THE TEXAS SHORELINE CHANGE PROJECT

Coastal Mapping of West and East Bays in the Galveston Bay System Using Airborne Lidar

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ABSTRACT

The Bureau of Economic Geology of The University of Texas at Austin acquired airborne light detection and ranging (lidar) data of the Galveston West and East Bays and associated minor bays between July 17th and September 21st of 2002. These data will assist the Texas General Land Office with implementation of the Coastal Erosion Planning and Response Act. The primary purpose of this study was to generate maps of the bay shorelines as a basis for monitoring future shoreline changes.

The data set accompanying this report contains digital elevation models (DEM) created from lidar point data for the shorelines and islands of Galveston West Bay and associated smaller bays (Bastrop Bay, Chocolate Bay, Christmas Bay, and Jones Bay), and Galveston East Bay. The DEMs lie within 21 U. S. Geological Survey 7-1/2 minute quadrangles between High Island to the northeast and Freeport to the southwest. Data for the West Bay system, including Galveston and Follets Islands, are parsed into separate but overlapping DEMs that lie within 35 quarter quadrangles. Data for the East Bay system, including Bolivar Peninsula and High Island, are parsed into separate DEMs that lie within 25 quarter quadrangles. All DEMs are provided on a set of DVDs.

The DEMs were derived from lidar X, Y, and Z point data generated by combining laser range and aircraft attitude data collected using an Optech Inc. Airborne Laser Terrain Mapper (ALTM) 1225 with once per second data collected using geodetic quality global positioning system (GPS) airborne and ground-based receivers. The Bureau's ALTM 1225 system was installed in a single engine Cessna 206 aircraft owned and operated by the Texas State Aircraft Pooling Board, and operated locally out of Scholes Field in Galveston, Texas. The lidar data were collected during 23 flights between 17 July and 21 September 2002. Flights are named according to the Julian day on which they were flown: 19802, 19902, 20002, 21102, 21202, 21302, 21402, 23302, 23402, 23502, 23602, 23702, 26302 and 26402. Lidar instrument settings and flight parameters for these flights were: (1) laser pulse rate: 25kHz, (2) scanner rate: 26Hz, (3) scan angle: +/-20deg, (4) beam divergence: narrow, (5) altitude: 460-1060m AGL, and (6) ground speed: 90-120kts. At least two GPS base stations were operated throughout each survey flight. Between the first and second portions of the Galveston Bay lidar survey, Tropical Storm Fay made landfall near Port O'Connor, Texas at

0900 UTC on September 7, 2002. Copious amounts of rain fell before and after the storm resulting in wide-spread areas of standing water during the lidar flights.

Lidar datasets can be used as an important coastal management tool. Shorelines extracted from lidar data have unprecedented accuracy and detail and can establish a baseline for shoreline change analysis. During the Galveston West and East Bay lidar mapping we acquired data approximately 2 km inland covering salt- and brackish-water marshes, tidal flats, and adjacent uplands. These data will be useful in mapping and understanding habitat changes. In addition, DEMs derived from the detailed topographic datasets covering Follets Island, Galveston Island, and Bolivar Peninsula can be used to determine potential storm-surge flooding, and can help with community planning.

INTRODUCTION

The Coastal Erosion Planning and Response Act (CEPRA) authorizes the Texas General Land Office (GLO) to implement a comprehensive coastal erosion response program that can include designing, funding, building, and maintaining erosion projects. Up-to-date erosion rates are needed to implement the CEPRA, and the GLO is named in the act as the entity that will monitor shoreline change rates with the assistance of the Bureau of Economic Geology (Bureau) and local governments. Through the Texas Shoreline Change Project (TSCP) the Bureau is working with the GLO to identify and quantify eroding areas. The TSCP is addressing requirements of the CEPRA regarding (1) the identification of "critical coastal erosion areas", (2) the monitoring of historical shoreline erosion rates, (3) making data accessible on the Internet, and (4) increasing public awareness of coastal erosion issues. This final report discusses the continuance of the TSCP during fiscal years 2002 and 2003 related to the acquisition of new shoreline data of West and East Bays and associated minor bays in the Galveston Bay System using lidar.

Goals of the Texas Shoreline Change Project

The overall goal of the TSCP is to establish a state-of-the-art regional shoreline-monitoring and shoreline-change analysis program that will help solve coastal erosion and

storm hazard problems along the bay and Gulf shorelines of Texas. The TSCP is doing the following:

(1) providing Texas with a comprehensive, up-to-date, digital data base of historical shoreline positions and average annual rates of shoreline change and making the data available to the public through the Internet,
(2) providing a regional framework for conducting local studies related to specific erosion control projects,
(3) providing data for assessing the susceptibility of the coast to episodic erosion and flooding by storms, and
(4) making available observations on the causes of shoreline change and making them understandable to the general public through the Internet and paper reports. See the Texas Shoreline Change Project Website at http://www.beg.utexas.edu/coastal/intro.htm.

Airborne Lidar: A Tool for Monitoring Coastal Environments

The Bureau is a leader in applying airborne lidar technology to coastal zones. Detailed topography of coasts obtained through lidar surveys is invaluable for mapping shorelines and marshes, determining flooding potential, mapping storm surge hazards, and quantifying the geomorphology and sediment budget of an area.

In the past, shorelines were mapped by using vertical aerial photographs. The shoreline is interpreted and drawn or digitized on the photograph and transferred to a base map for comparison with earlier shorelines. Typically the boundary between wet and dry sand on the beach, which is displayed as a tonal contrast on the photographs, is used as the shoreline. This boundary, however, is affected by recent water level and wave activity and may not be a reliable indicator of shoreline position. Error is also introduced to the shoreline position when the photograph is rectified to a base map. Because lidar surveys are GPS based, there is no need for transferring data or rectifying photographs to a base map. Furthermore, a contour line can be used as the shoreline, eliminating the ambiguity present in the wet sand/dry sand boundary. Along bay shorelines, where low-relief tidal flat and marshes exist, a reliable shoreline feature may be extremely difficult to identify in photography making the advantages of lidar even greater.

In addition to rigorously mapping bay shorelines, the detailed and accurate topography obtainable with lidar can be applied to mapping marshes and tidal flats and identifying potential areas for marsh reconstruction. During this project we acquired a corridor of highly accurate and detailed topography around West and East Bays (fig. 1) that will be used to model the expansion or contraction of marshes under various relative sea-level rise scenarios. As sea level rises, marshes may migrate landward across gently sloping topography causing no net loss. On the other hand, steep topography or development may prevent landward expansion and cause a net loss of wetlands.

The Bureau began conducting coastal lidar surveys of the Texas upper coast in November 1997, august 1998, and September 1998 with funding from NASA and the Texas Coastal Management Program (CMP). In conjunction with the ongoing NASA project, the TSCP mapped the entire Texas Gulf of Mexico shoreline during May 2000. In 2001 and 2002, the Bureau mapped the shoreline from Sabine Pass to San Luis Pass under the NASA project and a CMP project that is monitoring geotubes along the Gulf shoreline. The shoreline surveys include a swath approximately 500 m wide that covers the beaches, foredunes, and the seaward 3 rows of houses.

Results from the coastal surveys show that we can efficiently and accurately acquire beach and dune topography along hundreds of kilometers of coast using airborne lidar. Vertical precision is 5 to 15 cm (Root Mean Square Error). Absolute accuracy is also 5 to 15 cm after subtracting a bias error determined by comparing lidar data with GPS road surveys. Data-point spacing for these surveys is approximately 1 m.

This report summarizes the acquisition and processing of airborne lidar data of the shorelines and adjacent wetlands in West and East Bays and associated minor bays including Christmas Bay of the Galveston Bay System. The digital elevation models (DEM) and bay shorelines derived from the Lidar data will serve as important tools for managing coastal habitats. The proposed tasks and deliverables for this project are included for reference below.

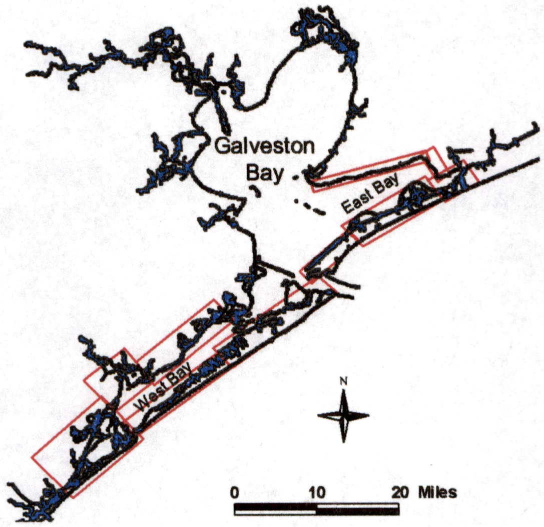

Figure 1: Approximate lidar survey area in the West and East Bay Systems.

Tasks and Deliverables

Task 1: Survey shorelines and adjacent emergent marine environments using airborne lidar.

Deliverable: Digital elevation models (DEM) with metadata for approximate areas shown in figure 1. DEM's will have a horizontal resolution of 1 m.

Task 2: Extract shoreline from lidar DEM's and integrate into GIS.

Deliverable: GIS file of 2002 bay shoreline.

Task 3: Prepare technical report describing the lidar survey procedures and parameters and characteristics of the data.

Deliverable: Two copies of hardcopy report.

Task 4: Make technical report, digital elevation models, and shoreline available for download on the web.

Deliverable: Page on the TSCP web site maintained by the Bureau.

GALVESTON WEST AND EAST BAY LIDAR SURVEY

The Bureau acquired airborne lidar data of the Galveston West and East Bays and associated minor bay systems between July 17th and September 21st of 2002. We completed flights for the East Bay area on August 2, 2002 while occupying primary (TUNA) and backup (ROLW) GPS base stations, both of which are located on Bolivar Peninsula. Our flights for the West Bay area began on August 21st and concluded on September 21st, after Tropical Storm Fay hit the Texas coast on September 6, 2002. During the West Bay flights we used both BEG8 and SCHL as primary and backup GPS base station locations (fig. 2).

