NOAA Technical Memorandum NESDIS NGDC-20

DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★

DIGITAL ELEVATION MODEL OF MONTEREY, CALIFORNIA: PROCEDURES, DATA SOURCES AND ANALYSIS

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UNITED STATES DEPARTMENT OF COMMERCE

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1. Introduction

In January 2008, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a bathymetric–topographic digital elevation model (DEM) of Monterey, California (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). The 1/3 arc-second[1] coastal DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3) and will be used for tsunami inundation modeling, as part of the tsunami forecast system SIFT (Short-term Inundation Forecasting for Tsunamis) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Monterey DEM.

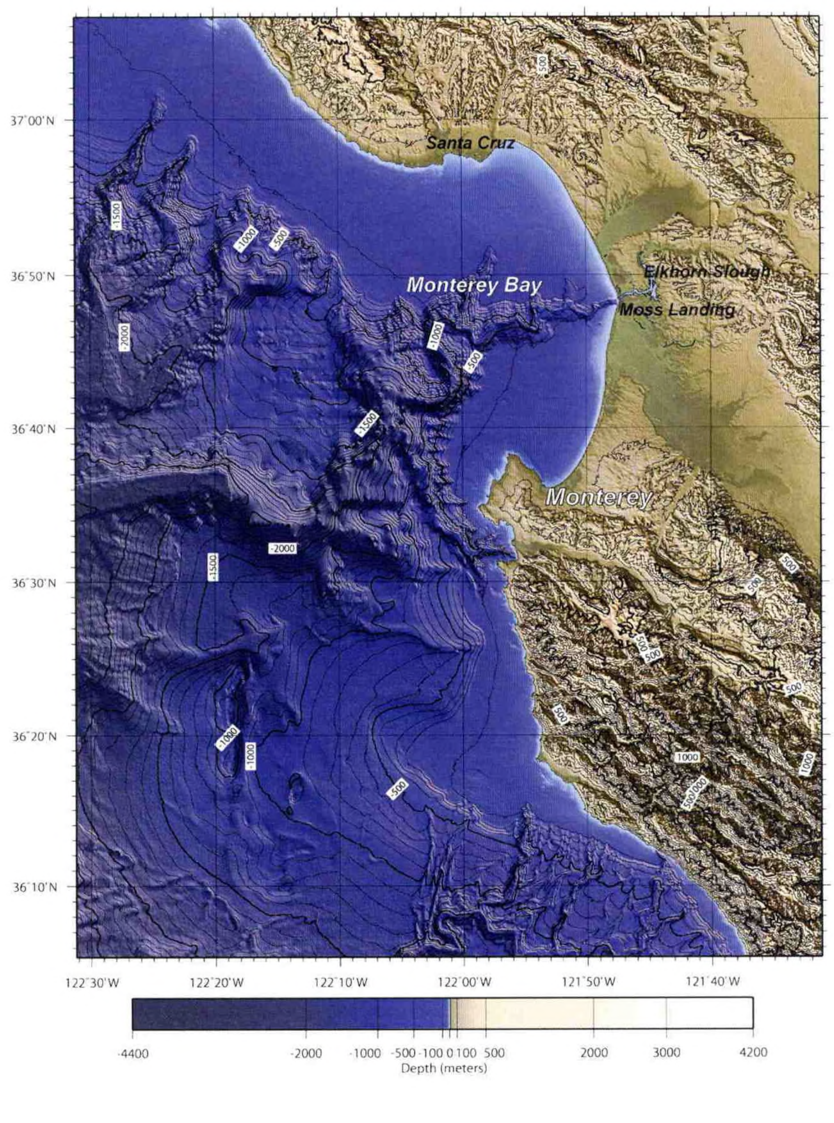

Figure 1. *Shaded-relief image of the Monterey, California DEM. Contour interval is 100 meters.*

1. The Monterey 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 Monterey, California (36°36.3′ N, 121°53.3′ W) 1/3 arc-second of latitude is equivalent to 10.275 meters; 1/3 arc-second of longitude equals 8.284 meters.

2. Study Area

The Monterey DEM covers the coastal region surrounding the town of Monterey, California from Ano Nuevo in the north to Dolan Rock in the south and includes the communities of Santa Cruz, Capitola, Moss Landing, Seaside, Monterey, Pacific Grove, and Carmel-by-the-Sea (Fig. 2). Encompassing a portion of the Monterey Bay National Marine Sanctuary, the DEM includes large underwater canyons. The region is home to many species of marine life, which provide recreation, educational, and economic benefits to the surrounding communities and offers research opportunities for the Monterey Bay Aquarium Research Institute in Moss Landing and the University of California Santa Cruz in Santa Cruz. The coastline varies from beaches to sea cliffs and the drive along the coast is considered to be one of the most scenic on the west coast.

The town of Monterey is located at the southernmost part of the bay and has a population of approximately 30,000. Originally a fishing and whaling community built up in the 1850s, the town developed a large recreational and agricultural based economy in the 1950s. Santa Cruz, at the northern end of the bay, has a population of approximately 55,000.

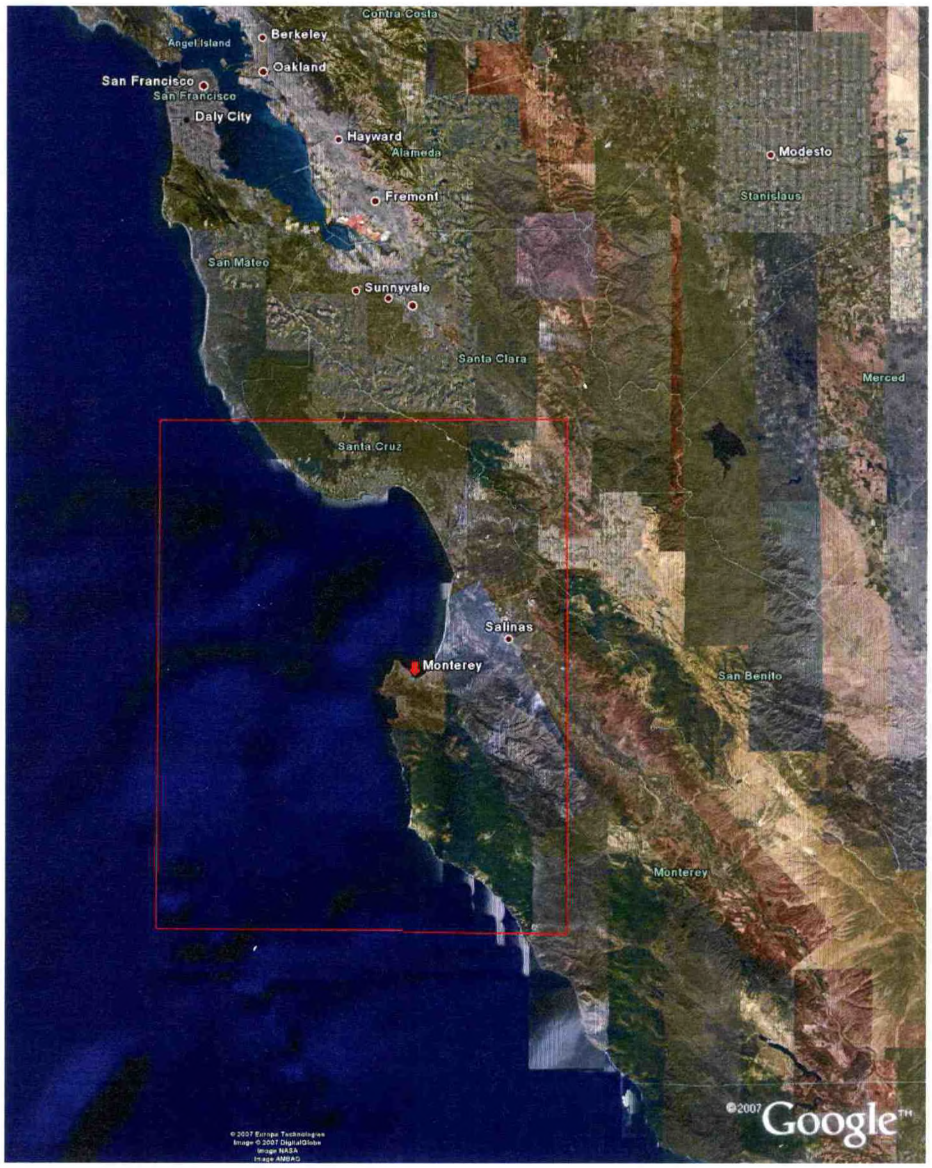

Figure 2. *The central California coast showing the Monterey DEM boundary in red.*

3. METHODOLOGY

The Monterey, California DEM was 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 digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum 1983 (NAD 83) and Mean High Water (MHW), for modeling of maximum flooding, respectively[2]. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1: PMEL specifications for the Monterey, California DEM.

Grid Area	Monterey, California
Coverage Area	121.51° to 122.52° W; 36.10° to 37.10° N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII 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 DEM. 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. This DEM is 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 DEM, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, topographic, and bathymetric–topographic digital datasets (Fig. 3) were obtained from several U.S. federal, state and local agencies including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS) and Coastal Services Center (CSC); California State University Seafloor Mapping Laboratory; the U.S. Geological Survey (USGS); and the California Department of Fish and Game Marine Region GIS unit (CDFG). Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to NAD 83 horizontal datum and to convert them into ESRI (http://www.esri.com/) ArcGIS shape files[3]. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using FME, based upon data from the NOAA Monterey tide station and NOAA's Office of Coast Survey and National Geodetic Survey VDatum model software (http://vdatum.noaa.gov). Applied Imagery's Quick Terrain Modeler software (http://www.appliedimagery.com/) was used to evaluate processing and gridding techniques.

