelf evolution in response to a rise in sea level, *in* Nummedal, D., Pilkey, O. H., and Howard, J. D., eds., Sea-level fluctuation and coastal evolution: Society of Economic Paleontologists and Mineralogists Special Publication 41, p. 49-57.

Hands, E. B., 1983, The Great Lakes as a test model for profile responses to sea level changes, *in* Komar, P. D., ed., CRC Handbook of Coastal Processes and Erosion, CRC Press, Boca Raton, Florida, p. 167-189.

Hanson, H., 1989, GENESIS - A generalized shoreline change numerical model: Journal of Coastal Research, v. 5, p. 1-27.

Hanson, H., and Kraus, N. C., 1989, "GENESIS: Generalized Model for Simulating Shoreline Change", Report 1: U.S. Army Corps of Engineers, Coastal Engineering Research Center, Technical Report CERC 89-19, 185 p.

Kana, T. W., Michel, J., Hayes, M. O., and Jensen, J. R., 1984, The physical impact of sea level rise in the area of Charleston South Carolina, *in* Barth, M. C., and Titus, J. G., eds., Greenhouse effect and sea level rise: Van Nostrand Reinhold Company, New York, p. 105-150.

Kriebel, D. L., and Dean R. G., 1985, Numerical simulation of time-dependent beach and dune erosion: Coastal Engineering, v. 9, p. 221-245.

LeMehaute, B., and Soldate, M., 1980, Numerical modelling for predicting shoreline change: U.S. Army Corps of Engineers, Coastal Engineering Research Center, 80-6.

National Research Council, 1987, Responding to changes in sea level: engineering implications: Committee on Engineering Implications of Changes in Relative Sea Level, Marine Board, National Academy Press, Washington D. C.

Park, R. A., Trehan, M. S., Mausel, P. W., and Howe, R. C., 1989, Coastal wetlands in the twenty-first century: profound alterations due to rising sea level, *in* Davis, F. E., ed., Proceedings of American Water Resources Association Annual Conference, Wetlands: Concerns and Successes, Tampa, Fl., p. 71-80.

Perlin, M. and Dean, R. G., 1985, 3D models of bathymetric response to structures: Journal of Waterways and Ports, Coastal Ocean Engineering, ASCE, v. 111, p. 153-170.

Pilkey, O. H., and Davis, R., 1987, An analysis of coastal recession models: North Carolina coast, *in* Nummedal, D., Pilkey, O. H., and Howard, J. D., Sea-level fluctuation and coastal evolution: Society of Economic Paleontologists and Mineralogists Special Publication 41, p. 59-68.

Rosen, P. S., 1978, A regional test of the Bruun Rule on shoreline erosion: Marine Geology, v. 26, p. M7-M16.

SCOR (Scientific Committee on Ocean Research) Working Group '89, 1991, The response of beaches to sea-level changes: A review of predictive models: Journal of Coastal Research, v. 7, p. 895-921.

Titus, J. G., ed., 1988, Greenhouse effect, sea level rise and coastal wetlands: Environmental Protection Agency, EPA-230-05-86-013, Washington, D. C., 152 p.

ADDENDUM 2: MONITORING BEACH DYNAMICS USING GPS SURVEYING TECHNIQUES

Robert A. Morton[1], Mark P. Leach[2], Jeffrey G. Paine[1], Michael A. Cardoza[2]

[1]Bureau of Economic Geology, The University of Texas at Austin
[2]Applied Research Laboratories, The University of Texas at Austin

Running Head: GPS BEACH SURVEYS

ABSTRACT

A need exists for frequent and prompt updating of shoreline positions, rates of shoreline movement, and volumetric nearshore changes. To effectively monitor and predict these beach dynamics, accurate measurements of beach morphology incorporating both shore-parallel and shore-normal transects are required. Although it is possible to monitor beach dynamics using conventional surveying methods, it is generally not practical to collect data of sufficient density and resolution to satisfy a three-dimensional beach-change model. The challenge to coastal scientists is to devise new beach monitoring methods that address these needs and are rapid, reliable, relatively inexpensive, and maintain or improve measurement accuracy.

The adaptation of Global Positioning System (GPS) surveying techniques to beach monitoring activities is a promising response to this challenge. An experiment that employed both GPS and conventional beach surveying was conducted, and a new beach monitoring method employing kinematic GPS surveys was devised. This new method involves the collection of precise alongshore and shore-normal GPS positions from a moving vehicle so that a three-dimensional beach surface model can be generated. Results show that the GPS measurements agree with conventional surveys at the 1 cm level, and repeated GPS measurements employing the moving vehicle demonstrate a precision of better than 1 cm. In addition, the increased resolution provided by the GPS surveying technique reveals alongshore beach morphologies that are undetected by conventional shore-normal profiles. The application of GPS surveying techniques combined with the refinement of appropriate methods for data collection and analysis provides a better understanding of nearshore dynamics, sediment transport, and storm impacts.

ADDITIONAL INDEX WORDS: *Shoreline change analysis, three-dimensional beach models, storm impact assessment, beach profiles.*

INTRODUCTION

Coastal erosion and deposition are three-dimensional phenomena that are usually inferred from changes in one-dimensional data such as shoreline position (map view) or changes in features on a beach profile (cross-section view). Beach monitoring is an important surveying application that provides a way of understanding beach dynamics and the factors that influence volumetric gains and losses along the coast. Beach monitoring can also reveal short-term trends in beach stability and rates of beach movement, which potentially can be incorporated in mathematical models to forecast shoreline positions. Until recently, field monitoring of dynamic coastal environments has been difficult because large spatial scales tended to limit the number of beach segments that could be surveyed efficiently, and therefore an integrated depiction of the beach surface over long distances has been incomplete.

Predicting future rates of coastal erosion and land loss has progressed from a purely academic exercise to one of environmental importance as many coastal states and government agencies rely on technical data to determine construction setback lines and insurance hazard zones (NATIONAL RESEARCH COUNCIL, 1990). To support these public policies some coastal states (Florida, North Carolina, South Carolina) have established elaborate networks of closely spaced profile monuments that are periodically revisited to assess magnitudes and rates of beach movement. This information is combined with other data, such as long-term beach stability trends and rates of change, to establish building zones. Currently the Federal Emergency Management Agency (FEMA) is recommending legislation that would establish hazard zones based on 10, 30, and 60 times the annual erosion rate (NATIONAL RESEARCH COUNCIL, 1990). Thus, accurately interpreting trends of beach movement and precisely quantifying the rates of movement are necessary to accurately predict future beach positions.

Beach profiles oriented perpendicular to the shoreline (Figure 1) can be obtained with various types of equipment ranging from simple graduated rods and chains (EMERY, 1961), to standard stadia rod and level, to an autotracking Geodimeter with reflecting prism (BIRKEMEIER *et al.*, 1991). The more sophisticated techniques offer greater measuring precision, but they also require more field support and data processing equipment, such as computers and specialized software.

A typical shore-normal beach survey yields a one-dimensional profile that represents the relative height of the beach from a fixed reference marker. This profile also displays the current position of particular beach features, such as shoreline, berm, dune, vegetation line, or datum intercept such as the National Geodetic Vertical Datum (NGVD). A subsequent beach profile survey, conducted several months later, when compared to the earlier survey yields a two-dimensional cross-sectional area, which represents the amount of beach erosion and deposition that occurred between surveys. A three-dimensional volumetric change in the beach is derived by extrapolating between these cross-sectional areas. There are two potentially large errors associated with this approach to estimating beach erosion or deposition. The first is that all of the measurements are made relative to a fixed monument. If this marker is lost or damaged, accurate comparison of previous surveys with subsequent surveys would be extremely difficult. The second potential error involves the three-dimensional extrapolation from two-dimensional data. The extrapolated results are subject to significant errors if the two-dimensional profiles neglect subtle changes in beach surface or if the adjacent profiles are widely spaced.

Practical limitations associated with conventional beach monitoring are (1) the long time required to conduct extensive surveys, (2) the common loss of “permanent” monuments where the beach is either rapidly eroding or subjected to substantial wave penetration during storms, and (3) the errors associated with calculating volumetric changes interpolated between widely spaced profiles. Estimates of volumetric beach changes can be significantly improved if the beach is surveyed by an intersecting grid of profiles oriented both perpendicular and parallel to the shoreline (Figure 2). By providing a more accurate representation of the actual beach surface, a grid of profiles can reduce the error that currently is introduced when unknown elevation changes between profiles are ignored or estimated by interpolation.

To overcome existing field limitations, new beach monitoring techniques are needed that are rapid, as accurate as conventional surveys, independent of site-specific monuments, and that integrate most of the beach surface so that two-dimensional representations closely approximate real conditions. GPS surveying techniques are emerging as likely solutions to this dilemma because they can provide extremely accurate three-dimensional locations of remote sites with a minimum of field operation time. In addition, GPS surveys conducted from vehicles provide synoptic two-dimensional representations of long beach segments, an accomplishment that is not easily achieved using traditional surveying equipment and foot-power.

GPS OVERVIEW

GPS is a satellite-based system developed by the U.S. Department of Defense (DOD) to provide continuous, worldwide, all weather navigation, primarily for military users. The principal observations that GPS provides include the pseudorange, a clock biased pulsed range measurement, the carrier phase, a continuous biased range measurement, and the satellite broadcast ephemerides (predicted but not actual positions). There are different mathematical approaches for utilizing these observations for positioning, but the basic concept can be thought of as triangulation with satellites as ranging sources. At least four satellites must be observed to solve for a three-dimensional position and time.

There are two levels of real time accuracy provided by the system: the Standard Positioning Service (SPS) provides 100 meter accuracy (3-D rms), whereas the Precise Positioning Service (PPS) provides 16 m accuracy (3-D rms). There are no restrictions on access to the SPS but the PPS is only available to DOD and other selected users. The PPS accuracy is degraded to SPS levels by implementation of Selective Availability (SA). SA is implemented through the corruption of the satellite clock and orbit information broadcasted by the satellites.

Users that require greater accuracy than an autonomous system provides typically employ a differential GPS technique that effectively negates the effects of SA. Differential GPS is a data collection and processing approach in which two or more receivers track the same satellites simultaneously. One receiver is typically located over a known reference mark and the position of a desired point (platform, survey mark, sensor) is determined relative to that reference point. Because the errors in GPS positioning (satellite clock and orbit errors, along with SA effects) are highly correlated as a function of the baseline length between the two receivers, the differential technique effectively eliminates these common mode errors. This allows differential position accuracy to far exceed the normal GPS system accuracy for a single receiver operating autonomously. Differential GPS users are able to determine the position of dynamic platforms (vehicles, vessels, and aircraft) at the few meter level in real time and at the centimeter level in postprocessing. Accuracies of a 0.5 cm plus one to two parts-per-million (ppm) of the baseline length are routine, and specialized analyses can result in improvement of one or even two orders of magnitude. The accuracies achievable using differential GPS have allowed GPS technology to be successfully employed in a number of other applications including: surveying and geodesy, photogrammetric mapping, hydrography, gravimetry, and crustal motion studies.