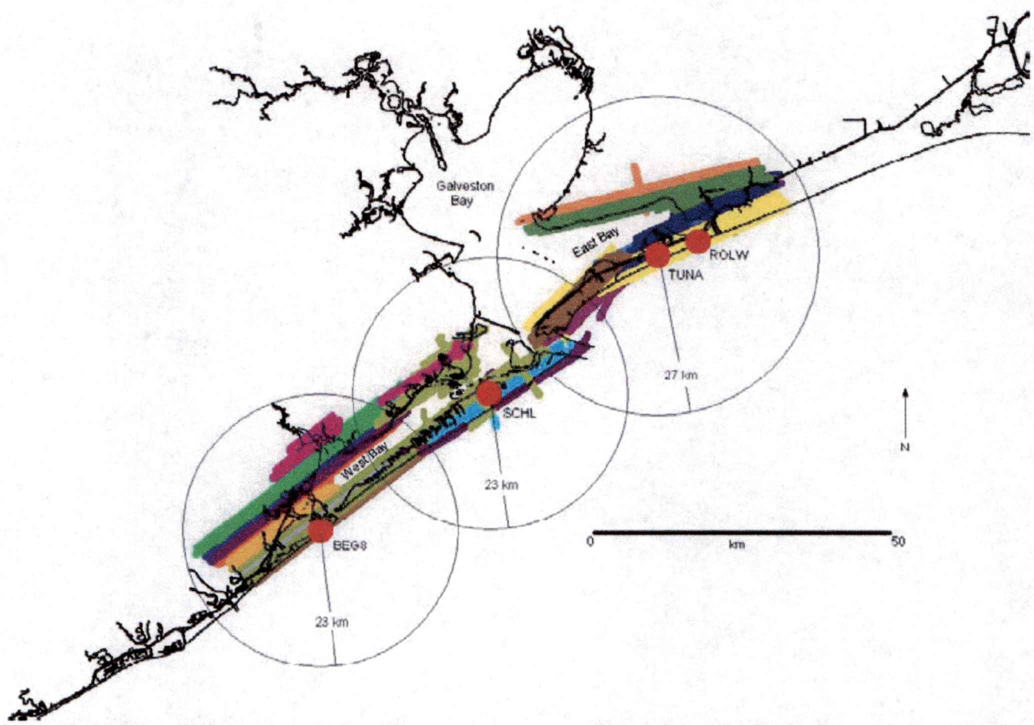

Figure 2: Areas mapped by lidar in the Galveston West and East Bay Systems. Red dots show base station locations. Maximum distances between base station and aircraft during mapping are shown for BEG8, SCHL, and TUNA base stations. Colored strips reflect flights completed on different days.

Airborne Lidar Technical Background

Lidar is a laser ranging technology that has a wide variety of applications from atmospheric composition determination to terrain mapping. Lidar instruments can be mounted on satellites or small aircraft (fixed-wing or helicopter). The amount of detail that can be mapped using an airborne lidar system in part depends upon the flight altitude. The Bureau generates highly accurate and detailed terrain maps using an Optech Inc. ALTM 1225 laser altimeter, which we own and operate. The ALTM 1225 can collect data to generate highly accurate terrain maps from between 410 and 2000 m above ground level. For mapping along the Texas coast we install the instrument in a Cessna 206 single-engine-aircraft operated by the Texas State Aircraft Pooling Board.

Airborne lidar mapping requires the integration of three basic measurement sources: (1) laser ranges and associated scan angle information; (2) aircraft attitude information from an inertial measurement unit (IMU); and (3) absolute aircraft trajectory derived from a differential, geodetic global positioning system (GPS) network (Wehr and Lohr, 1999). The laser is a pulsing, solid-state, infrared laser with a wavelength of 1064 nm. Lasers of this wavelength do not penetrate water and are blocked by clouds. The IMU (set of three orthogonal accelerometers and gyroscopes) records the aircraft attitude 50 times per second (50 Hz); a GPS receiver provides aircraft position data once per second. An oscillating scanner mirror in the instrument sensor head sends laser pulses across the ground in a zigzag pattern perpendicular to the direction of flight to illuminate a swath underneath the aircraft. Ground laser-point-spacing varies by adjusting the laser scanner angle from zero to 20 degrees and the scanner rate from zero to 28 Hz. The laser can pulse as fast as 25,000 times per second (25 kHz). During the Galveston West and East Bay surveys the ALTM 1225 did not digitize and record the waveform of each laser reflection, but did record the range and backscatter intensity of the first and last laser returns of each laser reflection using an avalanche photo diode, a constant-fraction discriminator, and two timing interval meters (TIM).

Laser ranges are generated and written to tape during the flight by multiplying the speed of light by the time-of-flight of the laser signal and dividing by 2 as the total time includes the outgoing and the return laser pulse. Before a range measurement can be output from the ALTM however, the reflected pulse must be converted from an analog to a digital signal. The magnitude of the converted signal is proportional to the intensity or brightness of the returned laser pulse. During processing, Optech Inc.'s proprietary software compensates for range biases related to differing intensities using a correction table. Range values with intensity readings over 6000 are considered poor as the laser return signal is very strong and tends to saturate the electronics, resulting in a less accurate range determination (Optech Inc, 2003).

The maximum value on the ALTM 1225 intensity correction table is 5984; however, we recorded intensities up to 8000 during the Galveston West and East Bay Lidar Survey. The intensity table provided with our ALTM 1225 system was generated in the Optech laboratory. Lab measurements to obtain the intensity table are not sufficient to test the entire dynamic range, which accounts for the intensity table ending at 5984. For those wishing to use range information associated with large intensity values (>6000), Optech Inc. recommends generating a new intensity table. This can be done by flying over a relatively flat body of water and post-processing to obtain a flat surface. Range corrections are adjusted and new values are added to the intensity table so that each data point has a range correction corresponding to it's intensity value. (Optech Inc., 2003). Impacts from incorporating ranges generated from uncorrected, off-scale intensity values into the digital elevation models are discussed in later sections of this report.

Lidar Survey Operations

Mission timing is determined by several critical factors. These include:

- Weather – the laser will not operate below 410 m altitude due to eye-safety restrictions nor will the laser penetrate clouds.
- GPS constellation – In order to get a highly accurate solution for the location of the aircraft (also know as the aircraft trajectory) surveys are conducted when there is a minimum of seven satellites visible at 20 degrees above the horizon.
- Air traffic – During flights the aircraft may be diverted from a particular lidar pass by air traffic controllers.
- Daylight –Because of safety considerations while flying a single-engine plane, surveys must be conducted during the day.

- Water levels – Differences in tides, wave heights, and surges can cause inconsistent water levels to show up in a single area that is mapped at different times. This is something we have to live with.

Oftentimes, an optimal GPS constellation will not correspond with optimal water level conditions. Beach width and water level inconsistency is often sacrificed in order to survey during optimal GPS conditions. Coordination of these critical factors as well as GPS base station and aircraft personnel and equipment can prove to be challenging during a lidar survey.

Global Positioning System Base Stations

To be able to compute accurate aircraft trajectories, it is important to have nearby base stations. Red dots in figure 2 show locations of survey markers that served as GPS base station locations during the lidar flights. At least two base stations operate on the ground during every lidar survey. We occupied TUNA and ROLW for primary and backup base stations, respectively during the East Bay survey. Since TUNA is located very near the center of the East Bay survey area the aircraft was able to stay within 25 km of the base station throughout the East Bay survey. ROLW is located on the southwest side of Rollover Pass. Bureau personnel installed survey markers at both TUNA and ROLW base station locations in preparation for this study.

We occupied BEG8 and SCHL locations during the West Bay survey. BEG8 serves as a reference mark for beach profile surveys just south of San Luis Pass and is located near the south end of the West Bay survey area. BEG8 functioned as the primary and SCHL as the backup base station locations while surveying the southwestern portion of the West Bay area. The base stations switched functions while surveying in the northeastern portion of the West Bay area. SCHL is a base station location established for this survey at Scholes Airfield on Galveston Island (fig. 3).

Figure 3. Geodetic receiver and fixed height pole with antenna as base station setup on unused taxiway at Scholes Field in Galveston, Texas.

Ground Control Survey

Bureau personnel conducted GPS kinematic surveys along two relatively flat roads to use as ground truth (calibration and bias estimate) targets: Boyt Road on Bolivar Peninsula for the East Bay survey and Bob Smith Road on Galveston Island near Jamaica Beach for the West Bay survey. We conducted the kinematic survey by fixing a magnetic mounted GPS antenna to the top of a field vehicle and collecting GPS data while slowly driving up and down the road for approximately one hour. The ground control surveys are usually conducted using the same GPS base stations used during the lidar surveys. Passes over the calibration target are conducted at least once per day to estimate roll and scale scanner biases and vertical biases in the laser range data (fig. 4).

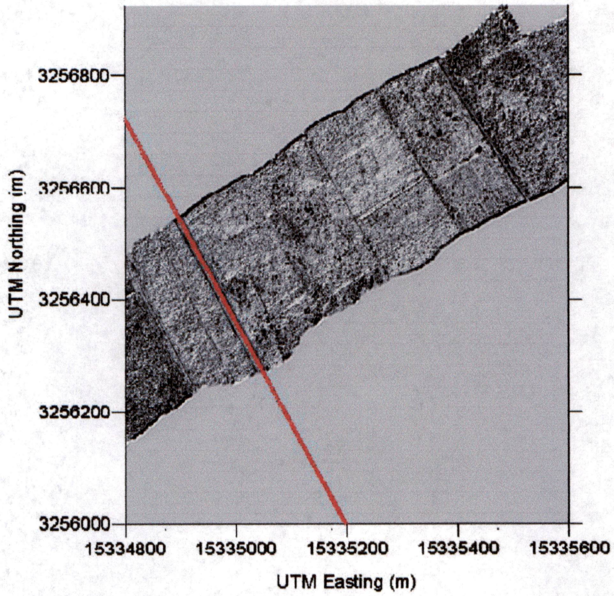

Figure 4. Flight passes perpendicular to a portion of Boyt Rd. road on Bolivar Peninsula. The GPS ground kinematic survey (points in red) is overlain on the lidar data.

Flight Parameters

Parameters that are adjusted during a lidar survey to optimize accuracy and spacing of points on the ground include (1) aircraft altitude; (2) scanner rate; (3) scanner angle; and (4) overlap of adjacent flight lines. The objective for this survey was to acquire lidar data with a point spacing of equal to or less than 1 m along approximately 600 m wide swaths with a 30 percent sidelap. This amount of sidelap or sideways overlap of swaths should be sufficient to prevent gaps in coverage due to unexpected tilting of the aircraft during atmospheric turbulence. The flight altitude for this idealized configuration is approximately 800 m.

Persistent cloud coverage and numerous storms in the Galveston Bay area during Spring and Summer of 2002 prevented us from flying over 500 m altitude during most of the Galveston West and East Bay surveys. To fly below the clouds and maintain at least a 30 percent swath overlap, we had to fly at a lower altitude, and consequently complete a greater number of flight passes than originally planned (see table 1 and table 2).

Parameters other than altitude and overlap remained constant throughout the surveys. The settings we used were: scanner rate = 26 Hz; scanner angle = 20 degrees. A benefit of flying lower during data collection over the West and East Bay systems was that we obtained sub-meter data point spacing on the ground for much of the survey area. Therefore, we are able to meet the primary objective of the Galveston Bay System lidar survey, which is to accurately map the bay shoreline.

Table 1. Flight operation information for Galveston East Bay System flights named by Julian Day. Occasionally we flew at more than one altitude during a single flight.

East Bay Flights

Flight	Date Flown	Base Station	Approx. Altitude (m)	Swath Width (m)	No. of Passes
19802a	07/17/02	TUNA	810	590	6
19802b	07/17/02	TUNA	460	335	16
19902a	07/18/02	TUNA	810	590	15
19902b	07/18/02	TUNA	460	335	10
20002	07/19/02	TUNA	460	335	2
21102	07/30/02	TUNA	460	335	5
21202a	07/31/02	TUNA	460	335	9
21202b	07/31/02	TUNA	460/610	335/445	12
21302a	08/01/02	TUNA	460	335	9
21302b	08/01/02	TUNA	460/610	335/445	8
21402a	08/01/02	TUNA	460	335	4
21402b	08/01/02	TUNA	460/610	335/445	9

Table 2. Flight operation information for Galveston West Bay System flights named by Julian Day. Some flights were flown at more than one altitude.

