Digital Elevation Models of Port San Luis, California: Procedures, Data Sources and Analysis

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Contents

1. Introduction 1
2. Study Area 2
3. Methodology 4
   3.1 Data Sources and Processing 5
      3.1.1 Shoreline 6
      3.1.2 Bathymetry 7
      3.1.3 Topography 12
   3.2 Establishing Common Datums 14
      3.2.1 Vertical datum transformations 14
      3.2.2 Horizontal datum transformations 14
   3.3 Digital Elevation Model Development 15
      3.3.1 Verifying consistency between datasets 15
      3.3.2 Smoothing of bathymetric data 15
      3.3.3 Building the NAVD 88 DEM 17
      3.3.4 Building the MHW DEM 18
   3.4 Quality Assessment of the DEMs 20
      3.4.1 Horizontal accuracy 20
      3.4.2 Vertical accuracy 20
      3.4.3 Slope map and 3-D perspectives 20
      3.4.4 Comparison with National Geodetic Survey geodetic monuments 23
      3.4.5 NAVD 88 DEM comparison with source data files 24
4. Summary and Conclusions 27
5. Acknowledgments 27
6. References 27
7. Data Processing Software 27

List of Figures

Figure 1. Shaded-relief image of the Port San Luis NAVD 88 1/3 arc-second DEM. 1
Figure 2. Overview of the Port San Luis DEM region 2
Figure 3. Morro Rock, located in Morro Bay, California 3
Figure 4. Source and coverage of datasets used in compiling the Port San Luis DEMs 5
Figure 5. Histogram of the differences between the NOS bathymetric surveys and the arc-second pre-surfaced bathymetric grid 16
Figure 6. Histogram of the differences between the NGDC multibeam data and the 1 arc-second pre-surfaced bathymetric grid 16
Figure 7. Image of NGDC Port San Luis conversion grid 18
Figure 8. Perspective view from the southwest of the 1/3 arc-second Port San Luis DEM 20
Figure 9. Slope map of the Port San Luis NAVD 88 DEM. 21
Figure 10. Data contribution plot of the Port San Luis NAVD 88 DEM 22
Figure 11. Location of NGS geodetic monuments in the Port San Luis region 23
Figure 12. Histogram of the differences between NGS geodetic monument elevations and the Port San Luis NAVD 88 DEM 23
Figure 13. Histogram of the differences between a portion of the CSUMB multibeam data and the NAVD 88 DEM 24
Figure 14. Histogram of the differences between a portion of the NGDC multibeam data and the NAVD 88 DEM 24
Figure 15. Histogram of the differences between the NED data and the NAVD 88 DEM 25
Figure 16. Histogram of the differences between the NOS hydrographic survey data points and the NAVD 88 DEM 25
Figure 17. Histogram of the differences between the CSC lidar survey and the NAVD 88 DEM 25
Figure 18. Histogram of the differences between the CSC IfSAR data and the NAVD 88 DEM 26

List of Tables

Table 2. Shoreline datasets used in developing the Port San Luis NAVD 88 DEM. 6
Table 3. Bathymetric datasets used in compiling the Port San Luis NAVD 88 DEM. 7
Table 4. Digital NOS hydrographic surveys used in developing the Port San Luis DEM 8
Table 5. Digital NOS hydrographic surveys used in developing the Port San Luis DEM 10
Table 6. Topographic datasets used in compiling the Port San Luis DEMs. 12
Table 7. Tide stations in the Port San Luis area and relationships between MHW and NAVD 88 14
Table 8. Data hierarchy used to assign gridding weight in *MB-System* 17

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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 Port San Luis, California (Fig. 1). First, a 1/3 arc-second[1] DEM referenced to the 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. 4). A 1/3 arc-second conversion grid was then created to represent the relationship between NAVD 88 and Mean High Water (MHW) vertical datums in the Port San Luis region. Finally, the vertical datum conversion grid was combined with the DEM referenced to NAVD 88 in order to create an additional 1/3 arc-second DEM referenced to MHW. 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 to develop the Port San Luis DEMs.

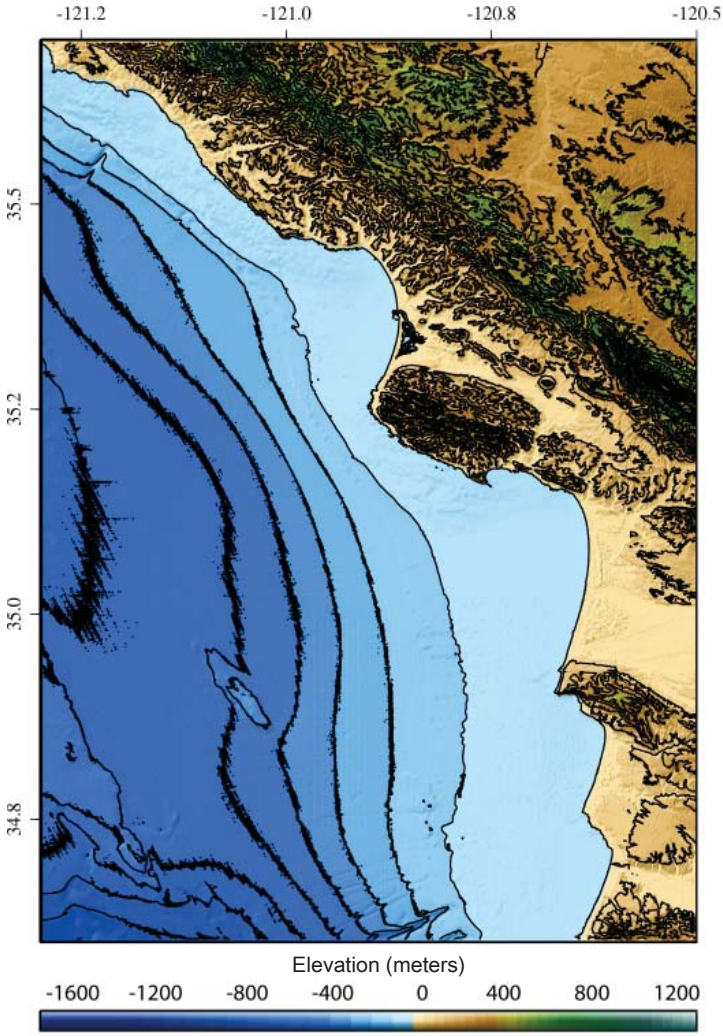

Figure 1. Shaded-relief image of the Port San Luis NAVD 88 1/3 arc-second DEM.

1. The Port San Luis DEM is 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 Port San Luis, California, (35°10’44”N, 120°44’03”W) 1/3 arc-second of latitude is equivalent to 10.27 meters; 1/3 arc-second of longitude equals 8.43 meters.

2. Study Area

The Port San Luis DEM provides coverage of the area surrounding the town of San Luis Obispo, California– from Ragged Point to Lompoc– roughly halfway between Monterey and Santa Barbara (Fig. 2). The DEM includes coverage of San Simeon Bay, Cambria, El Paso de Robles, Estero Bay, Morro Bay, Port San Luis and San Luis Obispo Bay, Pismo Beach, Grover Beach, the Guadalupe Dunes, and Vandenberg Airforce Base.

The Port San Luis DEM coverage area exhibits both sandy beaches and rocky headlands. The volcanic formations along the coast include Morro Rock in San Luis Obispo County (see Fig. 3) and outcroppings of basaltic lava elsewhere. Morro Rock, located a the entrance to Morro Bay, is one of a chain of nine extinct volcanic necks that stretch approximately 12 miles from Morro Bay to San Luis Obispo. The chain is known by two names-- the seven sisters or the nine morros (morro is a spanish word meaning 'snout' or 'nose'), depending on how the peaks are counted. It is theorized that the 22-28 million year old volcano chain originally erupted along a fault line south of where they are currently located. They moved north along the San Andreas fault to their present day locations. Morro Rock was mined to provide breakwater material in Morro Bay and San Luis Obispo Bay.

