NOAA Technical Memorandum NESDIS NGDC-49

DIGITAL ELEVATION MODELS OF NEW ORLEANS, LOUISIANA: PROCEDURES, DATA SOURCES AND ANALYSIS

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

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Digital Elevation Models of New Orleans, Louisiana: Procedures, Data Sources and Analysis

1. Introduction

In April of 2010, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed three bathymetric–topographic digital elevation models (DEMs) of New Orleans, LA (Fig. 1). The DEMs were developed for NOAA Coastal Survey Development Laboratory (CSDL) through the American Recovery and Reinvestment Act (ARRA) of 2009[1] to evaluate the utility of the *Vertical Datum Transformation* tool (*VDatum*), developed jointly by NOAA's Office of Coast Survey (OCS), National Geodetic Survey (NGS), and Center for Operational Oceanographic Products and Services (CO-OPS) (http://vdatum.noaa.gov/). The 1/3 arc-second[2] DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was carefully developed and evaluated. A NAVD 88 to mean high water (MHW) 1/3 arc-second conversion grid derived from *VDatum* project areas was then created to model the relationship between NAVD 88 and MHW in the New Orleans region. NGDC combined the NAVD 88 DEM and the conversion grid to develop a 1/3 arc-second MHW DEM. The same process was used to generate a mean lower low water (MLLW) 1/3 arc-second conversion grid. The NAVD 88 DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Figures 1, 5 and 10) and the DEMs will be used for storm surge inundation and sea level rise modeling. This report provides a summary of the data sources and methodology used in developing the three New Orleans DEMs.

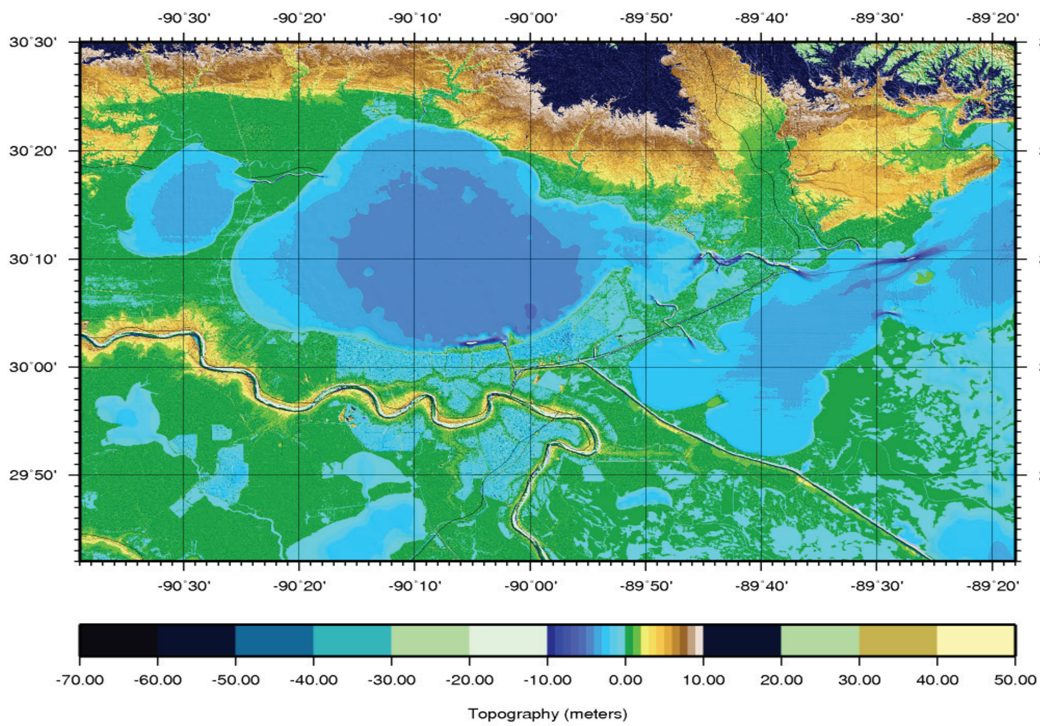

Figure 1. *Shaded Relief image of the New Orleans NAVD 88 DEM.*

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1. On Feb. 13, 2009, Congress passed the American Recovery and Reinvestment Act of 2009 at the urging of President Obama, who signed it into law four days later. A direct response to the economic crisis, the Recovery Act's three goals are to create new jobs as well as save existing ones, spur economic activity and invest in long-term economic growth and foster unprecedented levels of accountability and transparency in government spending (http://www.recovery.gov/Pages/home.aspx).

2. The New Orleans 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 New Orleans, LA (29°57′53″N 90°4′14″W) 1/3 arc-second of latitude is equivalent to 9.8462 meters; 1/3 arc-second of longitude equals 9.8462 meters.

2. Study Area

The New Orleans DEMs cover the area surrounding the City of New Orleans, Louisiana, including portions of south-western Mississippi (Fig 2). New Orleans is the largest city in the State of Louisiana, and is located between the Mississippi River and Lake Pontchartrain. The New Orleans DEM consists of portions of 11 Louisiana parishes (Orleans, St. Bernard, Plaquenies, Jefferson, St. Charles, St. James, St. John the Baptist, Ascension, Livingston, Tangipahoa and St. Tammany) and portions of 3 Mississippi counties (Pearl River, Harrison and Hancock) (Fig. 2).

The New Orleans region is a part of the Mississippi River Delta. As a result, silt deposits from the Mississippi River make up the geology of the New Orleans region. The City of New Orleans was originally settled along the natural levees created through the silt deposits of the Mississippi River. The United States Army Corps of Engineers (USACE) later built floodwalls and man-made levees around the city, incorporating surrounding marshland and swamp, also reducing the yearly silt deposits in the city brought by the Mississippi River, placing much of New Orleans at or below sea-level (Fig. 3). The natural and man-made levees surrounding New Orleans protect the low-lying areas from possible inundation by the surrounding water bodies.

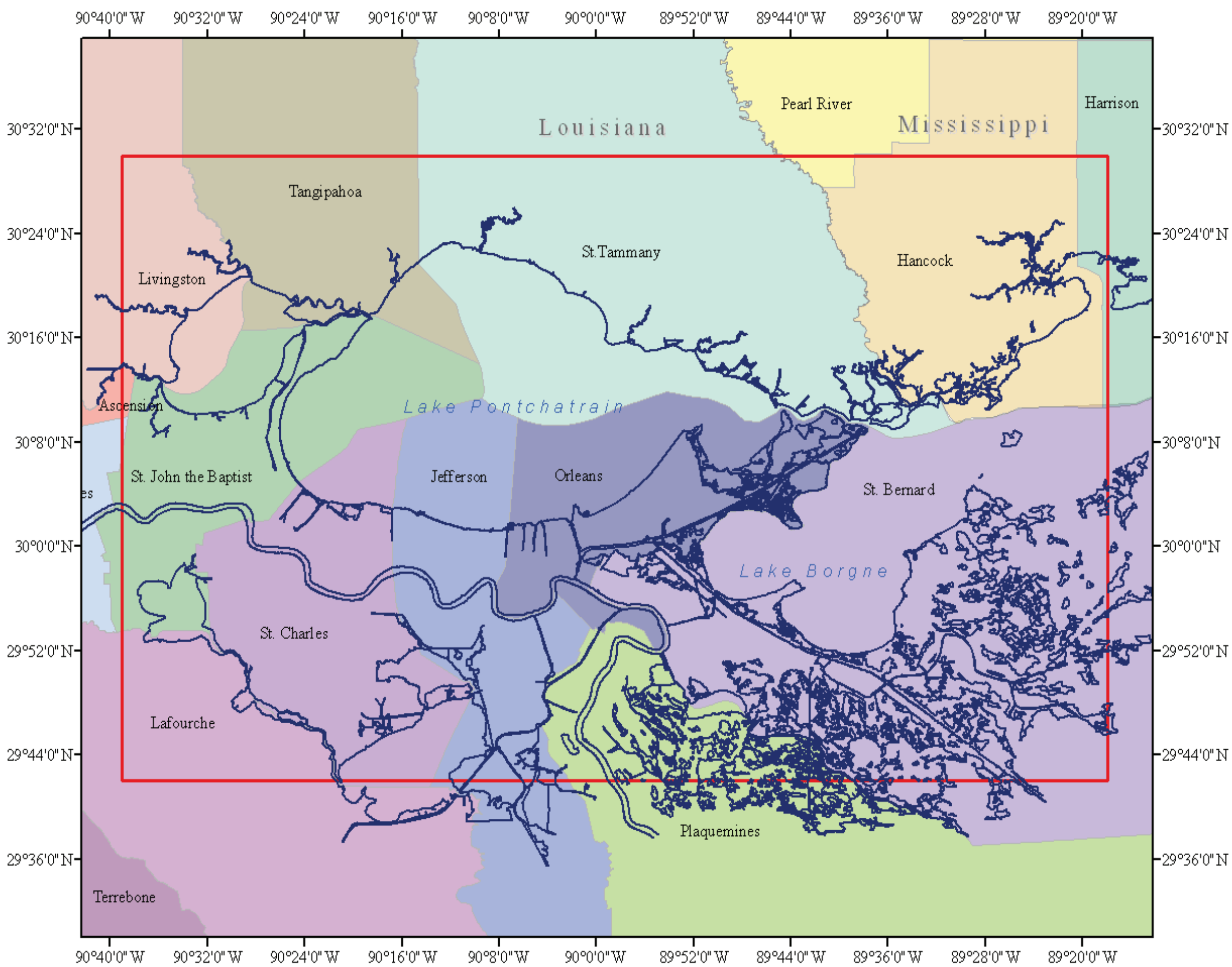

Figure 2. *Extents of the New Orleans DEM, outlined in red.*

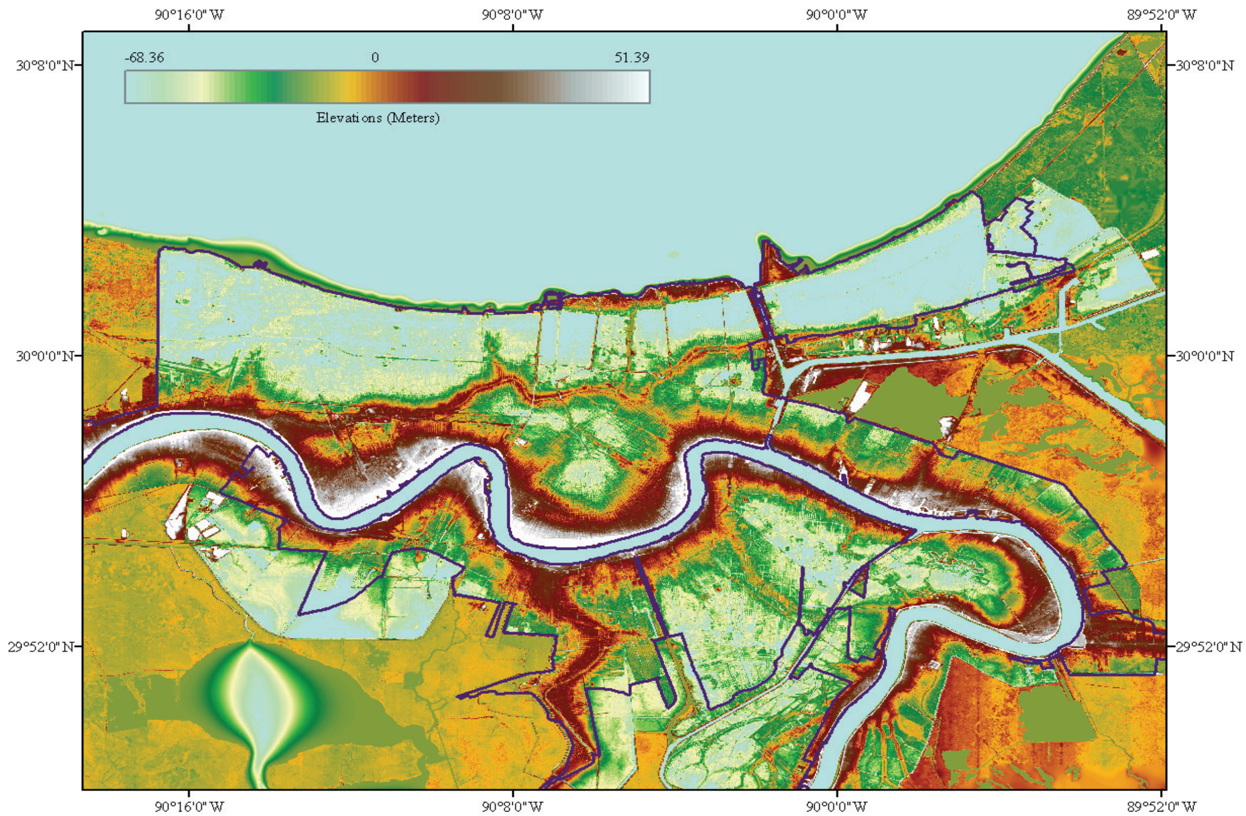

Figure 3. *Portion of the New Orleans NAVD 88 DEM showing the city of New Orleans, outlined in purple.*

3. Methodology

The New Orleans DEMs were constructed to meet CSDL specifications, based on storm surge and sea level rise modeling requirements (Tables 1 to 3). The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum 1983 (NAD 83) and North American Vertical Datum (NAVD 88). NGDC developed two conversion grids derived from *VDatum* project areas to transform the New Orleans DEM in its entirety from NAVD 88 to Mean High Water (MHW), for modeling of maximum flooding, and to Mean Lower Low Water (MLLW) (Sect. 3.3.4 & 3.3.5). Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and the DEM assembly and assessment are described in the following subsections.

Table 1. Specifications for the New Orleans NAVD 88 DEM

Grid Area	New Orleans, LA
Coverage Area	90.65º to 89.3º W; 29.7º to 30.5º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	North American Datum 1983 (NAD 83)
Vertical Datum	North American Vertical Datum 1988 (NAVD 88)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

Table 2. Specifications for the New Orleans MHW DEM

Grid Area	New Orleans, LA
Coverage Area	90.65º to 89.3º W; 29.7º to 30.5º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	North American Datum 1983 (NAD 83)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

Table 3. Specifications for the New Orleans MLLW DEM

Grid Area	New Orleans, LA
Coverage Area	90.65º to 89.3º W; 29.7º to 30.5º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	North American Datum 1983 (NAD 83)
Vertical Datum	Mean Lower Low (MLLW)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

3.1 Data Sources And Processing

3.1.1 Coastline

Coastline datasets of the New Orleans region were obtained from a variety of sources. The main coastline dataset used in developing a combined detailed coastline was the hydro-breakline dataset distributed through the LSU Atlas GIS (Fig. 4). This dataset provided a detailed NAVD 88 coastline for most of the New Orleans coverage area. NGDC evaluated but did not use the OCS coastline.

For areas not included in the detailed hydro-breaklines, a detailed coastline was digitized to aerial imagery. The digitized coastline was assumed to be drawn to the MHW coastline, and consists almost entirely of marsh-land.

Table 4. Coastline datasets used in building the New Orleans DEM

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*	*URL*
LSU	1999	Composite vectorized hydrologic breaklines	Not defined	NAD 83 geographic	NAVD 88	http://atlas.lsu.edu/rasterdown.htm
NGDC	2009	Composite vectorized coastline from aerial photography	Not defined	NAD 83 geographic	MHW	
OCS		Composite vectorized coastline	Not defined	NAD 83 geographic	MHW	http://shoreline.noaa.gov/data/datasheets/composite.html

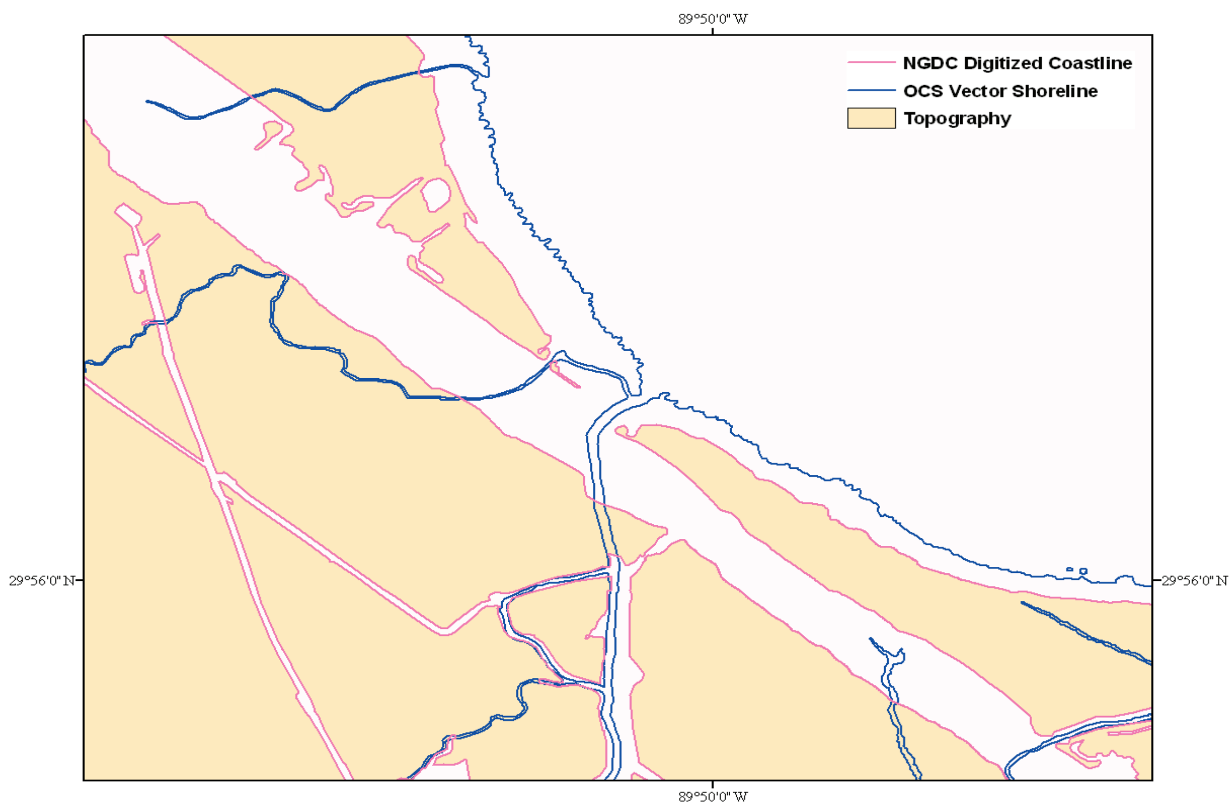

Figure 4. *Portion of Hydro-Breakline and other coastline datasets in the New Orleans DEM.*

3.1.2 Bathymetry

Bathymetric datasets available in the New Orleans region included 20 NOS hydrographic surveys, 5 NOS high-resolution hydrographic surveys in BAG format and 11 USACE hydrographic surveys of dredged channels and cross sections of lakes (Table 5; Fig. 5).

