NOAA Technical Memorandum NESDIS NGDC-52

DIGITAL ELEVATION MODELS OF CENTRAL CALIFORNIA AND SAN FRANCISCO BAY: PROCEDURES, DATA SOURCES AND ANALYSIS

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UNITED STATES DEPARTMENT OF COMMERCE

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Also available from the National Technical Information Service (NTIS)
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Digital Elevation Models of Central California and San Francisco Bay: Procedures, Data Sources and Analysis

1. Introduction

In June of 2010, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed four integrated bathymetric–topographic digital elevation models (DEMs) of Central California and San Francisco Bay (Figs. 1 and 2). A 1/3 arc-second[1] DEM of San Francisco Bay and a 1 arc-second DEM of Central California each referenced to North American Vertical Datum of 1988 (NAVD 88) and a second matching pair of DEMs referenced to mean high water (MHW) were carefully developed and evaluated. The 1 arc-second and 1/3 arc-second MHW DEMs will be used as input for the Method of Splitting Tsunami (MOST) model developed by Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The NAVD 88 DEMs were generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 4) and were shifted to MHW for tsunami inundation modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the DEMs.

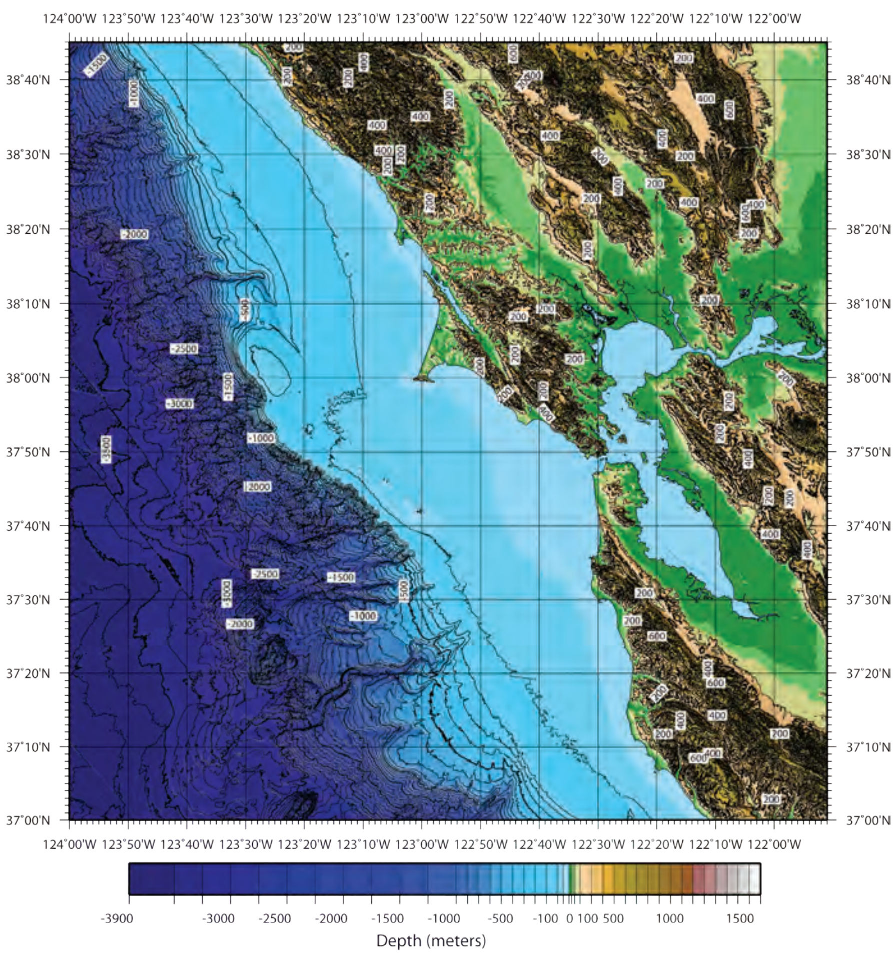

Figure 1. Shaded-relief image of the Central California 1 arc-second NAVD 88 DEM. Contour interval is 100 meters. Image is in Mercator projection.

1. The Central California and San Francisco Bay DEMs are 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 San Francisco, California, (37°46' 45.48"N, 122°25'9.12"W) 1 arc-second of latitude is equivalent to 30.83 meters; 1 arc-second of longitude equals 24.47 meters.

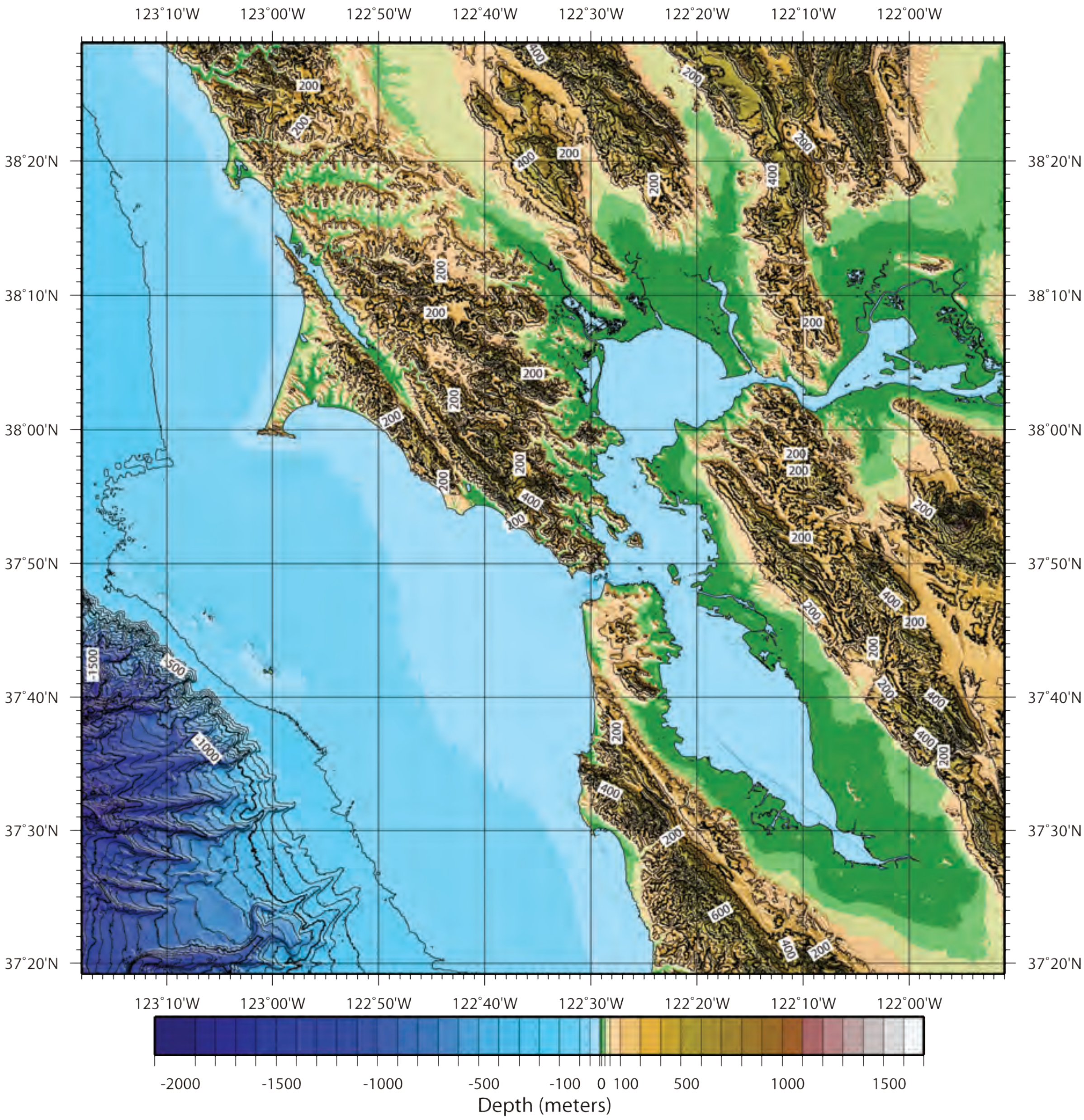

Figure 2. Shaded-relief image of the San Francisco Bay 1/3 arc-second NAVD 88 DEM. Contour interval is 100 meters. Image is in Mercator projection.

2. Study Area

The Central California DEM covers the coastal region north of Santa Cruz to Gualala Point and extends inland to the confluence of the Sacramento and San Joaquin Rivers and seaward past the Farallon Islands and the continental shelf. The San Francisco Bay DEM shares the same eastern boundary as the Central California DEM, encompasses the Farallon Islands to the west, extends north to the outlet of the Russian River, and south to San Gregorio Beach (Fig. 3).

A number of major faults cross the area covered by these DEMs, trending from southeast to northwest making this region at high risk for earthquakes. The 1964 Alaskan earthquake generated a tsunami that resulted in damage within San Francisco Bay and along the Southern California coast (http://www.ngdc.noaa.gov/hazard/tsu.shtml).

Figure 3. Map view of the region covered by the Central California and San Francisco Bay DEMs.

3. Methodology

The Central California and San Francisco Bay 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 Center 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 then to MHW, for modeling of maximum flooding. Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1a. PMEL specifications for the 1 arc-second Central California DEM.

Grid Area	Central California
Coverage Area	121.85º to 124.00º W; 37.00º to 38.75º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	Mean high water (MHW)
Vertical Units	Meters
Cell Size	1 arc-second
Grid Format	ESRI ASCII raster grid

Table 1b. PMEL specifications for the 1/3 arc-second San Francisco Bay DEM.

Grid Area	San Francisco Bay
Coverage Area	121.85º to 123.30º W; 37.32º to 38.48º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	Mean high water (MHW)
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI 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. 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 (Fig. 4) were obtained from several U.S. federal, state and local agencies, and academic institutions including: NGDC; NOAA's National Ocean Service (NOS), and Office of Coast Survey (OCS); the California Department of Fish and Game (CDFG); the California Department of Water Resources (CA DWR); the California State University at Monterey Bay Seafloor Mapping Laboratory (CSUMB); the National Center of Airborne Laser Mapping (NCALM); the Federal Emergency Management Agency (FEMA); the City and County of San Francisco; the U.S. Army Corps of Engineers (USACE); the U.S. Geological Survey (USGS); and Geosciences Network's (GEON) OpenTopography Portal. Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 geographic horizontal datum and to convert them into ESRI *ArcGIS* shapefiles[3]. The shapefiles were then displayed with *ArcGIS* and Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*) to assess data quality and manually edit datasets. Vertical datum transformations to NAVD 88 were accomplished using NOAA's *VDatum* transformation tool. ESRI's online *World 2D* imagery was used to analyze and modify data. *QT Modeler*, *Gnuplot* and Interactive Visualization System's *Fledermaus* software were used to evaluate processing and gridding techniques.

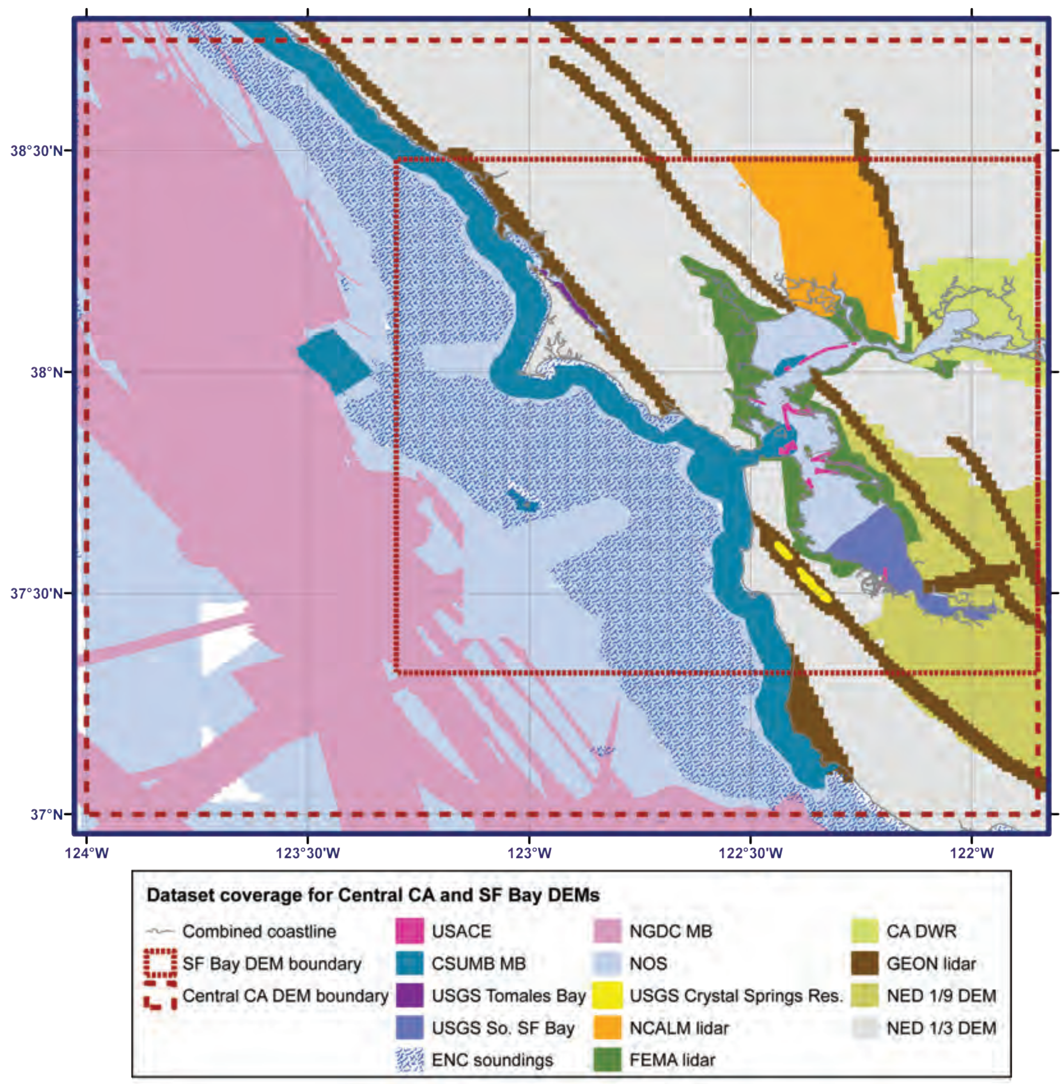

Figure 4. Dataset coverage for the Central California and San Francisco Bay DEMs.

3. *FME* 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 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 Coastline

Coastline datasets of the Central California region were obtained from NOAA's OCS as Electronic Navigational Charts (ENCs)[4], the City and County of San Francisco Enterprise GIS Program, CDFG's Marine Region GIS Unit, and CSUMB (Table 2; Fig. 5). These four datasets were used to develop a "combined coastline" of Central California.

Table 2. Shoreline datasets used in compiling the Central California and San Francisco Bay DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
OCS	2009	ENC		WGS 84 geographic	MHW	http://w1.nauticalcharts.noaa.gov/staff/chartspubs.html
City and County of San Francisco	2000	Vector shoreline		NAD 83 California State Plane III (feet)	Unknown	http://gispub02.sfgov.org/
CDFG	1996	Digitized 1:24,000 USGS quadrangles	1:24,000	NAD 83 geographic	Mean high tide	http://www.dfg.ca.gov/marine/gis/
CSUMB	2001	Digitized 1:24,000 USGS quadrangles	1:24,000	WGS 84 UTM zone 10 north	Mean high tide	http://seafloor.csumb.edu/SFMLwebDATA.htm

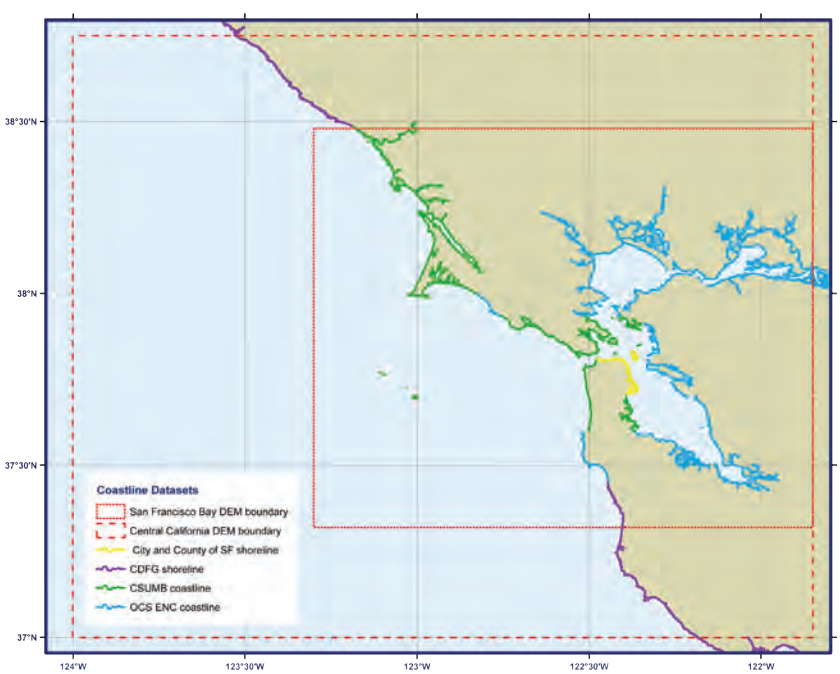

Figure 5. Coastline datasets used in compiling a "combined coastline" of the Central California region.

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

1) Office of Coast Survey extracted Electronic Navigational Chart coastline

Fourteen ENCs were available for the Central California area (Table 3) and were downloaded from NOAA's Office of Coast Survey web site. The ENCs are in S-57 format and included coastline data referenced to MHW. The coastline shapefiles were extracted from the ENCs using *ArcCatalog* and compared to large-scale RNCs and ESRI's *World 2D* imagery.

Table 3. Nautical charts available in the Central California region.

Chart	*Title*	*Format*	*Edition*	*Issue Date*	*Scale*
18640	San Francisco to Point Arena	ENC and RNC	9	2009	1: 207,840
18643	Bodega and Tomales Bays; Bodega Harbor	RNC	18	2009	1:30,000
18645	Gulf of Farallones; Southeast Farallon	ENC and RNC	11	2009	1:100,000
18647	Drakes Bay	RNC	16	2009	1:40,000
18649	Entrance to San Francisco Bay	ENC and RNC	9	2009	1:40,000
18650	San Francisco Bay-Candlestick Point to Angel Island	ENC and RNC	36	2009	1:20,000
18651	San Francisco Bay-Southern part Redwood Creek Oyster Point	ENC and RNC	14	2009	1:40,000
18653	San Francisco Bay-Angel Island to Point San Pedro	ENC and RNC	20	2009	1:20,000
18654	San Pablo Bay	ENC and RNC	11	2009	1:40,000
18655	Mare Island Strait	ENC and RNC	10	2009	1:10,000
18656	Suisan Bay	ENC and RNC	3	2009	1:25,000
18657	Carquinez Strait	ENC and RNC	13	2009	1:200,000
18658	Suisan Bay-Roe Island and vicinity	ENC and RNC	4	2009	1:10,000
18659	Suisan Bay-Mallard Island to Antioch	ENC and RNC	3	2009	1:15,000
18660	San Joaquin River-Stockton Deepwater Channel Antioch to Medford Island	ENC and RNC	14	2009	1:196,948
18680	Point Sur to San Francisco	ENC and RNC	14	2009	1:210,668

2) City and County of San Francisco shoreline

The San Francisco shoreline dataset was downloaded from the San Francisco Enterprise GIS webpage in shapefile format and transformed to NAD 83 geographic using *ArcCatalog*.