West Bay Flights

Flight	Date Flown	Base Station	Approx. Altitude (m)	Swath Width (m)	No. of Passes
23302a	08/21/02	SCHL	460	335	8
23302b	08/21/02	BEG8	460/610	335/445	4
23402a	08/22/02	BEG8	460	335	8
23402b	08/22/02	BEG8	460	335	6
23502	08/23/02	BEG8	460	335	6
23602a_1	08/24/02	BEG8	460	335	3
23602a_2	08/24/02	SCHL	460	335	8
23602b	08/24/02	BEG8	810	590	5
23702	08/25/02	BEG8	610	445	11
26302a	09/20/02	SCHL	1000	665	5
26302b	09/20/02	SCH2	1000	665	19
26402	09/21/02	SCHL	810/1000	590/665	7

Lidar Data Processing

During field operations we download all data after each flight, make backup copies of all data, and complete abbreviated processing to check for data quality and completeness. The first step is to transfer raw ALTM 1225 flight data (laser ranges with associated scan angle information and IMU data), airborne GPS data, and ground-based GPS data to an NT workstation. Then we compute preliminary aircraft trajectories and generate a decimated lidar point file using the Optech Inc. Realm 2.27 software. Lastly, we view the decimated lidar point files to check data coverage (i.e. sufficient overlap of flight lines and point spacing).

Following are the steps required for complete lidar data processing.

- GPS base station computation
- GPS aircraft trajectory computation
- Inertial Navigation Solution (INS) computation
- Scanner calibration and vertical bias estimation
- X, Y, Z-point generation
- Point-data editing, parsing, and gridding

Global Positioning System Solutions

Our first task for final data processing is to generate solutions for the base station locations. This we accomplish by computing differentially corrected GPS solutions using up to four days of data from each of the four locations (BEG8, ROLW, SCHL, and TUNA) combined with reference and control station data from sites operated by the National Geodetic Survey (NGS). The reference and control stations used for the differentially corrected solutions are four sites from the NGS's network of continuously operating reference stations: The reference station, GAL1, is located on Galveston Island. The three control stations, ADKS, HOUS, and NETP are all located in the Houston, Texas area. The GPS base station solutions for BEG8, ROLW, SCHL, and TUNA are accurate to within 1 to 3 cm (table 3). We compute the base station coordinates using National Geodetic Survey's PAGESNT software.

Using the base station coordinates as local reference stations we then compute differentially corrected solutions for the position of the aircraft (aircraft trajectory), followed by transformation of the trajectories from the International Terrestrial Reference Frame of 2000 (ITRF00) into the North American Datum of 1983 (NAD83). Aircraft trajectories for all flights are computed using National Geodetic survey's Kinematic and Rapic Static (KARS) software in the ITRF00 because this is the datum in which GPS data are broadcast.

Table 3. Coordinates for GPS Base Station data. We use coordinates in the ITRF00 X, Y, and Z format to generate differentially corrected aircraft trajectories. Also included for reference are geographic and UTM coordinates in NAD83.

GPS Base	Geographic Coordinates (NAD83)		
Station	Latitude	Longitude	HAE (m)
BEG8	29 03 13.01414	-95 08 53.84989	-24.424
ROLW	29 30 24.69118	-94 30 0.55969	-24.963
SCHL	29 16 11.08736	-94 51 28.66221	-25.379
TUNA	29 29 8.03705	-94 34 20.74562	-25.7110

GPS Base	UTM zone 15 Coordinates (NAD83)		
Station	Easting (m)	Northing (m)	HAE (m)
BEG8	290,838.5273	3,215,830.5554	-24.4240
ROLW	354,594.8645	3,265,081.0239	-24.9630
SCHL	319,489.8608	3,239,303.0889	-25.3790
TUNA	347,556.8112	3,262,813.8743	-25.7110

GPS Base	Earth-centered, Earth-fixed Coordinates (ITRF00)		
Station	X (m)	Y (m)	Z (m)
BEG8	-500,709.1177	-5,557,421.3221	3,079,085.2320
ROLW	-435,884.3860	-5,538,234.7997	3,122,903.9218
SCHL	-471,553.5596	-5,548,255.2978	3,100,003.9195
TUNA	-442,962.6502	-5,538,838.2833	3,120,849.2886

Inertial Navigation Solutions

Inertial navigation solutions (INS) are post-processed 50Hz IMU or aircraft attitude data using Applanix Inc. POSProc (version 2.1.4) software. A real time INS solution is generated during the flight and output by the lidar instrument, but this solution is not as accurate as a post-processed INS solution. The INS solutions are constrained by the post-processed, differentially corrected aircraft GPS solution that has been transformed into NAD83 and also input into the POSProc software. Secondary output from the INS

computation is a GPS aircraft solution that is interpolated from 1 to 50 Hz. The 50 Hz aircraft trajectory is called a smoothed-best-estimate of trajectory (SBET).

Scanner Calibration and Bias Estimation

By combining an SBET and INS with laser range data in the REALM software we process subsets of flights to generate x, y, z datasets using nominal values for pitch, roll, and scale corrections. Roll, scale, and pitch corrections are necessary to compensate for offsets in alignment of the scanner mirror and the IMU inside the sensor head component of the ALTM 1225.

We used three methods to determine the calibration parameters (1) generate a digital elevation model and evaluate the image for seams between flight passes (fig. 5), (2) graphically compare points from crossing passes against the ground truth file in cross section (fig. 6), and (3) run an in-house computer program that estimates calibration and vertical bias corrections.

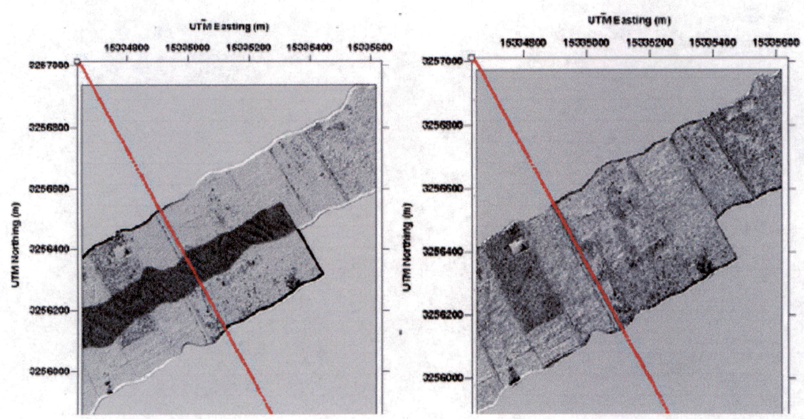

Figure 5. Shaded relief images of aircraft passes flown perpendicular to Boyt Road ground truth target (red) showing passes before (left) and after (right) scanner scale, roll and pitch bias corrections were applied. Differences in passes in image on left are accentuated due to errors in the GPS trajectory (note offset of road in shaded relief image).

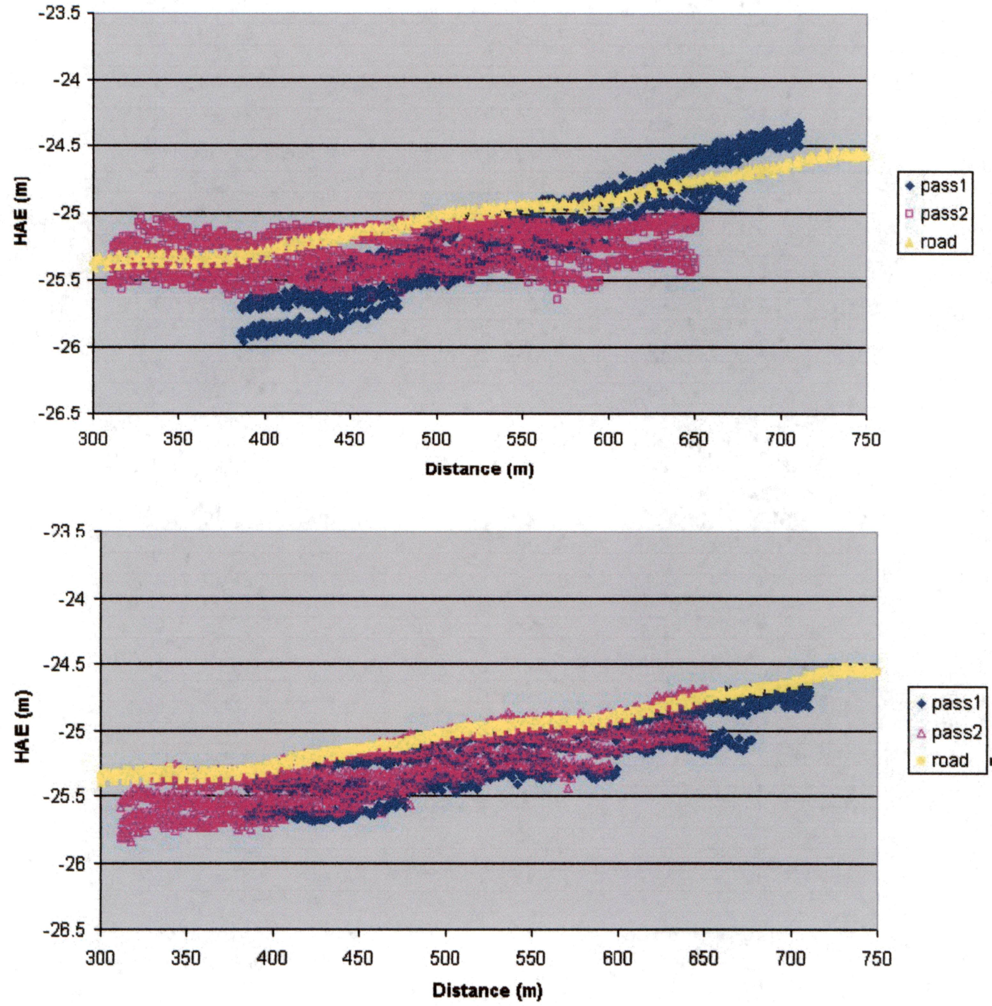

Figure 6. Transect of two flight passes (pink and blue) and kinematic GPS solution for Boyt Road (yellow) before (top) and after (bottom) calibration corrections are applied. Also note the vertical offset between the ground GPS and lidar data.

Multiple iterations of calibration parameter adjustment and reprocessing are usually required. We estimate vertical biases in the lidar data by taking the difference between the average height of points in a flight pass and points on the ground only for those points that are spaced within 0.5 m of each other in the x and y directions.

X, Y, Z-Point Generation

After obtaining good estimates of the calibration parameters (scanner pitch, roll, and scale corrections), we generated X, Y, Z and intensity values for each laser shot in the entire flight using the SBET (50 Hz aircraft trajectory), the INS (post-processed aircraft attitude information), and the laser range data. The output is a 9-column ASCII data set with the

following format: time tag; first pulse Easting, Northing, HAE; last pulse Easting, Northing, HAE; first pulse intensity; and last pulse intensity. It is at this point in the processing where the intensity table range corrections are applied to the Z value according to the magnitude of the intensity.

Range corrections in the intensity table originally provided by Optech vary between zero and 12 cm. Specular reflections from quiescent water caused off-scale intensity returns along the center of selected flight lines resulting in artifacts (ridges) along the center (nadir) of selected flight lines (fig. 7). This phenomenon has also been observed by lidar researchers at the University of Florida (Carter and others, 2001).