Table 5. Bathymetric datasets used in building the New Orleans NAVD 88 DEM

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*	*URL*
NOS - CSDL	1888 to 2001	Hydrographic survey soundings	Ranges from 1:5,000 to 1:80,000 (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 83 geographic	MLLW or MLW	http://www.nauticalcharts.noaa.gov/csdl/welcome.htm
NOS/ OCS/ HSD	2007	High resolution hydrographic survey soundings	N/A	NAD 83 UTM Zone 16N	MLLW	http://www.ngdc.noaa.gov/ngdc.html
USACE New Orleans District	2009	Hydrographic survey soundings	Line spacing ranging from 60 to 120 m apart and point spacing 5 to 10 m	NAD 83 Louisiana State Plane (feet)	MLG / MLLW (feet)	http://www.mvn.usace.army.mil/
NGDC	2009	Digitized soundings	N/A	NAD 83 geographic	NAVD 88	

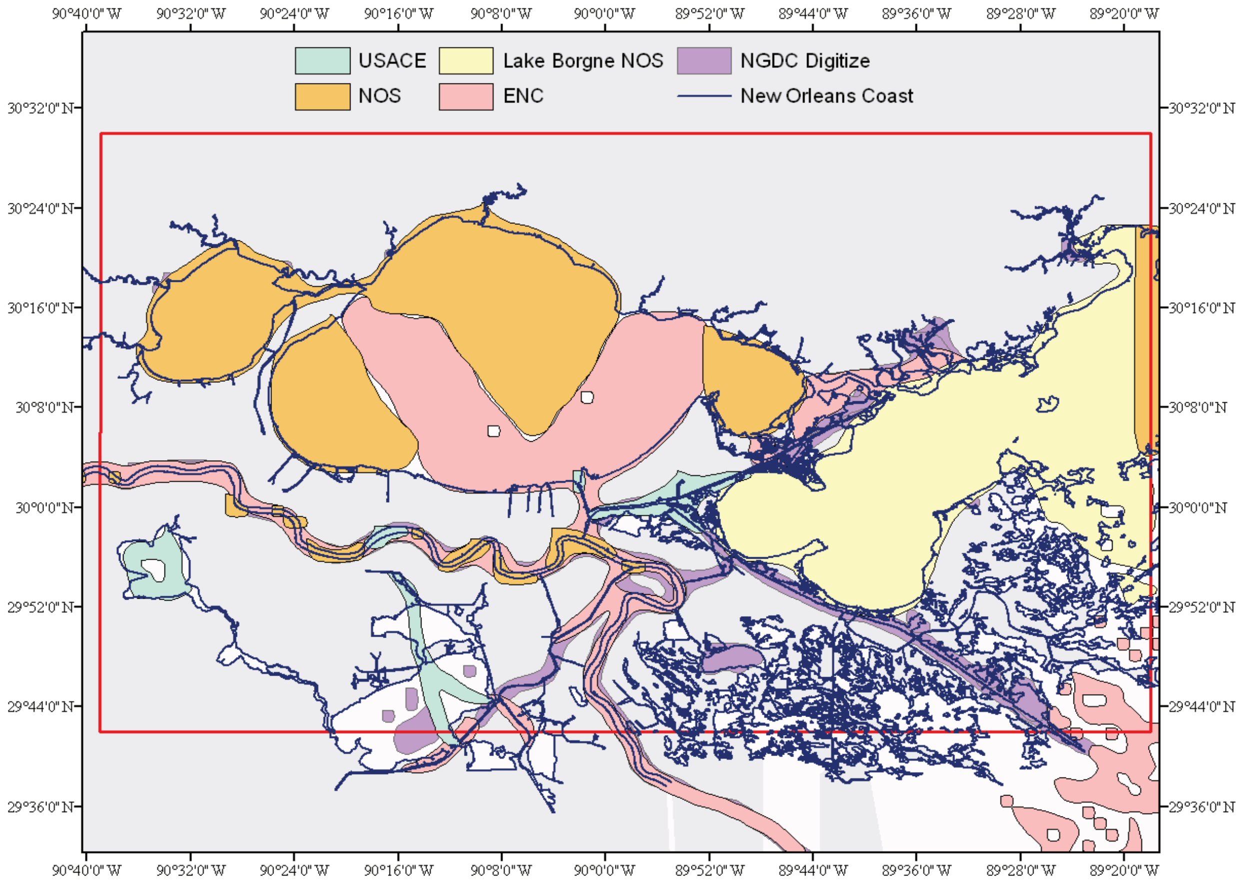

Figure 5. *Bathymetric data sources in the New Orleans region.*

1) NOS Hydrographic Surveys

A total of 20 NOS hydrographic surveys conducted between 1888 and 2001 were available for use in developing the New Orleans DEMs (Table 6; Fig. 6). CSDL provided NGDC with a non-superceded database of NOS hydrographic surveys. The database excluded NOS survey data if there were more recent NOS survey data at the same location. NGDC also manually edited older NOS hydrographic survey data that were inconsistent with USACE soundings in more recently dredged channels. The data are vertically referenced to MLLW or Mean Low Water (MLW) and horizontally referenced to NAD 83 geographic. Survey data were used in an area 0.05 degree (~5%) larger than the New Orleans DEM extent to support data interpolation across grid edges. Data point spacing for the NOS surveys varies by collection date. In general, earlier surveys have greater point spacing than more recent surveys.

NOS survey data were transformed from MLLW or MLW to NAVD 88 using *VDatum.* The data were displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to the various topographic and bathymetric data, the final coastline, and OCS Raster Navigational Charts (RNCs).

Five additional NOS surveys, collected in the areas surrounding Lake Borgne between 2007 and 2008, were available for use in the development of the New Orleans NAVD 88 DEM. These surveys consist of high density point data, with a vertical accuracy of 1-3 meters (see Table 6, Figure 7).

Table 6. Digital NOS hydrographic surveys available in the New Orleans DEM region.

Survey ID	Year	Scale / Vertical Accuracy	Original Vertical Datum	Provided Horizontal Datum
F00476	2001	10,000	MLLW	NAD 83
H03961	1917	1:40,000	MLW	Undetermined
H02381	1899	1:20,000	MLW	Undetermined
H02342	1898	1:20,000	MLW	Undetermined
H02341	1898	1:20,000	MLW	Undetermined
H02295	1897	1:20,000	MLW	Undetermined
H02380	1899	1:20,000	MLW	Undetermined
H09861	1979	20,000	LLL -Lake Champlin	NAD 27
H09354	1973	20,000	MLW	NAD 27
H09347	1972	20,000	MLW	NAD 27
H09279	1972	10,000	MLW	NAD 27
H09263	1971	10,000	MLW	NAD 27
H09262	1971	10,000	MLW	NAD 27
H09261	1971	20,000	MLW	NAD 27
H09200	1971	20,000	MLW	NAD 27
H09199	1971	10,000	MLW	NAD 27
H09177	1970	10,000	MLW	NAD 27
H09156	1970	10,000	MLW	NAD 27
H09028	1970	20,000	MLW	NAD 27
H08970	1968	10,000	MLW	NAD 27
H11612	2007	1-5 meters	MLLW	NAD 83
H11613	2007	1-5 meters	MLLW	NAD 83
H11614	2007	1-5 meters	MLLW	NAD 83
H11615	2007	1-5 meters	MLLW	NAD 83
H11616	2007	1-5 meters	MLLW	NAD 83

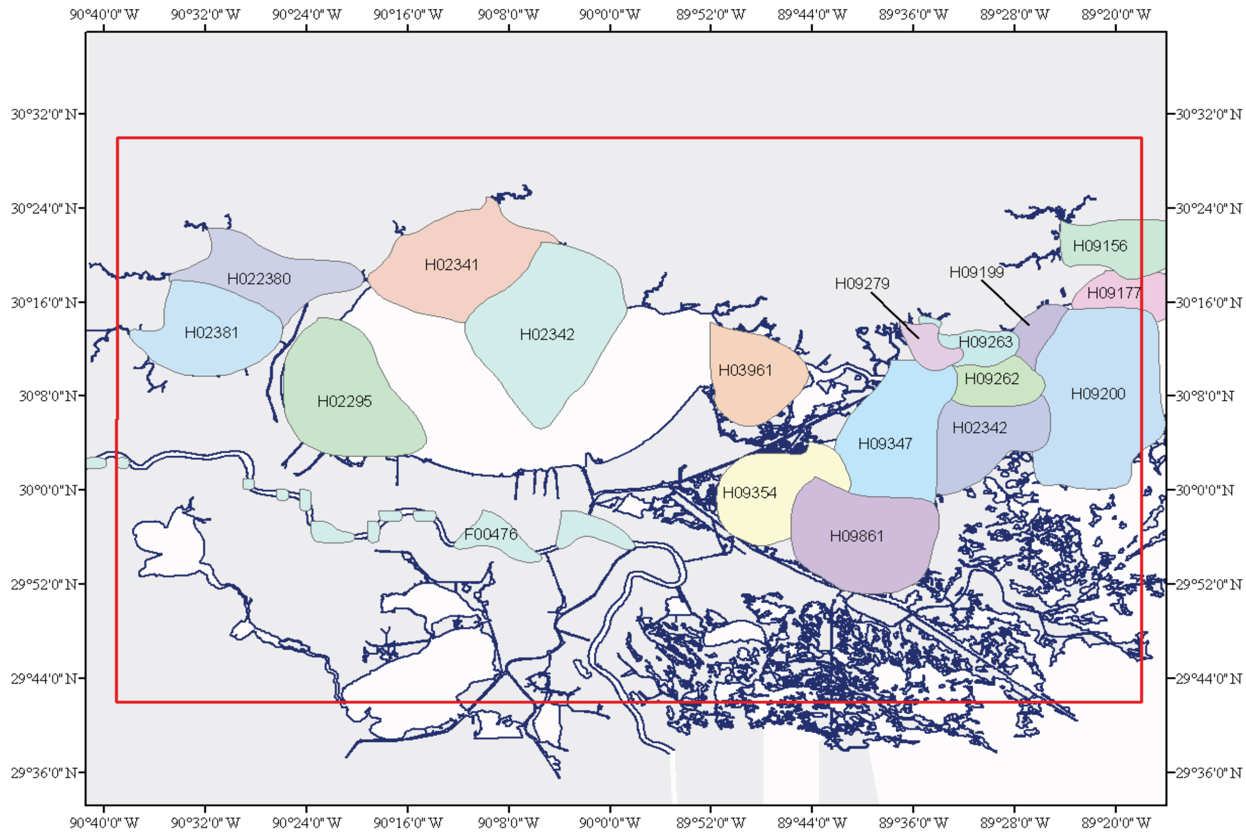

Figure 6. *NOS digital hydrographic survey coverage in the New Orleans region. Some soundings from earlier surveys were not used as they have been superseded by more recent surveys. DEM boundary in red.*

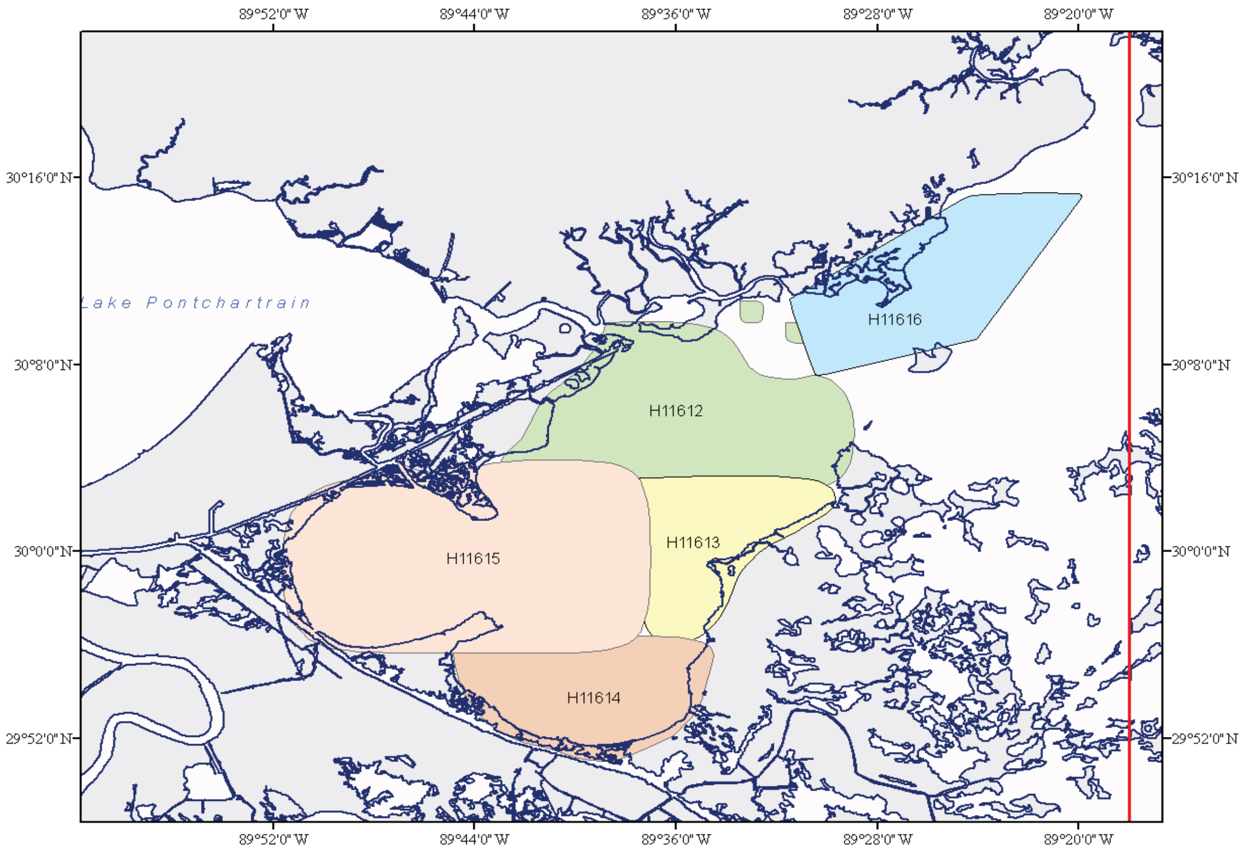

Figure 7. *Lake Borgne NOS hydrographic data coverage in the New Orleans region. DEM boundary in red.*

2) USACE hydrographic surveys

Three USACE bathymetric survey projects located at least partially within the New Orleans DEM project boundaries were downloaded from the USACE New Orleans District web site in Design (DGN) format (Table 7; Fig. 8). Seven additional surveys located within the New Orleans DEM were delivered to NGDC from the USACE New Orleans District as xyz ascii files. NGDC used *GDAL*[3] to extract xyz data from the DGN files. Several DGN files lacked corresponding xyz data. NGDC digitized the missing sections of the dredged channels to ensure their representation in the DEMs (Fig. 9). The surveys were collected in 2009, and referenced to NAD 83 Louisiana State Plane (feet) and MLG (Mean Low Gulf) (feet) datums. The files were converted to NAD 83 geographic and NAVD 88 (meters) using *Proj4* and *VDatum*[4]. Surveys consist of numerous, parallel, across-channel profiles, spaced 10 to 350 meters apart, with point soundings 1 to 10 meters apart.

3. *GDAL* is a translator library for raster geospatial data formats that is released under an X/MIT style Open Source license by the Open Source Geospatial Foundation. As a library, it presents a single abstract data model to the calling application for all supported formats. It also comes with a variety of useful commandline utilities for data translation and processing.

4. *Proj4* was used to horizontally transform datasets that originated in a State Plane datum before vertical transformations were performed using *VDatum*, which did not support state plane transformations at the time of development.

Table 7. USACE Hydrographic survey areas, named by project, used in building the New Orleans NAVD 88 DEM

Region	*Year of Survey*	*Spatial Resolution*	*Original Vertical Datum*	*Original Horizontal Datum*
Mississippi River Crossing (Fairview)	2008	~ 50 - 300 m profile spacing ~ 5 - 10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
Mississippi River Gulf Outlet	2009	~ 50 - 300 m profile spacing ~ 5 - 10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
New Orleans Harbor	2010	~ 50 - 300 m profile spacing ~ 5 - 10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)

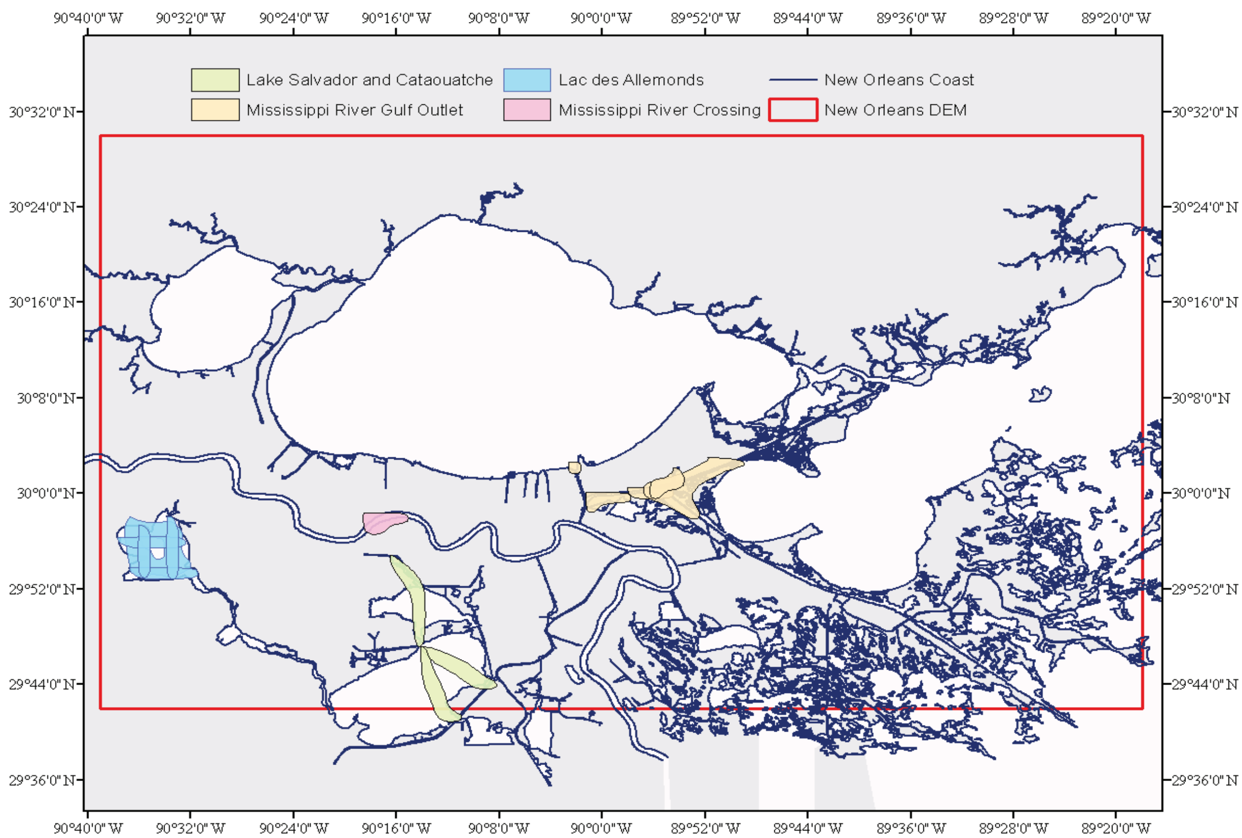

Figure 8. *USACE hydrographic data coverage in the New Orleans region.*

3) NGDC digitized soundings

NGDC used GEODAS Hydro-Plot[5] to digitize bathymetric soundings in estuary rivers and dredge channels. NGDC interpolated bathymetric soundings at 10 meter spacing based on available bathymetric soundings and OCS (Office of Coastal Survey) RNCs. Interpolated soundings were created in estuary rivers and dredged channels to more accurately model the channels' morphology where there were no NOS hydrographic survey soundings or the NOS soundings' point spacing were significantly greater than 10 meters (Fig. 9).