GPS KINEMATIC SURVEYING METHODS

Differential GPS kinematic survey techniques are designed for rapid, centimeter level positioning on moving platforms. The primary restriction in kinematic GPS is the requirement that the initial carrier phase cycle ambiguity be determined. This cycle ambiguity can be resolved by "indexing," starting the survey with both the reference and mobile GPS antennas located on known monuments, or by employing an antenna swap technique (REMONDI, 1985). Recently, sophisticated data processing strategies have emerged which allow the user to solve for the ambiguity under certain conditions without the requirement for indexing or an antenna swap. Whatever the method, once the initial phase ambiguity is known, the position of the mobile receiver can be determined from the change in the observed carrier phase of the mobile receiver, provided the receivers maintain continuous phase lock on the satellites being tracked. These techniques allow mobile data collection and are well suited for areas, such as an open coastline, where satellite visibility is not restricted.

In kinematic surveys, an independent solution is computed at each measurement epoch. This technique is well suited to continuously moving platforms where the vehicle path or platform trajectory is of interest. The density of solutions is determined by the speed of the vehicle and the sampling rate of the receiver. In "stop-and-go" kinematic surveys, the user is typically on land and interested in rapid surveys of a series of stationary points. The operational scenario involves "stopping" over a survey point long enough to employ averaging to reduce random errors and then "going" on to the next point. Typically a few minutes of data collected at each point is sufficient.

EXPERIMENT DESCRIPTION

Field experiments were conducted to evaluate GPS surveying techniques for monitoring beaches, to develop procedures for collecting and analyzing GPS data for coastal applications, and to evaluate the accuracy and potential sources of error of GPS beach surveys. The experiments also provided a means of establishing the minimum manpower, equipment and sampling parameters necessary for a successful beach survey, and a way of determining the advantages and disadvantages of GPS surveys compared to other surveying techniques. It was expected that the techniques developed during the pilot project phase could be modified to eventually become a standard field technique for surveying large beach areas, determining volumetric nearshore changes, monitoring movement of significant morphological features, conducting post-storm impact assessments, and establishing ground truth for aerial reconnaissance work.

Equipment

The GPS geodetic survey equipment employed during the experiments (Figures 3-5) included three battery-powered, 12-channel GPS receivers (two active units and one backup), three bipod range poles with special vehicle mounting brackets, a roof mount for attaching an antenna to the vehicle, a vehicle side mount for transporting the bipod and antenna between locations, and a pad of microwave absorbent material to prevent multipath signal reflection from the roof of the vehicle. The conventional survey equipment consisted of a theodolite and range pole. In order to allow precise reoccupation of transect stations, approximately 20-cm-long aluminum pins were placed as markers at each station. Each pin was previously indented with a small (2 mm radius by 2 mm deep) dimple to allow the pointed end of the bipod (Figure 4) to precisely reoccupy the same point on the pin.

A 2-km segment of sand beach at Galveston Island State Park was selected as the experiment site. This area is controlled by Park officials and was chosen to mitigate the possibility of interference from unauthorized vehicles, beach scraping, or vandalism. The site was also selected because beach profiles have been surveyed there since 1983 (MORTON AND PAINE, 1985). Four beach transects oriented perpendicular to the shore (Figure 1) were established using conventional surveying equipment and a two-man crew. Survey stations along each transect were located where beach morphology changed (landward edge of dunes, dune crest, dune toe, vegetation line, berm), or were spaced 5 m apart on the uniformly sloping barren beach. Each station was marked with a flathead pin driven flush with the beach surface, and the pin and surrounding sand were sprayed with a bright water-based paint for easy identification. Each transect consisted of 11 to 13 stations depending on beach width at high tide (Figure 1). Those station marker pins located immediately seaward of the vegetation line, at the berm, and on the forebeach were also marked with surveyors flags (Figure 2) so that they could be spotted from a moving vehicle. Together the dune stations and beach stations formed a network of survey transects from which a beach surface could be constructed.

GPS Surveys

For the GPS surveys, both the indexing method and the antenna swap method were employed for resolving the initial carrier phase ambiguity. A reference point and an index point were established landward of the dunes located approximately 7 m apart. This distance was chosen to allow for convenient antenna swaps. Any reasonable baseline up to approximately 10 km could have been used for the indexing approach. Experience has shown that beyond 10 km the baseline-dependent errors make it difficult to resolve the initial carrier phase ambiguity to the 1-cm-level precision required for this experiment.

GPS surveys were conducted during daylight hours and at times that maximized the number of satellites in view, on November 15 (day 319) and 16 (day 320), 1991. As many as seven satellites were tracked simultaneously and no survey was conducted with less than four satellites in view. Although at least four satellites are required to solve for the four unknowns (3-D position and time), collecting data from more than four satellites improves the geometric strength of the solution and provides additional robustness to the data reduction process in the event of satellite shading or change in the satellite scenario.

Both kinematic and stop-and-go kinematic surveys were conducted. Each technique was replicated on consecutive days and one stop-and-go survey was replicated on the same day to test the accuracy and repeatability of GPS surveys under different satellite geometries. The stop-and-go kinematic surveys involved a field operator, with a GPS receiver carried in a backpack and the GPS antenna mounted on a bipod range pole, collecting data at a 6 second data rate at fixed stations in rapid succession. The kinematic technique involved mounting the GPS antenna to a roof-mounted bracket (Figure 5) on a vehicle. The vehicle was then driven in a quasi-orthogonal pattern that encompassed both shore-normal and shore-parallel profiles (Figure 2), while collecting GPS data at a 1 second data rate. During the kinematic survey, the vehicle was stopped when the antenna was over a flag, and data were collected for approximately 2 min. These stationary events were recorded and numbered to signify tie points (flagged stations) that were common to both the shore-parallel and shore-normal profiles. Each shore-normal profile was repeated by driving from the water toward the dunes, and then backing down the profile. The kinematic experiments achieved two goals: they tested the accuracy of positions obtained dynamically, and they linked the shore-normal and shore-parallel profiles so that a more accurate representation of the beach surface could be obtained.

The time required to survey a shore-normal transect using stop-and-go techniques varied from 35 to 50 min, including initialization of the receivers at the reference site. This compares favorably with the time required for a typical theodolite survey, which varied from 45 min to 1 hr for each transect, including equipment set up. In general, the time required to conduct stop-and-go GPS surveys depends on the number of transect stations and the duration of data collection at each station. The kinematic survey on day 319 and its replicate on day 320 were each completed in 1.5 hr, which included 1 hr of actual driving time (three shore-parallel transects and four shore-normal transects) and 15 min before and after the survey for antenna swaps at the reference site.

Experiment Anomalies

During high tide, between GPS surveys on days 319 and 320, as much as 10 cm of sand was locally deposited on the forebeach burying the most seaward pins on shore-normal transects A and B (Figure 1). This cover of sand was removed at each pin so that replicate stop-and-go surveys measured the same predeposition surface. Locally removing the sand was necessary to test GPS repeatability and to avoid introducing a real change in the beach height.

At some beach sites the vehicle weight caused slight sand compaction, depending on the location of the trackline. Hard-packed sand seaward of the berm prevented any significant compaction, whereas the dry sand of the backbeach compacted as much as 2 cm. The lowered elevation attributable to sand compaction was within the overall error of the surveys. Some minor differences in the trackline between surveys were caused by the driver's inability to precisely reoccupy tire tracks of the previous kinematic survey.

DATA ANALYSIS

GPS Data Reduction

A static GPS survey was conducted prior to the beach monitoring experiment to determine the coordinates for the reference and index sites and to tie these coordinates and the experimental data to the established WGS 84 coordinate system. Approximately 3 hrs of GPS data was collected at each site and at a permanent GPS Regional Reference Point (RRP) site near Houston, which is operated by the Texas Department of Transportation (TxDOT). Data from these sites were postprocessed using the vendor-supplied static processing software package, utilizing the TxDOT RRP site as the known reference position. The TxDOT RRP site is part of the National Geodetic Survey (NGS) high-precision network, and thus the reference site, and all of the field survey data, were tied to the NGS high-precision network through this process.

The stop-and-go kinematic survey positions for each transect station were generated using the NGS OMNI kinematic postprocessing software. The OMNI software was used to produce a centimeter level position for the roving antenna at every epoch, and averaging was employed during the occupation times, reducing the random error in the independent positions and producing a single position for each transect station. The vehicle kinematic GPS data were also reduced using the NGS OMNI software package, again producing an independent position for the roving antenna at every epoch. During times when the vehicle was static over the survey flags, the independent solutions were averaged to produce a single position for the vehicle GPS antenna.

Contouring Software

Preliminary editing of the postprocessed data was accomplished using plots of ellipsoidal height versus time (Figure 6). When this type of plot is annotated with field notes, it can be used to recognize extraneous values and possible problems with the GPS receivers. At this stage of data reduction, extraneous values can be eliminated and clusters of data at each transect station can be averaged to a single value for plotting on graphs or maps.

GPS vertical positions are reported as heights above the ellipsoid that approximates the geoidal surface (LEICK, 1990). These heights are not elevations above a sea level datum such as the North American Datum of 1983 (NAD 83), but can be related to mean sea-level height with knowledge of the local geoidal height. GPS computed positions were corrected to represent a point on the ground by subtracting the constant height of the antenna above the beach surface. The antenna-height correction for the stop-and-go survey of transects C and D on day 319 was 1.898 m, and the antenna-height correction for the remaining stop-and-go surveys was 1.893 m. The antenna-height correction for the kinematic surveys was 2.040 m and 2.135 m, on day 319 and day 320, respectively.

A contouring program employing a trend-surface routine was used to generate a beach surface from more than 3250 data points, most of which were collected from transects nearly parallel to the shoreline. Mapping the unedited data revealed two contouring problems. First, clusters of data at tie points in the survey grid caused local "bulls eyes" that were eliminated by averaging static data at the flagged stations. This was accomplished by averaging z (height) values of all data points that do not exceed certain user-specified changes in lateral coordinates (x and y). A 1 m threshold value was used for detecting changes in position. The second contouring problem involved some large anomalies introduced at the ends of the survey because of a lack of data. This end effect is a common difficulty with contouring programs.

RESULTS

A necessary condition for assessing the integrity of a GPS kinematic survey is the degree to which the initial phase ambiguity was resolved. Ideally, the carrier phase ambiguity is resolved to whole integer carrier phase cycles. In general, for a successful kinematic survey, the cycle ambiguity should be resolved to better than 25% of a cycle, which corresponds to an error of less than 5 cm. In all cases for this experiment, the phase ambiguity was determined to within 2% of a carrier phase cycle or better. This represents an error of <0.4 mm. The consistency and accuracy of the GPS kinematic (including stop-and-go) survey can be estimated by examining the magnitude of the closing errors when the mobile GPS antenna is returned to the index point at the end of the survey. Ideally, the closure should be on the order of the measurement noise, typically at the few mm level. In this experiment, the closing errors approached the ideal, with the typical error in each component being less than 0.5 cm.

