NOAA Technical Memorandum NESDIS NGDC-12

# DIGITAL ELEVATION MODEL OF GALVESTON, TEXAS: PROCEDURES, DATA SOURCES AND ANALYSIS

L.A.Taylor
B.W. Eakins
K.S. Carignan
R.R. Warnken
T. Sazonova
D.C. Schoolcraft

National Geophysical Data Center
Marine Geology and Geophysics Division
Boulder, Colorado
January 2008

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Environmental Satellite, Data, and Information Service

NOAA Technical Memorandum NESDIS NGDC-12

# DIGITAL ELEVATION MODEL OF GALVESTON, TEXAS: PROCEDURES, DATA SOURCES AND ANALYSIS

Lisa .A. Taylor[1]
Barry .W. Eakins[2]
Kelly .S. Carignan[2]
Robin .R. Warnken[1]
Tatiana Sazonova[2]
David C. Schoolcraft[1]

[1]NOAA, National Geophysical Data Center, Boulder, Colorado

[2]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder

National Geophysical Data Center
Marine Geology and Geophysics Division
Boulder, Colorado
January 2008

**UNITED STATES DEPARTMENT OF COMMERCE**

**Carlos M. Gutierrez**
**Secretary**

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

VADM Conrad C. Lautenbacher, Jr.
Under Secretary for Oceans and Atmosphere/Administrator

National Environmental Satellite, Data, and Information Service

Mary E. Kicza
Assistant Administrator

# NOTICE



*Corresponding author contact:*
Lisa A. Taylor
NOAA, National Geophysical Data Center
Marine Geology and Geophysics Division
325 Broadway, E/GC 3
Boulder, Colorado 80305
Phone: 303-497-6767
Fax: 303-497-6513
E-mail: Lisa.A.Taylor@noaa.gov
http://www.ngdc.noaa.gov/mgg/inundation/

---

Also available from the National Technical Information Service (NTIS)
(http://www.ntis.gov)

## Contents



## List of Figures



## List of Tables

# Digital Elevation Model of Galveston, Texas: Procedures, Data Sources and Analysis

## 1. Introduction

In May 2007, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a bathymetric–topographic digital elevation model (DEM) of Galveston, Texas (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). The 1/3 arc-second[1] coastal DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3) and will be used for tsunami inundation modeling, as part of the tsunami forecast system SIFT (Short-term Inundation Forecasting for Tsunamis) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Galveston DEM.

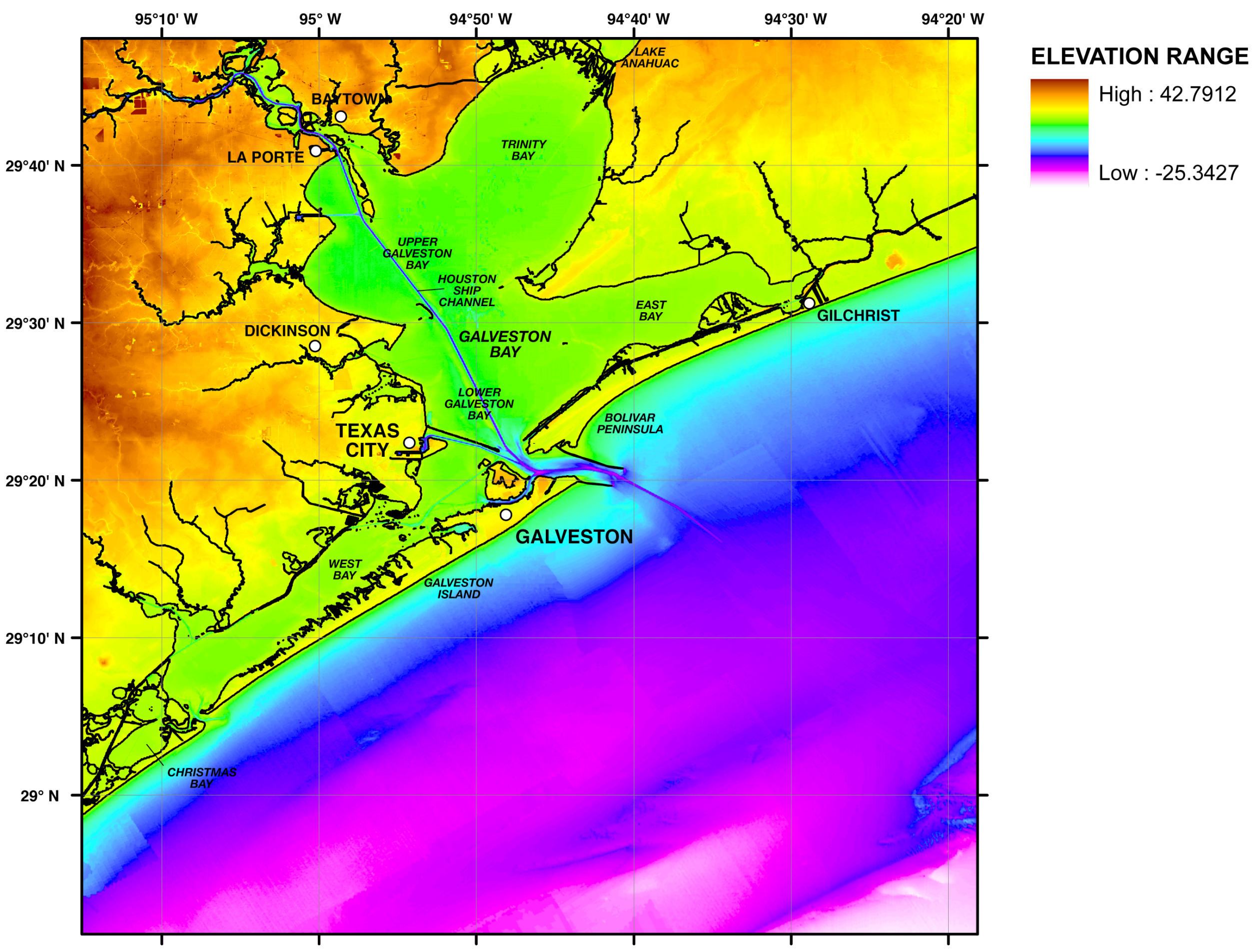


***Figure 1**. Color image of the Galveston, Texas region. Coastline in black.*

1. The Galveston DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Galveston, Texas (29°18′ N, 94°48′ W) 1/3 arc-second of latitude is equivalent to 10.26 meters; 1/3 arc-second of longitude equals 9.01 meters.

## 2. Study Area

The Galveston DEM covers the coastal region centered on the city of Galveston, Texas, and includes the communities of Galveston, Texas City, Dickinson, La Porte, Baytown and Gilchrist (Fig. 1). The Galveston Bay estuarine system and its tributaries (Fig. 2) consist of six sub-bays: Christmas Bay, West Bay, Lower Galveston Bay, Upper Galveston Bay, East Bay, and Trinity Bay (Fig. 1). Galveston Bay covers approximately 600 square miles (1,500 km²), and is 30 miles (50 km) long and 17 miles (27 km) wide. The bay is on average 7-9 feet (3 m) deep, and supports a wide variety of uses, including industrial processing (such as oil and gas extraction and petrochemical operations), shipping, fisheries, recreation, and tourism. These activities have a direct affect on the shorelines of the bay and its tributaries. Development along the shoreline often creates problems through disturbance or destruction of habitats, modification of flood plains, worsening pollution, increasing erosion, and introduction of litter. The Houston Ship Channel, connecting the Port of Houston to the Gulf, passes through Galveston Bay, and is regularly dredged by the U.S. Army Corps of Engineers. The bay provides nursery and spawning grounds for large amounts of marine life, and is important for both commercial and recreational fishing. (http://gbic.tamug.edu/gbeppubs/baybriefings06/GI-348_Shoreline_Mgmt.pdf)

The smoothly curved sides of Trinity and Galveston Bays have been sculpted by the scouring action of successive hurricane storm surges and runoff events. In contrast, the leading edge of the barrier islands is comparatively straight. The Bolivar Peninsula to the east of the inlet shows a tendency to curve where the silt and sand have been trapped by a restraining jetty. Galveston Island exhibits a pencil-straight coastal margin—its Gulf coast reinforced with a 17-foot high seawall constructed after the devastating hurricane of 1900. Most of the beach along the Galveston seawall was lost by wave attack during the storm surge of Hurricane Carla in 1961. (http://www.lpi.usra.edu/publications/slidesets/oceans/oceanviews/slide_31.html)


***Figure 2.*** *Galveston Bay, right* (http://gulfsci.usgs.gov/galveston/maps.html) *and Galveston Island, left, looking southwest* (http://www.beg.utexas.edu/news-events/graphics5/coastal0905_pop.jpg).