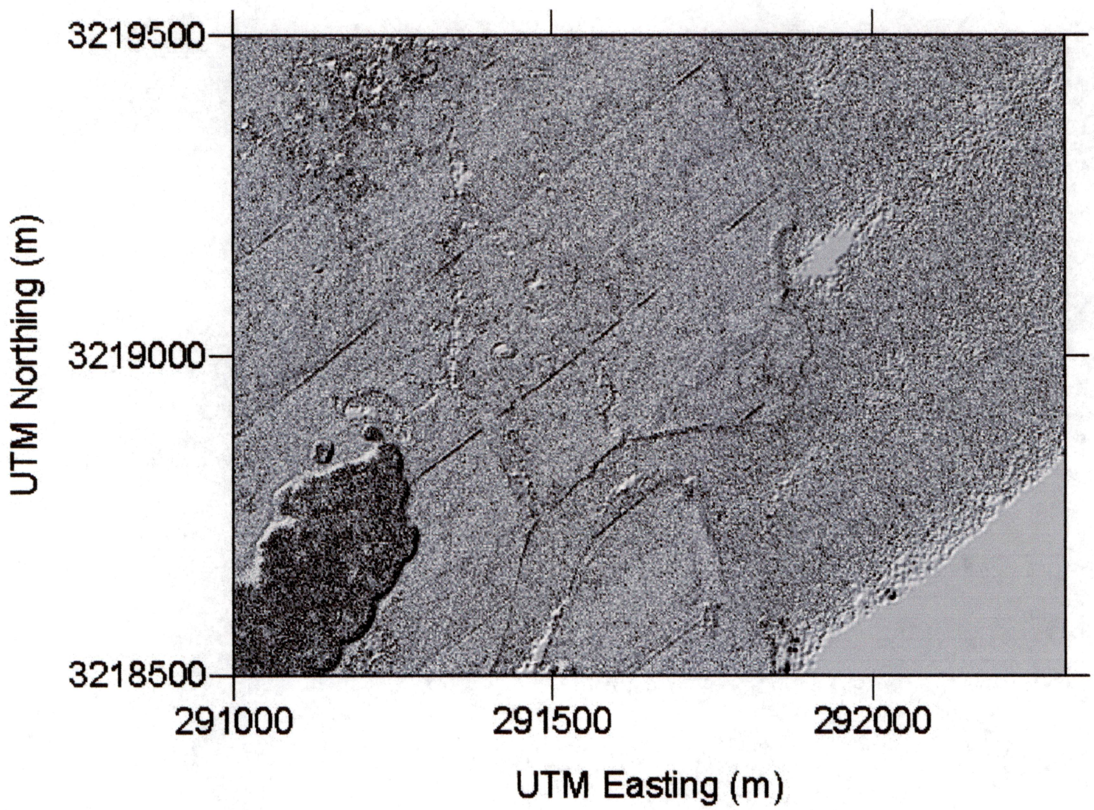

Figure 7. . Shaded relief image of gridded X, Y, and Z data on Mud Island showing ridges along center of flight lines.

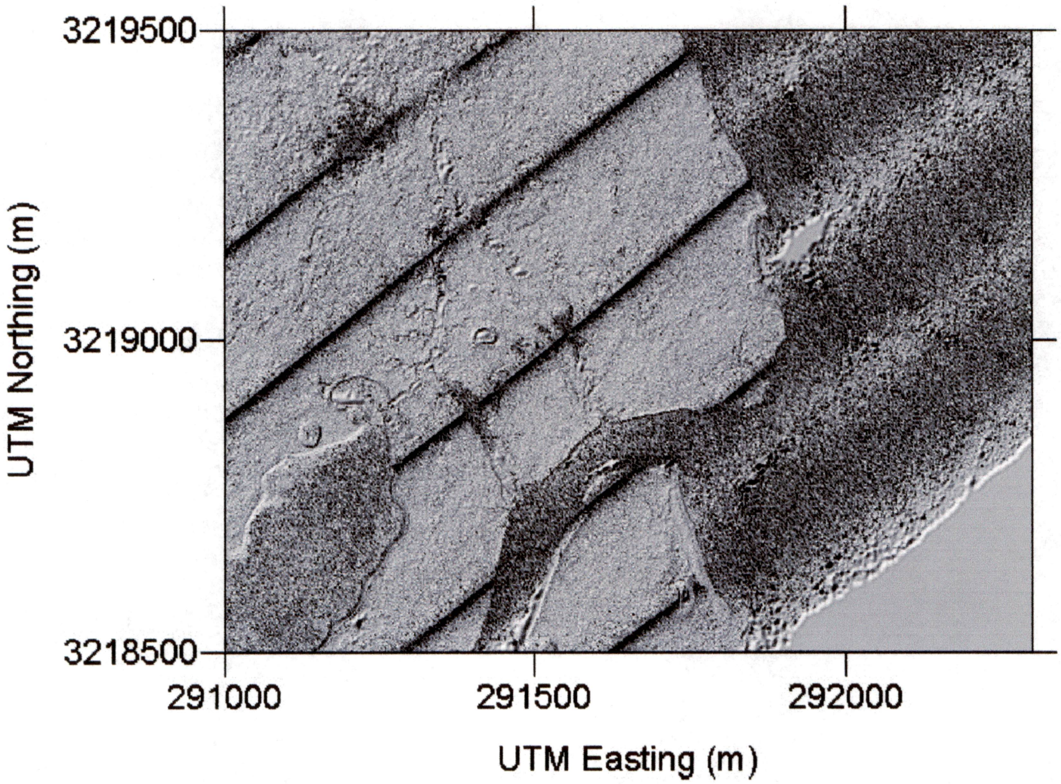

Figure 8. Shaded relief image of gridded X, Y, and Intensity data on Mud Island showing high intensity values along center of flight lines. Note that the high intensity values are the dark stripes in this hill-shaded image.

Even after generating a new intensity range correction table, we were unable to completely remove the near nadir artifacts from our Galveston West and East Bay datasets. In some areas we did not completely remove the ridges and in other areas we converted ridges to small (5 to 10 cm) ditches. Our solution to this problem was to edit the X, Y, Z and intensity data sets to omit points that had intensity values high enough to cause an artifact.

Lidar X, Y, Z points are output in Universal Transverse Mercator (UTM) coordinates and height above the GRS-80 ellipsoid (HAE). The ASCII-file sizes of X, Y, Z points for an entire flight are too large (table 4 and table 5) to be manipulated using software generally available for a personal computer so at this stage we copy the X, Y, Z output to a UNIX platform for further processing.

Table 4. File sizes and vertical bias corrections for the East Bay flights.

East Bay Flights

Flight	Date Flown	X, Y, Z-file Size (GB)	Vertical Bias Correction (m) TIM1	Vertical Bias Correction (m) TIM2
19802a	07/17/02	2.0	0.13	0.14
19802b	07/17/02	8.1	0.13	0.14
19902a	07/18/02	6.7	0.07	0.09
19902b	07/18/02	7.8	0.00	0.02
20002	07/19/02	1.3	0.00	0.00
21102a	07/30/02	3.2	0.12	0.12
21202a	07/31/02	4.8	0.00	0.01
21202b	07/31/02	4.1	0.01	0.02
21302a	08/01/02	2.7	0.01	0.02
21302b	08/01/02	9.1	-0.04	-0.03
21402a	08/01/02	3.1	-0.01	-0.01
21402b	08/01/02	5.2	0.08	0.07

Table 5. File sizes and vertical bias corrections for the West Bay flights.

West Bay Flights

Flight	Date Flown	X, Y, Z-file Size (GB)	Vertical Bias Correction (m) TIM1	Vertical Bias Correction (m) TIM2
23302a	08/21/02	6.5	0.04	0.06
23302b	08/21/02	3.6	-0.15	-0.12
23402a	08/22/02	6.4	0.00	0.03
23402b	08/22/02	3.1	0.00	0.02
23502	08/23/02	3.8	0.04	0.06
23602a_1	08/24/02	2.6	0.04	0.05
23602a_2	08/24/02	6.0	0.04	0.05
23602b	08/24/02	5.2	0.04	0.05
23702	08/25/02	11.2	0.04	0.07
26302a	09/20/02	3.0	0.04	0.06
26302b	09/20/02	5.5	0.04	0.06
26402	09/21/02	2.7	-0.01	-0.01

Digital Elevation Model Construction

A digital elevation model (DEM) is a lidar-derived product with many practical uses. The software product Surfer allows us to grid subsets of the X, Y, Z point data (file sizes up to ~500 MB) to create a DEM from which we can generate shaded relief or color-coded elevation images to view intermediate lidar data products (fig. 9).

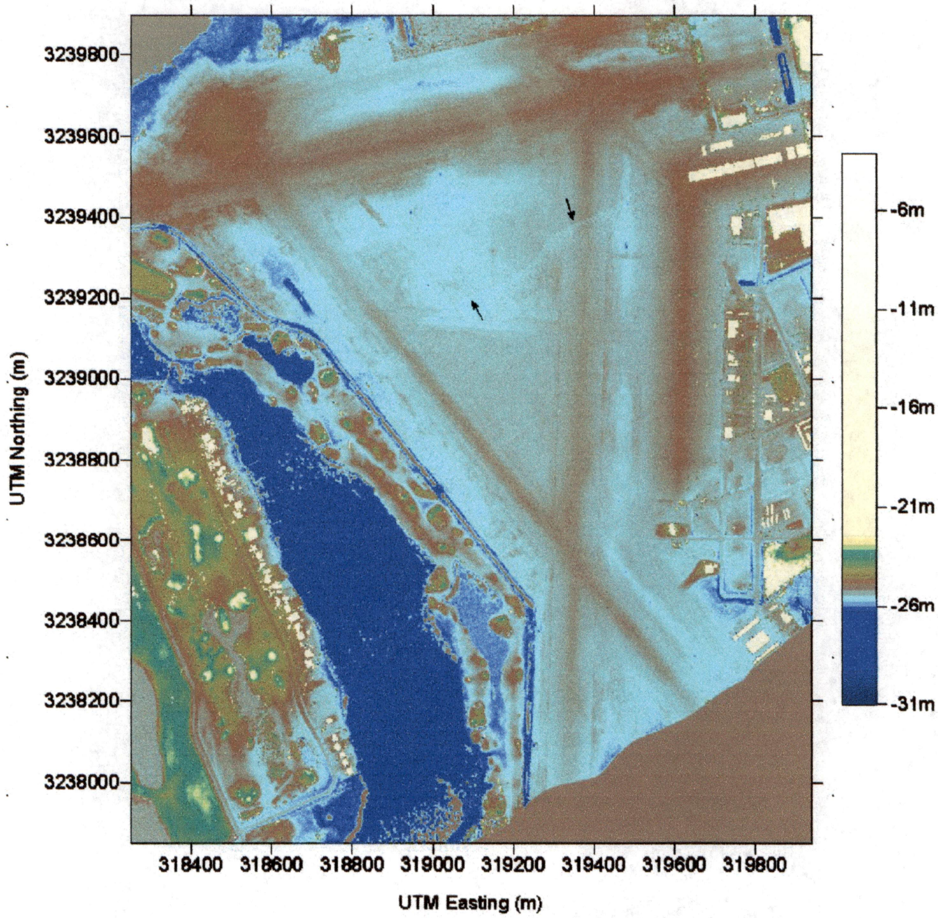

Figure 9. Color-coded elevation (HAE) image of Scholes Field generated from Surfer DEM. Elevations are in HAE (m). Note artifact from slight roll error in a single flight pass running northeast-southwest between arrows.