The County of San Luis Obispo is home to about 270,000 people, according to a 2009 Census Bureau estimate. The area is vulnerable to extensive loss of life and monetary damages in the event of a severe tsunami or storm surge.

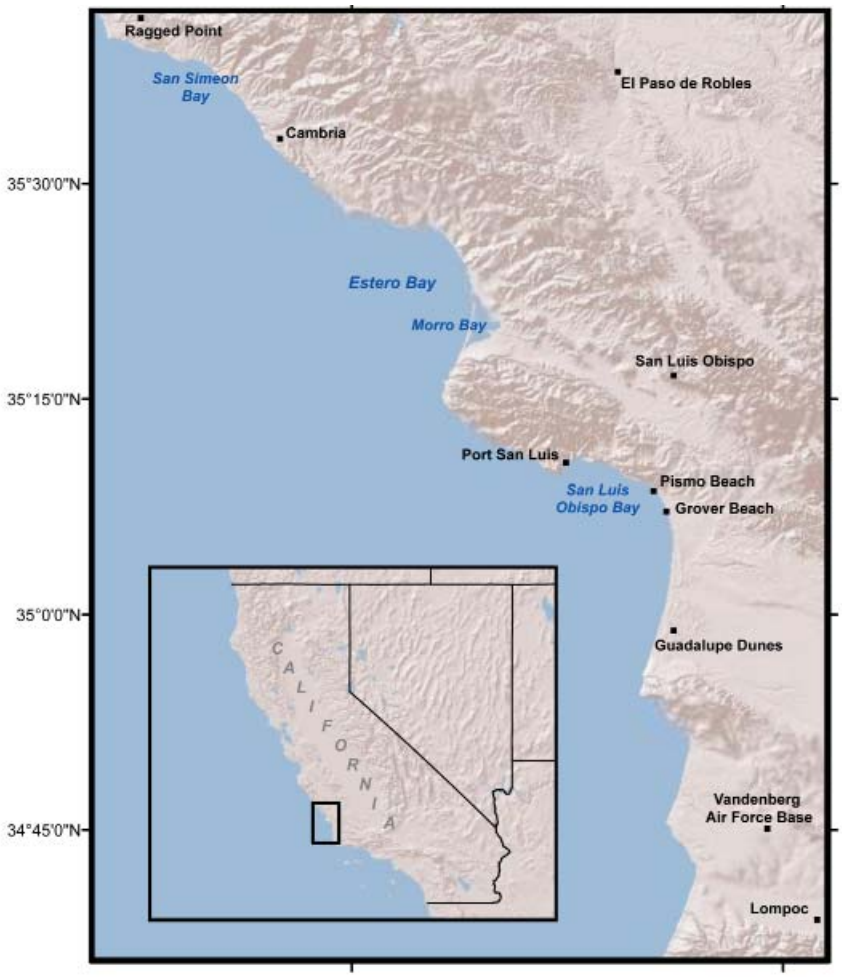

Figure 2. Overview of the Port San Luis DEM region. Outermost black box represents Port San Luis DEM extents.

Figure 3. Morro Rock, located in Morro Bay, California. (Wikipedia Commons)

3. METHODOLOGY

The Port San Luis 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 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 vertical conversion grid. Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensured that gridding occured 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 Port San Luis DEMs.

Grid Area	Port San Luis, California
Coverage Area	120.45º to 121.30º W; 34.60º to 35.70º 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. 4) including: NGDC; NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS) and Coastal Services Center (CSC); the United States Army Corps of Engineers (USACE); the United States Geological Survey (USGS); The California State University at Monterey Bay (CSUMB) Seafloor Mapping Laboratory; and the Bureau of Economic Geology— University of Texas at Austin (BEG). All datasets were shifted to NAD 83 geographic horizontal datum using ESRI's *ArcGIS* and *Proj4*. 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 NOAA's Vertical Datum Tranformation Tool (*VDatum)*.

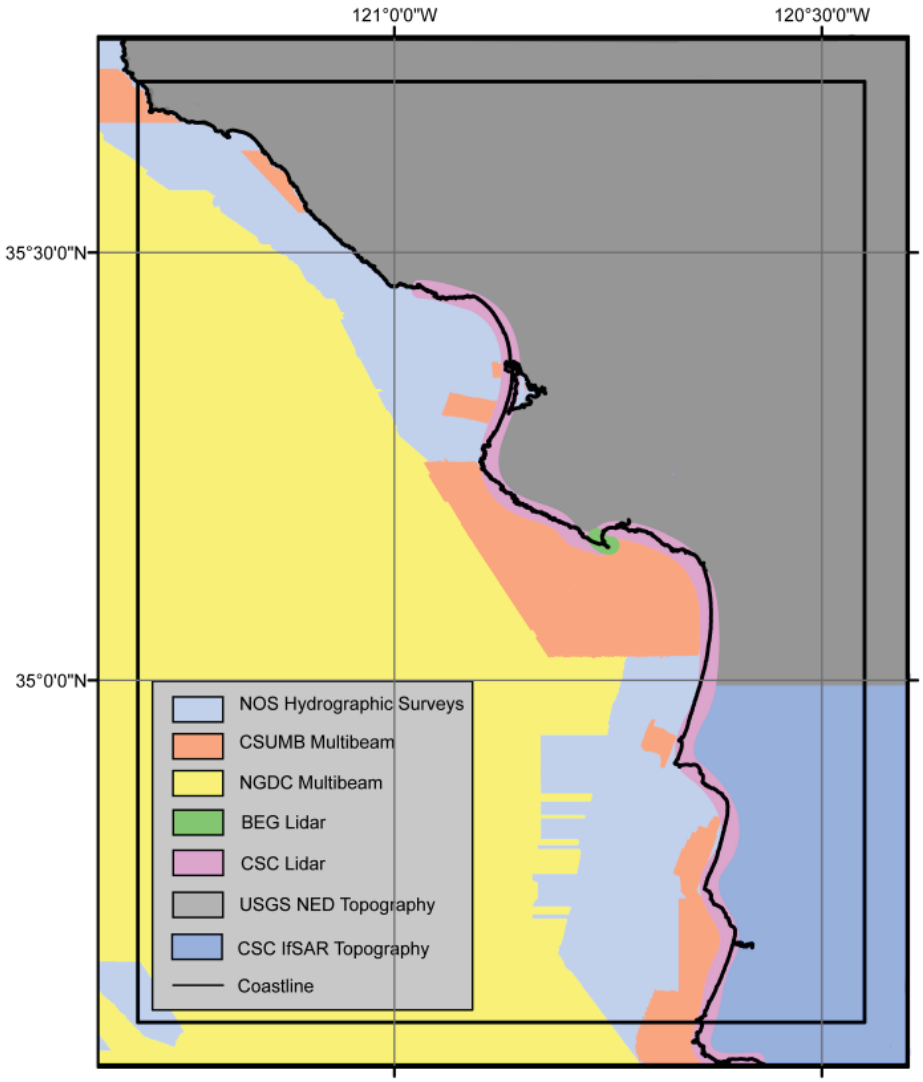

Figure 4. Source and coverage of datasets used in compiling the Port San Luis DEMs.

3.1.1 Shoreline

Shoreline data of the Port San Luis region were acquired from NOAA's OCS (Table 2). The data were obtained from the OCS website in 2007 for an earlier version of the Port San Luis DEM. The coastline was adjusted to better fit the coastal morphology suggested in topographic datasets, bathymetric datasets, assorted maps and aerial imagery. The coastline was also modified to include large offshore rocks and small islets that appeared in the aerial imagery and in Raster Nautical Charts (RNCs).