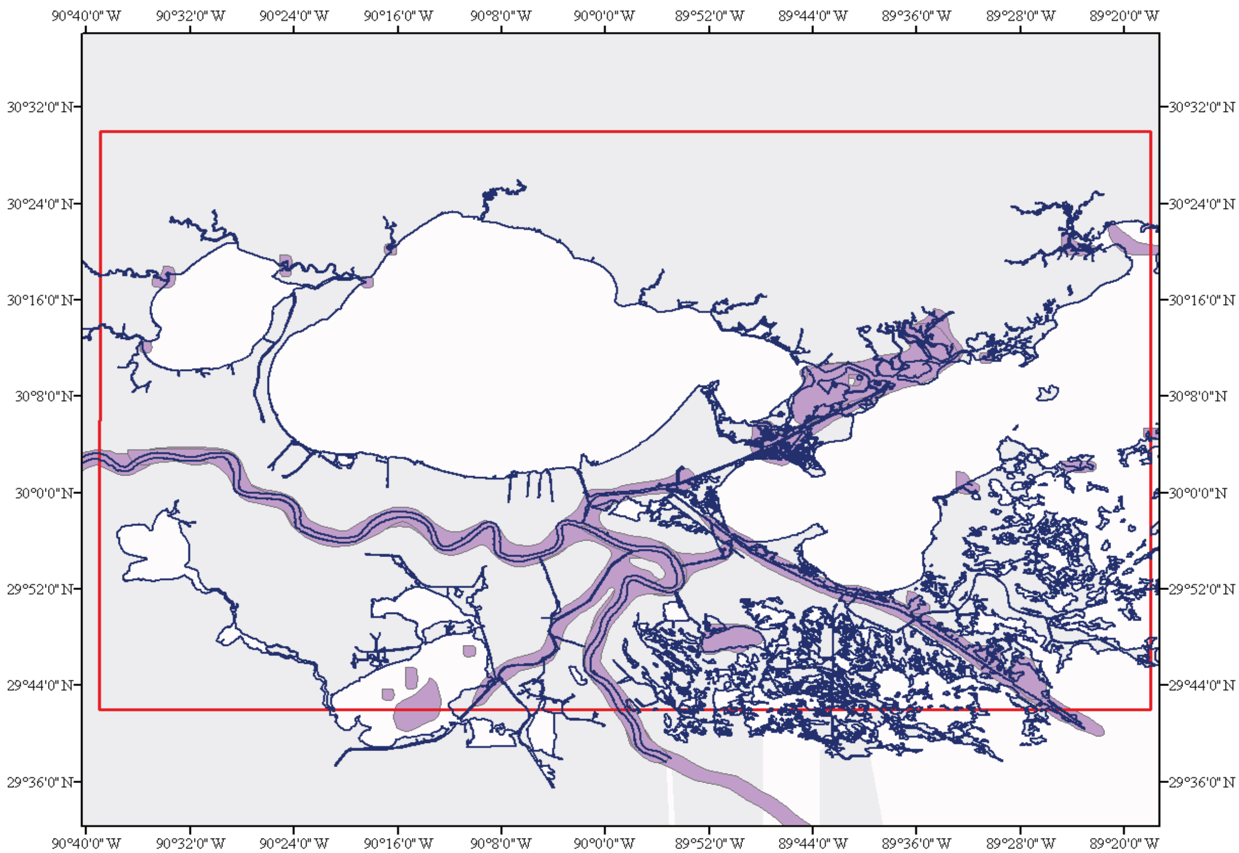

Figure 9. *NGDC HydroPlot digitization coverage in the New Orleans region.*

5. *Hydro-Plot* is a MS Windows and Linux-x86 GEODAS application developed by NGDC to display geographical plots of data from the *GEODAS* DVD sets, including NOS Hydrographic Surveys, Marine Trackline Geophysics and *GEODAS* Gridded Databases, as well as XYZ-type data files, Arc-type grids and ESRI shapefiles for data, contours and coastlines. Hydro-Plot displays maps of data directly on the screen, coloring the data according to their value. *Hydro-Plot* can also be used for viewing histograms and profiles of the data, and for editing data, including deleting records, changing record fields, and creating new records, as well as for automated Quality control of data files [Extracted from *GEODAS Hydro-Plot* help section].

3.1.3 Topography

The topographic datasets used to build the New Orleans NAVD 88 DEM include: Louisiana State lidar; Hancock County, MS lidar; Harrison County, MS lidar; Pearl River County, MS lidar; CSC Merged Mississippi lidar and CSC Post Katrina Levees lidar (Table 8; Fig. 10). NGDC evaluated but did not use the USGS NED 1, NED 1/3 or NED 1/9th arc-second DEM due to the poor quality of data in the areas of interest (Fig 18). NGDC also evaluated but did not use in its entirety the USACE 2005 Post-Hurricane Katrina Topographic Mapping lidar as it was not processed to bare-earth, though a small portion was used to provide better representation of levees where no other data were available (Fig. 14).

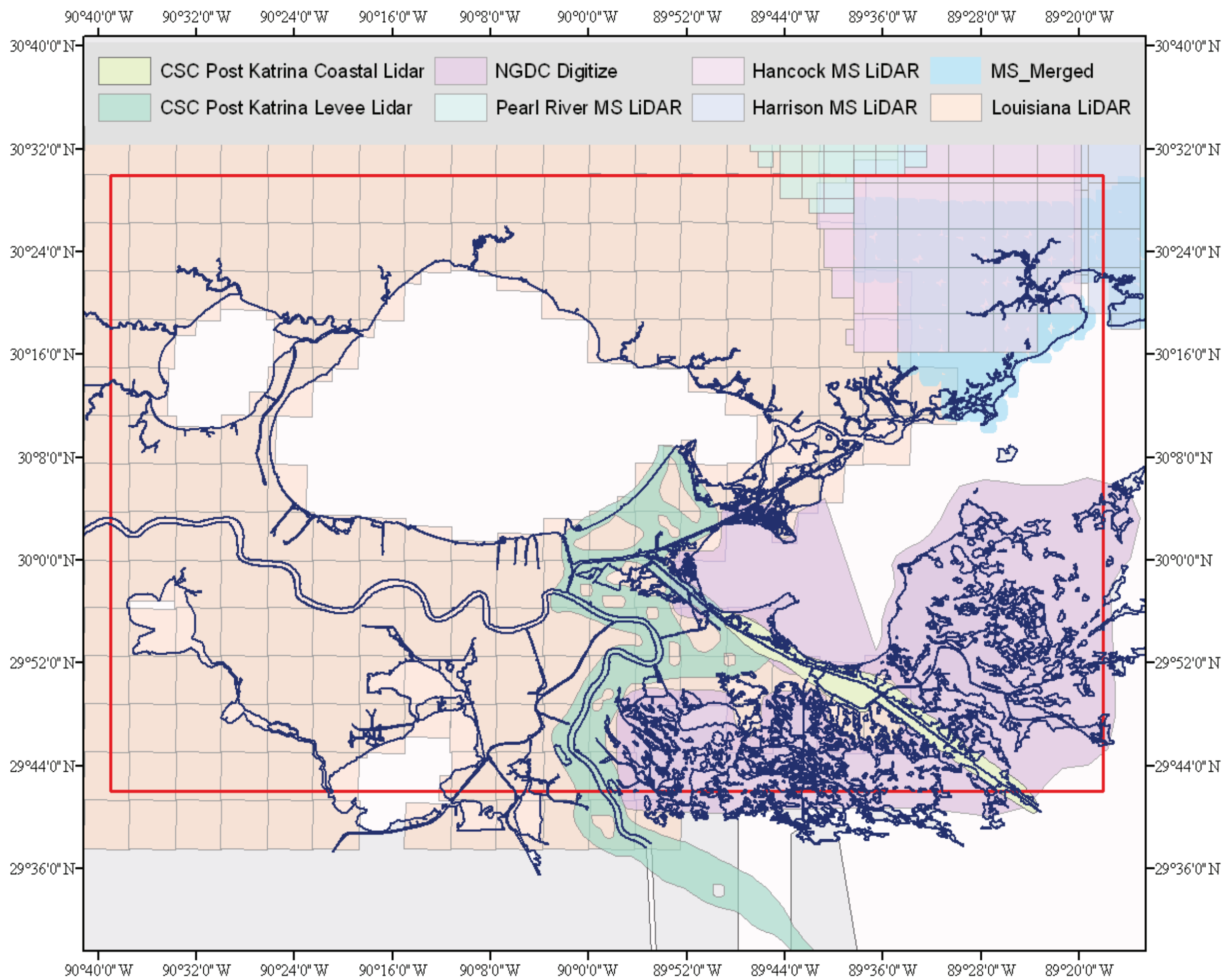

Figure 10. *Topographic data sources used in the New Orleans DEM*

Table 8. Topographic Datasets used in building the New Orleans NAVD 88 DEM

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
LSU Atlas	1999	Bare-earth lidar	1 - 5 meters	UTM Zone 15 N	NAVD 88 GEOID 2009 Feet	http://atlas.lsu.edu/lidar/
Mississippi State Government	2001	Bare-earth lidar	1 - 5 meters	NAD 83 Mississippi State Plane East	NAVD 88 GEOID03 Meters	
CSC	2005	Non Bare-earth lidar	1 - 5 meters	WGS 84	NAVD 88	http://webqa.csc.noaa.gov/digitalcoast/data/coastallidar/index.html
CSC	2005	Non Bare-earth Levees lidar	1 -5 meters	WGS 84	NAVD 88	http://webqa.csc.noaa.gov/digitalcoast/data/coastallidar/index.html
CSC	2005	Bare-earth merged lidar	1 -5 meters	UTM Zone 15N	NAVD 88	http://webqa.csc.noaa.gov/digitalcoast/data/coastallidar/index.html

1) State of Louisiana lidar

Topographic lidar of the State of Louisiana was collected by 3001 Inc. in 2003 for the United States Army Corps of Engineers, St. Louis District (Fig. 11). The data were provided by LSU Atlas GIS as ascii csv files and were referenced to NAD 83 UTM Zone 15N, with a vertical datum of NAVD 88 GEOID 1999. The assessed vertical accuracy was 17.44 cm average[6] RMSE[7], while the horizontal accuracy was not assessed.

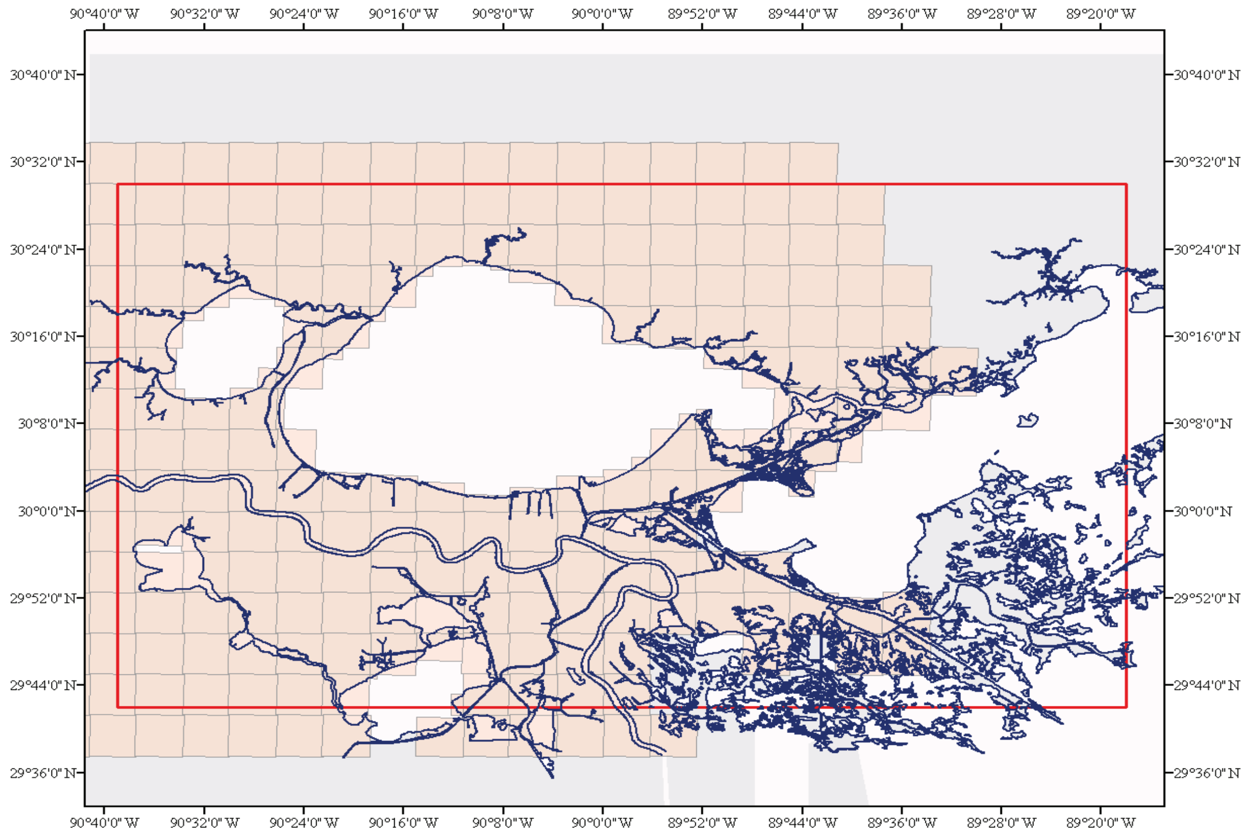

Figure 11. *Louisiana lidar data extents used in the New Orleans DEM*

6. An RMSE was not calculated for the entire project. The 'Average RMSE' represents the average of the RMSE values for the 'task-areas' used to build the New Orleans DEMs, which include task-areas 1,3,4,5,6 and 11.

7. Root Mean Square Error is defined as the square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points.

2) State of Mississippi County lidar

The Mississippi state Government collected topographic lidar for each of it's counties in 2002 (Fig. 12). The data for three counties (Pearl River, Hancock and Harrison) were provided to NGDC as ASPRS formatted LAS files, including bare-earth classifications, by the Mississippi State GIS Manager. Data were referenced to NAD 83 Mississippi State Plane East (feet).

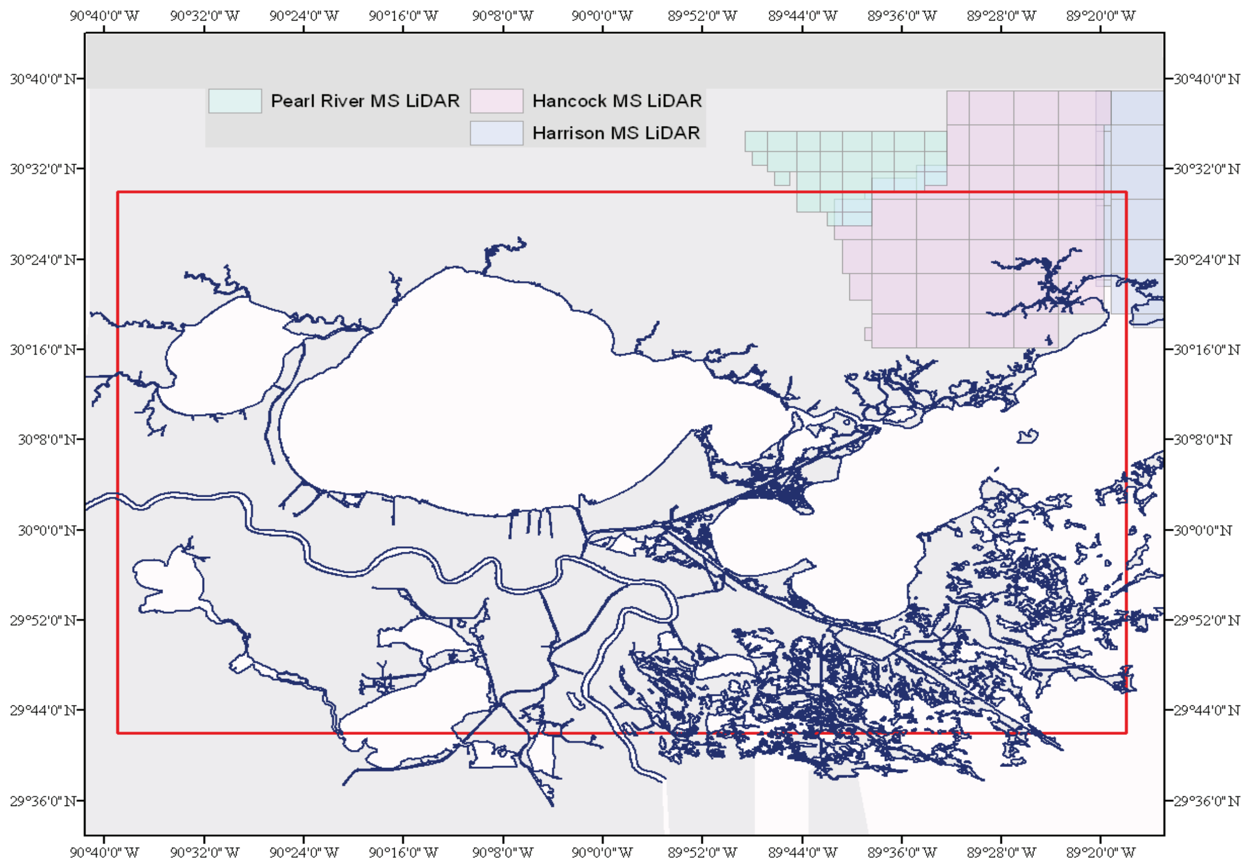

Figure 12. *Mississippi Lidar data sources used in the New Orleans DEM.*

3) CSC levee lidar

Helicopter-mounted topographic lidar data were collected for the U.S. Army Corps of Engineers over the New Orleans Hurricane Protection Levee System in Louisiana following Hurricane Katrina. The horizontal and vertical accuracies of this dataset was not assessed. These data were collected for the assessment of Hurricane Katrina's damage to the hurricane protection levees. Users should be aware that the data depict the heights at the time of the survey and are only accurate for that time. Users should not use this data for critical applications without a full awareness of its limitations.

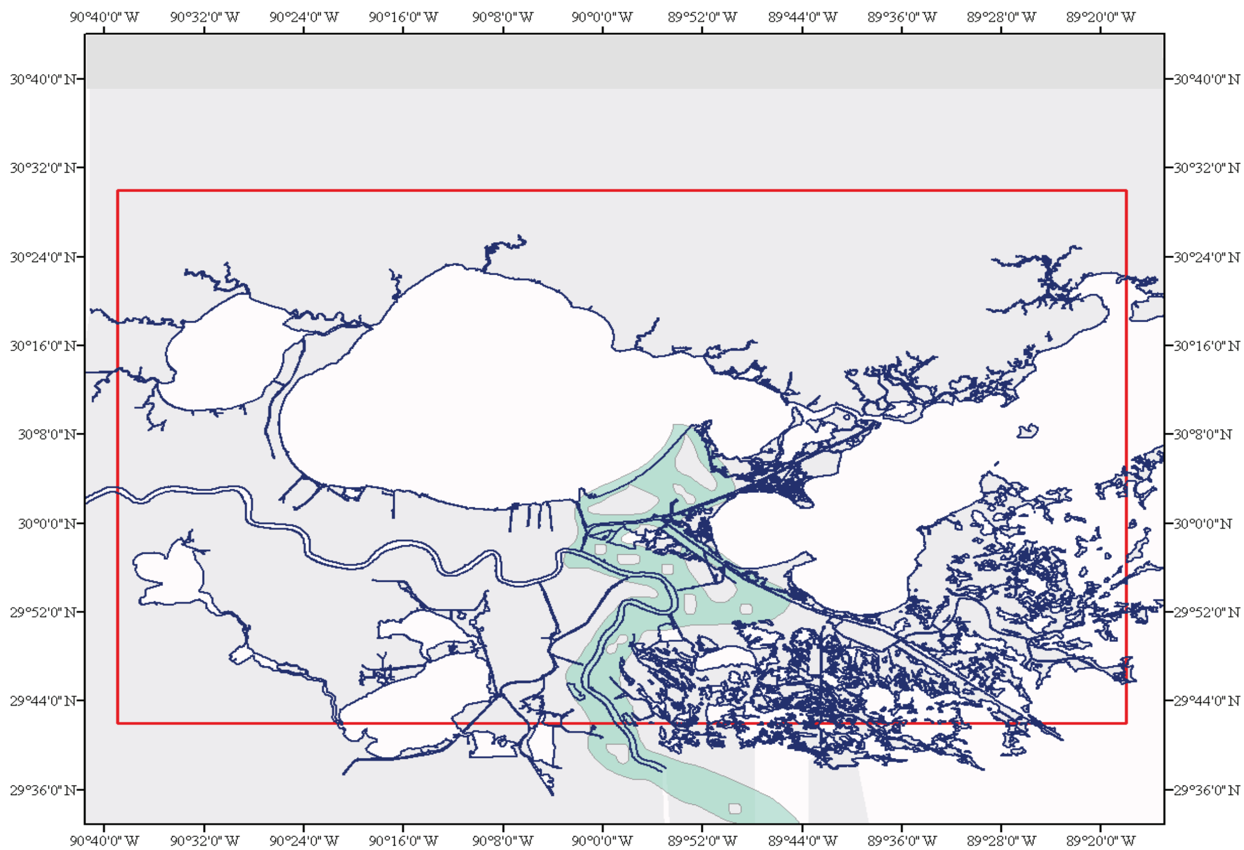

Figure 13. *CSC Post Katrina Levee Lidar data used in the New Orleans DEM.*

4) CSC Coastal lidar

The lidar-derived data were collected by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system. The data includes hydrographic and topographic data. The data were collected to depict the elevations above and below water along the immediate coastal zone. The survey generally extends 750 meters inland and up to 1500 meters over the water (depending on water depth and clarity). The goal of the project was to collect data covering the shoreline of the conterminous United States where feasible. The project was lead by the U.S. Army Corps of Engineers. The assessed vertical accuracy of this dataset was 0.20 meters at 1 sigma.