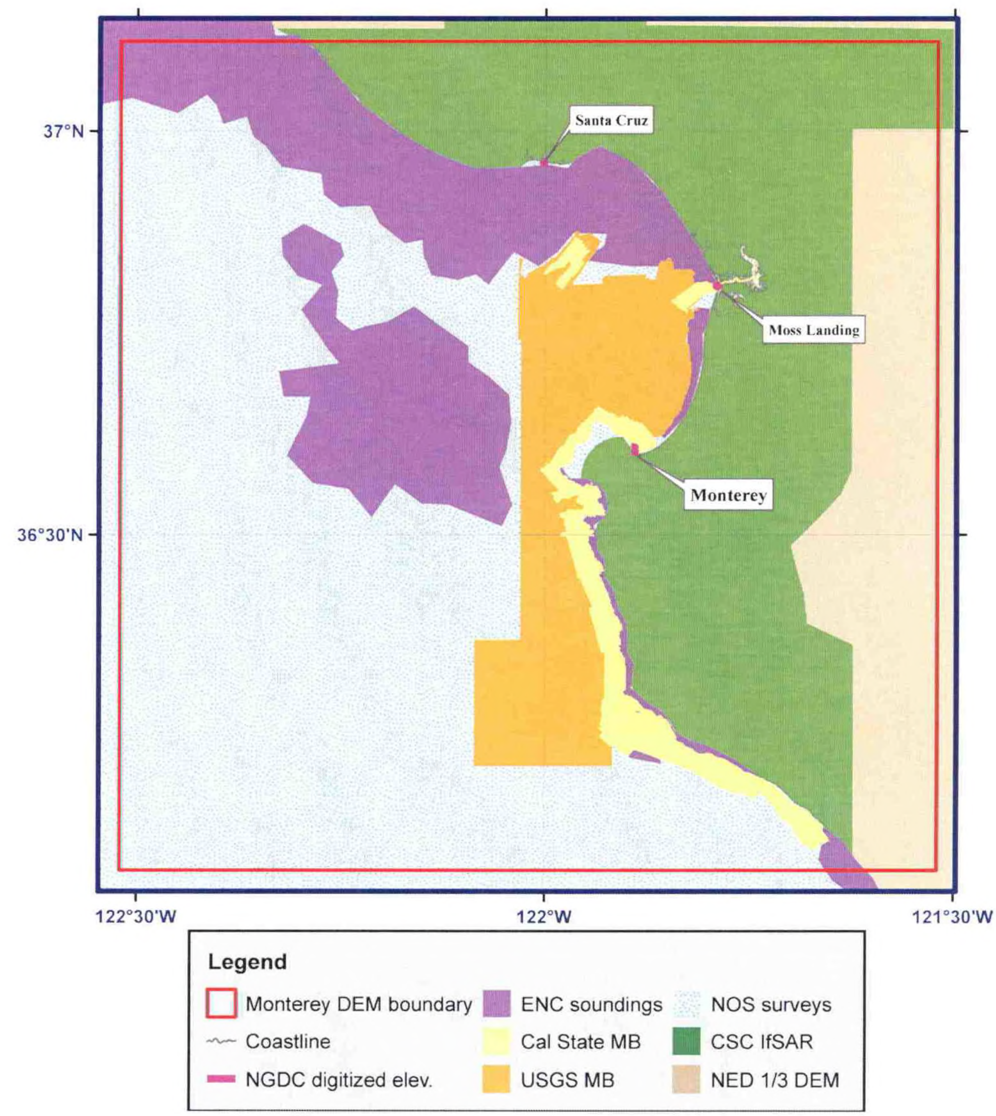

Figure 3. *Source and coverage of datasets used to compile the Monterey DEM.*

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

3.1.1 Shoreline

Coastline datasets of the Monterey region were obtained from NOAA's Office of Coast Survey (OCS) and the National Marine Fisheries Service, Southwest Fisheries Science Center/Moss Landing Marine Laboratory (NMFS,SWFSC/MLML); the California State Land Commission (CSLC); the California Dept. of Fish and Game, Marine Region GIS Unit (CDFG); and the U.S. Geological Survey (USGS) (Table 2; Fig. 4). Of these five datasets, the OCS electronic navigational charts (ENCs) and the CDFG coastline metadata records provided vertical datum reference and were used to develop the 'combined coastline' for the Monterey DEM.

Table 2: Shoreline datasets used in the Monterey DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
OCS ENCs	2007	Coastline	1:40,000 to 1:216,000	WGS 84 geographic (meters)	Mean High Water	http://nauticalcharts.noaa.gov/mcd/enc/index.htm
California Dept. of Fish and Game, Marine Region	1996	digitized 1:24,000 USGS quads	1:24,000	NAD 83 geographic (meters)	Mean High Tide	http://www.dfg.ca.gov/biogeodata/gis/mr.asp

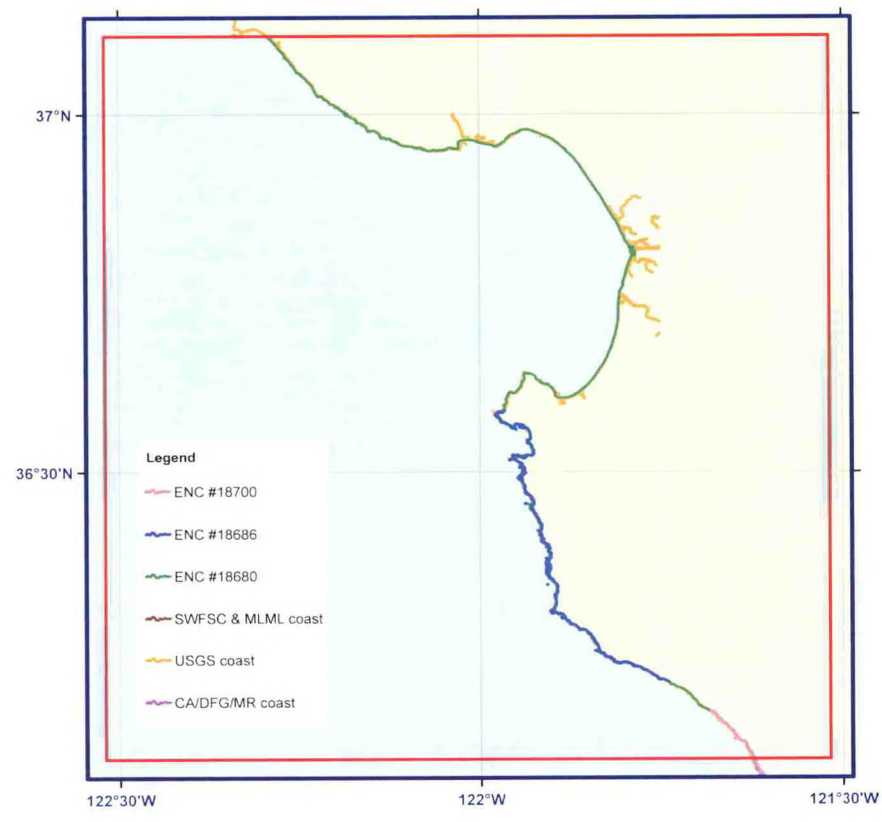

Figure 4. *Digital coastline datasets available in the Monterey region.*

1) OCS electronic navigational chart

Three electronic navigational charts (ENCs) were available for the Monterey area (Table 3) and downloaded from NOAA's Office of Coast Survey website (http://nauticalcharts.noaa.gov/mcd/enc/index.htm). The ENCs are in S-57 format and include coastline data files referenced to Mean High Water. The extracted ENC coastline was used primarily around the harbors at Monterey, Santa Cruz, and Moss Landing to define the harbor entrances and jetties.

Table 3: Electronic navigational charts available in the Monterey, California region.

Chart	*Title*	*Edition*	*Year of Source data*	*Issue Date*	*Scale*
18680	Point Sur to San Francisco	8	2001	2007	210,668
18686	Pfeiffer Point to Cypress Point	3	1999	2007	40,000
18700	Point Conception to Point Sur	5	2003	2007	216,116

2) California Dept. of Fish and Game, Marine Region GIS Unit (CDFG) coastline

The CDFG coastline was originally developed by the California State Land Commission from digitized USGS 7.5' quads to define the mean high tide line and was subsequently rebuilt to reduce tolerances by the CDFG in 1996. In order to define the current coastline, NGDC analyzed the most recent high-resolution topographic IfSAR dataset available from CSC and used the derived zero elevation line to manually adjust and clarify location of the mean high water line in the CDFG coastline.

The two coastline datasets were merged in ArcMap forming a 'combined coastline', which was edited to include channel inlets where digital bathymetric data are present. Modifications to the coastline include adjustments to remove piers, docks, and bridges. All modifications were done using ArcMap editing tools.

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the Monterey DEM include 42 NOS hydrographic surveys, 17 California State Sea Floor Mapping Lab multibeam sonar surveys located along the southern coast, 6 USGS multibeam sonar surveys that cover the deeper areas within the bay, and extracted ENC/RNC sounding data (Table 4; Fig. 3).