Table 2. Shoreline datasets used in developing the Port San Luis NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution or Scale*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
OCS Electronic Navigational Charts	2001 to 2006	Vector shoreline	Digitized from 1:216,116 scale electronic chart	WGS 84 geographic	Inferred MHW	http://chartmaker.ncd.noaa.gov
OCS MHW vector shoreline of Extero and Morro Bays	2003	Vector shoreline	Digitized from 1:40,000 and 1:80,000 scale raster charts	NAD 83 geographic	MHW	http://chartmaker.ncd.noaa.gov

OCS electronic navigational chart

One electronic navigational chart (ENC), #18700 (Point Conception to Point Sur, scale 1:216,116), and one raster nautical chart (RNC), #18703, provide digital coverage of the Port San Luis harbor and surrounding coastal region. The data were downloaded from NOAA's Office of Coast Survey (OCS) website. The electronic chart data include a coastline data file which was extracted from the ENC and compared with coastal topographic data and aerial imagery. OCS has also developed a MHW vector coastline for the United States, which was digitized from navigational charts. In the Port San Luis gridding region, the data are from nautical charts #18700 and #18703.

In order to define a current and high-resolution coastline, the two OCS datasets were combined and displayed with high resolution aerial imagery from several sources--including Bing, Google, and the National Agriculture Imagery Program (NAIP). The coastline was also compared with bathymetric and topographic datasets available for the Port San Luis region. The coastline was manually adjusted to ensure that features such as piers, jetties, and rocks were accurately reflected along the shore. The final edited coastline was converted to xyz data with 10 meter point spacing, using NGDC's *GEODAS*[3] software, for use in creating a 'pre-surface' bathymetric grid (See Sec. 3.3.2).

3. *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.

3.1.2 Bathymetry

The bathymetric datasets available for use in the compilation of the Port San Luis DEMs included 31 NOS hydrographic surveys from NGDC, 26 multibeam swath sonar surveys from NGDC, and 21 multibeam swath sonar surveys from CSUMB.

Several other bathymetric datasets were acquired and assessed, but many were superseded by higher quality or more recent datasets, and were not used as input in the final DEM. These datasets included some multibeam swath sonar surveys downloaded from the NGDC multibeam database, NOS hydrographic surveys that were overlapped by higher resolution multibeam data, and USACE hydrographic surveys.

Table 3. Bathymetric datasets used in compiling the Port San Luis NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1933 to 1994	NOS hydrographic survey soundings	Ranges from 10 meters to 1 kilmometer (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 27, NAD 83	MLLW, MLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1990 to 2010	Multibeam swath sonar surveys	1 arc-second	WGS 84 geographic	Assumed mean sea level (MSL)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
CSUMB	1999	Multibeam swath sonar surveys	2 to 5 meters	WGS 84 UTM Zone 10 N (meters)	NAVD 88	http://seafloor.csumb.edu/SFMLwebDATA.htm

1) California State University at Monterey Bay Seafloor Mapping Laboratory Multibeam Surveys

Twenty-one near-shore multibeam swath sonar surveys were downloaded from the Califronia State University at Monterey Bay website as xyz or gridded datasets (Table 4). These data were acquired, processed, archived, and distributed by CSUMB. The surveys were collected in 2009 and 2010. The files were reprojected using *Proj4* and reviewed using *QT Modeler* and *ArcMap*, and required no editing. Grid files were converted to xyz files for use in the final gridding process.

Table 4. Digital CSUMB hydrographic surveys used in developing the Port San Luis NAVD 88 DEM.

Survey Name	Resolution	Data Type	Original Horizontal Datum	Original Vertical Datum
Point Arguello to Santa Maria	1 meter	GeoTiff	WGS 84 UTM Zone 10 N	NAVD 88
Cambria Inlet	2 meter	GRID	WGS 84 UTM Zone 10 N	NAVD 88
Morro Bay	1 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Morro Bay Harbor	1 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Piedras Blancas Inlet	2 meter	GRID	WGS 84 UTM Zone 10 N	NAVD 88
South of Point Conception to Point Arguello	1 meter	GeoTiff	WGS 84 UTM Zone 10 N	NAVD 88
Vandenberg North Inlet	2 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Vandenberg South Inlet	2 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
White Rock Inlet	2 meter	GRID	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block A1	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block A2	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block A3	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AB	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AC	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AD	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AE	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AF	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AG	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AH	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AI	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88
Central Coast Block AJ	5 meter	xyz file	WGS 84 UTM Zone 10 N	NAVD 88

2) NGDC Multibeam Swath Sonar Surveys

A total of 26 multibeam swath sonar surveys were available for use in developing the Port San Luis DEM. The surveys were retrieved from the NGDC Multibeam Bathymetry Database (Figure 4). The NGDC Multibeam Bathymetry Database is comprised of original swath sonar surveys; most of the surveys are transits rather than dedicated sea-floor surveys.

The multibeam data were gridded to 1 arc-second resolution using *MB-System*[4]. Data errors are common in the multibeam surveys, due to noise along multibeam swath edges. In order to reduce the influence of these errors, surveys were removed where they were overlapped by multibeam surveys with smoother coverage. Anomalous points in the gridded data were also manually edited in *QT Modeler* before being used in creating the 'pre-surface' bathymetric grid (see 3.3.2) and the final DEM.

4. *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.]

3) National Ocean Service hydrographic survey data

A total of 36 NOS hydrographic surveys conducted between 1933 and 1994 were available for use in developing the Port San Luis DEMs (Table 5; Fig. 4). The surveys were extracted from NGDC's online NOS hydrographic database using *GEODAS*.

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 MLLW to NAVD 88 using a conversion grid developed from the *VDatum* transformation tool (see Sec. 3.2.1). The surveys were compared to the multibeam datasets, original survey smooth sheets, the DEM coastline, topographic lidar data, and NOS RNCs. NOS surveys were clipped to remove soundings that were overlapped by more recent bathymetric datasets, and several of the surveys were removed entirely. Most of the surveys removed were also available as multibeam swath sonar records from NGDC.

Table 5. Digital NOS hydrographic surveys used in developing the Port San Luis NAVD 88 DEM.

Survey ID	Year	Survey Scale	Original Horizontal Datum	Original Vertical Datum
B00085**	1986	50,000	NAD 83 geographic	MLLW
B00117**	1987	50,000	NAD 83 geographic	MLLW
B00118**	1987	50,000	NAD 83 geographic	MLLW
B00157**	1988	50,000	NAD 83 geographic	MLLW
B00161**	1988	50,000	NAD 83 geographic	MLLW
B00162**	1988	50,000	NAD 83 geographic	MLLW
H05476	1933	10,000	NAD 27 geographic	MLLW
H05508*	1933	10,000	NAD 27 geographic	MLLW
H05509	1934	10,000	NAD 27 geographic	MLLW
H05566	1933	40,000	NAD 27 geographic	MLLW
H05567	1934	40,000	NAD 27 geographic	MLLW
H05611	1933	80,000	NAD 27 geographic	MLLW
H05642*	1934	10,000	NAD 27 geographic	MLLW
H05671	1934	10,000	NAD 27 geographic	MLLW
H05681	1934	10,000	NAD 27 geographic	MLLW
H05682	1935	10,000	NAD 27 geographic	MLLW
H05692	1935	10,000	NAD 27 geographic	MLW
H05708	1935	10,000	NAD 27 geographic	MLLW
H05741	1934	10,000	NAD 27 geographic	MLLW
H05742	1934	10,000	NAD 27 geographic	MLLW

Survey ID	Year	Survey Scale	Original Horizontal Datum	Original Vertical Datum
H05743	1934	10,000	NAD 27 geographic	MLLW
H05746	1934	40,000	NAD 27 geographic	MLLW
H05747	1934	10,000	NAD 27 geographic	MLLW
H05748	1934	40,000	NAD 27 geographic	MLLW
H05749	1934	10,000	NAD 27 geographic	MLLW
H05750	1934	10,000	NAD 27 geographic	MLLW
H05751	1935	5,000	NAD 27 geographic	MLLW
H05772	1934	10,000	NAD 27 geographic	MLLW
H05774	1934	40,000	NAD 27 geographic	MLLW
H05776	1934	120,000	NAD 27 geographic	MLLW
H05777	1933	120,000	NAD 27 geographic	MLLW
H05831	1934	10,000	NAD 27 geographic	MLLW
H05832	1934	10,000	NAD 27 geographic	MLLW
H09737	1978	5,000	NAD 27 geographic	MLLW
H10531	1994	10,000	NAD 83 geographic	MLLW
H10532	1994	10,000	NAD 83 geographic	MLLW

*Surveys not used because they are overlapped by other, higher resolution datasets.
**Surveys not used and available in NGDC multibeam database

3.1.3 Topography

Four topographic datasets were available for use in compiling the Port San Luis NAVD 88 DEM (Table 6; Fig. 4). The two primary topographic datasets used were USGS NED grids and CSC IfSAR data. The DEM also includes two small lidar datasets from CSC and the Bureau of Economic Geology (BEG).