This dataset was evaluated and portions were used for the development of the New Orleans DEMs (Fig. 14) to better model levees where no other data were available. The entire dataset was not used in the development of the New Orleans DEMs due to the fact that the dataset was not filtered to bare earth.

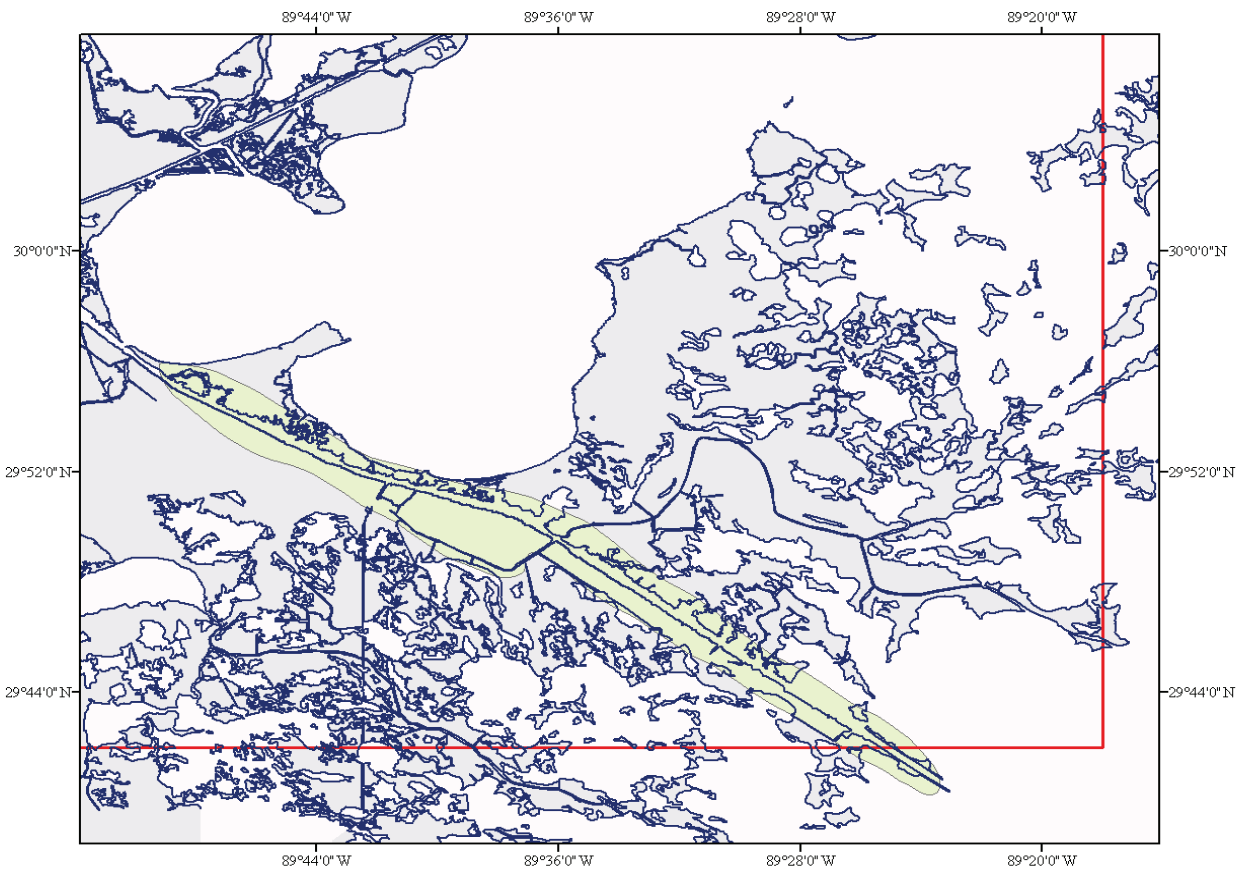

Figure 14. *Portion of CSC coastal lidar used in the development of the New Orleans DEMs*

5) CSC Merged Mississippi Lidar

Pre- and post-hurricane Katrina lidar datasets of Hancock, Harrison, and Jackson Counties, Mississippi, were merged into a seamless coverage by the URS Corporation (Fig. 15). The pre-Katrina lidar data were collected by EarthData International at a 5-meter posting density during the period of February 25 to March 30, 2005. Woolpert and USACE collected the post-Katina lidar data. Woolpert acquired 1-meter posting density data of coastal Mississippi between the dates of September 19 and October 9, 2005. USACE collected 1-meter posting density lidar of the Mississippi barrier islands over the same time period. Each dataset was clipped at the approximate location of the debris line. Data south of the debris line were removed from the Mississippi lidar dataset. Data north of the debris line were removed from the post-Katrina lidar dataset. The post-Katrina lidar dataset was then imported into the seamless Mississippi lidar dataset creating a merged seamless coverage.

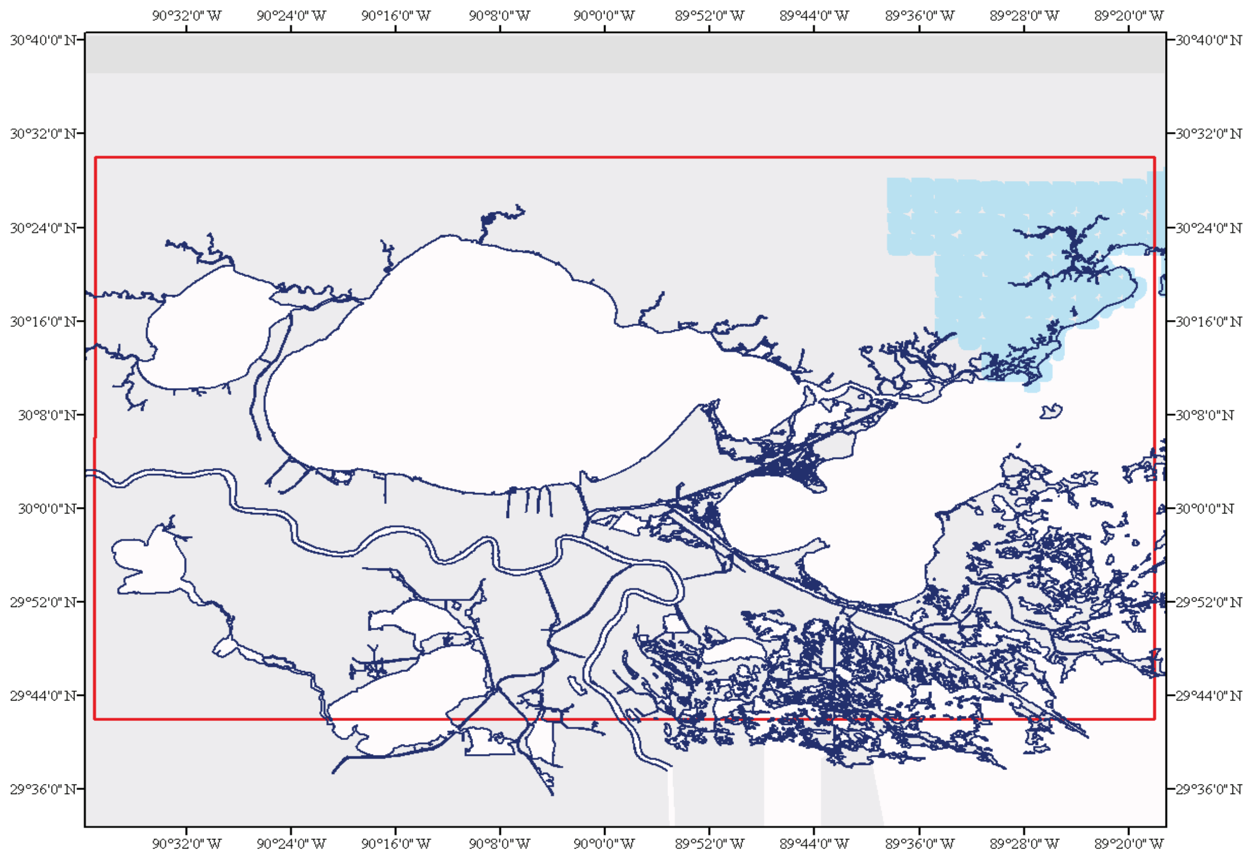

Figure 15. *CSC Mississippi Merged Lidar dataset used in the New Orleans DEM.*

6) NGDC Digitized elevations

The NGDC digitized topography in areas of heavy marshland and swamp (Fig. 16 and 17) in the areas surrounding Saint Bernard and Plaquemines parishes. Available USGS NED topographic data for this region were determined to be of poor quality and were not used (Fig. 18). NGDC utilized the 'NAVD 88 to MHW' conversion grid along with satellite imagery to determine the elevation values of the marshes and swamps. The vertical accuracy of this dataset has not been determined.

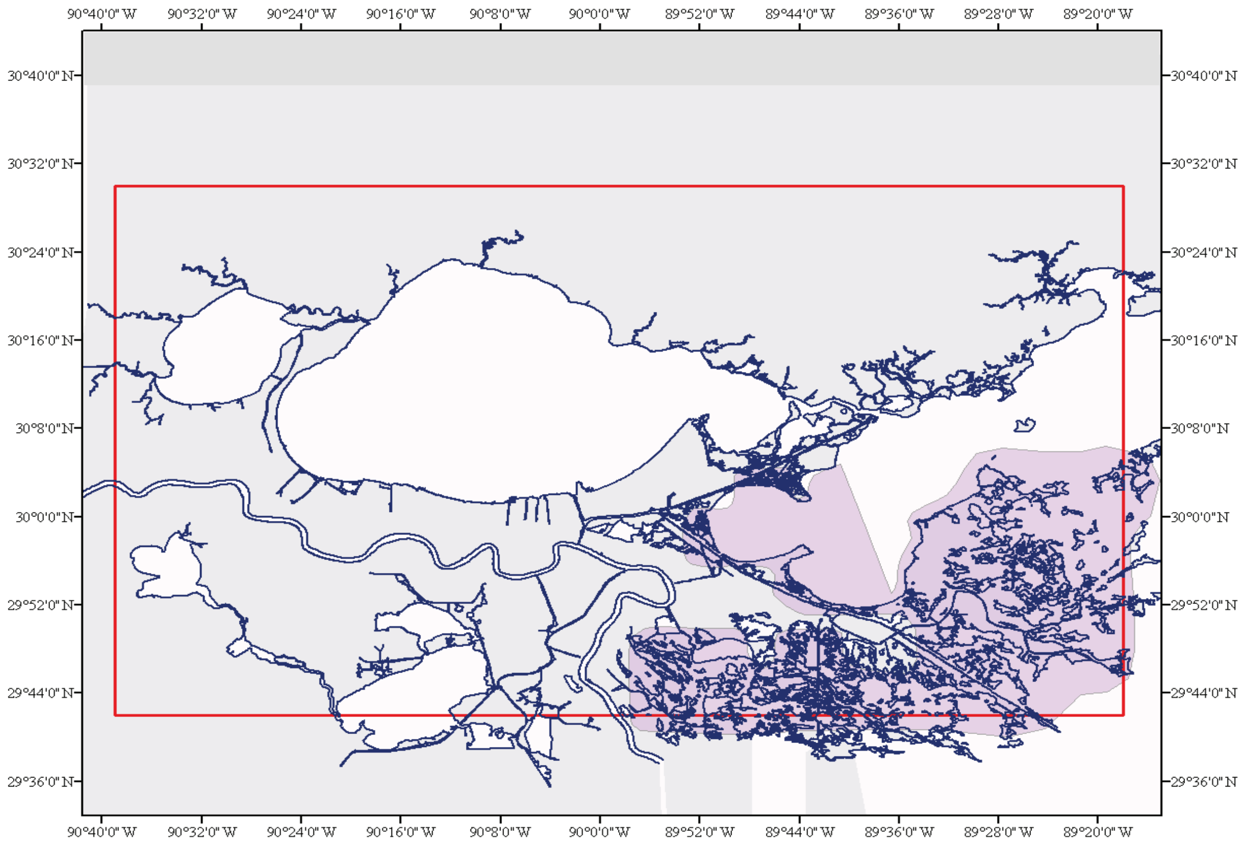

Figure 16. *NGDC Digitized elevations used in the New Orleans DEM.*

Figure 17. *Wetlands of St. Bernard Parish*

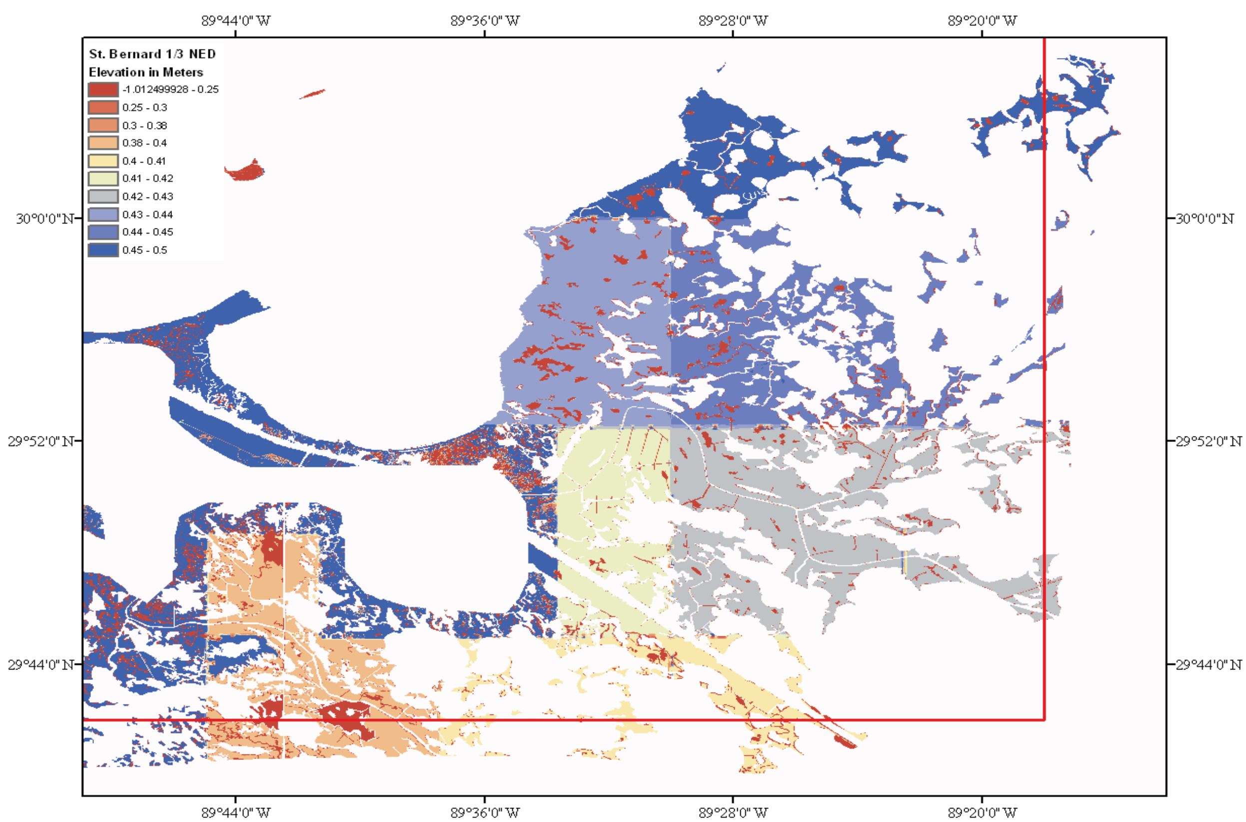

Figure 18. *USGS NED 1/3 topographic data available in Saint Bernard Parish.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the New Orleans NAVD 88 DEM were originally referenced to several vertical datums including MLLW, MLW, MLG and NAVD 88. All datasets were transformed to NAVD 88 using *VDatum*.

1) Bathymetric data

All hydrographic surveys were transformed from MLLW or MLW to NAVD 88, using *VDatum*.

2) Topographic data

All topographic datasets used in the compilation of the New Orleans NAVD 88 DEM originated in NAVD 88 vertical datum. No further vertical transformations were required for these datasets. Vertical transformations of the Louisiana lidar dataset were performed to increase the accuracy of the dataset (see Sect. 3.2.2).

3.2.2 Vertical Transformation of Louisiana Lidar dataset

The Louisiana lidar dataset was originally referenced to NAVD 88 GEOID 1999. Using *VDatum*, the dataset was transformed to be referenced to NAVD 88 GEOID 2009 (Fig. 19). The data were first transformed in *VDatum* from NAVD 88 GEOID 1999 to ellipsoidal heights. The resulting data were then transformed back to NAVD 88 in *VDatum* using GEOID 2009 as a reference model. The resulting data provides more accurate height values using the most up-to-date GEOID model (Sect. 3.2.2.1).

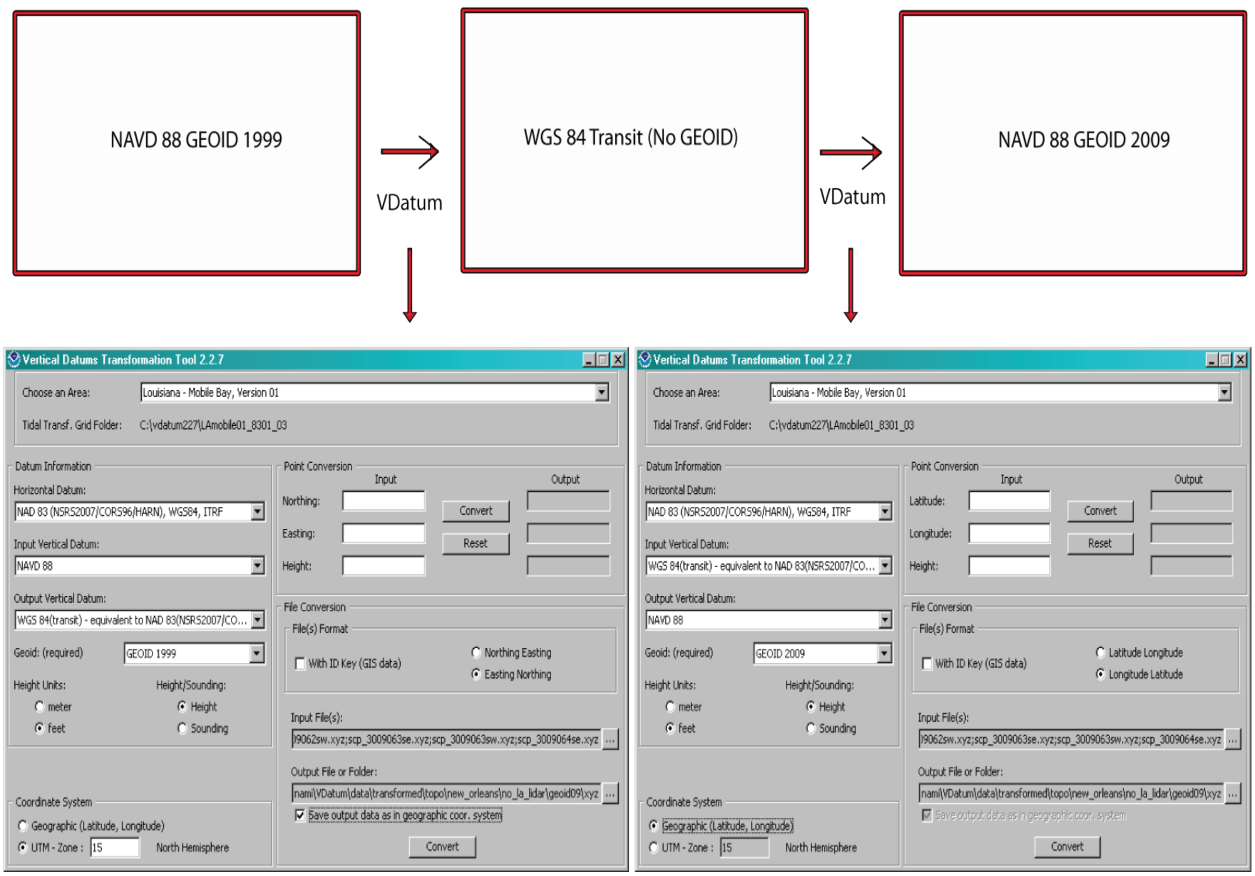

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Figure 19. *Louisiana lidar vertical transformations using VDatum.*

The vertical accuracy of the Louisiana lidar dataset was assessed by comparing the original dataset, which was referenced to GEOID 1999, and the transformed dataset, which was referenced to GEOID 2009, to the more accurate NOAA NGS geodetic monument dataset for Louisiana. The results of each were compared to confirm the validity of transforming the original dataset from GEOID 1999 to GEOID 2009.

