NOAA Technical Memorandum NESDIS NGDC-54

DIGITAL ELEVATION MODELS OF PALM BEACH, FLORIDA: PROCEDURES, DATA SOURCES AND ANALYSIS

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Marine Geology and Geophysics Division
Boulder, Colorado
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Contents

List of Figures

List of Tables

Digital Elevation Models of Palm Beach, Florida: Procedures, Data Sources and Analysis

1. Introduction

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed two bathymetric–topographic digital elevation models (DEMs) of Palm Beach, Florida (Fig. 1). First, a 1/3 arc-second[1] DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was developed and evaluated using diverse digital datasets available for the region (grid boundary and sources shown in Fig. 5). Then, a 1/3 arc-second conversion grid was created to represent the relationship between NAVD 88 and Mean High Water (MHW) vertical datums in the Palm Beach region. Finally, a 1/3 arc-second MHW DEM was developed by combining the NAVD 88 DEM and the vertical datum conversion grid. The MHW DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) 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 Palm Beach DEMs.

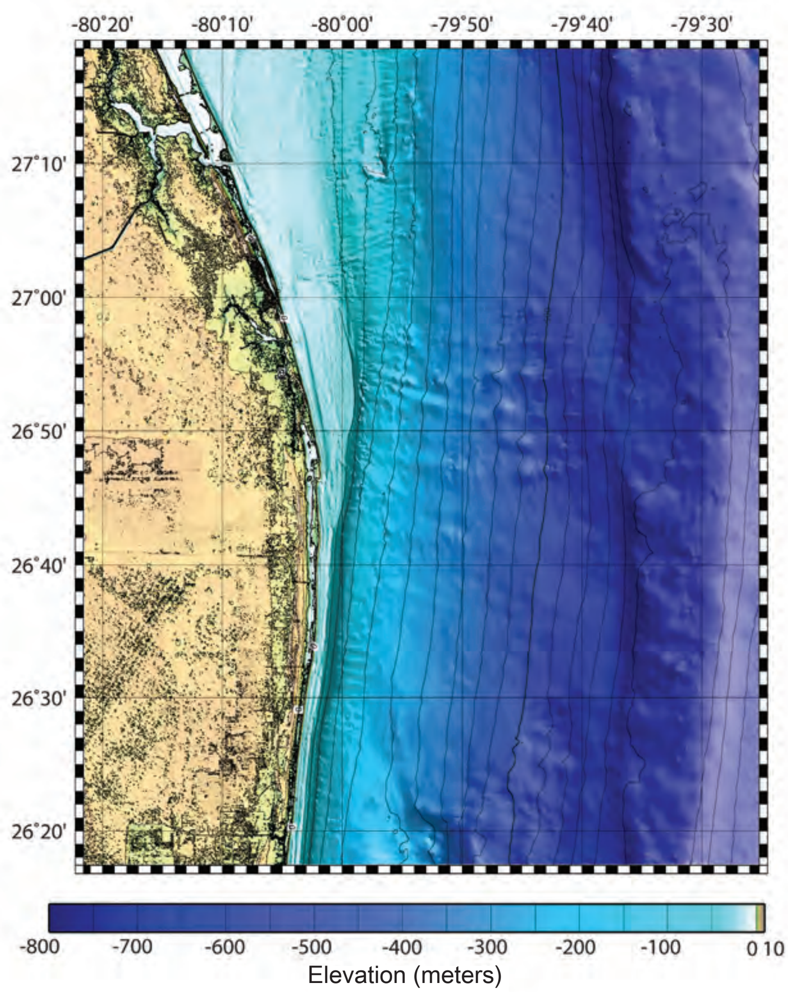

Figure 1. Shaded-relief image of the Palm Beach NAVD 88 1/3 arc-second DEM.

1. The Palm Beach DEMs are built upon a grid of cells that are square in geographic coordinates (latitiude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Palm Beach, Florida, (26°42' 54"N, 80°02'22"W) 1/3 arc-second of latitude is equivalent to 10.26 meters; 1/3 arc-second of longitude equals 9.21 meters.

2. Study Area

The Palm Beach DEM provides coverage of the area surrounding Palm Beach, Florida– from St.Lucie Inlet to Boca Raton (Fig. 2). The town of Palm Beach is located approximately 70 miles north of Miami and 150 miles south of Cape Canaveral. The town was founded in the early twentieth century as a resort destination, and its population remains mostly seasonal. The town has 10,000 year-round residents, with a seasonal population of about 30,000.

The town of Palm Beach is located on a barrier island, and is separated from the remainder of Palm Beach County by the Intracoastal Waterway (Fig. 3). Dredging work along the intracoastal waterway is performed frequently. In addition, many other man-made projects occur along the coast, including the construction of walled canals and yacht slips, golf course terrain creation projects, and beach restoration and sediment pumping operations.

Elevation modeling in the Palm Beach region is complicated by sand transport issues. The sand dunes and sand bars in the area (Fig. 4) are fragile and constantly migrate. Small disruptions to the environment, both natural and man-made, lead to rapid geomorphological changes along canals, rivers, islands, inlets, and coastal dunes in the area. The Palm Beach DEMs are representative of the basic terrain, but constant alterations to the landscape make it difficult to acquire and create coastal elevation data sets that will remain accurate throughout time.

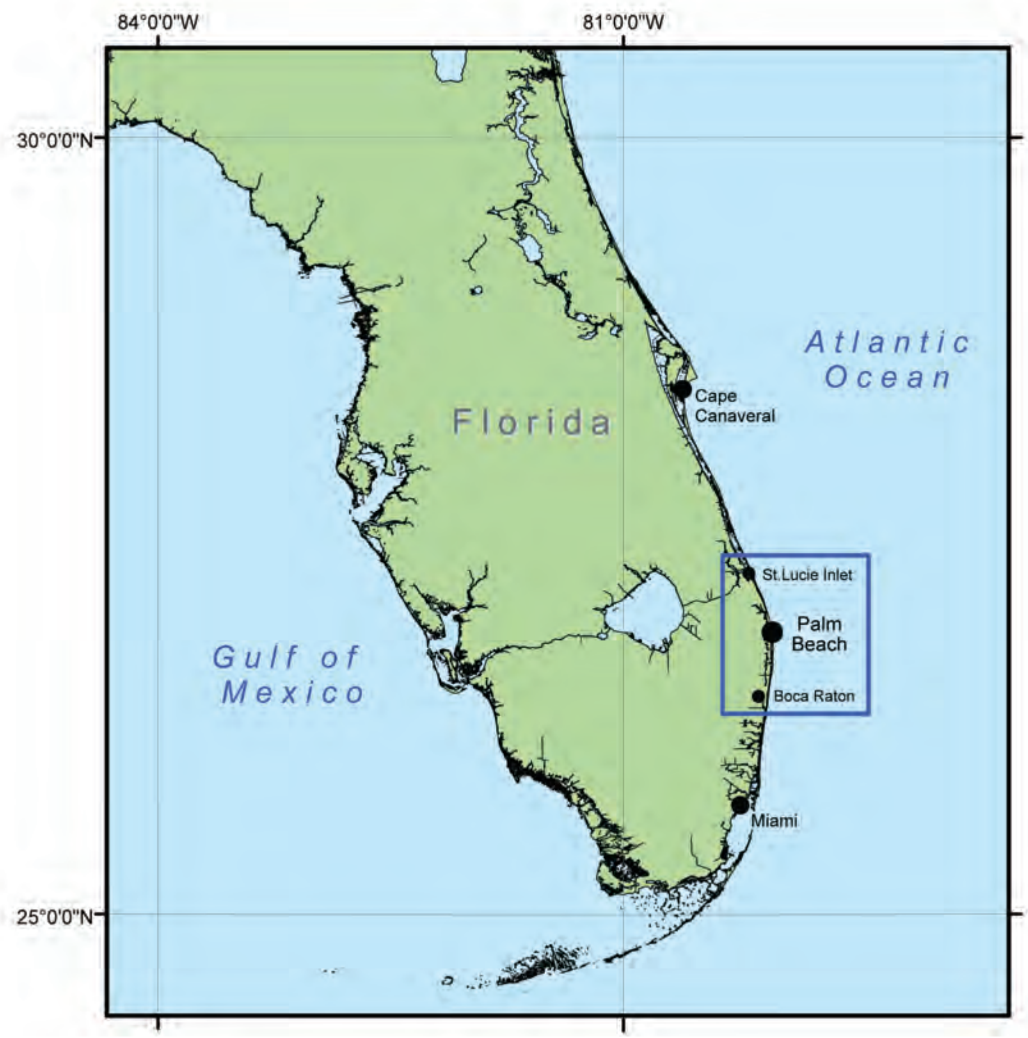

Figure 2. Overview of the Palm Beach DEM region. Blue box represents Palm Beach DEM extents.

Figure 3. Lake Worth Inlet and the intracoastal waterway. Palm Beach Island is located in the foreground; the remainder of Palm Beach County can be seen in the background. The intracoastal waterway is dredged between the island and mainland. (NOAA Photo Library)

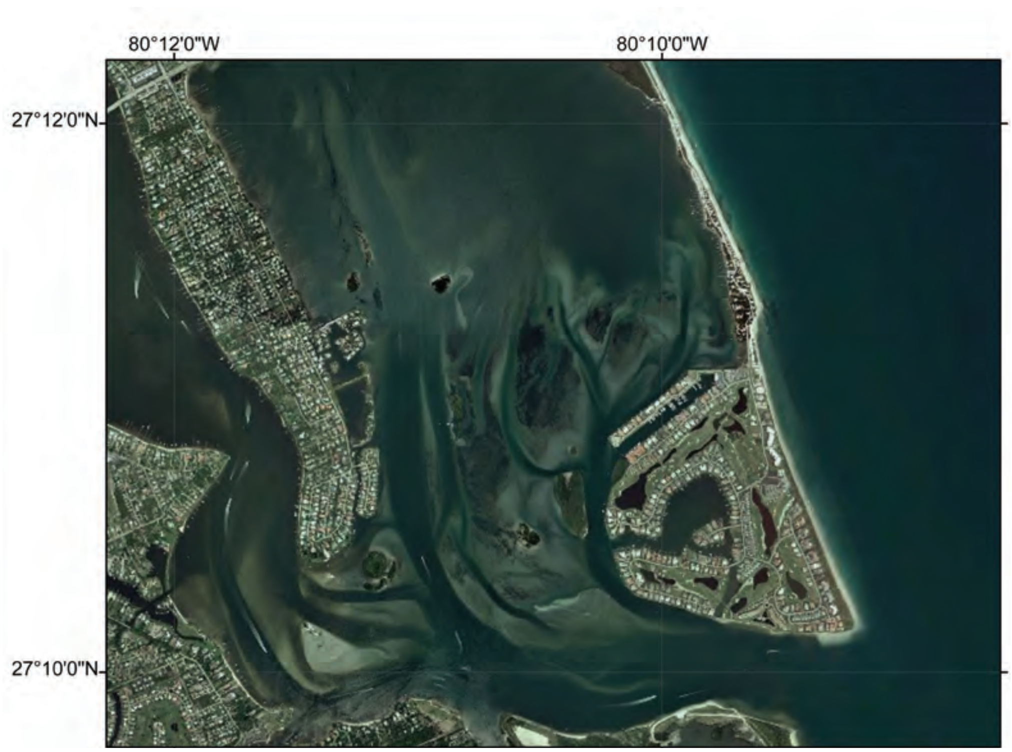

Figure 4. Aerial photograph showing sand bars of St.Lucie Inlet.
The channels between the sand bars migrate and change shape over time. (ESRI's online World 2D Imagery)

3. Methodology

The Palm Beach NAVD 88 and MHW DEMs were constructed to meet PMEL specifications (Table 1), based on input requirements for the development of Reference Inundation Models (RIMs) and Standby Inundation Models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT (Short-term Inundation-Forecasting for Tsunamis) to provide real-time tsunami forecasts in an operational environment. The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum of 1983[2] (NAD 83) and NAVD 88. An NAVD 88 DEM was developed using the data, and was shifted to MHW for modeling of maximum flooding using a conversion grid. Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensured that gridding occurred across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1: Specifications for the Palm Beach DEMs.

Grid Area	Palm Beach, Florida
Coverage Area	80.41º to 79.42º W; 26.29º to 27.31º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datums	a) North American Vertical Datum of 1988 (NAVD 88) b) Mean High Water (MHW)
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII raster grid

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEMs. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the wave's passage across ocean basins. These DEMs are identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEMs, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets were obtained from international, federal, state and local agencies and institutions (Fig. 5) including: NGDC; NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS) and Coastal Services Center (CSC); the U.S. Army Corps of Engineers (USACE); Japan's Ministry of Economy, Trade, and Industry (METI); the National Aeronautics and Space Administration (NASA); the Joint Airborne Lidar Bathymetry Center of Expertise (JALBTCX); the South Florida Water Management District (SFWMD); the County of Palm Beach; and the Florida Department of Emergency Management (FDEM). Datasets were shifted to NAD 83 geographic horizontal datum using Safe Software's *Feature Manipulation Engine* (*FME*), ESRI's *ArcGIS*, and NOAA's *Vertical Datum* (*VDatum)* transformation tool. Data were visually displayed with *ArcGIS* and Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*), to assess quality and manually edit datasets. Most vertical datum transformations were accomplished using *VDatum*, although *VDatum* did not provide transformations for the National Geodetic Vertical Datum of 1929 (NGVD 29, see Sec. 3.2.1).