Table 6. Topographic datasets used in compiling the Port San Luis DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
USGS NED	2006	GRID	1/3 arc-second grid	NAD 83 geographic	NAVD 88	http://seamless.usgs.gov
NOAA CSC	2002-2003	GRID	3 meter grid	NAD 83 UTM Zone 11, meters.	NAVD 88	http://www.csc.noaa.gov/lidar
NOAA CSC	1998	LAS files	10 meter grid	NAD 83 geographic, meters	NAVD 88	http://www.csc.noaa.gov.lidar
BEG	2004	LAS files	0.5 meter grid	NAD 83, UTM Zone 10, meters	NAVD 88	n/a

1) USGS NED

The USGS NED data are available for download as portions of a bare-earth raster DEM, and provide complete 1/3 arc-second coverage of the Port San Luis region. The elevations in the NED DEM have a vertical accuracy of +/- 7 to 15 meters, depending on the resolution of the source data used by the USGS. See the USGS Seamless website for specific source information. The dataset was mostly derived from USGS topographic quadrangle maps and aerial photographs based on topographic surveys conducted in the 1970s and 1980s; it has been revised using data collected in 1999. The NED includes “zero” elevation values over the open ocean, which were removed from the dataset by clipping it to the final coastline.

2) NOAA CSC IfSAR

The NOAA Coastal Services Center (CSC) collaborated with the Southern California Water Research Project (SCWRP) to conduct IfSAR (Interferometric Synthetic Aperture Radar) surveys in coastal areas of Souther California. This project was designed to collect, process, and disseminate topograhpic elevation data to provide coastal managers and partners with the decision support tools to more effectively manage and preserve America’s coastal zone. IfSAR data within the Port San Luis region were extracted from the CSC website as a 3-meter cell-size DEM. The grid was resampled to a 10-meter cell size grid for use as input in the final DEM. An edge effect along the north side of the CSC DEM required the removal of two rows of data on the edge of the resampled 10-meter DEM.

3) NOAA CSC Lidar Data

Lidar aquisition along portions of the U.S. West Coast was conducted by the NOAA Coastal Services Center (CSC), in partnership with the NASA Wallops Flight Facility, the USGS Center for Coastal and Regional Marine Geology, and the NOAA Aircraft Operations Center. Coastal lidar data of the Port San LUis region were downloaded from the CSC website.

No processing was done by CSC to remove returns from water or vegetation, thus data values offshore represented features on the ocean surface, not true topography. Examination of the data indicated that a cut-off of 0.75 meters above the NAVD 88 zero line would effectively eliminate most of the open-ocean surface returns while retaining much of the beach face morphology. Visual inspection of the lidar data after clipping revealed many remaining offshore data points that were removed with reference to NOAA nautical charts and aerial satellite imagery. There were some patches of anomalous returns, greater than 100 meters above MHW

in some cases, that did not correspond to offshore topographic features; these data points were also removed prior to final gridding. NGDC performed all processing of the CSC lidar data in 2007.

4) BEG topographic LiDAR data

The BEG at the University of Texas at Austin, in partnership with the USACE, collected topographic LiDAR data in 2004 over a breakwater at the mouth of San Luis Obispo Bay. BEG compared the LiDAR data to the 1998 coastal LiDAR data set for evaluation and processing; the data were not processed to bare earth. A DEM of the BEG LiDAR data at 0.5 meter cell size was supplied to NGDC by Randy Bucciarelli of the University of California at San Diego in 2007. The DEM was resampled to a 10-meter cell size by NGDC and used in the final gridding process. Water returns were clipped from the data using the final coastline. NGDC performed all processing of the BEG lidar data in 2007.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation of the Port San Luis NAVD 88 DEM were originally referenced to a number of vertical datums including MLLW, MSL, and NAVD 88. All datasets not in NAVD 88 were transformed to NAVD 88 using conversion grids derived from the the *VDatum* transformation tool (http://vdatum.noaa.gov/). An example of the methodology used to create the conversion grids can be seen in secton 3.3.4. The locations and tidal relationships at the Port San Luis area tide stations (http://tidesandcurrents.noaa.gov/) are provided in Table 7, and are compared to the difference values given in the conversion grids.

Table 7. Tide stations in the Port San Luis area and relationships between MHW and NAVD 88.

Tide Station	*Name*	*MHW*	*NAVD 88*	*Difference*	*Conversion Grid Value*	*Latitude*	*Longitude*
9412110	Port San Luis	1.408	0.024	1.384	1.39	35.17º W	120.76º N
9412553	San Simeon	1.381	0.068	1.313	1.46	35.64º W	121.19º N

1) Bathymetric data

The NOS hydrographic surveys and NGDC multibeam surveys were transformed from MLLW and MSL to NAVD 88 using *VDatum*. CSUMB multibeam surveys were downloaded in NAVD 88.

2) Topographic data

The USGS NED and the CSC IfSAR datasets were originally referenced to NAVD 88, and required no vertical transformations.

3.2.2 Horizontal datum transformations

Datasets used in the compilation of the Port San Luis NAVD 88 DEM were originally referenced to NAD 83 geographic, NAD 83 UTM Zone 11 North, and WGS 84 horizontal datums. The relationships and transformational equations between these geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using *Proj4*, *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 ESRI shapefiles were checked in *ArcMap* and *QTModeler* for inter-dataset consistency. 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 in preparation for gridding. Problems included:

- Inconsistent, overlapping high-resolution bathymetric datasets. Older datasets were clipped to newer datasets when possible. Datasets were weighted based on quality and year during the gridding process.
- Data values over the ocean in the SRTM and IfSAR DEM datasets. These datasets required automated clipping to the final coastline or were edited manually.
- Digital, measured bathymetric values from NOS surveys date back over 100 years. More recent data, such as the multibeam surveys, differed from older NOS data by as much as 70 meters vertically. The older NOS survey data were excised where more recent bathymetric data exists.

3.3.2 Smoothing of bathymetric data

The older NOS hydrographic survey data are generally sparse at the resolution of the Port San Luis DEM in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the form of lines or "pimples" in the DEM due to the low resolution datasets, and to provide effective interpolation into the coastal zone, 'pre-surface' bathymetric grids in MHW vertical datum were generated using *GMT*[5].

A Port San Luis 1 arc-second, 'pre-surface' grid was compiled from NOS hydrographic point data, CSUMB multibeam swath sonar survey data, and NGDC multibeam swath sonar survey data by converting the files to xyz format. These xyz files were combined into a single file. These point data were then smoothed using the *GMT* tool 'blockmedian' onto a 1 arc-second grid. The *GMT* tool 'surface' was applied to interpolate values for cells without data values. The *GMT* grid created by 'surface' was converted into an ESRI Arc ASCII grid file using the *MB-System* tool 'mbm_grd2arc' for viewing in ESRI *ArcMap*. *GDAL* software was used to clip the grid to the final coastline to eliminate data interpolation into land areas.

The 'pre-surface' grid was compared with the original soundings to ensure grid accuracy, and then exported as an xyz file for use in the final gridding process (Figs. 5 and 6). The statistical analyses of the differences between the 1 arc-second bathymetric surface at Port San Luis and the NOS hydrographic surveys and NGDC multibeam swath sonar surveys show that the majority of the surveys are in good agreement with the bathymetric surface. The few exceptions where the differences reached up to 16 meters are attributed to rugged bathymetry or overlapping datasets, where two or more closely positioned points were averaged to obtain the elevation of one grid cell. Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the surveys. In areas where more recent data were available, the older surveys were either clipped to the newer data or not used. The gridded bathymetric surfaces were then converted to xyz files for use in building the final DEMs.