Table 4: Bathymetric datasets used in compiling the Monterey DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1932 to 1989	Hydrographic survey soundings	Ranges from 10 m to 1 km (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 27 or NAD 83 geographic	Mean Lower Low Water	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
Cal State Seafloor Mapping Lab	2003	Multibeam sonar	1 to 3 meters	WGS 84 UTM zone 10N	Mean Lower Low Water or NAVD88	http://seafloor.csumb.edu/index.html
USGS	1995 to 1998	Multibeam sonar	5 meters	NAD 83 UTM zone 10N	assumed Mean Sea Level	http://geopubs.wr.usgs.gov/open-file/of01-179/index.html
OCS ENC	2006 to 2007	Extracted soundings	1:80,000 to 1:400,000	WGS 84 geographic	Mean High Water	http://nauticalcharts.noaa.gov/mcd/enc/index.htm

1) NOS hydrographic survey data

A total of 42 NOS hydrographic surveys conducted between 1932 and 1989 were available for use in developing the Monterey DEM. The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) and horizontally referenced to either NAD 27 or NAD 83 datums. Only 36 of the 42 surveys were used in building the Monterey DEM, as some older surveys have been superseded (Table 5; Fig. 7).

Data point spacing for the NOS surveys varied by collection date. In general, earlier surveys had greater point spacing than more recent surveys. All surveys were extracted from NGDC's online NOS hydrographic database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) referenced to NAD 83. The surveys were subsequently clipped to a polygon 0.05 degree (~5%) larger than the Monterey DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW using VDatum (see Section 3.2.1), 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 topographic and bathymetric datasets, the combined coastline, and NOS raster nautical charts (RNCs). The surveys were clipped to remove soundings that overlap the more recent multibeam surveys and where soundings from older surveys have been superseded by more recent NOS surveys.

Table 5: Digital NOS hydrographic surveys used in compiling the Monterey DEM.

Survey ID	*Year*	*Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H05247	1932	40,000	MLLW	NAD 27
H05472	1932	20,000	MLLW	NAD 27
H05287	1932	10,000	MLLW	NAD 27
H05366	1932	10,000	MLLW	NAD 27
H05405	1933	10,000	MLLW	NAD 27
H05406	1933	10,000	MLLW	NAD 27
H05412	1933	10,000	MLLW	NAD 27
H05414	1933	10,000	MLLW	NAD 27

H05415	1933	5,000	MLLW	NAD 27
H05452	1933	10,000	MLLW	NAD 27
H05453	1933	10,000	MLLW	NAD 27
H05477	1933	40,000	MLLW	NAD 27
H05245	1933	40,000	MLLW	NAD 27
H05266	1933	40,000	MLLW	NAD 27
H05313	1933	40,000	MLLW	NAD 27
H05373	1933	10,000	MLLW	NAD 27
H05393	1933	10,000	MLLW	NAD 27
H05473	1934	80,000	MLLW	NAD 27
H05618	1934	10,000	MLLW	NAD 27
H05619	1934	10,000	MLLW	NAD 27
H05620	1934	10,000	MLLW	NAD 27
H05640	1934	10,000	MLLW	NAD 27
H05279	1935	80,000	MLLW	NAD 27
H05312	1935	10,000	MLLW	NAD 27
H09809	1979	5,000	MLLW	NAD 27
B00034	1985	50,000	MLLW	NAD 83
B00039	1985	50,000	MLLW	NAD 83
B00079	1986	50,000	MLLW	NAD 83
B00081	1986	50,000	MLLW	NAD 83
B00093	1986	50,000	MLLW	NAD 83
B00119	1988	50,000	MLLW	NAD 83
B00121	1988	50,000	MLLW	NAD 83
B00123	1988	50,000	MLLW	NAD 83
B00128	1988	50,000	MLLW	NAD 83
B00209	1989	50,000	MLLW	NAD 83

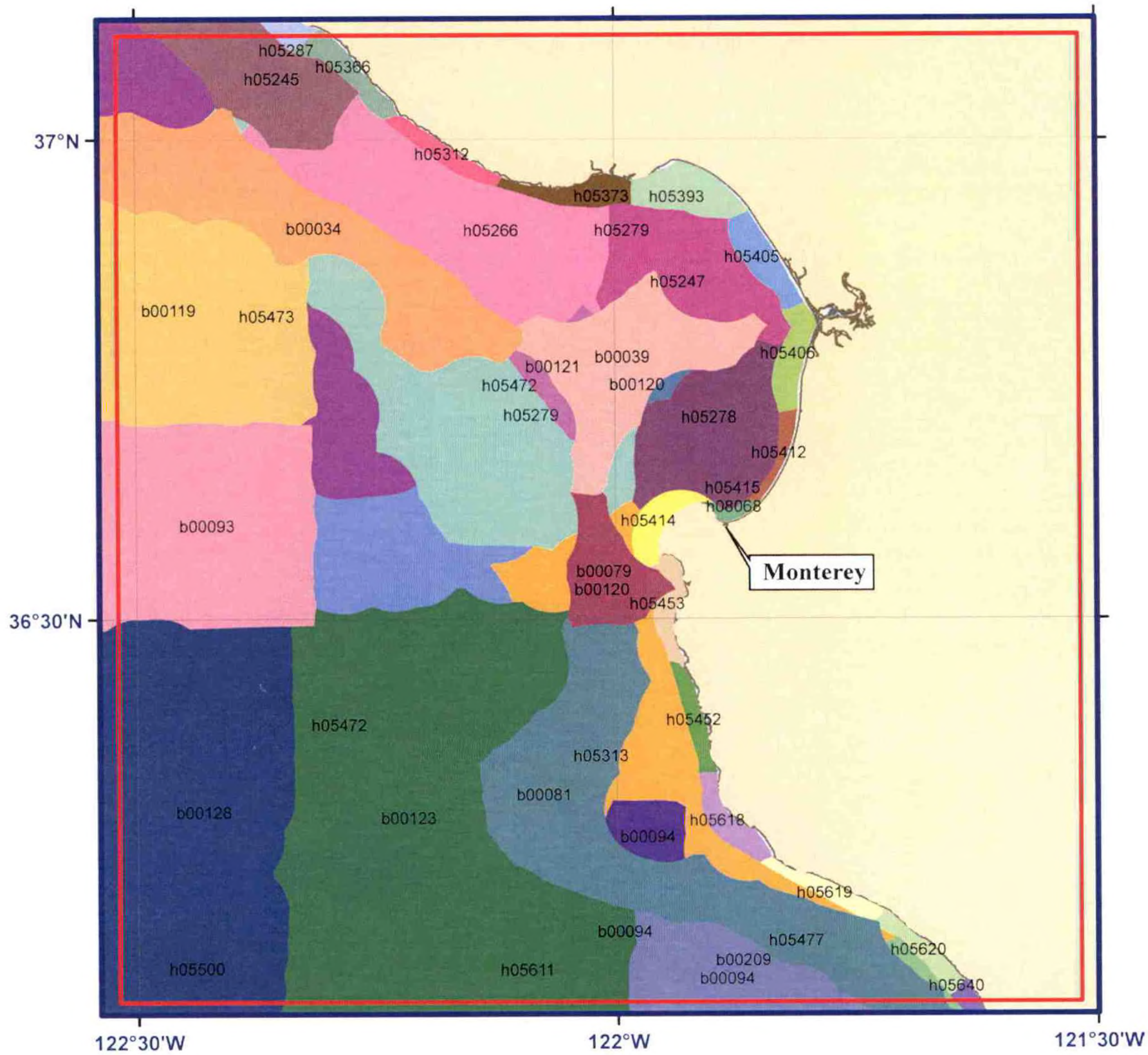

Figure 5. Digital NOS hydrographic survey coverage in the Monterey region. Some older surveys were not used as they have been superseded by more recent surveys. DEM boundary in red.

2) California State Seafloor Mapping Laboratory multibeam sonar surveys

Seventeen near-shore multibeam sonar surveys were downloaded from the California State Seafloor Mapping Laboratory website (http://seafloor.csumb.edu/index.html) as gridded data (Table 6, Fig. 6). The surveys were collected from 2000 to 2006, and referenced to WGS 84 UTM Zone 10N and either NAVD88 (meters) or MLLW datums. The files were converted to NAD 83 using ArcCatalog and to MHW using either the VDatum tool or, for inlet surveys at Elkhorn Slough, a constant derived from the VDatum tool (see section 3.2.1). The surveys were reviewed and edited as necessary to remove anomalous data points using QT Modeler and ArcMap.

Table 6: California State Seafloor Mapping Lab multibeam sonar surveys used in compiling the Monterey DEM.