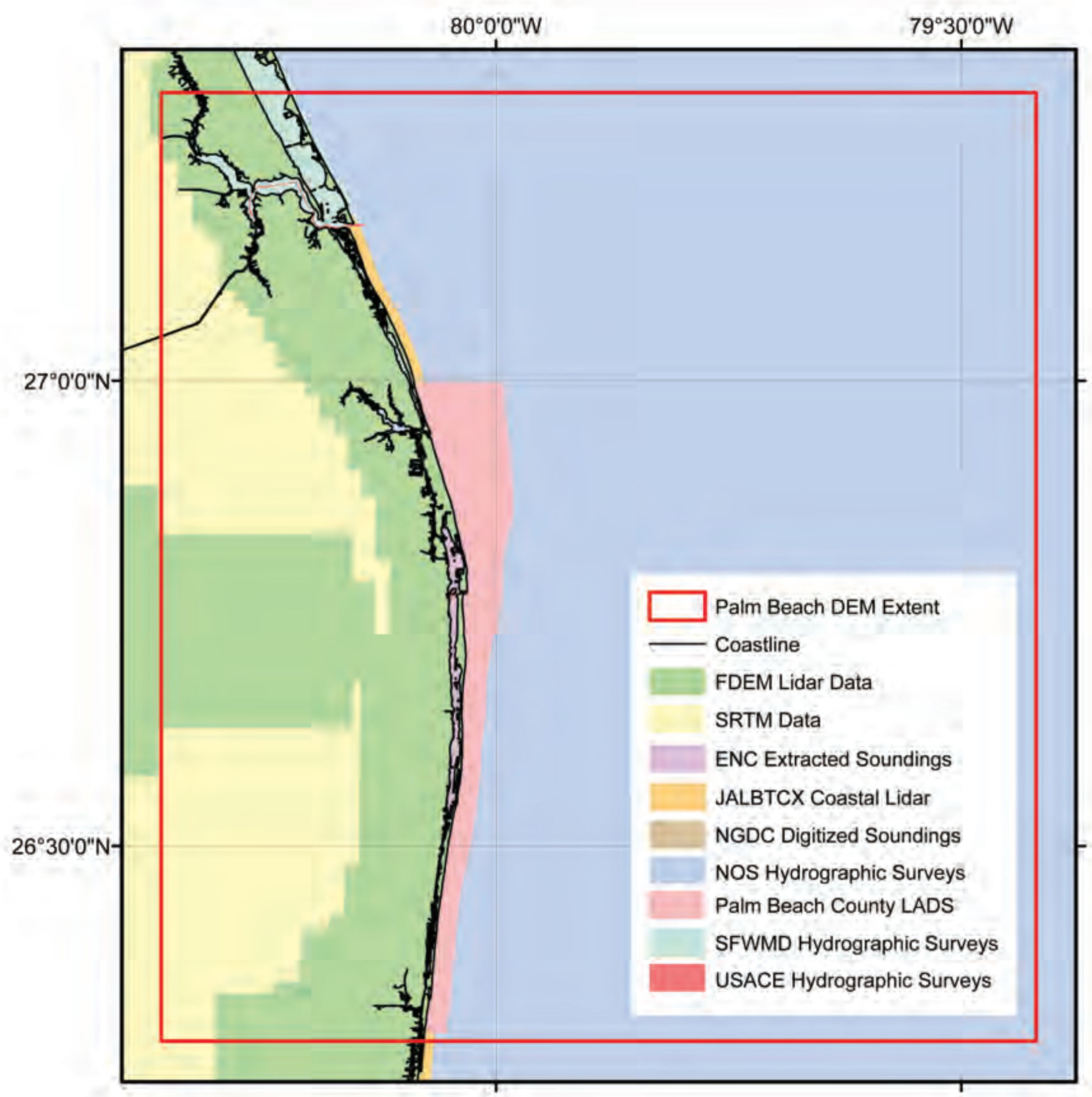

Figure 5. Source and coverage of datasets used in compiling the Palm Beach DEMs.

3.1.1 Shoreline

Shoreline data of the Palm Beach region were extracted from existing lidar-derived contour data (Table 2). The contour data were developed by CH2M Hill for the Florida Division of Emergency Management (FDEM), and were obtained from the Florida Geospatial Data Library (FGDL) web site (http://www.fgdl.org).

Table 2. Shoreline datasets used in developing the Palm Beach NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution or Scale*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
FDEM	2009	vector digital data	~5 meters	NAD 83 HARN	NAVD 88	ftp://ftp1.fgdl.org/pub/

1) Florida Division of Emergency Management

Lidar data of the Florida coastal zones were obtained for FDEM from 2006 -2009. The public lidar data are available from many organizations in many forms, including DEMs, LAS files, xyz files, and contour shapefiles. Lidar-derived contour shapefiles were downloaded from the FGDL by county, and the zero contour lines were extracted from the shapefiles using ArcGIS (Fig. 6).

The zero lines used in the Palm Beach DEM were assumed to represent the NAVD 88 coastlines for Broward County, Palm Beach County, Martin County, and St. Lucie County. The coastlines for each of the four counties were merged together, and slightly adjusted where necessary based on comparisons with aerial imagery, bathymetric data, wetland and mangrove data, lower resolution coastlines, and NOAA Raster Nautical Charts (RNCs). An xyz file of the adjusted coastline with points located every 10 meters was generated using NGDC's *GEODAS* software, for use in creating the 'pre-surface' bathymetric grid (See Sec. 3.3.2).

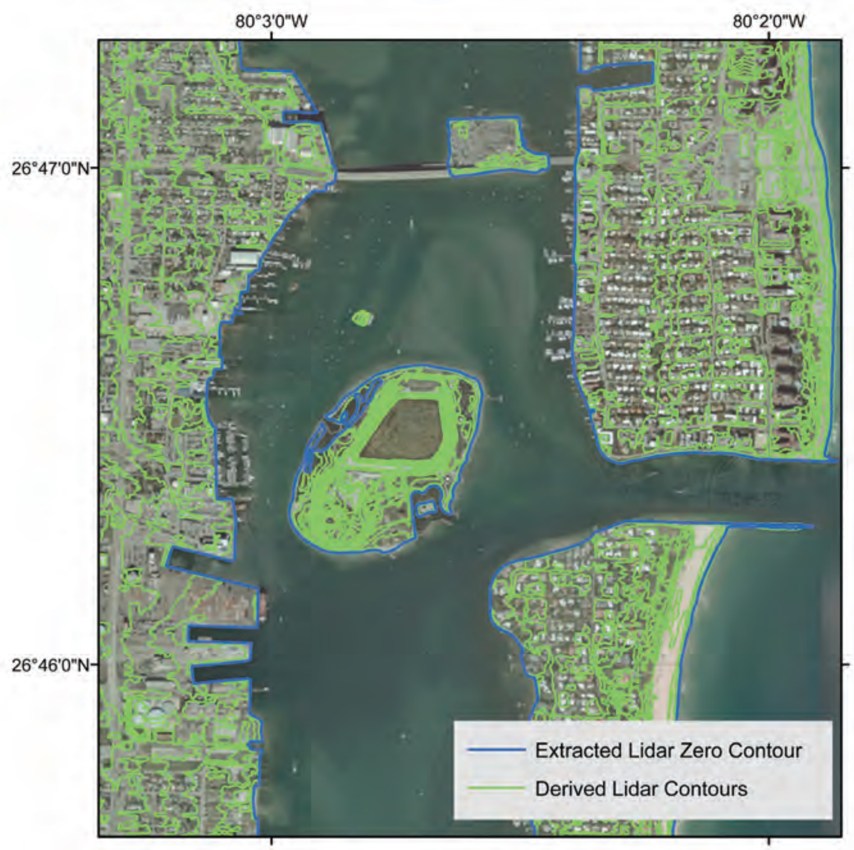

Figure 6. Portion of lidar-derived contours, shown with extracted zero contour line. The zero contour was used as the Palm Beach DEM coastline. ESRI's online World 2D Imagery in background.

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the Palm Beach DEMs included extracted points from two NOS Electronic Navigational Charts (ENCs); a bathymetric lidar survey from JALBTCX; 23 NOS hydrographic surveys; Laser Airborne Depth Soundings (LADS) from Palm Beach County; one hydrographic survey from the South Florida Water Management District (SFWMD);several hydrographic surveys from the USACE Jacksonville District; and NGDC digitized points of the intracoastal waterway, based on NOS RNCs and information from the United States Coast Pilot®. (Table 3; Fig. 7).

Several other bathymetric datasets were acquired and assessed, but they were superseded by higher quality or more recent datasets, and so were not used as input in the final DEM. These datasets included multibeam swath sonar surveys downloaded from the NGDC multibeam database, trackline surveys available from NGDC, and seven ebb tidal shoal hydrographic surveys available from Palm Beach County.

Table 3. Bathymetric datasets used in compiling the Palm Beach NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
ENC	2008 to 2009	Extracted soundings	Digitized from 1:40,000 scale RNC, point spacing 50 to 1000 meters	NAD 83 Geographic	MLLW	charts.noaa.gov/ENCs/ENCs.shtml
JALBTCX	2006	Lidar DEM	1 to 2 meters	NAD 83	NAVD 88	http://www.csc.noaa.gov/ldart
NGDC	2010	Digitized point soundings	Digitized from RNCs of varying resolutions based on depth information from the United States Coast Pilot	WGS 84	NAVD 88	n/a
NOS	1883 to 1969	Hydrographic survey xyz data	Ranges from less than 10 m to 600 m (varies with scale of survey, recentness of survey, and water depth or distance from shore)	NAD 83 geographic	MLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
Palm Beach County	2003	LADS survey xyz data	2 to 4 meters	State Plane Coordinate System NAD 83, East Florida Zone	NGVD 29	http://www.pbcgov.com/erm/coastal/shoreline/beach/data.htm
SFWMD	1998	Hydrographic survey point shapefile	1 meter to 300 meters	NAD 83 HARN	NGVD 29	http://my.sfwmd.gov/gisapps/sfwmdxwebdc/dataview.asp
USACE	2005 to 2010	Hydrographic survey xyz data	1 to 10 meters	State Plane Coordinate System NAD 27 and NAD 83, East Florida Zone	MLLW or MLW	http://www.saj.usace.army.mil/Divisions/Operations/Branches/HydroSurvey/hydro.php

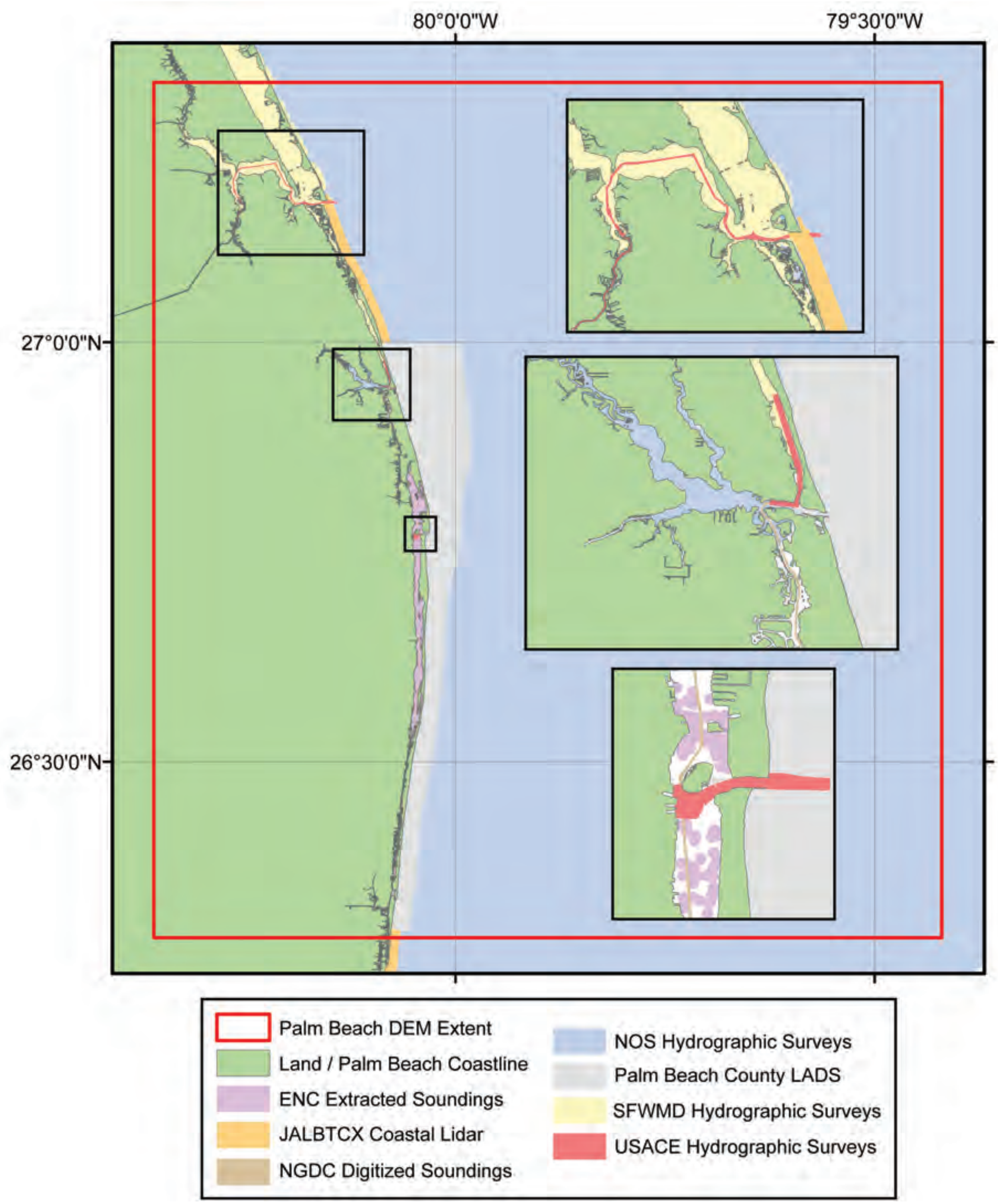

Figure 7. Source and coverage of bathymetric datasets used in compiling the Palm Beach DEMs.

1) Electronic navigational chart soundings

NGDC used *FME* software to extract bathymetric soundings from ENCs #11472 and #11467[3]. The soundings provided depth information in areas where higher resolution bathymetric data were unavailable. These areas existed in some places between the Florida barrier islands and the mainland (Fig. 8). The ENCs were downloaded from NOAA's Office of Coast Survey website, and were horizontally referenced to NAD 83 geographic. The extracted soundings were transformed from a vertical datum of MLLW to NAVD 88 using *VDatum*. Some soundings were contoured using GEODAS Hydroplot to interpolate point values along channels and in areas of sparse data.

