NOAA Technical Memorandum NESDIS NGDC-39

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

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Also available from the National Technical Information Service (NTIS)
(http://www.ntis.gov)

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Digital Elevation Model of Arena Cove, California: Procedures, Data Sources and Analysis

1. Introduction

In November 2009, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed an integrated bathymetric–topographic digital elevation model (DEM) of Arena Cove, 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 Short-term Inundation Forecasting (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 Arena Cove DEM.

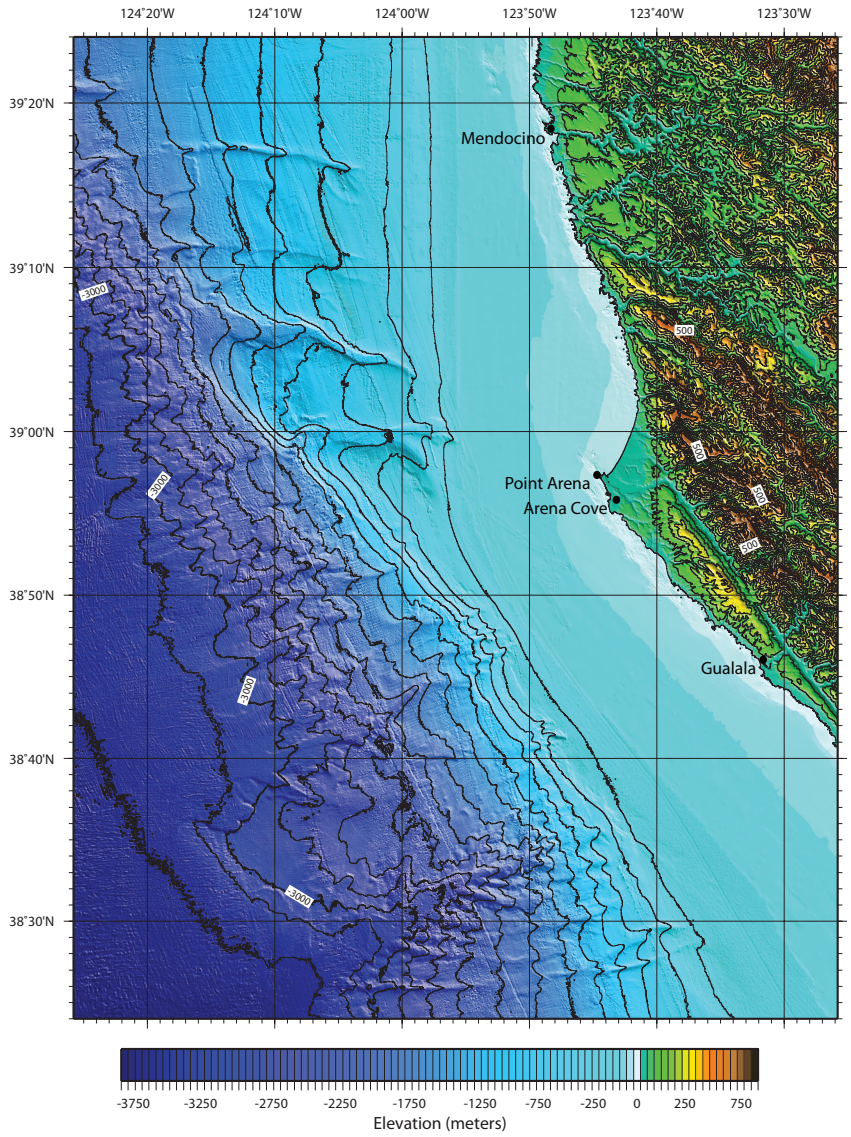

Figure 1. *Shaded-relief image of the Arena Cove DEM. Contour interval is 200 meters for bathymetry and 100 meters for topography.*

1. The Arena Cove 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. At the latitude of Arena Cove, California, (38°54.8′ N, 123°42.5′ W) 1/3 arc-second of latitude is equivalent to 10.28 meters; 1/3 arc-second of longitude equals 8.03 meters.