Survey ID	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Type*
Big Sur, Cooper Point	2005	NAVD88	WGS1984 UTM Zone 10N	2m grid
Big Sur, Grimes Point	2005 to 2006	NAVD88	WGS1984 UTM Zone 10N	2m grid
Big Sur, Hurricane Point	2004 to 2005	MLLW	WGS1984 UTM Zone 10N	2m grid
Big Sur, Kessler Point	2004 to 2006	MLLW	WGS1984 UTM Zone 10N	2m grid
Big Sur, Point Sur	2005 to 2006	MLLW	WGS1984 UTM Zone 10N	2m grid
Big Sur, Slate Rock	2006	NAVD88	WGS1984 UTM Zone 10N	2m grid
Big Sur, Soberanes Point	2004 to 2006	MLLW	WGS1984 UTM Zone 10N	2m grid
Big Sur, Yankee Point	2004 to 2006	MLLW	WGS1984 UTM Zone 10N	2m grid
Elkhorn Slough	2003	MLLW	WGS1984 UTM Zone 10N	5m grid
Elkhorn Slough	2005	MLLW	WGS1984 UTM Zone 10N	1m grid
Monterey Canyon	2006	NAVD88	WGS1984 UTM Zone 10N	3m grid
Moss Landing Harbor	unknown	assumed MLLW	WGS1984 UTM Zone 10N	1m xyz
Monterey Peninsula, Cypress Pt. to Pt. Pinos	2000 to 2006	MLLW	WGS1984 UTM Zone 10N	2m grid
Monterey Peninsula, Monastery to Cypress Pt.	2000 to 2006	MLLW	WGS1984 UTM Zone 10N	2m grid
Monterey Peninsula, Pt. Pinos to Shalebeds	2000 to 2006	MLLW	WGS1984 UTM Zone 10N	2m grid
Point Lobos	2000 to 2006	MLLW	WGS1984 UTM Zone 10N	2m grid
Soquel Canyon	2006	NAVD88	WGS1984 UTM Zone 10N	3m grid

Figure 6. *Spatial coverage of California State Seafloor Mapping Laboratory multibeam sonar surveys used to compile the Monterey DEM.*

3) USGS multibeam sonar surveys

The USGS created bathymetric grids along the California coast using EM1000 and EM300 multibeam sonar data (Table 7, Fig. 7). Seven surveys were downloaded from the USGS data catalog website (http://geopubs.wr.usgs.gov/open-file/of01-179/index.html) in 5-meter gridded format in NAD 83 geographic UTM Zone 10 horizontal datum. Metadata records provided no vertical datum reference and NGDC processed the data as mean sea level, converting the surveys to WGS 84 using ArcCatalog and MHW using VDatum tool. Further review and editing to remove anomalous data points was completed using QT Modeler.

Table 7: USGS multibeam sonar surveys used in compiling the Monterey DEM.

Survey ID	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Resolution*
mont95ng	1995	assumed Mean Sea Level	NAD 83 UTM Zone 10N	5m grid
mont95sg	1995	assumed Mean Sea Level	NAD 83 UTM Zone 10N	5m grid
mont95c	1995	assumed Mean Sea Level	NAD 83 UTM Zone 10N	5m grid
mtcan5g	1998	assumed Mean Sea Level	NAD 83 UTM Zone 10N	5m grid
mtshlf5g	1998	assumed Mean Sea Level	NAD 83 UTM Zone 10N	5m grid
sgf5g	1998	assumed Mean Sea Level	NAD 83 UTM Zone 10N	5m grid
sur5g	1998	assumed Mean Sea Level	NAD 83 UTM Zone 10N	5m grid

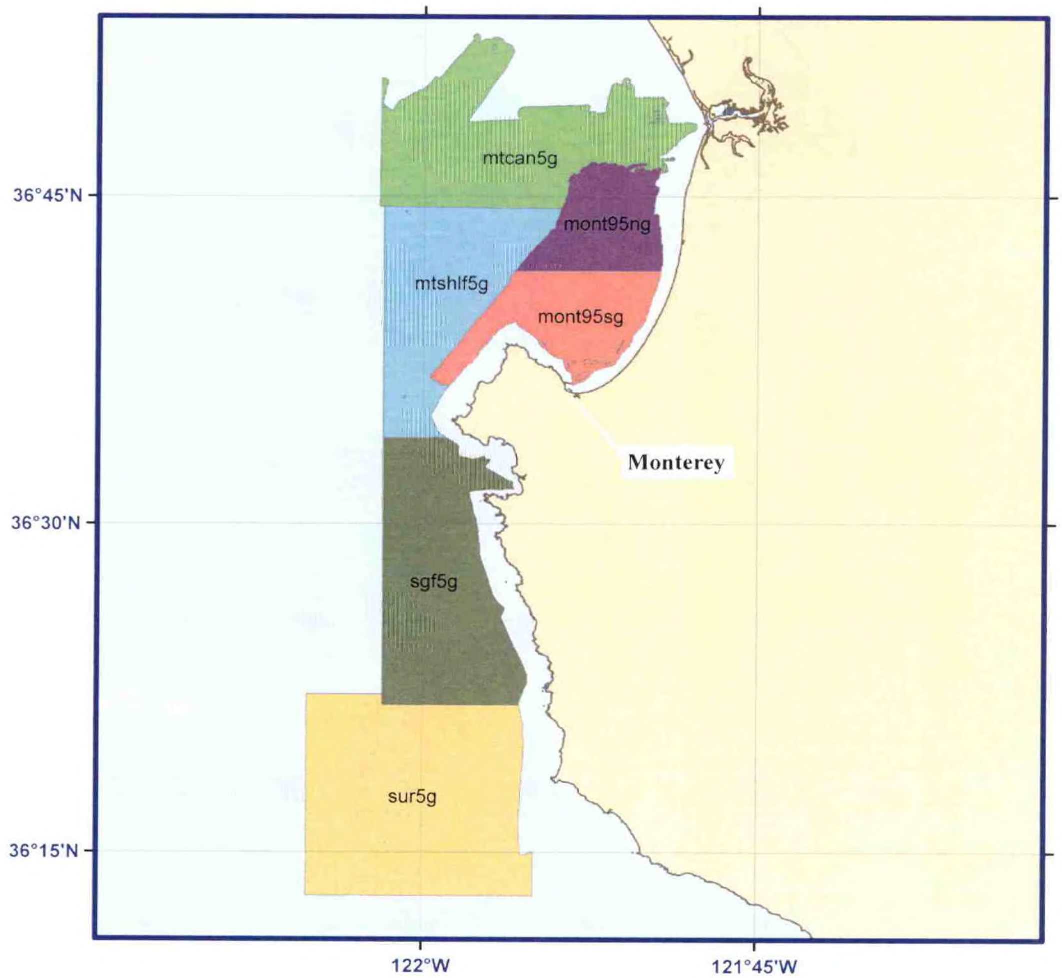

Figure 7. *Spatial coverage of USGS multibeam sonar surveys used to compile the Monterey DEM.*

Editing of the USGS multibeam data were necessary to remove suspect data crossing land at the beginning/end of survey lines of mtshlf5g and mont95sg. Survey mont95sg also contained an unknown feature which NGDC could not confirm (Fig. 8).

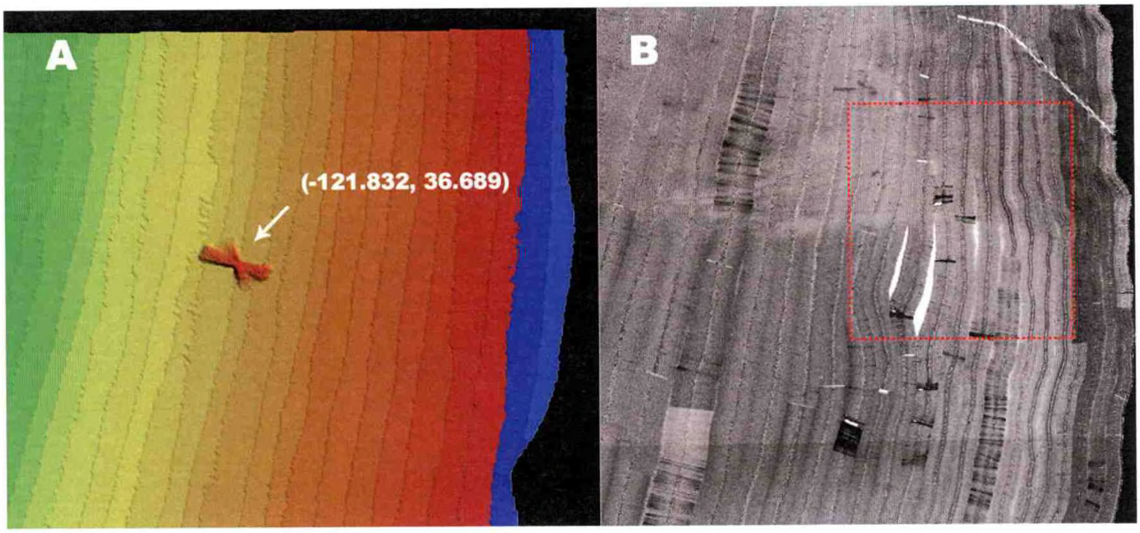

Figure 8. *Images of unknown feature in USGS multibeam survey south of Moss Landing Inlet. A) QT Modeler image of gridded multibeam data showing feature and coordinates. B) Sidescan sonar image. Red box is approximate area shown in image A. Diagonal white line in upper right corner is underwater pipeline from shore.*

4) Office of Coast Survey Electronic navigational chart extracted soundings

The OCS electronic navigational chart sounding data were extracted from charts #18680, 18700, and 18686 and converted to MHW using VDatum tool. Soundings from these ENCs were clipped to the multibeam surveys. Additional soundings digitized from RNCs were added near Moss Landing Harbor and Santa Cruz Harbor to ensure negative elevations in the bathymetric surface where no other sounding data were available (Fig. 9).