## 3. METHODOLOGY

The Galveston DEM was developed to meet PMEL specifications (Table 1), based on input requirements for the MOST inundation model. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: World Geodetic System 1984 (WGS84) and Mean High Water (MHW), for modeling of "worst-case scenario" flooding, respectively. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

**Table 1: PMEL specifications for the Galveston, Texas DEM.**

| | |
|---|---|
| **Grid Area** | Galveston, Texas |
| **Coverage Area** | 94.3º to 95.25º W; 28.85º to 29.8º N |
| **Coordinate System** | Geographic decimal degrees |
| **Horizontal Datum** | World Geodetic System 1984 (WGS84) |
| **Vertical Datum** | Mean High Water (MHW) |
| **Vertical Units** | Meters |
| **Grid Spacing** | 1/3 arc-second |
| **Grid Format** | ESRI Arc ASCII grid |

## 3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal, state and local agencies, including: NOAA's National Ocean Service (NOS); the U.S. Geological Survey (USGS); the Texas Water Development Board; Harris County, Texas; and the Texas General Land Office (TGLO). Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to WGS84 horizontal datum and to convert into ESRI (http://www.esri.com/) ArcGIS shape files. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets; NGDC's GEODAS software (http://www.ngdc.noaa.gov/mgg/geodas/) was used to manually edit large xyz datasets. Vertical datum transformations to MHW were accomplished using FME, based upon data from the NOAA Galveston Pier tide station, and offset grids (digital surfaces with values representing interpolated differences between various tidal datums and MHW) provided by PMEL. VDatum model software (http://vdatum.noaa.gov/) was not available for this area. Applied Imagery's Quick Terrain Modeler software (http://www.appliedimagery.com/) was used to edit and assess the quality of the LiDAR data.

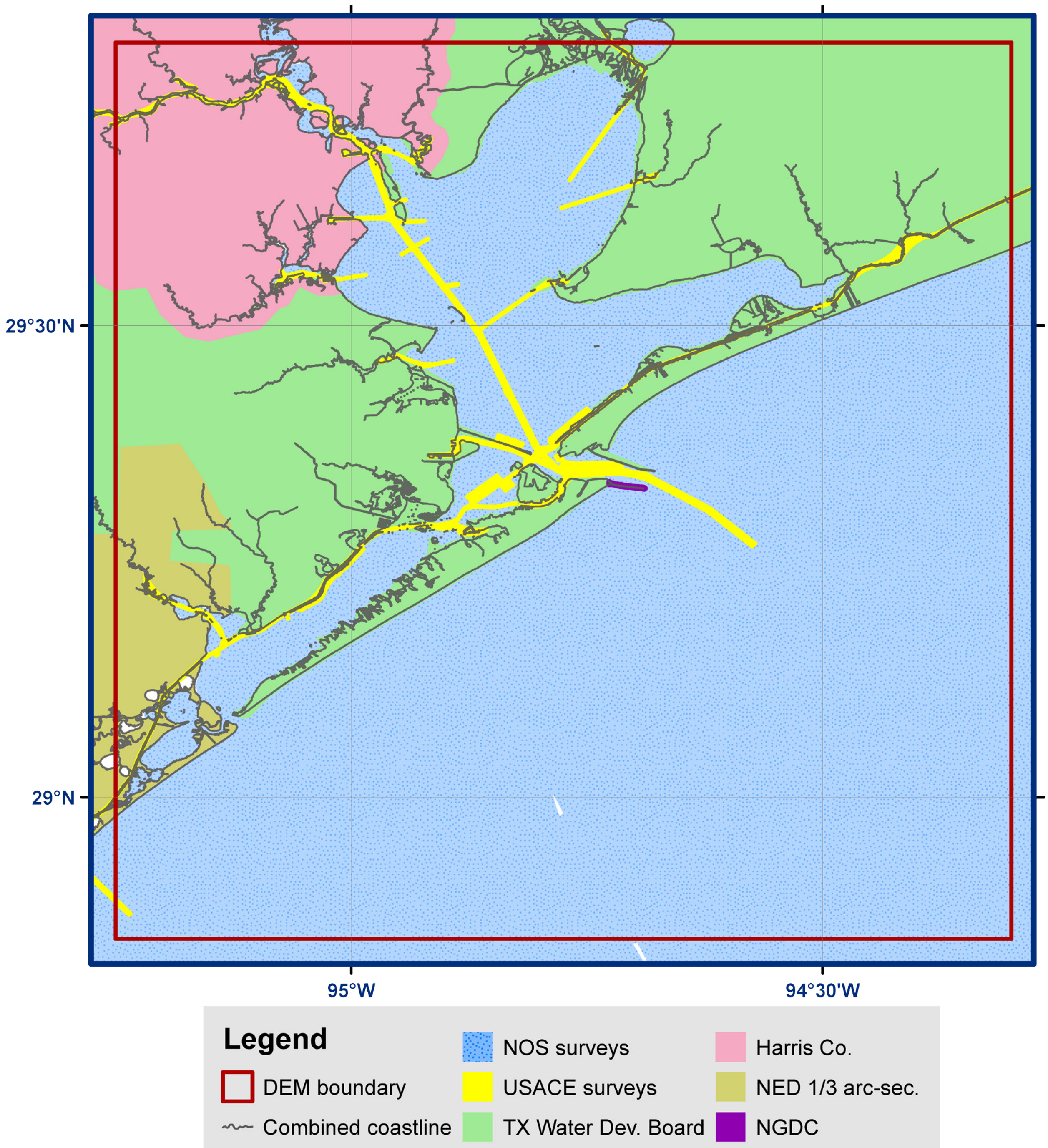


***Figure 3.*** *Source and coverage of datasets used to compile the Galveston DEM.*

### *3.1.1 Shoreline*

A high-resolution digital coastline of the Galveston region was obtained from the Texas General Land Office (TGLO; Table 2). Other digital coastlines form the National Geospatial Intelligence Agency (NGA) and NOAA's available Electronic Nautical Charts were not used as they were of lower resolution than the TGLO coastline.

**Table 2: Shoreline datasets used in compiling the Galveston DEM.**

| *Source* | *Year* | *Data Type* | *Spatial Resolution* | *Original Horizontal Datum/Coordinate System* | *Original Vertical Datum* | *URL* |
|---|---|---|---|---|---|---|
| TGLO | 1995 | digital | 1:24,000 or smaller | NAD27 | unknown | http://www.glo.state.tx.us/gisdata/gisdata.html |

**1) Texas General Land Office shoreline**

The Texas General Land Office shoreline is a compilation of digital coastline segments from U.S. Geological Survey and U.S. Fish and Wildlife Service National Wetlands Inventory digital line graph files and from digitized USGS maps. The shoreline contains hydrographic features of the coastal counties of Texas, including streams, bayous, canals, ditches, lakes, reservoirs, marshes, tidal flats, bays, and estuaries. The shoreline was created in 1995 with a horizontal datum of NAD27. The data were extracted and digitized by personnel from the Texas General Land Office, Jefferson County Appraisal District and other entities.

NGDC modified the TGLO coastline to remove manmade structures, such as piers, and small inland streams, canals, and water bodies (Fig. 4). The coastline was also adjusted to be consistent with recent NOS and USACE bathymetric surveys. The TGLO coastline was used only for pre-smoothing of bathymetric data (see Section 3.3.3), and not as a dataset used for creating the final Galveston DEM.

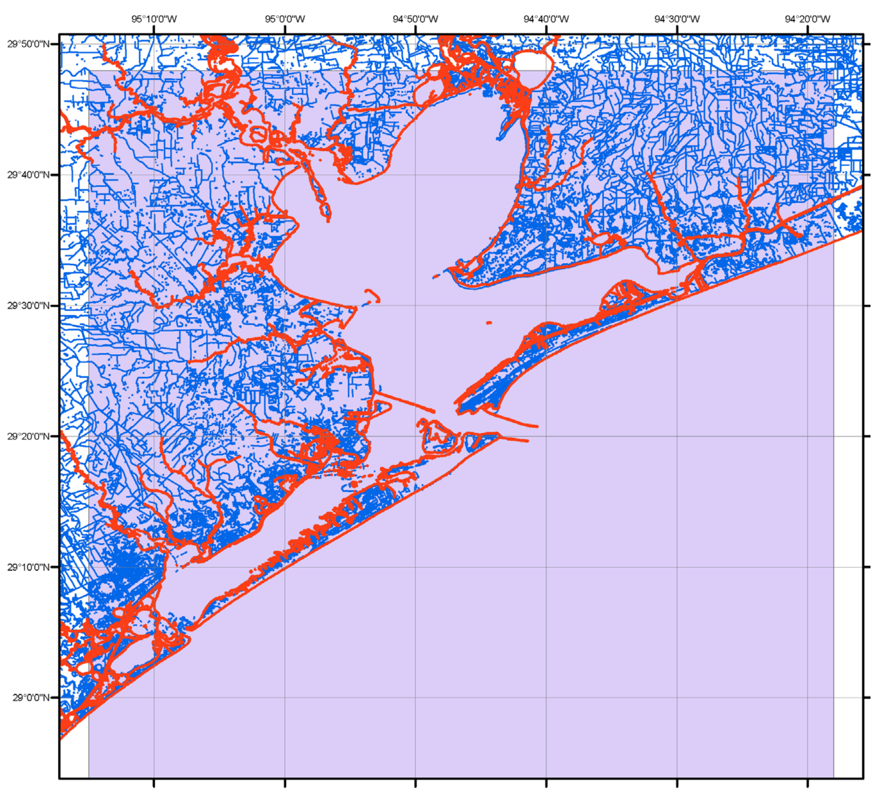


***Figure 4.*** *TGLO coastline (red) used in building the Galveston DEM. Small streams, canals, and water bodies (blue lines) in the original dataset were deleted. DEM area in purple.*

### 3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Galveston DEM (Fig. 5) include 76 NOS hydrographic surveys and 24 USACE surveys of dredged shipping channels (Table 3).