2. Study Area

The Arena Cove DEM covers a portion of coastal northern California in Mendocino County, from Mendocino to Gualala (Fig. 1). Arena Cove is a small, sheltered bay found along the western coast of the city of Point Arena, which has a population of approximately 500. The Point Arena lighthouse (Fig. 2) is found on the tip of a peninsula extending across the northern portion of Arena Cove, and is located four miles from the city of Point Arena.

The San Andreas fault extends into the Pacific Ocean north of Point Arena, making the area one of considerable geologic importance. The coastline in the area is very rocky, and is characterized by tall cliffs, small coves, and sandy beaches.

Figure 2. *Aerial photograph of the Point Arena lighthouse.*
(Photo credit: Scott Simpson; http://www.westofone.com)

3. Methodology

The Arena Cove 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 American Datum of 1983 (NAD 83) geographic[2] and mean high water (MHW), for modeling of maximum flooding. Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensured 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 1: PMEL specifications for the Arena Cove DEM.

Grid Area	Arena Cove, California
Coverage Area	123.43º to 124.43º W; 38.40º to 39.40º 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 Arc ASCII grid

3.1 Data Sources and Processing

Coastline, bathymetric, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal and state agencies: NOAA's Office of Coast Survey (OCS), Coastal Services Center (CSC) and NGDC; the U.S. Geological Survey (USGS); California State University at Monterey Bay (CSUMB); the California Department of Fish and Game (CDFG); and the California Spatial Information Library (CASIL). Safe Software's *Feature Manipulation Engine*[3] *(FME)* data translation tool package was used to horizontally shift datasets to NAD 83 geographic. Some topographic data were horizontally shifted using *PROJ.4* software, an open-source software application developed by Gerald Evenden of the USGS. The datasets were then displayed with ESRI's *ArcGIS,* ESRI's online *World 2D* imagery, and Applied Imagery's *Quick Terrain Modeler* software (*QT Modeler*) to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using NOAA's *Vertical Datum Transformation* (*VDatum*) software, *FME*, and *ArcGIS*, based upon data from the Arena Cove NOAA tide station (see Sec. 3.2.1).

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. *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 geographic to NAD 83 geographic. NADCON is the U.S. Federal Standard for NAD 27 geographic to NAD 83 geographic datum transformations.