5. 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.]

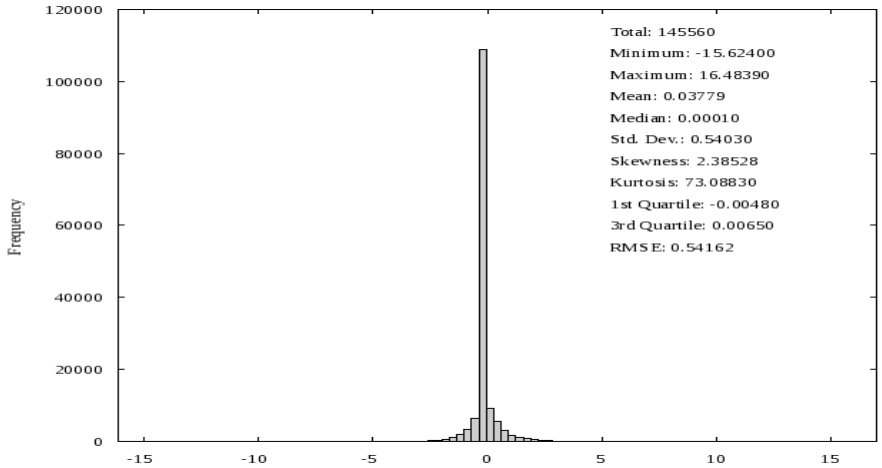

Figure 5. Histogram of the differences between the NOS bathymetric surveys and the 1 arc-second pre-surfaced bathymetric grid.

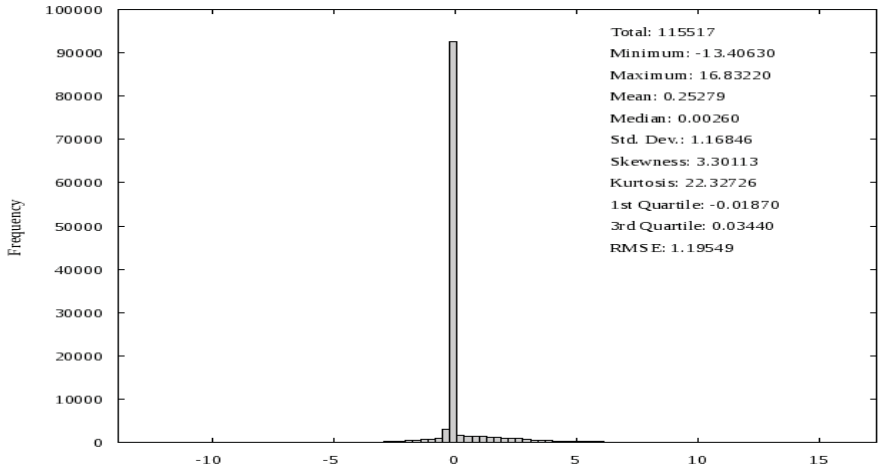

Figure 6. Histogram of the differences between the NGDC multibeam data and the 1 arc-second pre-surfaced bathymetric grid.

3.3.3 Building the NAVD 88 DEM

MB-System was used to create the 1/3 arc-second Port San Luis 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 Port San Luis 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*
NED	10
IfSAR	10
CSC Lidar	10
BEG Lidar	10
CSUMB Multibeam	1
NGDC Multibeam	1
NOS Hydrographic Soundings	1

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 Port San Luis DEMs, interpolating values inland to represent the differences between the two datums onshore (Fig. 7).

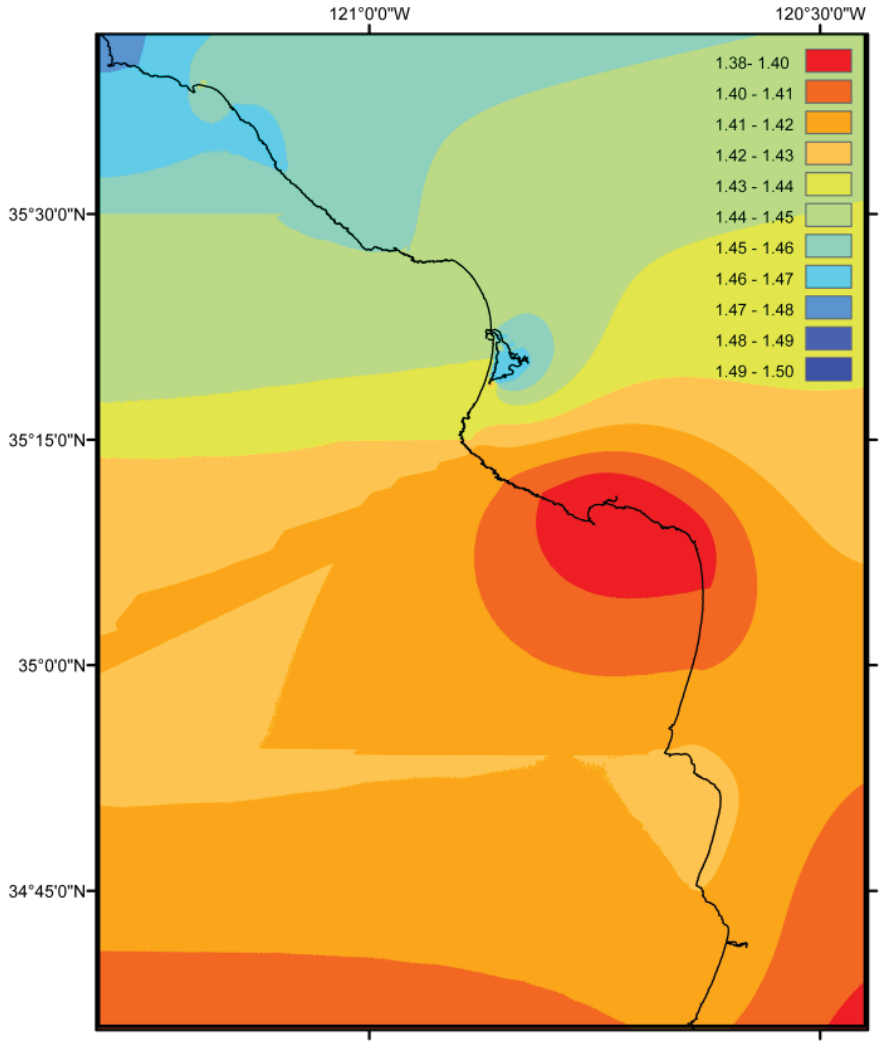

Figure 7. Image of NGDC Port San Luis conversion grid.
The conversion values represent the absolute values of the difference between NAVD 88 and MHW, as determined from VDatum.

2) 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 Port San Luis DEMs is dependent upon DEM cell size and source datasets. Topographic features have an estimated horizontal accuracy of 10 meters: gridded lidar data and IfSAR data have an accuracy less than five meters, and NED data are accurate to approximately 10 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 Port San Luis 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 and IfSAR data and up to 15 meters for NED 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 Port San Luis NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 9). The DEM was transformed to NAD 83 UTM California 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 Port San Luis NAVD 88 DEM in its final version. Figure 8 shows a perspective rendering of the final NAVD 88 DEM. Figure 10 shows a data contribution plot of the Port San Luis DEMs.