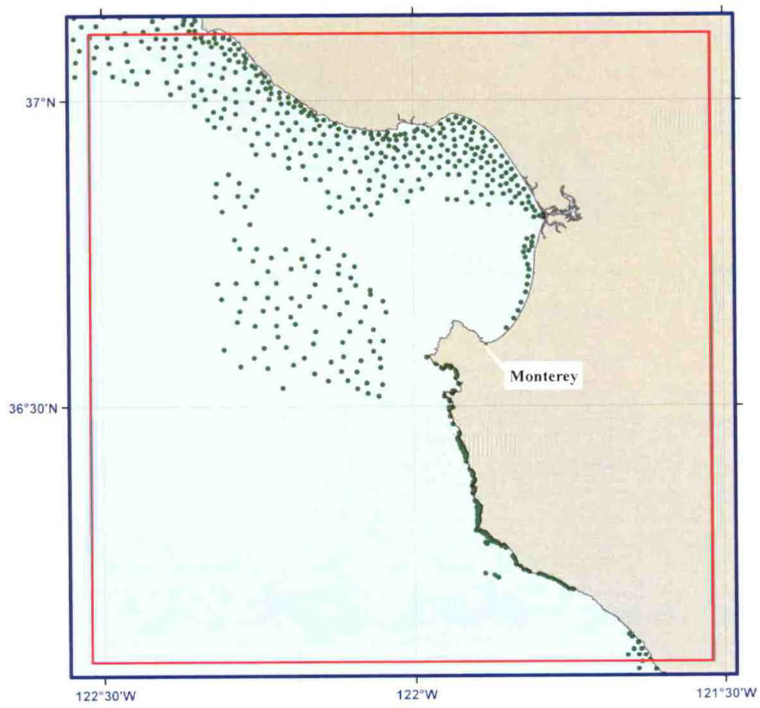

Figure 9. *Spatial coverage of ENC sounding data used to compile the Monterey DEM.*

3.1.3 Topography

Two topographic datasets in the Monterey region were obtained from the U.S. Geological Survey (USGS) and NOAA's Coastal Service Center and used to build the Monterey DEM (CSC; Table 8; Fig. 3). NGDC evaluated but did not use the Shuttle Radar Topography Mission (SRTM) Elevation 1 arc-second DEM available from USGS or CSC LiDAR data from 1998. NGDC digitized some elevation points to supplement the USGS and CSC datasets at Monterey, Santa Cruz, and Moss Landing.

Table 8: Topographic datasets used in compiling the Monterey DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
USGS	1999-2006	NED DEM	1/3 arc-second	NAD 83 geographic	NAVD88 (meters)	http://ned.usgs.gov/
CSC	2004 to 2005	IfSAR DEMs	5 meters	NAD 83 geographic	NAVD88 (meters)	http://www.csc.noaa.gov/crs/tcm/current.html
NGDC		digitized elevation points	~2.5 meters	WGS 84 geographic	MHW (meters)	

1) **USGS NED topographic DEM**

The U.S. Geological Survey (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provides complete 1/3 arc-second coverage of the Monterey region[4]. Data are in NAD 83 geographic coordinates and NAVD88 vertical datum (meters), and are available for download as raster DEMs. The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov/). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys; it has been revised using data collected in 1999 and 2006. The NED DEM included "zero" elevation values over the open ocean, which were removed from the dataset by clipping to the combined coastline. The data were then converted to xyz points and filtered to remove "zero" elevations within the 'combined coastline'.

2) **CSC Interferometric SAR topography (IfSAR) DEMs**

CSC provided 7.5 minute DEMs derived from 2004/2005 IfSAR data for the entire coastal region in raster tile format. Radar shadow and layover created some 'no data' areas in the raw data but were interpolated across in final processing steps by Intermap contractors in creating the DEMs. Harbor features in Monterey, Santa Cruz, and Moss Landing were not fully resolved in this dataset. The tiles were transformed to MHW and clipped to the 'combined coastline' using ArcCatalog then converted to xyz points. The data are not specified as bare earth and roadway overpasses, bridges, and piers were removed using QT Modeler.

This dataset was not used in constructing the publicly available version of the Monterey DEM because it is proprietary.

4. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED website]

3) NGDC digitized elevation points

To represent the jetties at Monterey, Santa Cruz, and Moss Landing (Figs. 10 and 11), NGDC created digital representations of the features using ArcMap and assigned elevations (Figs 12, 13, and 14). The elevation for the Monterey Coast Guard pier was set at 1.74 meters and the Monterey wharf and seawall at 3 meters and 1 meter respectively using the NGS tidal benchmarks. The elevations for the jetties at Santa Cruz and Moss Landing were set at 2.2 and 2.8 meters respectively based on values taken from the U.S. Army Corp of Engineer's Database of Navigation Projects and Structures (http://cirp.wes.army.mil/cirp/structdb/structdb.php3?sel=start). Point spacing for all digitized features is ~2.5 meters to ensure an even surface on the tops of features.

Figure 10. Aerial photographs of Moss Landing Harbor (Image A) and Monterey Harbor (Image B) used to confirm features not resolved in NED and CSC topographic datasets (http://nauticalcharts.noaa.gov/nsd/Cp7/CP7-40ed-Ch06_7.pdf).

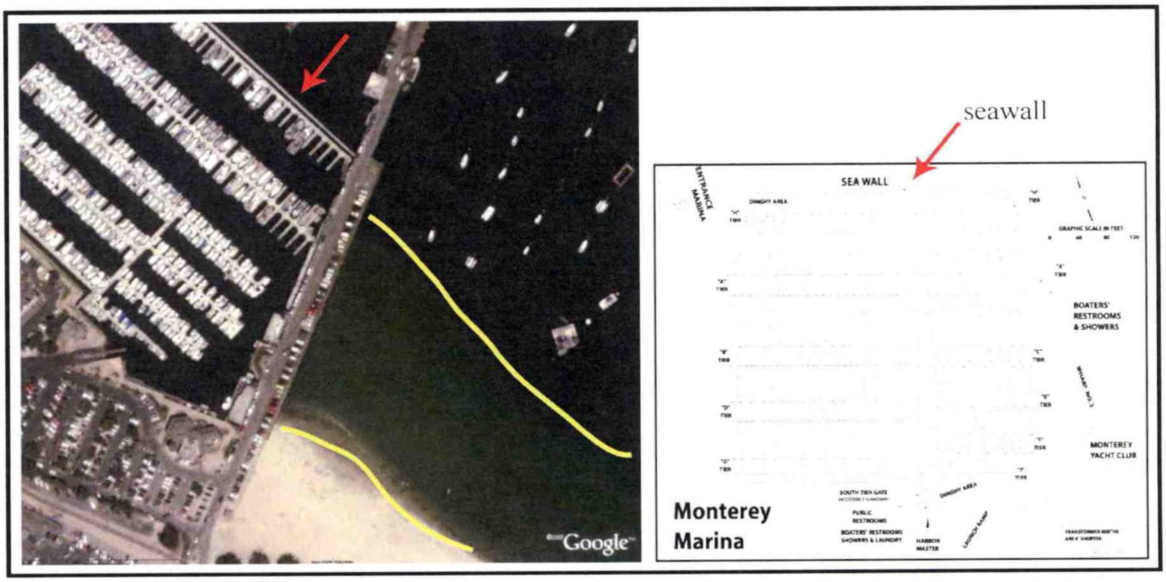

Figure 11. Details of the Monterey Harbor feature digitized by NGDC. A) Satellite image from Google Earth of Monterey Harbor. The red arrow points to installed seawall midway out the wharf. The yellow outlines the appearance of sediment deposition used in determining wharf characteristics. B) Graphic outlining marina details (http://www.monterey.org/harbor/marinamap.html) Red arrow points at seawall in image A.

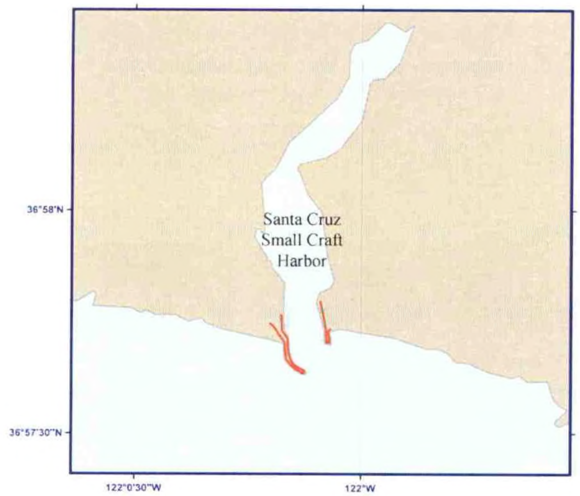

Figure 12. *Location of digitized harbor feature in Santa Cruz Harbor. East and west digitized jetties shown in red.*