In order to assess the potential benefit of GPS surveying techniques applied to beach monitoring, two issues are paramount: accuracy and repeatability. To evaluate GPS survey accuracy, comparisons were made between theodolite and GPS stop-and-go measurements. In order to assess GPS survey repeatability, the stop-and-go and kinematic surveys were repeated on day 320. In addition, the GPS kinematic positions were used in interpolation software to estimate changes in beach erosion and deposition between days 319 and 320. These results are discussed in detail in the following paragraphs.

Comparison of Theodolite and GPS Surveys

Even after correcting for theodolite and GPS instrument heights, the adjusted heights at each station cannot be compared directly because the theodolite survey was not referenced to a local GPS bench mark. Nevertheless, measured height changes between profile stations can be used to compare the two methods and to search for systematic biases in the data. Beach profiles obtained at transect B on day 319 using conventional ground surveys and stop-and-go GPS techniques are shown in Figure 7. The superimposed profiles and differences in beach height between stations (Table 1) demonstrate that stop-and-go GPS methods can accurately depict beach surfaces. The differences in beach height measured by the two methods range from 0.1 cm to 1.7 cm (Table 1).

GPS Repeatability Tests

Repeatability of the stop-and-go method was tested by surveying profile B on day 319 and twice on day 320 (Figure 8, Table 2). There is remarkably good agreement among all three surveys with errors in the range of ± 2 cm that are dominated by a bias in the day 320 data with respect to the day 319 data. The day 320 station marker pins are consistently lower than the day 319 pins by 1-2 cm. This is attributable to depression of the station marker pins caused by reoccupation of the marker with the bipod range pole. It should be noted that bipods used for the stop-and-go surveys have a vertical leg that is pointed at the lower end for precise positioning. This design concentrates the weight of the antenna on the vertical leg, causing a slight depression of dry sand at a few stations in the back beach and dunes. These repeatability tests suggest that GPS surveys are at least as accurate as theodolite and stadia rod surveys.

The postprocessed kinematic data were compared both analytically and visually to assess how much of the mapped difference was due to vagaries of the contouring, and how much was due to actual changes in the beach profile. These comparisons revealed nearly identical values along the stable backbeach and close agreement for the berm and forebeach transects. Figure 9 compares shore-parallel transects for the kinematic surveys and illustrates height changes and rhythmic topography along the backbeach, berm, and forebeach. Agreement between the two surveys is extremely good, especially where the backbeach was stable and the trackline was reoccupied. This one-dimensional comparison shows that at least along the tracklines the kinematic surveys can be replicated at the centimeter scale of accuracy.

The sand deposited at high tide between GPS surveys on days 319 and 320 also influenced the kinematic surveys. It was impractical to remove the high-tide sand deposit from the entire forebeach so a true change in beach height was included in the foreshore transect of day 320. At the most seaward stations on shore-normal transects the forebeach height increased about 9 to 10 cm (Figure 10).

Surface Integration Using Kinematic GPS Positions

The entire beach surface between the water line and the dune line was integrated using kinematic GPS postprocessed positions. Maps of the kinematic surveys on days 319 (Figure 11) and 320 accurately depict general morphological features of the beach surface, such as a steeper forebeach and more gently sloping backbeach. Furthermore, these maps accurately portray beach slopes and an increase in backbeach elevation from 2.1 to 2.2 m in a southwesterly direction. The data were contoured using several different algorithms and two different contouring programs to investigate the differences in surfaces attributable to software. Gridding was also altered to determine the sensitivity of parameter selection. Additional work is needed to determine which contouring routines provide the most accurate spatial representation of the data while introducing the least error attributable to the gridded values generated by the software.

Height differences were computed between beach surfaces to evaluate repeatability of GPS kinematic surveys on days 319 and 320 (Figure 12). Ignoring the obvious end effects, the largest errors are located between the shore-parallel transects where no data were collected. The isolated unexplained apparent differences in beach surfaces illustrated by the map are probably caused by contouring algorithms and the creation of data points for a predetermined grid.

The minimum volumetric change that can be detected when conducting subsequent kinematic surveys of the same area was estimated by comparing apparent height differences in beach surfaces between days 319 and 320. This error analysis includes volume estimates for both absolute and net differences in measured beach heights (Table 3). The absolute volume of both positive and negative differences is about 1100 m^3. This volume is equivalent to 0.55 m^3/m of beach or an average height difference of 1.1 cm for the entire length of beach surveyed (Table 3). The net volume difference between days 319 and 320 is approximately 77.4 m^3, which equates to 0.038 m^3/m or an average height error of 0.077 cm across the surveyed beach.

DISCUSSION

GPS Applications

Beaches are nearly ideal environments for conducting GPS surveys because the unobstructed horizontal field of view generally circumscribes a 180° arc and some undeveloped coasts provide unobstructed views of 360°. GPS surveys may not be practical along some developed coasts where tall, closely spaced buildings may interfere with the satellite signals. Isolated structures near the beach may cause minor shading or cycle slips, whereas dense, high-rise structures may entirely block the signal from satellites near the horizon or cause multipath reflections severe enough to invalidate the surveys.

Shore-parallel profiles (Figure 9) literally add a new dimension to beach monitoring that reveals alongshore morphological variability and suggests sediment transport directions. In the field, the beach surface appeared to be planar, but kinematic GPS surveys revealed that it is slightly undulatory alongshore. As expected, the low-relief rhythmic topography is most pronounced along the forebeach and is present along the backbeach, but is poorly expressed along the berm. Rhythmic topography of the forebeach has wavelengths of about 90 m, whereas the features are spaced about 120 to 150 m apart along the backbeach (Figure 9). The backbeach topography is enhanced by water ponding and runoff after heavy rains. Water draining from the backbeach to the Gulf of Mexico carves small narrow gullies that transect the berm and are obliterated by sediment movement on the forebeach. Shore-parallel beach profiles may be even more important than shore-normal profiles for monitoring beach shapes and elevation changes and their relationship to seasonal cyclicity, storm processes, and post-storm recovery. Parallel efforts are being conducted by the U.S. Army Corps of Engineers and U.S. Geological Survey to link GPS positioning with airborne laser and sea-based bathymetric surveys to monitor changes across the shoreface and in shallow water on the continental shelf.

Kinematic beach surveys are restricted to beaches where vehicular access is both possible and practical. Another limitation of a vehicular survey is that it excludes the dunes or densely vegetated upland areas adjacent to the beach. Driving in the dunes is both illegal and impractical, and upland areas are commonly private property. Nevertheless, including dunes and vegetated uplands into the survey is critical for analyzing beach dynamics because they commonly represent both sand sinks (dunes, washover fans, and storm terraces) and sand sources (nearshore erosion) and therefore are an integral part of the beach system. This limitation in data acquisition can be overcome by conducting stop-and-go surveys in areas that cannot be reached by driving and using control points in the backbeach to link the stop-and-go and kinematic surveys (Figure 2). Data generated by both techniques would be compatible by the very nature of GPS data since the positions are referenced to the WGS 84 ellipsoid.

Comparison of Conventional and GPS Beach Surveying Systems

Conventional and GPS surveying systems were evaluated on the basis of system performance including accuracy, repeatability, total cost, efficiency of operation, and support requirements (Table 4). Accuracy and repeatability were addressed in the preceding sections.

Both techniques utilize durable field equipment that can be easily transported, assembled, and maintained. Stored power is a minor inconvenience of GPS equipment, especially at remote locations where battery recharging facilities may not be available. The theodolite surveys averaged about 1 hr per profile, including time spent installing the pins and marking each station. Past experience has indicated this is a reasonable estimate for most beach profiles and the additional time required to index the profile did not add significantly to the total time. Most of the elapsed time is related to equipment set-up for theodolite and indexing of the GPS surveys.

Costs of GPS beach surveys may be substantially greater than conventional surveys because the highest accuracy requires two GPS receivers operating simultaneously. However, considering the rapid evolution in electronic equipment, it is likely that future GPS receivers will cost less, use less power, be more compact, have more data storage capacity, and perform more functions than those that are currently on the market. Potential additional field costs arise from the need to have a third person to protect the equipment at the reference station if the equipment can not be placed in a secure, weatherproof environment.

To evaluate surveying efficiencies, we examined both field operations and data analysis. Considering both aspects, GPS surveying systems have a distinct advantage over conventional surveys for several reasons. First, kinematic GPS positioning is a rapid and efficient beach surveying technique that cannot be matched with discrete, static records collected by conventional surveys. Second, each GPS receiver provides a user interface that allows for direct downloading of data to a computer for processing. GPS data are electronically recorded, stored, analyzed, and displayed, which is a marked improvement over conventional surveys that employ visual observations and manual records that require laborious encoding to prepare the data for computer analysis. It should be noted, however, that detailed descriptions of beach features and changes in surveying operations are essential to properly edit and analyze GPS data. In retrospect, a portable tape recorder would have been an ideal way to register the timing of significant events so that manual entry of notes would have been unnecessary.

Technological advancements such as GPS typically require special training to operate new equipment and to properly analyze the data. Although these requirements are more rigorous for GPS surveys than for conventional surveys, the GPS surveys are clearly superior to conventional beach surveys because they can be conducted in a kinematic mode and can provide absolute positioning in three dimensions rather than relative positions in two dimensions.

In summary, both surveying systems have advantages and disadvantages; however, GPS surveys are far superior to conventional surveys for most coastal applications (Table 4). This is because GPS kinematic surveys provide a continuous stream of highly accurate coordinates at speeds that allow rapid surveying of long uninterrupted beach segments without the need for permanent surveying monuments. The ability of GPS to determine absolute geographic coordinates and elevations without fixed monuments means that post-storm surveys can be conducted even where beach erosion has been so great that permanent monuments were destroyed. The main obstructions to kinematic beach surveys after storms would be the rubble from destroyed buildings and failed seawalls in heavily developed areas.

CONCLUSIONS

GPS surveys are suitable for the next generation of beach profiling techniques because of their superb positioning capabilities and greater utility compared to other available techniques. One-dimensional GPS surveys can provide rapid, moderately inexpensive monitoring of the berm, high-water line, or vegetation line where determining elevation is less important than establishing geographic position. Even more powerful are two-dimensional kinematic surveys that provide rapid synoptic measurement of shoreline indicators and the beach surface between the water line and vegetation line. Comparing surfaces generated by subsequent surveys of the same beach segment yields a three-dimensional (volumetric) representation of gains (deposition) and losses (erosion), thus improving the accuracy of pre- and post-storm beach surveys. Realtime navigation during subsequent surveys of the same beach segment would allow reoccupation of the same tracklines and improve the accuracy of repeated surveys.