3) California Department of Fish and Game vector shoreline

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. The dataset was downloaded as a shapefile and clipped to the higher-resolution coastline data.

4) California State University at Monterey Bay Seafloor Mapping Laboratory

The CSUMB coastline dataset covers two areas, Bodega Bay and the Farallon Islands. The data were downloaded as shapefiles and transformed to NAD 83 geographic with *ArcCatalog*.

The four datasets were integrated resulting in a "combined coastline" that was modified to include large offshore rocks and small islets shown on the larger-scale RNCs and clipped to 0.05 degrees larger than the Central California DEM boundary. Piers and docks within San Francisco Bay were deleted from the coastline. Large wharves in San Francisco Bay were included in the coastline and the DEMs as these structures have potential to affect tsunami movement. The coastline was further modified based on *World 2D* imagery to reflect the most current coastal morphology. An xyz file of the "combined coastline" with points every 10 meters was generated using NGDC's *GEODAS* software for use in creating a bathymetric surface (see Section 3.3.2). In addition, a second coastline that did not contain the wharves in the bay was developed for to ensure steep transitions from the seafloor to the surface of the wharves. An xyz file of this "no-structure" coastline was used in generating the bathymetric pre-surface for the 1/3 arc-second DEM of San Francisco Bay (see Sec. 3.3.2).

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Central California and San Francisco Bay DEMs included: NOS hydrographic surveys, USACE hydrographic surveys, CSUMB multibeam surveys, a multibeam and a hydrographic survey from USGS, NGDC multibeam swath sonar surveys, and NOAA ENC chart soundings (Table 4; Fig. 6). Datasets were originally horizontally referenced to NAD 13, NAD 27, NAD 83; WGS 84 geographic; NAD 83 UTM Zone 10 North; WGS 84 UTM Zone 10 North; or NAD 83 California State Plane Zone III. The data were vertically referenced to NAVD 88, MLW, MLLW, or MSL.

Table 4. Bathymetric datasets used in compiling the Central California and San Francisco Bay DEMs.

Source	***Year***	***Data Type***	***Spatial Resolution***	***Original Horizontal Datum/ Coordinate System***	***Original Vertical Datum***	***URL***
NGDC	1922 to 2000	NOS hydrographic survey soundings	Ranges from 5 meters to 1.5 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 13, NAD 27, NAD 83, NAD 83 UTM Zone 10 N, Undetermined Datum	MLW or MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USACE	2009	Hydrographic surveys	Ranges from 30 to 60 meter line spacing and 5 to 10 meter point spacing	NAD 83 California State Plane III (feet)	MLLW (feet)	http://www.spn.usace.army.mil/
CSUMB	2001 to 2007	Gridded and xyz multibeam survey data	1 to 10 meters	WGS 84 UTM Zone 10 N	MLLW	http://seafloor.csumb.edu/index.html
USGS	2005	Hydrographic survey	1 meter	NAD 83 UTM Zone 10 N	NAVD 88	http://pubs.usgs.gov/of/2007/1169/
USGS	2006	Gridded multibeam survey data	4 meters	WGS 84 geographic	MLLW	http://pubs.usgs.gov/of/2008/1237/
NGDC	2007	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NOAA ENCs	2008	NOAA digitized nautical chart soundings	~500 to 1200 meters	WGS 84 geographic	MLLW (meters)	http://nauticalcharts.noaa.gov/mcd/enc/

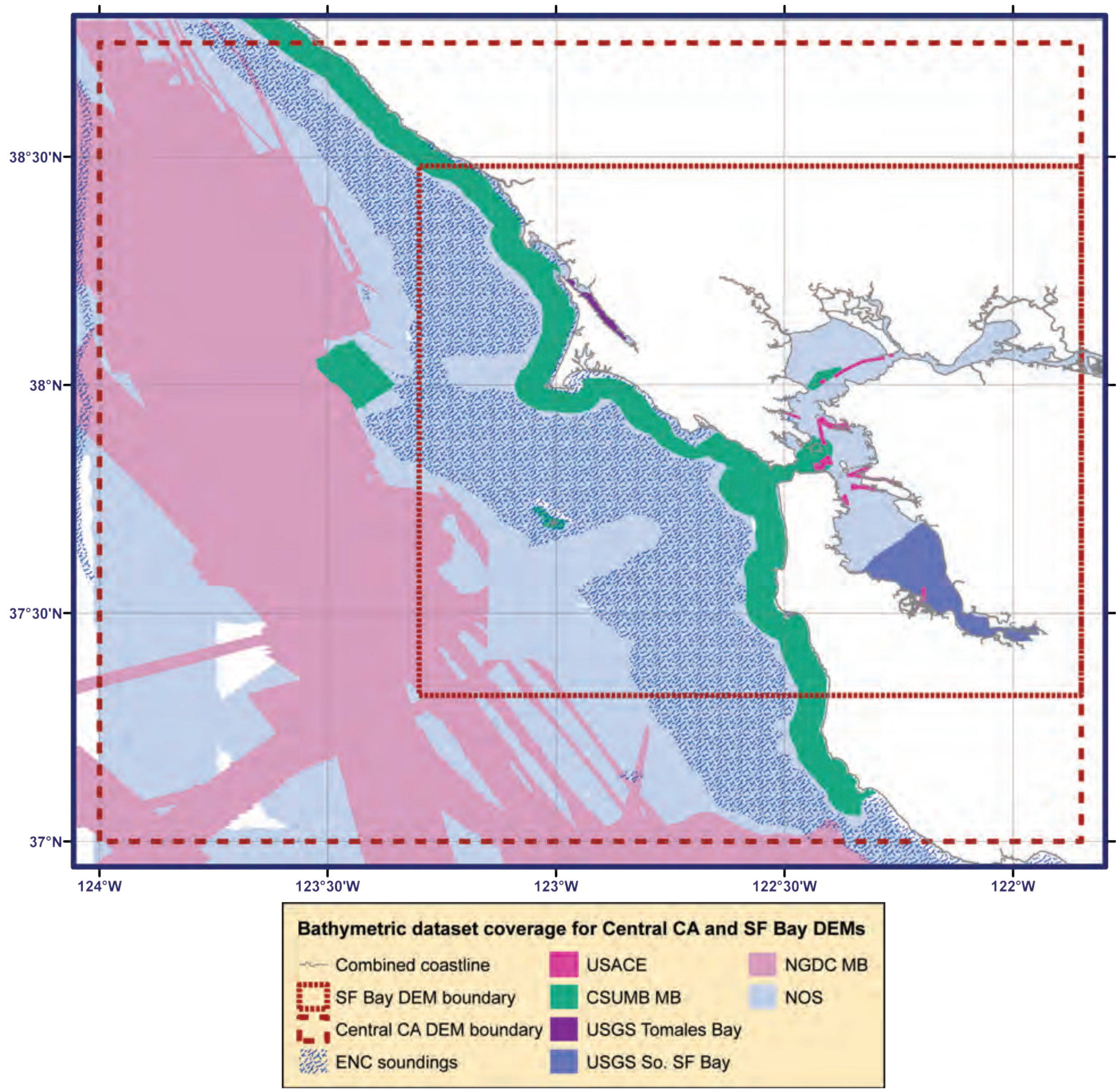

Figure 6. Bathymetric datasets used in compiling the Central California and San Francisco Bay DEMs.

1) National Ocean Service hydrographic survey data

A total of 181 NOS hydrographic surveys conducted between 1922 and 2000 were available for use in the Central California and San Francisco Bay DEM development (Fig. 7; Table 5). The hydrographic survey data were originally vertically referenced to MLW or MLLW and horizontally referenced to NAD 13, NAD 27, NAD 83 geographic; NAD 83 UTM Zone 10 North; or "undetermined" datums.

Data point spacing for the surveys ranged from approximately 5 meters in shallow water to 1.5 kilometers in deep water. All surveys were extracted from NGDC's NOS Hydrographic Survey Database using *GEODAS*[5] horizontally referenced to NAD 83 geographic. The surveys were subsequently clipped to a polygon 0.05 degrees (~5%) larger than the 1 arc-second gridding area to support data interpolation across DEM boundaries.

After converting all NOS survey data to NAVD 88 using the *VDatum* transformation tool (see Sec. 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 other bathymetric datasets, the combined coastline, and NOS raster nautical charts (RNCs). Older surveys were clipped to remove soundings that have been superseded by more recent NOS surveys, USACE surveys, and multibeam data.

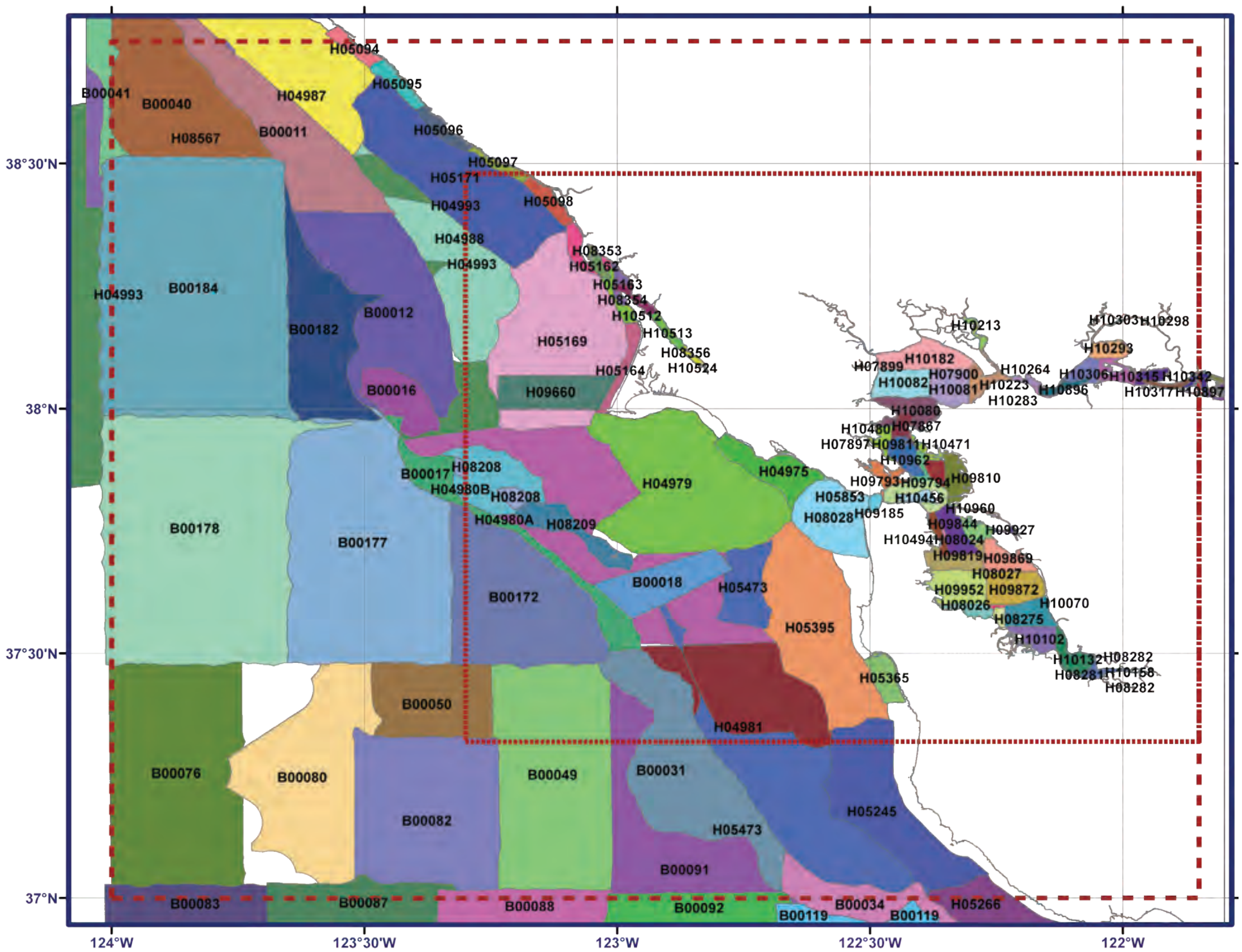

Figure 7. Spatial coverage of NOS surveys used in compiling the Central California and San Francisco Bay DEMs.

5. *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 NOS hydrographic survey data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

Table 5. Digital NOS hydrographic surveys available for use in the Central California and San Francisco Bay DEM region.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
B00011	1985	50,000	MLLW	NAD 83
B00012	1985	50,000	MLLW	NAD 83
B00016	1995	20,000	MLLW	NAD 83
B00017	1985	50,000	MLLW	NAD 83
B00018	1985	20,000	MLLW	NAD 83
B00031	1985	50,000	MLLW	NAD 83
B00034	1985	50,000	MLLW	NAD 83
B00040	1985	50,000	MLLW	NAD 83
B00041	1985	50,000	MLLW	NAD 83
B00049	1985	50,000	MLLW	NAD 83
B00050	1986	50,000	MLLW	NAD 83
B00076	1986	50,000	MLLW	NAD 83
B00080	1986	50,000	MLLW	NAD 83
B00082	1986	50,000	MLLW	NAD 83
B00083	1986	50,000	MLLW	NAD 83
B00087	1986	50,000	MLLW	NAD 83
B00088	1986	50,000	MLLW	NAD 83
B00091	1986	50,000	MLLW	NAD 83
B00092*	1986	50,000	MLLW	NAD 83
B00119*	1988	50,000	MLLW	NAD 83
B00172	1989	50,000	MLLW	NAD 83
B00177	1989	50,000	MLLW	NAD 83
B00178	1989	50,000	MLLW	NAD 83
B00182*	1989	50,000	MLLW	NAD 83
B00184	1989	50,000	MLLW	NAD 83
B00185*	1989	50,000	MLLW	NAD 83
F00242*	1983	10,000	MLLW	NAD 27
F00299*	1987	10,000	MLLW	NAD 27
F00311*	1987	10,000	MLLW	NAD 27
H04222*	1922	10,000	MLLW	Undetermined
H04229*	1922	10,000	MLLW	NAD 13
H04275*	1922	20,000	MLLW	NAD 13
H04280*	1922	10,000	MLLW	NAD 13
H04974*	1929	20,000	MLLW	NAD 13
H04975	1929	20,000	MLLW	NAD 13
H04977*	1929	20,000	MLLW	NAD 13
H04978*	1929	10,000	MLLW	NAD 13
H04979	1929	40,000	MLLW	NAD 13
H04980A	1929	80,000	MLLW	NAD 13
H04980B	1929	20,000	MLLW	NAD 13
H04981	1929	80,000	MLLW	NAD 13
H04986*	1929	20,000 to 10,000	MLLW	NAD 13
H04987	1929	40,000	MLLW	NAD 13
H04988	1929	40,000	MLLW	NAD 13
H04992*	1929	120,000	MLLW	NAD 13
H04993	1929	120,000	MLLW	Undetermined
H05094	1930	10,000	MLLW	NAD 27

NOS Survey ID	***Year of Survey***	***Survey Scale***	***Original Vertical Datum***	***Original Horizontal Datum***
H05095	1930	10,000	MLLW	NAD 27
H05096	1930	10,000	MLLW	NAD 27
H05097	1930	10,000	MLLW	NAD 27
H05098	1930	10,000	MLLW	NAD 27
H05129*	1931	20,000	MLLW	NAD 27
H05131*	1931	10,000	MLLW	NAD 27
H05133*	1931	10,000	MLLW	NAD 27
H05135*	1931	10,000	MLLW	NAD 27
H05139*	1931	10,000	MLLW	NAD 27
H05140*	1931	10,000	MLLW	NAD 27
H05162	1931	10,000	MLLW	NAD 13
H05163	1931	10,000	MLLW	NAD 13
H05164	1931	20,000	MLLW	NAD 13
H05165*	1931	10,000	MLLW	NAD 27
H05169	1932	40,000	MLLW	NAD 27
H05171	1932	40,000	MLLW	NAD 27
H05245	1933	40,000	MLLW	NAD 27
H05248*	1933	10,000	MLLW	NAD 27
H05266	1933	40,000	MLLW	NAD 27
H05279*	1935	80,000	MLLW	NAD 27
H05287*	1932	10,000	MLLW	NAD 27
H05294*	1932	10,000	MLLW	NAD 27
H05296*	1934	10,000	MLLW	NAD 27
H05312*	1935	10,000	MLLW	NAD 27
H05345*	1933	5,000	MLLW	NAD 27
H05365	1932	10,000	MLLW	NAD 27
H05366*	1932	10,000	MLLW	NAD 27
H05373A*	1933	10,000	MLLW	NAD 27
H05393*	1933	10,000	MLLW	NAD 27
H05395	1934	40,000	MLLW	NAD 27
H05472*	1932	120,000	MLLW	NAD 27
H05473	1934	80,000	MLLW	NAD 27
H05807*	1934	10,000	MLLW	NAD 27
H05853	1935	10,000	MLLW	NAD 27
H06014*	1933	10,000	MLLW	NAD 27
H06421*	1938	5,000	MLLW	NAD 27
H06523*	1940	10,000	MLW	NAD 27
H06524*	1940	10,000	MLW	NAD 27
H06525*	1941	10,000	MLW	NAD 27
H06725*	1941	5,000	MLLW	NAD 27
H06726*	1941	10,000	MLLW	NAD 27
H06735*	1942	10,000	MLLW	NAD 27
H06753*	1942	10,000	MLLW	NAD 27
H06794*	1942	10,000	MLLW	NAD 27
H07619*	1947	10,000	MLLW	NAD 27
H07620*	1947	10,000	MLLW	NAD 27
H07621*	1947 to 1948	10,000	MLLW	NAD 27
H07622*	1947	5,000	MLLW	NAD 27
H07623*	1947	5,000	MLLW	NAD 27

