Airborne Laser Topographic Mapping:
Applications to Hurricane Storm Surge Hazards

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INTRODUCTION

In the United States, the population and urbanization of the coastal zone is rapidly increasing. Currently, it is estimated that the population in the U.S. coastal zone increases on average by over 3600 people each day [Cullinton, 1998]. Cities along the Southeast and Gulf coast of the United States are particularly vulnerable to the hazards of hurricanes. The dramatic increases in the cost of hurricane damage experienced in recent decades can be directly attributed to increases in the population and wealth of these communities [Pielke and Landsea, 1998].

One of the greatest hazards posed by a hurricane is the storm surge. A storm surge is the abnormal rise of water levels along a coast caused by wind and pressure forces of an approaching hurricane or other intense storms. Historically, the storm surge has caused 90% of all hurricane related deaths, mostly from drowning [Simpson and Riehl, 1981; Elsner and Kara, 1999]. Flooding caused by storm surges is also a major cause of property damage.

Accurate topographic information is essential for predicting storm surge damage and flooding. These data are an integral component in the construction of evacuation maps based on numerical storm surge models such as the NOAA SLOSH model [Jelesnianski, et al., 1992]. In the U.S., the best existing topographic data usually consist of U.S. Geological Survey (USGS) contour maps produced at 5 to 10 foot (1.5 and 3 m) contour intervals. The absolute vertical accuracy of these maps is limited due to poor sampling and the analog techniques used to produce the contours. In low relief coastal plains, this poor accuracy and resolution can result in large errors in predicted flooding.
Airborne LIDAR (acronym for LIght Detection and Ranging) is an emerging technology which can accurately and inexpensively map topography over large areas. We present results of an Airborne Laser Terrain Mapping (ALTM) survey of eastern Broward County in southeast Florida and demonstrate how these data can be used to better predict the extent of storm surge flooding.

**LASER TOPOGRAPHIC MAPPING**

Airborne Laser Topographic Mapping (ALTM) is a subset of an active remote sensing technology known as LIDAR. LIDAR systems direct pulses of laser light toward the ground and detect the return times of reflected or back-scattered pulses in order to determine ranges to the reflecting surface. The use of LIDAR for airborne topographic mapping began in the late 1970's, but early systems suffered because of poor determination in the aircraft position and orientation. By the early 1990s, advances in navigation technology, electronic miniaturization and laser technology lead to the development of the first commercial ALTM systems. Other common acronyms used for ALTM include ALSM (Airborne Laser Swath Mapping) and ALS (Airborne Laser Surveying). A comprehensive review of current LIDAR mapping systems is given in Baltsavias [1999a] and Wehr and Lohr [1999].

Most ALTM systems consist of four basic components (Figure 1): the laser range finder, the scanner, the Inertial Measurement Unit (IMU), and a kinematic Global Position System (GPS). Data are recorded in flight and are later post processed to return X, Y, Z coordinates of the ground surface. Additional data analysis and filtering allows separation of non-surface features from the terrain surface. Finally, irregularly spaced points are usually interpolated onto a regularly spaced grid to produce a digital elevation model (DEM).

The LIDAR sensor detects the range from aircraft to ground by recording the time difference between laser pulses sent out and reflected back. Pulse repetition rates of most ALTM systems range between 5 and 25 kHz [Baltsavias, 1999a]. In addition, many systems allow the recording of multiple returns and the return intensity for each laser pulse. A scanner allows measurements to cover a wide swath beneath the flight path. In most systems, an oscillating mirror allows the laser to scan back and forth. This oscillation of the scanner mirror in combination with forward motion of the aircraft typically results in a zigzag scan pattern beneath the flight path (Figure 1).

Aircraft positioning and orientation are provided by the GPS and IMU systems. GPS receivers mounted in the aircraft and at one or more known ground positions continuously record GPS carrier phase data at sample rates of 1 Hz or higher. Post flight, differential GPS techniques compute a precise aircraft trajectory from the aircraft and ground station carrier phase data [Mader, 1986; Krabill and Martin, 1987]. The IMU consists of a set of gyroscopes and accelerometers that continu-
Figure 1. Schematic diagram showing the components of an ALTM system along with data acquisition parameters used for the Broward County, FL survey.