Kinematic surveys conducted with an off-road vehicle do not include the dunes and upland areas, which are essential to calculate total volume changes and to estimate sediment budgets. This deficiency can be overcome by combining intermediately spaced stop-and-go surveys of upland areas with kinematic surveys of the beach and upper shoreface. Consequently, GPS surveying techniques will likely replace conventional profiling as the preferred method of monitoring beach dynamics in the future.

ACKNOWLEDGMENTS

We are grateful for the cooperation of the Texas Department of Transportation for providing the GPS equipment. The Texas Department of Parks and Wildlife granted permission to use Galveston Island State Park as the test site and assisted in the field operations. Jennifer Aitken and Duane Kurtin (ARL:UT) helped during the data collection and postprocessing phases of the study and Rick Edson (BEG) assisted by plotting the postprocessed data. Partial funding for this work was provided by the U.S. Geological Survey Coastal Geology Program and a grant from the Applied Research Laboratories, The University of Texas at Austin.

REFERENCES

BIRKEMEIER, W. A., BICHNER, E. W., SCARBOROUGH, B. L., McCONATHY, M. A., and EISER, W. C., 1991. Nearshore profile response caused by Hurricane Hugo, *in* FINKL, C. W. and PILKEY, O. H., eds., Impacts of Hurricane Hugo, September 10-22, 1989. *Journal of Coastal Research*, Special Issue 8, 113-127.

EMERY, K. O., 1961. A simple method of measuring beach profiles. *Limnology and Oceanography*, 6, 90-93.

LEICK, A., 1990. *GPS satellite surveying*. John Wiley and Sons, New York, 352p.

MORTON, R. A., and PAINE, J. G, 1985. *Beach and vegetation-line changes at Galveston Island, Texas: Erosion, deposition, and recovery from Hurricane Alicia.* The University of Texas at Austin, Bureau of Economic Geology Geological Circular 85-5, 39p.

NATIONAL RESEARCH COUNCIL, 1990. *Managing coastal erosion.* National Academy Press, Washington, D.C., 182p.

REMONDI, B. W., 1985. Performing centimeter-level surveys in seconds with GPS carrier phase: Initial results. *Navigation, Journal of the Institute of Navigation* 32, 194-208.

Figure Captions

Figure 1. Generalized plan view of beach-profiling transects at Galveston Island State Park established using conventional surveying techniques and then replicated using stop-and-go GPS techniques. Station numbers and GPS baseline are shown in relation to beach features. Drawing is not to scale.

Figure 2. Conceptual layout of Galveston Island State Park test site showing GPS baseline and kinematic surveying tracklines in relation to beach and dune features. The arrows indicate the direction of vehicle movement. Drawing is not to scale.

Figure 3. Configuration of GPS equipment at reference point and index point of the baseline.

Figure 4. Configuration of GPS equipment during stop-and-go surveys. This procedure is comparable to a conventional land survey whereby static positioning data are collected at discrete stations along a transect.

Figure 5. Configuration of GPS equipment during kinematic surveys. This procedure provides continuous positioning of the vehicle (antenna). Density of data across the beach is determined by the vehicle speed and sampling period.

Figure 6. Station height versus time for GPS stop-and-go survey at transect B on day 319.

Figure 7. Comparison of beach profiles at transect B obtained using conventional surveying methods and stop-and-go GPS techniques.

Figure 8. Repeatability of GPS stop-and-go surveys conducted (A) on consecutive days (319 and 320) and (B) on the same day (320).

Figure 9. Alongshore plots of GPS kinematic surveys showing repeatability of height versus range measurements on (A) day 319 and (B) day 320.

Figure 10. Shore-normal GPS kinematic surveys at transect A on (A) day 319 and (B)day 320. Comparison of the two profiles shows 9 to 10 cm of increased height on day 320 attributed to high-tide sand deposition.

Figure 11. Representative segment of the beach surface contoured by integrating x, y, and z coordinate data for the GPS kinematic survey on day 319. Contour interval is 0.1 m.

Figure 12. Representative segment of residual differences between beach surfaces surveyed using GPS kinematic techniques on days 319 and 320. Systematic positive values seaward of the berm represent forebeach deposition during high tide. Contour interval is 0.01 m.

Table 1. Comparison of Δ heights obtained on day 319 at transect B using conventional surveying techniques and stop-and-go GPS techniques.

Station Number	Theodolite Height (m)	Δ Height (m)	GPS Height (m)	Δ Height (m)	Difference Δ Height (cm)
2	3.52		3.493		
		–0.51		–0.490	0.2
3	4.01		3.983		
		1.46		1.448	1.2
4	2.55		2.535		
		0.27		0.261	0.9
5	2.28		2.274		
		0.08		0.079	0.1
6	2.20		2.195		
		0.08		0.081	–0.1
7	2.12		2.114		
		0.11		0.115	–0.5
8	2.01		1.999		
		0.09		0.081	0.9
9	1.92		1.918		
		0.18		0.181	0.1
10	1.74		1.737		
		0.22		0.209	1.1
11	1.52		1.528		
		0.17		0.187	–1.7
12	1.35		1.341		

Table 2. Comparison of beach profiles at transect B surveyed using stop-and-go techniques on day 319, on day 320, and repeated on day 320.

Station	319 Height (m)	320 Height	319–320 Diff. (cm)	320(Rep) Height (m)	319-320(Rep) Diff. (cm)	320–320(Rep) Diff. (cm)
2	3.505	3.493	1.2	—	—	—
3	3.993	3.983	1.0	3.985	0.8	–0.2
4	2.542	2.535	0.7	2.524	1.8	1.1
5	2.278	2.274	0.4	2.259	1.9	1.5
6	2.203	2.195	0.8	2.180	2.3	1.5
7	2.120	2.114	0.6	2.093	2.7	2.1
8	2.012	1.999	1.3	1.988	2.4	1.1
9	1.917	1.918	–0.1	1.908	0.9	1.0
10	1.737	1.737	0.0	1.718	1.9	1.9
11	1.524	1.528	–0.4	1.516	0.8	1.2
12	1.351	1.341	1.0	1.350	0.1	–0.9

Table 3. Differences in beach surfaces constructed from GPS kinematic surveys on days 319 and 320.

	Volumetric Difference (m^3)	Normalized for Beach Area (cm)	Normalized for Beach Length (m^3/m)
Positive change	+ 511.7		
Negative change	–589.1		
Gross change	1,100.8	1.100	0.550
Net change	–77.4	0.077	0.038

Table 4. Comparison of advantages and disadvantages of conventional and GPS beach surveys.

Attributes	**Conventional Beach Surveys**	**GPS Beach Surveys**
Field Equipment	Portable, relatively inexpensive	Portable, moderately expensive; two multichannel receivers operating in differential mode are necessary for high precision
Power Requirements	None	Battery operated; recharging may be necessary for lengthy surveys
Spatial Limitations	Line-of-sight between instrument and rod	Line-of-sight between satellite and receiver; obstructions can block signal, cause fading, or create multipaths
Reference Station	None required	Must be within 10 km of survey for high precision
Operational Mode(s)	Static only	Static or dynamic
Areal Coverage	Discrete locations only	Discrete or continuous locations
Positioning	Relative heights unless starting from a known elevation; no geographic locations (latitude and longitude)	Absolute three-dimensional position (height, latitude, longitude) obtained after post-processing
Data Format	Visual observations and manual records	Digital signals and digital records stored in receiver
Data Storage and Transfer	Hand-written notes, computer transfer and manipulation requires data entry	Digital records stored in receiver; Directly downloads to computer
Data Reduction	Tables or simple trigonometric calculations	Complex equations requiring post-processing software
GIS Compatibility	Requires data entry	Fully compatible transfer
Training Requirements	Minimal training required, vendor manuals normally are adequate	Moderate training required; exceeds instructions provided by vendor manuals

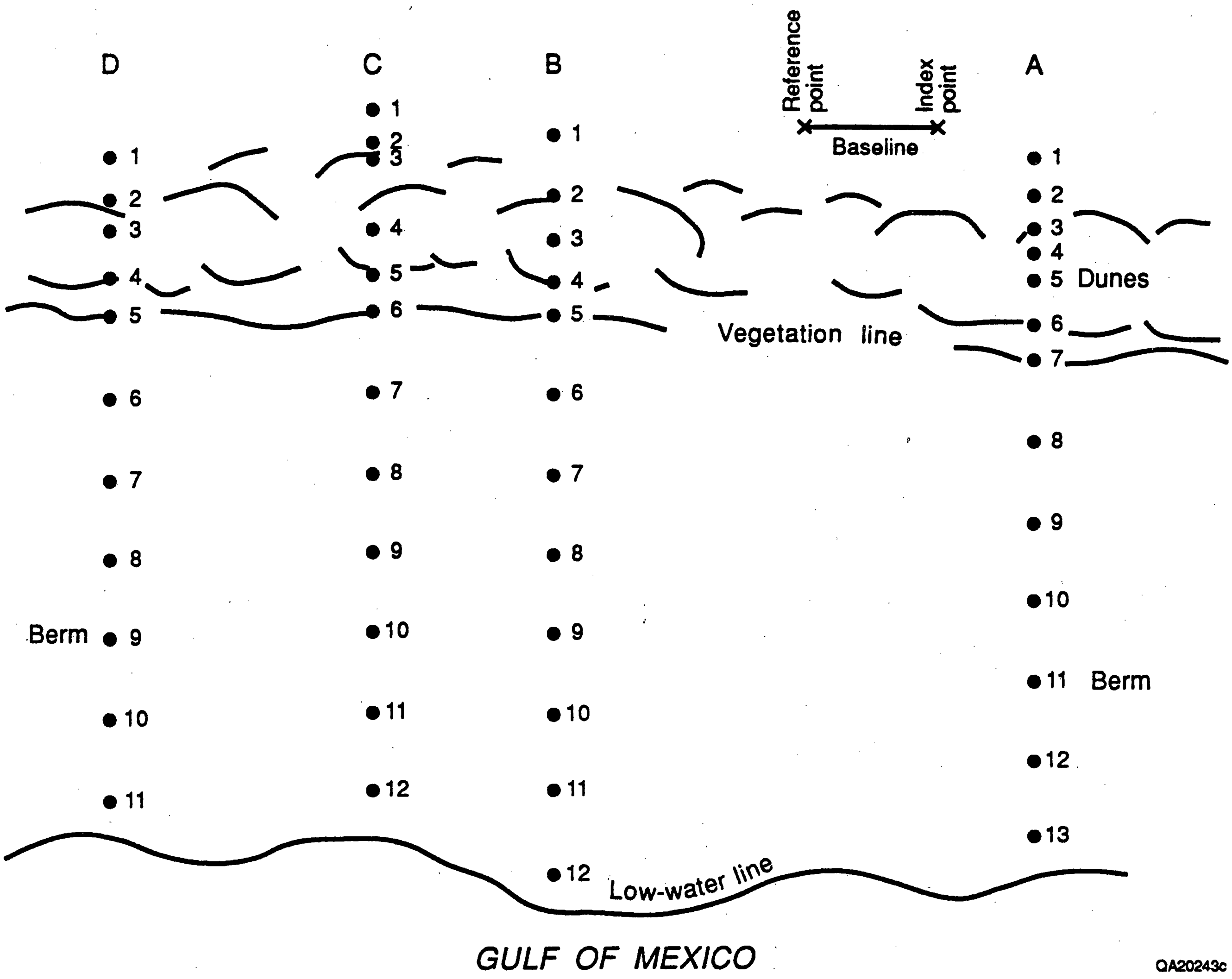

D
C
B
Reference point
Index point
Baseline
A
1
2
3
4
5
6
7
8
9
10
11
12
13
Dunes
Vegetation line
Berm
Berm
Low-water line
GULF OF MEXICO
QA20243c