Using 80 NOAA NGS geodetic monuments (Fig. 39) the calculated RMSE for the GEOID 1999 dataset was 31.5 cm, with a vertical accuracy of 61.7 cm at the 95 percent confidence level, while the calculated RMSE for the transformed GEOID 2009 dataset was 26.73 cm, with a vertical accuracy of 52.4 cm at the 95 percent confidence level.

The results of the statistical accuracy assessment (Figures 20 and 21; Tables 9 and 10) show an improvement in the accuracy of the Louisiana lidar dataset after transforming the dataset to be referenced to GEOID 2009 using *VDatum*.

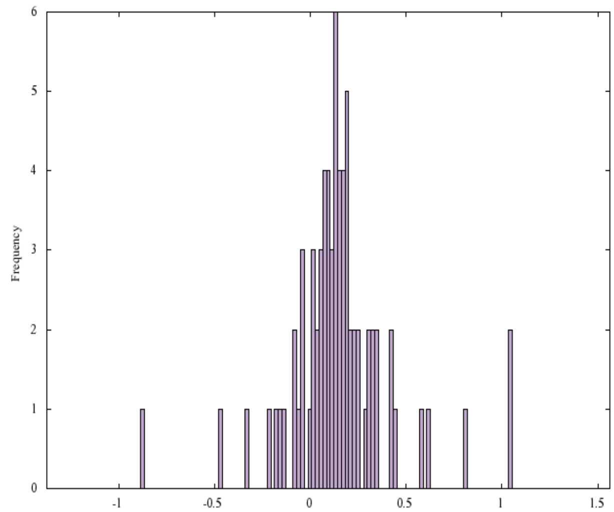

Figure 20. *Histogram of the differences between the Louisiana lidar dataset, referenced to GEOID 1999, and the NGS geodetic monuments.*

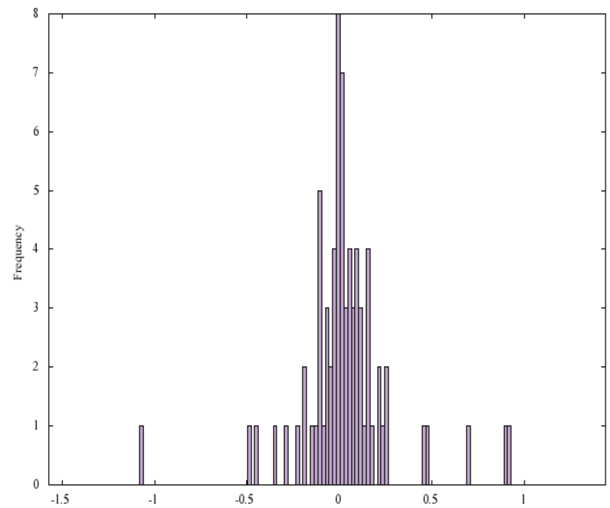

Figure 21. *Histogram of the differences between the Louisiana lidar dataset, referenced to GEOID 2009, and the NGS geodetic monuments.*

Table 9. Statistical Results of the Louisiana lidar dataset referenced to GEOID 1999 compared with NGS geodetic monuments. Units are in Meters.

Louisiana lidar dataset referenced to NAVD 88 GEOID 1999	
Average	0.09919
RMSE	0.314945
Vertical Accuracy (RMSE * 1.96)	0.617291

Table 10. Statistical Results of the Louisiana lidar dataset referenced to GEOID 2009 compared with NGS geodetic monuments. Units are in Meters.

Louisiana lidar dataset referenced to NAVD 88 GEOID 2009	
Average	0.071455
RMSE	0.26731
Vertical Accuracy (RMSE * 1.96)	0.523927

3.2.3 Horizontal datum transformations

Datasets used to build the New Orleans NAVD 88 DEM were downloaded or received referenced to WGS 84 geographic, NAD 83 geographic, NAD 83 Louisiana State Plane (feet) and NAD 83 UTM Zone 16 or 15 N horizontal datums. The relationships and transformational equations between these horizontal datums are well established. Data were converted to a horizontal datum of NAD 83 geographic using *Vdatum* or *Proj4.*

3.2.4 VDatum assessment

VDatum is a free software tool developed jointly by NOAA's OCS, NGS and CO-OPS. *VDatum* is designed to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datums - allowing users to convert their data from different horizontal/vertical references into a common system and enabling the fusion of diverse geospatial data in desired reference levels (http://vdatum.noaa.gov/).

VDatum proved useful in the transformations of a diverse range of datasets, all originating in various horizontal and vertical datums to a common horizontal/vertical reference system. The accuracy and reliability of an integrated bathymetric-topographic DEM depends upon the processes used to transform the various source datasets into common reference systems. *VDatum* provides a clear and reliable method of achieving datum parity between datasets.

VDatum also proved useful in the development of various 'conversion grids' used in creating the derivative New Orleans MHW and MLLW DEMs (Secs. 3.3.4 and 3.3.5), negating the need to apply constant offsets to achieve the same result at a lesser degree of accuracy. This methodology allows for the development of one NAVD 88 DEM, which can then be used to generate various DEMs in any of the supported *VDatum* vertical datums, allowing for any source data updates to be performed solely on the NAVD 88 DEM, using the *VDatum* derived conversion grids to generate the derivative DEMs in various datums.

Possible improvements to *VDatum* include: support for State Plane horizontal datums and the inclusion of support for the input and output of ASPRS formatted LAS lidar files. These two improvements would lessen the need for pre-processing of data prior to use in *VDatum* and improve the overall workflow involved in transforming a variety of datasets to common horizontal/vertical datums.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the ascii xyz files were converted to ESRI shapefiles for review. The resulting ESRI shapefiles were checked for consistency between datasets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files using FME in preparation for gridding.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic survey data are generally sparse relative to the resolution of the 1/3 arc-second New Orleans NAVD 88 DEM. This is especially true for deeper-water surveys in the Gulf of Mexico and shallow water surveys in Lake Pontchartrain where data have point spacing up to 350 meters apart. In order to reduce the effect of artifacts created in the DEM by the low-resolution NOS datasets, and to provide effective interpolation in the deep water and into the coastal zone, a 1/3 arc-second-spacing 'pre-surface' bathymetric grid was generated using *Generic Mapping Tools*[8] (*GMT)*. The coastline elevation value was set at 0 meters to ensure a bathymetric surface below zero in areas where data are sparse or non-existent.

The point data were median-averaged using the *GMT* tool 'blockmedian' to create a 1/3 arc-second grid 0.05 degrees (~5%) larger than the New Orleans NAVD 88 DEM gridding region. The *GMT* tool 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The netcdf grid created by 'surface' was converted into an ESRI Arc ASCII grid file, and clipped to the final coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original NOS soundings to ensure grid accuracy (Fig. 22), and then exported as an xyz file for use in the final gridding process (Table 9).

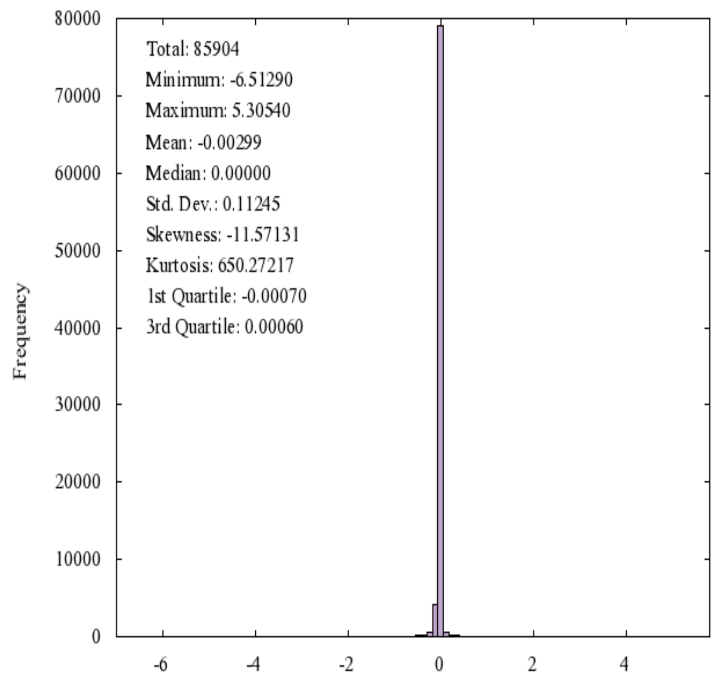

Figure 22. *Histogram of the differences between the NOS hydrographic soundings and the New Orleans bathymetric surface*

8. *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.]

3.3.3 Building the NAVD 88 DEM

MB-System[9] was used to create the 1/3 arc-second New Orleans NAVD 88 DEM. *MB-System* is an NSF-funded open source 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’ 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 11. The resulting binary grid was converted to an Arc ASCII grid using the *MB-System* tool ‘mbm_grd2arc’ to create the final 1/3 arc-second New Orleans NAVD 88 DEM. Figure 23 illustrates cells in the DEM that have interpolated values (shown as white) versus data contributing to the cell value (shown as black).

Table 11. Data hierarchy used to assign gridding weight in *MB-System*

Dataset	Relative Gridding Weight
CSC levees lidar	200
Louisiana Lidar	150
CSC bathymetric-topographic lidar	20
Pearl River County Lidar	10
Harrison County Lidar	10
Hancock County Lidar	10
Mississippi Merged Lidar	5
NOS hydrographic surveys	5
USACE hydrographic surveys	5
Digitized features	5
Pre-surfaced bathymetric grid	0.5

9. *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.]

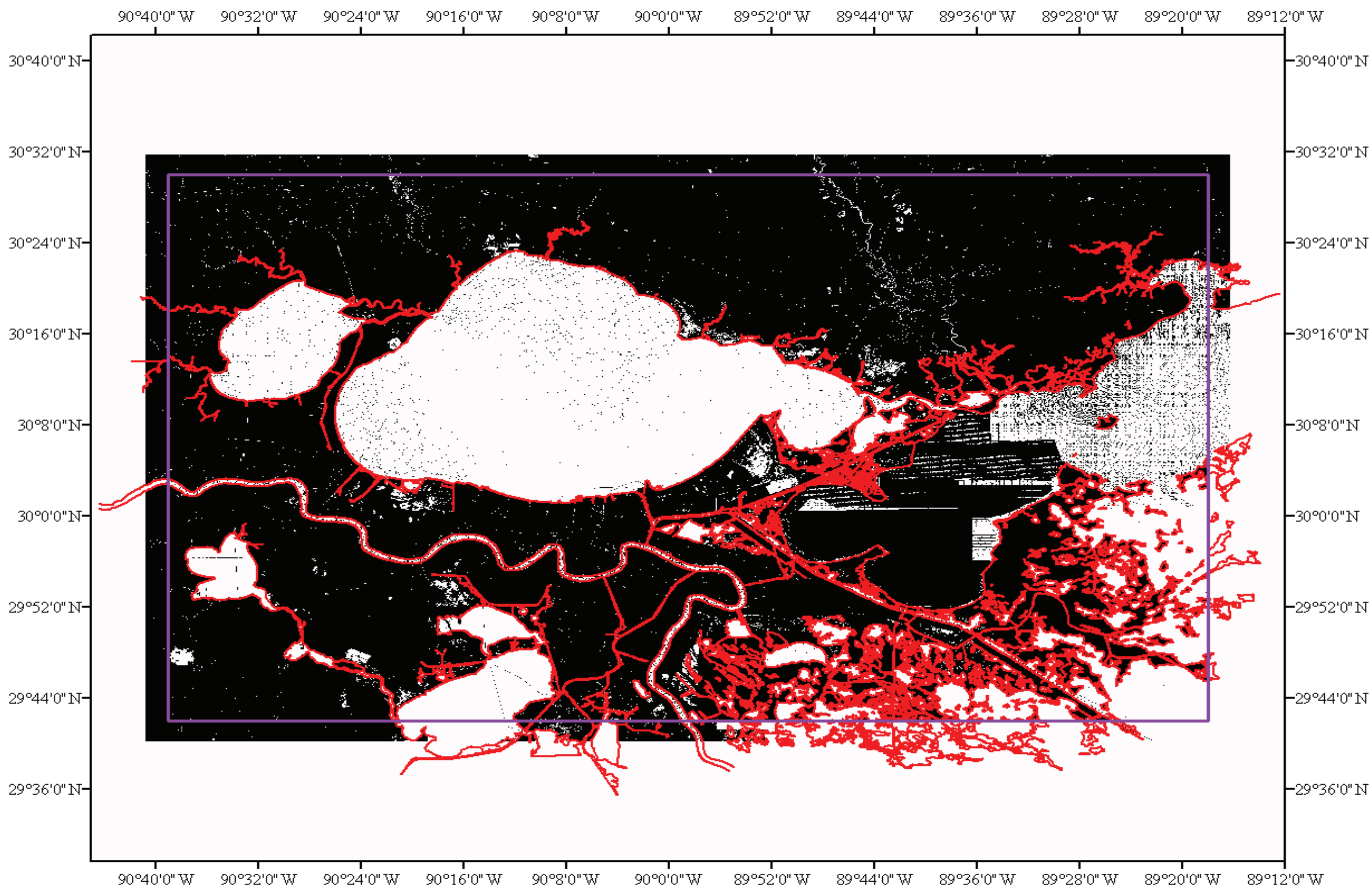

Figure 23. *Data Density of New Orleans; Areas where source data were available are depicted in black; areas where grid interpolation was necessary are depicted in white; New Orleans coastline in red.*

3.3.4 *Developing the MHW DEM*

The MHW DEM was created by adding a 'NAVD 88 to MHW' conversion grid to the NAVD 88 DEM.

1) Developing the conversion grid

Using extents slightly larger (~5%) than the NAVD 88 DEM, an initial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. 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-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.

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 extents of the NAVD 88 DEM. NGDC then used the *GMT* tool 'surface' to interpolate values that represented the differences between the two datums onshore to the DEM extents (Fig. 24).

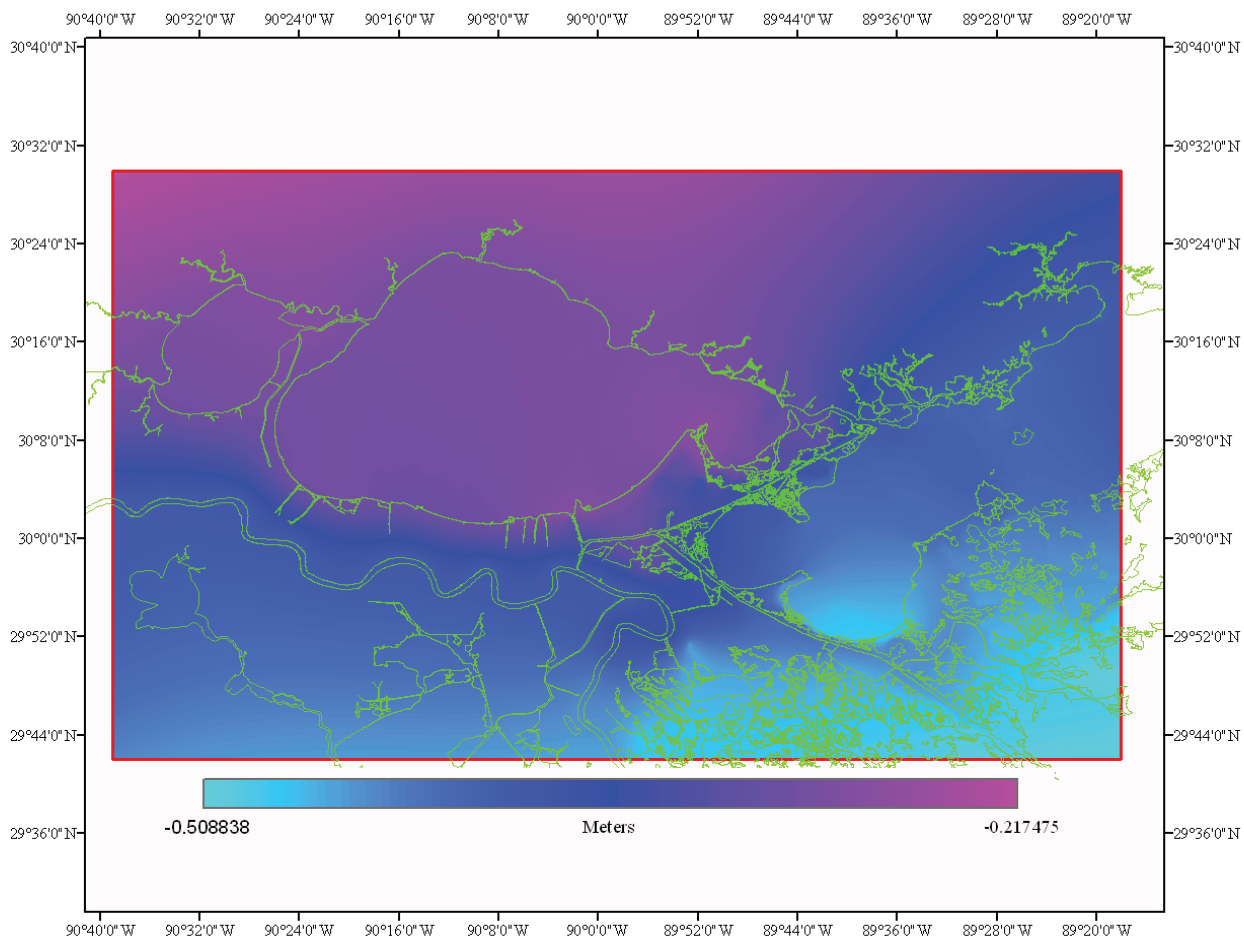

Figure 24. *Elevation conversion values of the 'NAVD 88 to MHW' conversion grid derived from VDatum. Values equal difference between NAVD 88 and MHW.*

2) Assessing accuracy of conversion grid

The 'NAVD 88 to MHW' conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLW and MLLW to NAVD 88 using *VDatum*. The resultant xyz files were filtered to remove any null values and then were merged together to form a single xyz file of the NOS hydrographic survey data with a vertical datum of NAVD 88. A second xyz file of NOS data was created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 xyz files were computed.