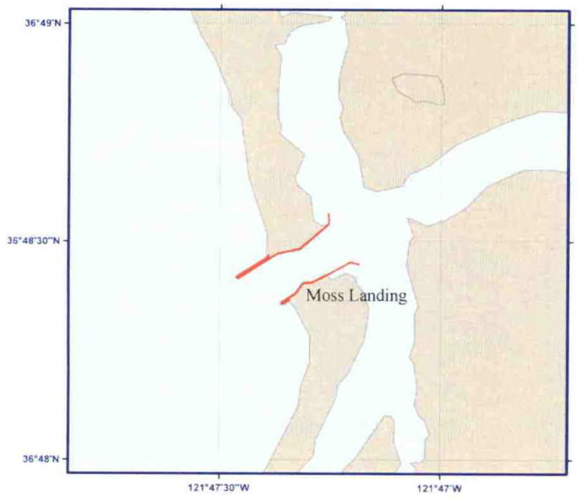

Figure 13. *Location of digitized harbor features in Moss Landing. North and south jetties shown in red.*

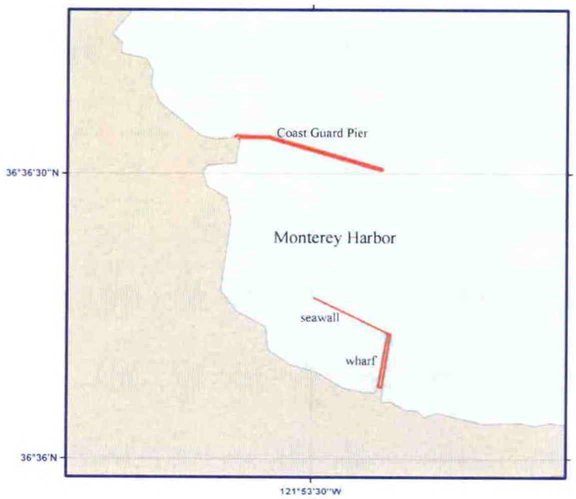

Figure 14. *Location of digitized harbor features in Monterey Harbor. Coast Guard pier, wharf, and seawall shown in red.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Monterey DEM were originally referenced to a number of vertical datums including Mean Lower Low Water (MLLW), Mean Sea Level (MSL), and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to MHW to provide the maximum flooding for inundation modeling.

1) Bathymetric data

The NOS hydrographic surveys, the ENC extracted soundings, the California State University Seafloor Mapping Laboratory, and USGS multibeam sonar surveys were transformed from MLLW and MSL to MHW, using the VDatum tool (http://vdatum.noaa.gov) based on VDatum coverage (Fig. 15).

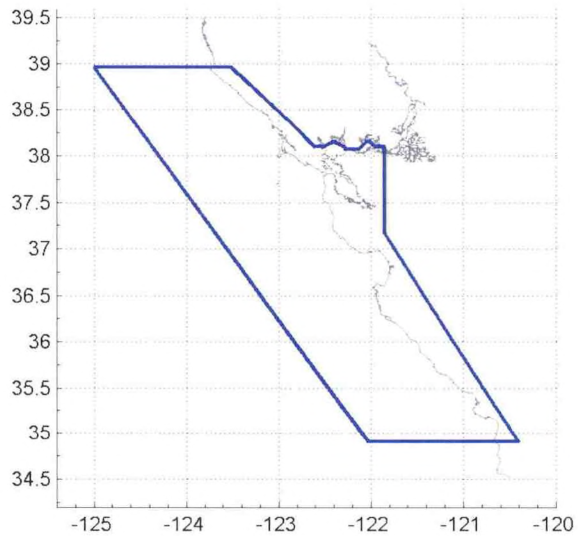

Figure 15. *Coverage of VDatum tool for the Monterey DEM region.*

California State University Seafloor Mapping Laboratory surveys located in Moss Landing Inlet and Elkhorn Slough were transformed using a constant derived from the VDatum transformation tool, as the tool coverage does not extend past the main harbor channel entrance (Fig. 16). Data points entered in the transformation tool that do not lie within the tool boundary are output with elevation value of -999999 and subsequently filtered out using FME. Viewing all datasets in ArcMap prior to using the VDatum tool eliminated the possibility of missing data in final gridding.

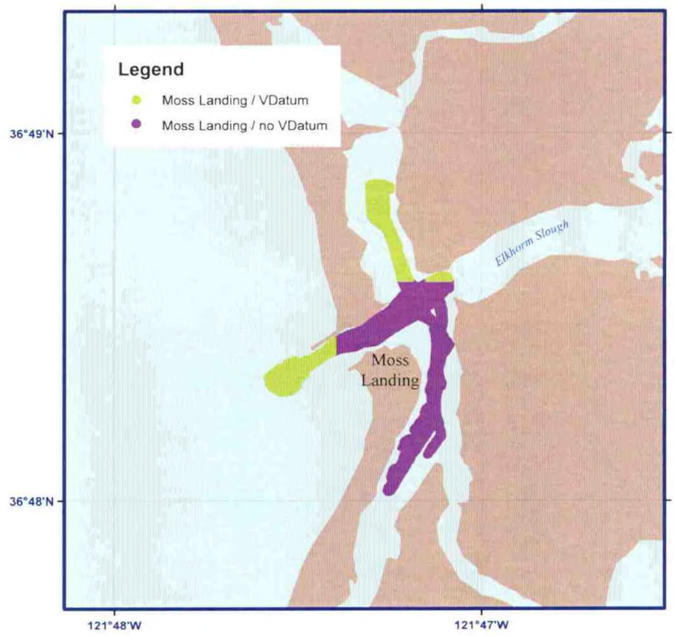

Figure 16. *Illustration of VDatum tool limitation within Moss Landing inlet. Green area designates California State Seafloor Mapping Laboratory multibeam sonar data transformed by VDatum tool. Purple shows multibeam data not transformed by VDatum.*

2) Topographic data

The USGS NED 1/3 arc-second DEMs and the CSC IfSAR DEMs were originally referenced to NAVD88. Conversion to MHW, using FME software and ArcCatalog, was accomplished by adding a constant offset of -1.457 meters (Table 9) the average of the Monterey Harbor and Elkhorn Slough tide stations (#9413450 and #9413663).

Table 9. Relationship between Mean High Water and other vertical datums used in the Monterey DEM.

Vertical datum	*Difference to MHW**
NAVD88	-1.457
MSL	-0.556
MLLW	-1.441

*average of the Monterey Harbor and Elkhorn Slough tide stations (#9413450 and #9413663)

3.2.2 Horizontal datum transformations

Datasets used to compile the Monterey DEM were originally referenced to WGS 84 geographic, WGS 84 UTM Zone 10 North, NAD 83 UTM Zone 10 North, NAD 83 geographic, or NAD 27 geographic horizontal datums. The relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of NAD 83 geographic using FME software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

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

- Suspect topographic elevations located on and within inlets and estuaries.
- Data values over the ocean and rivers in the NED topographic data. The dataset required automated clipping to the combined coastline.
- Topographic IfSAR dataset not processed to bare earth. The dataset required filtering of elevation values on land and manual editing of individual features.
- Digital, measured bathymetric values from NOS surveys date back over 70 years. More recent data, such as the multibeam surveys differed from older NOS data by as much as 100 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 surveys are generally sparse at the resolution of 1/3 arc-second in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the form of lines of "pimples" in the DEM due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing 'pre-surface' bathymetric grid was generated using GMT, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The NOS hydrographic point data, in xyz format, were clipped to remove overlap with the USGS and California State multibeam data then combined with the ENC sounding data along with points extracted from the combined coastline—to provide a buffer along the entire coastline. The coastline elevation value was set at -1.0 m to ensure a bathymetric surface below zero in areas where data is sparse or non-existent.

Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the NOS hydrographic surveys. Coastal erosion and development have modified the coastline to the extent that harbors surveyed in the early 20th century have had changes in structures and design. In areas where more recent data were available, the older surveys were either edited or removed. The extracted ENC/RNC sounding data were used only where there was a significant lack of current bathymetric data (see Fig. 9). These areas include the northern half of Monterey Bay close to the shoreline, at the entrance to Moss Landing, the southern shoreline within the Bay, the near shore area from Carmel-by-the-Sea extending southward, and in deeper water due west of Point Sur. The region in the deeper water posed significant gridding difficulties due to the extreme low resolution of the hydrographic surveys (data point spacing ranges from 200 up to 1000 meters).

The point data were median-averaged using the GMT tool 'blockmedian' to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Monterey 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 GMT grid created by 'surface' was converted into an ESRI Arc ASCII grid file, and clipped to the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy (e.g., Fig. 17) and exported as an xyz file for use in the final gridding process (see Table 11).

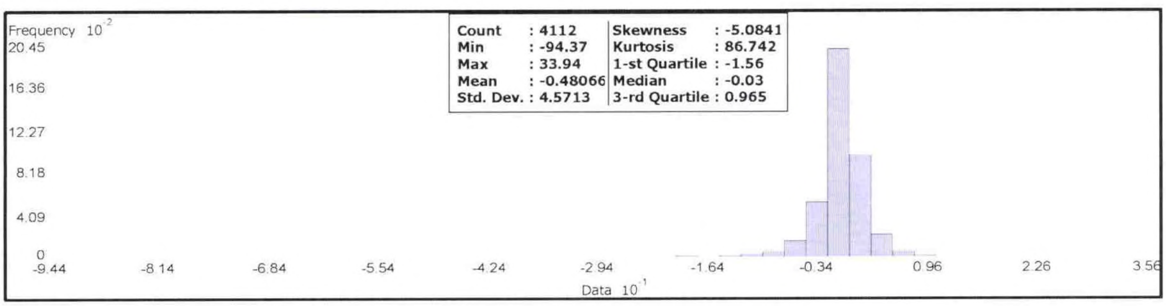

Figure 17. *Histogram of the differences between NOS hydrographic survey H05414 and the 1 arc-second pre-surfaced bathymetric grid.*

3.3.3 *Gridding the data with MB-System*

MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/) was used to create the 1/3 arc-second Monterey DEM. MB-System is an NSF-funded share-ware software application specifically designed to manipulate submarine multibeam sonar data, though it can utilize a wide variety of data types, including generic xyz data. The MB-System tool 'mbgrid' 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 10. Greatest weight was given to the CSC IfSAR data. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid. Gridding was performed in quadrants with the resulting Arc ASCII grids seamlessly merged in ArcCatalog to create the final 1/3 arc-second Monterey DEM.