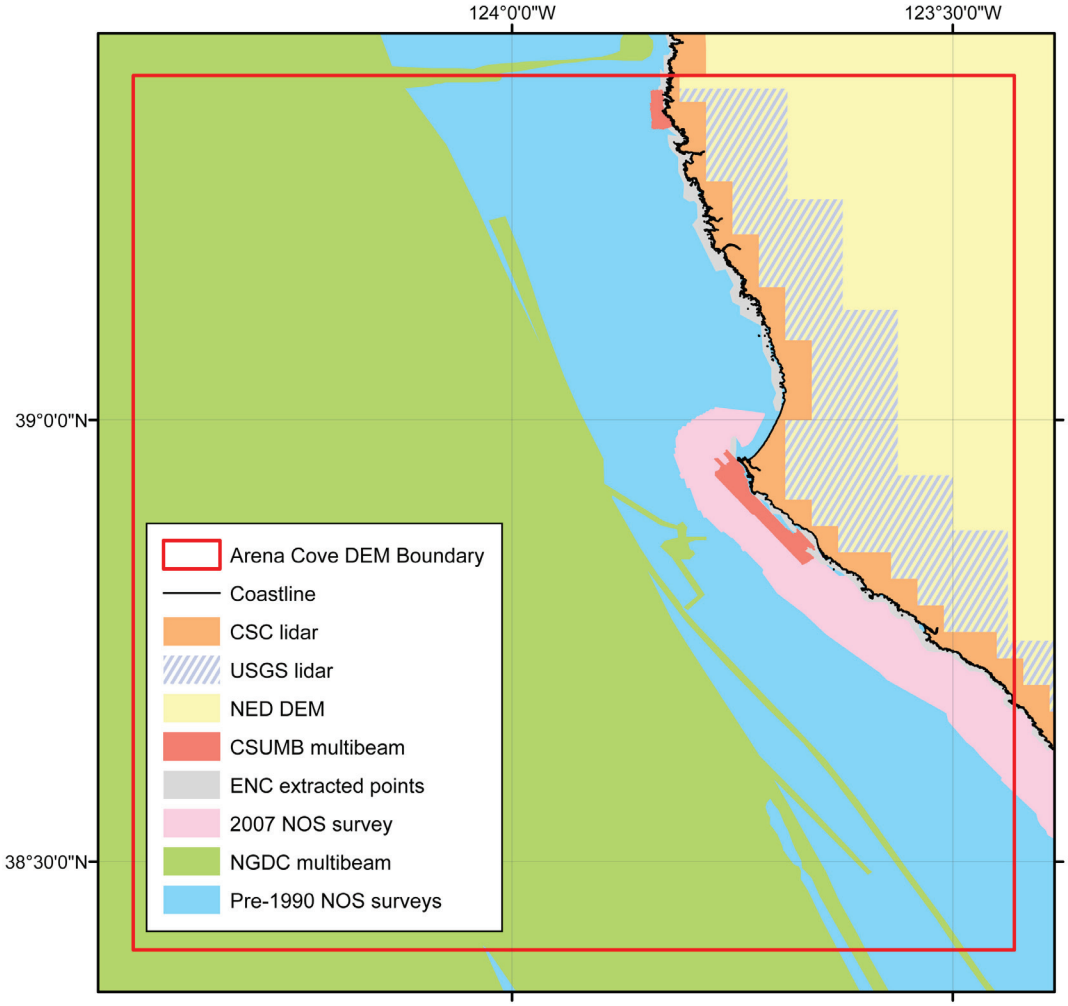

Figure 3. *Source and coverage of datasets used in compiling the Arena Cove DEM.*

3.1.1 Coastline

Coastline datasets for the Arena Cove region were obtained from the California Department of Fish and Game (CDFG), NOAA's OCS (http://www.nauticalcharts.noaa.gov), and the California Spatial Information Library (CASIL) (http://www.atlas.ca.gov). The CDFG coastline was used in the development of the Arena Cove DEM (Table 2). NGDC evaluated but did not use coastline data obtained from OCS and CASIL, as the CDFG coastline was more detailed and more closely matched bathymetric and high-resolution topographic datasets (Fig. 4).

Table 2: Coastline dataset used in developing the Arena Cove DEM.

Source	*Year*	*Data Type*	*Spatial Resolution or Scale*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
CDFG	1994	Vector	1:24000	NAD 83 geographic	Mean high tide	http://www.dfg.ca.gov/biogeodata

1) California Department of Fish and Game Coastline

The CDFG coastline was downloaded from the CDFG web site. It was originally developed in 1994 by the California State Lands Commission. The coastline represents the mean high tide line and is a high-quality digitization of USGS 7.5-minute quadrangle maps. In 1994 the digital coastline was rebuilt by CDFG to reduce tolerances.

In order to define the current coastline, NGDC compared the CDFG coastline with high-resolution coastal lidar data, USGS topographic digital elevation models, National Ocean Service (NOS) hydrographic soundings, and ESRI's *World 2D* online imagery to manually adjust the location of the mean high tide line. The comparison also ensured that features such as piers, jetties, and rocks were accurately reflected along the coastline. The final edited coastline was converted to xyz data with 10 meter point spacing, using NGDC's *GEODAS* software, for use in building a pre-surfaced bathymetric grid (see Sec. 3.3.2) and the final DEM.