To verify the conversion grid methodology, the difference xyz file was used to generate a histogram using *Gnuplot*[10] to evaluate the performance of the 1/3 arc-second conversion grid by comparing the 'NAVD 88 to MHW' grid to the combined difference xyz files from the *VDatum* project area (Fig. 25). Errors in the vertical datum conversion method will reside for the most part in the 'NAVD 88 to MHW' conversion grid, as the topographic data are already referenced to NAVD 88. Errors in the source datasets will require rebuilding just the NAVD 88 DEM.

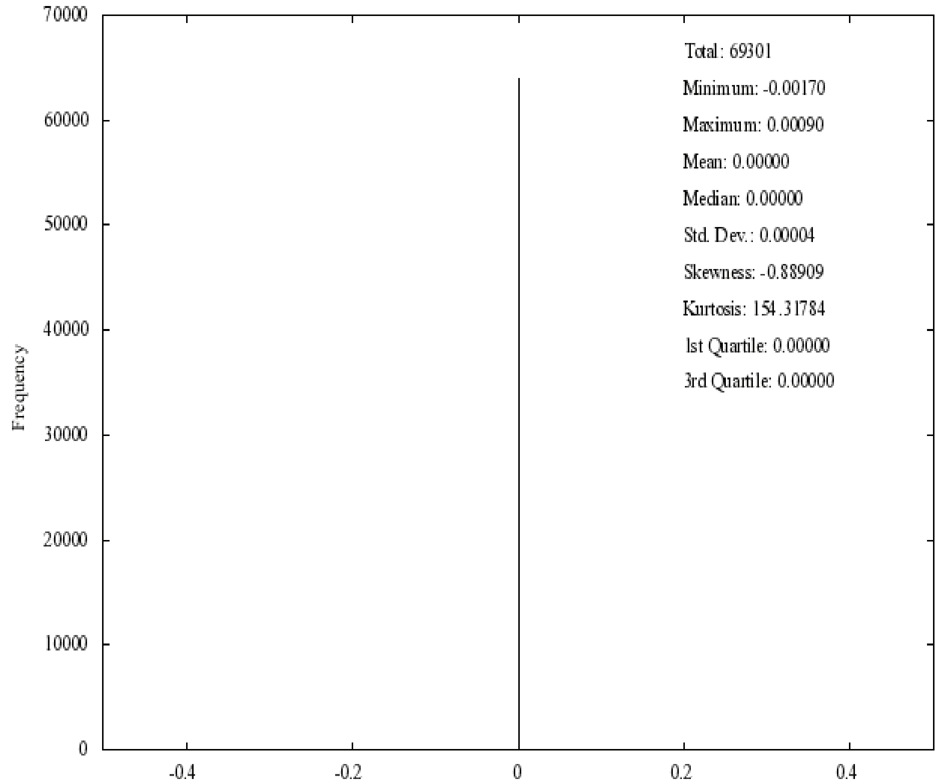

Figure 25. *Histogram of the differences between the conversion grid and xyz difference files using NOS hydrographic survey data.*

3) Creating the MHW DEM

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

10. *Gnuplot* is an open-source command-driven interactive function plotting program. It can be used to plot functions and data points in both two- and three-dimensional plots in many different formats. It is designed primarily for the visual display of scientific data.

3.3.5 *Developing the MLLW DEM*

The MLLW DEM was created by adding a ‘NAVD 88 to MLLW’ conversion grid to the NAVD 88 DEM.

1) Developing the conversion grid

Using extents slightly larger (~5%) than the NAVD 88 DEM, an initial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. 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-grid was then converted to an intermediate xyz file using the *GMT* tool ‘grd2xyz.’ Conversion values from NAVD 88 to MLLW at each xyz point were generated using *VDatum* and the null values were removed.

The median-averaged xyz file was then interpolated with the *GMT* tool ‘surface’ to create the 1/3 arc-second ‘NAVD 88 to MLLW’ conversion grid with the extents of the NAVD 88 DEM. NGDC then used the *GMT* tool ‘surface’ to interpolate values that represented the differences between the two datums onshore to the DEM extents (Fig. 26).

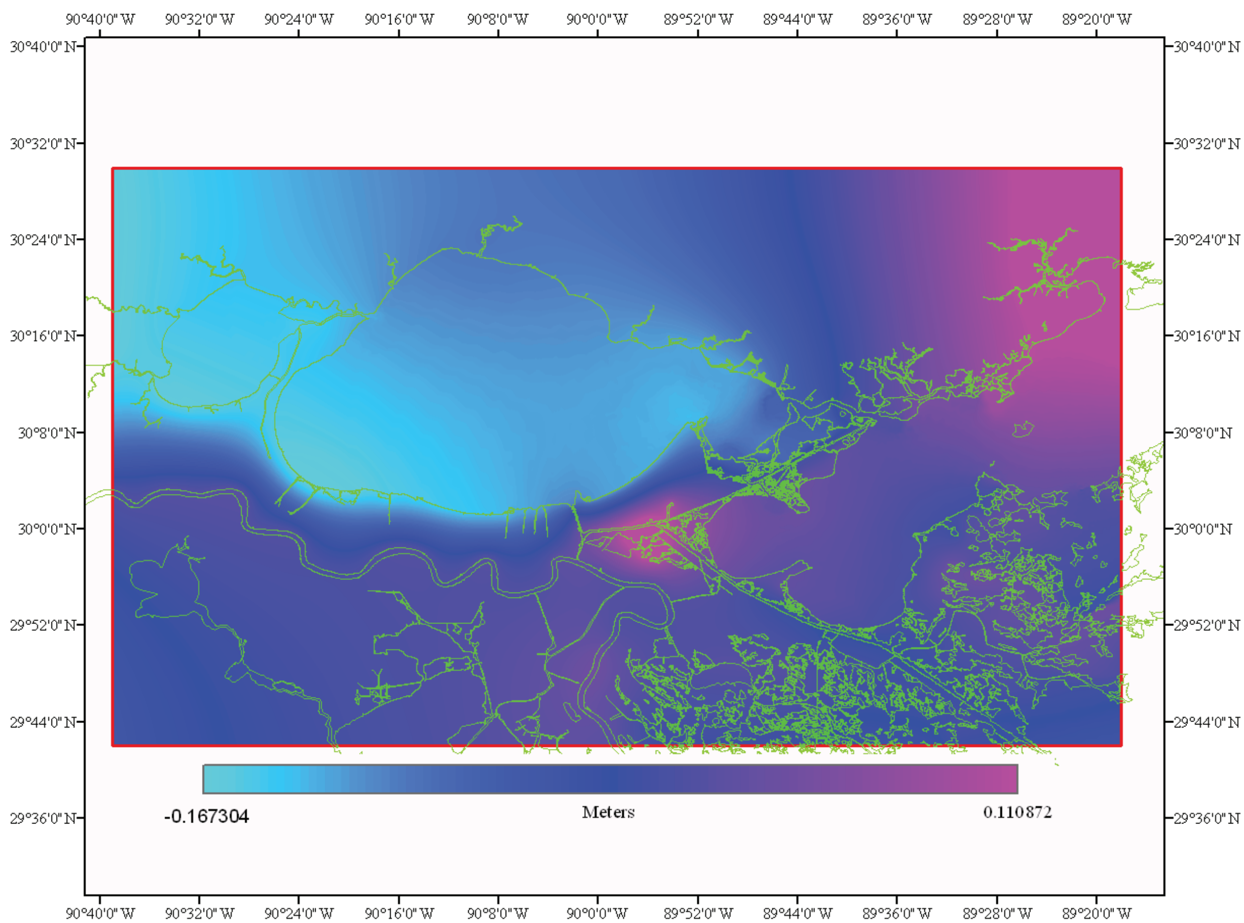

Figure 26. *Elevation conversion values of the ‘NAVD 88 to MLLW’ conversion grid derived from VDatum. Values equal difference between NAVD 88 and MLLW.*

2) Assessing accuracy of conversion grid

The 'NAVD 88 to MLLW' conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLW and MLLW to NAVD 88 using *VDatum*. The resultant xyz files were filtered to remove any null values and then were merged together to form a single xyz file of the NOS hydrographic survey data with a vertical datum of NAVD 88. A second xyz file of NOS data was created with a vertical datum of MLLW using the same method. Elevation differences between the MLLW and NAVD 88 xyz files were computed.

To verify the conversion grid methodology, the difference xyz file was used to generate a histogram using *Gnuplot* to evaluate the performance of the 1/3 arc-second conversion grid by comparing the 'NAVD 88 to MLLW' grid to the combined difference xyz files from the VDatum project area. Errors in the vertical datum conversion method will reside for the most part in the 'NAVD 88 to MLLW' conversion grid, as the topographic data are already referenced to NAVD 88. Errors in the source datasets will require rebuilding just the NAVD 88 DEM.

3) Creating the MLLW DEM

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

3.4 Quality assessment of the DEM

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the New Orleans DEMs are dependent upon the datasets used to determine corresponding DEM cell values and the cell size of the DEM. The horizontal accuracy is 10 meters where topographic lidar datasets contribute to the DEM cell value. The horizontal accuracy is 0.75 meters at 1 sigma where only bathymetric—topographic lidar-derived data contributes to the DEM cell value. Bathymetric features are resolved only 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; potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys; and by the morphologic change that occurs in this dynamic region.

3.4.2 Vertical accuracy

Vertical accuracy of the New Orleans DEMs are also highly dependent upon the source datasets contributing to DEM cell values. Topographic lidar has an estimated RMSE of 13.9 to 20 cm. Bathymetric—topographic lidar-derived data have a vertical accuracy of 0.20 meters at 1 sigma. 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.

3.4.3 Slope maps and 3D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the New Orleans NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 27). The DEM was transformed to UTM Zone 15 North 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 was accomplished using ESRI *ArcScene*. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 28 shows a perspective view image of the 1/3 arc-second New Orleans NAVD 88 DEM in its final version.

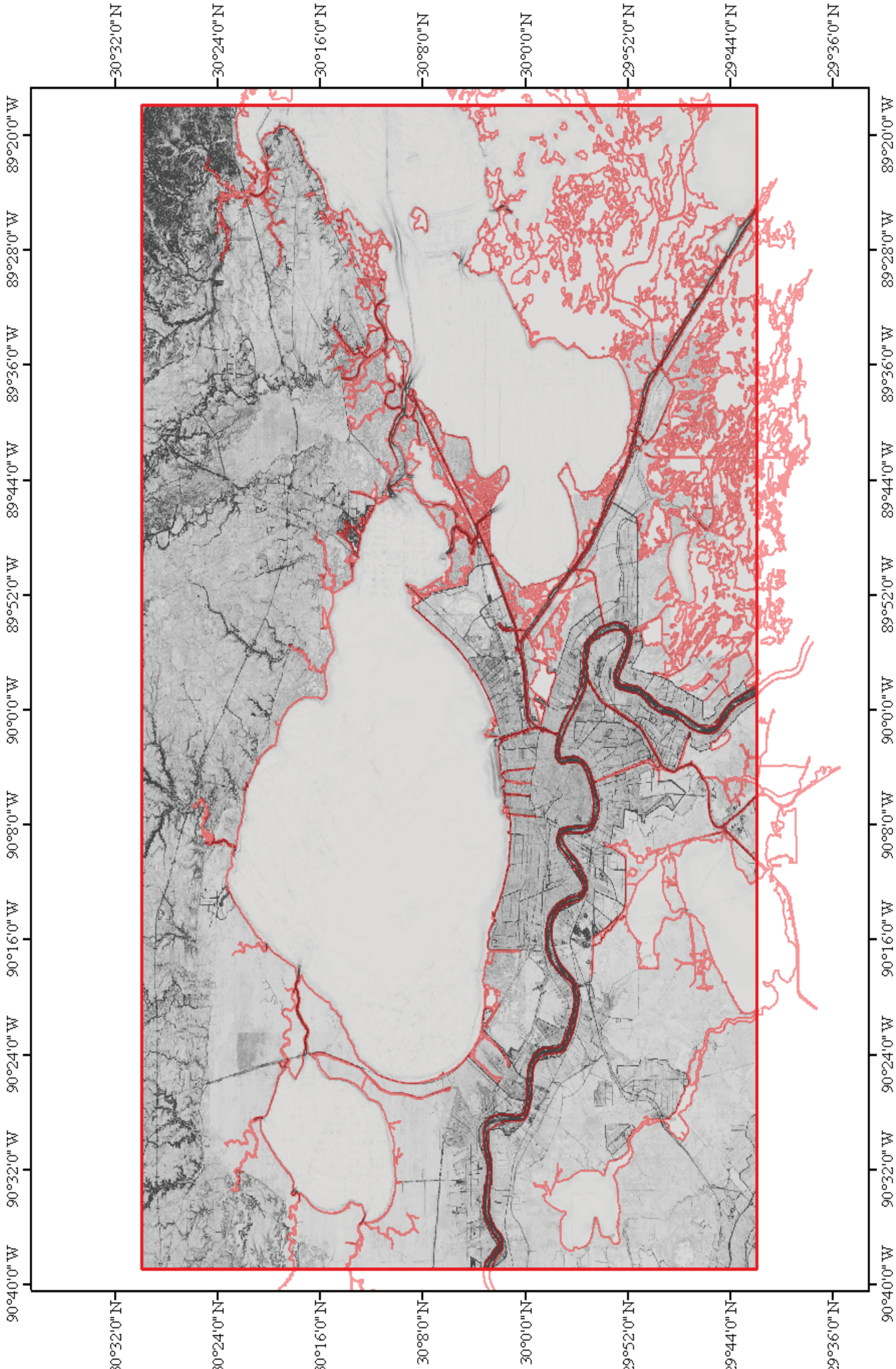

Figure 27. *Slope map of the New Orleans NAVD 88 DEM. Flat-lying slope are white; dark shading denotes steep slopes.*

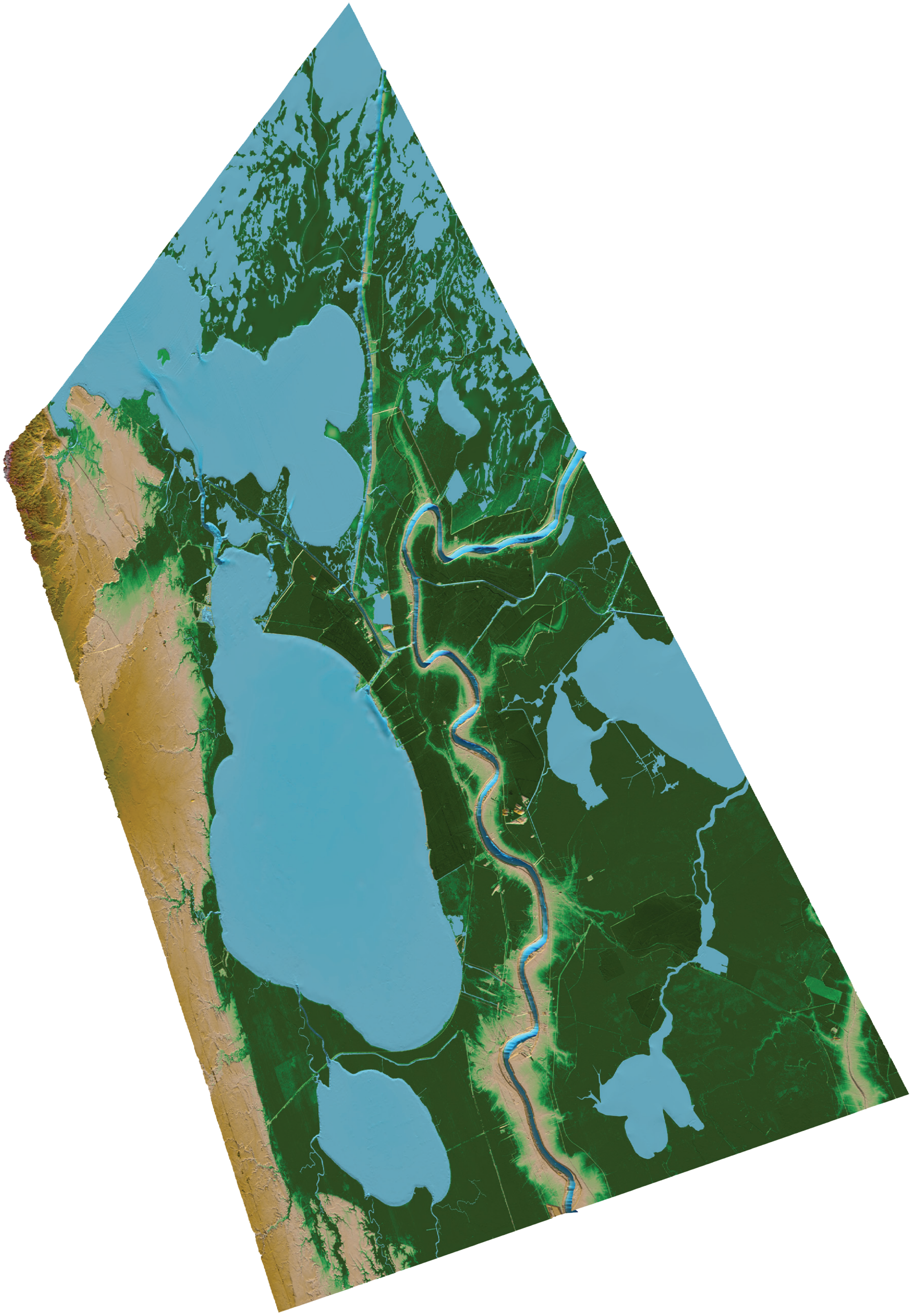

Figure 28. *Perspective view from the southwest of the New Orleans NAVD 88 DEM. Fifteen times vertical exaggeration.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the New Orleans NAVD 88 DEM was compared to source data files. All bathymetric and topographic source data were compared to the New Orleans NAVD 88 DEM using *Python, GDAL* and *Gnuplot.* Histograms of the differences between individual datasets and the New Orleans NAVD 88 DEM are shown in Figures 29 - 40. Largest differences between source datasets and the DEM resulted from the averaging of multiple topographic source datasets where data coverage overlapped, particularly in regions of steep slopes.