Figure 1

Topographic Data

Broward County lies in a low relief coastal plain with elevations ranging between 0 and 8 m (Plate 1). With a population of over 1.5 million people (1999), Broward is Florida’s second most populous county and includes the municipalities of Ft. Lauderdale and Hollywood. The most prominent topographic feature in Broward County is the Atlantic Coastal Ridge. Before development, the Atlantic Coastal Ridge formed the eastern rim of the Everglades. Early urbanization in southeast Florida was confined to the higher elevation ridge because these areas were less susceptible to flooding. Starting in the 1930s canals were cut through the ridge to drain water from the Everglades and provide more land for farming and urbanization. In recent decades, urbanization has spread westward into the low-lying wetlands of the Everglades and eastward onto the coastal lowlands and barrier islands. This urban growth increasingly has placed popula-
Plate 1. Pseudocolored topographic imagemap of eastern Broward County, FL showing highways and physiographic features. Elevations are from ALTM bare earth DEM, sub-averaged to 30 m resolution. Color scale shows elevation categories.
tions in areas susceptible to both inland flooding due to rainfall and to storm surge [Finkl, 1994; 2000].

In 2000-2001, Florida International University (FIU) collected ALTM measurements in eastern Broward and Palm Beach Counties to assist emergency management personnel in revising their hurricane evacuation maps. Elevations were collected with an Optech ALTM 1210 LIDAR mapping system jointly owned and operated by FIU and the University of Florida [Gutelius et al., 1998; Shrestha, et al., 2000]. Data were collected as a series of 600-meter-wide swaths consisting of points spaced approximately every 2.5 m beneath the flight path. Flight lines were spaced 500 m apart to allow sufficient overlap in order to avoid data gaps and to assess measurement repeatability. Each deployment typically took 4-5 hours during which GPS data were continuously recorded on both the aircraft and on the ground. In total, 160 separate swaths were collected.

Data from overlapping swaths were checked for internal consistency, combined and subdivided into smaller and more manageable sized portions. These consisted of 1.5-km² tiles, each containing 1 – 2 million points. In total, the project measured over 700 million irregularly spaced ground elevations and covered over 1300 km². Additional technical details of the data acquisition for this project are found in the report by Whitman [2000].

The ALTM system returns a 3-dimensional cloud of points corresponding to laser reflections off various objects (Plate 2). In order to model and visualize variations in the ground surface, reflections from non-ground features such as buildings, vegetation, and vehicles must be classified and removed [Kraus and Pfeifer, 1998; Shrestha et al., 1999]. Since a given DEM pixel can often contain both ground and non-ground surface reflections, terrain classification is best performed on the raw, irregularly spaced laser points rather than on gridded data. After classification, the remaining ground surface points are then gridded to produce a “bare earth” DEM.

A simple approach for removing non-ground points is to estimate a minimum ground surface envelope and classify the reflections based on their proximity to that envelope. An iterative algorithm, which utilizes expanding search windows and proximity thresholds, was used to classify the points. First, points outside a specified vertical range were excluded. Each tile was then subdivided into a series of overlapping 1 m square blocks and all points except the minimum elevation in each block were discarded. For the next iteration the blocks were doubled in size and the minimum elevation in each block was determined. Then, all points with elevations greater than a threshold above the minimum were discarded. The process was repeated with the block widths and classification thresholds doubling in size until the block size was 128 m or no points were discarded from the previous iteration.

After filtering, data for each tile were gridded into a 2 m resolution DEM. Because terrain filtering often produces large data gaps in areas covered by buildings and vegetation, elevations were interpolated using kriging with a
Plate 2. Example of raw ALTM data before terrain filtering and gridding. A) Color coded point elevations (in meters, NAVD88) of irregularly spaced ALTM. Black line denotes position of section in B. Horizontal coordinates are in UTM 17 meters. B) Cross profile showing points remaining after each iteration of terrain filter. Elevations were projected from a 75 m-wide swath into the section shown in A (black line). After 5 iterations, only ground surface returns remain (blue dots).
search radius of 50 m. Grid cells outside the 50 m search radius were assigned a value of NODATA. An example of a tile gridded after terrain filtering is shown in Plate 3. The color shaded relief image clearly shows the Atlantic Coastal Ridge running through the center of the tile. Roads appear as lower elevations cut into the background topography. Even subtle drainage features such as the elevated road crowns can be resolved. The footprints of buildings removed by terrain filtering appear as raised platforms, which presumably correspond to the ground elevations at the base of the buildings.

Like all remote measurements, airborne LIDAR measurements are subject to error. Errors arise from three main sources: laser range, aircraft trajectory, and INS measurements (Baltasavias, 1999b). Comparison of the LIDAR data with an independent dataset of higher accuracy is necessary in order to estimate absolute uncertainties in the elevations. Verification of the data is also necessary in order to ensure against systematic errors or offsets in the data caused by instrument malfunctions or processing blunders.