fig 1

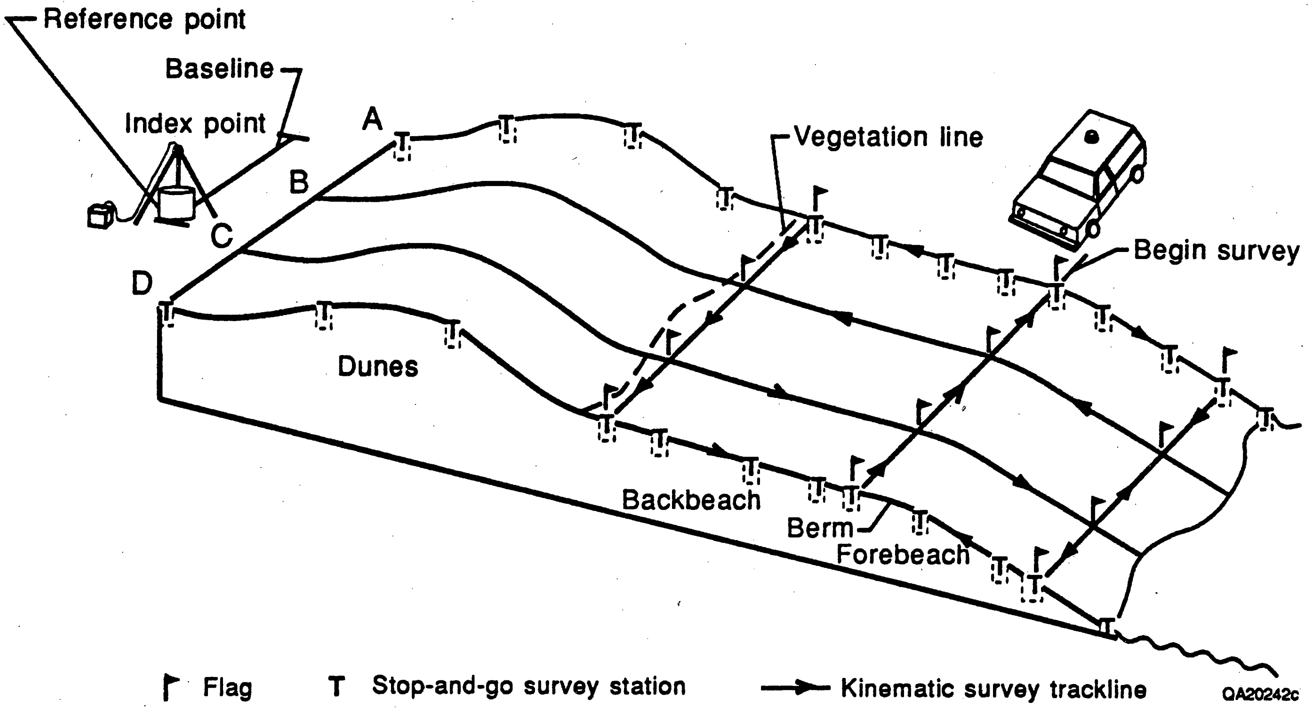

Reference point
Baseline
Index point
A
B
C
D
Vegetation line
Begin survey
Dunes
Backbeach
Berm
Forebeach
Flag
T Stop-and-go survey station
Kinematic survey trackline
QA20242c

fig 2

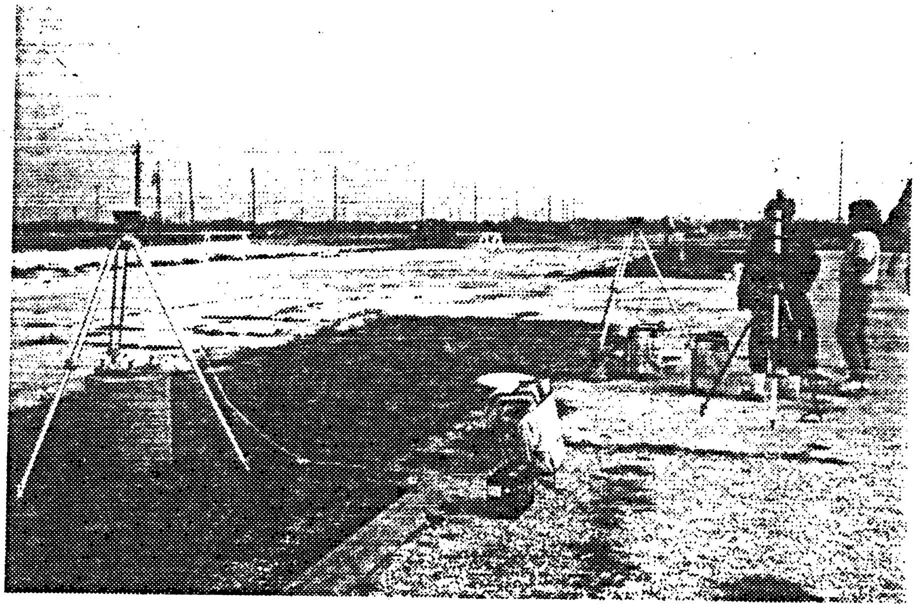


fig 3

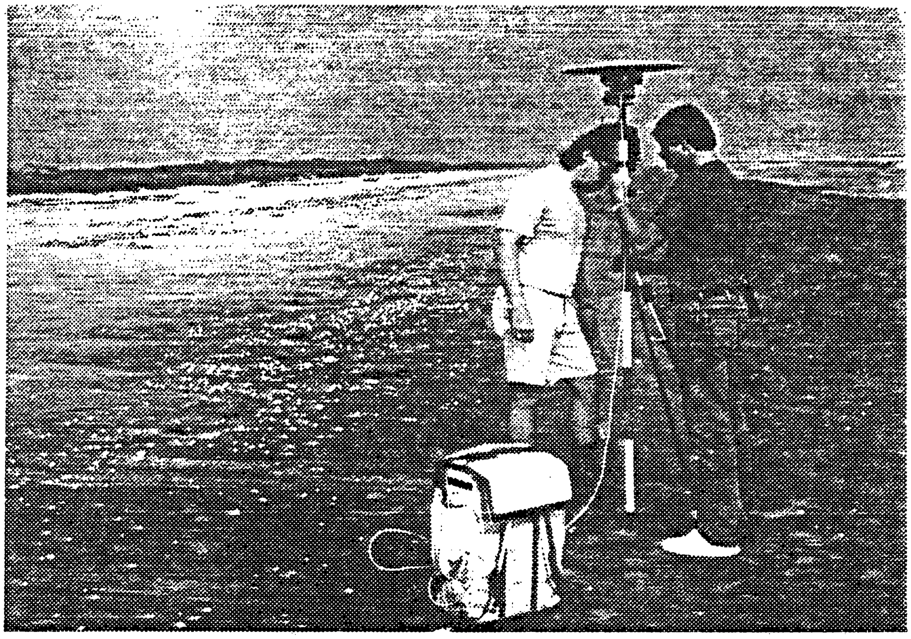
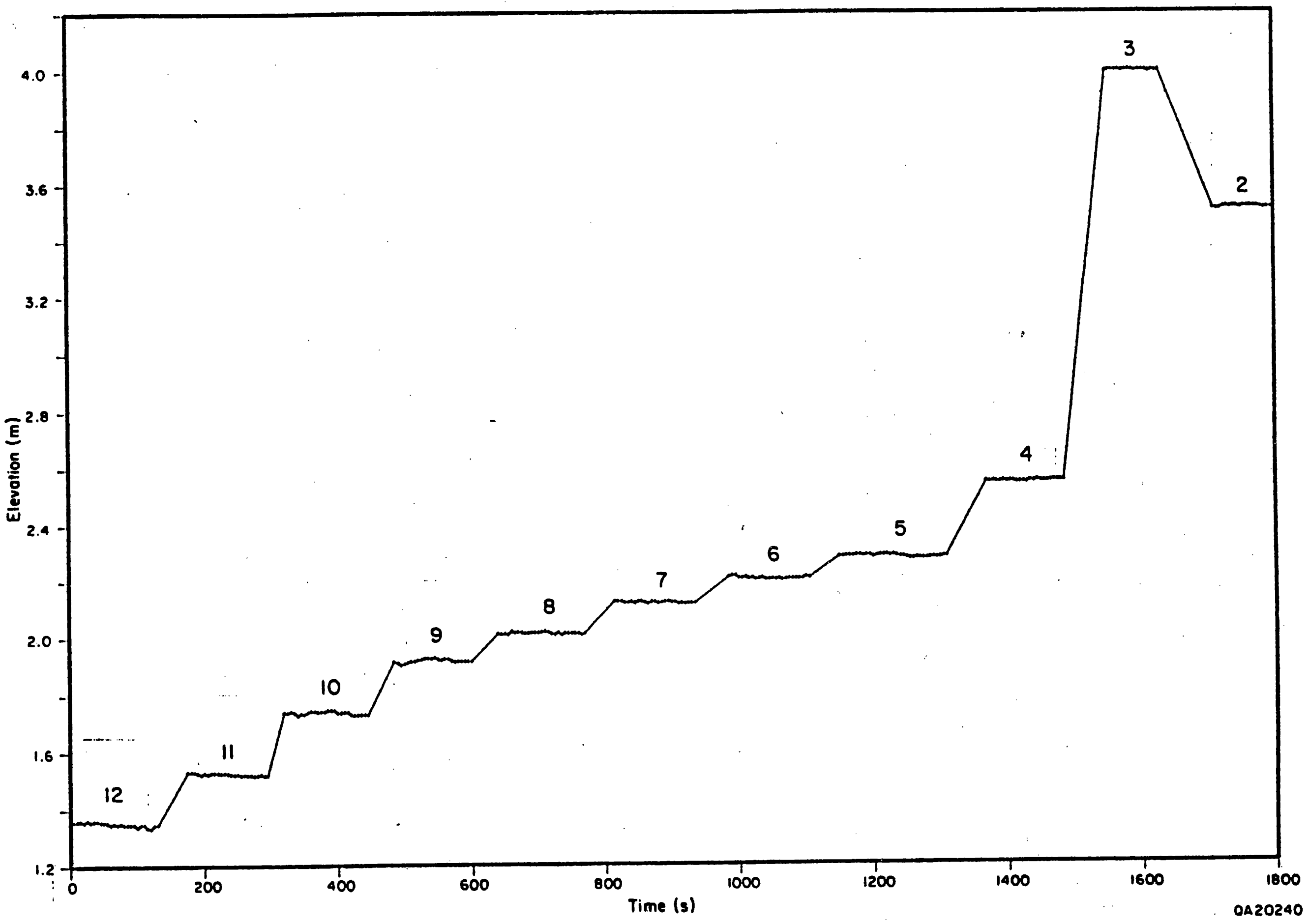