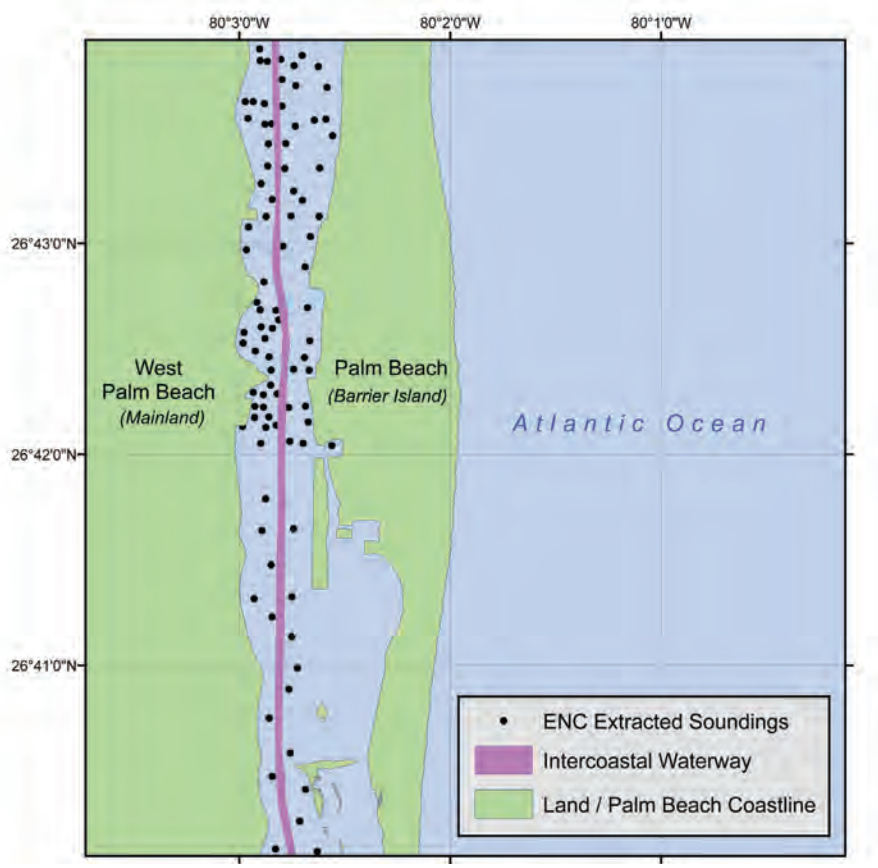

Figure 8. ENC coverage in the Palm Beach area.

2) Joint Airborne Lidar Bathymetry Technical Center of Expertise lidar data

Lidar data of the Palm Beach area were acquired from the Coastal Services Center (CSC) website. These data were collected by JALBTCX, for USACE, as part of the National Coastal Mapping Program in 2006. Only the bathymetric portion of the data were used, because the topographic portion of the data was not processed to bare-earth. The bathymetric lidar data were vertically referenced to NAVD 88 and were horizontally referenced to NAD 83 geographic. The JALBTCX lidar data were used to provide coverage for sections of coast that were not included in the newer Palm Beach County LADS data.

3. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site; http://w1.nauticalcharts.noaa.gov/mcd/enc/index.htm]

3) National Geophysical Data Center digitized points

NGDC used information from NOS RNCs and from the United States Coast Pilot® to digitize 1 arc-second point data of the intracoastal waterway in areas where this data was not otherwise available. The digitized points were used in the southern area of the DEM, between the barrier islands and the mainland (see Fig. 9), where SFWMD data and USACE data did not provide coverage. The location of the intracoastal waterway was acquired from RNCs, and the NAVD 88 depth of the intracoastal waterway was estimated in the Coast Pilot® to be about 10 feet, or about 3.05 meters.

4) National Ocean Service hydrographic survey data

A total of 23 NOS hydrographic surveys conducted between 1883 and 1969 were available for use in developing the Palm Beach DEMs (Table 4; Fig. 9). The surveys were extracted from NGDC's online NOS hydrographic database using *GEODAS*[4]. The hydrographic survey data were downloaded vertically referenced to mean low water (MLW) and horizontally referenced to NAD 83 geographic.

The data point spacing of the surveys varies by scale. In general, small scale surveys have greater point spacing than large scale surveys. All NOS surveys were converted from MLW to NAVD 88 using the *VDatum* transformation tool (see Sec. 3.2.1). The data were converted to shapefiles using *FME* software, and were edited and clipped to the DEM area in ESRI's *ArcGIS*. The surveys were compared to the original survey smooth sheets, other bathymetric datasets, the Palm Beach lidar coastline, topographic lidar data, and NOS raster nautical charts (RNCs). Older surveys were clipped to remove soundings that were overlapped by more recent bathymetric data.

Table 4. Digital NOS hydrographic surveys used in developing the Palm Beach NAVD 88 DEM.

NOS Survey ID	*Year of Survey*	*Area of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
H01570	1883	Indian River- Inlet to Eden	1:20,000	Undetermined	MLW
H01571	1883	Indian River - Eden to Jupiter Narrows	1:20,000	Undetermined	MLW
H04914	1929	Jupiter Inlet to Lake Worth Inlet	1:20,000	Undetermined	MLW
H04930	1929	Hillsboro Inlet to Vicinity of New River Inlet	1:20,000	Undetermined	MLW
H04963	1929	Lake Worth Inlet to Hypoluxo Island	1:20,000	Undetermined	MLW
H04968	1929	Lake Worth Inlet to Palm Beach	1:10,000	Undetermined	MLW
H05015	1929	Villa Rica to Hillsboro Inlet	1:5,000	Undetermined	MLW
H05016	1929	Hypoluxo Island to Villa Rica	1:20,000	Undetermined	MLW
H05022	1930	St. Lucie Inlet to Lake Worth Inlet	1:20,000	NAD 27	MLW
H05023	1930	St. Lucie Inlet	1:10,000	NAD 27	MLW
H05026	1930	St. Lucie Shoal	1:20,000	NAD 27	MLW
H05031	1930	North of St.Lucie Inlet	1:20,000	NAD 27	MLW
H05040	1930	Fort Pierce Inlet to Pierce Shoal	1:40,000	NAD 27	MLW
H05047	1930	Gilberts Shoal to Jupiter Inlet	1:40,000	NAD 27	MLW
H05057	1930	Fort Pierce Inlet to Gilberts Shoal	1:40,000	NAD 27	MLW
H08782	1964	Atlantic Ocean- East Coast Surveys	1:100,000	NAD 27	MLW
H08783	1964	Atlantic Ocean- East Coast Surveys	1:100,000	NAD 27	MLW
H08953	1967	Jupiter Inlet and Vicinity	1:10,000	NAD 27	MLW
H08954	1967	St. Lucie Inlet and Vicinity	1:10,000	NAD 27	MLW
H08955	1967	Coastline North of Jupiter Inlet	1:20,000	NAD 27	MLW
H08956	1967	Gilbert Shoal and Vicinity	1:20,000	NAD 27	MLW
H08957	1967	Coastline South of Fort Pierce	1:20,000	NAD 27	MLW
H09007	1969	Loxahatchee River	1:10,000	NAD27	MLW

4. *GEODAS* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml) developed by NOAA's National Geodetic Survey (NGS) to convert hydrographic survey data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

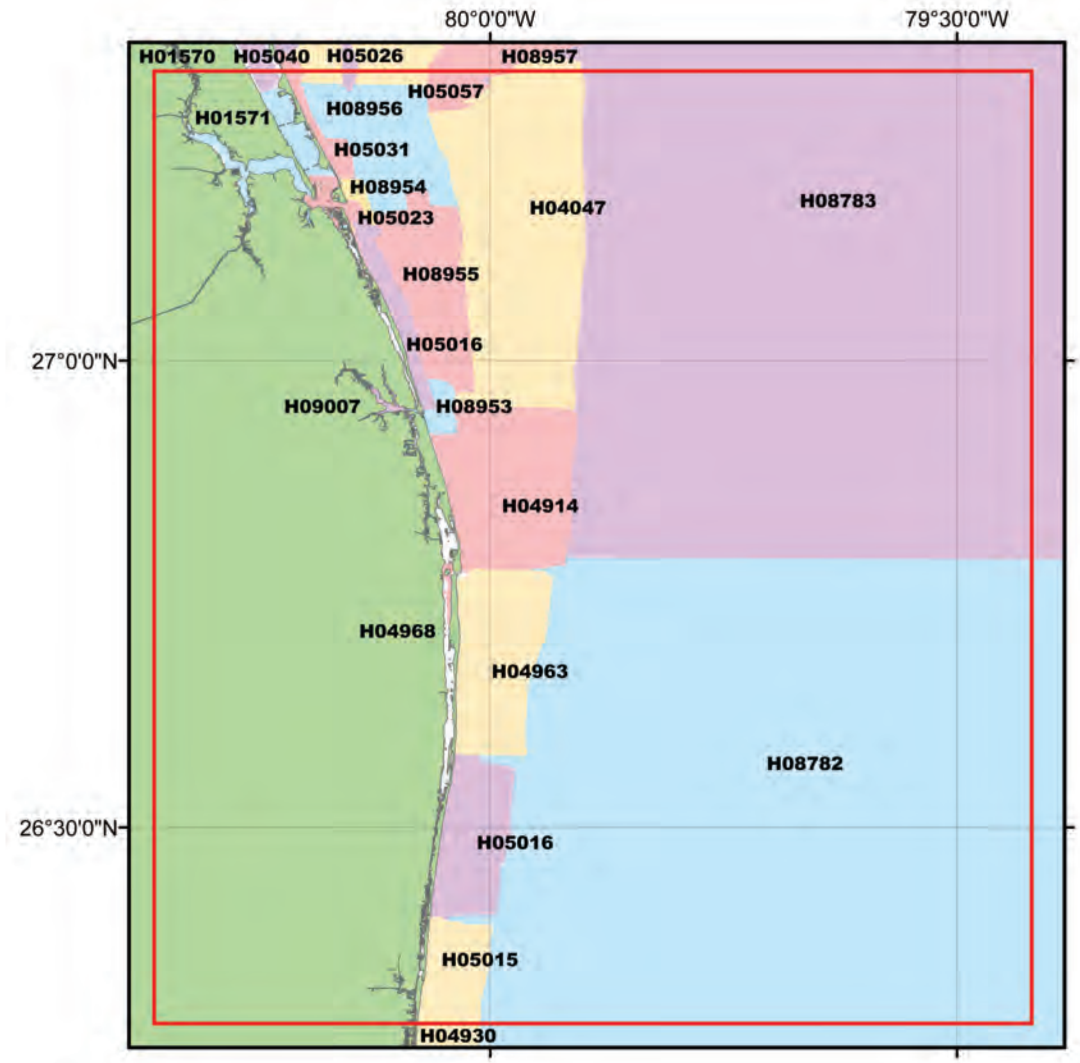

Figure 9. NOS hydrographic survey coverage in the Palm Beach region. Red box represents DEM extents.

5) Palm Beach County Laser Airborne Depth Soundings

LADS data for the Palm Beach area were released in 2003. The Palm Beach County Environmental Resources Manangement division contracted the data collection through Coastal Planning and Engineering, Inc.Processed xyz files provide bathymetric nearshore coverage (see Fig. 10), and are available through Palm Beach County's Environmental Resources Management website. The data were provided to NGDC, however, via ftp by Brian K. Walker, Ph.D, of the National Coral Reef Institute at Nova Southeastern University.

The Palm Beach County LADS data were referenced to NGVD 29. *VDatum* software does not provide transformations from this vertical datum, so the data were transformed to NAVD 88 using an averaged constant from tide stations in the Palm Beach area (See Sec. 3.2.1). The LADS data were converted from NAD 83 Florida State Plane East Florida Zone to WGS 84 using FME, and were clipped to the Palm Beach lidar derived coastline. The data are of a high level of accuracy (International Hydrographic Organization Order 1), and reveal near shore bathymetric irregularities such as dredging holes and established reefs.

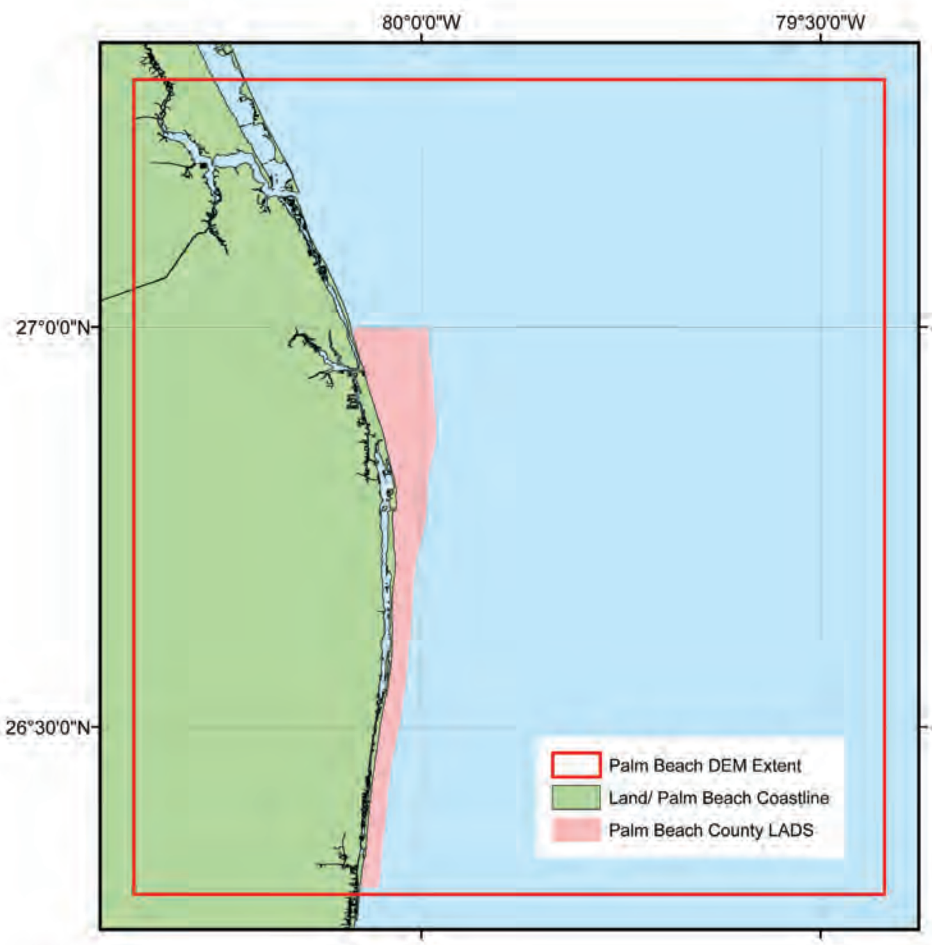

Figure 10. Spatial Coverage of the Palm Beach County LADS data.