NOS Survey ID	Year of Survey	Survey Scale	Original Vertical Datum	Original Horizontal Datum
H07704*	1951	10,000	MLLW	NAD 27
H07705*	1948	10,000	MLLW	NAD 27
H07706*	1949	5,000	MLLW	NAD 27
H07716*	1948	5,000	MLLW	NAD 27
H07717*	1948	2,400	MLLW	NAD 27
H07784*	1949	5,000	MLLW	NAD 27
H07785*	1950	10,000	MLLW	NAD 27
H07786*	1949	10,000	MLLW	NAD 27
H07797*	1950	10,000	MLLW	NAD 27
H07798*	1950	5,000	MLLW	NAD 27
H07867	1950	10,000	MLLW	NAD 27
H07868	1951	2,500	MLLW	NAD 27
H07897	1951	10,000	MLLW	NAD 27
H07898*	1951	10,000	MLLW	NAD 27
H07899	1951	10,000	MLLW	NAD 27
H07900	1951	20,000	MLLW	NAD 27
H08023*	1954	5,000	MLLW	NAD 27
H08024	1954	10,000	MLLW	NAD 27
H08025*	1955	10,000	MLLW	NAD 27
H08026	1956	10,000	MLLW	NAD 27
H08027	1955	20,000	MLLW	NAD 27
H08028	1956	20,000	MLLW	NAD 27
H08088*	1954	10,000	MLLW	NAD 27
H08208	1954	20,000	MLLW	NAD 27
H08209	1954	20,000	MLLW	NAD 27
H08210*	1956	10,000	MLLW	NAD 27
H08275	1956	10,000	MLLW	NAD 27
H08281	1956	10,000	MLLW	NAD 27
H08282	1956	10,000	MLLW	NAD 27
H08353	1957	10,000	MLLW	NAD 27
H08354	1957	10,000	MLLW	NAD 27
H08355*	1957	10,000	MLLW	NAD 27
H08356	1957	10,000	MLLW	NAD 27
H08566*	1962	160,000	MLLW	NAD 27
H08567*	1960	160,000	MLLW	NAD 27
H09185	1971	5,000	MLLW	NAD 27
H09660	1976	20,000	MLLW	NAD 27
H09793	1978	10,000	MLLW	NAD 27
H09794	1978	10,000	MLLW	NAD 27
H09810	1979	10,000	MLLW	NAD 27
H09811	1979	10,000	MLLW	NAD 27
H09819	1979	10,000	MLLW	NAD 27
H09844	1979 to 1981	10,000	MLLW	NAD 27
H09869	1980	10,000	MLLW	NAD 27
H09872	1980	10,000	MLLW	NAD 27
H09873	1980 to 1981	5,000	MLLW	NAD 27
H09927	1981	5,000	MLLW	NAD 27
H09952	1981 to 1982	10,000	MLLW	NAD 27
H09984*	1981 to 1983	10,000	MLLW	NAD 27

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H10070	1982 to 1983	10,000	MLLW	NAD 27
H10080	1983	10,000	MLLW	NAD 27
H10081	1983	10,000	MLLW	NAD 27
H10082	1983	10,000	MLLW	NAD 27
H10102	1983 to 1984	10,000	MLLW	NAD 27
H10132	1984 to 1985	10,000	MLLW	NAD 27
H10158	1984 to 1985	10,000	MLLW	NAD 27
H10182	1985 to 1986	20,000	MLLW	NAD 27
H10213	1986	10,000	MLLW	NAD 27
H10223	1986 to 1987	10,000	MLLW	NAD 27
H10264	1988	10,000	MLLW	NAD 27
H10283	1988 to 1989	10,000	MLLW	NAD 27
H10293	1989	10,000	MLLW	NAD 27
H10298	1989	10,000	MLLW	NAD 27
H10303	1989	10,000	MLLW	NAD 27
H10306	1989	10,000	MLLW	NAD 27
H10315	1989	10,000	MLLW	NAD 27
H10317	1989 to 1990	10,000	MLLW	NAD 27
H10342	1990 to 1991	10,000	MLLW	NAD 27
H10373	1991	10,000	MLLW	NAD 83
H10398	1991	10,000	MLLW	NAD 83
H10456	1993	10,000	MLLW	NAD 83
H10471	1993	10,000	MLLW	NAD 83
H10480	1993	10,000	MLLW	NAD 83
H10494	1993	10,000	MLLW	NAD 83
H10512	1993 to 1994	10,000	MLLW	NAD 83
H10513	1993 to 1994	10,000	MLLW	NAD 83
H10524	1994	10,000	MLLW	NAD 83
H10727*	1996	10,000	MLLW	NAD 83
H10895	1999	10,000	MLLW	NAD 83
H10896	1999	10,000	MLLW	NAD 83
H10897	1999 to 2000	10,000	MLLW	NAD 83
H10898*	1999	10,000	MLLW	NAD 83
H10960	2000	10,000	MLLW	NAD 83 UTM Zone 10 N
H10961	2000	10,000	MLLW	NAD 83 UTM Zone 10 N
H10962	2000	10,000	MLLW	NAD 83 UTM Zone 10 N

* Survey not used in developing the Central California or San Francisco Bay DEMs.

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

USACE conducted high-resolution hydrographic harbor surveys in San Francisco Harbor in 2009 (Table 6; Fig. 8). These surveys were originally referenced to NAD 83 California State Plane Zone III coordinates (feet) and MLLW vertical datum (feet). The resolution of the surveys ranges from roughly 5 to 10 meters and the depths range from -1.1 to -11.3 meters at MHW.

Table 6. USACE bathymetric surveys used in compiling the Central California and San Francisco Bay DEMs.

Survey name	*Date*	*Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*
SF9_29Oct2009	2009	Channel line survey spacing ~30 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
PS_6_7Jul2009_AD	2009	Channel line survey spacing ~60 meters apart with ~10 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
PS_Oct2009_BD	2009	Channel line survey spacing ~60 meters apart with ~10 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
SF10_17Nov2009	2009	Channel line survey spacing ~60 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
Larkspur_17_18_ Sept2009_CON	2009	Channel line survey spacing ~30 meters apart with ~2 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
RI_Santa_ Fe_11Sept2009	2009	Channel line survey spacing ~30 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
southampton_ postdredge_9July2009	2009	Channel line survey spacing ~60 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
long-wharf_07_08_2009	2009	Channel line survey spacing ~30 meters apart with ~3 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
RI_Reaches1_7_ May_June 2009_BD	2009	Channel line survey spacing ~30 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
AL_01Dec2009	2009	Channel line survey spacing ~60 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
ALE_22Sept2009_ CON	2009	Channel line survey spacing ~60 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
OI_Mar_Sept2009_ AD COMP_Entrance	2009	Channel line survey spacing ~30 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
OI_Mar_Sept2009_ AD COMP_Inner	2009	Channel line survey spacing ~30 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
OO_20009O_M_ COMP	2009	Channel line survey spacing ~30 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
Brooklyn_Basin_South_ Ch_09Sept2009_CON	2009	Channel line survey spacing ~30 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
ANAS_May2009_ CON	2009	Channel line survey spacing ~60 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
RC_Oct2009_BD	2009	Channel line survey spacing ~30 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
islais_ creek_16June2009	2009	Channel line survey spacing ~60 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW
islais_creek_ ext_16June2009	2009	Channel line survey spacing ~60 meters apart with ~5 meter point spacing	NAD 83 California State Plane Zone III (feet)	MLLW

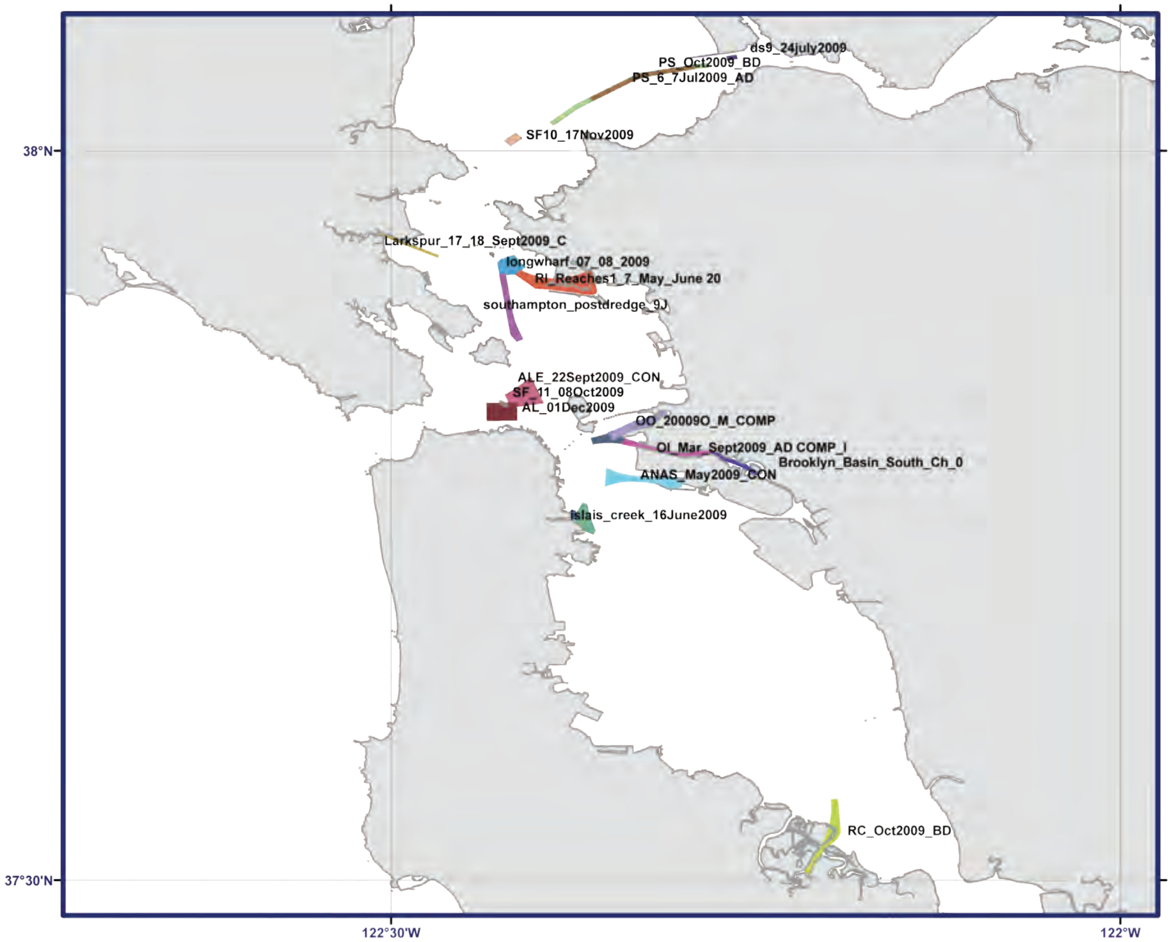

Figure 8. USACE survey coverage for the San Francisco Bay region.

3) CSUMB Seafloor Mapping Laboratory multibeam surveys

As a partner in the California Seafloor Mapping Project, California State University, Monterey Bay provides multibeam survey data online (Table 7; Fig. 9). Data for the DEMs were downloaded in either xyz or gridded format and transformed to geographic coordinates and NAVD 88 using *FME* and *VDatum*, respectively. The data were then compared to other bathymetric data and reviewed in *ArcMap*.

Table 7. CSUMB multibeam surveys used in compiling the Central California and San Francisco Bay DEMs.

Survey	*Date*	*Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*
Farallon Islands	2001	1 meter	WGS 84 UTM Zone 10 North	MLLW
Bodega Bay	2001	1 meter	WGS 84 UTM Zone 10 North	MLLW
Cordell Bank	2006	3 meter	WGS 84 UTM Zone 10 North	MLLW
San Francisco Bay	2004 - 2005	2 meters	WGS 84 UTM Zone 10 North	MLLW
Presidio Shoals	2007	1 meter	WGS 84 UTM Zone 10 North	MLLW
San Pablo Bay	2006	1 meter	WGS 84 UTM Zone 10 North	MLLW
West Bay	2004	2 meters	WGS 84 UTM Zone 10 North	MLLW
CA Seafloor Mapping Program - Phase 1	2007	2 meters	WGS 84 UTM Zone 10 North	MLLW
CA Seafloor Mapping Program - Phase 2 A	2007	2 meters	WGS 84 UTM Zone 10 North	MLLW
CA Seafloor Mapping Program - Phase 2 B	2006 - 2007	2 meters	WGS 84 UTM Zone 10 North	MLLW

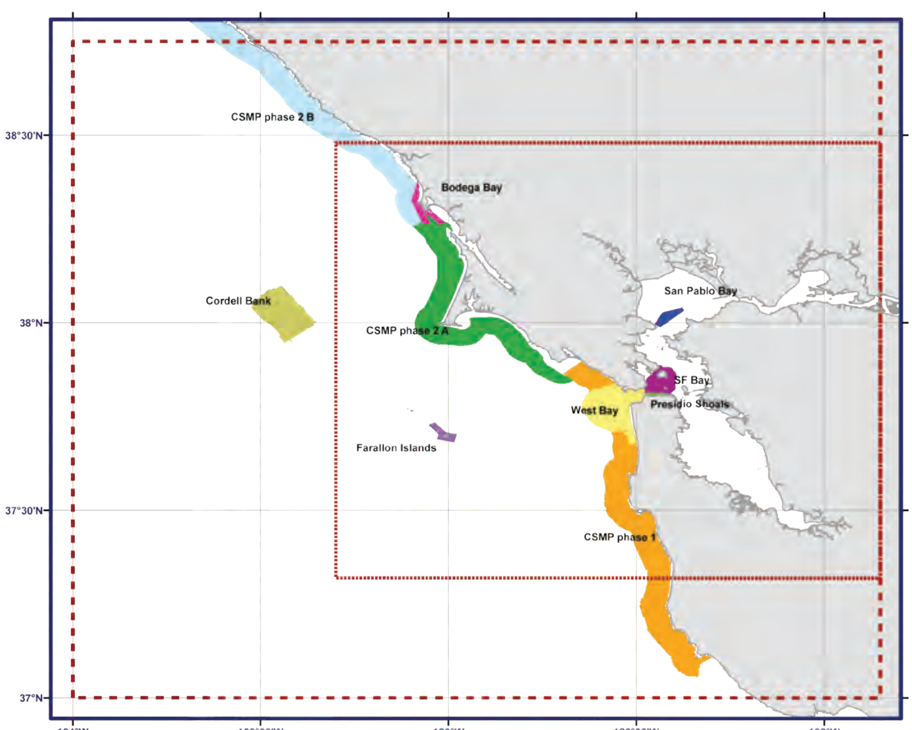

Figure 9. CSUMB survey coverage in the Central California and San Francisco Bay DEM region.

4) USGS hydrographic survey of South San Francisco Bay

A bathymetric survey of the South San Francisco Bay was available from the USGS. The survey was completed in 2005 and used to assess topographic changes in the bay floor and for tracking restoration changes in the salt ponds. Specific information on data acquisition and processing by USGS is detailed in the *2005 Hydrographic Survey of South San Francisco Bay, California* report (Foxgrover, et al., 2007). The data were downloaded in xyz format and converted to a shapefile using *FME* for reviewing in *ArcMap*. Preliminary gridding showed that the using the survey data in its original form, with the survey lines were spaced roughly 100 meters apart and points spacing of 1 meter (e.g., Fig. 10), resulted in the bathymetric surface having a washboard texture. To minimize the washboard effect, the data were surfaced to 1 arc-second with weighted moving average of 7 to interpolate between survey lines using *Fledermaus*, shown in Figure 11, and exported to an xyz file and clipped to the original survey data boundary using *FME* before using in the final DEM gridding.

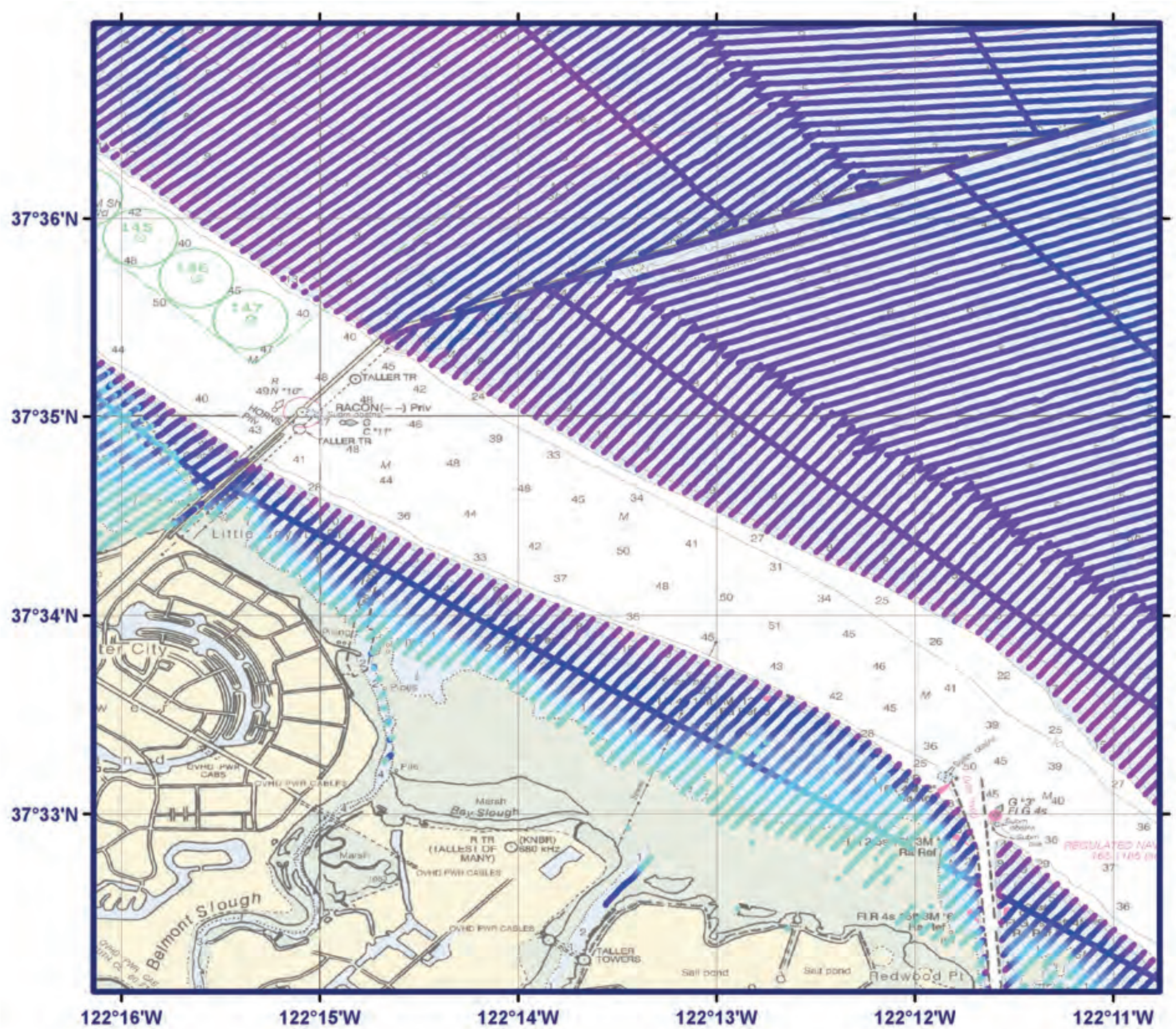

Figure 10. Example of the USGS South San Francisco Bay survey data near San Mateo overlaying nautical chart # 18651.