**Table 3: Bathymetric datasets used in compiling the Galveston DEM.**

| *Source* | *Year* | *Data Type* | *Spatial Resolution* | *Original Horizontal Datum/ Coordinate System* | *Original Vertical Datum* | *URL* |
|---|---|---|---|---|---|---|
| USACE, Galveston District | 1996 to 2006 | Hydrographic survey soundings | Profiles spaced 10 m to 300 m apart. Point spacing along profiles <1 m. | NAD27 State Plane Texas South or South Central | Mean Low Tide | http://www.swg.usace.army.mil/ |
| NOS | 1897 to 2002 | Hydrographic survey soundings | Ranges from 10 m to 1 km (varies with scale of survey, depth, traffic, and probability of obstructions) | NAD27 or NAD83 | Mean Low Water or Mean Lower Low Water | http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html |

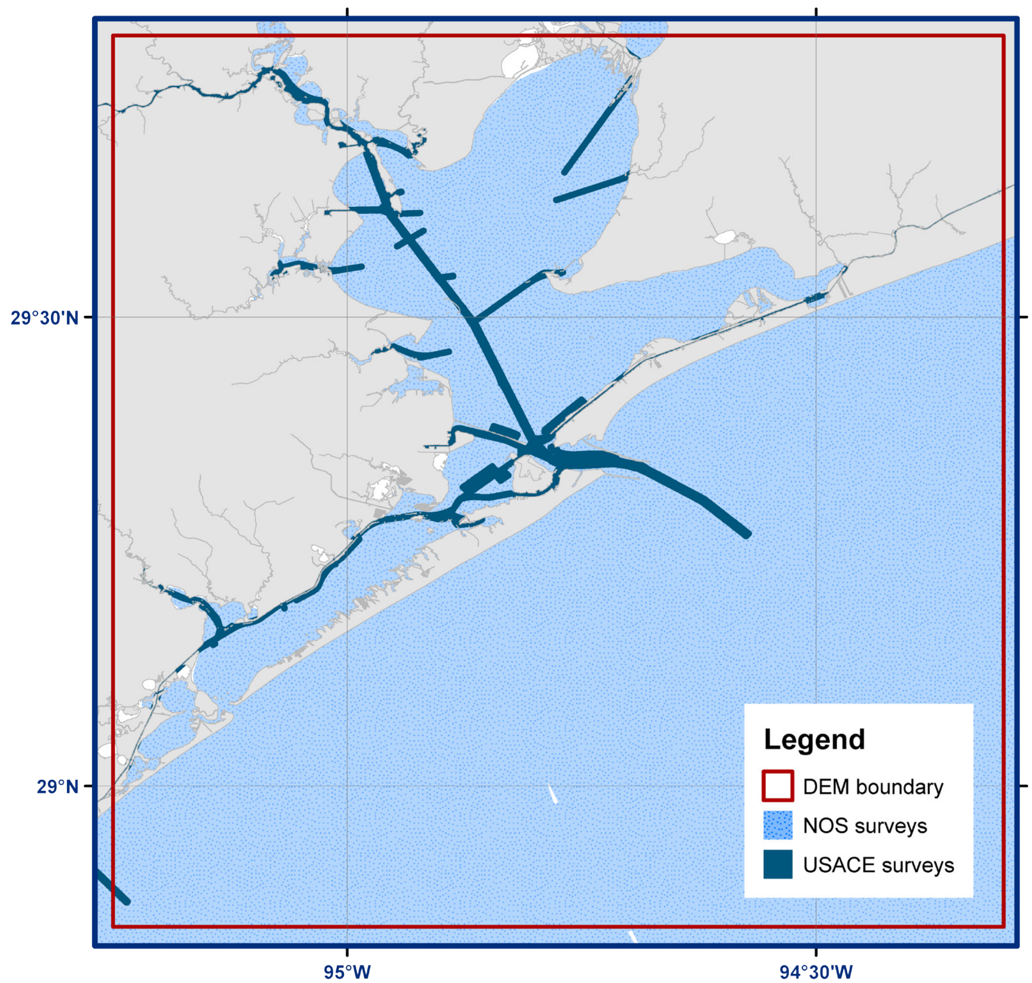


***Figure 5.*** *Spatial coverage of bathymetric datasets used to compile the Galveston DEM.*

**1) NOS hydrographic survey data**

A total of 76 NOS hydrographic surveys conducted between 1931 and 2002 were utilized in developing the Galveston DEM (Table 4; Fig. 6). The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) or Mean Low Water (MLW) and horizontally referenced to either NAD27 or NAD83 datums.

Data point spacing for the NOS surveys varied by collection date. In general, earlier surveys had greater point spacing than more recent surveys. All surveys were extracted from NGDC's online NOS hydrographic database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in their original, digitized datums (Table 4). The data were then converted to WGS84 and MHW using FME software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com). The surveys were subsequently clipped to a polygon 0.05 degrees (~5%) larger than the Galveston DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW (see Section 3.2.1), the data were displayed in ESRI ArcMap and reviewed for digitizing errors against scanned original survey smooth sheets and compared to the topographic LiDAR and NED data, the TGLO coastline, RNCs, and *Google Earth* satellite imagery. The surveys were also clipped to remove soundings that overlap the more recent USACE surveys of dredged shipping channels, and where soundings from older surveys have been superceded by more recent NOS surveys.

**Table 4: Digital NOS hydrographic surveys used in compiling the Galveston DEM.**

| NOS Survey ID | Year of Survey | Survey Scale | Original Vertical Datum | Original Horizontal Datum |
|---|---|---|---|---|
| H05121 | 1931 | 5,000 | mean low water | NAD27 |
| H05122 | 1931 | 5,000 | mean low water | NAD27 |
| H05123 | 1931 | 5,000 | mean low water | NAD27 |
| H05124 | 1931 | 5,000 | mean low water | NAD27 |
| H05125 | 1931 | 5,000 | mean low water | NAD27 |
| H05126 | 1931 | 5,000 | mean low water | NAD27 |
| H05127 | 1931 | 5,000 | mean low water | NAD27 |
| H05128 | 1931 | 5,000 | mean low water | NAD27 |
| H05398 | 1933 | 10,000 | mean low water | NAD27 |
| H05399 | 1933 | 20,000 | mean low water | NAD27 |
| H05424 | 1933/34 | 10,000 | mean low water | NAD27 |
| H05488 | 1933/34 | 10,000 | mean low water | NAD27 |
| H05489 | 1934 | 20,000 | mean low water | NAD27 |
| H05511 | 1933 | 20,000 | mean low water | NAD27 |
| H05521 | 1934 | 20,000 | mean low water | NAD27 |
| H06251 | 1937 | 40,000 | mean low water | NAD27 |
| H06252 | 1937 | 40,000 | mean low water | NAD27 |
| H06253 | 1937 | 40,000 | mean low water | NAD27 |
| H06398 | 1938 | 40,000/20,000 | mean low water | NAD27 |
| H08693 | 1962 | 10,000 | mean low water | NAD27 |
| H08694 | 1962 | 10,000 | mean low water | NAD27 |
| H08695 | 1962 | 12,500 | mean low water | NAD27 |
| H08740 | 1963/65 | 20,000 | mean low water | NAD27 |
| H08741 | 1963/65 | 10,000 | mean low water | NAD27 |
| H08742 | 1962/63 | 10,000 | mean low water | NAD27 |
| H08743 | 1963/65 | 20,000 | mean low water | NAD27 |
| H08745 | 1965 | 20,000 | mean low water | NAD27 |
| H08746 | 1962/65 | 5,000 | mean low water | NAD27 |
| H08747 | 1965 | 10,000 | mean low water | NAD27 |
| H08748 | 1962/65 | 10,000 | mean low water | NAD27 |