6) Southern Florida Water Management District Hydrographic Surveys

Hydrographic surveys for the St. Lucie Estuary, north of Palm Beach County, were acquired in 1998, and were processed and distributed as shapefiles on behalf of the SFWMD (see Fig. 11). The data consist of channel profiles spaced ~300 meters apart. The points were horizontally referenced to NAD 83 HARN and vertically referenced to NGVD 29. The data were converted to xyz points, and triangulated using the *GMT* 'triangulate' tool to provide a surface more representative of the actual bathymetry (see Fig. 12).

Figure 11. Spatial coverage of the SFWMD hydrographic survey in St.Lucie estuary.

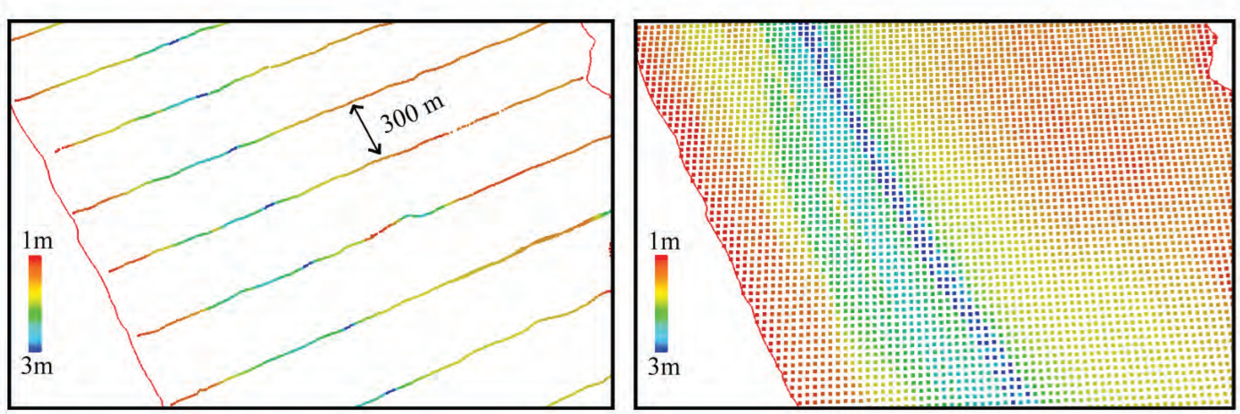

Figure 12. Comparison of original SFWMD hydrographic survey xyz points and NGDC triangulated surface. The image on the left shows a portion of the original SFWMD hydrographic survey data, acquired as channel profiles and spaced at 300 meters. NGDC triangulated this data to create a more uniform coverage surface, shown on the right. This triangulated surface better represented the bathymetry of the area, especially the intracoastal waterway (dark blues).

7) U.S. Army Corps of Engineers hydrographic surveys

Six line survey datasets were downloaded from the USACE Jacksonville District website for use in building the Palm Beach DEMs (Table 5; Fig. 13). The surveys provided depth information for important navigational channels and dredged areas along the coast.

The surveys were horizontally referenced to Florida State Plane Coordinate System East Zone of NAD 83 or NAD 27. The data were transformed to NAD 83 geographic using *FME*. The surveys were vertically reference to either MLW or MLLW, and were transformed to NAVD 88 using *VDatum* software. The USACE line surveys consist of dense data profiles across dredged channels that are sparsely staggered, and so were triangulated using the *GMT* 'triangulate' tool to provide a more representative surface (See Fig. 12).

Table 5. USACE hydrographic surveys used in compiling the Palm Beach DEMs.

Survey ID Number	*Survey Name*	*Date*	*Original Vertical Datum*	*Original Horizontal Datum*	*Resolution*
98-183	Okeechobee Waterway, St.Lucie River, Florida	July 1998	MLW	NAD 27 Florida State Plane East Zone	~ 5 to 30 meters
01-092	Okeechobee Waterway, St. Lucie Canal, Florida	May 2001	MLLW	NAD 27 Florida State Plane East Zone	~ 5 to 30 meters
07-079	Intracoastal Waterway, Palm Beach County, Florida	April 2010	MLW	NAD 27 Florida State Plane East Zone	~ 5 to 30 meters
08-106	Intracoastal Waterway, Martin County, Florida	September 2008	MLW	NAD 83 Florida State Plane East Zone	~ 5 to 30 meters
09-029	St. Lucie Inlet, Florda	April 2009	MLLW	NAD 83 Florida State Plane East Zone	~ 5 to 30 meters
10-051	Palm Beach Harbor, Florida	March 2010	MLLW	NAD 83 Florida State Plane East Zone	~ 5 to 30 meters

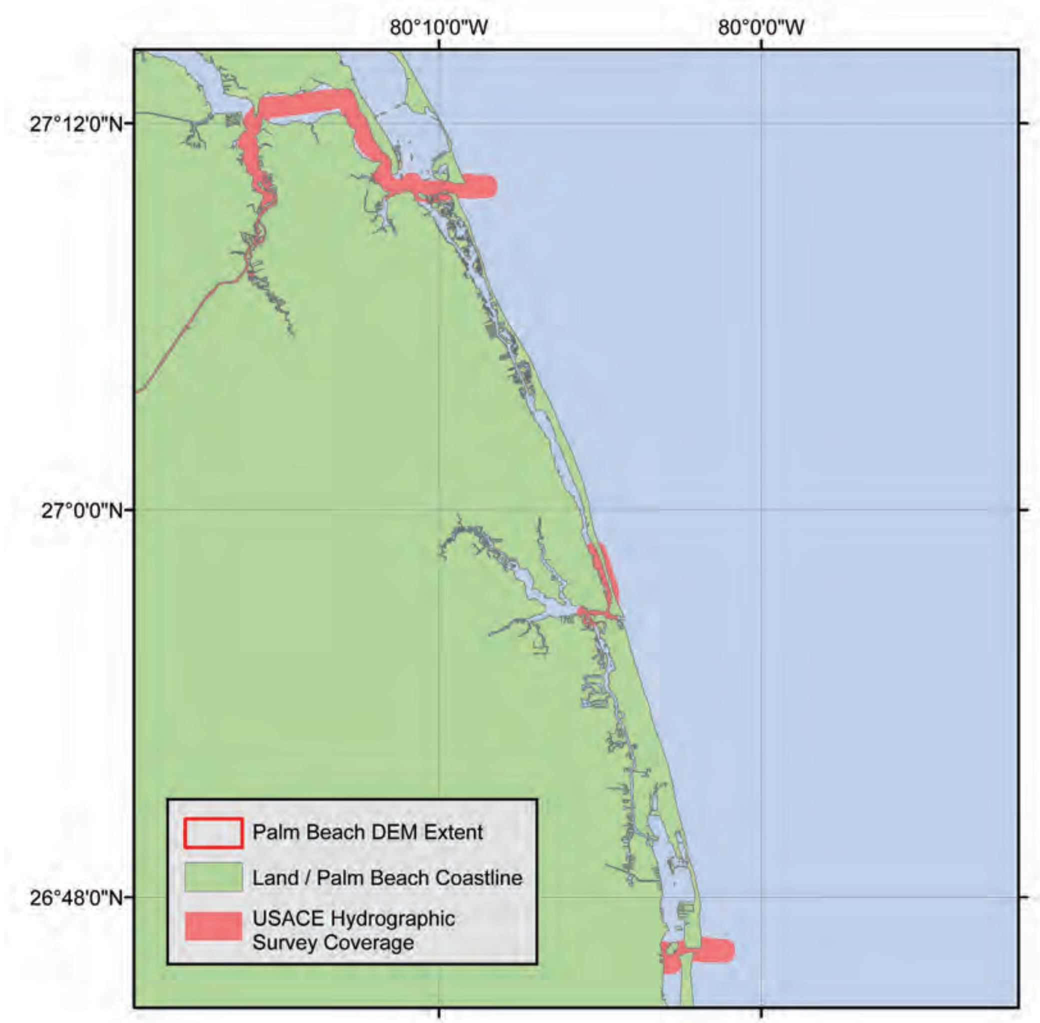

Figure 13. Spatial coverage of USACE hydrographic survey data in the vicinity of Palm Beach.

3.1.3 *Topography*

Two topographic datasets in the Palm Beach region were used to build the Palm Beach NAVD 88 DEM (Table 6; Fig. 14). The FDEM lidar dataset included lidar projects from two separate years. NASA SRTM data were used to fill holes where lidar data were unavailable. USGS NED data and ASTER data were assessed, but were not used in the final DEM due to quality issues.

Table 6. Topographic datasets used in compiling the Palm Beach DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
FDEM	2006-2009	Lidar	5-7 meters	NAD 83 geographic	NAVD 88	http://my.sfwmd.gov/gisapps/sfwmdxwebdc/dataview.asp?/ and http://csc.noaa.gov/digitalcoast/
NASA	1999	SRTM	1 arc-second	NAD 83 geographic	NAVD 88	http://ned.usgs.gov/

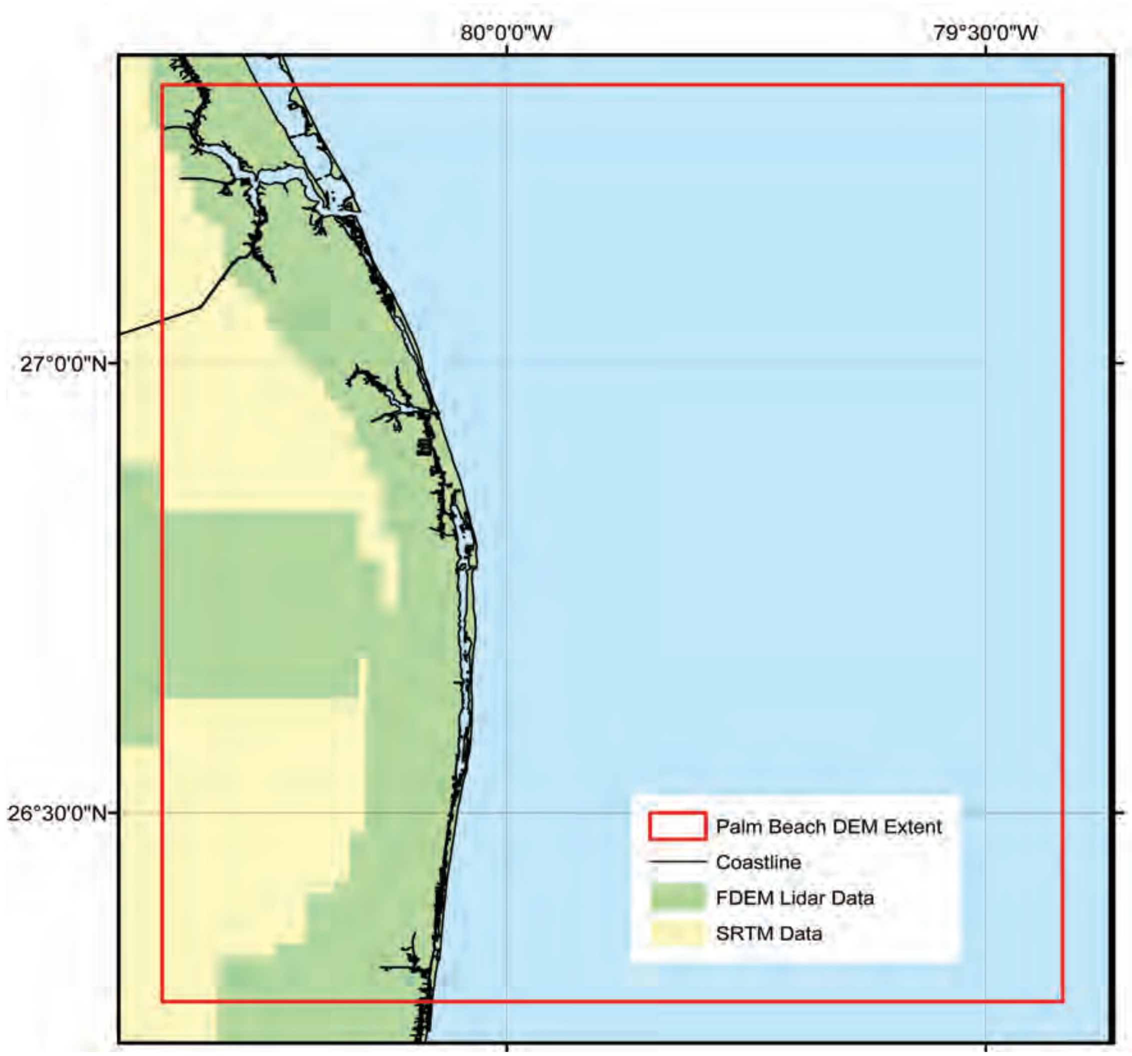

Figure 14. Source and coverage of topographic datasets used in compiling the Palm Beach DEMs.

1) Florida Department of Emergency Management Coastal Lidar

The topographic lidar datasets used in compiling the Palm Beach DEM were collected in 2006 and 2009 for a variety of organizations, including FDEM, the Florida Water Management Districts, the Florida Fish and Wildlife Conservation Commission, the Florida Department of Environmental Protection, the USACE Jacksonville District, and other state and federal agencies. The ultimate goal of this project was to use the lidar data as new elevation inputs for updated Sea, Lake, and Overland Surges from Hurricanes (SLOSH) data grids, resulting in updates of the Regional Hurricane Evacuation Studies (RHES; http://www.saw.usace.army.mil/floodplain/Hurricane%20Evacuation.htm) for the state.