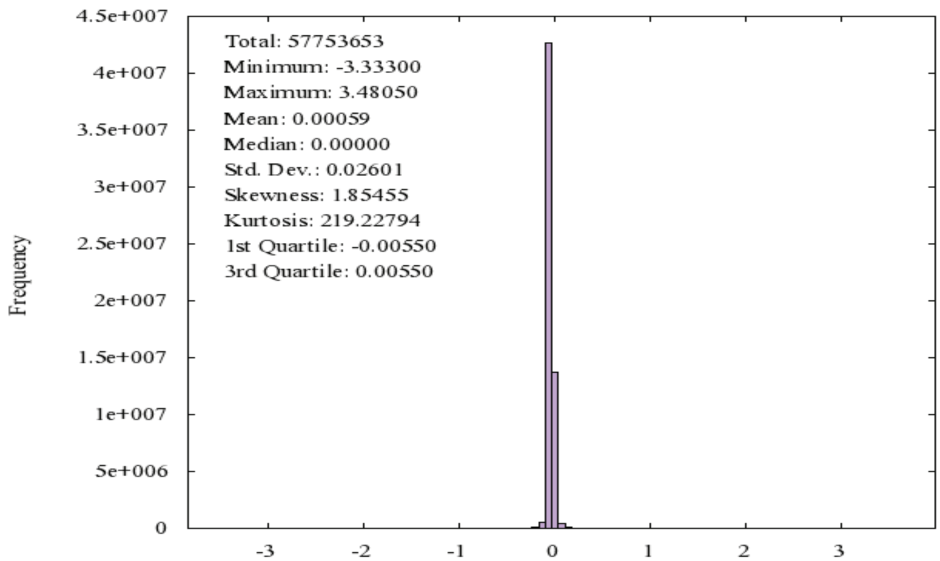

Figure 29. *Histogram of the differences between the Louisiana lidar dataset and the New Orleans DEM*

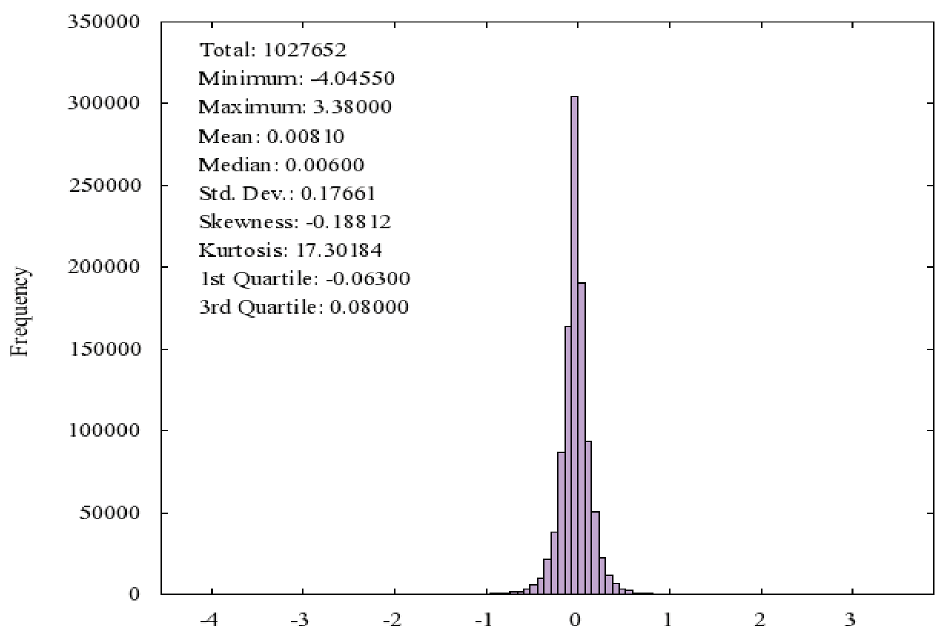

Figure 30. *Histogram of the differences between the Harrison County, MS lidar dataset and the New Orleans DEM*

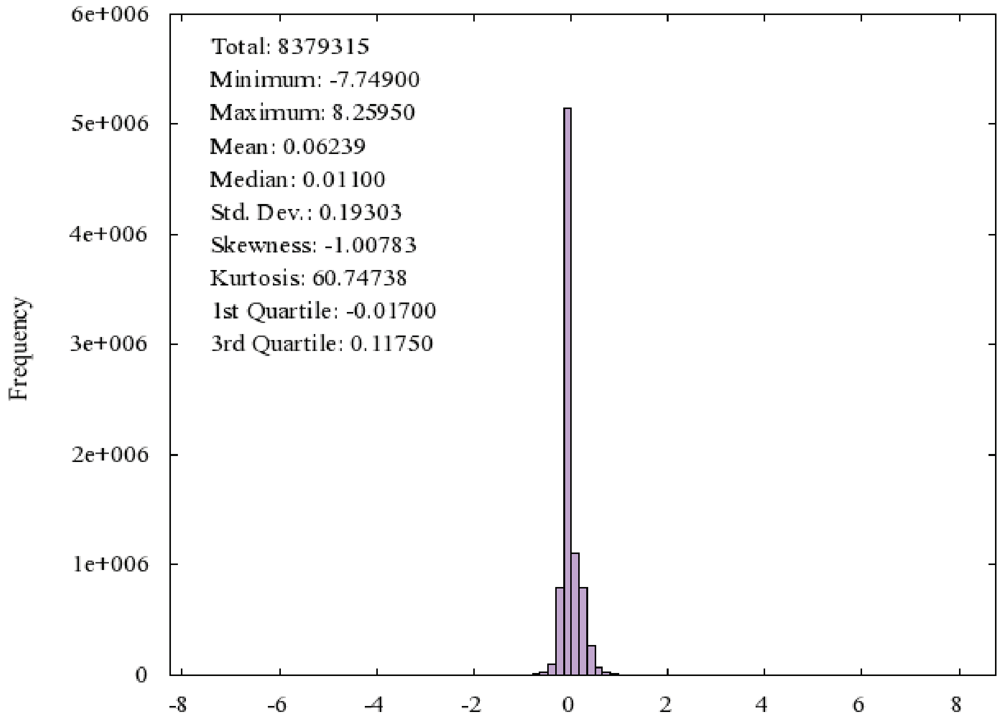

Figure 31. *Histogram of the differences between the Hancock County, MS lidar dataset and the New Orleans DEM*

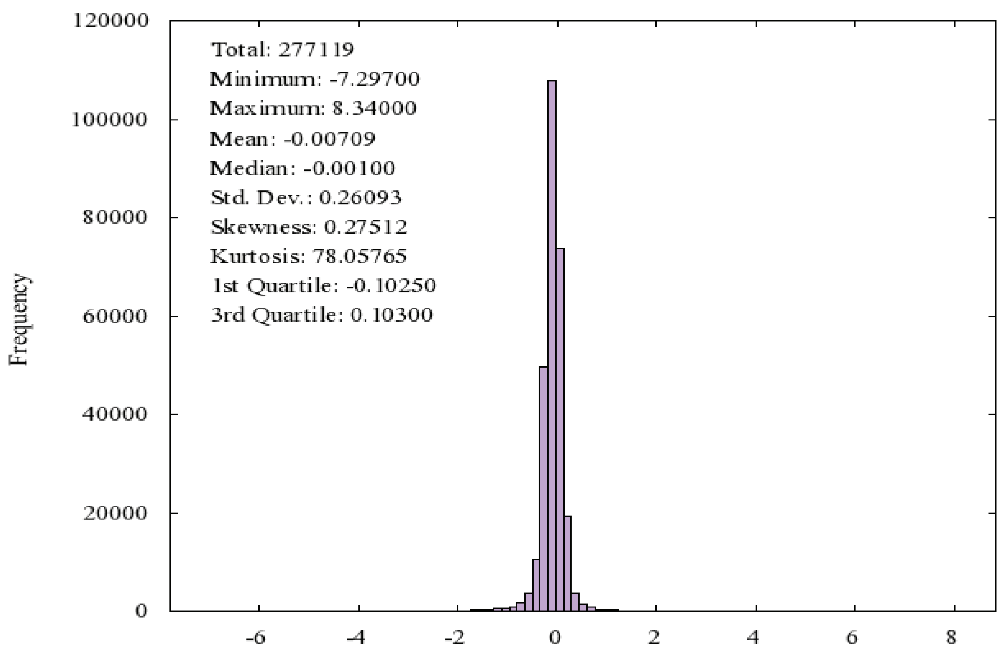

Figure 32. *Histogram of the differences between the Pearl River County, MS lidar dataset and the New Orleans DEM*

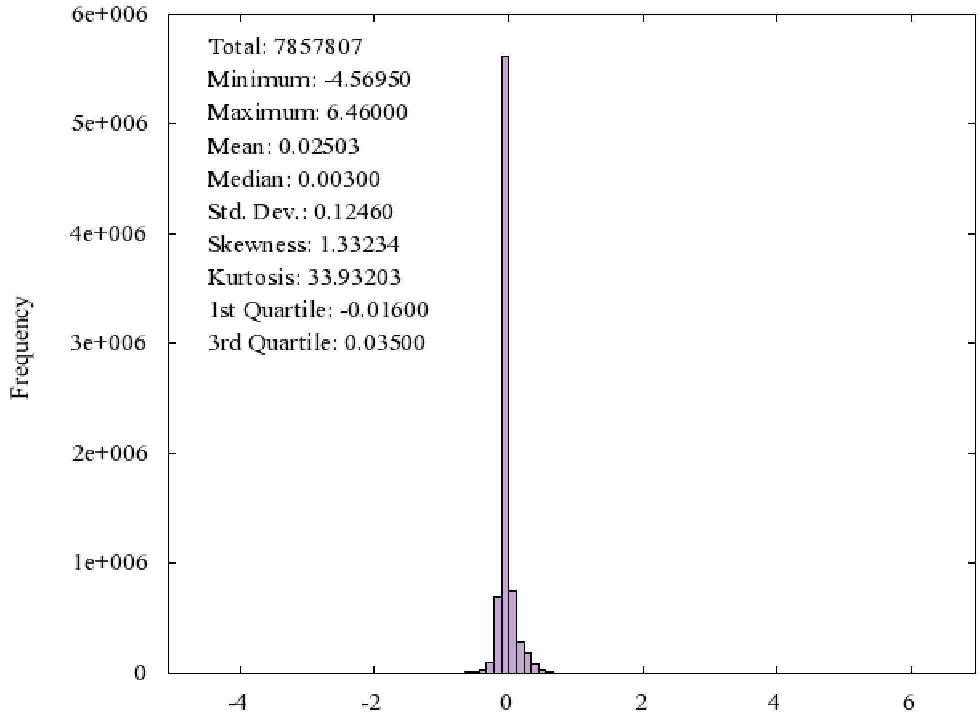

Figure 33. *Histogram of the differences between the Mississippi Merged lidar dataset and the New Orleans DEM*

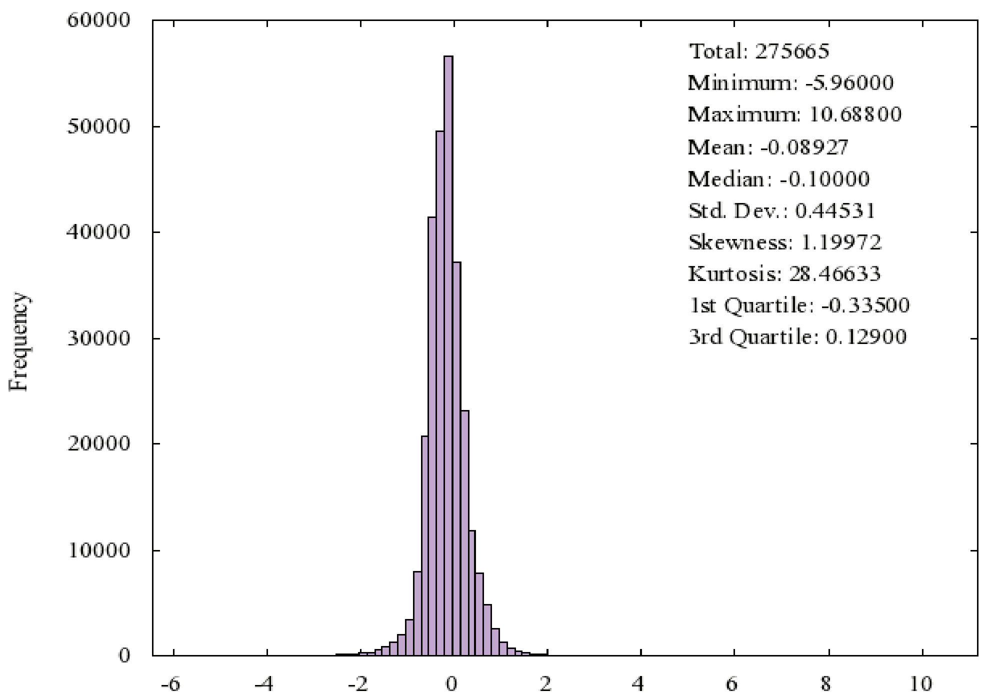

Figure 34. *Histogram of the differences between the CSC Post Katrina Levees lidar dataset and the New Orleans DEM*

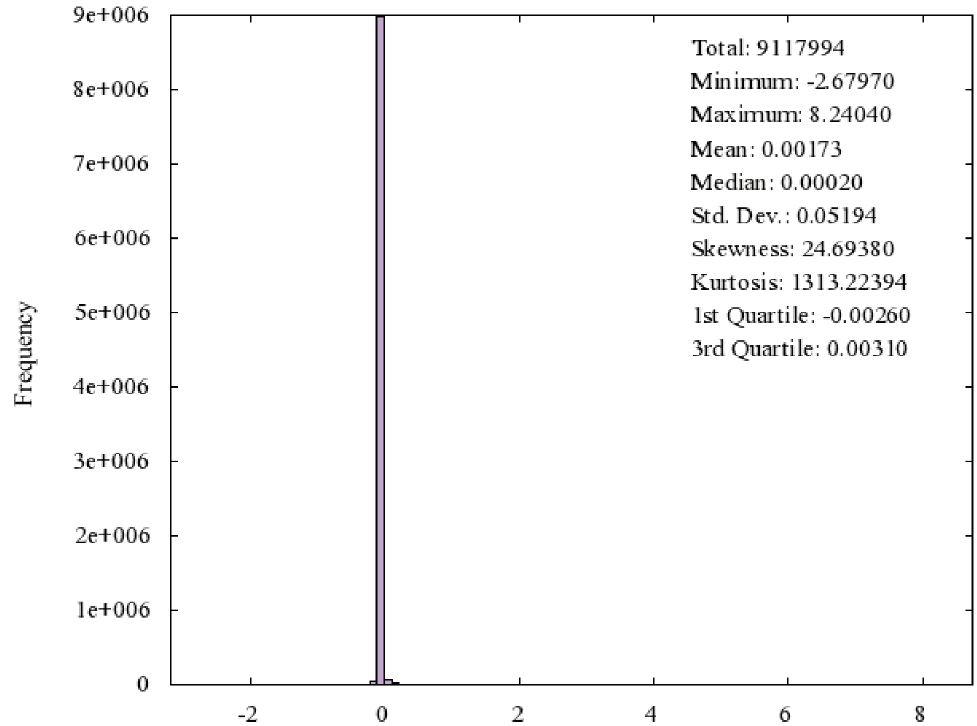

Figure 35. *Histogram of the differences between the NGDC Digitized topographic dataset and the New Orleans DEM*

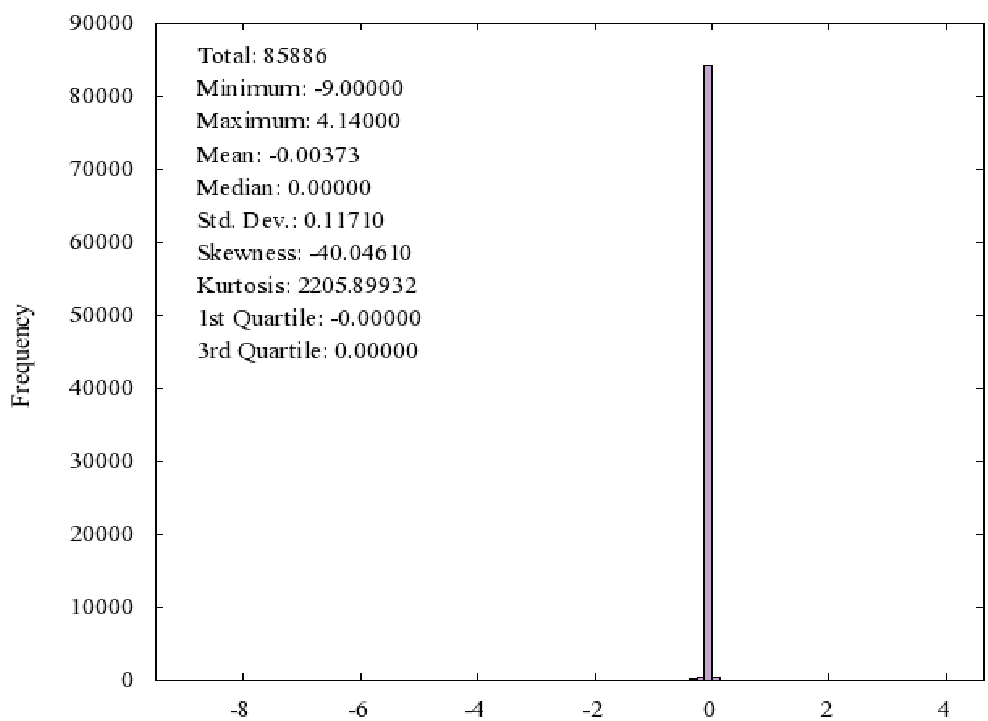

Figure 36. *Histogram of the differences between the NOS Hydrology soundings and the New Orleans DEM*

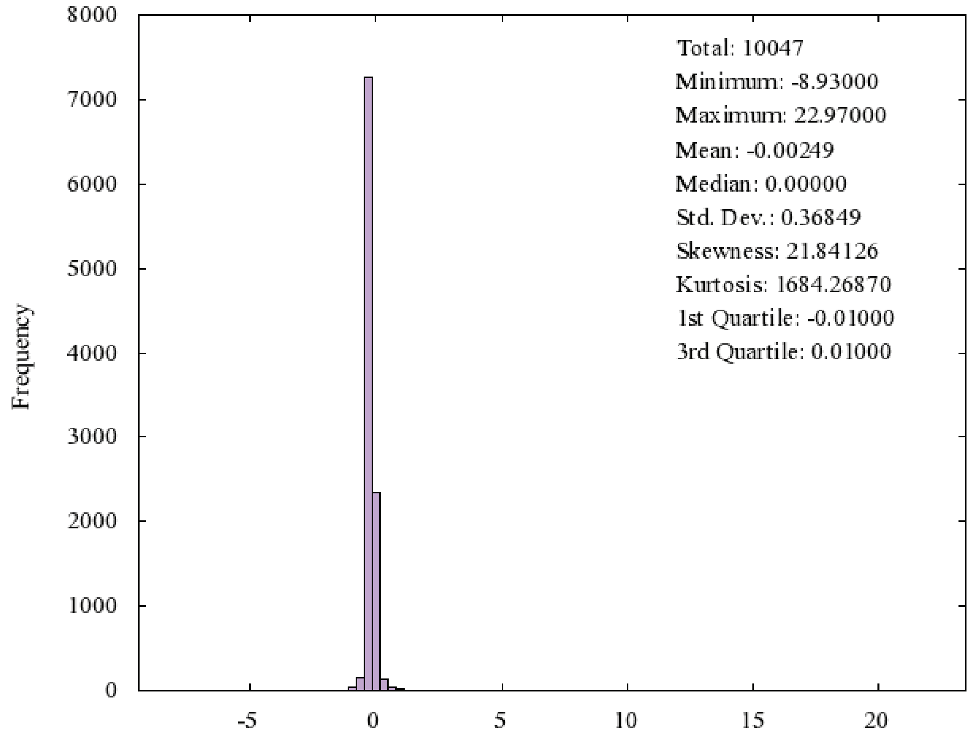

Figure 37. *Histogram of the differences between the ENC Bathymetry dataset and the New Orleans DEM*

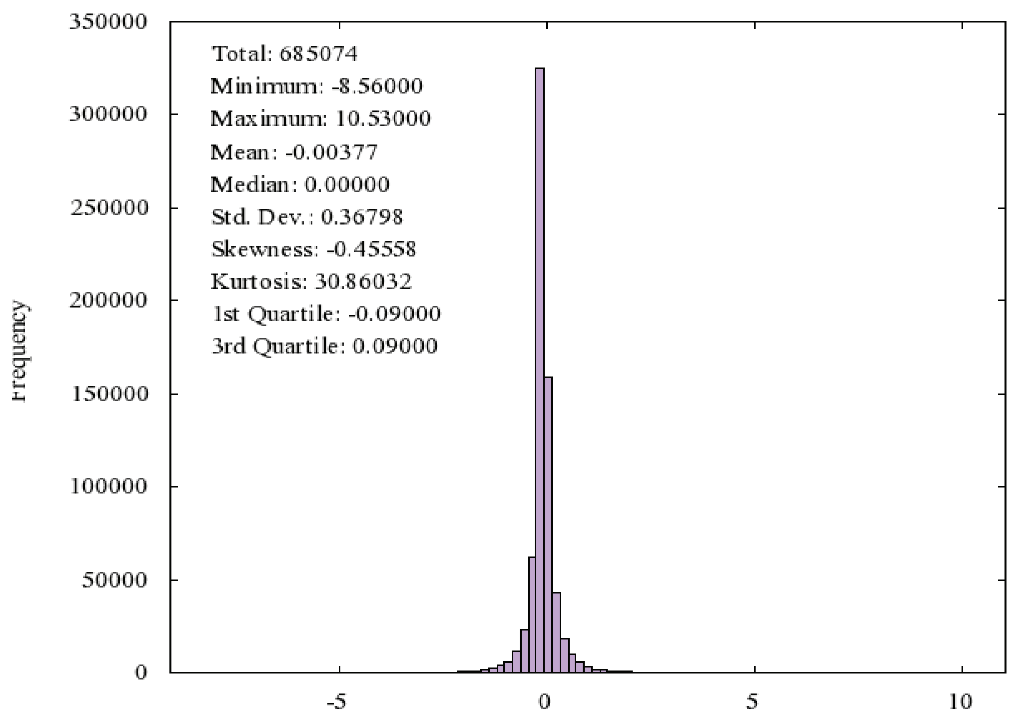

Figure 38. *Histogram of the differences between the USACE Bathymetry dataset and the New Orleans DEM*