| | | | | |
|---|---|---|---|---|
| H08749 | 1965 | 5,000 | mean low water | NAD27 |
| H08750 | 1966 | 10,000 | mean low water | NAD27 |
| H08751 | 1962/63 | 20,000 | mean low water | NAD27 |
| H08752 | 1963/65 | 20,000 | mean low water | NAD27 |
| H08795 | 1964 | 40,000 | mean low water | NAD27 |
| H08837 | 1965 | 20,000 | mean low water | NAD27 |
| H08873 | 1966 | 20,000 | mean low water | NAD27 |
| H08876 | 1966 | 20,000 | mean low water | NAD27 |
| H09765 | 1978 | 20,000 | mean low water | NAD27 |
| H09769 | 1978 | 20,000 | mean low water | NAD27 |
| H09774 | 1978 | 20,000 | mean low water | NAD27 |
| H09775 | 1978 | 40,000 | mean low water | NAD27 |
| H09784 | 1978 | 40,000 | mean low water | NAD27 |
| H09843 | 1979 | 20,000 | mean low water | NAD27 |
| H09851 | 1979 | 40,000 | mean low water | NAD27 |
| H09885 | 1980 | 40,000 | mean low water | NAD27 |
| H10011 | 1982 | 20,000 | mean low water | NAD27 |
| H10014 | 1982 | 20,000 | mean low water | NAD27 |
| H10021 | 1982 | 20,000 | mean low water | NAD27 |
| H10111 | 1983 | 20,000 | mean lower low water | NAD27 |
| H10119 | 1983/84 | 10,000 | mean lower low water | NAD27 |
| F00403 | 1994 | 20,000 | mean lower low water | NAD83 |
| F00418 | 1995 | 10,000 | mean lower low water | NAD83 |
| H10574 | 1994/95 | 20,000 | mean lower low water | NAD83 |
| H10584 | 1994/95 | 10,000 | mean lower low water | NAD83 |
| H10585 | 1994/95 | 10,000 | mean lower low water | NAD83 |
| H10586 | 1994/96 | 10,000 | mean lower low water | NAD83 |
| H10588 | 1995/96 | 10,000 | mean lower low water | NAD83 |
| H10589 | 1995/96 | 10,000 | mean lower low water | NAD83 |
| H10614 | 1995 | 10,000 | mean lower low water | NAD83 |
| H10619 | 1995 | 10,000 | mean lower low water | NAD83 |
| H10638 | 1995 | 10,000 | mean lower low water | NAD83 |
| H10660 | 1995 | 10,000 | mean lower low water | NAD83 |
| H10661 | 1195/96 | 10,000 | mean lower low water | NAD83 |
| H10663 | 1996 | 10,000 | mean lower low water | NAD83 |
| H10664 | 1996 | 10,000 | mean lower low water | NAD83 |
| H10666 | 1996 | 10,000 | mean lower low water | NAD83 |
| H10805 | 1998 | 20,000 | mean lower low water | NAD83 |
| H10835 | 1998/99 | 20,000 | mean lower low water | NAD83 |
| H10850 | 1999 | 20,000 | mean lower low water | NAD83 |
| H10873 | 1999/2000 | 20,000 | mean lower low water | NAD83 |
| H10875 | 1999 | 20,000 | mean lower low water | NAD83 |
| H10876 | 1999/2000 | 20,000 | mean lower low water | NAD83 |
| H10915 | 1999/2000 | 20,000 | mean lower low water | NAD83 |
| H10943 | 1999/2000 | 20,000 | mean lower low water | NAD83 |
| H11061 | 2001/02 | 40,000 | mean lower low water | NAD83 |

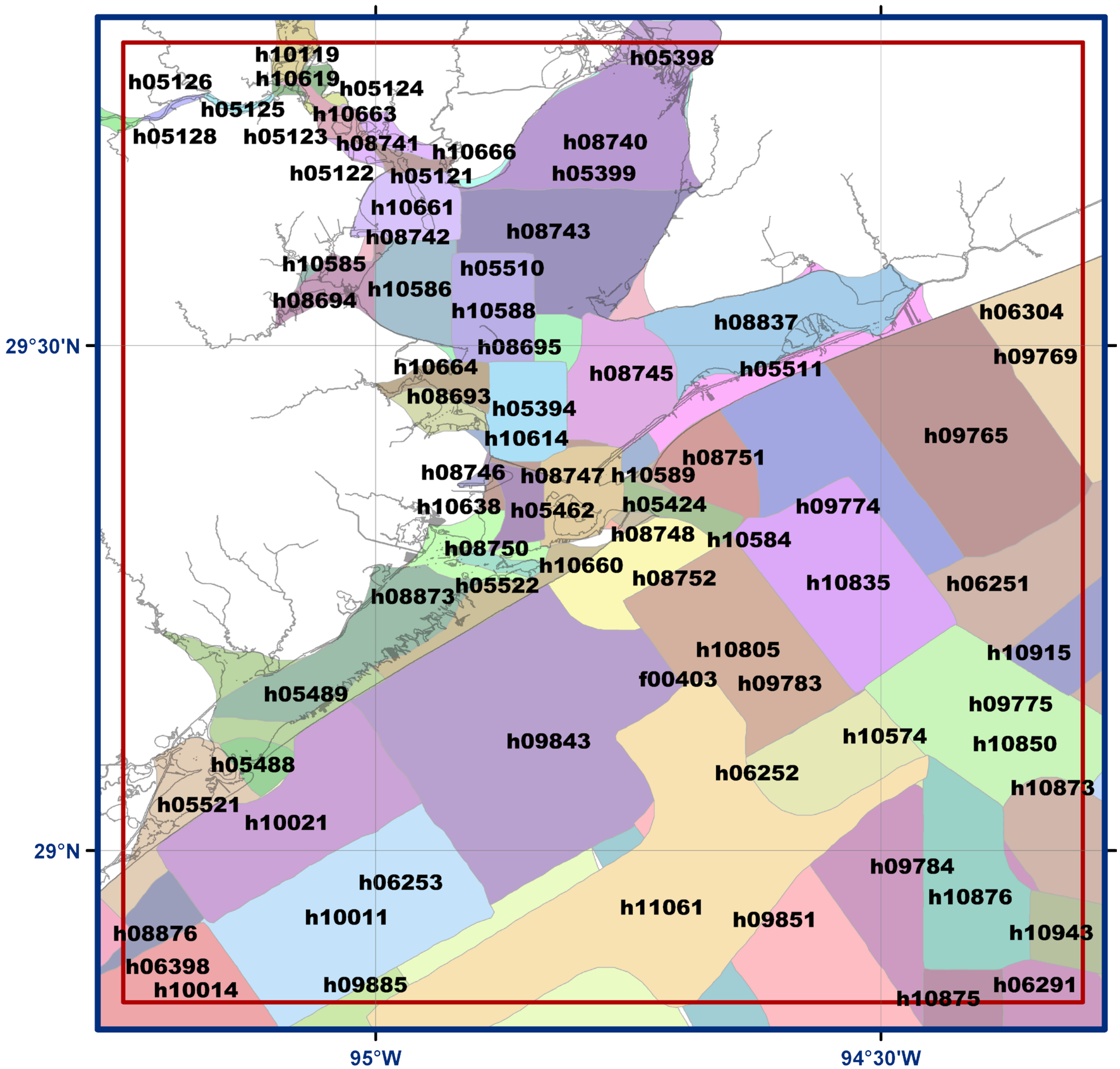


*Figure 6.* *Digital NOS hydrographic survey coverage in the Galveston region. Some older surveys were not utilized as they have been entirely superceded by more recent surveys. DEM boundary in red.*

**2) U.S. Army Corps of Engineers surveys of dredged channels**

The USACE, Galveston District provided NGDC with recent bathymetric surveys spanning the Texas Gulf Coast, including the Gulf Intracoastal Waterway and dredged shipping channels (Table 5, Fig. 7). The surveys were collected from 1996 to 2006, and were referenced to Mean Low Tide (MLT) vertical datum, which was assumed to be equivalent to Mean Low Water (MLW). Some files contained zero latitude and longitude position for individual soundings, which were deleted during conversion to WGS84 using FME.