FDEM coastal lidar for Palm Beach County and Broward County were provided to NGDC as raster DEM datasets from the FDEM GIS Administrator, Richard Butgereit. FDEM coastal lidar data for Martin County and St. Lucie County were obtained online as raster DEM datasets from the SFWMD online GIS Data Catalog. The 2009 coastal lidar data for all four counties were horizontally referenced to NAD 83 Florida State Plane West (feet) and vertically referenced to NAVD 88. The data were transformed from feet to meters and to WGS 84 geographic using *ArcGIS*. The coastal lidar data were edited to remove bridges, and were converted to xyz points to be used in the final gridding process.

NGDC obtained inland xyz lidar data from NOAA CSC website. The inland lidar data were horizontally referenced to WGS 84 geographic and were vertically referenced to NAVD 88; no transformations were necessary. The inland lidar data were edited to remove some roads and buildings that remained, and were converted to xyz points to be used in the final gridding process

All FDEM lidar data were clipped to the Palm Beach lidar-derived coastline in order to remove empty data values over the open ocean. This prevented empty values from overlapping with the bathymetric datasets used in compiling the Palm Beach DEMs.

2) Shuttle Radar Topography Mission InSAR data

The SRTM was a joint international project run by the National Geospatial Intelligence Agency (NGA) and NASA[5]. In 2000, the SRTM project obtained global elevation data at 1 arc-second resolution using an interferometric synthetic aperature rader (InSAR) system. Two SRTM raster grid tiles were downloaded from the SRTM webstie for use in the Palm Beach DEM; the data were used to provide coverage in the northwest and southwest inland portions of the Palm Beach DEM topography, where FDEM lidar data was unavailable.

SRTM data were referenced to the WGS 84 horizontal datum and were assumed to be vertically referenced based on the Earth Gravitational Model (EGM) 1996 Geoid. NGDC used a conversion grid and *VDatum* to convert the data to NAVD 88 based on the 2009 Geoid (See Sec. 3.2.1).

The SRTM dataset was the best coverage option when compared to ASTER and NED datasets, but the SRTM dataset contained many water returns due to the marshy nature of the area, and were non-bare earth so contained canopy values. NGDC edited the SRTM data in order to remove canopy heights and to smooth water returns, but the SRTM was still inconsistent with the FDEM lidar data. In many places along the seam of the two datasets, a step in data values is visible in the Palm Beach DEM. To minimize the modeling effects of the step, an empty buffer was installed between the datasets to allow for smoothing and interpolation at the seam.

5. The SRTM data sets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA – previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies, to generate a near-global digital elevation model (DEM) of the Earth using radar interferometry. The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60 meter long baseline. A description of the SRTM mission can be found in Farr and Kobrick (2000). Synthetic aperture radars are side-looking instruments and acquire data along continuous swaths. The SRTM swaths extended from about 30 degrees off-nadir to about 58 degrees off-nadir from an altitude of 233 km, and thus were about 225 km wide. During the data flight the instrument was operated at all times the orbiter was over land and about 1000 individual swaths were acquired over the ten days of mapping operations. Length of the acquired swaths range from a few hundred to several thousand km. Each individual data acquisition is referred to as a "data take." SRTM was the primary (and pretty much only) payload on the STS-99 mission of the Space Shuttle Endeavour, which launched February 11, 2000 and flew for 11 days. Following several hours for instrument deployment, activation and checkout, systematic interferometric data were collected for 222.4 consecutive hours. The instrument operated almost flawlessly and imaged 99.96% of the targeted landmass at least one time, 94.59% at least twice and about 50% at least three or more times. The goal was to image each terrain segment at least twice from different angles (on ascending, or north-going, and descending orbit passes) to fill in areas shadowed from the radar beam by terrain. This 'targeted landmass' consisted of all land between 56 degrees south and 60 degrees north latitude, which comprises almost exactly 80% of Earth's total landmass. [Extracted from SRTM online documentation; http://srtm.usgs.gov/]

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation of the Palm Beach NAVD 88 DEM were originally referenced to a number of vertical datums including MLW, MLLW, NGVD 29, and NAVD 88. All datasets were transformed to NAVD 88 using the *VDatum* transformation tool (http://vdatum.noaa.gov/), except for those referenced to NGVD 29, which were transformed using an averaged constant based on local tide station values (Fig.15). The locations and tidal relationships at the Palm Beach area tide stations (http://tidesandcurrents.noaa.gov/) are provided in Table 7.

1) **Bathymetric data**

The ENC extracted soundings, JALBTCX lidar surveys, NOS hydrographic surveys, and USACE hydrographic surveys were transformed from MLLW and MSL to NAVD 88 using *VDatum*. LADS data and SFWMD data in NGVD 29 were transformed to NAVD 88 using a constant value of 0.47 meters, averaged from the values at all tide stations (Table 7).

2) **Topographic data**

All FDEM lidar datasets were originally referenced to NAVD 88, and required no vertical transformations. SRTM data were transformed from the EGM 1996 Geoid to the NAVD 88 Geoid 2009 using a geoid height transformation grid acquired from the National Geospatial Intelligence Agency (http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm96/egm96.html) and *VDatum*.

Table 7. Tide stations in the Palm Beach area and relationships between NGVD 29 and NAVD 88.

Tide Station	*Name*	*Difference NGVD 29 to NAVD 88 (m)*	*Latitude*	*Longitude*
8722472	North Loxachatchee River	0.458	26.9867	-80.1417
8722481	Loxachatchee River	0.54	26.97	-80.1267
8722478	North Fork Loxachatchee River	0.456	26.9867	-80.1417
8722486	Tequesta, North Fork, Loxachatchee River	0.458	26.975	-80.1133
8722488	Tequesta, Loxachatchee River	n/a	26.9517	-80.1017
8722487	Tequestra	n/a	26.9517	-80.1017
8722496	Loxachatchee River Lock	0.46	26.935	-80.143
8722492	Jupiter West	n/a	26.9467	-80.09
8722491	Jupiter Sound	0.459	26.9517	-80.08
8722495	Jupiter Inlet	n/a	26.9433	-80.0733
8722512	Lake Worth Creek	0.446	26.9117	-80.08
8722548	PGA Boulevard Bridge	0.461	26.8433	-80.0667
8722557	North Palm Beach	0.472	26.8267	-80.055
8722588	Port of West Palm Beach, Lake Worth	n/a	26.77	-80.0517
8722607	Palm Beach	0.462	26.733	-80.0417
8722621	Palm Beach Brazilian Dock	0.464	26.705	-80.045
8722654	West Palm Beach	0.497	26.645	-80.045
8722670	Lake Worth Pier	0.468	26.6117	-80.0333
8722706	Boynton Beach	0.476	26.5483	-80.0533
8722746	Delray Beach	0.473	26.4733	-80.0617
8722761	South Delray Beach	0.472	26.4467	-80.065
8722784	Yamato	0.469	26.4033	-80.07

Tide Station	*Name*	*Difference NGVD 29 to NAVD 88 (m)*	*Latitude*	*Longitude*
8722802	Lake Wyman	0.556	26.37	-80.07
8722445	Hobe Sound State Park	0.453	27.0367	-80.1067
8722429	Hobe Sound Bridge	0.451	27.065	-80.1233
8722414	Gomez	0.455	27.0933	-80.1367
8722404	Peck Lake	0.449	27.1133	-80.145
8722381	Great Pocket	0.444	27.155	-80.1717
8722383	Port Salerno	0.442	27.1517	-80.195
8722371	Sewall Point	0.444	27.175	-80.1883
8722357	Stuart	0.446	27.2	-80.2583
8722334	North Fork, St. Lucie River	0.45	27.2433	-80.3133
	Average	0.47		

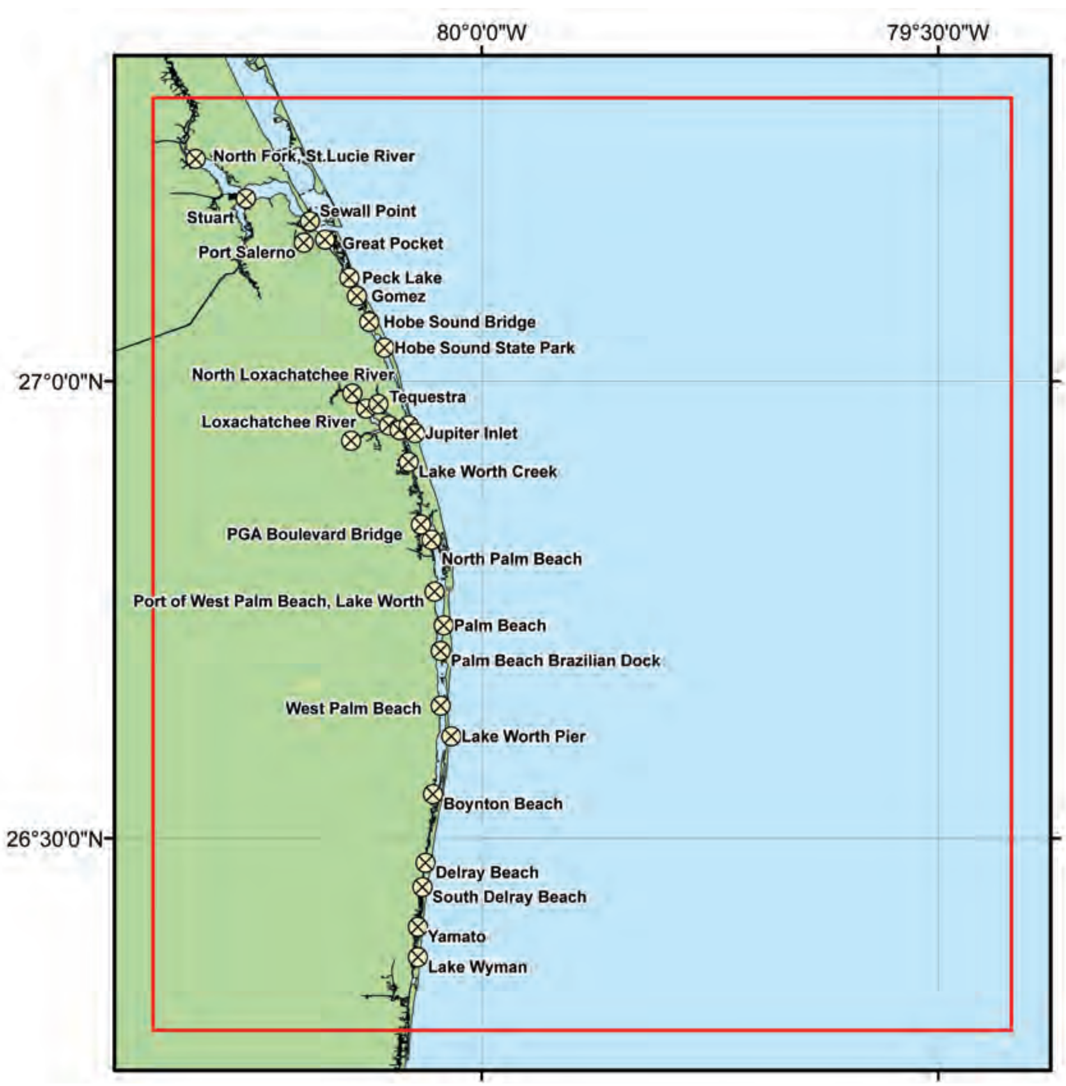

Figure 15. Locations of NOAA tide stations in the Palm Beach area.

3.2.2 Horizontal datum transformations

Datasets used in the compilation of the Palm Beach NAVD 88 DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 83 State Plane Coordinate System East Florida Zone, and NAD 27 State Plane Coordinate System East Florida Zone horizontal datums. The relationships and transformational equations between these geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using *FME*, *ArcGIS*, and *VDatum* software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting data were viewed in *ArcMap* and *QT Modeler* for consistency. Any problems and errors were identified and resolved before proceeding with subsequent gridding steps. Once evaluated, compared, and corrected, the data were converted into final xyz files in preparation for the DEM gridding process. Problems included:

- Inconsistent overlapping datasets. Older data sometimes overlapped newer data, and data values varied between the years. Older data were eliminated in these areas. Data were also weighted during the final gridding process based on resolution, quality, and age.
- Topograhic lidar data values over the bathymetric portions of DEM. Some topographic lidar data contained water-return or empty values over the open ocean, which needed to be clipped from the datasets using the Palm Beach coastline.
- Inconsistencies between lidar data and SRTM data. These inconsistencies were caused by water returns in swamps, and the bare-earth or non- bare-earth nature of the datasets. The SRTM data were removed where they were overlapped by higher quality, bare-earth lidar, and were edited to remove canopy values and water return values. A small buffer was also used between the two datasets to allow for interpolation between them. This prevented the appearance of a "step" or "wall" in the final DEM where the datasets meet.
- Outdated NOS data. Bathymetric values from NOS surveys dated back over 100 years. More recent data, such as the Palm Beach County LADS data, differed from old NOS data by as much as 50 meters vertically. The older NOS survey data were removed where more recent bathymetric data exists.
- Non-bare-earth values in lidar datasets from buildings, lakes, and bridges. Obvious non-bare-earth returns were manually removed from the lidar data.
- Inconsistencies between NGDC digitized points along the intracoastal waterway and SFWMD and USACE hydrographic data. Digitized points were removed where other data existed.
- Staggered spacing of dense channel profile coverage in the SFWMD and USACE hydrographic surveys due to data collection techniques. These data were triangulated before gridding to create a more uniform coverage surface.

3.3.2 Smoothing of bathymetric data

The older NOS hydrographic survey data are generally sparse at the resolution of the Palm Beach DEMs. To reduce the effect of artifacts due to this, a 1 arc-second cell size 'pre-surface' bathymetric grid in NAVD 88 vertical datum was generated using *GMT*[6], an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/). Additionally, a near-shore 1/3 arc-second cell size 'pre-surface' bathymetric grid in NAVD 88 was created, to prevent the interpolation of positive values from known ocean areas.

To create the bathymetric surfaces, all bathymetric datasets were converted into xyz points, and were combined with points extracted from the Palm Beach coastline—to provide a breakline along the entire coastline. The coastline elevation values were set to -0.85 meters, to ensure the bathymetric surface approached zero relative to NAVD 88 in areas where bathymetric data are sparse or non-existent.