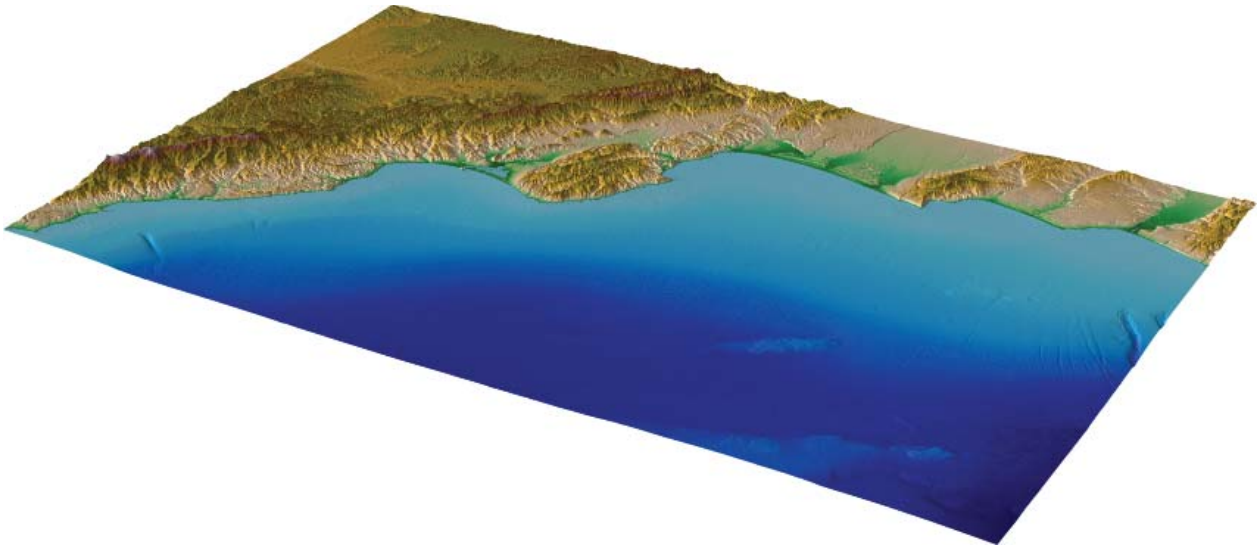

Figure 8. Perspective view from the southwest of the 1/3 arc-second Port San Luis NAVD 88 DEM. Vertical exaggeration–times 5.

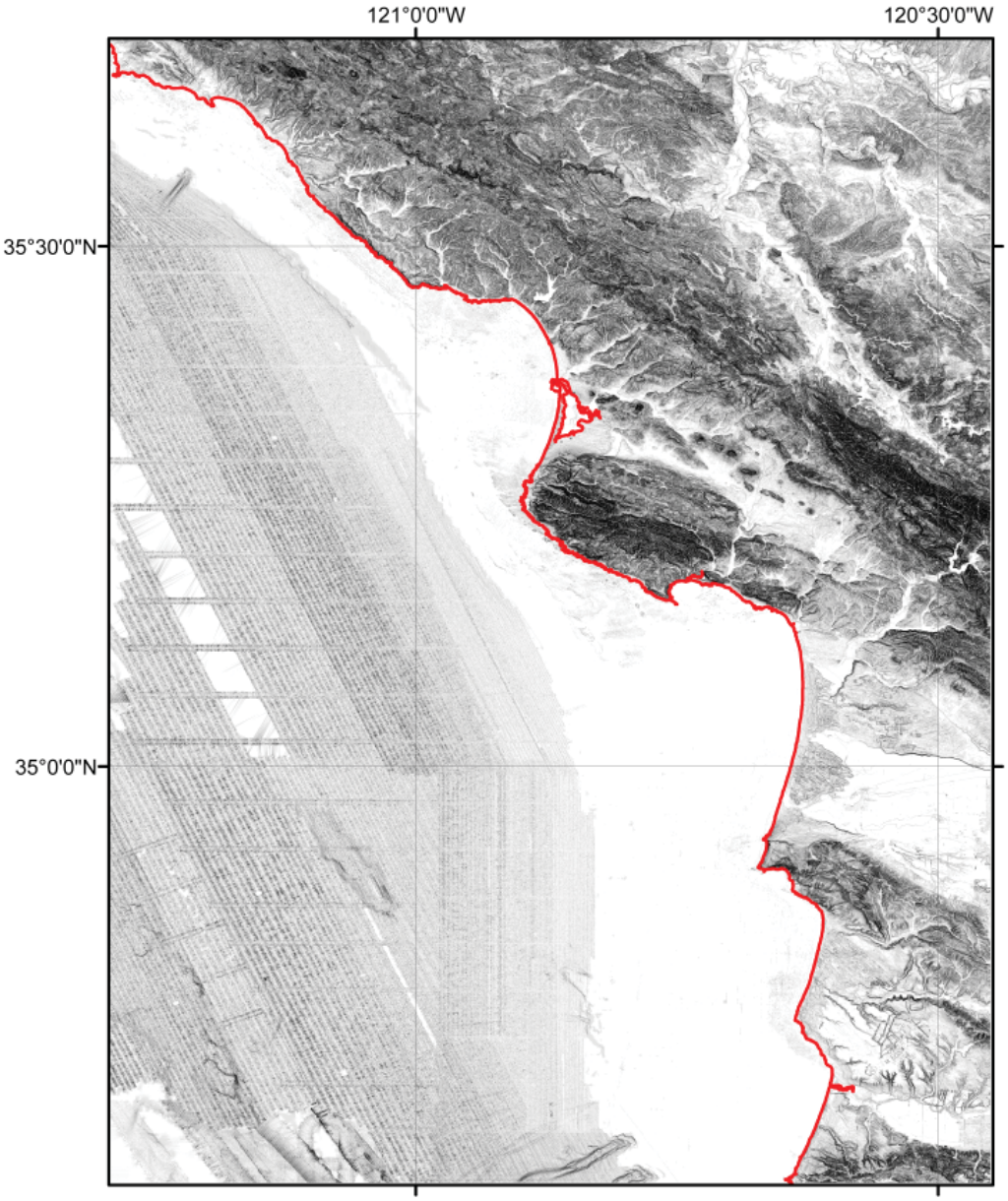

Figure 9. Slope map of the Port San Luis NAVD 88 DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined coastline indicated in red.