fig 4

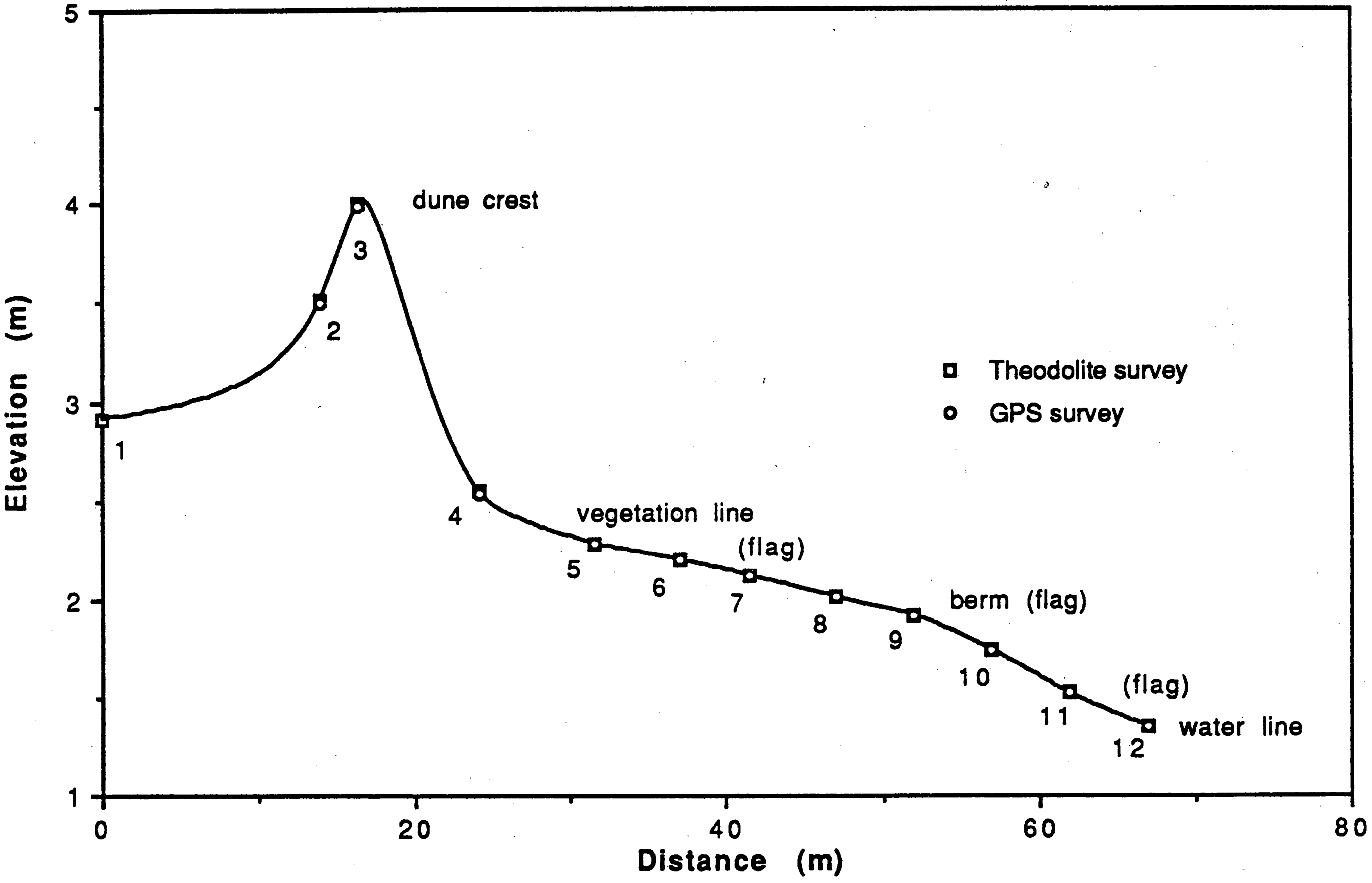
fig 5


4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
Elevation (m)
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)
12
11
10
9
8
7
6
5
4
3
2
0A20240

[illegible]

[illegible]

fig 6



5
4
3
2
1
Elevation (m)
0
20
40
60
80
Distance (m)
dune crest
vegetation line
(flag)
berm (flag)
(flag)
water line
1
2
3
4
5
6
7
8
9
10
11
12
◻ Theodolite survey
○ GPS survey

fig 7

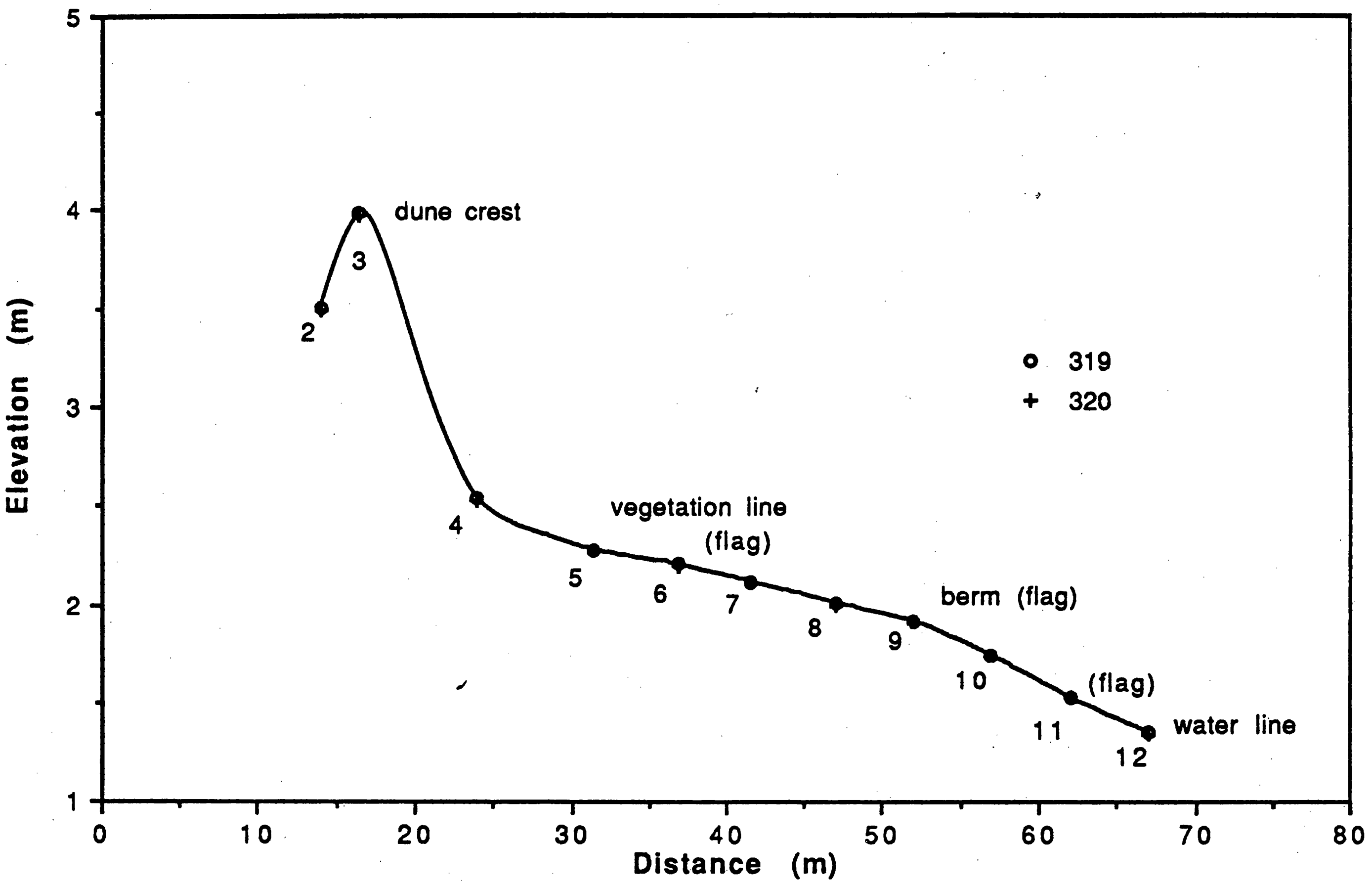

5
4
3
2
1
Elevation (m)
0
10
20
30
40
50
60
70
80
Distance (m)
dune crest
vegetation line
(flag)
berm (flag)
(flag)
water line
2
3
4
5
6
7
8
9
10
11
12
o 319
+ 320