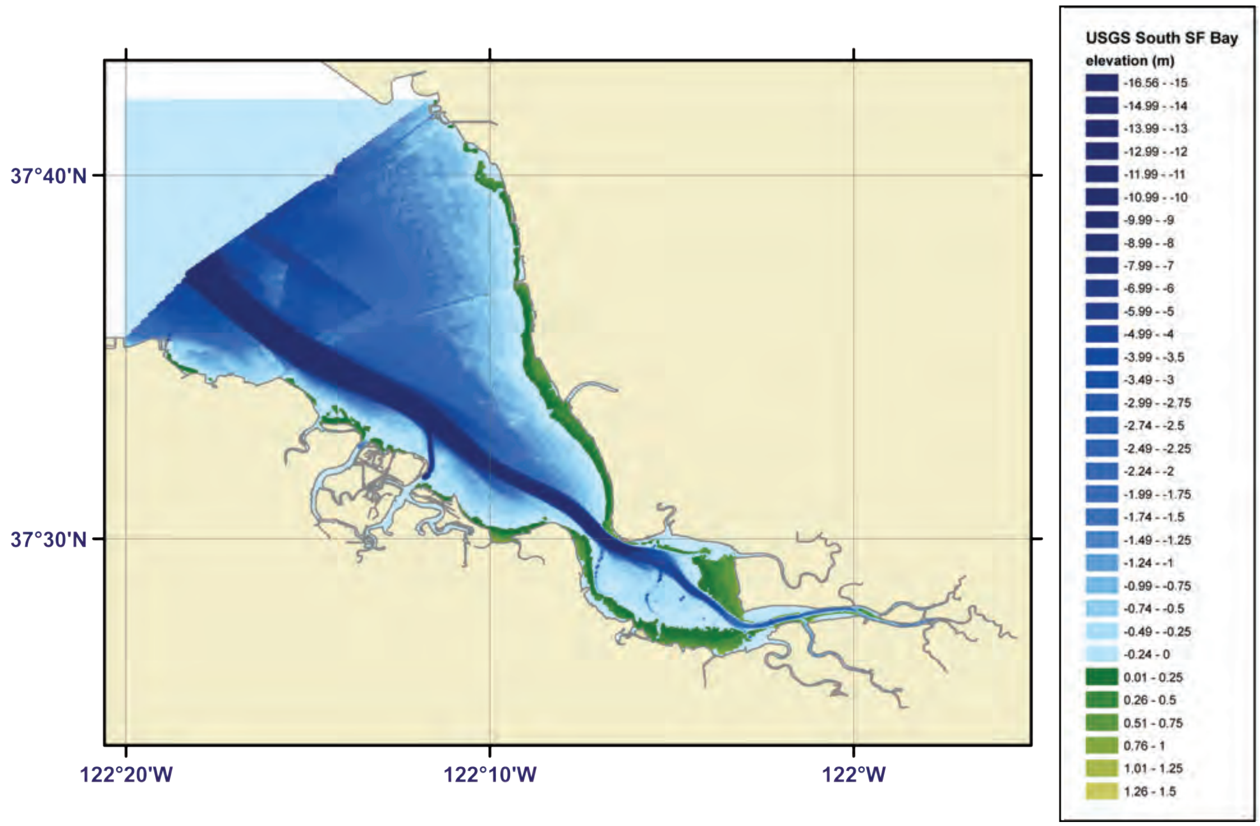

Figure 11. USGS South San Francisco Bay survey data after gridding with Fledermaus. Data generated by interpolation to the northwest shown in light blue was clipped out before use in final gridding.

5) USGS multibeam survey Tomales Bay

A composite grid of three bathymetric surveys was available online from USGS for Tomales Bay (Fig. 12). The data were downloaded in xyz format with horizontal reference of WGS 84 geographic and vertical reference of NAVD 88. The data were converted to shapefile format and reviewed in *ArcMap* against nautical charts and recent NOS surveys.

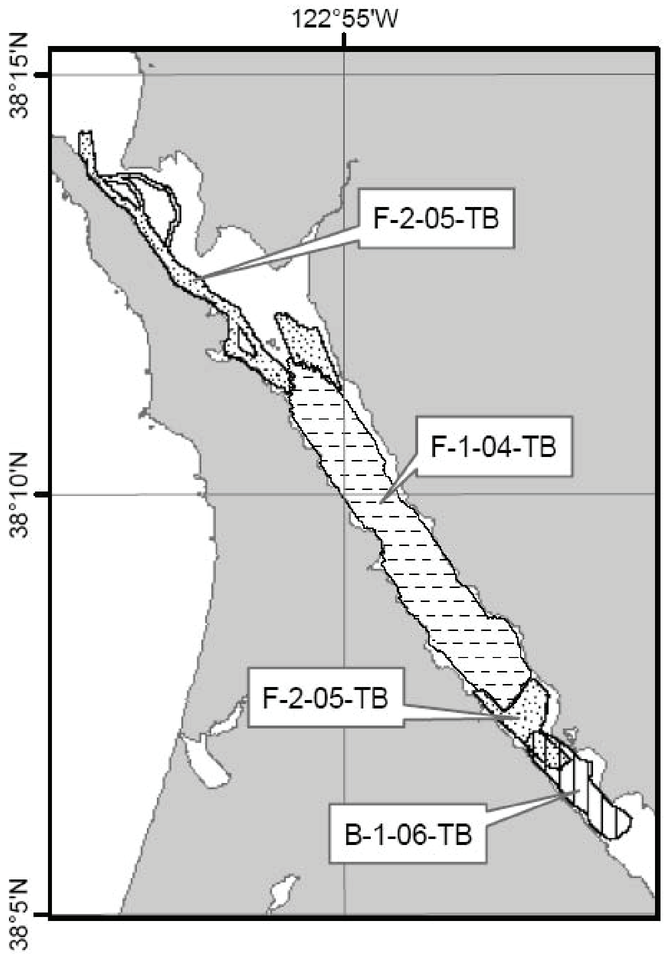

Figure 12. USGS Tomales Bay survey coverage.

6) NOAA NGDC multibeam database surveys

Thirty-four multibeam swath sonar surveys (Table 8) available from the NGDC multibeam sonar bathymetry database were used in building the DEMs. This database is comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. Surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be essentially MSL.

The downloaded data were gridded to 1 arc-second resolution using *MB-System*[6]. The gridded data were transformed to NAVD 88 using *VDatum*. Further editing of the gridded data was done using *QT Modeler* and clipped to more recent bathymetric data if present.

Table 8. Multibeam swath sonar surveys used in compiling the Central California and San Francisco Bay DEMs.

Cruise ID	*Ship*	*Year*	*Collecting Institution*
AT07L14	Atlantis	2002	Woods Hole Oceanographic Institution (WHOI)
AT11L33	Atlantis	2005	WHOI
AT15L07	Atlantis	2006	WHOI
AT15L08	Atlantis	2006	WHOI
AT15L11	Atlantis	2006	WHOI
AVON08MV	Melville	1999	University of California, Scripps Institution of Oceanography (UC/SIO)
AVON10MV	Melville	1999	UC/SIO
AVON11MV	Melville	1999	UC/SIO
AVON12MV	Melville	1999	UC/SIO
CNTL04RR	Roger Revelle	2003	UC/SIO
DRFT01RR	Roger Revelle	2001	UC/SIO
EW0209	Maurice Ewing	2002	Columbia University, Lamont-Doherty Earth Observatory (CU/LDEO)
EW0407	Maurice Ewing	2004	USGS

6. 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. [Extracted from MB-System web site; http://www.ldeo.columbia.edu/res/pi/MB-System/]

Cruise ID	*Ship*	*Year*	*Collecting Institution*
EW9407	Maurice Ewing	1994	CU/LDEO
EW9414	Maurice Ewing	1995	CU/LDEO
EW9504	Maurice Ewing	1995	CU/LDEO
EW9505	Maurice Ewing	1995	CU/LDEO
EW9506	Maurice Ewing	1995	CU/LDEO
EW9904	Maurice Ewing	1999	CU/LDEO
EX0907	Okeanos Explorer	2009	NOAA
HLY03TA	USCGC Healy	2003	U.S. Coast Guard (USCG)
KIWI02RR	Roger Revelle	1997	UC/SIO
LPRS02RR	Roger Revelle	2002	UC/SIO
LWAD99MV	Melville	1999	UC/SIO
Monterey	Ocean Alert	1998	Monterey Bay Aquarium Research Institute (MBARI)
NECR01RR	Roger Revelle	2000	UC/SIO
NPAL98MV	Melville	1998	UC/SIO
Pioneer	Ocean Alert	1998	MBARI
REM-01MV	Melville	1993	UC/SIO
REM-02MV	Melville	1993	UC/SIO
RNDB03WT	Thomas Washington	1988	UC/SIO
SO108	Sonne	1996	University of Kiel, Germany, GEOMAR Forshungszentrum (GEOMAR)
Tran2sou	Ocean Alert	1998	MBARI
WEST15MV	Melville	1995	UC/SIO

7) **OCS Electronic Navigational Chart soundings**

NOAA Nautical charts #18640, 18645, 18651, 18653, 18654, 18655, 18656, 18657, 18659, and 18680 were available from OCS in Electronic Navigational Chart (ENC)[7] format. Sounding data were transformed from MLLW to NAVD 88 using *VDatum*, clipped to more recent multibeam data, then converted to xyz format for use in creating a bathymetric pre-surface and in the final DEM. Figure 13 shows the coverage of the extracted soundings within the Central California region.

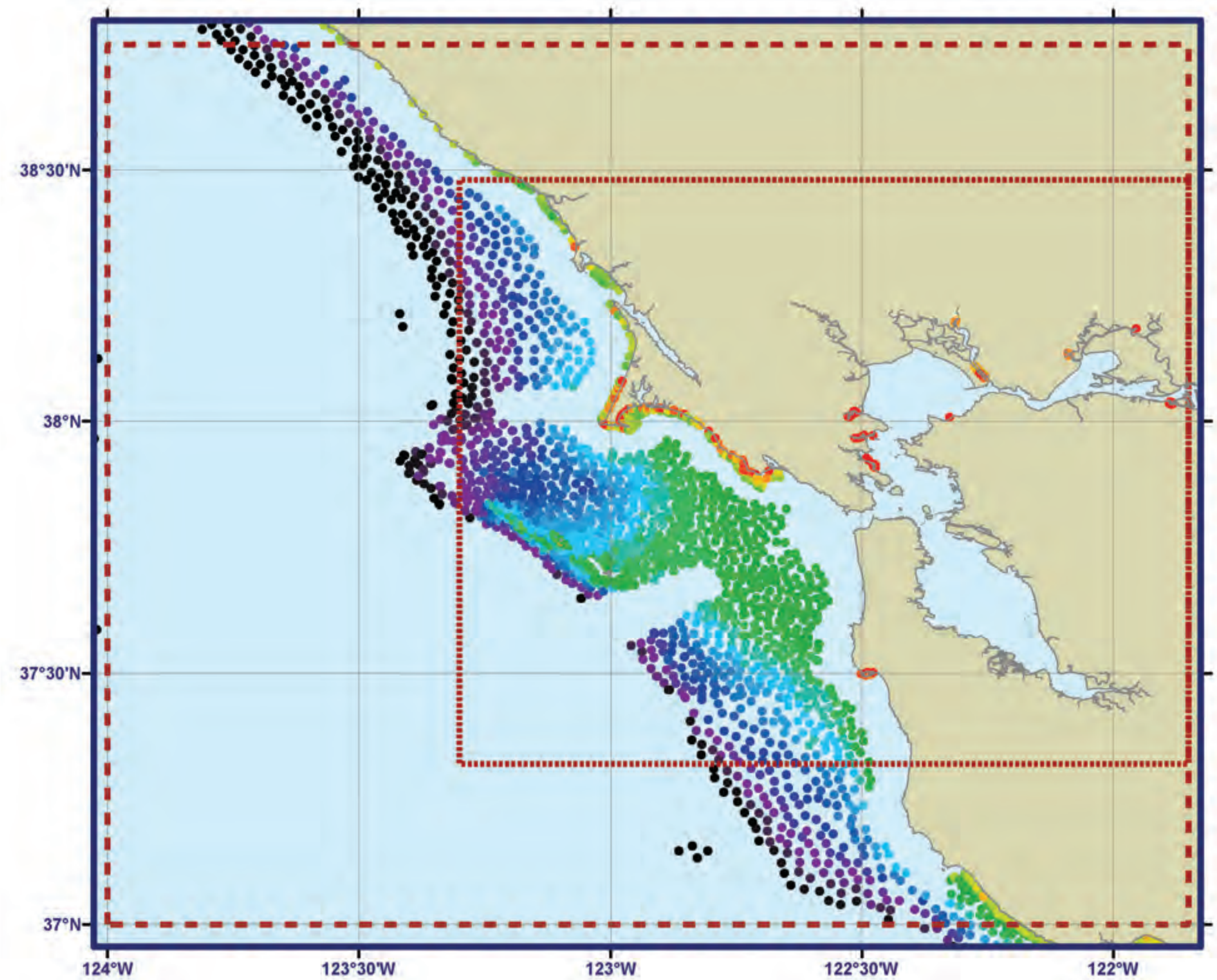

Figure 13. Coverage of OCS ENC extracted soundings within the Central California region.

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

3.1.3 Topography

Topographic datasets in the Central California region were obtained from: USGS, GEON's OpenTopography Portal, NCALM, FEMA, and CA DWR (Table 9; Fig. 14).

Table 9. Topographic datasets used in compiling the Central California and San Francisco Bay DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
USGS NED	2006	Topographic DEMs	1/9 and 1/3 arc-second grids	NAD 83 geographic	NAVD 88	http://seamless.usgs.gov/
GEON	2007	Bare-earth DEMs	5 meters	WGS 84 UTM Zone 10 North (meters)	Ellipsoid (WGS 84)	http://www.opentopography.org/index.php
NCALM	2003 to 2006	Bare-earth DEMs	1 meter	NAD 83 UTM Zone 10 North (meters)	NAVD 88 geoid 99 or NAVD 88 geoid 03	http://calm.geo.berkeley.edu/ncalm/ddc.html
FEMA	2004	DTM	1 meter	NAD 83 California State Plane III (feet)	NAVD 88	
CA DWR	2007	Bare-earth lidar points	1 meter	NAD 83 UTM Zone 10 North (meters)	NAVD 88	http://delta-vision.gforge.projects.atlas.ca.gov/

Figure 14. Spatial coverage of topographic datasets used in compiling the Central California and San Francisco DEMs.

1) U.S. Geological Survey National Elevation Dataset topography

USGS National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the Central California region[8]. The dataset is available for download as raster DEMs in NAD 83 geographic horizontal datum and NAVD 88 (meters) vertical datum. 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). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys.

The USGS NED 1/3 arc-second DEM data were downloaded from the USGS web site. *ArcCatalog* tools were used to clip the NED DEMs to the combined coastline. *FME* was used to convert the rasters to xyz format. Several NED tiles included data errors such as gridding and tiling artifacts (Fig. 15). Other higher-resolution data were available to replace the NED data in some areas. To partially minimize propogation of the errors where no other data were available, elevation values in the NED dataset that were below 1.5 meters were converted to 1 meter (see Lim et al., 2009 for further details).

The USGS NED 1/9 arc-second DEM data were available for Alameda, Contra Costa, and Santa Clara counties. This data is generated from 2006, 2007, and 2008 lidar. The data were converted from rasters to xyz format and clipped to the coastline using *QT Modeler*. This data contained positive elevation values over water of up to 0.16 meters which were filtered using *FME* or manually edited using *QT Modeler*.

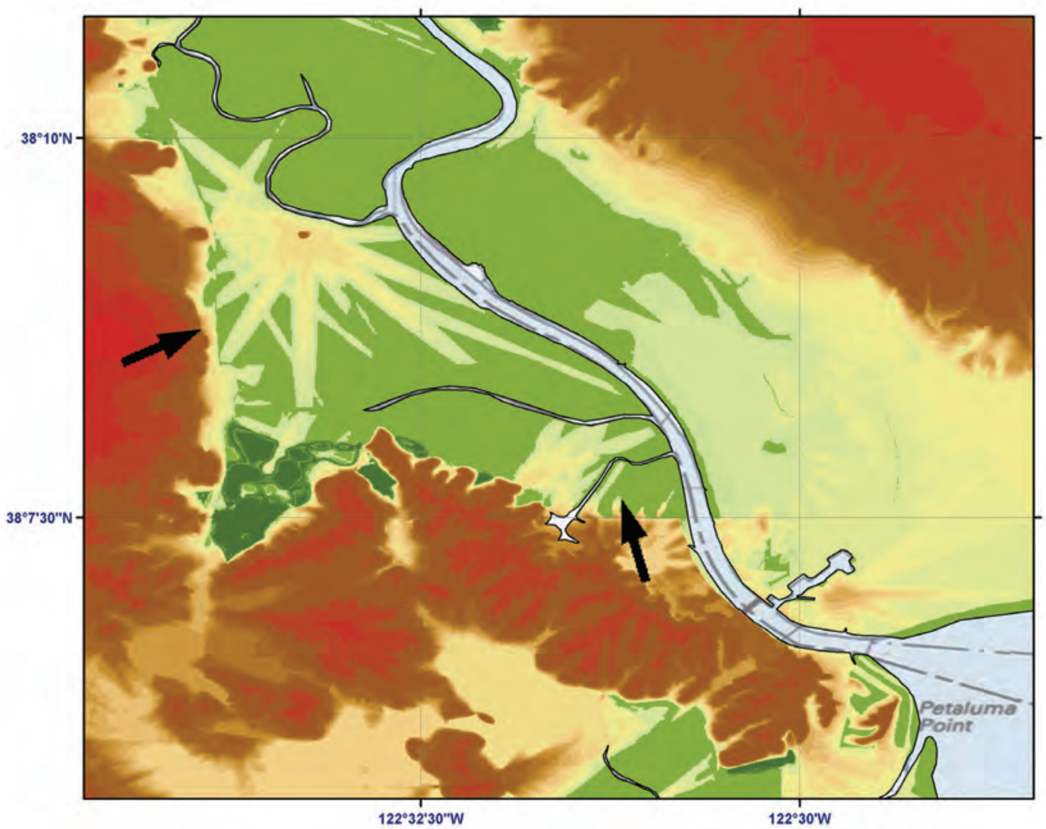

Figure 15. Example of data errors in the NED 1/3 arc-second DEM at low elevations. Black arrows point to areas in the data where cell elevation values were modified to minimize error propagation in the DEMs.

8. The USGS National Elevation Dataset (NED; http://ned.usgs.gov/) 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 California. The dataset provides seamless coverage of the United States, HI, CA, 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 Alaska, which is NAD 27. The vertical datum is NAVD 88, except for Alaska, which is NGVD 29. 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 web site; http://ned.usgs.gov/]

2) GEON Lidar

GEON's OpenTopography Portal[9] provides access to the GeoEarthScope Northern California Lidar Project which acquired high-resolution airborne laser swath mapping imagery along major active faults as part of the EarthScope Facility project funded by the National Science Foundation (NSF).

The bare-earth data were downloaded with a 5 meter, mean average local binning algorithm using the OpenTopography Portal system and exported as an xyz format point file. The data were transformed from WGS 84 UTM Zone 10 to NAD 83 geographic with *FME*. Elevations were referenced to the ellipsoid (WGS 84) and transformed to NAVD 88 using *VDatum*. Returns on piers and water returns, example shown in Figure 16, were removed using *QT Modeler* before final gridding.