After transferring the X, Y, Z data sets to a UNIX platform, the 9-column ASCII-data from each flight are (1) parsed into 3.75-minute quarter-quadrangles, (2) adjusted for vertical bias corrections (see table 4 and table 5 for values), (3) edited to remove artifacts, and (4) gridded to produce the digital elevation models (DEM). The final processing step is conversion of the DEM's from height above the GRS80 ellipsoid to orthometric height using

the G99SSS gravimetric geoid model (see http://www.ngs.noaa.gov/GEOID/GEOID99/). Therefore Z-values in the DEMs are in the North American Vertical Datum of 1988 (NAVD88).

The Galveston West Bay DEMs cover portions of 35 quarter quadrangles in 13 of the United States Geological Survey 7-1/2 minute quadrangles between Freeport and Galveston, Texas. The East Bay DEMs cover portions of 25 quarter quadrangles in 10 of the United States Geological Survey 7-1/2 minute quadrangles between Galveston and High Island, Texas. Minimum and maximum coordinates for both the West and East Bay datasets are included in metadata files accompanying the DEMs.

Gridding to produce the DEM is accomplished with in-house software that uses a weighted-inverse-distance-algorithm to interpolate cell values. We are able to grid simultaneously the four following data attributes: first return z, first return intensity, second return z, and second return intensity. Data are then output into one of two formats:

(1) An ArcInfo ASCII raster file. Using this format, each one of the four attributes listed above must be output to a separate file for import into ArcView (must have Spatial Analyst extension) or ArcInfo. This format consists of a matrix of attribute values preceded by six lines of header information including number of columns, number of rows, x coordinate of the lower-left cell, y coordinate of the lower-left cell, cell size, and null value.

(2) A raw 4-byte binary raster file. Using this format, we can generate multi-band, band interleave files containing one, two, three, or all four of the attribute data referenced above.

Additionally, we output a header file in ERMapper's ".ers" format for each of the binary files so that the data can be viewed in ERMapper or ArcView, with the appropriate ECW plug-in. These header files contain the same information as the ArcInfo-format header files (except the coordinate values are of the upper-left cell) plus datum and projection information.

Flat areas that had standing water have gaps along nadir of flight lines due to filtering of high intensity values to remove artifacts (i.e. in the vicinity of Mud Island). After experimenting with different gridding parameters we realized that we could increase the search radius and smooth over the nadir gaps, but this also smoothed bay shoreline features.

Therefore, we chose to leave gaps in the DEM's rather than increase the search radius in the gridding algorithm and generate the most accurate shoreline.

SHORELINE EXTRACTION FROM LIDAR DEM

The shoreline was extracted by manually digitizing a line that represents approximately the mean higher high water elevation. Through comparisons with tide gauges in West and Christmas Bays the 0.3 m level relative to NAVD88 was determined to be the mean higher high water level. This elevation generally coincides with the water line in images of the DEM. Where low marsh is present the line is along the seaward edge, which is consistent with shorelines interpreted on historical aerial photography. The DEM was contoured with the 0.3 m line and overlain on an image of the DEM. Because of the very subtle topography, variations in vegetation height, and errors in the lidar data, the 0.3 m contour line is highly broken up into short segments in places. To acquire a continuous shoreline, therefore, the line was digitized using the 0.3 m contour line and the DEM image for guidance. However, the 0.3 m contour line was extracted where it was continuous. This method provided a continuous shoreline, where justified, while preserving the greatest amount of detail and accuracy.

LIDAR DEM APPLICATIONS

The shoreline extracted from the lidar data has unprecedented detail and accuracy and establishes a new baseline for shoreline change analysis. It can be compared to earlier shorelines derived from vertical aerial photography. The lidar-derived shoreline, however, is defined more rigorously than what is possible through interpreting aerial photography. It is also possible to extract other contour lines from the DEM. For example, a line representing the upper limit of marine influence could be delineated and compared with future surveys.

For the Galveston West and East Bay lidar mapping, we acquired swaths of data extending approximately 2 km inland. This area includes salt- and brackish-water marshes, tidal flats, and adjacent uplands. The lidar data will be useful in mapping and understanding changes in the habitats of these areas. For example, in a study of wetlands on Matagorda Island and Matagorda Peninsula along the central Texas coast, mapping of wetlands in one

area was supported by lidar data acquired in the spring of 2002. The lidar-derived images provided detailed elevation data that helped differentiate between regularly and irregularly flooded marshes and tidal flats, and areas that were transitional between uplands and wetlands (White and others, 2002; Gibeaut and others, 2003). From that detailed study, we know the distribution in elevation of various barrier island habitats, and we can use this information to model changes in these habitats during various sea-level rise scenarios. The lidar data of East and West Bays can be used to show where and how wetland habitats will shift during the next few decades as sea level rises. The lidar data, therefore, have the potential to be an important coastal management tool.

The lidar DEM's cover all of Follets Island, Galveston Island, and Bolivar Peninsula. This detailed topographic data set will be useful for determining storm-surge flooding and can help with community planning. It will also aid in studies of the origin and geologic evolution of these barrier islands. Finally, the DEM is an educational resource from which people can gain insight into the three-dimensional character of a barrier island, its environments, and human impacts.

REFERENCES

Carter, W., Shrestha, R., Tuell, G., Bloomquist, D., and Sartori, M., 2001, Mapping the Surface of Sheet Flow Water in the Everglades, *in* International Archives of Photogrammetry and Remote Sensing, Volume XXXIV -3/W4 Annapolis, MD Oct. 2001, pp 175-180.

Gibeaut, J. C., White, W. A., Smyth, R. C., Andrews, J. R., Tremblay, T. A., Gutiérrez, Roberto, Hepner, T. L., and Neuenschwander, Amy, 2003, Topographic variation of barrier island subenvironments and associated habitats, *in* Coastal Sediments '03: Crossing disciplinary boundaries: Proceedings, Fifth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes, Clearwater Beach, Florida, May 18-23, 10 p., CD-ROM.

Optech, Inc, 2003, e-mail communication with Paul Conrad of Optech, Inc, Toronto, Canada.

Wehr, A. and U. Lohr, 1999, Airborne laser scanning - an introduction and overview, *in* ISPRS Journal of Photogrammetry and Remote Sensing, vol. 54, no.2-3, pp.68-82.

White, W. A., Tremblay, T. A., Waldinger, R. L., and Calnan, T. R., 2002, Status and trends of wetland and aquatic habitats on Texas barrier islands, Matagorda Bay to San Antonio Bay: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Texas General Land Office and National Oceanic and Atmospheric Administration, under GLO contract no. 01-241-R, 66 p

APPENDIX A: EAST BAY METADATA

Identification_Information:
 Citation:
  Citation_Information:
   Originator: Bureau of Economic Geology, The University of Texas at Austin
   Publication_Date: 20030831
   Title: Coastal Mapping of the East Galveston Bay System Using Airborne Lidar
   Geospatial_Data_Presentation_Form: There are 25 quarter-quads in this series of West Bay DVDs. For each quarter-quad we have included a 1st-return DEM (denoted by "oz1") in the ArcInfo ASCII Raster format. These files can be converted to ArcInfo GRIDs using the File| Import Data Source commands in ArcView (you must have the Spatial Analyst extension) or the "asciigrid" command in ArcInfo.
   Other_Citation_Details: Quarter-Quadrange (File Name)
    caplen_ne (geb02_cap_ne.oz1.grd)
    caplen_nw (geb02_cap_nw.oz1.grd)
    flake_ne (geb02_flake_ne.oz1.grd)
    flake_nw (geb02_flake_nw.oz1.grd)
    flake_se (geb02_flake_se.oz1.grd)
    flake_sw (geb02_flake_sw.oz1.grd)
    frozen_point_ne (geb02_fp_ne.oz1.grd)
    frozen_point_nw (geb02_fp_nw.oz1.grd)
    frozen_point_se (geb02_fp_se.oz1.grd)
    frozen_point_sw (geb02_fp_sw.oz1.grd)
    galveston_ne (geb02_gal_ne.oz1.grd)
    high_island_ne (geb02_hi_ne.oz1.grd)
    high_island_nw (geb02_hi_nw.oz1.grd)
    high_island_se (geb02_hi_se.oz1.grd)
    high_island_sw (geb02_hi_sw.oz1.grd)
    lake_stephenson_ne (geb02_ls_ne.oz1.grd)
    lake_stephenson_nw (geb02_ls_nw.oz1.grd)
    lake_stephenson_se (geb02_ls_se.oz1.grd)
    lake_stephenson_sw (geb02_ls_sw.oz1.grd)
    mud_lake_nw (geb02_ml_nw.oz1.grd)
    mud_lake_sw (geb02_ml_sw.oz1.grd)
    port_bolivar_se (geb02_portb_se.oz1.grd)
    smith_point_se (geb02_smithp_se.oz1.grd)
    stanolind_reservoir_se (geb02_stanr_se.oz1.grd)
    the_jetties_nw (geb02_tj_nw.oz1.grd)
 Description:
  Abstract: This data set contains Digitial Elevation Models (DEMs) created from lidar point data for Galveston East Bay. The geographic extent of the data set is equivalent to the 25 quarter-quadrangles listed in Identification_Information, Citation, Citation_Information, Other_Citation_Details plus 30m of overedge beyond the extents of each quarter-quadrangle (serves as overlap between qquads). The DEMs were derived from lidar X, Y, and Z point data generated by combining laser range and aircraft attitude data collected using an airborne light detection and ranging

(lidar) instrument with once-per-second data collected using geodetic quality (dual phase) Global Positioning System (GPS) airborne and ground-based receivers. Our lidar system (Optech Inc. ALTM 1225, serial number 99d118) was installed in a single engine Cessna Stationaire 206 aircraft(tail number N4589U) owned and operated by the Texas State Aircraft Pooling Board, and operated locally out of Scholes Field in Galveston, Texas U.S.A. The lidar data described in this document were collected during 11 flights between 17 July and 02 August 2002, Julian days 19802, 19902, 20002, 21102, 21202, 21302 and 21402, GPS weeks 1175 (days 3, 4, and 5); 1177 (days 2, 3, 4 and 5)(see Data_Quality_Information, Lineage, Source_Information, Source_Contribution(1) for detailed flight and time information). The 99d118 instrument settings for these flights were: (1)laser pulse rate: 25kHz,(2)scanner rate: 26Hz, (3)scan angle: +/-20deg, (4)beam divergence: narrow, (5)altitude: 460-850m AGL, and (6)ground speed: 85-135kts. Two GPS base stations (TUNA and ROLW) were operated during the survey, using either Ashtech Z-12 receivers. The base stations were at the following locations: central Bolivar Peninsula (TUNA) near the gulf-side beach on the south side of Rollover Pass (ROLW) (see Data_Quality_Information, Lineage, Source_Information, Source_Contribution(2) for base station coordinates). Copious amounts of rain fell throughout the Summer of 2002 resulting in wide-spread areas of standing water during the lidar flights.