fig 8

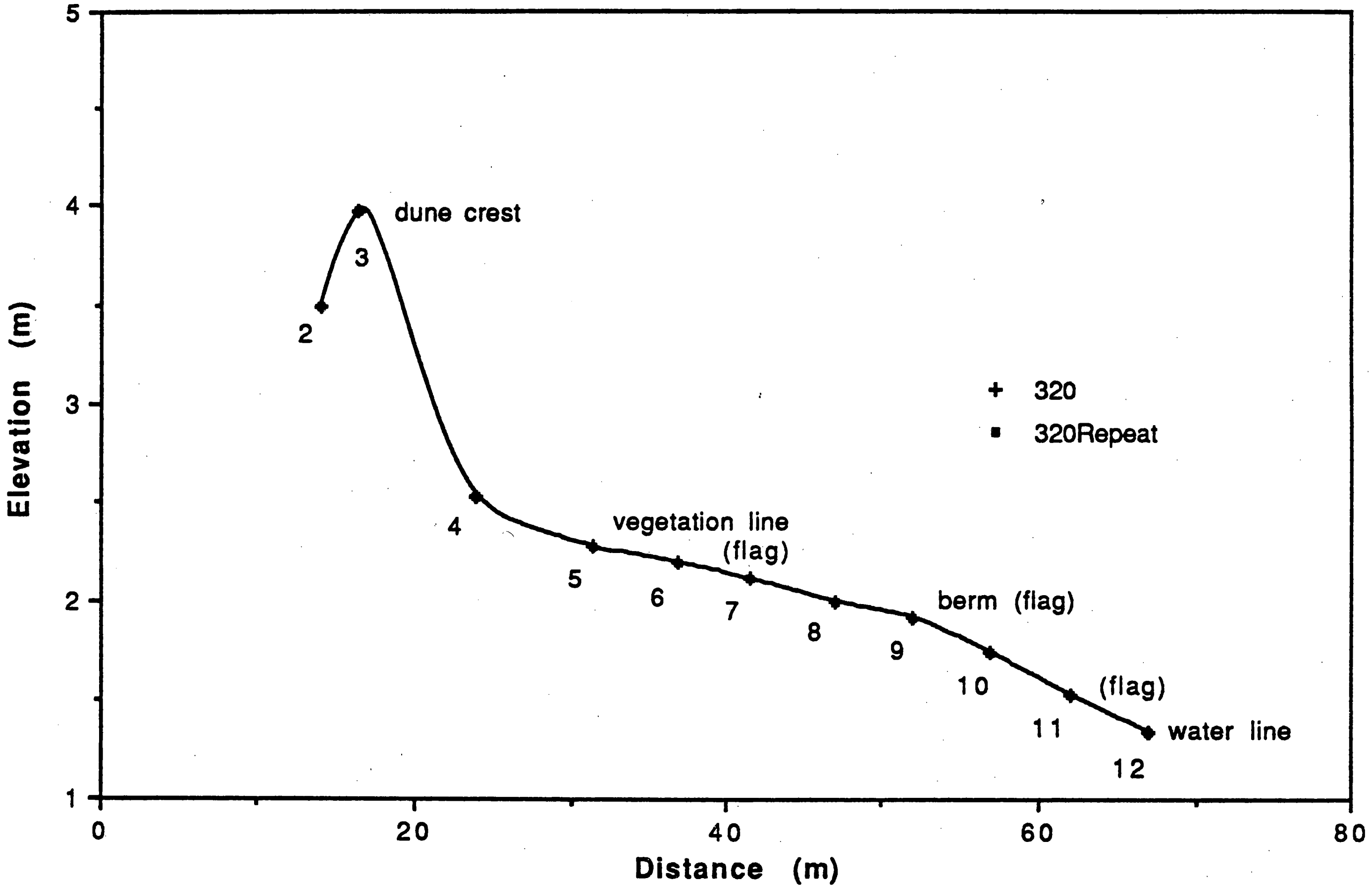

5
4
3
2
1
Elevation (m)
0
20
40
60
80
Distance (m)
dune crest
3
2
4
vegetation line
(flag)
5
6
7
8
9
berm (flag)
10
(flag)
11
water line
12
+ 320
■ 320Repeat

fig 8b

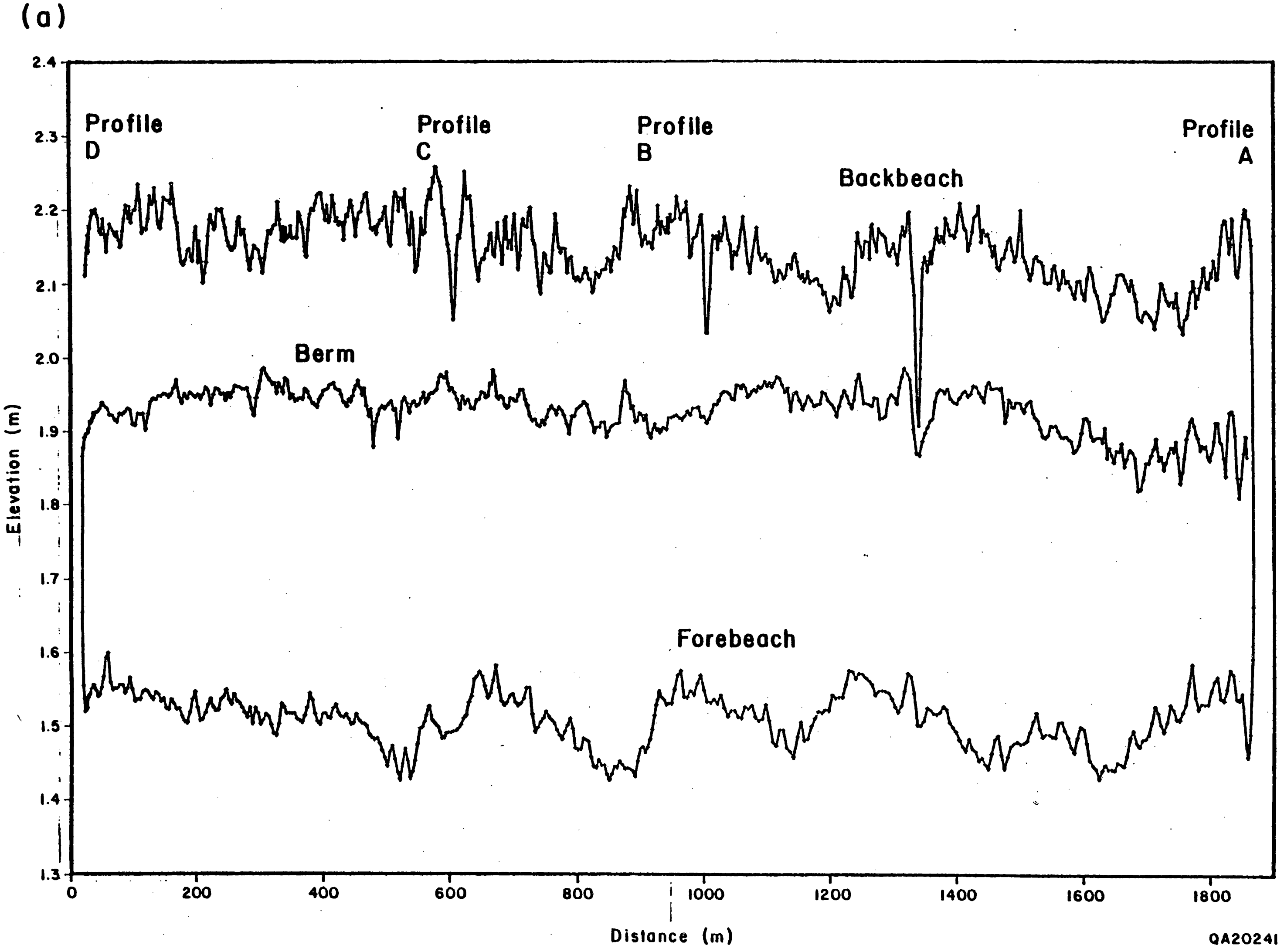

(a)
Profile D
Profile C
Profile B
Profile A
Backbeach
Berm
Forebeach
Elevation (m)
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
0
200
400
600
800
1000
1200
1400
1600
1800
Distance (m)
QA20241

fig. 9a

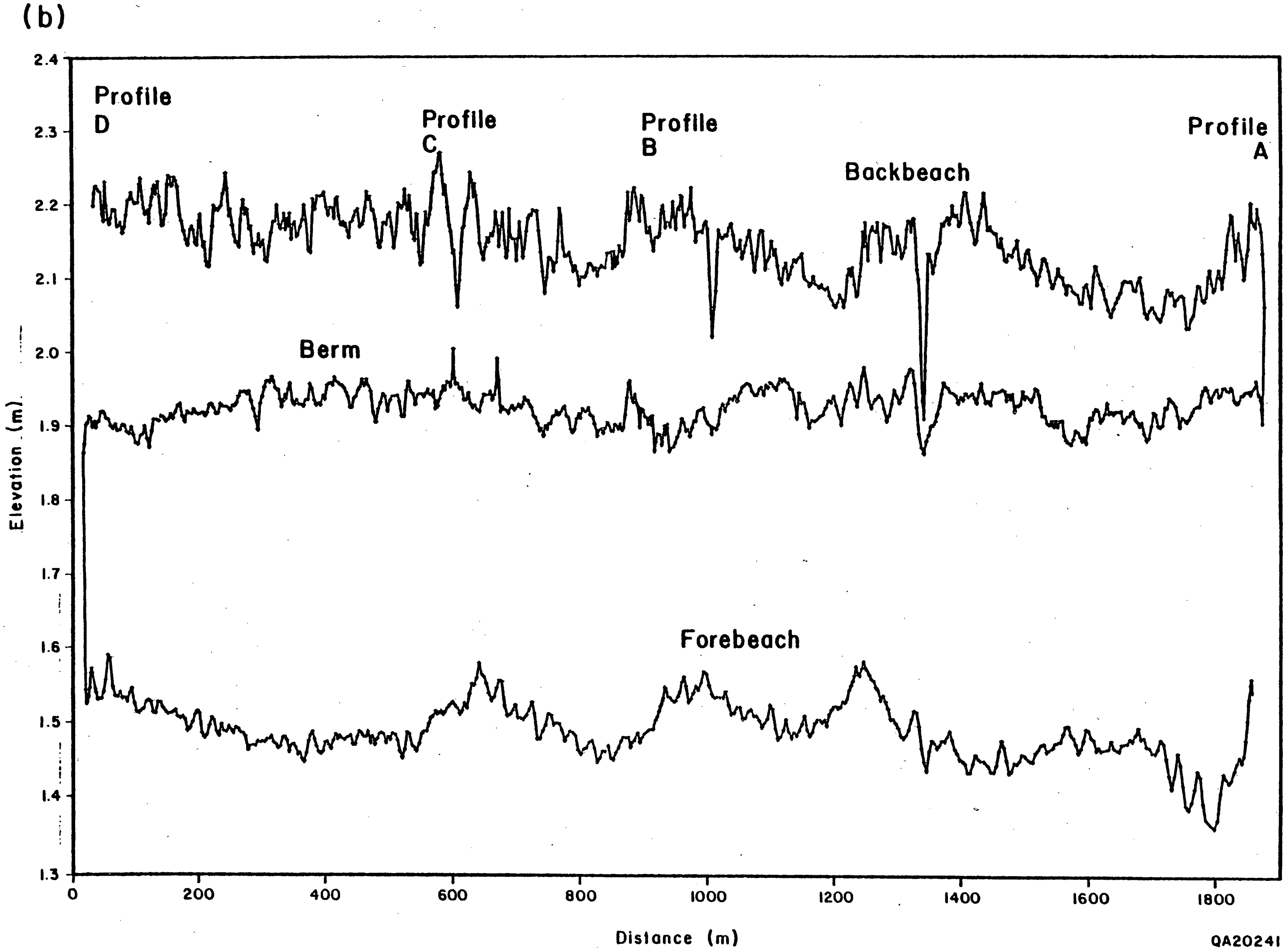

(b)
Profile D
Profile C
Profile B
Backbeach
Profile A
Berm
Forebeach
Elevation (m)
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
Distance (m)
0
200
400
600
800
1000
1200
1400
1600
1800
QA20241