The 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 Palm Beach DEM region, and a near-shore 1/3 arc-second coverage grid. The *GMT* tool 'surface' was used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by 'surface' was converted into an ESRI Arc ASCII grid file, and clipped to the Palm Beach coastline .

The resulting surface was compared with original bathymetric soundings to ensure grid accuracy, and to be certain that the real data quality was not being affected. Examples of these comparisons are shown in Figures 16 and 17, which show histograms of the NOS and total bathymetric data xyz points, respectively, compared to the 1 arc-second pre-surfaced bathymetric grid. Differences cluster around zero with a range of -9 to +15 meters when compared to the bathymetric surface. Points with the largest differences are located where dense data contain multiple elevation

9. *GMT* is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest. hawaii.edu/ [Extracted from GMT web site.]

values per cell, which were averaged to create the final DEM value.

The gridded bathymetric surfaces were converted into xyz files for use in building the final Palm Beach NAVD 88 DEM (See Sec. 3.3.3).

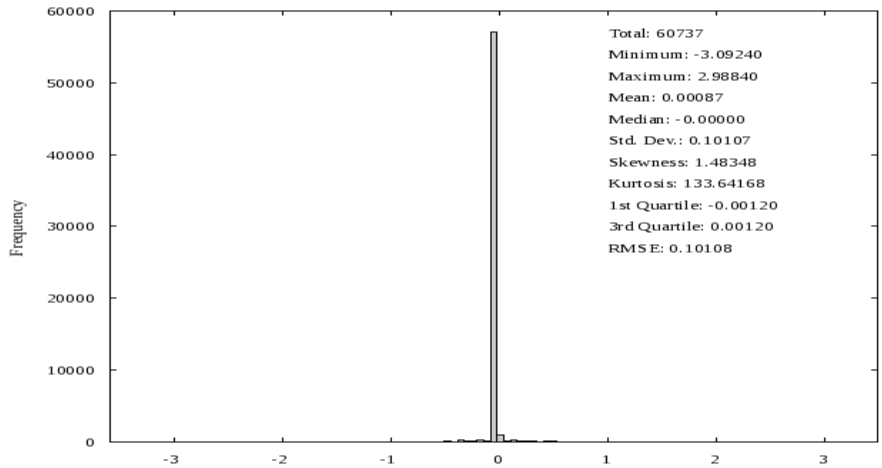

Figure 16. Histogram of the differences between the NOS bathymetric surveys and the 1 arc-second pre-surfaced bathymetric grid.

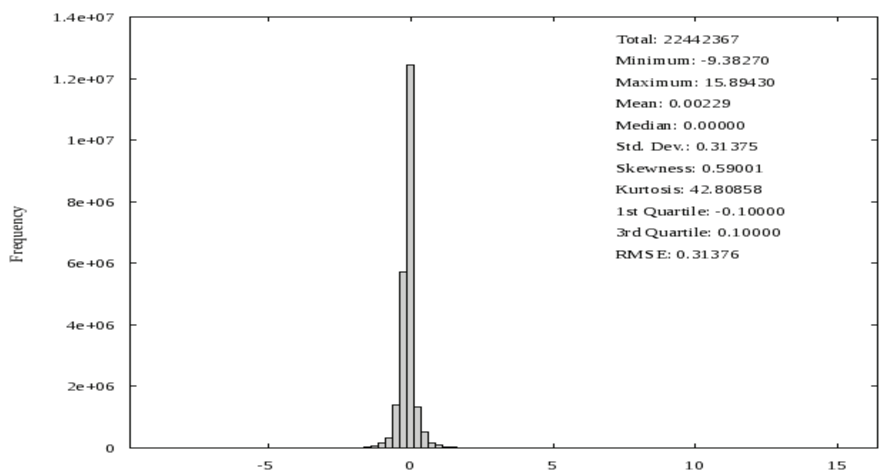

Figure 17. Histogram of the differences between all original bathymetric data and the 1 arc-second pre-surfaced bathymetric grid.

3.3.3 Building the NAVD 88 DEM

MB-System[7] was used to create the 1/3 arc-second Palm Beach NAVD 88 DEM. The *MB-System* tool 'mbgrid' was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 8. The greatest weights were assigned to the lidar datasets, the bathymetric surface, and the Palm Beach County LADS data. The least weight was given to the SRTM data, ENC extracted soundings, and NGDC digitized points.

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

Dataset	*Relative Gridding Weight*
SRTM InSAR Data	0.1
FDEM Topographic Lidar	1
ENC Extracted Soundings	1
Lidar Derived Coastline Extracted Points	1
NGDC Digitized Intracoastal Waterway Points	1
NOS Hydrographic Soundings	10
USACE Hydrographic Soundings	10
SFWMD Hydrographic Soundings	10
JALBTCX Bathymetric Lidar	100
Palm Beach County LADS	100
Pre-Surfaced Bathymetric Grid	100

3.3.4 Building the MHW DEM

The MHW DEM was created by adding an "NAVD 88 to MHW" conversion grid to the NAVD 88 DEM.

1) Developing the conversion grid

Using extents slightly larger (~ 5 percent) than the DEM, an initial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the area. The elevation value at each of the points was set to zero. The *GMT* tool 'surface' applied a tension spline to interpolate cell values, making a zero-value 3 arc-second grid. This zero-value grid was then converted to an intermediate xyz file using the *GMT* tool 'grd2xyz'. Conversion values from NAVD 88 to MHW at each xyz point were generated using *VDatum* and the null values were removed. NGDC used the *GMT* tool 'blockmedian' to median-average multiple elevation values where *VDatum* project areas overlapped.

The median-averaged xyz file was then interpolated with the *GMT* tool 'surface' to create the 1/3 arc-second 'NAVD 88 to MHW' conversion grid with the extent of the Palm Beach DEMs, interpolating values inland to represent the differences between the two datums onshore (Fig. 18).

7. *MB-System* is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for *MB-System* is freely available (for free) by anonymous ftp (including "point and click" access through these web pages). A complete description is provided in web pages accessed through the web site. *MB-System* was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for *MB-System* development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994-1997), NOAA (2002-2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ [Extracted from *MB-System* web site.]

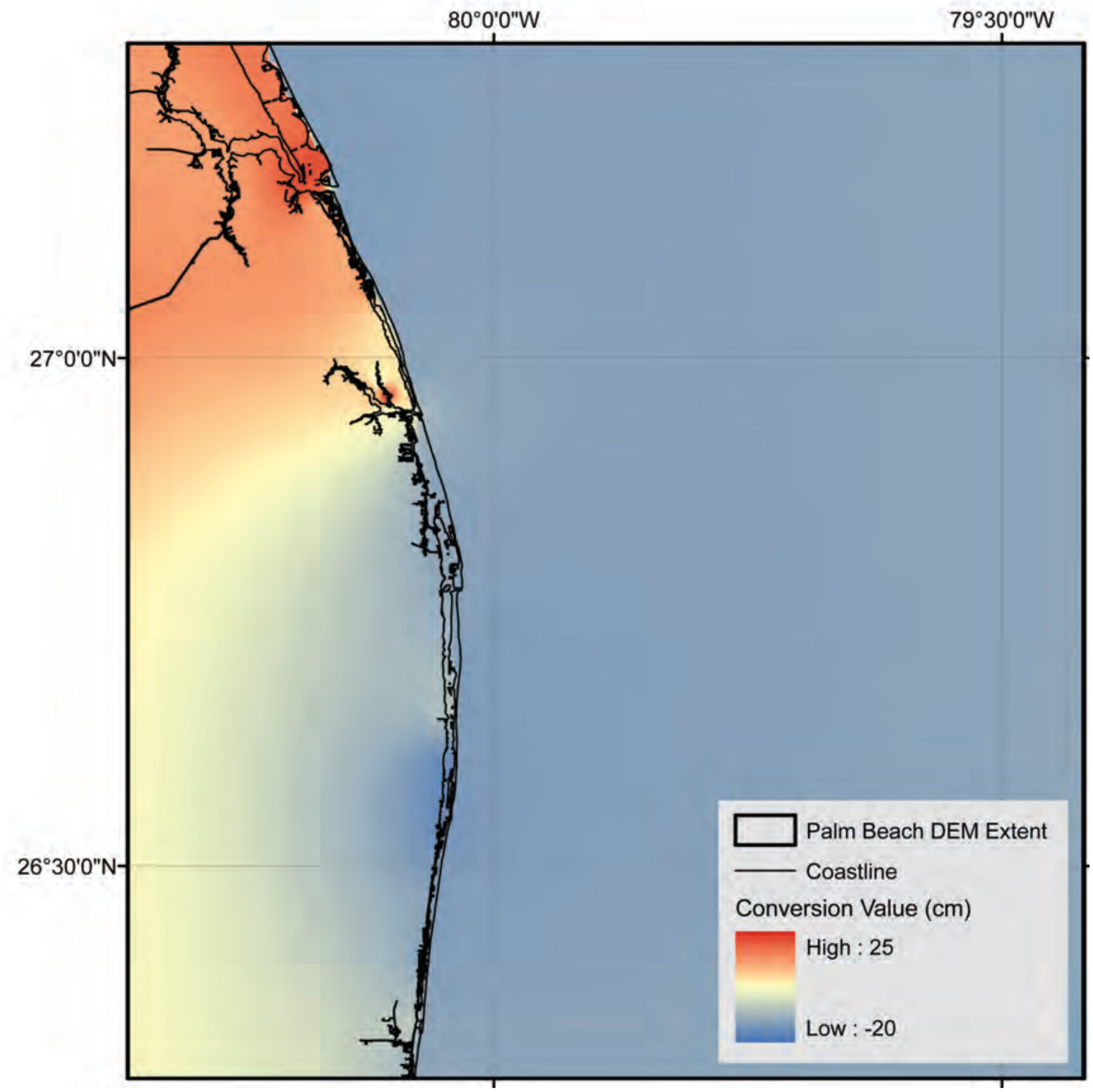

Figure 18. Image of NGDC Palm Beach conversion grid.
The conversion values represent the difference between NAVD 88 and MHW, as determined from VDatum and further interpolation.

2) Assessing the accuracy of the conversion grid

The NAVD 88-to-MHW conversion grid was assessed using the NOS survey data. The NOS hydrographic survey data were transformed from MLLW to NAVD 88, and from MLLW to MHW, using *VDatum*. Null values were removed and the elevation differences between the MHW and NAVD 88 values were meaured (Fig. 19). A new xyz file was created, containing these difference values.

The accuracy of the 1/3 arc-second conversion grid was checked by comparing the 'NAVD 88-to-MHW' grid to the NOS conversion difference xyz file. The results indicated agreement to approximately +/- 0.2 meters with a mean difference of 0.00008 meters.

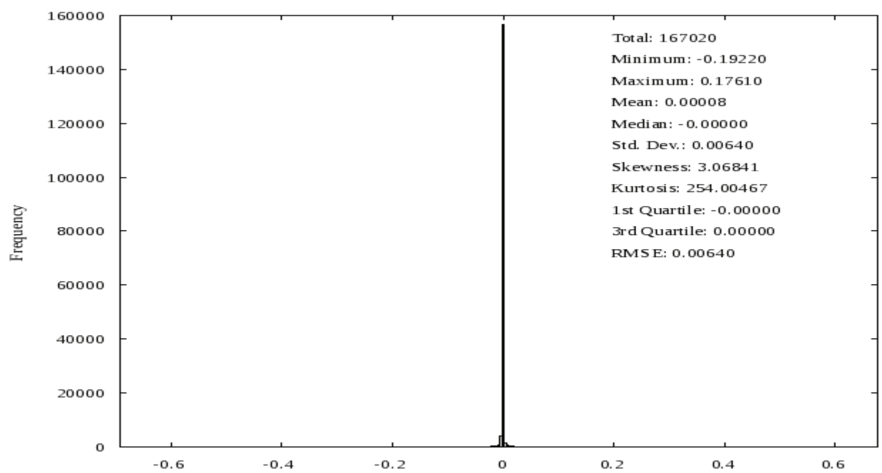

Figure 19. Histogram of the differences between the conversion grid and xyz difference files using NOS hydrographic survey data.

3) Creating the MHW DEM

Once the NAVD 88 DEM was complete and assessed for errors, the conversion grid was added to it using *ArcCatalog*. The resulting MHW DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI *World 2D* imagery.

3.4 Quality Assessment of the DEMs

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Palm Beach DEMs is dependent upon DEM cell size and source datasets. Topographic features have an estimated horizontal accuracy of 10-30 meters: gridded lidar data have an accuracy less than five meters, and SRTM data are accurate to approximately 30 meters. Bathymetric features are resolved to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings and potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values in the Palm Beach DEMs is also dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy less than 1 meter for bare-earth lidar data and 20 meters for non bare-earth SRTM DEMs. Bathymetric values have an estimated accuracy between 0.1 meters and 5% of water depth. The values were derived from a wide range of sounding measurements, from the late nineteenth century to recent, GPS-navigated LADS surveys. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Palm Beach NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 20). The DEM was transformed to NAD 83 UTM Florida East Zone coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids using *QT Modeler* and *Fledermaus* revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Palm Beach NAVD 88 DEM in its final version. The transition in topographic high-resolution bare-earth lidar and low resolution non bare-earth SRTM data can be seen. Figure 21 shows a perspective rendering of the final NAVD 88 DEM. Figure 22 shows a data contribution plot of the Palm Beach DEMs.