**Table 5: USACE hydrographic surveys used in compiling the Galveston DEM.**

| *Region* | *Original horizontal datum* | *Original vertical datum* | *Spatial Resolution* |
|---|---|---|---|
| Anahuac Channel | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~65 m long, spaced 60 m to 300 m apart, with <1 m point spacing |
| Atkinson Island | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~80 m long, spaced ~20 m to 125 m apart, with <1 m point spacing |
| Barbour ship Channel | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~125 m to 625 m long, spaced 70 m apart, with <1 m point spacing |
| Bayport Ship Channel | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~160 m to 1300 m long, spaced ~50 m to 140 m apart, with <1 m point spacing |
| Brady Island | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~50 m long, spaced ~20 m to 85 m apart, with <1 m point spacing |
| Cedar Bayou | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~85 m long, spaced 185 m apart, with <1 m point spacing |
| Chocolate Bayou | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~60 m long, spaced ~100 m apart, with <1 m point spacing |
| Clear Creek | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~25 m to 55 m long, spaced ~ 50 m to 125 m apart, with <1 m point spacing |
| Coast Guard Basins | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~25 m to 100 m long, spaced ~10 m apart, with <1 m point spacing |
| Dickinson Bayou | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~75 m long, spaced ~50 m to 125 m apart, with <1 m point spacing |
| Double Bayou | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~100 m long, spaced ~75 m to 125 m apart, with <1 m point spacing |
| Five Mile Cut | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~60 m long, spaced ~60 m to 120 m apart, with <1 m point spacing |
| Freeport Harbor | NAD83 State Plane Texas South Central | Mean Low Tide | Profiles ~170 m to 300 m long, spaced ~25 m to 125 m apart, with <1 m point spacing |
| Galveston Harbor | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~450 m to 950 m long, spaced ~50 m to 125 m apart, with <1 m point spacing |
| GIWW | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~75 m to 1800 m long, spaced ~50 m to 300 m apart, with <1 m point spacing |
| Greens Bayou | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~50 m to 250 m long, spaced ~25 m to 125 m apart, with <1 m point spacing |
| Houston Ship Channel | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~75 m to 250 m long, spaced ~50 m to 125 m apart, with <1 m point spacing |
| Liberty | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~75 m long, spaced ~50 m to 125 m apart, with <1 m point spacing |
| Nasa | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~50 m long, spaced ~75 m apart, with <1 m point spacing |
| Offatts Bayou | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~75 m to 100 m long, spaced ~50 m to 100 m apart, with <1 m point spacing |
| Port Bolivar | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~40 m to 300 m long, spaced ~25 m to 65 m apart, with <1 m point spacing |
| Sims Bayou | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~40 m to 90 m long, spaced ~10 m to 30 m apart, with <1 m point spacing |
| Texas City Harbor | NAD83 State Plane Texas South Central | Mean Low Tide | Profiles ~50 m to 300 m long, spaced ~10 m to 100 m apart, with <1 m point spacing |
| Trinity River | NAD27 State Plane Texas South Central | Mean Low Tide | Profiles ~10 m to 100 m long, spaced ~50 m to 75 m apart, with <1 m point spacing |

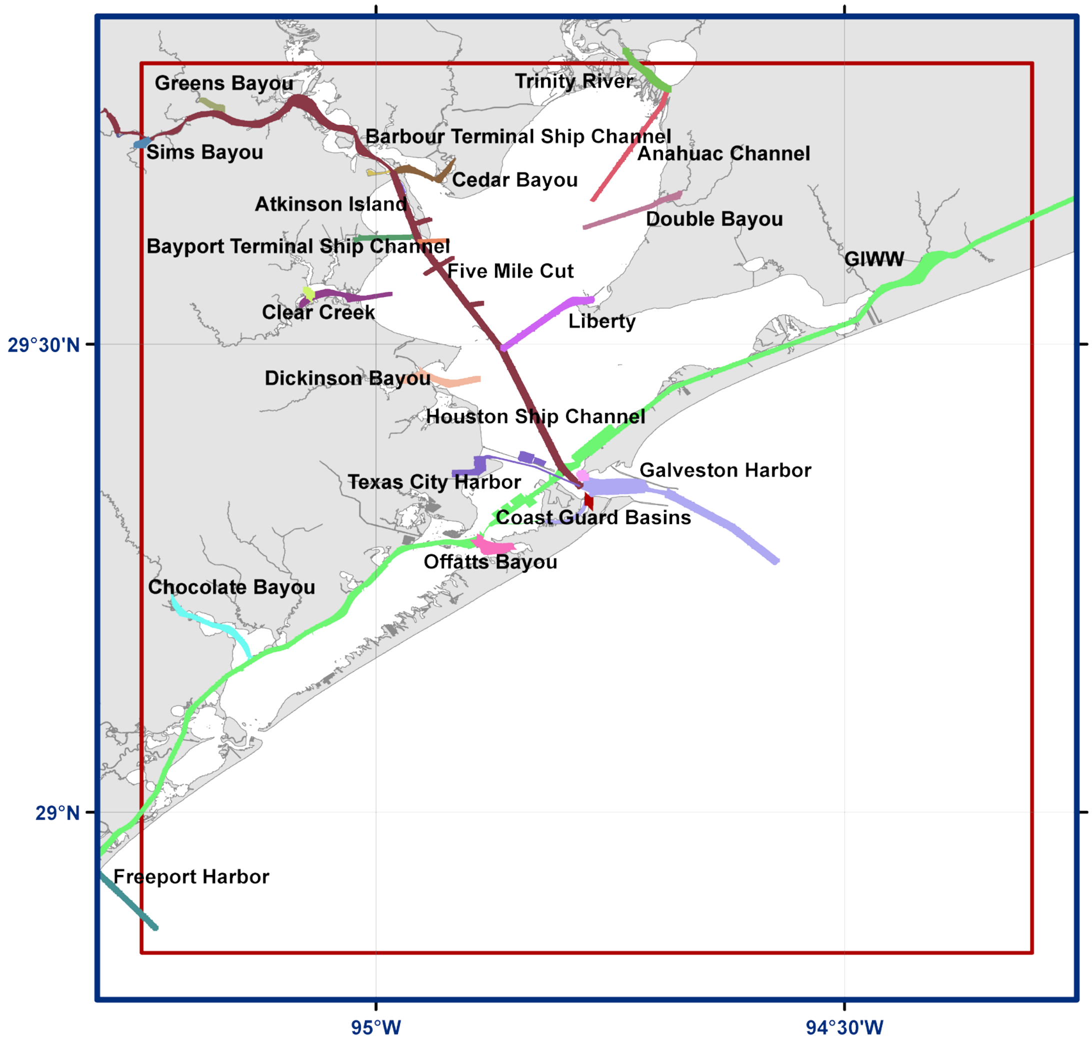


***Figure 7.*** *Digital USACE hydrographic survey coverage within the Galveston region. DEM boundary in red.*

### 3.1.3 Topography

Topographic datasets in the Galveston region were obtained from the Texas Water Development Board, Harris County, Texas, and the U.S. Geological Survey (Table 6; Fig. 8).

**Table 6: Topographic datasets used in compiling the Galveston DEM.**

| *Source* | *Year* | *Data Type* | *Spatial Resolution* | *Original Horizontal Datum/Coordinate System* | *Original Vertical Datum* | *URL* |
|---|---|---|---|---|---|---|
| Texas Water Development Board | 2006 | Bare-earth LiDAR | average < 5 m | NAD83 UTM zone 14 North | NAVD88 (feet) | http://www.twdb.state.tx.us/home/index.asp |
| Harris County Flood Control District | 2002 | Bare-earth DEM | 15 ft | NAD83 Texas State Plane, South Central | NAVD88 (feet) | http://www.tsarp.org |
| USGS | 2001 | NED DEM | 1/3 arc-second | NAD83 geographic | NAVD88 (meters) | http://ned.usgs.gov/ |
| NGDC | 2007 | digitized jetty | ~10 m | WGS84 geographic | MHW | |