Accuracy was assessed by comparing the bare earth DEMs with an independent dataset consisting of approximately 321 GPS control points provided by the Broward County Engineering Department. These control points usually consist of survey tacks placed in the pavement of road intersections and are spaced approximately every 800 m and have vertical and horizontal accuracies of 1-2 cm. At each control point, the DEM elevations were calculated by bilinear interpolation and were compared with the control point elevations. This analysis returned a vertical root mean squared error (RMSE) of 0.12 m.

FLOOD MODELS

In the U. S., the most widely used numerical storm surge model is the National Weather Service SLOSH (sea, lake, and overland surges form hurricanes) model [Jelesnianski et al, 1992]. The SLOSH model computes water height above mean sea level at a network of grid points in a pie-shaped geographical area known as a basin. SLOSH uses a hyperbolic coordinate system and the model cells vary in size. For a typical basin, the size of each grid cell varies from 0.5 km near the center or pole of the basin to over 7 km at the outer boundaries of the basin. Typically, a basin is oriented such that the highest density of points is over land where surge heights are of greatest interests. Bathymetry or topography relative to sea level is specified at each grid point. The model can also incorporate sub-grid cell features such as barriers, levees, rivers, and channels. A series of overlapping basins provide coverage for most of the Gulf and Atlantic coastlines.

Output from a composite of numerous SLOSH runs are used to define flood prone areas for evacuation planning. Strength is modeled using central pressure and storm eye size parameterized by the five categories of storm intensity developed by Saffir and Simpson [Simpson and Riehl, 1981]. For each category of
Plate 3. Color shaded relief map of bare earth DEM gridded from filtered point elevations in a 1 km² tile in a residential neighborhood of Hollywood, FL. Over 200,000 irregularly spaced measurements were gridded to produce this DEM. Linear features in this image are road crowns. The elevated feature in the center of the tile is the Atlantic Coastal Ridge. The white box shows location of the data in Plate 2A.
Figure 2. Maximum predicted flooding from category 5 hurricane. A) Flooding predicted from SLOSH model only. B) Predicted flooding from combined SLOSH and ALTM 30m DEM. Background topography is from ALTM 30m DEM shown in Plate 1.

storm, the NWS typically calculates surge heights for 200 - 300 hypothetical storms impacting a basin at various locations and from various directions. The results of these model runs are combined, and the maximum storm surge height at each grid cell is selected in order to construct a map of maximum potential storm surge height for each Saffir-Simpson category. These maximum of maximum (MOM) storm surge maps indicate all areas that could potentially flood for a given storm strength.

The SLOSH model is not sensitive to topographic features of small dimension and tends to overestimate the flooded area because of its relatively coarse resolution (> 500m) (Figure 2A). In order to simulate the effect of higher resolution topography on predicted flooding, we use a GIS to combine the MOM output with higher resolution DEMs. First, a lower resolution topographic dataset was produced by mosaicing the tiles and subaveraging the 2 m pixels to 30 m reso-
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...Then, heights in the hyperbolic SLOSH storm surge grid were resampled to the resolution of the DEM with bilinear interpolation. Finally, the DEM elevations were overlaid and subtracted from the SLOSH flood heights to produce a map of flood depth above the ground surface. Regions with flood depths greater than zero indicate flooded areas.

Flooding maps were calculated by combining both the ALTM DEM with the MOM maps computed for Safir-Simpson category 1-5 storm scenarios. Differences in predicted flooding produced by combining SLOSH with the higher resolution DEMs are most apparent for the category 5 storms (Figure 2). Inundated areas predicted from SLOSH and ALTM topography cover 54% less area than that predicted from SLOSH alone.

The reduction in predicted flooding is most apparent along E-W trending tidal water bodies such as the New River and the Dania Cutoff Canal that traverse the Atlantic Coastal Ridge (Figure 2). This is largely a consequence of the large (600–800 m wide) SLOSH cells. These water bodies are considerably narrower than a SLOSH model cell and are modeled in SLOSH as sub-grid cell features. Flooding does not occur throughout the whole cell because high elevations near the canal confine flooding to a relatively narrow strip. A similar effect is seen for portions of the coastal barrier islands where elevations as high as 5 m prevent flooding even for category 5 storms.

DISCUSSION

An important goal in emergency management is to protect people who are in potential danger while minimizing the overall impact and disruption to society. When a hurricane warning is issued by the NHC, local authorities usually request the evacuation of residents living in predetermined evacuation zones susceptible to storm surge. Evacuation of people constitutes a significant expense in any hurricane emergency, with estimates as high as one million dollars per mile of coastline evacuated. These costs remain even for cases of “false alarms” where warnings are issued, but the hurricane does not strike. In addition, persons who are unnecessarily evacuated are often placed in harm’s way. Often, the safest place for people to reside during a hurricane is at home, unless the residence is subject to storm surge flooding or is of a type vulnerable to wind damage (e.g. mobile homes). For this reason, it is important that the best possible information be used when determining whom to evacuate.