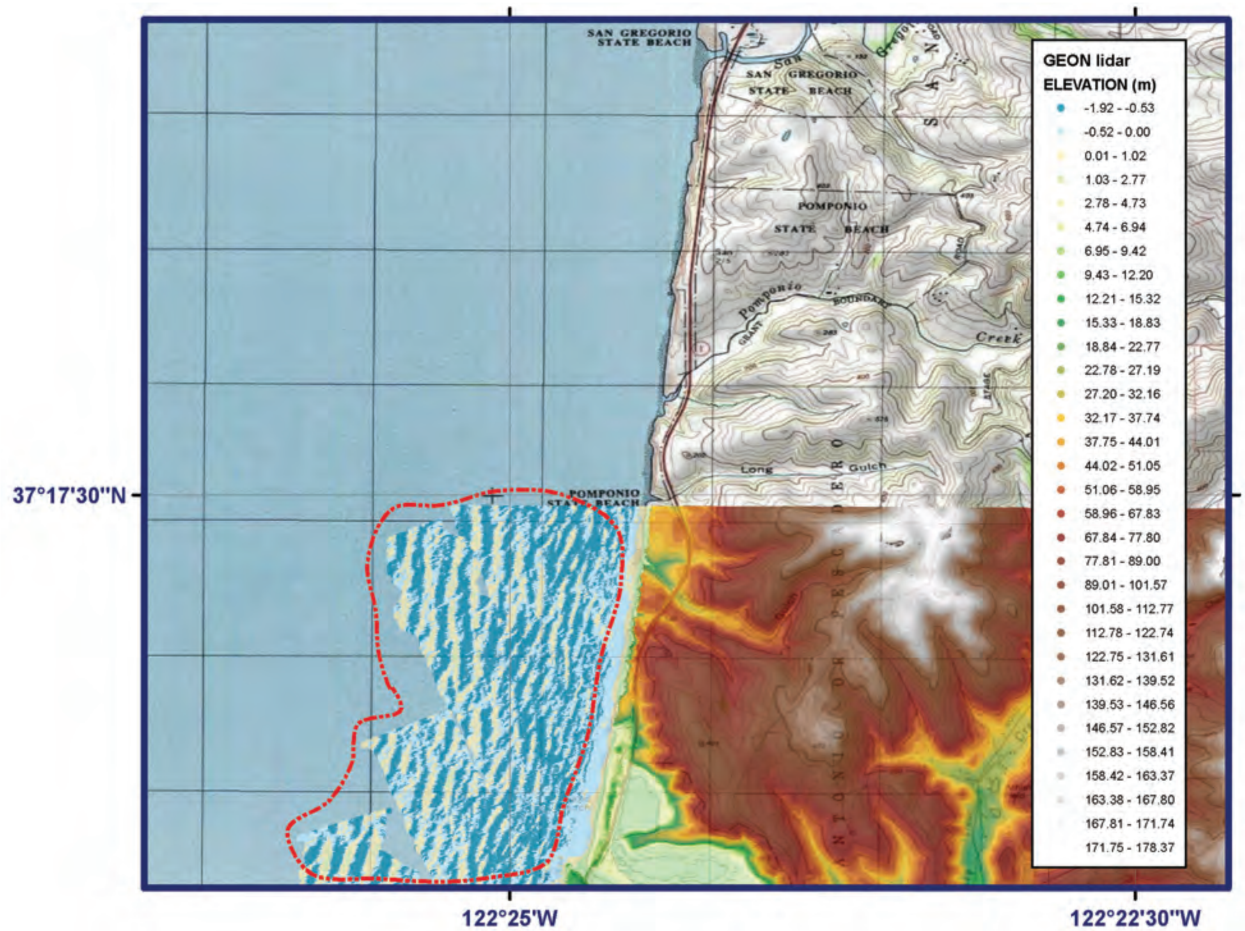

Figure 16. An example of the GEON lidar dataset along the coast south of Gregorio Beach. Water returns in the data, outlined in red, were removed using QT Modeler.

9. This material is based on services provided by the Plate Boundary Observatory operated by UNAVCO for EarthScope (http://www.earthscope.org) and supported by the National Science Foundation (No. EAR-0350028 and EAR-0732947). This material is based on [data, processing] services provided by the OpenTopography Facility with support from the National Science Foundation under NSF Award Numbers 0930731 & 0930643.

3) NCALM Lidar

Two datasets, the Napa River Watershed and Lone Tree Creek, were downloaded from the NCALM web site. The bare-earth gridded data were transformed from NAD 83 UTM Zone 10 North and resampled from 1 meter resolution to ~ 3 meters (1/9 arc-second) before converting to xyz format using *FME*. Both datasets were clipped to the coastline using *QT Modeler*. Remaining buildings in the Napa River Watershed dataset, an example shown in Figure 17, were also edited using *QT Modeler* before final gridding.

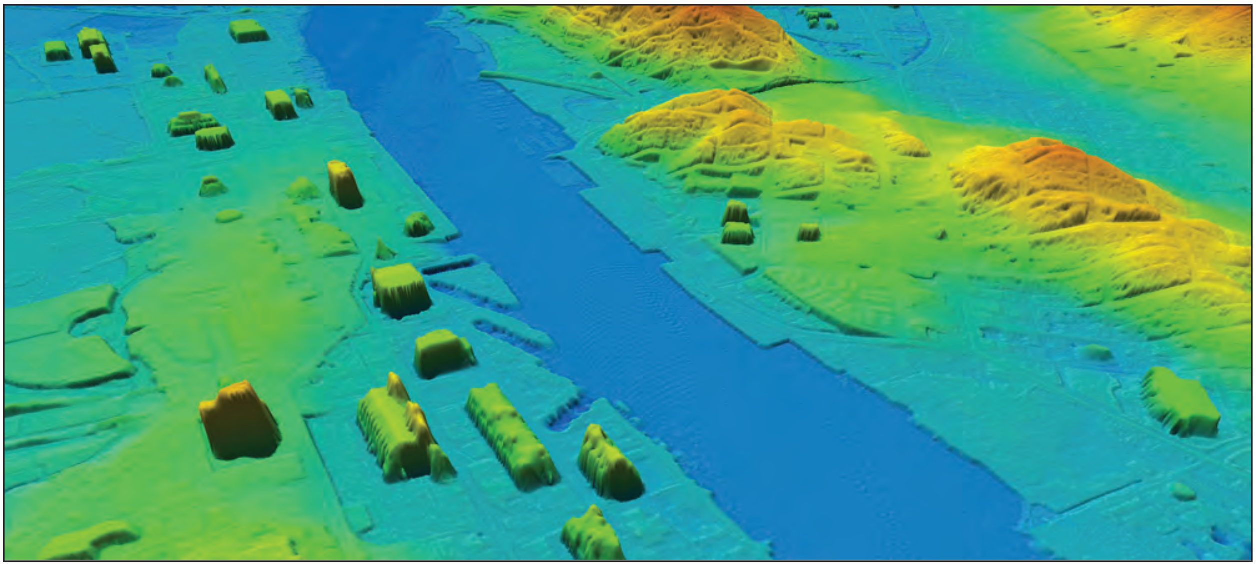

Figure 17. Perspective view of NCALM lidar data at Mare Island Channel at the east end of San Pablo Bay. The image shows buildings present in the bare-earth lidar dataset. These were removed before final gridding.

4) FEMA Lidar

Two lidar datasets of North and Central San Francisco Bay were provided to NGDC by FEMA for the San Francisco region. The data, in .las format, were converted to xyz format using *FME* while filtering to bare-earth classification. The data were then edited manually using *QT Modeler* to remove values over water and structures that were not filtered out by classification. Figure 18 shows an example of features remaining in data after filtering process that were manually edited out of data before use in final grid.

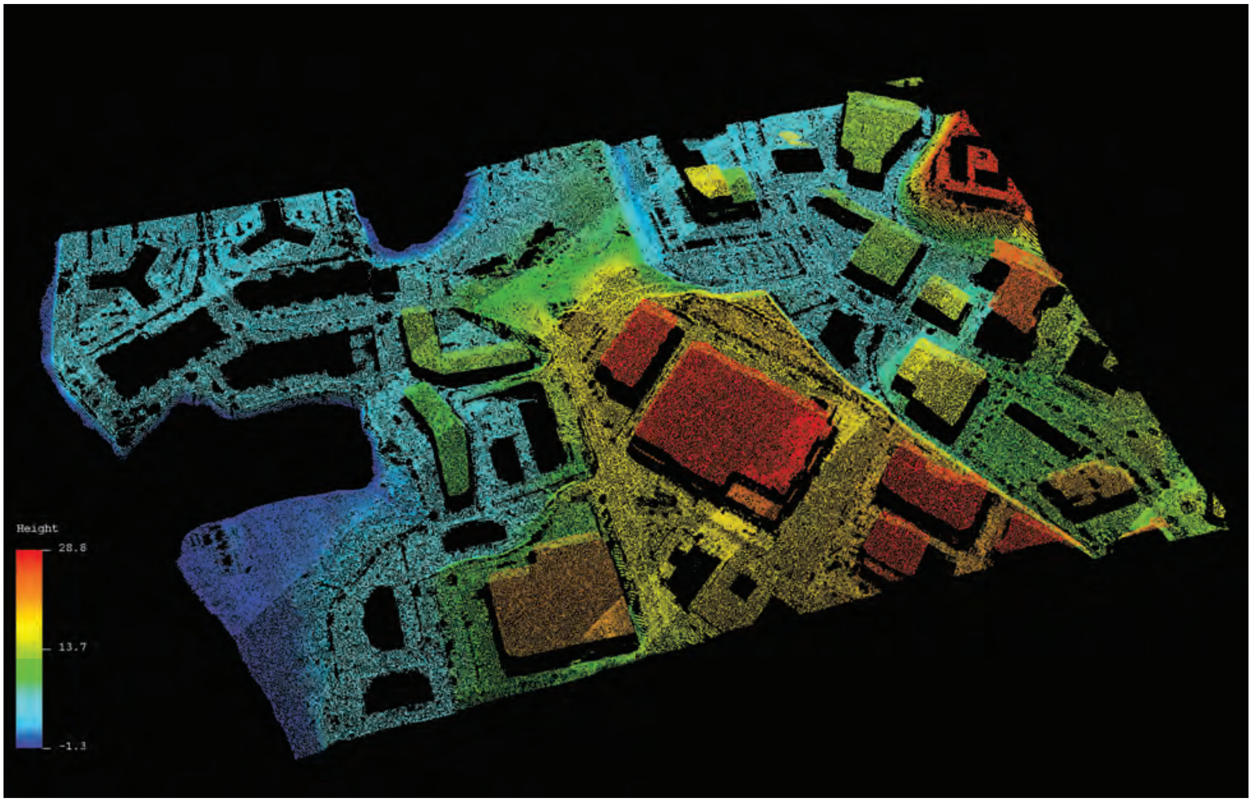

Figure 18. Example of FEMA lidar data after filtering by classification. Further editing was done manually to remove the remaining buildings from the dataset.

5) CA DWR Sacramento - San Joaquin Delta lidar

Bare-earth lidar point tiles at 1 meter resolution for the Sacramento - San Joaquin River Delta were downloaded from the CA DWR, DeltaVision Project web site. The data were transformed from NAD 83 UTM Zone 10 to NAD 83 geographic with *FME*. Lidar tiles along shorelines required manual editing to remove data values over water as the dataset included many areas inland with valid below zero elevation values. Automated editing would have resulted in eliminating data that accurately resolved these low laying regions that other datasets did not. Figure 19 shows one tile of the dataset, the area consists of low or below zero elevations relative to NAVD 88.

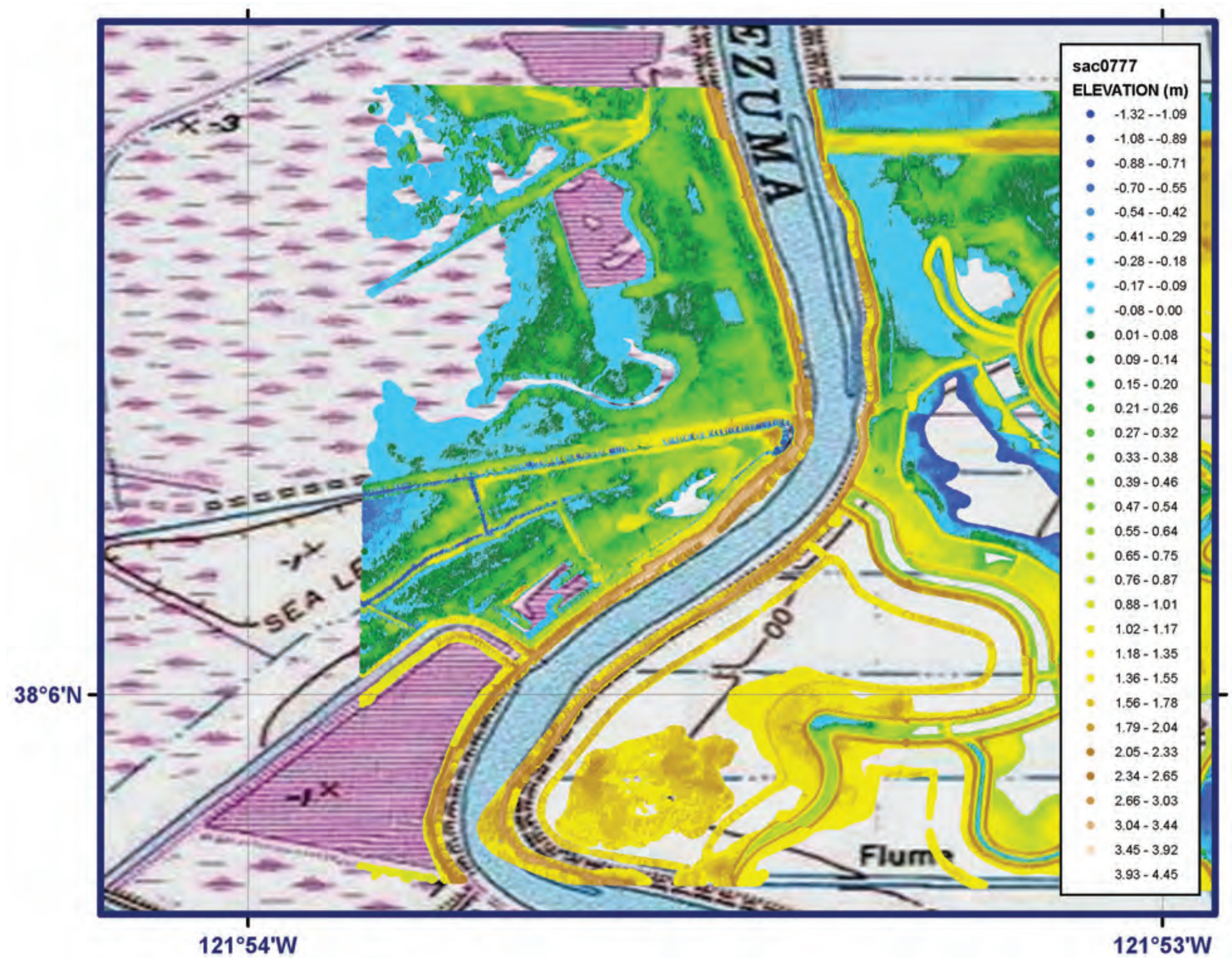

Figure 19. Example of the CA DWR Sacramento-San Joaquin Delta lidar dataset. Manual editing of the dataset was neccessary in order to retain below zero elevation values,

3.1.4 Bathymetry–Topography

One dataset from USGS was used in San Mateo County covering the Crystal Springs Reservoir System (Fig. 20, Finlayson et al., 2010).

1) **USGS merged multibeam and lidar for Crystal Springs Reservoir System**

   The USGS dataset consists of two merged multibeam and lidar DEMs for the Crystal Springs Reservoir and San Andreas Lake in San Mateo County. The data are a combination of 1 meter gridded multibeam data conducted in 2007 and 2008 and a portion of the GEON lidar (see section 3.1.3 part 2). The data were downloaded in xyz format, horizontally referenced to WGS 84 G1150/ITRF2000 UTM Zone 10 North and vertically referenced to NAVD 88. The data were transformed to geographic coordinates using *FME*.

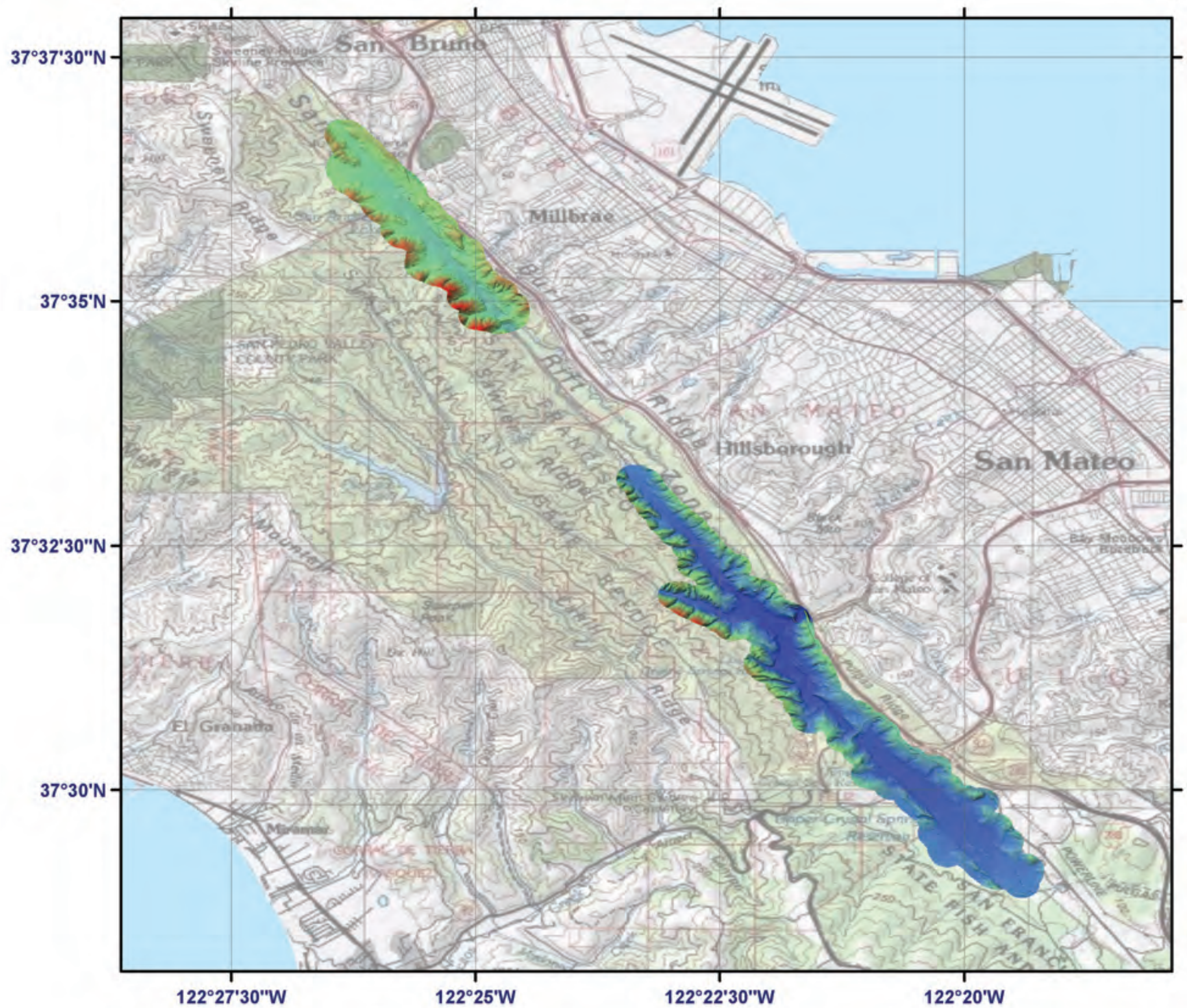

Figure 20. Coverage of the USGS merged DEMs for the Crystal Springs Resevoir System.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Central California and San Francisco Bay DEMs were originally referenced to a number of vertical datums including: MLW, MLLW, MSL, NAVD 88 Geoid 99, NAVD 88 Geoid 03, and the 2003 ellipsoid. All datasets were transformed to NAVD 88 (unspecified geoid) using the *VDatum* transformation tool. Spatial coverage of *VDatum* is shown in Figure 21.