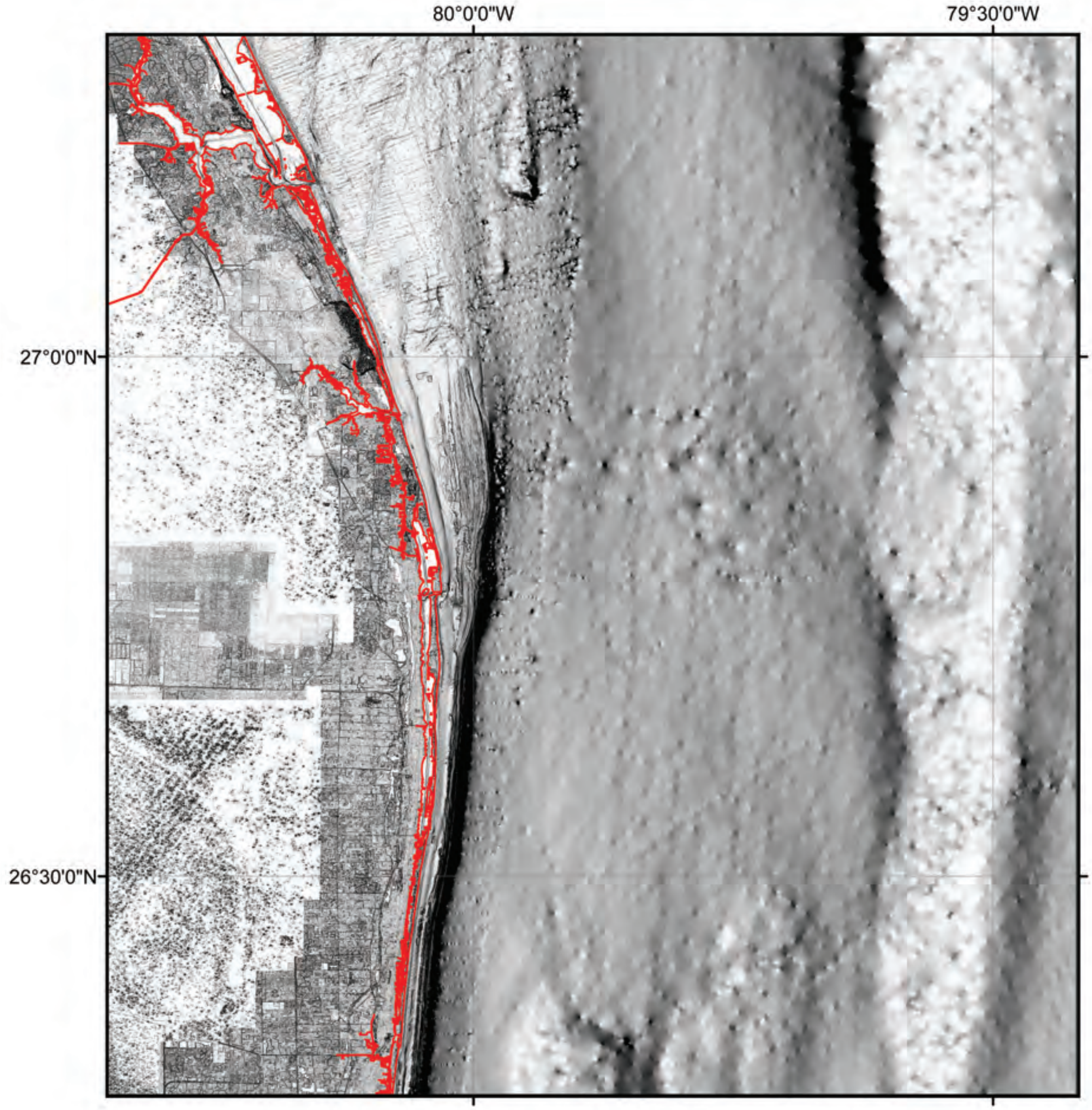

Figure 20. Slope map of the Palm Beach NAVD 88 DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined coastline indicated in red.

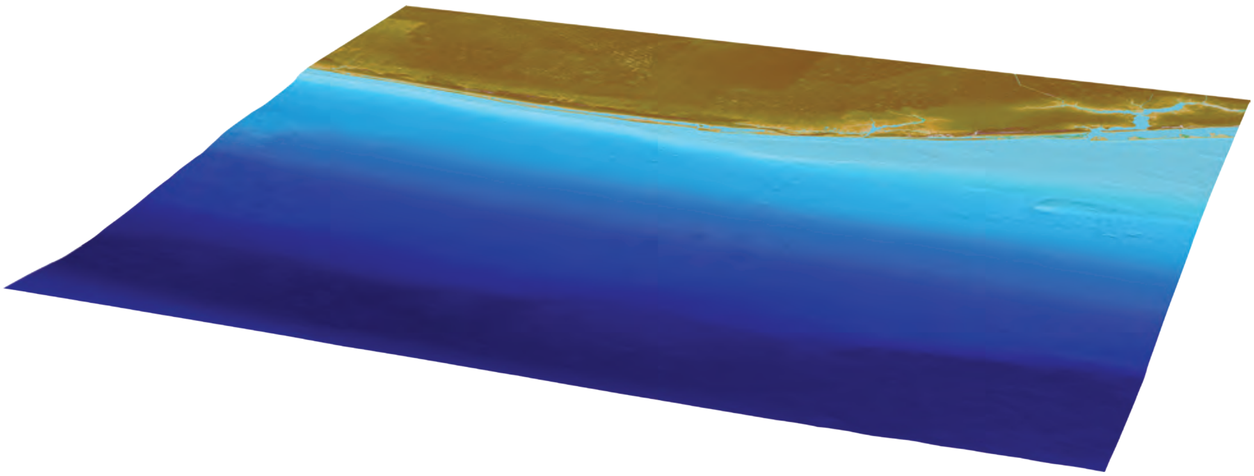

Figure 21. Perspective view from the northeast of the 1/3 arc-second Palm Beach NAVD 88 DEM. Vertical exaggeration–times 5.

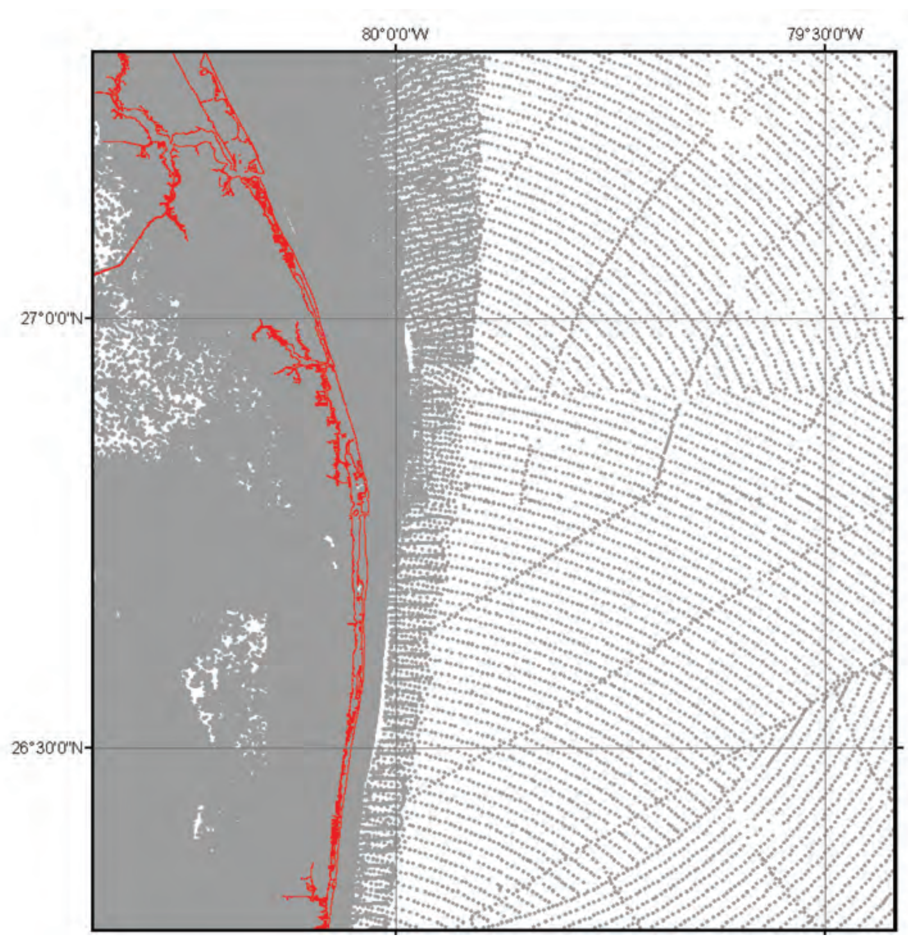

Figure 22. Data contribution plot of the Palm Beach NAVD 88 DEM. Grey depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. Coastline is shown in red; DEM boundary in black.

3.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 2236 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (see Fig. 23 for monument locations). The associated shapefile attributes provided high accuracy monument postions in NAD 83 geographic, and elevations in NAVD 88. These elevation data were compared to the Palm Beach NAVD 88 DEM elevation values (Fig. 24). Differences between the DEM and the monument elevations range from -15.24510 to 89.75030 meters, with a mean of 1.3 meters. Large differences in elevations occurred where monuments are located on major roads and bridges, pilings, or buildings, and in areas where the grid elevations were derived from the SRTM data.

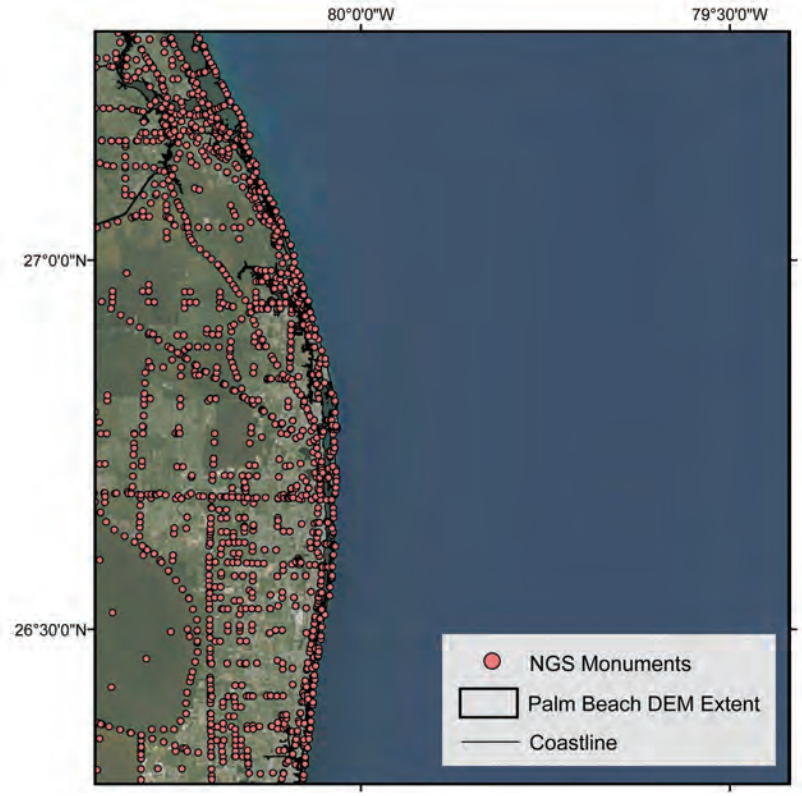

Figure 23. Location of NGS geodetic monuments in the Palm Beach region.

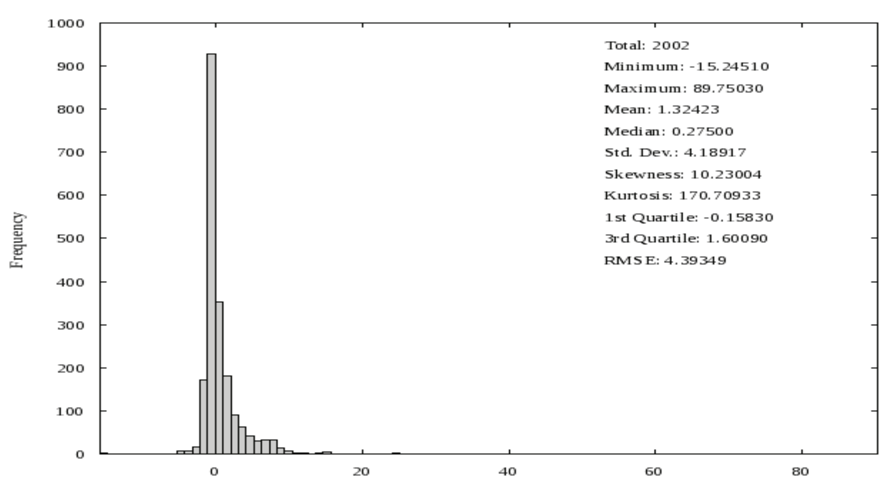

Figure 24. Histogram of the differences between NGS geodetic monument elevations and the Palm Beach NAVD 88 DEM.

3.4.5 NAVD 88 DEM comparison with source data files

To ensure grid accuracy, the Palm Beach NAVD 88 DEM was compared to source data files. Select bathymetric data and topographic data files were compared to the Palm Beach NAVD 88 DEM.

The deep-water portions of the NOS hydrographic survey dataset was the first compared to the Palm Beach NAVD 88 DEM (Fig. 25). The differences in elevations are clustered around zero and the majority are within ± 2.5 meters. These values are very accurate because NOS was the only available data in the deep-water areas of the DEM. The shallow-water portions of the NOS hydrographic survey dataset was also compared to the Palm Beach NAVD 88 DEM (Fig. 26). These values are clustered around zero, but vary by ± 5 meters. The age of the shallow-water NOS data, which were collected over fifty years ago, probably causes these differences where the shallow-water NOS data meets more recent datasets, such as the USACE hydrographic surveys.

Comparisons of the USACE hydrographic survey data and the Palm Beach NAVD 88 DEM are shown in Figure 27. Elevation differences range from -9.15840 to 5.74300 meters. Differences from the grid occur where the USACE data overlaps other high-resolution datasets, such as the JALBTCX lidar data and the Palm Beach County LADS data at the mouth of inlets. A difference histogram comparing the SFWMD hydrographic survey dataset with the Palm Beach NAVD 88 DEM is shown in figure 28. The largest differences (± 3 meters) between the SFWMD data and the final grid also occur where the data overlap other datasets.

Comparisons of the bathymetric JALBTCX lidar data and the Palm Beach County LADS data against the NAVD 88 DEM are shown in figures 29 and 30. The differences in elevation cluster around zero, with the JALBTCX lidar data varying by about ± 6 meters and the LADS data varying by about ± 4 meters. These differences occur where the high-resolution datasets meet the coast and are affected by interpolation with topographic data, and also where the data meet other bathymetric datasets, such as the USACE and NOS hydrographic survey datasets.

FDEM topographic lidar data was compared to the grid (Fig. 31), and showed very little differences. A small amount of points differed by ± 4 meters, and all of these points were located near data boundaries, such as the coastline and the area where the lidar meets the SRTM data.