Fig 9b

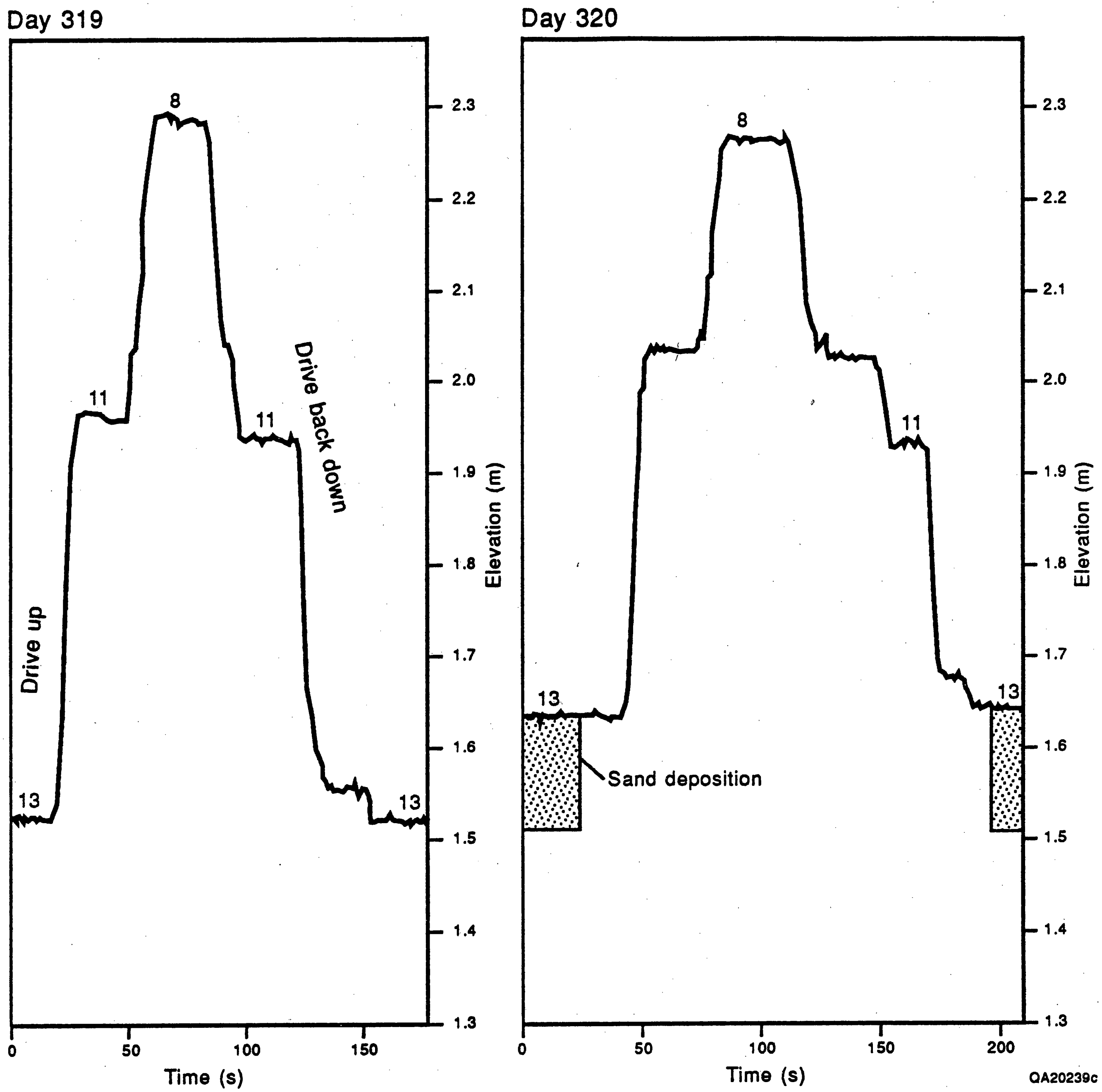

Day 319
Day 320
Drive up
Drive back down
13
11
8
11
13
13
8
11
13
Sand deposition
Elevation (m)
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
Time (s)
0
50
100
150
200
QA20239c

fig. 10

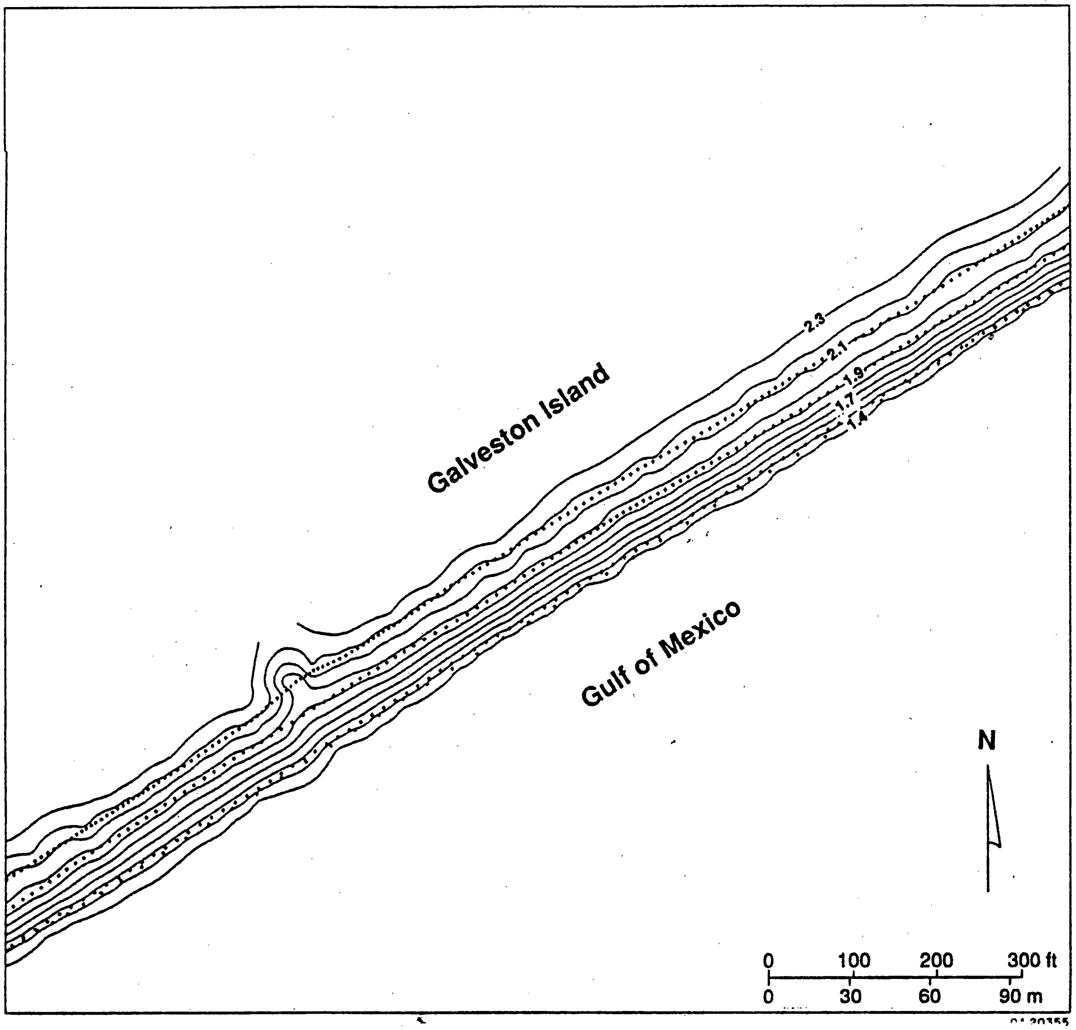
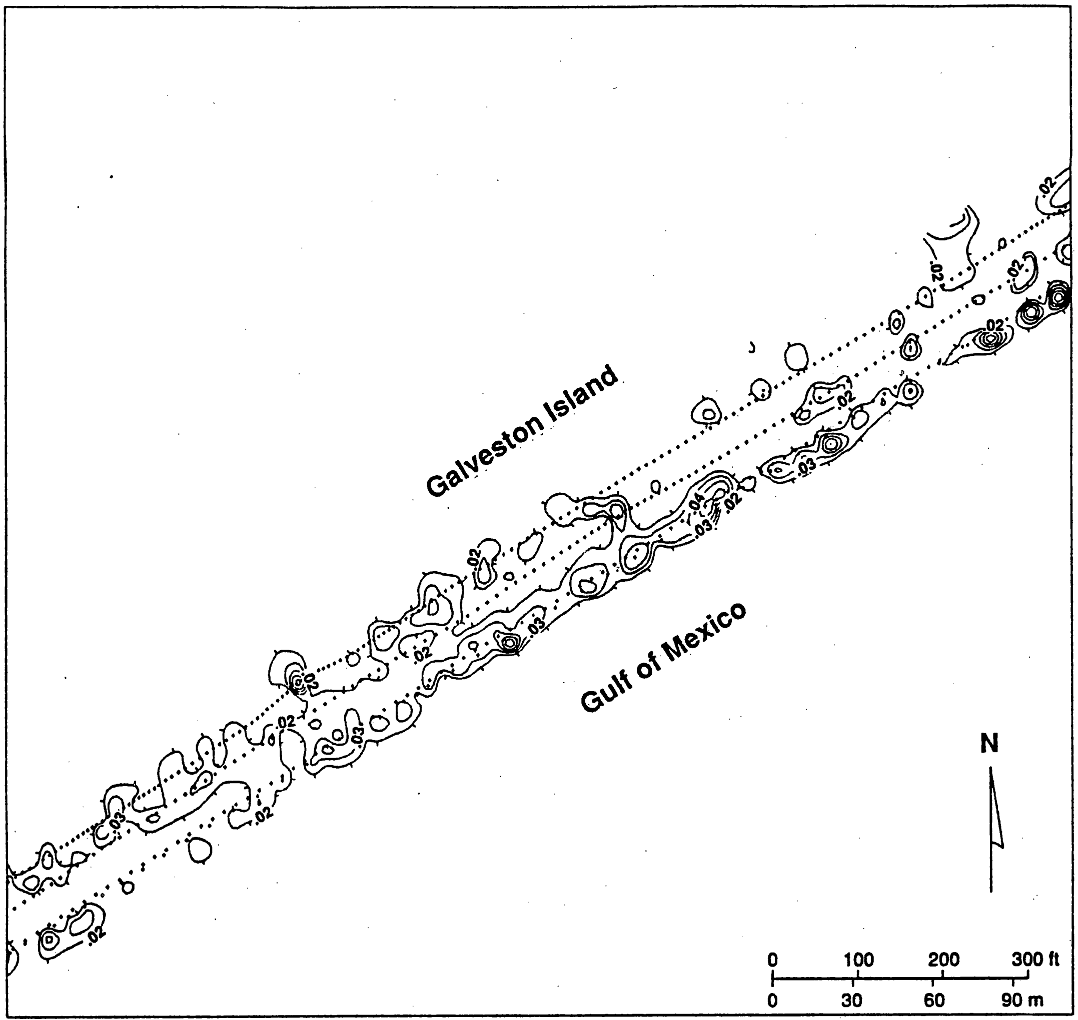

Galveston Island
Gulf of Mexico
2.3
2.1
1.9
1.7
1.4
N
0
100
200
300 ft
0
30
60
90 m
20355

fig 11



QA 20356

fig 12