Purpose: The lidar and GPS data described in this document were used to create Digital Elevation Models of the Galveston East Bay Area including Bolivar Peninsula and High Island. The DEMs are being used to map the position of the bay shorelines as a basis for determining future rates of shoreline change.

Supplemental_Information:

The ALTM 1225 99D118 lidar instrument has the following specifications: operating altitude = 410-2,000m AGL; maximum laser pulse rate = 25kHz; laser scan angle = variable from 0 to +/-20deg from nadir; scanning frequency = variable, maximum of 28Hz at the 20deg scan angle; and beam divergence setting: narrow = 0.2 milliradian (half angle, 1/e). During the Galveston West and East Bay surveys the ALTM 1225 did not digitize and record the waveform of each laser reflection, but did recorded the range and backscatter intensity of the first and last laser returns of each laser reflection using an avalanch photo diode, a constant-fraction discriminator and two Timing Interval Meters (TIM).

Lidar digital elevation points are computed using three sets of data: laser ranges and their associated scan angles, platform position and orientation information, and calibration data and mounting parameters (Wehr and Lohr, 1999). Global Positioning System (GPS) receivers in the aircraft and on the ground provide platform positioning data. The GPS receivers record pseudo-range and phase information for post-processing. Platform orientation information comes from an Inertial Measurement Unit (IMU) containing sets of three orthogonal accelerometers and gyroscopes. An aided-Inertial Navigation System (INS) solution for the aircraft's attitude is estimated from the IMU output and the GPS information.

Wehr, A. and U. Lohr, 1999, Airborne laser scanning - an introduction and overview, ISPRS Journal of Photogrammetry and Remote Sensing, vol. 54, no.2-3, pp.68-82.

Time_Period_of_Content:

Time_Period_Information:
  Range_of_Dates/Times:
    Beginning_Date: 20020601
    Ending_Date: 20030831
  Currentness_Reference: ground condition

Status:
  Progress: Complete
  Maintenance_and_Update_Frequency: As needed, but none planned.
Spatial_Domain:
  Bounding_Coordinates:
    West_Bounding_Coordinate: -94.816547464
    East_Bounding_Coordinate: -94.336273344
    North_Bounding_Coordinate: 29.643234411
    South_Bounding_Coordinate: 29.342879564
Keywords:
  Theme:
    Theme_Keyword_Thesaurus: none
    Theme_Keyword: digital elevation model (DEM)
    Theme_Keyword: Lidar (Light Detection and Ranging)
    Theme_Keyword: quarter-quadrangle
    Theme_Keyword: bay shoreline
    Theme_Keyword: topography
    Theme_Keyword: laser
    Theme_Keyword: Global Positioning System (GPS)
    Theme_Keyword: inertial navigation solution (INS)
    Theme_Keyword: Inertial Motion Unit (IMU)
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    Place_Keyword: Gulf of Mexico
    Place_Keyword: Texas
    Place_Keyword: Galveston Island
    Place_Keyword: High Island
    Place_Keyword: Rollover Pass
  Temporal:
    Temporal_Keyword_Thesaurus: none
    Temporal_Keyword: 2002
    Temporal_Keyword: July
    Temporal_Keyword: August
Access_Constraints: none
Use_Constraints: These data were collected for the purpose of determining amounts and rates of shoreline change in the vicinity of Galveston Bay. Any conclusions drawn from analysis of this information are not the responsibility of the Bureau of Economic Geology or The University of Texas at Austin.
Point_of_Contact:
  Contact_Information:
    Contact_Person_Primary:

Contact_Person: James C. Gibeaut
Contact_Organization: Bureau of Economic Geology, The University of Texas at Austin
Contact_Position: Research Associate
Contact_Address:
Address_Type: mailing address
Address: University Station Box X
City: Austin
State_or_Province: Texas
Postal_Code: 78713
Country: United States of America
Contact_Voice_Telephone: 512-471-0344
Contact_Facsimile_Telephone: 512-471-0140
Contact_Electronic_Mail_Address: jim.gibeaut@beg.utexas.edu
Data_Set_Credit: Bureau of Economic Geology, University of Texas at Austin: R. Smyth, J. Gibeaut, J. Andrews, T. Hepner, and R. Gutierrez.

Data_Quality_Information:
Logical_Consistency_Report: Not applicable
Completeness_Report:
Positional_Accuracy:
Horizontal_Positional_Accuracy:
Horizontal_Positional_Accuracy_Report: Selected portions from each lidar data set were used to generate a 1m x 1m digital elevation model (DEM). Data estimated to have a horizontal accuracy of 0.01-0.03m from ground surveys using kinematic GPS techniques were superimposed on the lidar DEM and examined for any mismatch between the horizontal position of the ground GPS and the corresponding feature on the lidar DEM. Horizontal agreement between the ground kinematic GPS and the lidar was within the resolution of the 1m x 1m DEM.
Vertical_Positional_Accuracy:
Vertical_Positional_Accuracy_Report: Ground GPS surveys were conducted within the lidar survey area to acquire ground "truth" information. The ground survey points are estimated to have a vertical accuracy of 0.01-0.03m. Roads or other open areas with an unambiguous surface were surveyed using kinematic GPS techniques. A lidar data set was sorted to find data points that fell within 0.5m of a ground GPS survey point. The mean elevation difference between the lidar and the ground GPS was used to estimate and remove an elevation bias from the lidar. The standard deviation of these elevation differences provides estimates of the lidar precision. The 2002 Galveston East Bay lidar data set was determined to have an average elevation bias of 0.04m (TIM1) and 0.05m (TIM2) when compared to ground truth. Vertical biases were determined for and removed from each flight (numbered by julian day).
Lineage:
Source_Information:
Source_Citation:
Citation_Information:
Originator: Bureau of Economic Geology, The University of Texas at Austin
Publication_Date: 20020717-20020802
Title: Raw lidar data output from ALTM 1225

Type_of_Source_Media: digital file
Source_Time_Period_of_Content:
Time_Period_Information:
Range_of_Dates/Times:
Beginning_Date: 20020717
Ending_Date: 20020802
Source_Currentness_Reference: ground condition
Source_Citation_Abbreviation: lidar
Source_Contribution: raw lidar data from ALTM 1225-all times are UTC
Day 19802 (flight a) - 14:00 to 15:57
Day 19802 (flight b) - 16:58 to 20:11
Day 19902 (flight a) - 13:08 to 16:04
Day 19902 (flight b) - 17:00 to 20:03
Day 20002 (1 flight) - 17:05 to 17:55
Day 21102 (1 flight) - 12:54 to 15:18
Day 21202 (flight a) - 12:54 to 15:13
Day 21202 (flight b) - 16:18 to 19:31
Day 21302 (flight a) - 12:59 to 15:03
Day 21302 (flight b) - 16:05 to 18:53
Day 21402 (flight a) - 12:52 to 14:24
Day 21402 (flight b) - 15:20 to 19:03
Source_Information:
Source_Citation:
Citation_Information:
Originator: Bureau of Economic Geology, The University of Texas at Austin
Publication_Date: 20020717-20020802
Title: Air and Ground GPS files from lidar flights on Julian days 19802, 19902, 20002, 21102, 21202, 21302, 21402
Type_of_Source_Media: digital file
Source_Time_Period_of_Content:
Time_Period_Information:
Range_of_Dates/Times:
Beginning_Date: 20020717
Ending_Date: 20020802
Source_Currentness_Reference: ground condition
Source_Citation_Abbreviation: GPS
Source_Contribution: air and ground GPS files
Base Station Coordinates: UTM zone 15 NAD83 Easting (m), Northing (m), HAE (m):
Central Bolivar Peninsula (TUNA): 347,556.8112, 3,262,813.8743, -25.7110
Southwest side of Rollover Pass near beach (ROLW): 354,594.8645, 3,265,081.0239, -24.9630
Process_Step:
Process_Description:
Transfer raw ALTM 1225 flight data (laser ranges with associated scan angle information and IMU data), airborne GPS data collected at 1Hz using Ashtech Z-12 receiver, and ground-based GPS data collected at 1Hz using Ashtech Z-12 or Trimble

4000SSI receivers to NT workstation. Generate decimated lidar point file from above three data sets using Optech Inc. Realm 2.27 software. This is a 9-column ASCII data set with the following format: time tag; first pulse Easting, Northing, HAE; last pulse Easting, Northing, HAE; first pulse intensity; and last pulse intensity. View decimated lidar point file to check data coverage (i.e. sufficient overlap of flight lines and point spacing).

Compute base station coordinates using National Geodetic Survey's PAGESNT software. Compute aircraft trajectories for all base stations using National Geodetic survey's (Kinematic and Rapic Static (KARS) software. Coordinates for base stations and trajectories are in the International Terrestrial Reference Frame of 2000 (ITRF00) datum. Transform trajectory solution from ITRF00 to North American Datum of 1983 (NAD83). Use NAD83 trajectories and aircraft IMU data in Applanix Inc. POSProc (version 2.1.4) software to compute optimal 50Hz inertial navigation solution (INS) and smoothed best estimate of trajectory (SBET). Substitute the INS and SBET into Realm 2.27. Extract calibration area data set from lidar point file for quality control and instrument calibration checks. If necessary, use multiple iterations to adjust calibration parameters (pitch, roll, and scale) and reprocess sample data set. Then generate lidar point file (9-column ASCII file)for entire flight. Transfer point file from NT workstation to UNIX workstation.

Parse the 9-column lidar point file into 3.75-minute quarter-quadrangles and apply elevation bias correction (determined during calibration step). Grid the quarter-quad point files with software written by Bureau personnel. This in-house gridding software uses a weighted inverse distance algorithm to interpolate cell values. Use the Geiod99 geoid model to convert z-values from height above the GRS80 Ellipsoid to elevations with respect to the North American Vertical Datum 88 (NAVD88). We are able to grid simultaneously the four following data attributes: first return z, first return intensity, second return z, and second return intensity.

Data are then output into one of two formats: (1) An ArcInfo ASCII raster file. Using this format, each one of the four attributes listed above must be output to a separate file for import into ArcView (must have Spatial Analyst extension) or ArcInfo. This format consists of a matrix of attribute values preceded by six lines of header information including: number of columns, number of rows, x coordinate of the lower-left cell, y coordinate of the lower-left cell, cell size, and null value. (2) A raw 4-byte binary raster file. Using this format, we can generate multi-band, band interleave files containing one, two, three, or all four of the attribute data referenced above.

Additionally, we output a header file in ERMapper's ".ers" format for each of the binary files so that the data can be viewed in ERMapper or ArcView, with the appropriate ECW plug-in. These header files contain the same information as the ArcInfo-format header files (except the coordinate values are of the upper-left cell) plus datum and projection information.