Table 10. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
CSC topographic coastal IfSAR	100,000
USGS NED topographic DEM	100
NGDC digitized topographic harbor features	10,000
Combined coastline	100
USGS multibeam surveys	10,000
Cal State multibeam surveys	10,000
NOS hydrographic surveys	10
ENC/RNC soundings	10
Pre-surfaced bathymetric grid	1

3.4 Quality Assessment of the DEM

3.4.1. *Horizontal accuracy*

The horizontal accuracy of topographic and bathymetric features in the Monterey DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of up to 10 meters: CSC topographic IfSAR data have accuracy better than 2 meters; NED topography is accurate to within about 10 meters. 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 subaerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings; potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys, and by the morphologic change that occurs in this dynamic region.

3.4.2 *Vertical accuracy*

Vertical accuracy of elevation values for the Monterey DEM is also highly dependent upon the source datasets contributing to DEM cell values. Topographic areas have an estimated vertical accuracy better than 1 meter for CSC topographic IfSAR data, and up to 7 meters for NED topography. Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth. Those values were derived from the wide range of input sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine values between sparse, poorly-located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope maps and 3-D perspectives

ESRI ArcCatalog was used to generate a slope grid from the Monterey DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 18). The DEM was transformed to UTM Zone 10 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 DEM was accomplished using QT Modeler. Figure 19 shows a perspective rendering generated using ArcMap. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Monterey DEM in its final version.

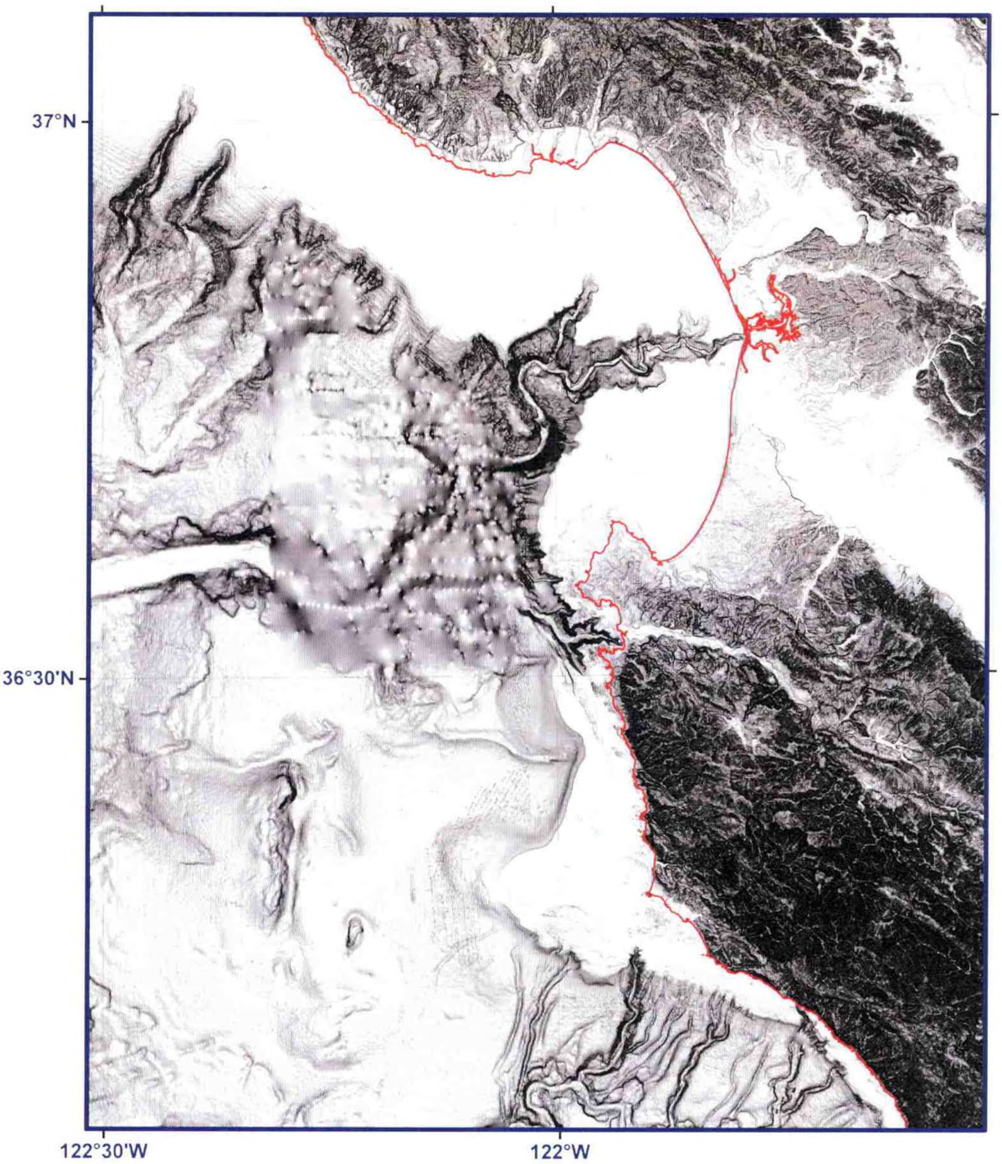

Figure 18. *Slope map of the Monterey DEM. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

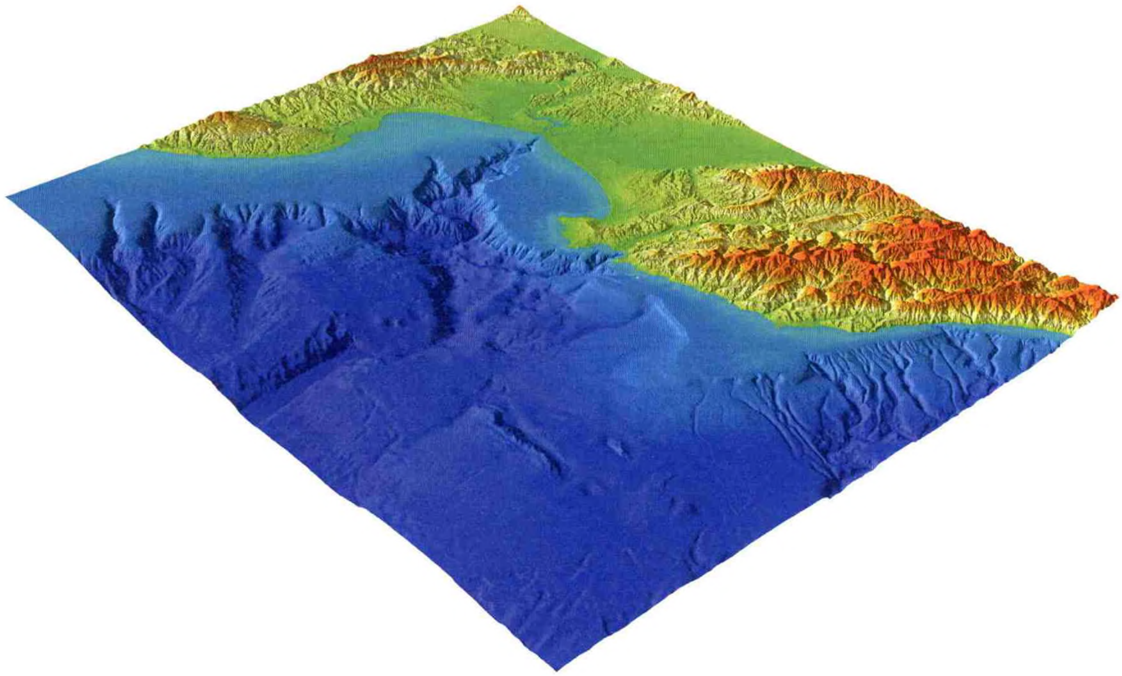

Figure 19. Perspective view from the southwest of the Monterey DEM. Vertical exaggeration 1.5 times.

3.4.4 Comparison with source data files

To ensure grid accuracy, the Monterey DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the differences between a CSC topographic IfSAR survey tile and the Monterey DEM is shown in Figure 20. Differences cluster around zero, with only a handful of soundings, in regions of steep topography, exceeding 0.5-meter discrepancy from the DEM.