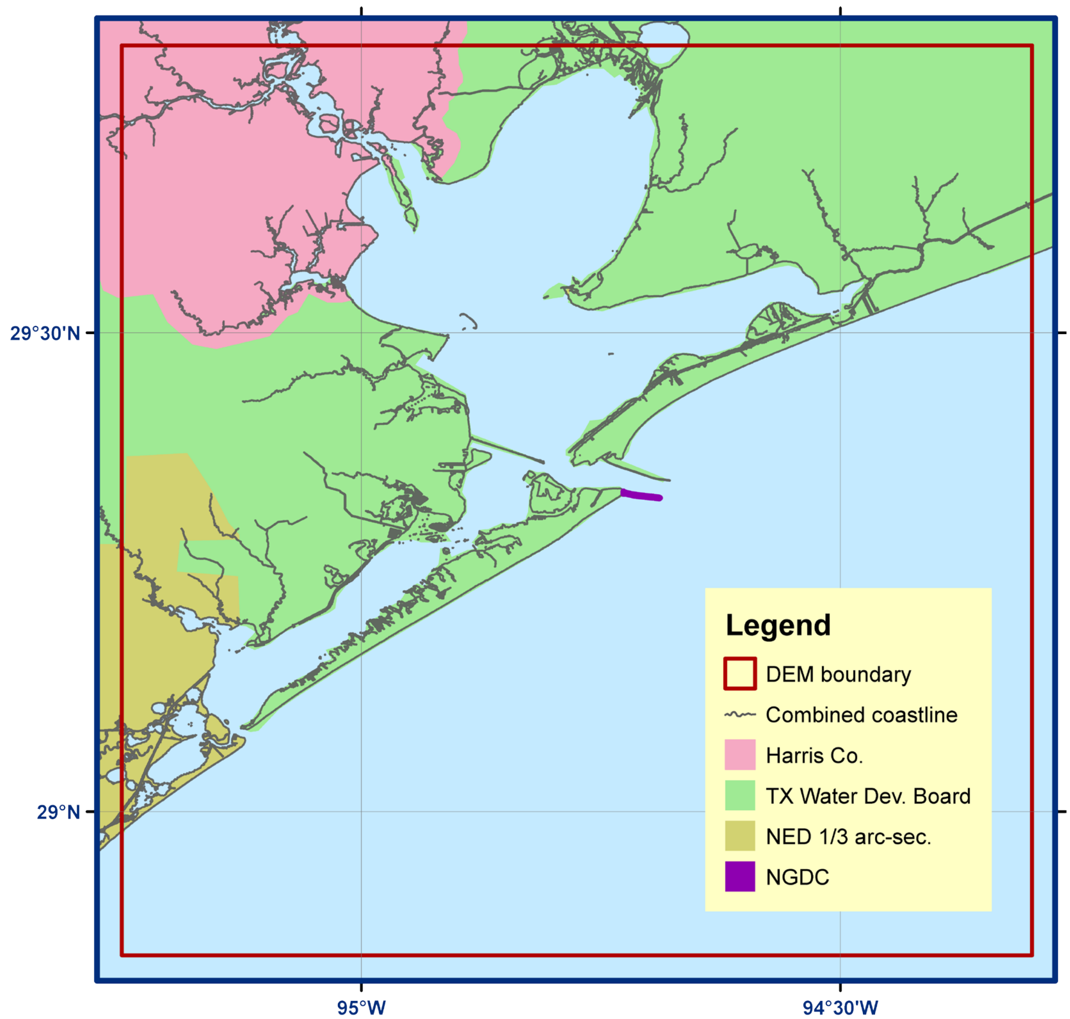


***Figure 8.*** *Source and coverage of topographic datasets used to compile the Galveston DEM.*

**1) Texas Water Development Board topographic LiDAR**

The Texas Water Development Board (TWDB) provided NGDC with topographic LiDAR datasets for several coastal counties of the state of Texas, including Galveston, Brazoria, Chambers, and Jefferson (Fig. 9). The LiDAR data had been processed to bare earth and supplied in tiles, with each data tile covering approximately 3 km$^2$. Data are in NAD83 UTM Zone 14, and NAVD88 (feet).

The LiDAR data files contained position, elevation and intensity values for both land and water areas. Examination of the data indicated that values less than 1 foot in elevation and with intensity values less than 1 represented water-surface returns. FME was used in initial processing to remove all those elevation values less than 1 ft and intensity values less than 1. The LiDAR files were then evaluated and edited using QT Modeler—specifically removing values remaining over water, as well as from piers and occasional points with anomalously high elevation. A final total of 1,121,029,758 TWDB LiDAR points from the four counties were used in building the Galveston DEM.

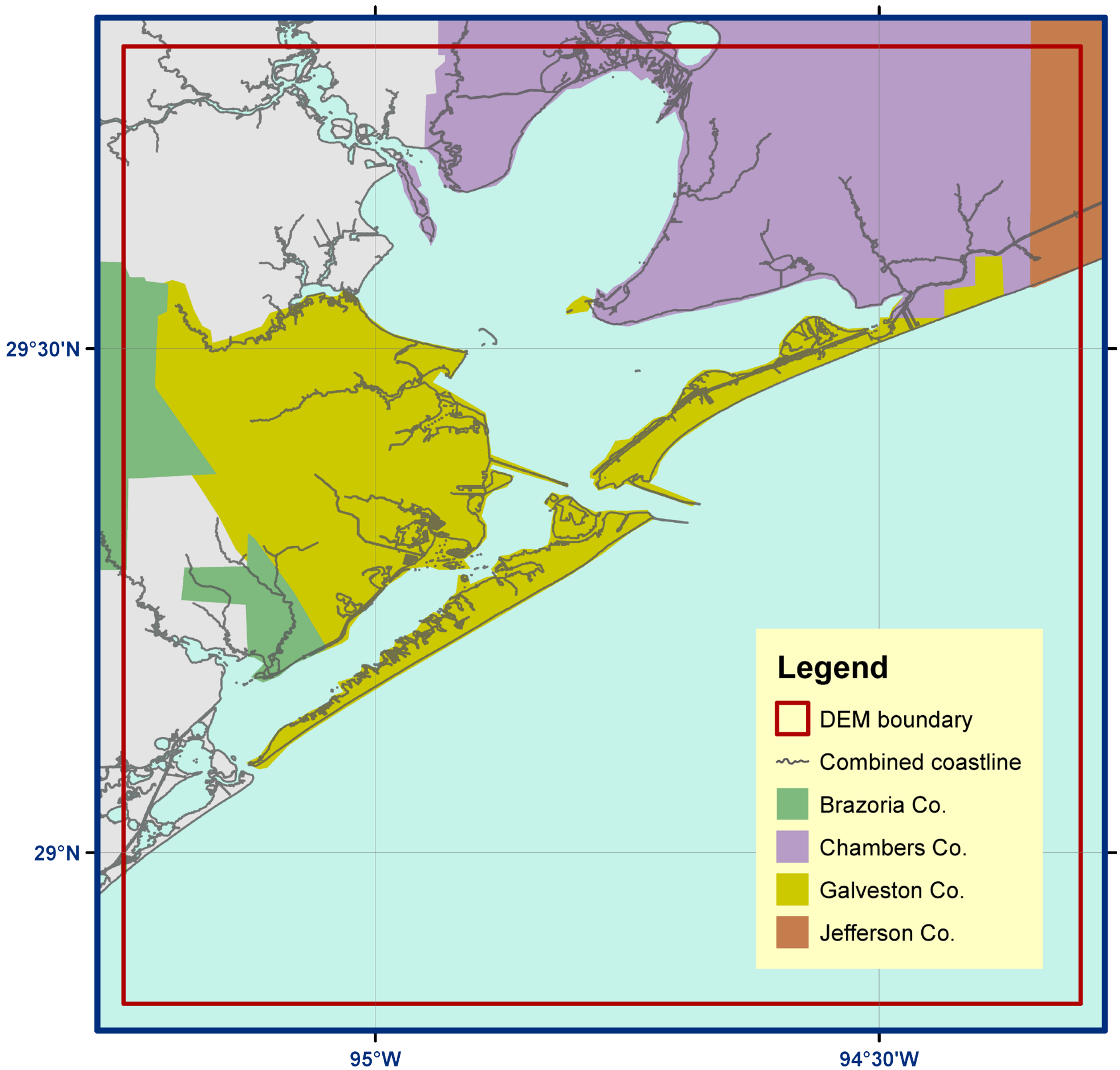


***Figure 9.*** *Texas Water Development Board topographic LiDAR data sets used to compile the Galveston DEM, separated by county.*

**2) Harris County Flood Control District topographic LiDAR DEM**

Bare-earth topographic LiDAR data of Harris County, Texas were collected in October 2001 with an Airborne LiDAR Topographic Mapping System (ALTMS). The data were obtained in DEM format with a grid cell spacing of 15 feet, in NAD83 State Plane Texas South Central and NAVD88. The LiDAR data were acquired for use in the Tropical Storm Allison Recovery Project (http://www.tsarp.org/).

**3) USGS NED topographic DEM**

The U.S. Geological Survey (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provided complete 1/3 arc-second coverage of the Galveston region[2]. Data are in NAD83 geographic coordinates and NGVD88 vertical datum (meters), and are available for download as raster DEMs. The extracted bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov/). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys; it has been revised using data collected in 1999 and 2004.

The NED DEM included "zero" elevation values over the open ocean, which were removed from the dataset by clipping to the TGLO coastline.

**4) NGDC-digitized Galveston south jetty**

The jetty at the entrance to Galveston Bay is only partly represented in the available topographic datasets. The TWDB LiDAR data for Galveston County includes the northern jetty, but not the southern one. The southern jetty *is* represented in the NASA Space Shuttle Radar Topography Mission, though it is both mislocated relative to the most recent NOS hydrographic surveys and has elevations that range from -15 to +9 meters; the northern jetty is consistently about 0.5 meters above MHW. NGDC chose to hand digitize this feature as a collection of points approximately 10 meters apart, with 0.5 meter elevation above MHW (see Fig. 3 for location).