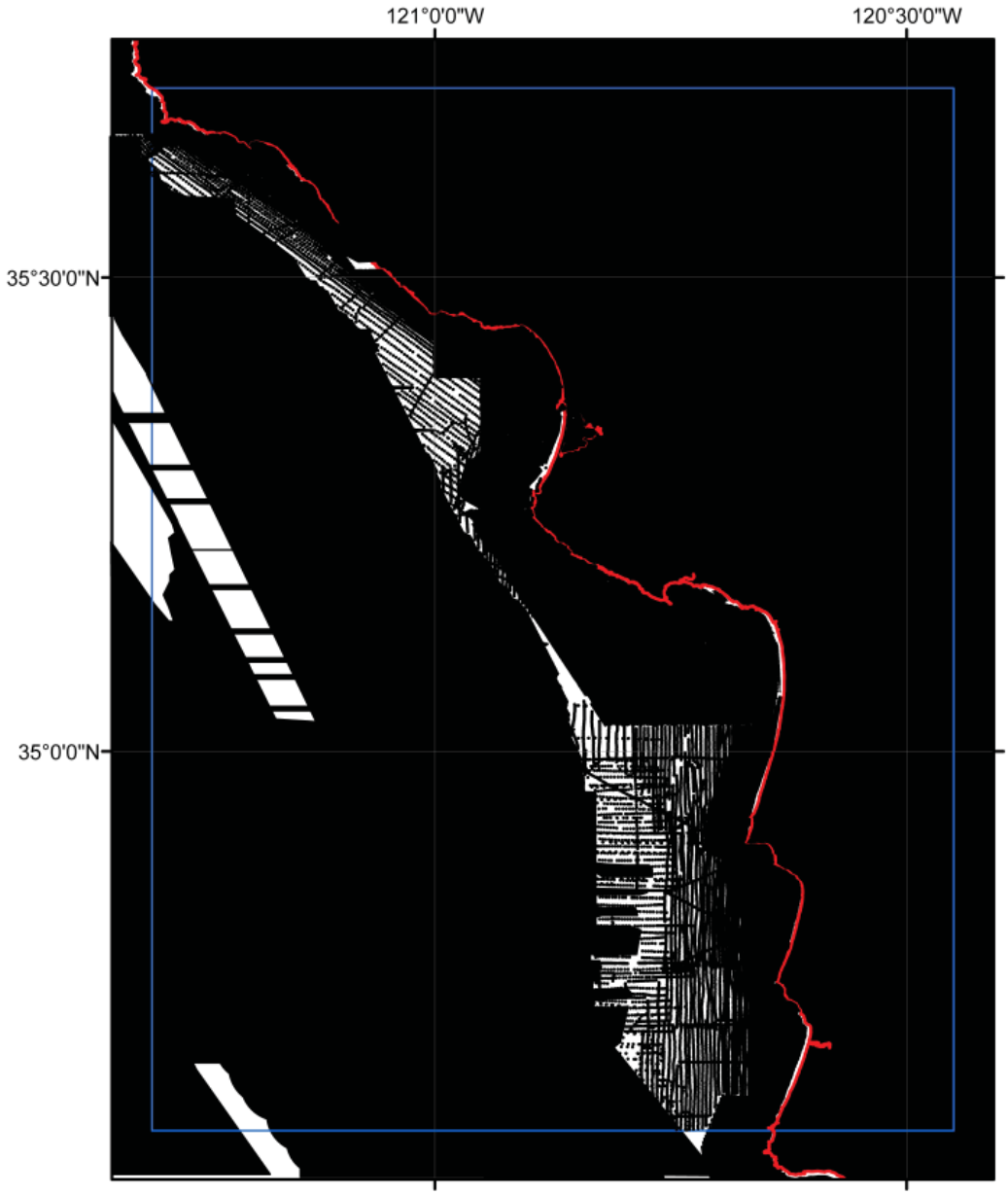

Figure 10. Data contribution plot of the Port San Luis NAVD 88 DEM. Black depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. Coastline is shown in red; DEM boundary in blue.

3.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 62 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (see Fig. 11 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 Port San Luis NAVD 88 DEM elevation values (Fig. 24). Differences between the DEM and the monument elevations range from -36.41 to 10.64 meters, with a mean of -0.64 meters. Large differences in elevations occurred where monuments are located on major roads and bridges, pilings, or buildings.

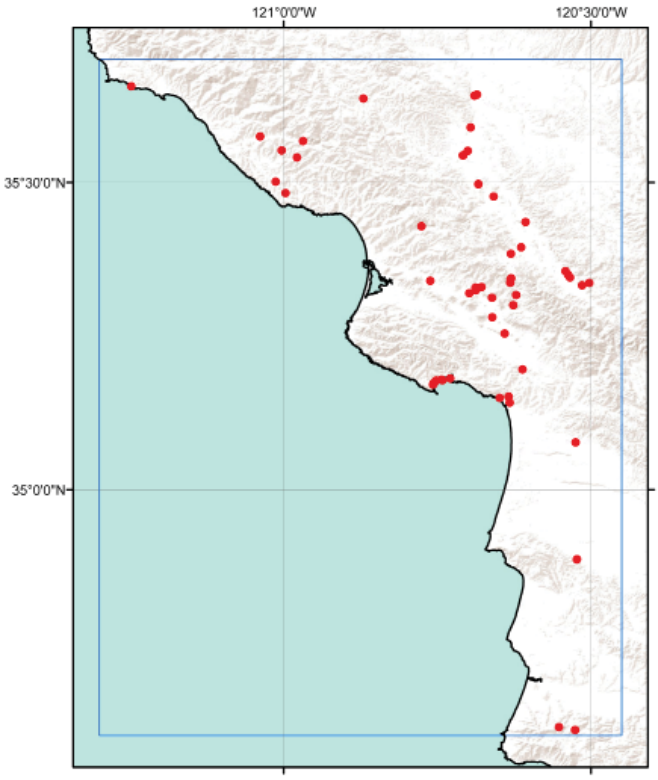

Figure 11. Location of NGS geodetic monuments in the Port San Luis region.

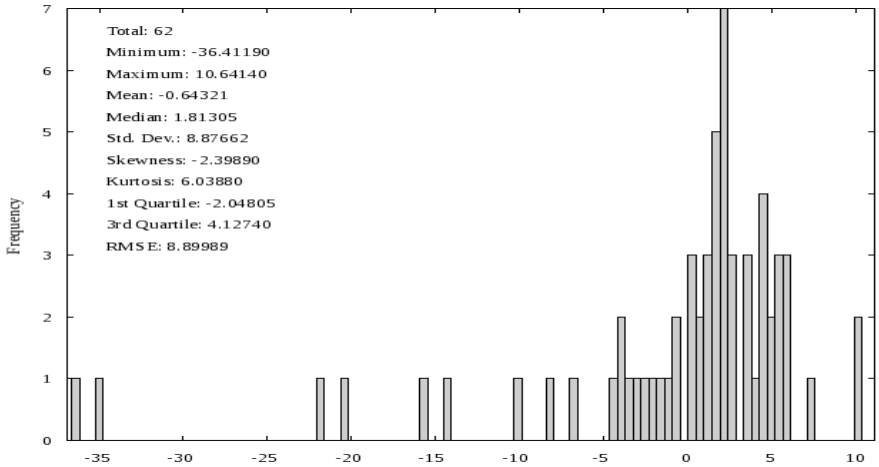

Figure 12. Histogram of the differences between NGS geodetic monument elevations and the Port San Luis NAVD 88 DEM.

3.4.5 NAVD 88 DEM comparison with source data files

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

The CSUMB multibeam data portions of the NOS hydrographic survey dataset was the first compared to the Port San Luis NAVD 88 DEM (Fig. 13). The differences in elevations are clustered around zero and the majority were within ± 1 meter. The NGDC multibeam data was also compared to the Port San Luis NAVD 88 DEM (Fig.14). These values are clustered around zero, but vary by ± 10 meters. The NGDC multibeam data are less accurate because it is older data which needed cleaning, and also because it provided coverage in deep water areas— where ten meter differences are less significant than in shallow water.

Comparisons of the USGS NED data and the Port San Luis NAVD 88 DEM are shown in Figure 15. Elevation differences range from -48.81 to 46.41 The majority of differences are clustered around zero and are within ten meters. Large variations are due to NED overlap with lidar and IfSAR datasets.

Comparisons between shallow-water NOS data, CSC lidar data, and CSC IfSAR data are shown in figures 16-18. All exhibited consistency with the Port San Luis DEM, with values clustered around zero and within ± 5 meters. Outliers in these datasets occur where the data overlap the multibeam and NED datasets.

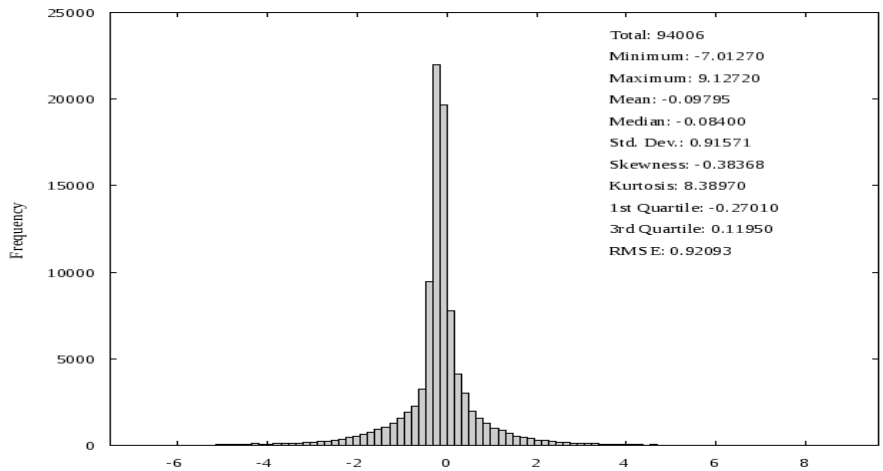

Figure 13. Histogram of the differences between a portion of the CSUMB multibeam data and the NAVD 88 DEM.