Source_Used_Citation_Abbreviation: lidar and GPS
Process_Date: 20021001-20030831
Process_Contact:
 Contact_Information:
  Contact_Person_Primary:
   Contact_Person: Becky Smyth and John Andrews

Contact_Organization: Bureau of Economic Geology, The University of Texas at Austin
Contact_Position: Research Scientist Associate
Contact_Address:
Address_Type: mailing address
Address: University Station Box X
City: Austin
State_or_Province: Texas
Postal_Code: 78713
Country: United States of America
Contact_Voice_Telephone: Becky: 512-471-0232; John: 512-471-4951
Contact_Facsimile_Telephone: 512-471-0140
Contact_Electronic_Mail_Address: Becky: rebecca.smyth@beg.utexas.edu; John: john.andrews@beg.utexas.edu

Spatial_Data_Organization_Information:
Direct_Spatial_Reference_Method: Raster
Raster_Object_Information:
Raster_Object_Type: Grid Cell

Spatial_Reference_Information:
Horizontal_Coordinate_System_Definition:
Planar:
Grid_Coordinate_System:
Grid_Coordinate_System_Name: Universal Transverse Mercator
Universal_Transverse_Mercator:
UTM_Zone_Number: 15
Transverse_Mercator:
Scale_Factor_at_Central_Meridian: 0.999600
Longitude_of_Central_Meridian: -93.000000
Latitude_of_Projection_Origin: 0.000000
False_Easting: 500000.000000
False_Northing: 0.000000
Planar_Coordinate_Information:
Planar_Coordinate_Encoding_Method: coordinate pair
Coordinate_Representation:
Abscissa_Resolution: 0.01
Ordinate_Resolution: 0.01
Planar_Distance_Units: meters
Geodetic_Model:
Horizontal_Datum_Name: North American Datum of 1983
Ellipsoid_Name: Geodetic Reference System of 1980 (GRS80)
Semi-major_Axis: 6378137.000000
Denominator_of_Flattening_Ratio: 298.257222
Vertical_Coordinate_System_Definition:
Altitude_System_Definition:
Altitude_Datum_Name: North American Vertical Datum 1988

Altitude_Resolution: 0.05
Altitude_Distance_Units: meters
Altitude_Encoding_Method: Explicit elevation coordinate included with horizontal coordinates

Entity_and_Attribute_Information:
Overview_Description:
Entity_and_Attribute_Overview: Each grid file has a single attribute, "value", which represents an interpolated elevation average value for each 1m cell.
Entity_and_Attribute_Detail_Citation: Bureau of Economic Geology, The University of Texas at Austin, 2003.

Distribution_Information:
Distributor:
Contact_Information:
Contact_Person_Primary:
Contact_Person: James C. Gibeaut
Contact_Organization: Bureau of Economic Geology, The University of Texas at Austin
Contact_Position: Research Associate
Contact_Address:
Address_Type: mailing address
Address: University Station Box X
City: Austin
State_or_Province: Texas
Postal_Code: 78713
Country: United States of America
Contact_Voice_Telephone: 512-471-0344
Contact_Facsimile_Telephone: 512-471-0140
Contact_Electronic_Mail_Address: jim.gibeaut@beg.utexas.edu
Hours_of_Service: 0800-1700 Monday-Friday
Contact_Instructions: also available at www.beg.utexas.edu
Distribution_Liability: These data was collected for the purpose of determining amounts and rates of shoreline change in the vicinity of the Galveston East Bay. Any conclusions drawn from analysis of this information are not the responsibility of the Bureau of Economic Geology or The University of Texas at Austin.
Custom_Order_Process: This data can be obtained by contacting the above named individual.

Metadata_Reference_Information:
Metadata_Date: 20030821
Metadata_Review_Date: 20030831
Metadata_Contact:
Contact_Information:
Contact_Person_Primary:
Contact_Person: Rebecca C. Smyth
Contact_Organization: Bureau of Economic Geology, The University of Texas at Austin

Contact_Position: Research Scientist Associate
Contact_Address:
Address_Type: mailing address
Address: University Station Box X
City: Austin
State_or_Province: Texas
Postal_Code: 78713
Country: United States of America
Contact_Voice_Telephone: 512-471-0232
Contact_Facsimile_Telephone: 512-471-0140
Contact_Electronic_Mail_Address: rebecca.smyth@beg.utexas.edu
Metadata_Standard_Name: FGDC Content Standards for Digital Geospatial Metadata
Metadata_Standard_Version: FGDC-STD-001-1998

APPENDIX B: WEST BAY METADATA

Identification_Information:

Citation:
Citation_Information:
Originator: Bureau of Economic Geology, The University of Texas at Austin
Publication_Date: 20030829
Title: Coastal Mapping of the West Galveston Bay System Using Airborne Lidar
Geospatial_Data_Presentation_Form: There are 35 quarter-quads in this series of West Bay DVDs. For each quarter-quad we have included a 1st-return DEM (denoted by "oz1") in the ArcInfo ASCII Raster format. These files can be converted to ArcInfo GRIDs using the File | Import Data Source commands in ArcView (you must have the Spatial Analyst extension) or the "asciigrid" command in ArcInfo.
Other_Citation_Details: Quarter-Quadrange (File Name)
christmas_point_ne (gwb02_cp_ne.oz1.grd)
christmas_point_nw (gwb02_cp_nw.oz1.grd)
christmas_point_se (gwb02_cp_se.oz1.grd)
christmas_point_sw (gwb02_cp_sw.oz1.grd)
freeport_ne (gwb02_free_ne.oz1.grd)
freeport_nw (gwb02_free_nw.oz1.grd)
galveston_ne (gwb02_gal_ne.oz1.grd)
galveston_nw (gwb02_gal_nw.oz1.grd)
galveston_se (gwb02_gal_se.oz1.grd)
galveston_sw (gwb02_gal_sw.oz1.grd)
hitchcock_se (gwb_hitch_se.oz1.grd)
hoskins_mound_ne (gwb02_hm_ne.oz1.grd)
hoskins_mound_nw (gwb02_hm_nw.oz1.grd)
hoskins_mound_se (gwb02_hm_se.oz1.grd)
hoskins_mound_sw (gwb02_hm_sw.oz1.grd)
lake_como_ne (gwb02_lc_ne.oz1.grd)

lake_como_nw (gwb02_lc_nw.oz1.grd)
lake_como_sw (gwb02_lc_sw.oz1.grd)
oyster_creek_ne (gwb02_oc_ne.oz1.grd)
oyster_creek_nw (gwb02_oc_nw.oz1.grd)
oyster_creek_se (gwb02_oc_se.oz1.grd)
oyster_creek_sw (gwb02_oc_sw.oz1.grd)
san_luis_pass_ne (gwb02_slp_ne.oz1.grd)
san_luis_pass_nw (gwb02_slp_nw.oz1.grd)
sea_isle_ne (gwb02_si_ne.oz1.grd)
sea_isle_nw (gwb02_si_nw.oz1.grd)
sea_isle_se (gwb02_si_se.oz1.grd)
sea_isle_sw (gwb02_si_sw.oz1.grd)
see_christmas_point_nw (gwb02_see_cp_nw.oz1.grd)
see_galveston_nw (gwb02_see_g_nw.oz1.grd)
the_jetties_nw (gwb02_tj_nw.oz1.grd)
virginia_point_ne (gwb02_vp_ne.oz1.grd)
virginia_point_nw (gwb02_vp_nw.oz1.grd)
virginia_point_se (gwb02_vp_se.oz1.grd)
virginia_point_sw (gwb02_vp_sw.oz1.grd)

Description:

Abstract: This data set contains Digital Elevation Models (DEMs) created from lidar point data for Galveston West Bay and associated smaller bays (Bastrop Bay, Chocolate Bay, Christmas Bay, and Jones Bay). The geographic extent of the data set is equivalent to the 35 quarter-quadrangles listed in Identification_Information, Citation, Citation_Information, Other_Citation_Details plus 30m of overedge beyond the extents of each quarter-quadrangle (serves as overlap between qquads). The DEMs were derived from lidar X, Y, and Z point data generated by combining laser range and aircraft attitude data collected using an airborne light detection and ranging (lidar) instrument with once-per-second data collected using geodetic quality (dual phase) Global Positioning System (GPS) airborne and ground-based receivers. Our lidar system (Optech Inc. ALTM 1225, serial number 99d118) was installed in a single engine Cessna Stationaire 206 aircraft(tail number N4589U) owned and operated by the Texas State Aircraft Pooling Board, and operated locally out of Scholes Field in Galveston, Texas U.S.A. The lidar data described in this document were collected during 11 flights between 21 August and 21 September 2002, Julian days 23302, 23402, 23502, 23602, 23702, 26302 and 26402, GPS weeks 1180 (days 3, 4, 5, and 6); 1181 (day 0); and 1184 (days 5 and 6) (see Data_Quality_Information, Lineage, Source_Information, Source_Contribution(1) for detailed flight and time information). The 99d118 instrument settings for these flights were: (1)laser pulse rate: 25kHz,(2)scanner rate: 26Hz, (3)scan angle: +/-20deg, (4)beam divergence: narrow, (5)altitude: 460-1060m AGL, and (6)ground speed: 90-120kts. Three GPS base stations (BEG8, SCHL, and SCH2) were operated during the survey, using either Ashtech Z-12 or Trimble 4000ssi receivers. The three base stations were at the following locations: northeast end of Follets Island south of San Luis Pass (BEG8) and on unused taxi way at Scholes Airfield on Galveston Island (SCHL and SCH2) (see Data_Quality_Information, Lineage, Source_Information, Source_Contribution(2) for base station coordinates). Between the first and second portions of the Galveston West Bay lidar survey, Tropical Storm Fay made landfall near Port O'Connor, Texas at 0900 UTC on September 7, 2002. Copious amounts of rain fell before and after the storm resulting in wide-spread areas of standing water during the lidar flights.

Purpose: The lidar and GPS data described in this document were used to create Digital Elevation Models of the Galveston West Bay Area including Follets and Galveston Islands. The DEMs are being used to map the position of the bay shorelines as a basis for determining future rates of shoreline change.

Supplemental_Information:

The ALTM 1225 99D118 lidar instrument has the following specifications: operating altitude = 410-2,000m AGL; maximum laser pulse rate = 25kHz; laser scan angle = variable from 0 to +/-20deg from nadir; scanning frequency = variable, maximum of 28Hz at the 20deg scan angle; and beam divergence setting: narrow = 0.2 milliradian (half angle, 1/e). During the Galveston West and East Bay surveys the ALTM 1225 did not digitize and record the waveform of each laser reflection, but did recorded the range and backscatter intensity of the first and last laser returns of each laser reflection using an avalanch photo diode, a constant-fraction discriminator and two Timing Interval Meters (TIM).

Lidar digital elevation points are computed using three sets of data: laser ranges and their associated scan angles, platform position and orientation information, and calibration data and mounting parameters (Wehr and Lohr, 1999). Global Positioning System (GPS) receivers in the aircraft and on the ground provide platform positioning data. The GPS receivers record pseudo-range and phase information for post-processing. Platform orientation information comes from an Inertial Measurement Unit (IMU) containing sets of three orthogonal accelerometers and gyroscopes. An aided-Inertial Navigation System (INS) solution for the aircraft's attitude is estimated from the IMU output and the GPS information.

Wehr, A. and U. Lohr, 1999, Airborne laser scanning - an introduction and overview, ISPRS Journal of Photogrammetry and Remote Sensing, vol. 54, no.2-3, pp.68-82.