## 3.2 Establishing Common Datums

### *3.2.1 Vertical datum transformations*

Datasets used in the compilation and evaluation of the Galveston DEM were originally referenced to a number of vertical datums including Mean Lower Low Water (MLLW), Mean Low Water (MLW), Mean Low Tide (MLT), and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to MHW to provide the worst-case scenario for inundation modeling. Units were converted from feet to meters as appropriate.

**1) Bathymetric data**

The NOS hydrographic surveys and the USACE surveys were transformed from MLLW, MLW and MLT to MHW, using FME software, by adding an offset grid provided by PMEL.

**2) Topographic data**

The USGS NED 1/3 arc-second DEM, the Harris County DEM, and the Texas Water Development Board LiDAR data were originally referenced to NAVD88. Conversion to MHW, using FME software, was accomplished by adding a constant offset of -0.377 m (Table 7) derived from the Galveston Pier tide-station.

2. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD83, except for AK, which is NAD27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED website]

**Table 7.** *Relationship between Mean High Water and other vertical datums in the Galveston region.*

| *Vertical datum* | *Difference to MHW* |
|---|---|
| NAVD88 | -0.377 meters |
| MLW | Determined by adding PMEL offset grid |
| Mean Low Tide+ | Determined by adding PMEL offset grid |
| MLLW | Determined by adding PMEL offset grid |

* Datum relationships determined by values from tide station #8771450 Galveston Pier.
+ Assumed to be equivalent to MLW.

### *3.2.2 Horizontal datum transformations*

Datasets used to compile the Galveston DEM were originally referenced to NAD83 UTM Zone 14, NAD83 Texas State Plane – South Central, NAD27 geographic, NAD83 geographic, or WGS84 geographic horizontal datums. The relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of WGS84 using FME software.

## 3.3 Digital Elevation Model Development

### *3.3.1 Verifying consistency between datasets*

After horizontal and vertical transformations were applied, the resulting ESRI shape files were checked in ESRI ArcMap for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shape files were then converted to xyz files in preparation for gridding. Problems included:

- Presence of man-made structures and extensive small streams, canal and water bodies in the TGLO coastline dataset, which had to be removed.
- Inconsistencies between the coastline dataset and bathymetric, and topographic datasets. These inconsistencies are partly the result of differing resolution between datasets and of morphologic change in the highly dynamic coastal zone.
- Data values over the open ocean and rivers in the NED, Harris County DEMs and TWDB LiDAR data. Each dataset required automated clipping to the TGLO coastline.
- Digital, measured bathymetric values from NOS surveys date back over 70 years. More recent data, such as USACE surveys in dredged shipping channels and the Gulf Intracoastal Waterway, differed from older, pre-dredging NOS data by as much as 10 meters. The older NOS survey data were excised where more recent bathymetric data exists.

### *3.3.2 Interpolating between USACE hydrographic profiles*

USACE hydrographic surveys were conducted along profiles perpendicular to the axis of each channel. Data points along the profiles are closely spaced (up to 1 m apart), but the distance between the profiles can be as great as several hundreds of meters. Initial gridding produced a poor representation of the channels due to the large distances between profiles; higher elevations along the flanks of the channels tended to interpolate across the channels, producing isolated bathymetric "wells" rather than a more accurate linear channel morphology. To remedy this, NGDC developed custom code to extract the middle point in each profile and perform a linear interpolation between these middle points. The resulting dataset contains lines of closely spaced points (10 m apart) located in the middle (deepest part) of each channel, thus providing a more realistic representation of the channels in the final Galveston DEM.

### *3.3.3 Smoothing of bathymetric data*

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 arc-second Galveston DEM: in deep water, the NOS survey data have point spacings up to 600 m apart. In order to reduce the effect of artifacts in the form of lines of "pimples" in the DEM due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing 'pre-surface' or grid was generated using GMT, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.Texas.edu/).

The NOS hydrographic point data, in xyz format, were combined with the USACE soundings and interpolated soundings into a single file, along with points extracted from the TGLO coastline—to provide a "zero" buffer along the entire coastline. These point data were then median-averaged using the GMT tool 'blockmedian' to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Galveston DEM gridding region. The GMT tool 'surface' then applied a tight spline tension to interpolate cells without data values. The GMT grid created by 'surface' was converted into an ESRI Arc ASCII grid file, and clipped to the TGLO coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy (e.g., Fig. 10), converted to a shape file, and then exported as an xyz file for use in the final gridding process (see Table 8).

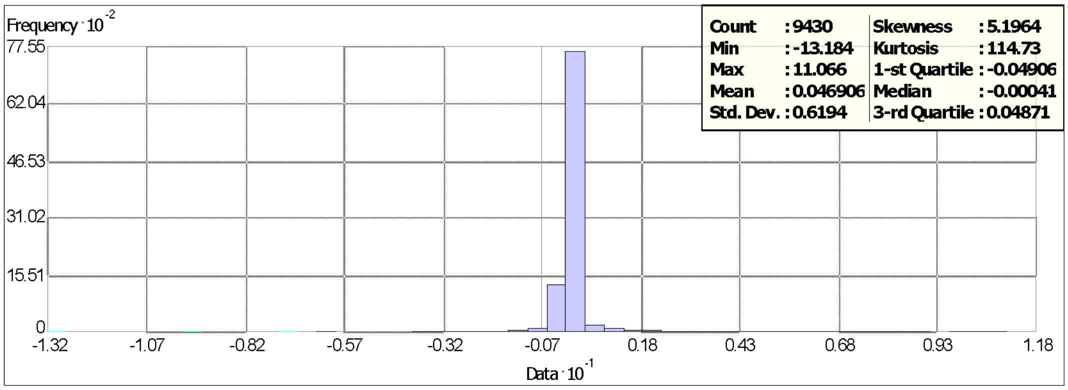


***Figure 10.*** *Histogram of the difference between NOS hydrographic survey H10584 and the 1 arc-second pre-surfaced bathymetric grid. Large discrepancies between survey soundings and the pre-surface grid occur where multiple, closely spaced points, in regions with significant relief, contribute to one cell value.*

### *3.3.4 Gridding the data with MB-System*

MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/) was used to create the 1/3 arc-second Galveston DEM. MB-System is an NSF-funded share-ware software application specifically designed to manipulate submarine multibeam sonar data, though it can utilize a wide variety of data types, including generic xyz data. The MB-System tool 'mbgrid' applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 8. Greatest weight was given to the USACE bathymetric surveys. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid. Gridding was performed in quadrants, each with a 5% data overlap buffer. The resulting Arc ASCII grids were seamlessly merged in ArcCatalog to create the final 1/3 arc-second Galveston DEM.

**Table 8. Data hierarchy used to assign gridding weight in MB-System.**

| *Dataset* | *Relative Gridding Weight* |
|---|---|
| USACE bathymetry | 100,000 |
| TWDB topographic LiDAR | 1000 |
| Harris County topographic LiDAR DEM | 1000 |
| USGS NED topographic DEM | 1 |
| NOS hydrographic surveys: bathymetric soundings | 100 |
| Pre-surfaced bathymetric grid | 1 |

## 3.4 Quality Assessment of the DEM

### *3.4.1. Horizontal accuracy*

The horizontal accuracy of topographic and bathymetric features in the Galveston DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of 10 to 15 meters: Harris County and TWDB topographic LiDAR data have an accuracy of approximately 1 meter, NED topography is accurate to within about 15 meters. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and dredged shipping channels have an accuracy approaching that of subaerial topographic features. Positional accuracy is limited by: the sparseness of deep-water soundings; potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys; and by the rapid morphologic change that occurs in this dynamic region.

### *3.4.2 Vertical accuracy*

Vertical accuracy of elevation values for the Galveston DEM is also highly dependent upon the source datasets contributing to DEM cell values. Topographic areas have an estimated vertical accuracy between 0.1 to 0.3 meters for Harris County and TWDB LiDAR data and up to 7 meters for NED topography. Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth. Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine values between sparse, poorly-located NOS soundings degrades the vertical accuracy of elevations in deep water.

### *3.4.3 Slope maps and 3-D perspectives*

ESRI ArcCatalog was used to generate a slope grid from the Galveston DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 11). The DEM was transformed to UTM Zone 14 coordinates (horizontal units in meters) in ArcCatalog for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM (Fig. 12) was accomplished using ESRI ArcScene. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Galveston DEM in its final version.