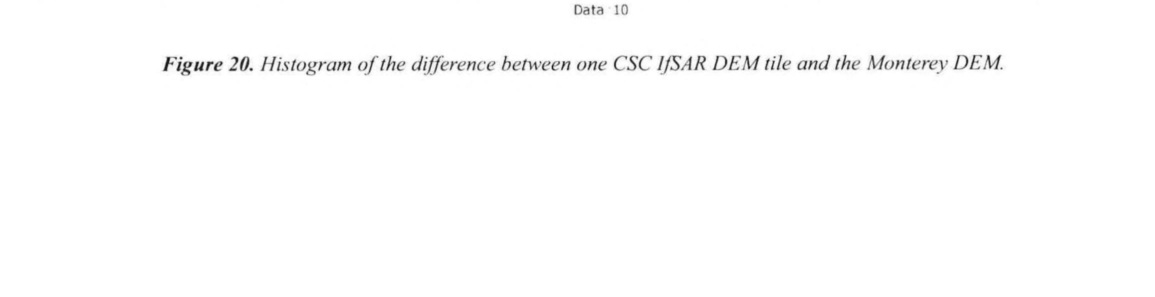

***Figure 20.** Histogram of the difference between one CSC IfSAR DEM tile and the Monterey DEM.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 1025 NOAA NGS geodetic monuments were extracted from online shape files of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl.), which give monument positions in NAD 83 (typically sub-mm accuracy) and elevations in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 10) for comparison with the Monterey DEM (see Fig. 22 for monument locations). Differences between the Monterey DEM and the NGS geodetic monument elevations range from -435 to 306 meters, with the majority of them being within ± 2 meters. Negative values indicate that the monument elevation is less than the DEM (Fig. 21). Only 160 monuments out of 1025 total showed significant deviations from the DEM at locations located primarily along the coast and at high elevations. Other larger discrepancies occurred where monuments are located on buildings, towers, and bridges.

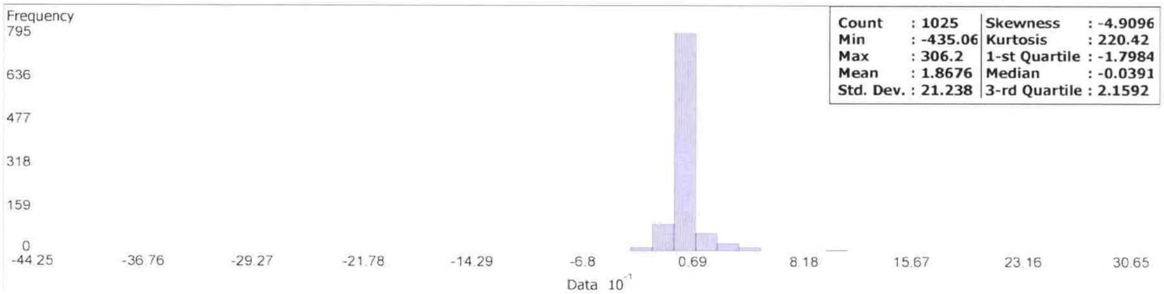

Figure 21. *Histogram of the differences between NGS geodetic monument elevations and the Monterey DEM.*

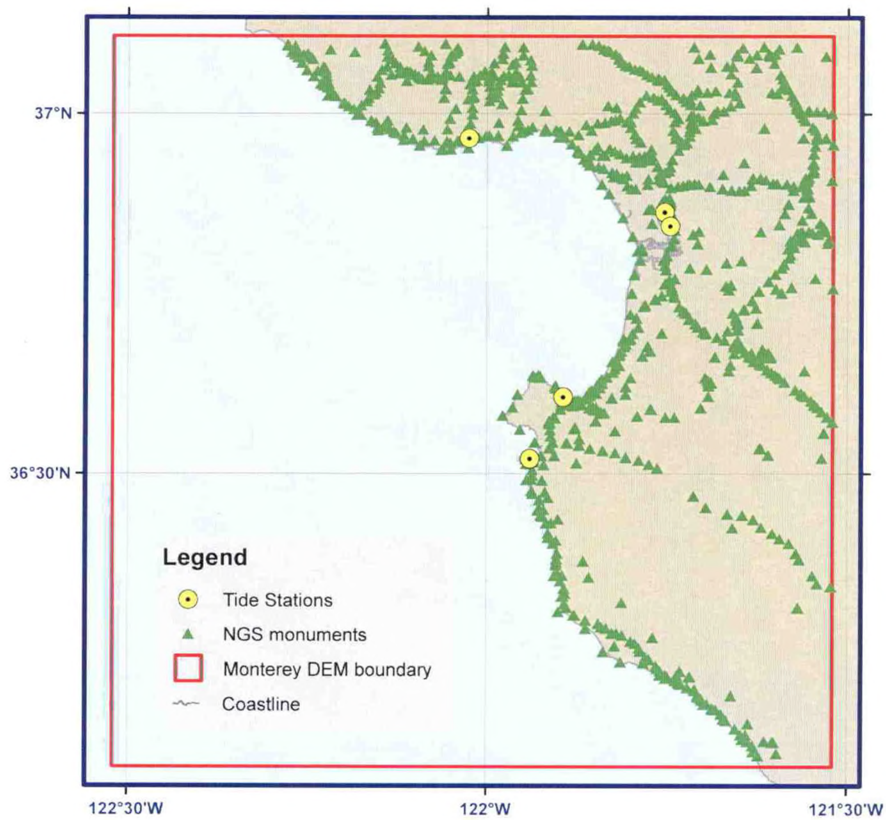

Figure 22. *Location of NGS geodetic monuments, shown as green triangles, and the NOAA tide stations, yellow circles. NGS monument elevations were used to evaluate the DEM.*

4. Summary and Conclusions

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

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

- Conduct hydrographic surveys for near-shore areas especially in harbors, inlets, and estuaries.
- Conduct bathymetric–topographic LiDAR surveying of entire region.
- Conduct deep water multibeam surveys for northern Monterey Bay.

5. Acknowledgments

The creation of the Monterey DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Chris Chamberlin and Vasily Titov (PMEL), Keil Schmid of NOAA, CSC, and George Fong of U.S. Army Corp of Engineers, San Francisco District. Data used in this study were acquired, processed, archived, and distributed by the Seafloor Mapping Lab of California State University Monterey Bay.

6. References

Nautical Chart #18680 (ENC), 8th Edition, 2007. Point Sur to San Francisco. Scale 1: 210,668. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18686 (ENC), 3rd Edition, 2007. Pfeiffer Point to Cypress Point. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18700 (ENC), 5th Edition, 2007. Point Conception to Point Sur. Scale 1:216,116. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18685 (RNC), 33rd Edition, 2005. Monterey Bay. Scale 1:50,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.2 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/

FME 2007 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.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. 4.1.4 – 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. 6.0.1 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/

GDAL v. 1.4.4 – Geospatial Data Abstraction Library, freeware developed and maintained by Frank Warnerdam, http://www.gdal.org

POV-Ray v. 3.6 – Persistence of Vision Raytracer, freeware developed and maintained by Persistence of Vision Raytracer Pty. Ltd., http://www.povray.org

8. Appendix A

Contact Barry Eakins (barry.eakins@noaa.gov; 303-497-6505) to make arrangements to obtain the gridded data, if you are a NOAA employee or part of the US Coastal Management Community as defined in the EULA.

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Weeks Bay NERR
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San Francisco Bay NERR
Tijuana River NERR
Delaware NERR
Apalachicola Bay NERR
GTM NERR
Rookery Bay NERR
Sapelo Island NERR
Waquoit Bay NERR
Chesapeake Bay (MD) NERR
Wells NERR
Grand Bay NERR
North Carolina NERR
Great Bay NERR
Mullica River NERR
Hudson River NERR
St. Lawrence River Basin NERR
Old Woman Creek NERR
South Slough NERR
Jobos Bay NERR
Narragansett Bay NERR
ACE Basin NERR
North Inlet-Winyah Bay NERR
Chesapeake Bay (VA) NERR
Padilla Bay NERR
Shorelands and Environmental Assistance Program
Coastal Management Organizations
University of Wisconsin Sea Grant Institute
ADCNR, Coastal Programs Office
California Coastal Commission
SF Bay Conservation and Development Commission
Office of Long Island Sound Programs
FL Coastal Management Program
GA Coastal Management Program
Hawaii CZM Program
MA CZMP
Maine Coastal Program
MN Coastal Program
MS Coastal Program
NH Coastal Program
NJ Coastal Program
OH Dept of Natural Resources
OR Coastal Management Program
PA CZMP
PR Coastal Program/ Dept of Natural Resources

Coastal Resource Management Council
SC CZMP
VA Coastal Program
VI Coastal Zone Program
WI Coastal Management Program
AL Dept of Environmental Management
Alabama Division of Wildlife & Fisheries
CA Dept of Boating & Waterways
CA Dept of Fish and Game
CA Dept of Water Resources
CA Ocean Resources Management
California Coastal Conservancy
CT DEP Bureau of Natural Resources
DNREC Div of Fish & Wildlife
DNREC Div of Soil & Water Conservation
DNREC Div of Water Resources
FL Fish & Wildlife Conservation Commission
GA DNR/Environ. Prot. Div.
Hawaii Department of Land and Natural Resources
IN Dept of Environmental Management
LA Dept of Wildlife & Fisheries
MA Dept of Environmental Management
Massachusetts Department of Environmental Protection
MD Dept of the Environment
Maine Department of Environmental Protection
ME Dept of Conservation
ME Dept of Marine Resources
Michigan Department of Natural Resources
MN Board of Water & Soil Resources
MN Pollution Control Agency
Mississippi Department of Environmental Quality
NC Division of Marine Fisheries
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