1) Bathymetric data

The NOS hydrographic and multibeam surveys, the USACE survey data, USGS multibeam surveys, and the nautical chart soundings were transformed from MLW, MSL, and MLLW to NAVD 88, using *VDatum* software. The average of the relationships between the various vertical datums and NAVD 88 based on tide stations in the DEM region are listed in Table 10. Survey data further inland were transformed using a constant derived from the *VDatum* transformation tool, as the *VDatum* tool coverage does not extend up several of the smaller river channels. 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.

2) Topographic data

The NED DEMs, FEMA lidar DTMs, and the CA DWR lidar were originally referenced to NAVD 88 and no transformations were made to the data. The NCALM and GEON DEMs were referenced to NAVD 88 Geoid 99, NAVD 88 Geoid 03, or the ellipsoid, respectively. Conversions to NAVD 88 (unspecified geoid) were accomplished by using *VDatum* software.

Table 10. Average relationships between NAVD 88 and other vertical datums within the Central California DEM region.

Vertical datum	*Difference to NAVD 88 in meters*
MHHW	1.85
MHW	1.67
MTL	1.02
MSL	1.01
MLW	0.38
NAVD 88	0
MLLW	-0.05
NGVD 29	0.82

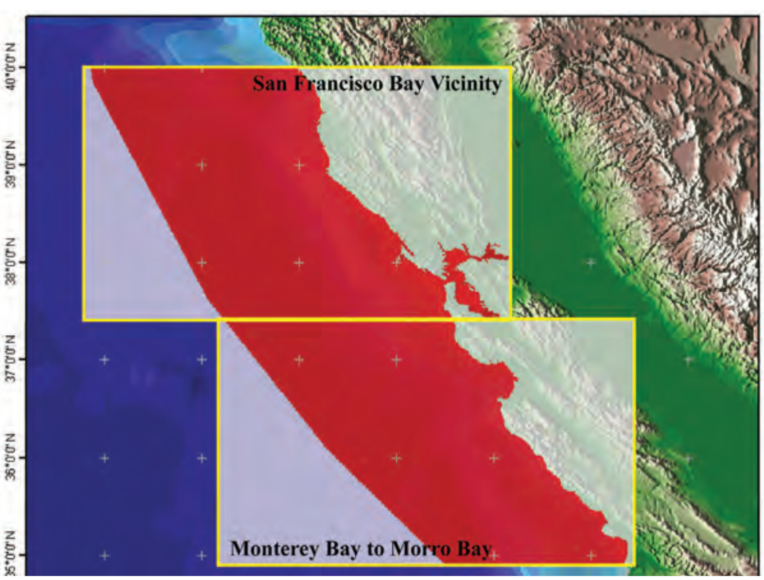

Figure 21. Coverage of the VDatum transformation tool in the Central California region.

3.2.2 Horizontal datum transformations

Datasets used in compiling the Central California and San Francisco Bay DEMs were originally referenced to: NAD 13, NAD 27, NAD 83, and WGS 84 geographic; NAD 83 UTM Zone 10 North (meters); NAD 83 California State Plane Zone III (feet); WGS 84 UTM Zone 10 North (meters); and "undetermined" horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established and transformation to NAD 83 geographic were done using *FME* or *ArcGIS* software. The NOS surveys referenced to NAD 13, NAD 27, and "undetermined" horizontal datums were downloaded referenced to NAD 83 geographic using *GEODAS* and the locations were then reviewed in *ArcMap*.

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 ESRI *ArcMap* and *QT Modeler* 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:

- Data values over the water in topographic datasets. Data required automated clipping to the combined coastline or manual editing.
- Inconsistent, overlapping topographic datasets. Lower-resolution datasets were clipped to higher-resolution data and all datasets were weighted based on quality and age in gridding process.
- Sparse, older bathymetric data in outer shelf region.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 and 1 arc-second grids in both deep water and near shore; the NOS survey data have point spacing up to 1.5 kilometers apart. In order to reduce the effect of artifacts in the form of lines of "pimples" in the 1/3 arc-second DEM due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 1/3 and 1 arc-second-spacing "pre-surface" or grid was generated using *GMT*[10].

The NOS hydrographic point data, in xyz format, were combined with the USACE surveys, ENC sounding, NOS hydrographic lidar, and NGDC multibeam swath sonar bathymetry data into a single file. Points extracted every 10 meters from the combined coastline were also included and assigned elevation values of zero meters to ensure that the offshore elevations remained negative; this was necessary due to the sparseness of the bathymetric data near the coast. These point data were then smoothed using the *GMT* tool "blockmedian" onto a 3 arc-second grid. The *GMT* tool "surface" was then applied to interpolate values for cells without data values. The netcdf grid created by "surface" was converted into an ESRI Arc ASCII grid file using the *MB-System* tool "mbm_grd2arc". Conversion of this Arc ASCII grid file into an Arc raster permitted clipping of the grid with the combined coastline (to eliminate data interpolation into land areas).

For San Francisco Bay and along the coastline, gridding artifacts, such as "humps" and > 5 meters dips in the surface where topographic data slopes steeply, were generated due to sparse data (Fig. 22). A higher resolution 1/3 arc-second bathymetric surface was generated for these areas. By decreasing the cell size within the bay and along portions of the coastline, as well as digitizing additional points in the bay and in areas where there was no topographic data coverage, NGDC minimized the artifacts. This corrected 1/3 arc-second surface for the DEMs was converted to an xyz file and used along with the 1 arc-second surface xyz file in the final gridding process (see Sec. 3.3.3).

10. 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. [Extracted from GMT web site; http://gmt.soest.hawaii.edu/]

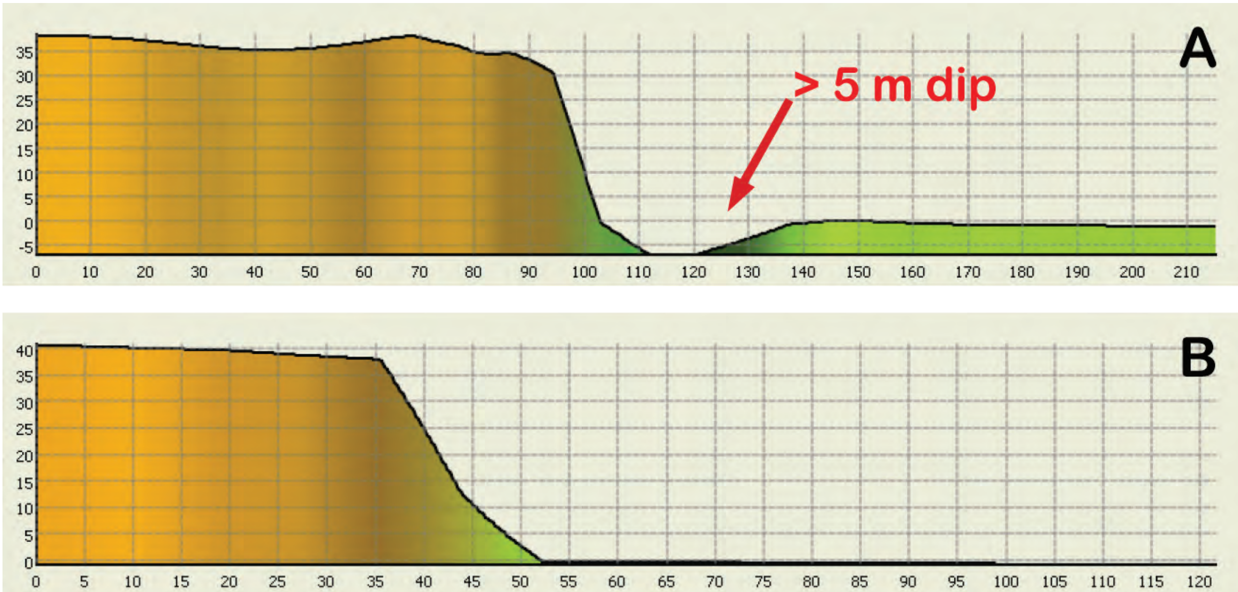

Figure 22. Profiles of DEM test surface at coast. A) DEM without additional 1/3 arc-second bathymetric surface data. B) DEM with additional 1/3 bathymetric surface data.

The resulting surface was compared with original soundings to ensure grid accuracy, converted to an xyz file for use in the final gridding process (see Table 8). The statistical analysis of the differences between the 1/3 arc-second bathymetric surface and the most recent NOS surveys showed that the majority of the NOS soundings are in good agreement with the bathymetric surface (Fig. 23). The exceptions where the difference reached a few meters are located close to the coastline. Figures 24 and 25 are histograms of data comparisons for the USACE data and the USGS South San Francisco Bay hydrographic data, respectively.

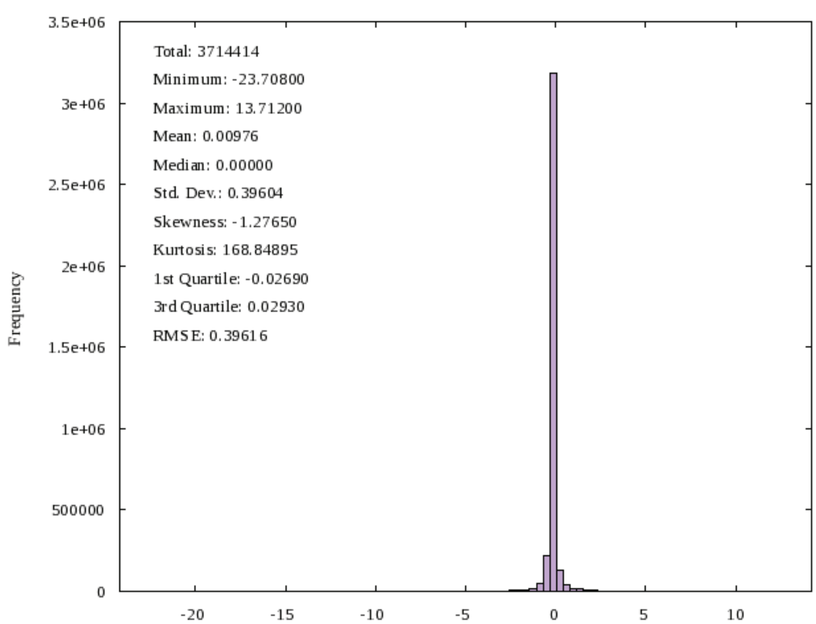

Figure 23. Histogram of the differences between the most recent NOS hydrographic survey data and the 1/3 bathymetric surface for San Francisco Bay.

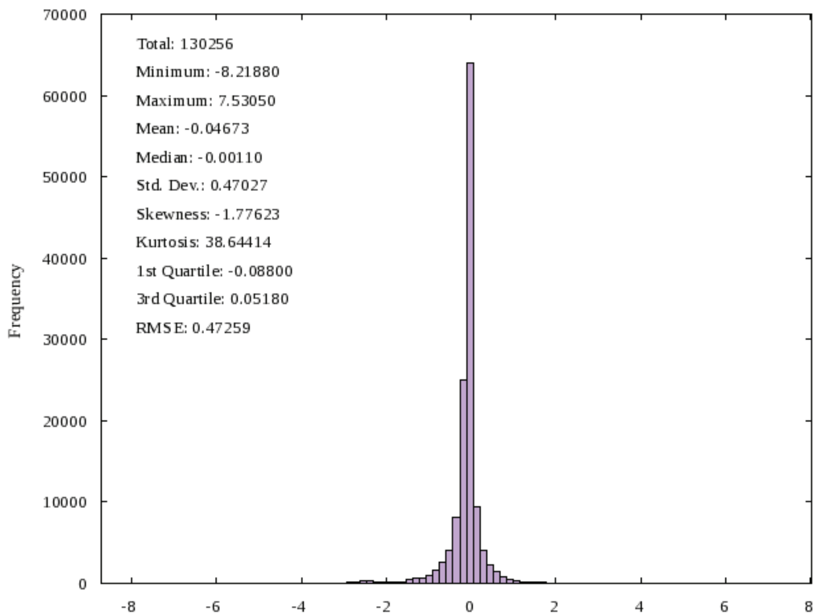

Figure 24. Histogram of the differences between the USACE hydrographic data and the 1/3 bathymetric surface for San Francisco Bay.

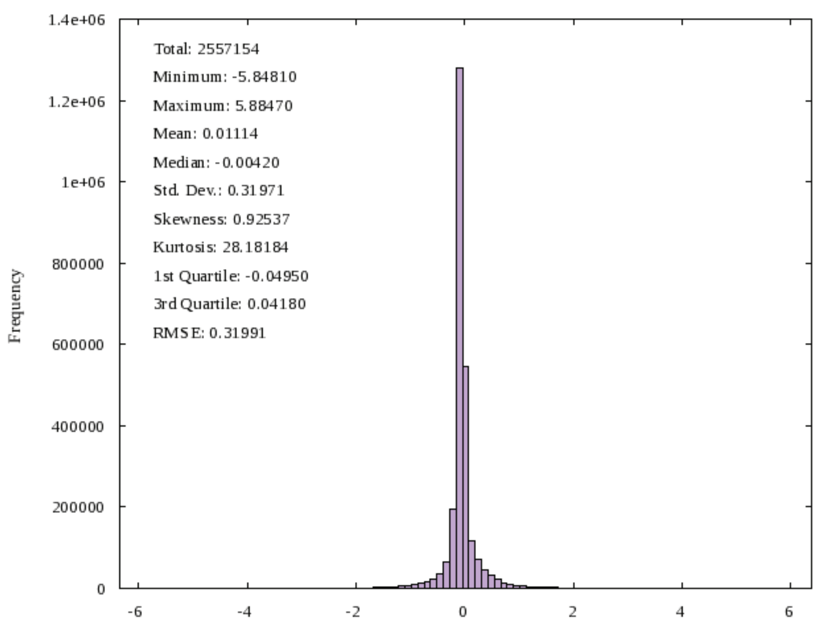

Figure 25. Histogram of the differences between the USGS South San Francisco Bay hydrographic survey and the 1/3 bathymetric surface for San Francisco Bay.

3.3.3 Building the 1 arc-second and 1/3 arc-second NAVD 88 DEMs

MB-System was used to create 1 arc-second and 1/3 arc-second DEMs of Central California and San Francisco Bay. The *MB-System* tool "mbgrid" applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the "mbgrid" gridding algorithm, as relative gridding weights, is listed in Table 11. Greatest weight was given to the high-resolution USGS lidar and CSUMB datasets. Least weight was given to the low resolution NED 1/3 DEM, NOS hydrographic surveys, deep water NGDC multibeam, and pre-surfaced bathymetric grids.

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

Dataset	*Relative Gridding Weight*
USGS NED 1/9 DEM	100
USGS Crystal Springs Reservoir System lidar	100
USGS Tomales Bay multibeam	100
CSUMB multibeam	100
CA DWR Sacramento-San Joaquin Delta lidar	10
FEMA lidar	10
NGDC digitized topographic features	10
GEON lidar	10
NCALM lidar	10
USGS South San Francisco Bay hydrographic survey	10
OCS ENC soundings	10
USACE hydrographic surveys	10
Combined coastline	10
USGS NED 1/3 DEM	1
NOS hydrographic surveys	1
Bathymetric 'pre-surfaced' data	1
NGDC multibeam data	1

3.3.4 Developing the Mean High Water DEMs

The MHW DEMs were created by adding "NAVD 88 to MHW" conversion grids to the NAVD 88 DEMs.

1) Developing the conversion grids

Using extents slightly larger (~ 5 percent) than the DEMs, an initial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The *GMT* tool "surface" applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-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*. Null values were removed and a converted xyz file was created by clipping the data to the combined coastline using *FME*. The converted xyz file was then interpolated with the *GMT* tool "surface" to create the 1 arc-second "NAVD 88 to MHW" conversion grid with the extents of the Central California NAVD 88 DEM and a 1/3 arc-second conversion grid with the extents of the San Francisco Bay NAVD 88 DEM.

2) Assessing accuracy of conversion grids

The "NAVD 88 to MHW" conversion grids were assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLLW to NAVD 88 using *VDatum*. Shapefiles of the resultant xyz files were created and null values removed using *FME*. The shapefiles were then merged to create a single shapefile of all NOS surveys with a vertical datum of NAVD 88. A second shapefile of NOS data was created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 shapefiles were computed after performing a spatial join in *ArcGIS*.

To verify the conversion grid methodology, the difference shapefile created using *ArcGIS* was converted to xyz format using *FME*. The CrossCheck module in *Fledermaus* was used to evaluate the performance of the 1 and 1/3 arc-second conversion grids by comparing the "NAVD 88 to MHW" grids to the difference xyz files. The *Fledermaus* results indicated agreement to approximately +/- 0.0002 meters. The *Fledermaus* results were then converted to shapefile format using *FME* to visualize the comparison and to produce a histogram of the variations in *ArcGIS*. The same methodology was used to check the 1/3 arc-second "NAVD 88 to MHW" conversion grid against a USACE harbor survey with similar results.

Errors in the vertical datum conversion method will reside for the most part in the "NAVD 88 to MHW" conversion grids, most topographic data are already in NAVD 88. Errors in the source datasets will require rebuilding just the NAVD 88 DEMs.

3) Creating the MHW DEMs

Once the NAVD 88 DEMs were complete and assessed for errors, the conversion grids were added using *ArcCatalog*. The resulting MHW DEMs were reviewed and assessed using RNCs, USGS topographic maps, and ESRI *World 2D* imagery. Problems encountered were determined to reside in source datasets, which were corrected before building new NAVD 88 DEMs.

3.4 Quality Assessment of the DEMs

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Central California and San Francisco Bay DEMs are dependent upon DEM cell size and the datasets used to determine corresponding DEM cell values. Topographic features inland have an estimated horizontal accuracy of less than 10 meters, based on the documented accuracy of the dataset. Bathymetric features in areas covered by early 20th century NOS hydrographic soundings—along the margins of the DEM—are resolved only to within a few tens of meters in shallow water, and hundreds of meters in deep-water areas; their positional accuracy is limited by the sparseness of soundings, and potentially large positional accuracy of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys. More recent NOS surveys, CSUMB multibeam, USGS multibeam, and USACE bathymetric data have accuracy of less than 10 meters.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the DEMs are also highly dependent upon the source datasets contributing to grid cell values. Topographic datasets have vertical accuracies of less than 1 meter, derived from USGS, FEMA, CA DWR, GEON, and NCALM lidar data, and the NED topographic data, estimated vertical accuracy of 10 meters. Bathymetric values are derived from a wide range of input data, consisting of single and multibeam sounding measurements from the early 20th centuries to recent: modern NOS standards are 0.3 meters in 0 to 20 meters of water, 1.0 meters in 20 to 100 meters of water, and 1% of the water depth in 100 meters of water. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water to about 5% of water depth.

3.4.3 Slope maps, 3-D perspectives and data contribution plot

ESRI *ArcCatalog* was used to generate slope grids from the 1 arc-second Central California and 1/3 arc-second San Francisco Bay DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Figs. 26 and 27). The DEMs were transformed to NAD 83 UTM Zone 10 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Dark areas indicate steeper slopes while lighter areas indicate low slope.