Time_Period_of_Content:
 Time_Period_Information:
  Range_of_Dates/Times:
   Beginning_Date: 20020821
   Ending_Date: 20030829
 Currentness_Reference: ground condition
Status:
 Progress: Complete
 Maintenance_and_Update_Frequency: As needed, but none planned.
Spatial_Domain:
 Bounding_Coordinates:
  West_Bounding_Coordinate: -95.370343994
  East_Bounding_Coordinate: -94.689220217
  North_Bounding_Coordinate: 29.384345933
  South_Bounding_Coordinate: 28.957939361
Keywords:
 Theme:

Theme_Keyword_Thesaurus: none
Theme_Keyword: digital elevation model (DEM)
Theme_Keyword: Lidar (Light Detection and Ranging)
Theme_Keyword: quarter-quadrangle
Theme_Keyword: bay shoreline
Theme_Keyword: topography
Theme_Keyword: laser
Theme_Keyword: Global Positioning System (GPS)
Theme_Keyword: inertial navigation solution (INS)
Theme_Keyword: Inertial Motion Unit (IMU)
Theme_Keyword: Tropical Storm Fay
Place:
Place_Keyword_Thesaurus: none
Place_Keyword: Gulf of Mexico
Place_Keyword: Texas
Place_Keyword: Galveston Island
Place_Keyword: Follets Island
Place_Keyword: San Luis Pass
Temporal:
Temporal_Keyword_Thesaurus: none
Temporal_Keyword: 2002
Temporal_Keyword: July
Temporal_Keyword: August
Temporal_Keyword: September
Temporal_Keyword: Tropical Storm Fay
Access_Constraints: none
Use_Constraints: These data were collected for the purpose of determining amounts and rates of shoreline change in the vicinity of Galveston Bay. Any conclusions drawn from analysis of this information are not the responsibility of the Bureau of Economic Geology or The University of Texas at Austin.
Point_of_Contact:
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Contact_Facsimile_Telephone: 512-471-0140
Contact_Electronic_Mail_Address: jim.gibeaut@beg.utexas.edu

Data_Set_Credit: Bureau of Economic Geology, University of Texas at Austin: R. Smyth, J. Gibeaut, J. Andrews, T. Hepner, and R. Gutierrez,

Data_Quality_Information:
Logical_Consistency_Report: Not applicable
Completeness_Report: Data were edited to remove points with intensity values over 400.
Positional_Accuracy:
Horizontal_Positional_Accuracy:
Horizontal_Positional_Accuracy_Report: Selected portions from each lidar data set were used to generate a 1m x 1m digital elevation model (DEM). Data estimated to have a horizontal accuracy of 0.01-0.03m from ground surveys using kinematic GPS techniques were superimposed on the lidar DEM and examined for any mismatch between the horizontal position of the ground GPS and the corresponding feature on the lidar DEM. Horizontal agreement between the ground kinematic GPS and the lidar was within the resolution of the 1m x 1m DEM.
Vertical_Positional_Accuracy:
Vertical_Positional_Accuracy_Report: Ground GPS surveys were conducted within the lidar survey area to acquire ground "truth" information. The ground survey points are estimated to have a vertical accuracy of 0.01-0.03m. Roads or other open areas with an unambiguous surface were surveyed using kinematic GPS techniques. A lidar data set was sorted to find data points that fell within 0.5m of a ground GPS survey point. The mean elevation difference between the lidar and the ground GPS was used to estimate and remove an elevation bias from the lidar. The standard deviation of these elevation differences provides estimates of the lidar precision. The 2002 Galveston West Bay lidar data set was determined to have an average elevation bias of 0.01m (TIM1) and 0.03m (TIM2) when compared to ground truth. Vertical biases were determined for and removed from each flight (numbered by julian day).
Lineage:
Source_Information:
Source_Citation:
Citation_Information:
Originator: Bureau of Economic Geology, The University of Texas at Austin
Publication_Date: 20020821-20020921
Title: Raw lidar data output from ALTM 1225
Type_of_Source_Media: digital file
Source_Time_Period_of_Content:
Time_Period_Information:
Range_of_Dates/Times:
Beginning_Date: 20020821
Ending_Date: 20020921
Source_Currentness_Reference: ground condition
Source_Citation_Abbreviation: lidar
Source_Contribution: raw lidar data from ALTM 1225-all times are UTC
Day 23302 (flight a) - 14:29 to 17:34
Day 23302 (flight b) - 22:38 to 00:16
Day 23402 (flight a) - 14:20 to 17:02
Day 23402 (flight b) - 22:36 to 00:26
Day 23502 (1 flight) - 22:27 to 00:37

Day 23602 (flight a) - 13:48 to 17:26
Day 23602 (flight b) - 22:05 to 00:16
Day 23702 (1 flight) - 13:39 to 17:25
Day 26302 (flight a) - 18:20 to 19:29
Day 26303 (flight b0 - 20:38 to 23:45
Day 26402 (1 flight) - 17:30 to 19:29

Source_Information:
Source_Citation:
Citation_Information:
Originator: Bureau of Economic Geology, The University of Texas at Austin
Publication_Date: 20020821-20020921
Title: Air and Ground GPS files from lidar flights on Julian days 23302, 23402, 23502, 23602, 23702, 26302, 26402
Type_of_Source_Media: digital file
Source_Time_Period_of_Content:
Time_Period_Information:
Range_of_Dates/Times:
Beginning_Date: 20020821
Ending_Date: 20020921
Source_Currentness_Reference: ground condition
Source_Citation_Abbreviation: GPS
Source_Contribution: air and ground GPS files
Base Station Coordinates: UTM zone 15 NAD83 Easting (m), Northing (m), HAE (m):
Northeast end of Follets Island just south of San Luis Pass (BEG8): 290838.5273, 3215830.5554, -24.42
Scholes Field Taxiway primary base station location (SCHL): 319489.8608, 3239303.0889, -25.379
Scholes Field Taxiway secondary base station location (SCH2): 319483.5743, 3239303.1520, -25.389

Process_Step:
Process_Description:

Transfer raw ALTM 1225 flight data (laser ranges with associated scan angle information and IMU data), airborne GPS data collected at 1Hz using Ashtech Z-12 receiver, and ground-based GPS data collected at 1Hz using Ashtech Z-12 or Trimble 4000SSI receivers to NT workstation. Generate decimated lidar point file from above three data sets using Optech Inc. Realm 2.27 software. This is a 9-column ASCII data set with the following format: time tag; first pulse Easting, Northing, HAE; last pulse Easting, Northing, HAE; first pulse intensity; and last pulse intensity. View decimated lidar point file to check data coverage (i.e. sufficient overlap of flight lines and point spacing).

Compute base station coordinates using National Geodetic Survey's PAGESNT software. Compute aircraft trajectories for all base stations using National Geodetic survey's (Kinematic and Rapic Static (KARS) software. Coordinates for base stations and trajectories are in the International Terrestrial Reference Frame of 2000 (ITRF00) datum. Transform trajectory solution from ITRF00 to North American Datum of 1983 (NAD83). Use NAD83 trajectories and aircraft IMU data in Applanix Inc. POSProc

(version 2.1.4) software to compute optimal 50Hz inertial navigation solution (INS) and smoothed best estimate of trajectory (SBET). Substitute the INS and SBET into Realm 2.27. Extract calibration area data set from lidar point file for quality control and instrument calibration checks. If necessary, use multiple iterations to adjust calibration parameters (pitch, roll, and scale) and reprocess sample data set. Then generate lidar point file (9-column ASCII file)for entire flight. Transfer point file from NT workstation to UNIX workstation.

Parse the 9-column lidar point file into 3.75-minute quarter-quadrangles and apply elevation bias correction (determined during calibration step). Grid the quarter-quad point files with software written by Bureau personnel. This in-house gridding software uses a weighted inverse distance algorithm to interpolate cell values. Use the Geiod99 geoid model to convert z-values from height above the GRS80 Ellipsoid to elevations with respect to the North American Vertical Datum 88 (NAVD88). We are able to grid simultaneously the four following data attributes: first return z, first return intensity, second return z, and second return intensity.

Data are then output into one of two formats: (1) An ArcInfo ASCII raster file. Using this format, each one of the four attributes listed above must be output to a separate file for import into ArcView (must have Spatial Analyst extension) or ArcInfo. This format consists of a matrix of attribute values preceded by six lines of header information including: number of columns, number of rows, x coordinate of the lower-left cell, y coordinate of the lower-left cell, cell size, and null value. (2) A raw 4-byte binary raster file. Using this format, we can generate multi-band, band interleave files containing one, two, three, or all four of the attribute data referenced above.

Additionally, we output a header file in ERMapper's ".ers" format for each of the binary files so that the data can be viewed in ERMapper or ArcView, with the appropriate ECW plug-in. These header files contain the same information as the ArcInfo-format header files (except the coordinate values are of the upper-left cell) plus datum and projection information.

Source_Used_Citation_Abbreviation: lidar and GPS
Process_Date: 20021001-20030821
Process_Contact:
 Contact_Information:
  Contact_Person_Primary:
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John: john.andrews@beg.utexas.edu

Spatial_Data_Organization_Information:
Direct_Spatial_Reference_Method: Raster
Raster_Object_Information:
Raster_Object_Type: Grid Cell

Spatial_Reference_Information:
Horizontal_Coordinate_System_Definition:
Planar:
Grid_Coordinate_System:
Grid_Coordinate_System_Name: Universal Transverse Mercator
Universal_Transverse_Mercator:
UTM_Zone_Number: 15
Transverse_Mercator:
Scale_Factor_at_Central_Meridian: 0.999600
Longitude_of_Central_Meridian: -93.000000
Latitude_of_Projection_Origin: 0.000000
False_Easting: 500000.000000
False_Northing: 0.000000
Planar_Coordinate_Information:
Planar_Coordinate_Encoding_Method: coordinate pair
Coordinate_Representation:
Abscissa_Resolution: 0.01
Ordinate_Resolution: 0.01
Planar_Distance_Units: meters
Geodetic_Model:
Horizontal_Datum_Name: North American Datum of 1983

Ellipsoid_Name: Geodetic Reference System of 1980(GRS80)
Semi-major_Axis: 6378137.000000
Denominator_of_Flattening_Ratio: 298.257222
Vertical_Coordinate_System_Definition:
Altitude_System_Definition:
Altitude_Datum_Name: North American Vertical Datum 1988
Altitude_Resolution: 0.05
Altitude_Distance_Units: meters
Altitude_Encoding_Method: Explicit elevation coordinate included with horizontal coordinates

Entity_and_Attribute_Information:
Overview_Description:
Entity_and_Attribute_Overview: Each grid file has a single attribute, "value", which represents an interpolated elevation average value for each 1m cell.
Entity_and_Attribute_Detail_Citation: Bureau of Economic Geology, The University of Texas at Austin, 2003.

Distribution_Information:
 Distributor:
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   Contact_Instructions: also available at www.beg.utexas.edu
 Distribution_Liability: These data was collected for the purpose of determining amounts and rates of shoreline change in the vicinity of the Galveston West Bay. Any conclusions drawn from analysis of this information are not the responsibility of the Bureau of Economic Geology or The University of Texas at Austin.
 Custom_Order_Process: This data can be obtained by contacting the above named individual.

Metadata_Reference_Information:
 Metadata_Date: 20030821
 Metadata_Review_Date: 20030829
 Metadata_Contact:
  Contact_Information:
   Contact_Person_Primary:
    Contact_Person: Rebecca C. Smyth
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 Metadata_Standard_Name: FGDC Content Standards for Digital Geospatial Metadata
 Metadata_Standard_Version: FGDC-STD-001-1998