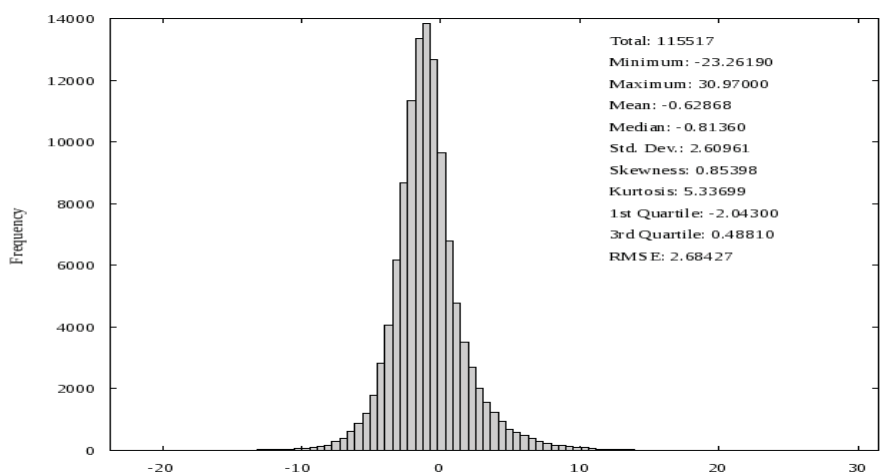

Figure 14. Histogram of the differences between a portion of the NGDC multibeam data and the NAVD 88 DEM.

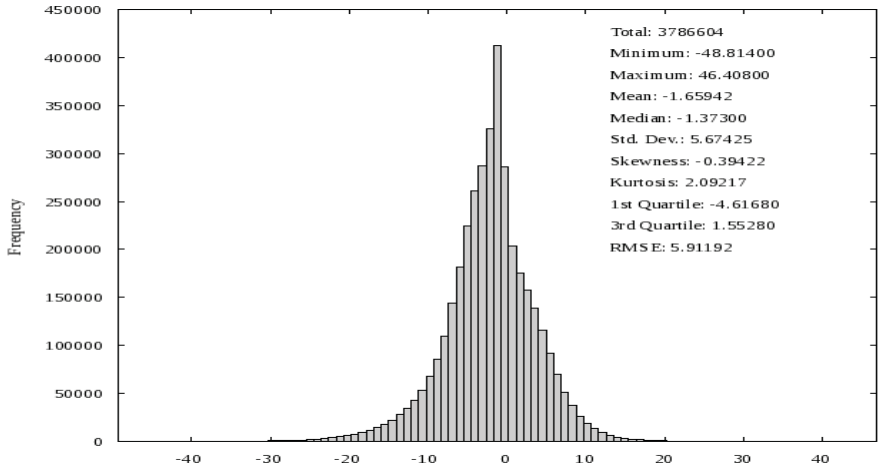

Figure 15. Histogram of the differences between the NED data and the NAVD 88 DEM.

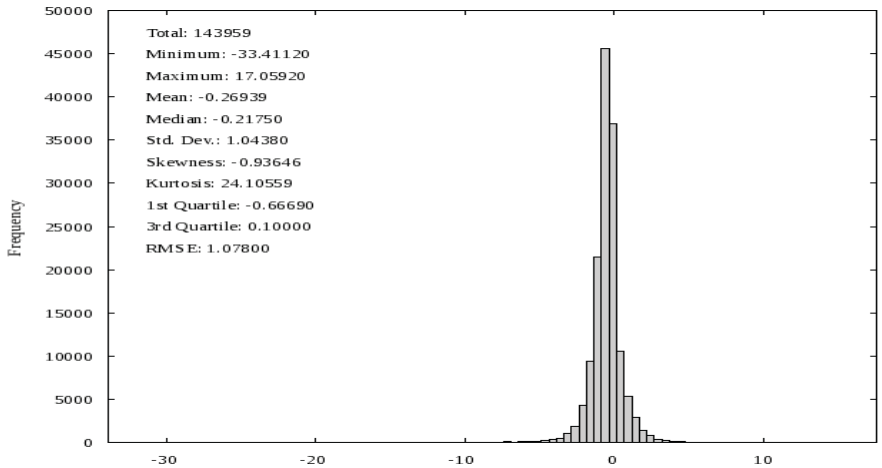

Figure 16. Histogram of the differences between the NOS hydrographic survey data points and the NAVD 88 DEM.

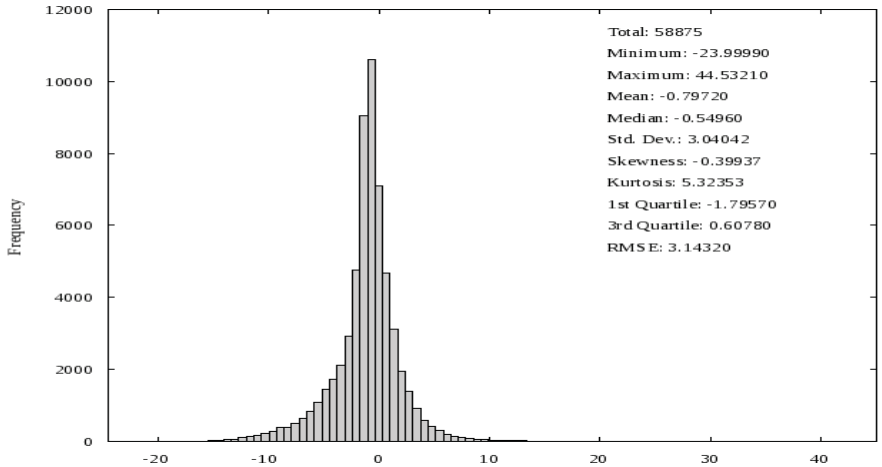

Figure 17. Histogram of the differences between the CSC lidar survey and the NAVD 88 DEM.

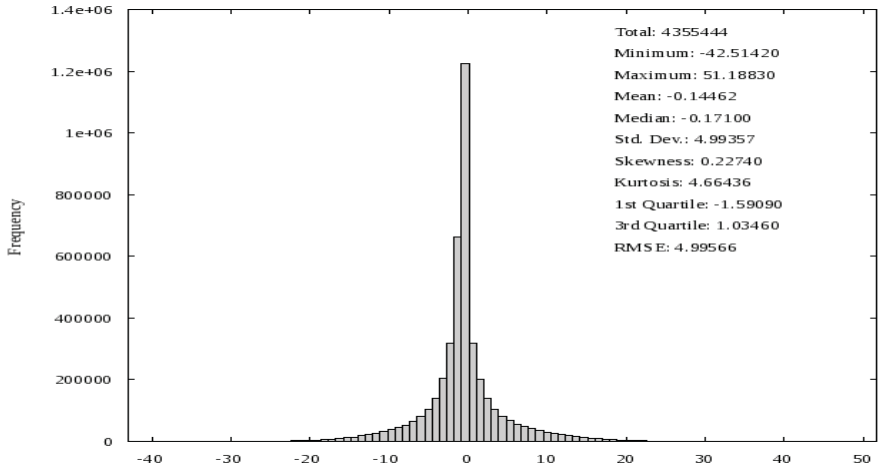

Figure 18. Histogram of the differences between the CSC IfSAR data and the NAVD 88 DEM.

4. Summary and Conclusions

Two integrated bathymetric–topographic digital elevation models of the Port San Luis, California 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*, *GMT*, *MB-System*, *QT Modeler*, and *VDatum* software.

Recommendations to improve the Port San Luis 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.

5. Acknowledgments

The creation of the Port San Luis DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL) and Erik Hund (CSC)

6. References

Taylor, L.A., B.W. Eakins, K.S. Carignan, R.R. Warnken, D.C. Schoolcraft, and G.F. Sharman. Digital Elevation Model of Port San Luis, California: Procedures, Data Sources and Analysis. 2008. NOAA Technical Memoradum NESDIS NGDC-30. http://www.ngdc.noaa.gov/mgg/inundation/tigp/ngdc/data/port_san_luis_ca/port_san_luis_ca.pdf

Nautical Chart #18700 (RNC), 35th Edition, 2008. Point Conception to Point Sur. Scales 1:216,116. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18703 (ENC and RNC), 38th Edition, 2008. Estero Bay, and Morro Bay inset. Scales 1:40,000 and 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18704 (ENC and RNC), 16th Edition, 2010. San Luis Obispo Bay 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 10.0 – 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, California/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.