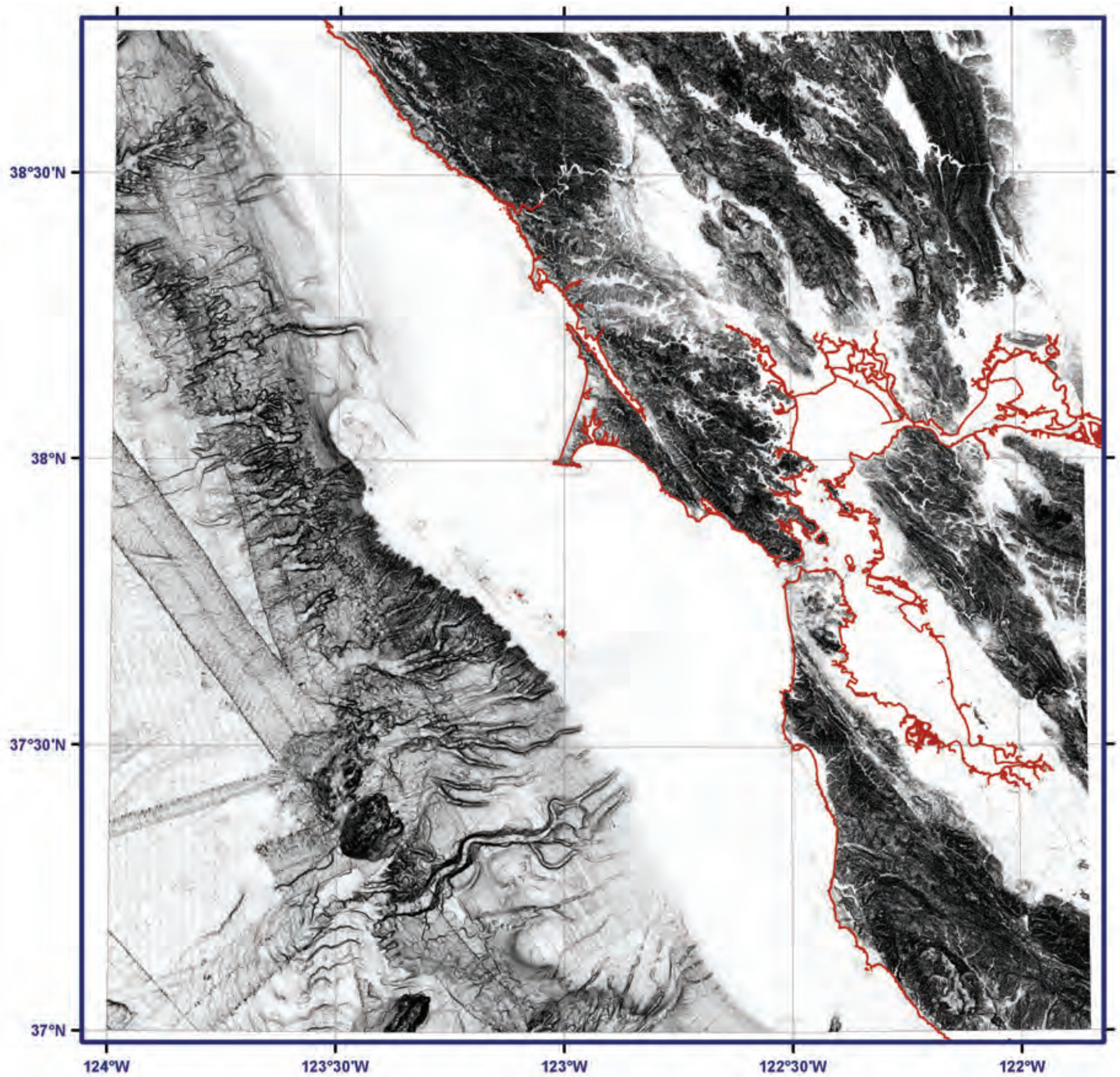

Figure 26. Slope map of the Central California 1 arc-second NAVD 88 DEM.

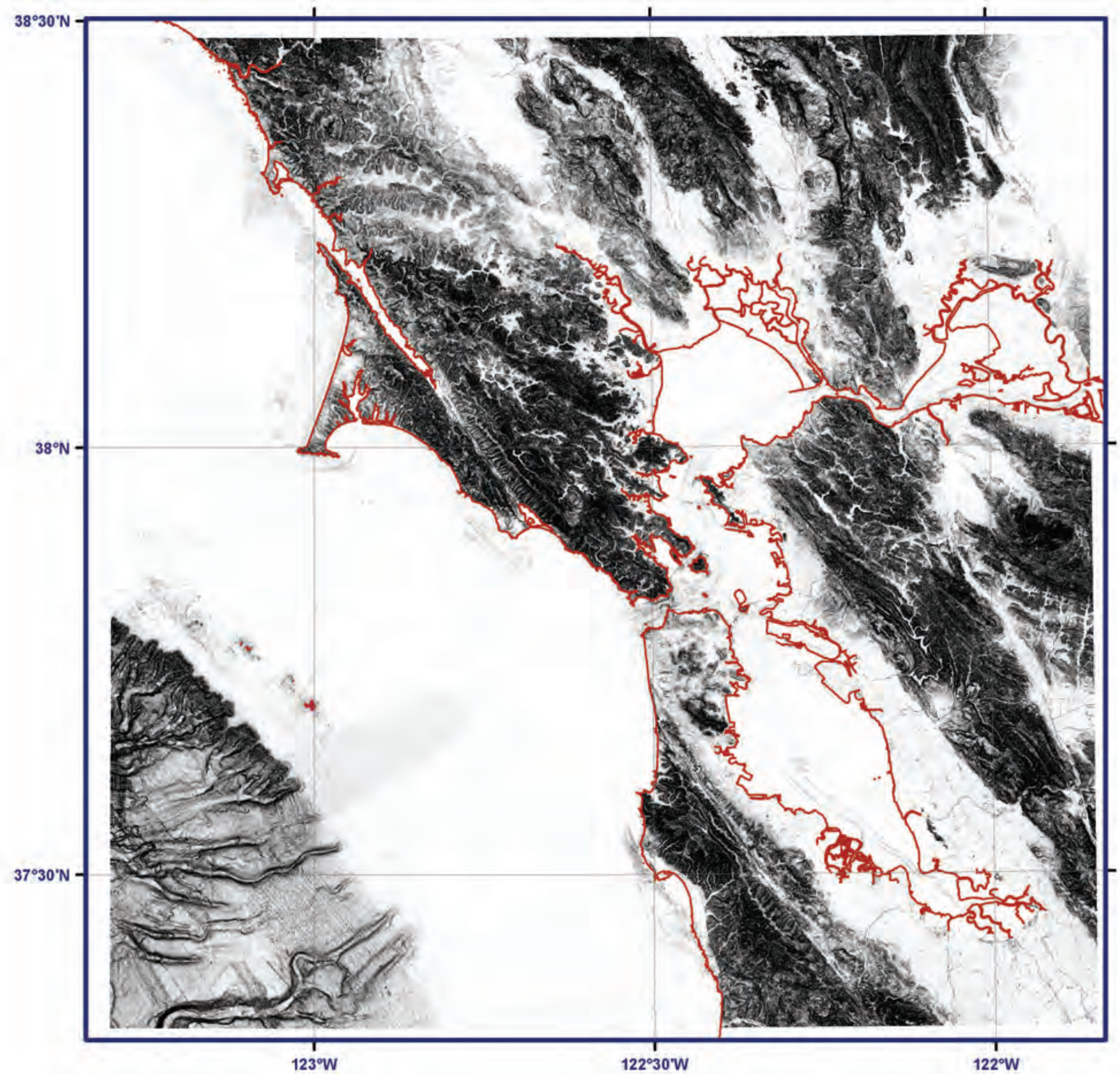

Figure 27. Slope map of the San Francisco Bay 1/3 arc-second NAVD 88 DEM.

High resolution perspective images were generated using *GDAL* and *POV-Ray,* providing three-dimensional viewing of the DEMs (Figs. 28 and 29). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEMs.

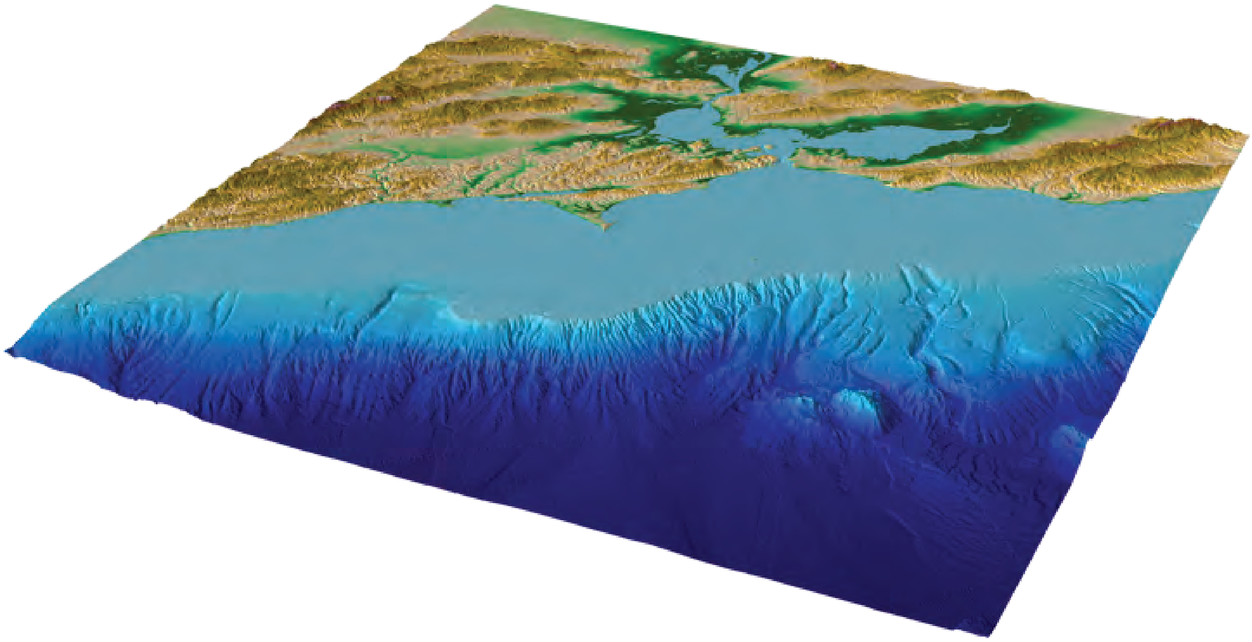

Figure 28. Perspective image of the Central California 1 arc-second NAVD 88 DEM. View is from the southwest, vertical exageration is 2 times.

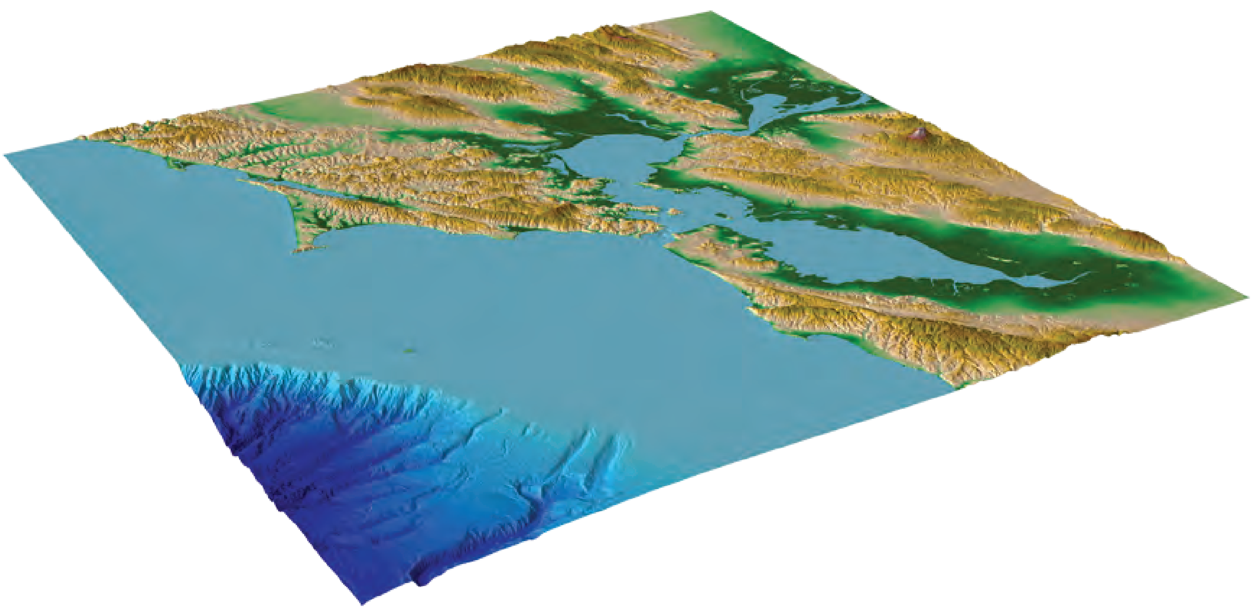

Figure 29. Perspective image of the San Francisco Bay 1/3 arc-second NAVD 88 DEM. View is from the southwest, vertical exageration is 2 times.

The data contribution plot in Figure 30 depicts DEM cells constrained by source data and cells with elevation values derived from interpolation.

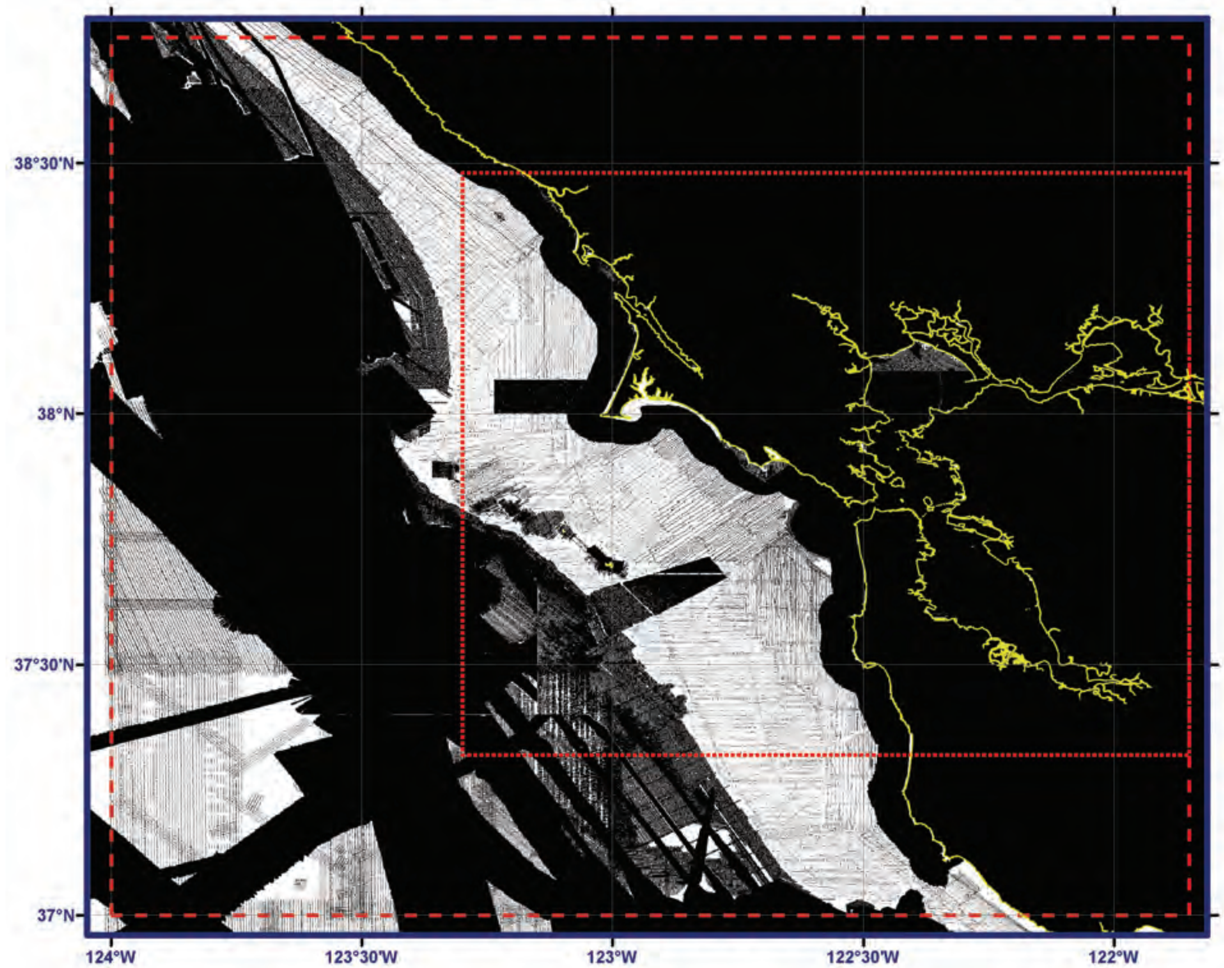

Figure 30. Data contribution plot of the Central California 1 arc-second NAVD 88 DEM. Black depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. DEM boundaries in red, combined coastline in yellow.

3.4.4 NAVD 88 DEM comparison with source data files

To ensure grid accuracy, the 1 arc-second Central California and the 1/3 arc-second San Francisco Bay DEMs were compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas. Entire bathymetric datasets were used for comparing the deep-water NOS B surveys, the near-shore CSUMB surveys, and USGS Tomales Bay survey to the DEMs. Large differences between the NOS B survey data and the Central California NAVD 88 DEM occur in steep terrain and where the sparse NOS B survey data abuts higher resolution multibeam data (Fig. 31).

A random sample of data files were used for comparing the high-resolution lidar topographic files to the DEMs. Figures 31 thru 40 show histograms of the differences between the DEMs and the data. The largest differences between the GEON lidar and the Central California NAVD 88 DEM were located in small steep canyons where the dataset overlaps other high-resolution lidar and along the coast at the data boundaries (Fig. 35). The largest differences between the NED 1/3 DEM and the Central California NAVD 88 DEM were located the dataset overlaps high-resolution lidar (Fig. 36). The largest differences between the NCALM lidar and the Central California NAVD 88 DEM were located on steep terrain and coastal cliffs (Fig. 37). The largest differences between the NCALM lidar and the San Francisco Bay NAVD 88 DEM were located in small steep canyons and along the coast (Fig. 38).

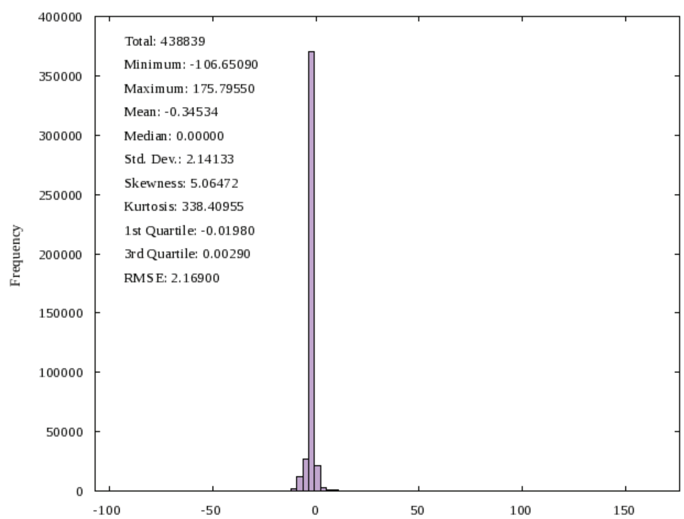

Figure 31. Histogram of the differences between the NOS B hydrographic surveys compared to the Central California NAVD 88 DEM.