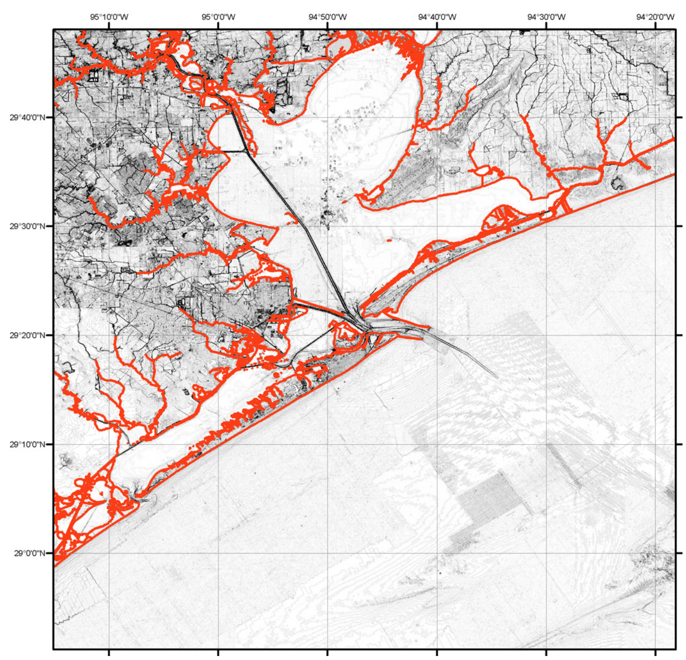


***Figure 11.*** *Slope map of the Galveston DEM. Flat-lying slopes are white; dark shading denotes steep slopes; TGLO coastline in red.*

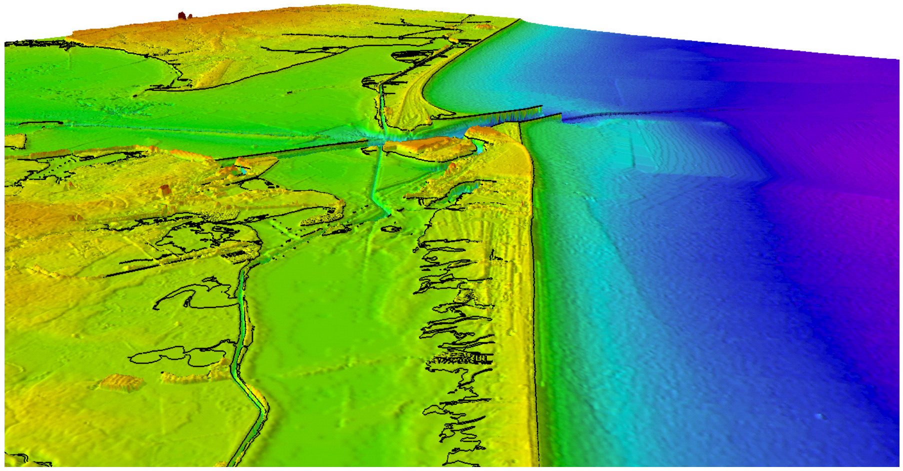

***Figure 12.*** *Perspective view northeast along Galveston Island, as modeled in the Galveston DEM. TGLO coastline in black; vertical exaggeration–times 50.*

### *3.4.4 Comparison with source data files*

To ensure grid accuracy, the Galveston DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the difference between a TWDB topographic LiDAR survey file and the Galveston DEM is shown in Figure 13. Differences cluster around zero, with only a handful of soundings, in regions of steep topography, exceeding 0.5-meter discrepancy from the DEM.

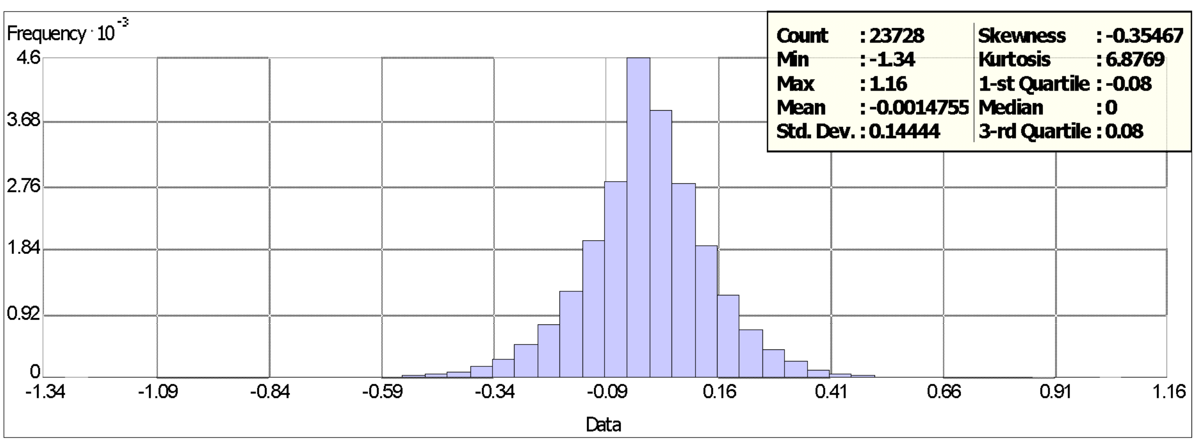


***Figure 13.*** *Histogram of the difference between one USACE survey (along the Gulf Intracoastal Waterway) and the Galveston DEM.*

### *3.4.5 Comparison with NGS geodetic monuments*

The elevations of 1414 NOAA NGS geodetic monuments were extracted from online shape files of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD83 (sub-mm accuracy) and elevations in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 7) for comparison with the Galveston DEM (see Fig. 15 for monument locations). Differences between the Galveston DEM and the NGS geodetic monument elevations range from -19 to 21 meters, with a negative value indicating that the monument elevation is less than the DEM (Fig. 14). Examination of the monuments with the largest offsets from the DEM revealed that they are located on bridges, piers, buoys, or within tunnels.

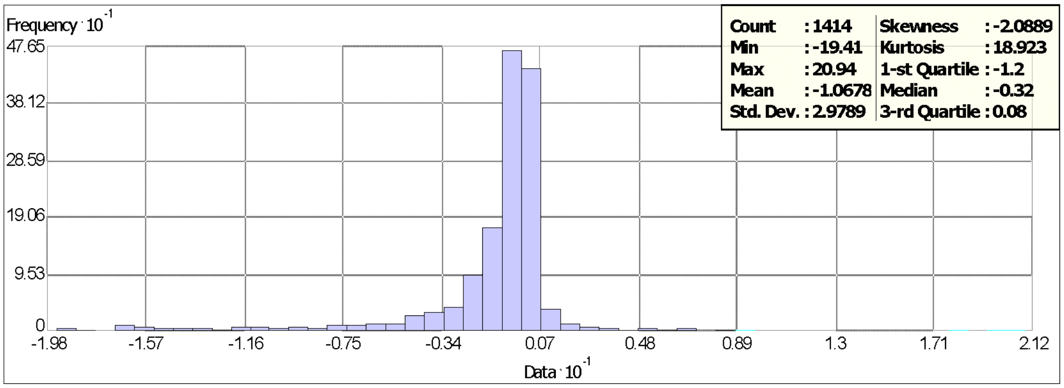


***Figure 14.*** *Histogram of the differences between NGS geodetic monument elevations and the Galveston DEM. The largest differences derive from monuments located on bridges, piers, buoys or within tunnels.*


***Figure 15.*** *Location of NGS monuments and NOAA tide stations in the Galveston region. NGS monument elevations were used to evaluate the DEM.*

## 4. Summary and Conclusions

A topographic–bathymetric digital elevation model of the Galveston, Texas region, with cell spacing of 1/3 arc-second, was developed for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state and local agencies, and academic institutions were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT, MB-System and Quick Terrain Modeler software.

Recommendations to improve the Galveston DEM, based on NGDC's research and analysis, are listed below:

- Obtain LiDAR data processed to bare earth for the southwest corner of the DEM.

## 5. Acknowledgments

The NOAA Pacific Marine Environmental Laboratory funded the development of the Galveston DEM. The authors thank Chris Chamberlin and Vasily Titov (PMEL), Linda Carberry (USACE, Galveston District), Drew Decker (Texas Water Development Board), Tiffany Hepner (University of Texas, Bureau of Economic Geology) and Jacob Spen (Harris County Flood Control District).

## 6. References

Coast Pilot 5, 34th Edition, 2006. Atlantic Coast: Gulf of Mexico, Puerto Rico, and Virgin Islands. U.S. Department of Commerce, NOAA, National Ocean Service.

Nautical Chart #11360, 7th Edition, 2006. Galveston River Approach. Scale 1:456,394. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

## 7. Data Processing Software

ArcGIS v. 9.1, developed and licensed by ESRI, Redlands, California, http://www.esri.com/

Electronic Navigational Chart Data Handler for ArcView, developed by NOAA Coastal Services Center, http://www.csc.noaa.gov/products/enc/

FME 2006 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/

GEODAS v. 5 – Geophysical Data System, shareware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/

GMT v. 4.1.4 – Generic Mapping Tools, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.Texas.edu/

MB-System v. 5.1.0, shareware developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

Quick Terrain Modeler v. 6.0.1, LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/