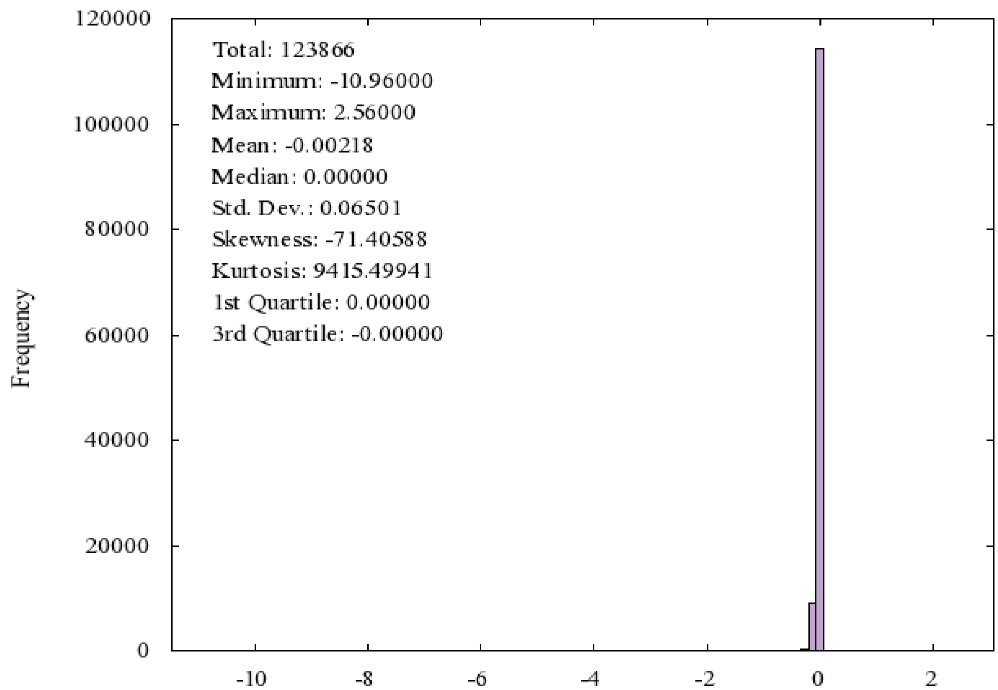

Figure 39. *Histogram of the differences between the High Resolution Lake Borgne Bathymetry dataset and the New Orleans DEM*

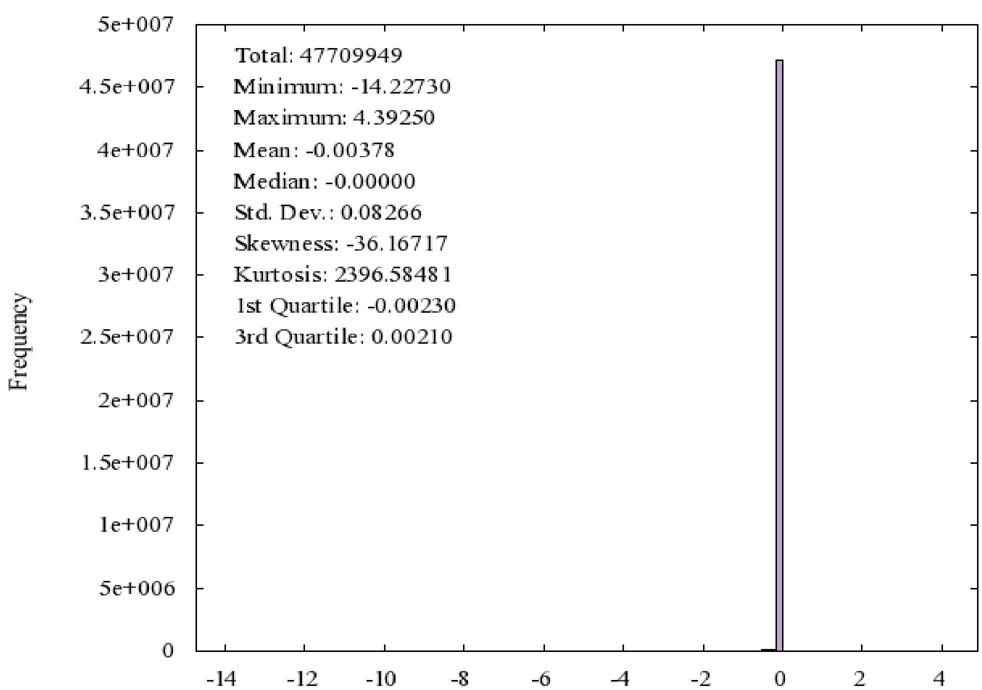

Figure 40. *Histogram of the differences between the Bathymetry Pre-Surface dataset and the New Orleans DEM*

3.4.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of 80 NOAA NGS geodetic monuments (Fig. 41) were extracted from online shapefiles of NGS Geodetic monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Monument elevations were compared with elevations of the New Orleans NAVD 88 DEM. Differences between the New Orleans NAVD 88 DEM and the NGS geodetic monument elevations range from -0.86 to 32.3183 meters, with the majority of them being within +/-1 meter (Fig. 42). Negative values indicate that the monument elevation is less than the DEM elevation. After examination, it was determined that those monuments with the largest deviations do not represent ground surface as they are located on top of an observation tower, light house or at the apex of other structures.

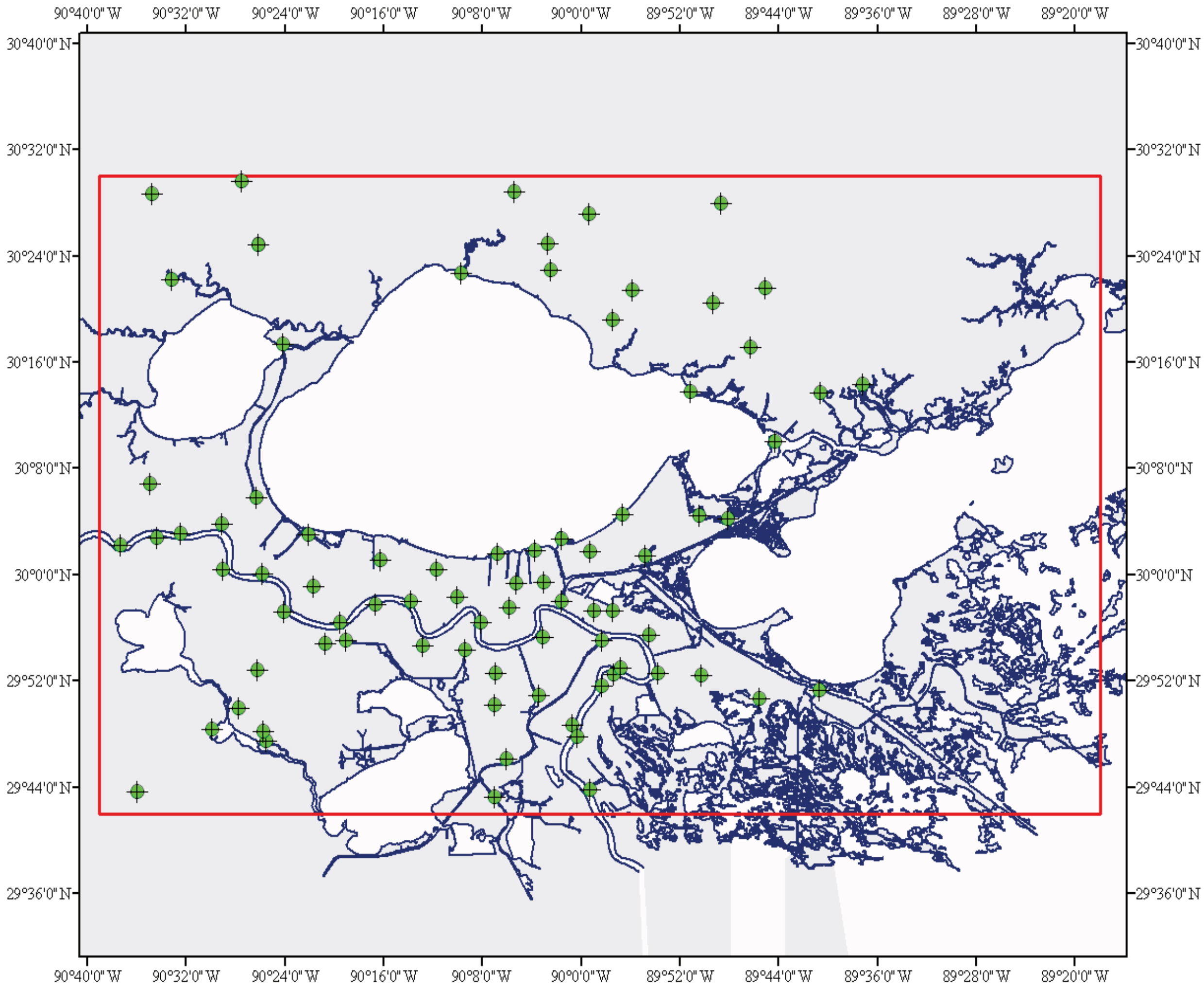

Figure 41. *Locations of NGS monuments used in the evaluation of the New Orleans NAVD 88 DEM.*

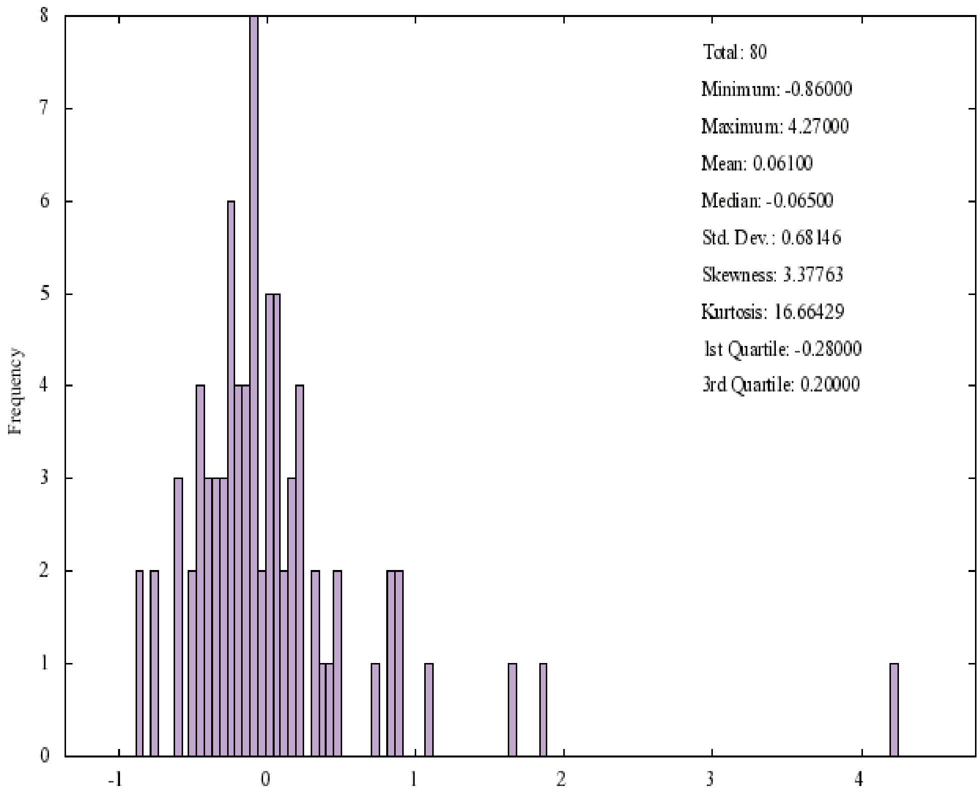

Figure 42. *Histogram of the differences between the NGS monument elevation values and the New Orleans DEM*

3.4.6 Independent Accuracy Assessment

An independent accuracy assessment was performed on the NAVD 88 DEM by Dr. Roy Dokka of Louisiana State University (LSU). The assessment was performed only on the topographic portion of the DEM.

The assessment found that there is a marked geographical bias to the errors. Areas of the DEM in Plaquemines and Orleans Parishes are lower than reality, whereas areas to the north (St. Tammany and Orleans Parishes) are higher than reality. The reason for this, in opinion of the assessment, is the spatial variability of the quality of the vertical control at the time of lidar acquisition. Much of the original data are from the LSU Atlas State-wide lidar data set. These data were acquired between 2001 and 2005, a time in which NGS had no confidence in vertical control in south Louisiana. Contrary to FEMA and the contractors, there was no way to link to NAVD88 in the area during this interval. The test data are based on the National CORS network and ~5 cm geoid model.

The assessment found the data to be good to ±0.4m (95% CI) and with the independent assessment the DEM is the only verified data in the region, with the conclusion that the New Orleans NAVD 88 DEM is the best available topographic DEM available.

Table 12. Statistical results from the Independent Accuracy Assessment.

Number of Test Points	20620
Minimum	-0.948
Maximum	1.009
Sum	-2880.073012
Mean	-0.139674 meters
Standard Deviation	0.193519 meters

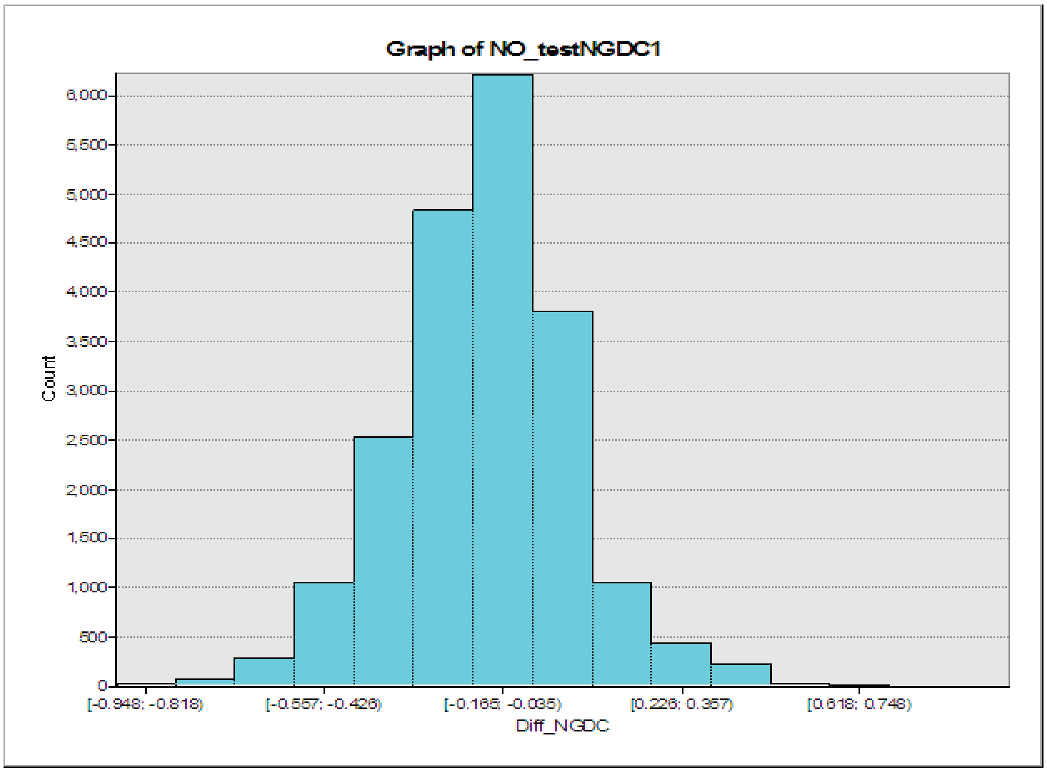

Figure 43. *Histogram of differences between independent ly collected control points and New Orleans DEM.*

4. Summary And Conclusions

Three bathymetric–topographic digital elevation models of the New Orleans, Louisiana region, with cell spacing of 1/3 arc-second, and vertical datums of NAVD 88, MHW and MLLW were developed for CSDL through the American Recovery and Reinvestment Act (ARRA) of 2009. The DEMs were developed to validate the utility of NOAA's OCS, NGS, and CO-OPS jointly developed *VDatum* tool and will be used for storm surge inundation and sea level rise modeling. The best available digital data from U.S. federal, state and local 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*, *FME*, *GMT*, *MB-System*, *Quick Terrain Modeler*, *GDAL*, *Proj4*, *Gnuplot* and *Fledermaus* software. *VDatum* was utilized throughout the development of the New Orleans DEMs to transform data to common vertical datums. Furthermore, NGDC developed a conversion grid derived from the *VDatum* project area that transformed the New Orleans NAVD 88 DEM to MHW and MLLW.

Recommendations to improve the New Orleans DEMs, based on NGDC's research and analysis, are listed below:

- Process USACE 2005 Post-Hurricane Katrina Topographic Mapping lidar to bare-earth.
- Conduct up-to-date topographic lidar surveys for all near-shore regions.
- Conduct NOS hydrographic surveys in hydrographic data gaps and in estuary bays and rivers.
- Conduct up-to-date topographic surveys of Saint Bernard Parish and sourounding marsh-lands.

Recommendations to improve *VDatum*, based on NGDC's research and analysis, are listed below:

- Develop support for State Plane Coordinate Systems.
- Develop support for additional input filetypes, such as ASPRS LAS files.

5. Acknowledgments

The creation of the New Orleans DEMs was funded by the American Recovery and Reinvestment Act (ARRA) of 2009. The authors thank the GIS Administrator of the State of Mississippi for providing lidar data of the Mississippi counties included in the New Orleans DEMs, and Jay Ratcliff of the United States Army Corps of Engineers for supplying otherwise unavailable bathymetric surveys. The authors also thank Cuong Hoang and Maureen Kenny (NOAA CSDL) for providing NGDC with the NOS survey non-superceded database.

6. References

Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix A, 2003. Federal Emergency Management Agency, Flood Hazard Mapping Program.

Nautical Chart #11367 (RNC) 34th Edition, 2007. Mississippi River Extension. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11368 (RNC) 34th Edition, 2007. New Orleans Harbor. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11363 (RNC) 34th Edition, 2007. Chandeleur and Breton Sounds. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11364 (RNC) 34th Edition, 2007. Mississippi River, Venice to New Orleans. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11366 (RNC) 34th Edition, 2007. Approaches to Mississippi River. Scale 1:250,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11369 (RNC) 34th Edition, 2007. Lakes Pontchartrain and Maurepas. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11371 (RNC) 34th Edition, 2007. Lake Borgne and Approaches. Scale 1:80,000. 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 Imagery World 2D Online World Imagery 2D – ESRI ArcGIS Resource Centers, http://resources.esri.com/arcgisonlineservices/.

Fledermaus v. 7.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/.

FME 2009 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada,, http://www.safe.com/.

GDAL v. 1.7.1 – Geographic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://gdal.org/.

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

GMT v. 4.2.1 – Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/.

Gnuplot v. 4.2, free software developed and maintained by Thomas Williams, Colin Kelley, Russell Lang, Dave Kotz, John Campbell, Gershon Elber, Alexander Woo, http://www.gnuplot.info/.

MB-System v. 5.1.0, free software 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/.

Proj4 v. 4.7.0, free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/.

Quick Terrain Modeler v. 6.0.6, 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, 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/.