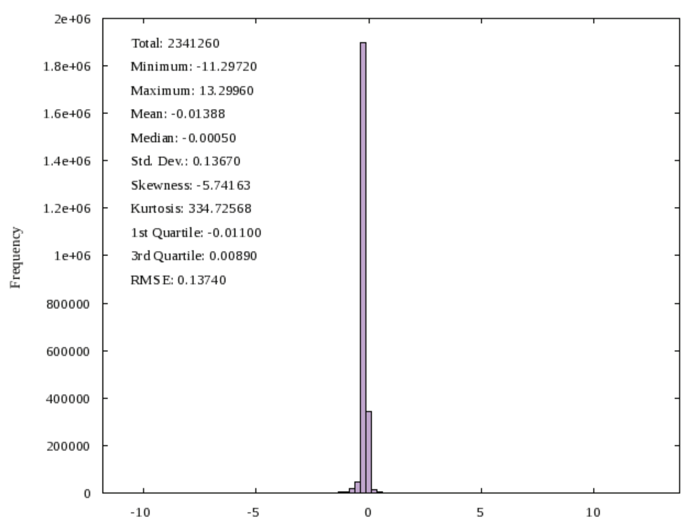

Figure 32. Histogram of the differences between the CSUMB bathymetric data compared to the Central Califormia NAVD 88 DEM.

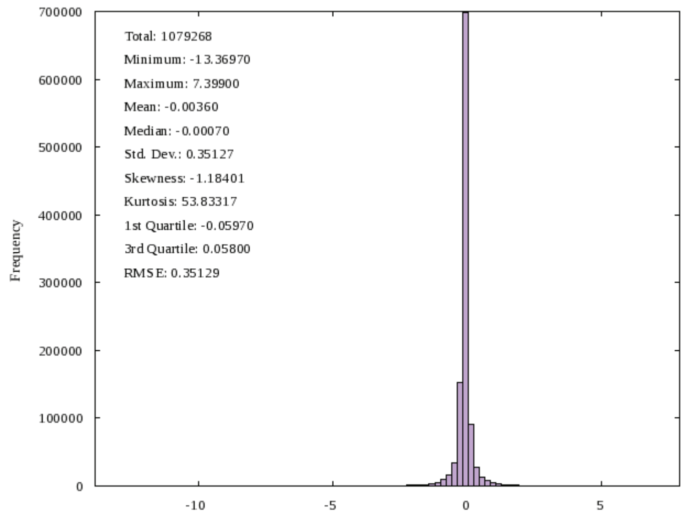

Figure 33. Histogram of the differences between the USGS Tomales Bay bathymetric data compared to the Central California NAVD 88 DEM.

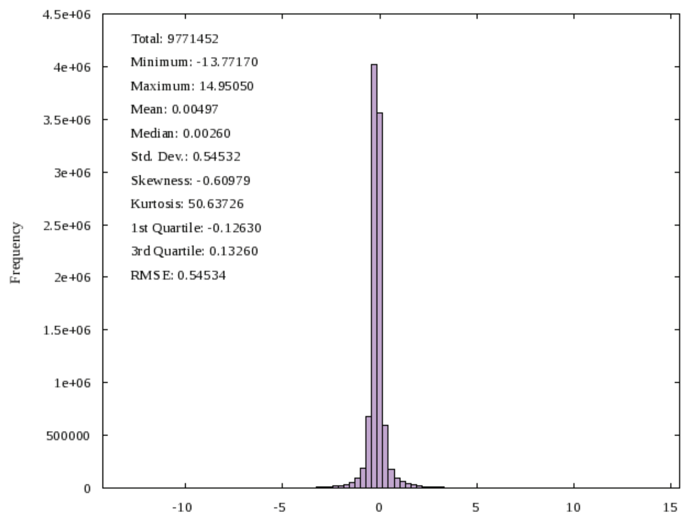

Figure 34. Histogram of the differences between a random selction of the FEMA topographic lidar data compared to the Central California NAVD 88 DEM.

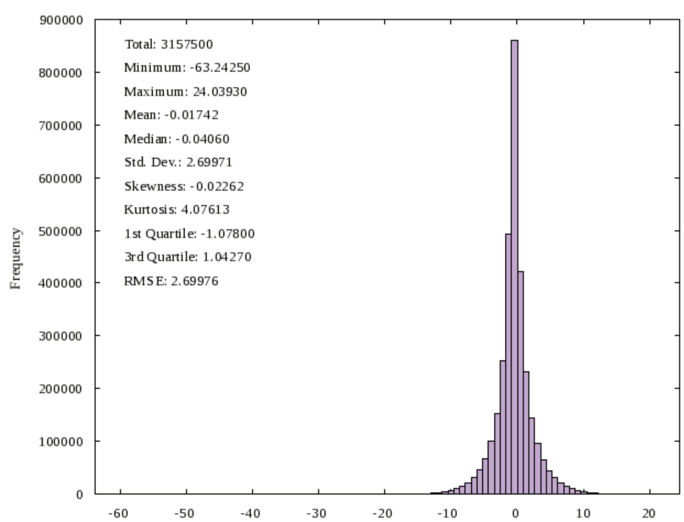

Figure 35. Histogram of the differences between a random selection of the GEON topographic lidar data and the Central California NAVD 88 DEM.

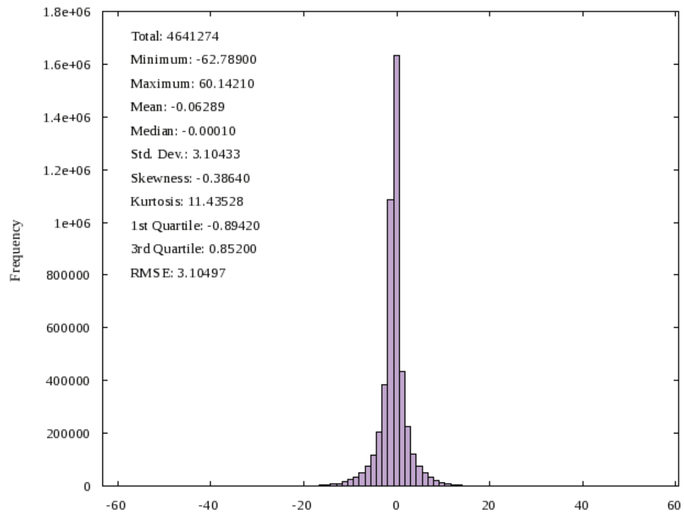

Figure 36. Histogram of the differences between a random selection of the NED 1/3 topographic DEM data and the Central California NAVD 88 DEM.

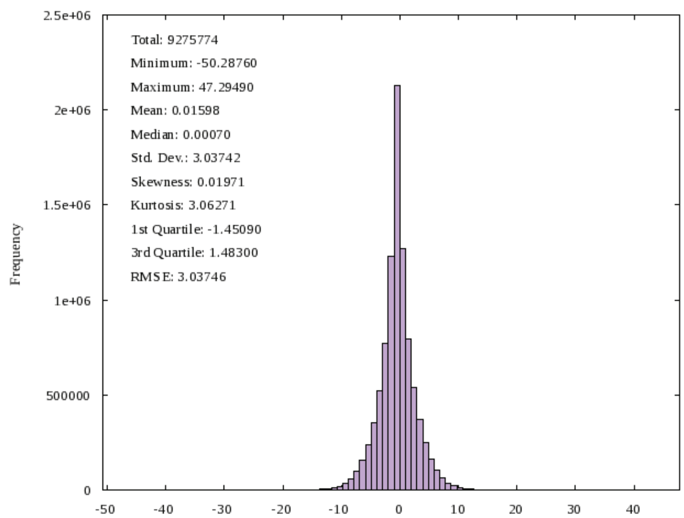

Figure 37. Histogram of the differences between a random selection of the NCALM topographic lidar data and the Central California NAVD 88 DEM.

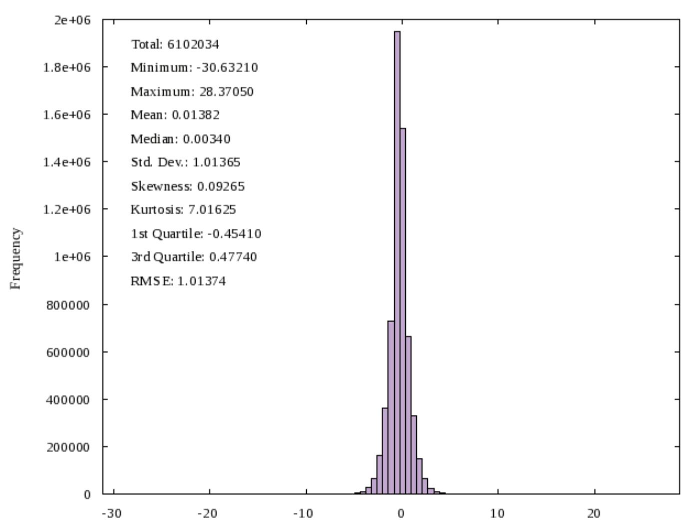

Figure 38. Histogram of the differences between a random selection of the NCALM topographic lidar data and the San Francisco Bay NAVD 88 DEM.

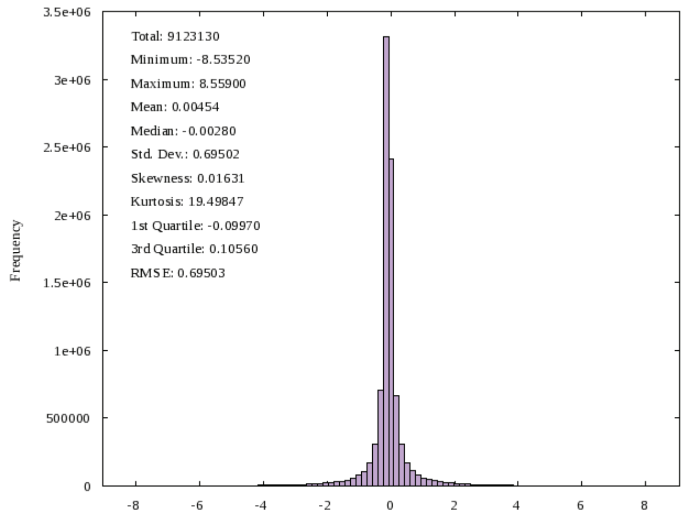

Figure 39. Histogram of the differences between a random selection of the CA DWR Sacramento - San Joaquin River Delta lidar data and the Central California NAVD 88 DEM.

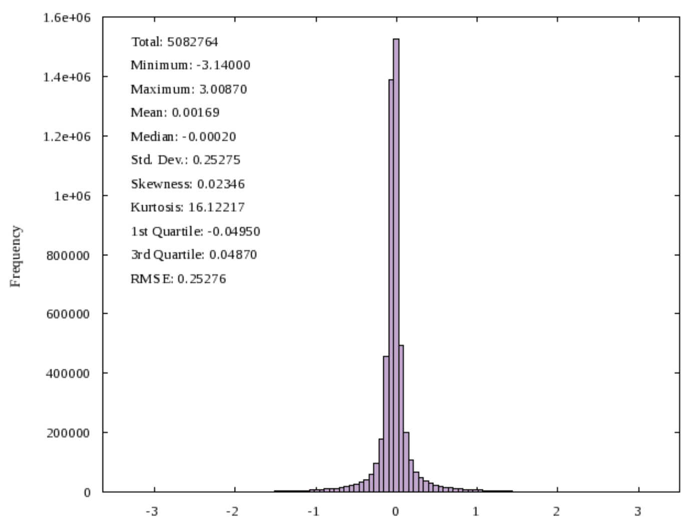

Figure 40. Histogram of the differences between a random selection of the CA DWR Sacramento - San Joaquin River Delta lidar data and the San Francisco Bay NAVD 88 DEM.

3.4.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of 6005 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (see Fig. 41 for monument locations). Shapefile attributes give positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Elevations were compared to the Central California NAVD 88 DEM (Fig. 42). Differences between the DEM and the monument elevations range from -305.06 to 550.88 meters, over 80% of which are within ± 5 meters. Large differences in elevations occurred where monuments are located on steep terrain, on top of a tower, lost due to urban development, or have not been recovered.

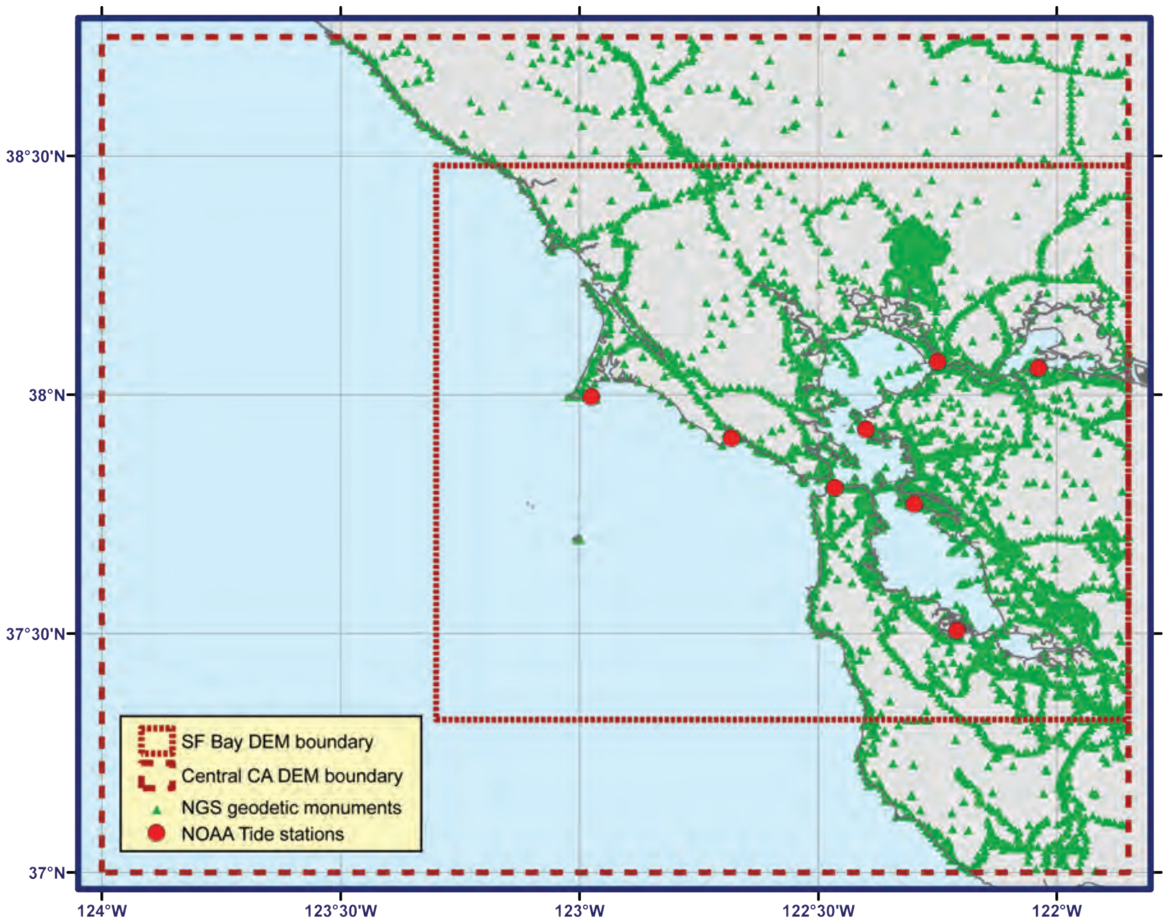

Figure 41. Locations of NGS geodetic monuments and NOAA tide stations in the Central California and San Francisco Bay DEM region.

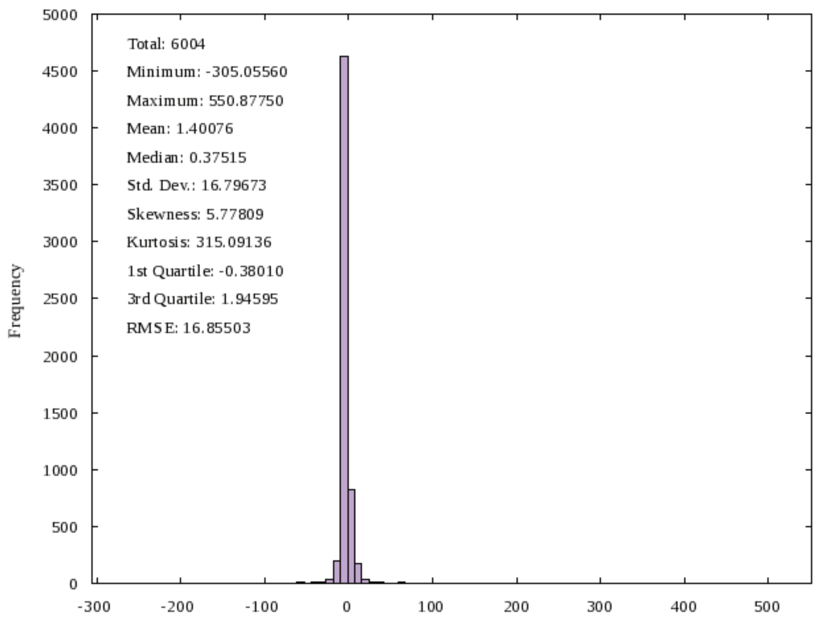

Figure 42. Histogram of the differences between the NGS geodetic monuments and the Central California 1 arc-second NAVD 88 DEM.

4. Summary and Conclusions

Four integrated bathymetric–topographic DEMs of Central California and San Francisco Bay with cell size of 1 arc-second and 1/3 arc-second, respectively, vertically referenced to NAVD 88 and MHW were developed for the PMEL NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state and local agencies, and academic institutions were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using *ArcGIS*, *Fledermaus*, *FME*, *GDAL*, *GMT*, *Gnuplot*, *GEODAS*, *Quick Terrain Modeler*, *MB-System*, and *VDatum* software.

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

- Conduct bathymetric surveys in the south-western quarter of the Central California DEM area.
- Conduct coastal bathymetric–topographic lidar surveys within San Francisco Bay.
- Conduct higher resolution bathymetric data for the outer-shelf region.

5. Acknowledgments

The creation of the DEMs were funded by NOAA Center for Tsunami Research at PMEL. The authors thank Nazila Merati and Vasily Titov (PMEL), David P. Finlayson (USGS), Joel Dudas (CA DWR), Robert Yang and Quenn Finch (USACE), Scott McAfee and Kathleen Schaefer (FEMA), and Gary Nelson and Brooke McMahon (NOS Pacific Hydrographic Branch).

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7. Data Processing Software

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

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

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

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

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

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

GMT v. 4.3.4 – Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/.

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

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

Persistence of Vision Pty. Ltd (POV Ray) v. 3.6 – Persistence of VisionTM Raytracer. Persistence of Vision Pty., Williamstown, Victoria, Australia, http://www.povray.org/

Quick Terrain Modeler v. 7.0.0 – 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 v. 2.2.7 – California - San Francisco Bay Vicinity, v. 01 and Monterey Bay to Morro Bay, 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/