Lastly, the SRTM data was compared to the grid (Fig. 32) and it showed significant differences from the DEM. It did not overlap with other data sets, but was non-bare earth data, and so the result was expected as the data were edited and were allowed to interpolate in some areas.

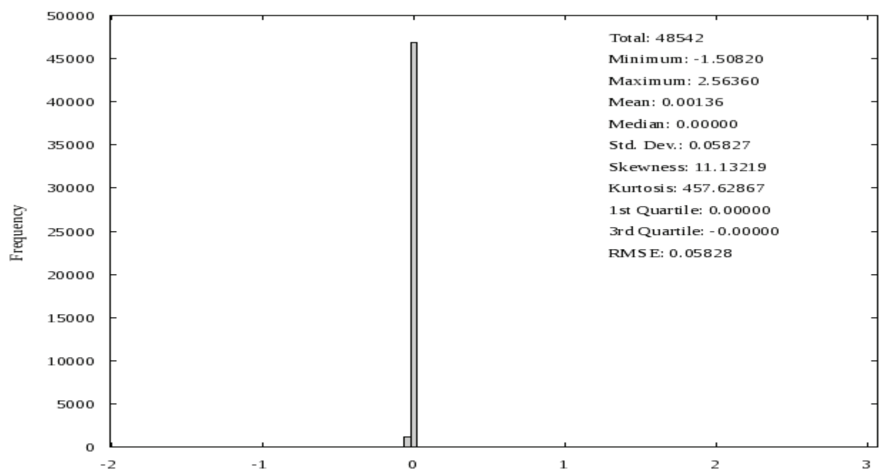

Figure 25. Histogram of the differences between the deep water portion of the Palm Beach NOS DEM data points and the NAVD 88 DEM.

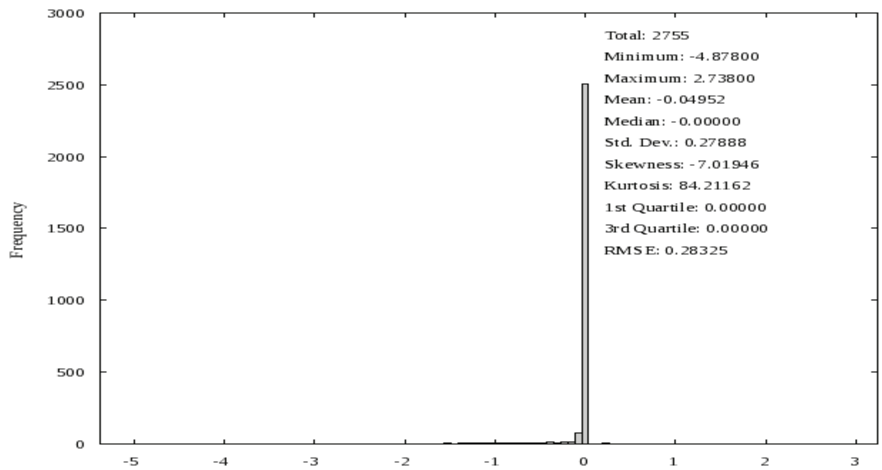

Figure 26. Histogram of the differences between the shallow water portion of the Palm Beach NOS DEM data points and the NAVD 88 DEM.

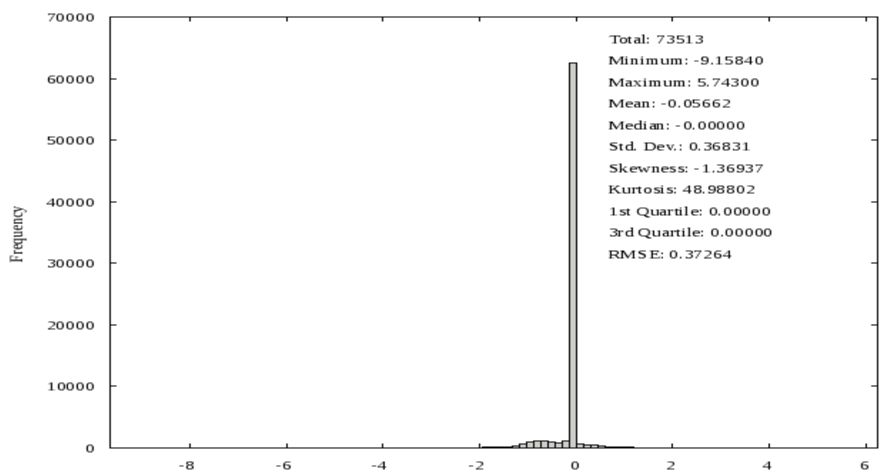

Figure 27. Histogram of the differences between the Palm Beach USACE hydrographic survey DEM data points and the NAVD 88 DEM.

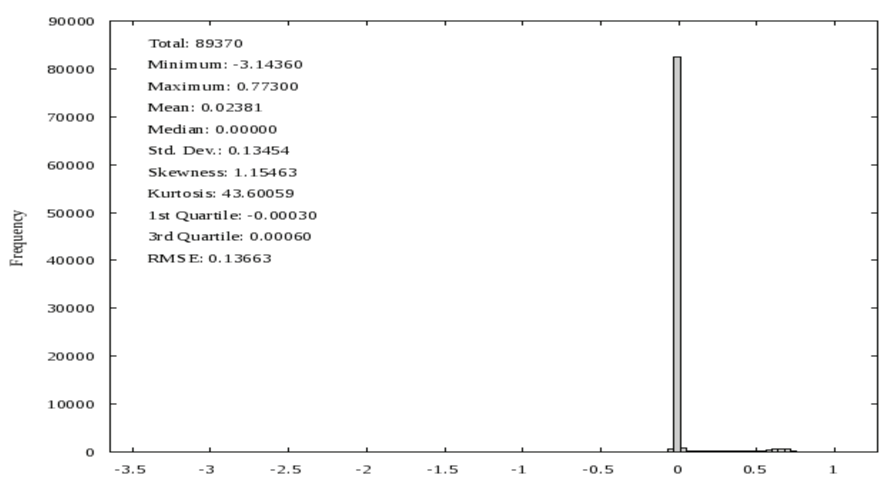

Figure 28. Histogram of the differences between the SFWMD hydrographic survey DEM data points and the NAVD 88 DEM.

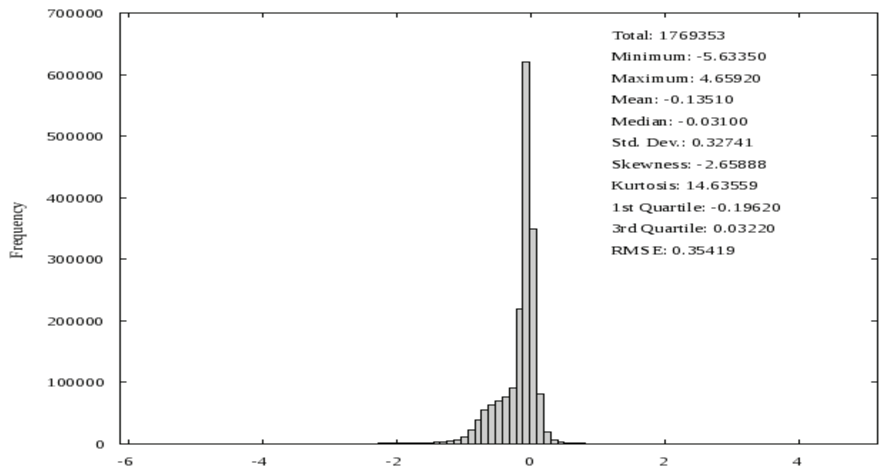

Figure 29. Histogram of the differences between the Palm Beach JALBTCX lidar survey DEM data points and the Palm Beach NAVD 88 DEM.

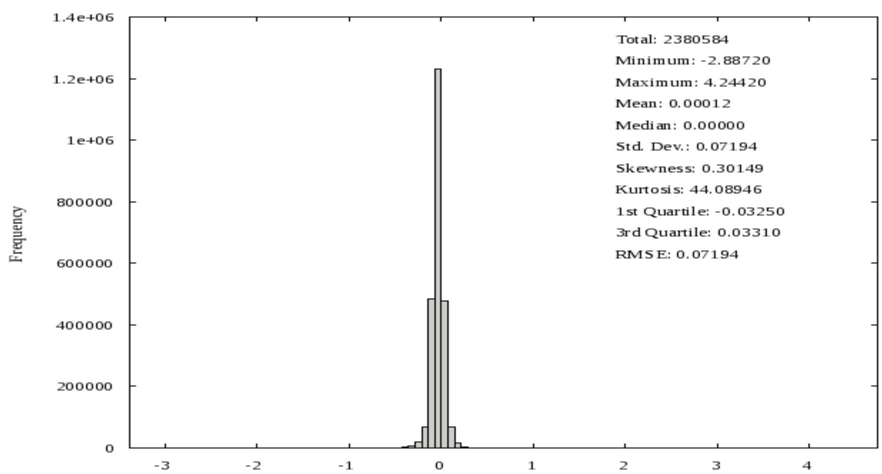

Figure 30. Histogram of the differences between the Palm Beach County LADS DEM data points and the Palm Beach NAVD 88 DEM.

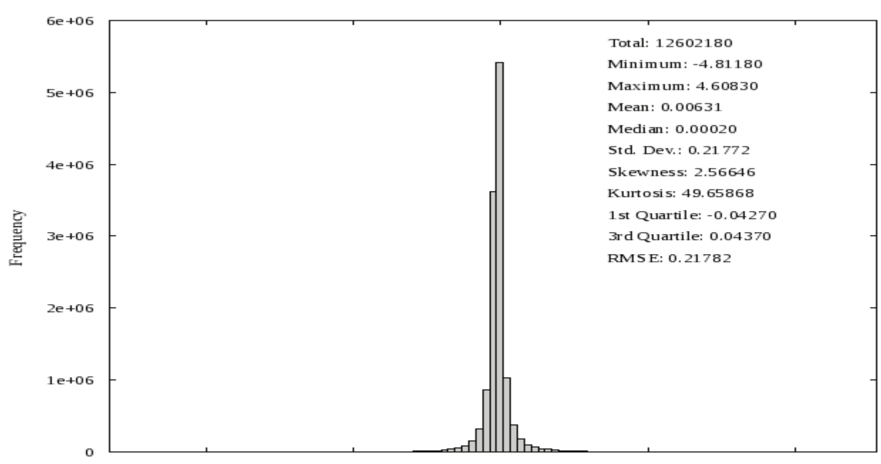

Figure 31. Histogram of the differences between FDEM lidar surveys DEM data points and the Palm Beach NAVD 88 DEM.

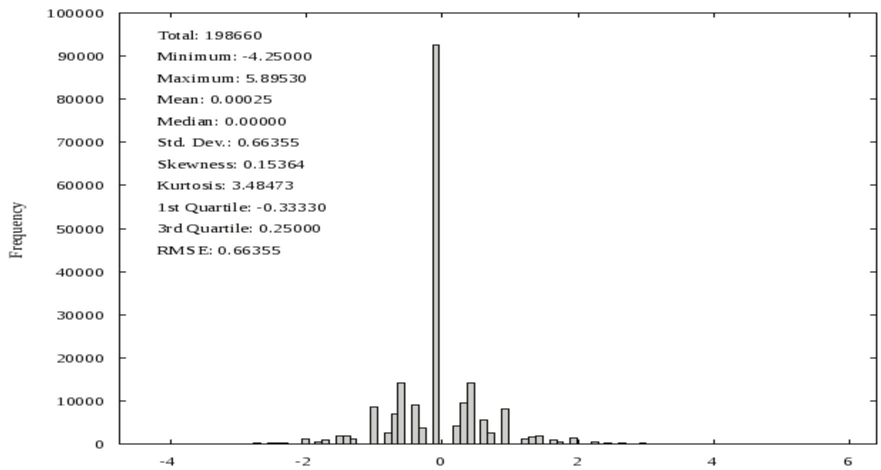

Figure 32. Histogram of the differences between SRTM DEM data points and the Palm Beach NAVD 88 DEM.

4. Summary and Conclusions

Two integrated bathymetric–topographic digital elevation models of the Palm Beach, Florida region, with cell sizes of 1/3 arc-second, were developed for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state, local, and academic agencies 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*, ESRI *ArcGIS World Imagery 2-D*, *FME*, *Fledermaus*, *GMT*, *MB-System*, *QT Modeler*, and *VDatum* software.

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

- Conduct surveys to improve topographic data coverage of inland areas.
- Conduct additional bathymetric-topographic lidar surveys along the coast.
- Conduct high-resolution bathymetric surveys in deep water areas.
- Conduct surveys along the entire Intracoastal Waterway.

5. Acknowledgments

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6. References

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Coast Pilot 4, 41st Edition, 2009. Atlantic Coast: Cape Henry to Key West, FL. U.S. Department of Commerce, NOAA, National Ocean Service.

Nautical Chart #11428 (RNC), 35th Edition, 2008. St.Lucie Inlet to Fort Meyers and Lake Okeechobee. Scales 1:25,000; 1:40,000; 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11466 (ENC and RNC), 38th Edition, 2008. Jupiter Inlet to Fowey Rocks. Scales 1:10,000 and 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11467 (ENC and RNC), 16th Edition, 2010. Intracoastal Waterway- West Palm Beach to Miami. Scale 1:24,000 and 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11460 (ENC and RNC), 42nd Edition, 2009. Cape Canaveral to Key West. Scale 1:466,940. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11474 (ENC and RNC), 10th Edition, 2000. Bethel Shoal to Jupiter Inlet. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11472 (ENC and RNC), 34th Edition, 2009. Palm Shores to West Palm Beach. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.3.1 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/.

ESRI World Imagery (ESRI_Imagery_World_2D) – ESRI ArcGIS Resource Centers http://resources.esri.com/arcgisonlineservices/.

FME 2010 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/.

Fledermaus v. 6.7.0 and 7.0.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/.

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

GMT v. 4.3.4 – Generic Mapping Tools, freeware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.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. 7.0.2 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.

VDatum Transformation Tool, Florida/Georgia - Fort Lauderdale to Sapelo Island, v. 01 – developed and maintained by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/welcome.html.

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