Broward County used SLOSH model output combined with results of this ALTM study to revise their hurricane evacuation zones in 2000 (Figure 3). In designing these zones, the Broward County emergency managers also considered other information such as road access and population demographics. For practical purposes, well-known cultural features such as major roads were used for the zone boundaries. The revised maps significantly reduced the evacuation areas for...
all Saffir-Simpson categories. Category 1-2 evacuations (Figure 3, Plan A) are reduced in area by over 68% and are confined only to the barrier islands to the east of Atlantic Intercoastal Waterway. For major hurricanes (Saffir-Simpson categories 3-5), the revised evacuation zone area decreased by over 45% and in general, only includes regions to the east of the Atlantic Coastal Ridge. Over 175,000 less people will need to evacuate in the event of a major hurricane impacting Broward County.

One surprising result of this study was that much of the coastal barrier islands do not appear to be flooded even for the largest storms. However, the revised evacuation plan still requires evacuation of these islands for all hurricanes. This decision was prudent because access to the bridges and causeways to these islands will likely be threatened in any hurricane. In addition, SLOSH does not model wave set-up
and run-up, which could be significant along the Broward County coastline. The identification of potentially dry areas on the islands will be useful in determining locations of refuges of last resort and for deployment of emergency vehicles.

ALTM data combined with 3-dimensional computer visualization can play an important role in educating people to the hazards of storm surges. Studies have shown that 85% of the current residents of the hurricane-vulnerable Gulf and Atlantic coasts of the US have never experienced the effects of a direct hit by a major hurricane [Jarrell et. al, 1992]. In the US, most people are well informed by the media about whether they live in an evacuation zone. In spite of this knowledge, many choose not to evacuate. One reason that some ignore hurricane evacuations may be that they do not relate the 2-dimensional maps of the evacuation zones to their 3-dimensional life experience. Three-dimensional computer graphics afford the opportunity to substitute for this lack of personal experience. Digital images taken from the air and from ground-level photography would provide the real-life skin to be put over the wire-mesh of elevations obtained by the airborne laser.

ALTM data have many other applications to storm hazard mitigation. The intense rainfall of tropical cyclones can cause severe flooding even for relatively weak storms. For example, flooding from a minimal category 1 hurricane, Irene, caused over $600 million of damage in Miami-Dade, Broward, and Palm Beach Counties in October, 1999. Many of the affected areas were not even in mapped FEMA flood zones. High resolution DEMs combined with surface hydrologic models and rainfall estimates from weather radar will allow the prediction of flooding in urban areas on a street-by-street basis and will be a useful tool in updating flood insurance maps.

Tropical cyclones and other coastal storms are also a major cause of coastal erosion. Recent studies have demonstrated the utility of airborne laser altimetry in mapping shoreline position and topography [Carter et al., 1998; Sallenger, et al., 1999; Krabill et al., 2000, Zhang et al., 2000]. Shoreline surveys can be scheduled seasonally or after the passage of major storms to assess quantitatively the amount of beach erosion, dune scarping, and overwash deposition. This new technology will fill a major void in terms of providing timely and accurate data for scientific assessments and coastal management programs.

This paper has focused on the application of high-resolution airborne laser altimetry to the hazards caused by hurricanes and other coastal storms. Obviously, this technology will find a wide range of other applications in urban settings. In hazard mitigation, applications include flood plain mapping, identification of ground subsidence related to groundwater withdrawals, and detection of active fault scarps for determining seismic risk. For urban planning, ALTM data may be used for mapping infrastructure, planning construction, and cataloging vegetation. For public information purposes, these data can be combined with advanced computer graphics and database technology to create realistic 3-D renderings of the urban landscape.
CONCLUSIONS

High-resolution topography collected by airborne laser topographic mapping systems is a useful tool in delineating hazard zones due to hurricane storm surge. When combined with the output from lower resolution numerical storm surge models, these data can provide more accurate predictions and can reveal the extent of flooding on the scale of individual streets. In Broward County, south-east Florida, topography from an ALTM survey combined with output from the SLOSH storm surge model reduces the areas of predicted flooding by over 50% compared with that predicted from SLOSH alone. In Broward County, the results of this survey may prevent over 175,000 people from being unnecessarily evacuated in the event of a major hurricane.

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REFERENCES


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