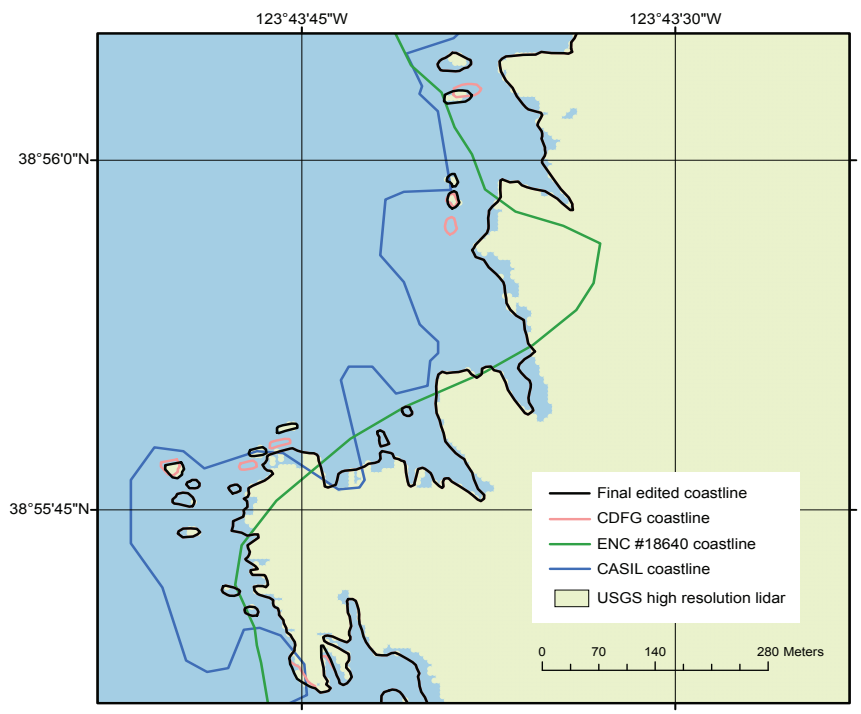

Figure 4. *Portion of available digital coastline datasets of the Arena Cove region. The CDFG coastline included the most detail and closely matched other datasets, such as the USGS high-resolution lidar dataset.*

3.1.2 Bathymetry

Bathymetric data used in the compilation of the Arena Cove DEM include 31 NOS hydrographic surveys, 28 multibeam swath sonar surveys from NGDC, two multibeam swath sonar surveys from CSUMB, and extracted points from OCS Electronic Navigational Charts (ENC's) (Table 3).

Table 3: Bathymetric datasets used in compiling the Arena Cove DEM.

Source	*Year*	*Data Type*	*Spatial Resolution or Scale*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1929 to 2007	NOS hydrographic survey soundings	Ranges from 1 meter to 2 kilometers (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 13, NAD 27 or NAD 83 geographic, WGS 84 UTM Zone 10, or undetermined	Mean lower low water (MLLW)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1993 to 2006	Multibeam swath sonar surveys	1 arc-second	WGS 84 geographic	Assumed mean sea level (MSL)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
CSUMB	1999	Multibeam swath sonar surveys	1 to 2 meters	WGS 84 UTM Zone 10 N (Meters)	MLLW	http://seafloor.csumb.edu/SFMLwebDATA.htm
OCS	2000 to 2005	Extracted points from ENC	Ranges from 1:40,000 to 1:207,840 (varies by chart)	WGS 84 geographic	MLLW	http://www.nauticalcharts.noaa.gov

1) NOS hydrographic survey data

A total of 31 digital NOS hydrographic surveys conducted between 1929 and 2007 were available for use in developing the Arena Cove DEM (Table 4, Fig. 5). The hydrographic survey data were downloaded from NGDC's NOS Hydrographic Survey Database using *GEODAS*[4]. In order to support data interpolation across grid edges, survey data were downloaded in an area 0.05 degrees larger than the Arena Cove DEM extent.

The data were originally vertically referenced to the mean lower low water (MLLW) datum. Most of the pre-1990 surveys were originally horizontally referenced to NAD 13 geographic, NAD 27 geographic, or NAD 83 geographic. The newer NOS surveys were horizontally referenced to WGS 84 UTM Zone 10 N. All NOS survey data were converted to NAD 83 geographic either during download or using *FME*, and to MHW (see Sec. 3.2.1) using *VDatum*.

The NOS survey data were then displayed in ESRI *ArcMap*. The data were reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to other bathymetric datasets, coastline datasets, and NOS Raster Nautical Charts (RNCs). Soundings that overlapped more recent and more accurate bathymetric surveys were removed. Data point spacing within the NOS surveys ranged from three meters to approximately two kilometers, and varied by collection date. In general, earlier surveys had greater point spacing than more recent surveys. Five earlier surveys were not used because more recent, higher resolution surveys existed at those locations (see Table 4).

4. NGDC's *GEODAS* 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 geographic and NAD 13 geographic to NAD 83 geographic. NADCON is the U.S. Federal Standard for NAD 27 geographic to NAD 83 geographic datum transformations.

Table 4: Digital NOS hydrographic surveys available in the Arena Cove region.

Name	*Year*	*Scale or Resolution of Survey*	*Original Horizontal Datum*
B00007	1985	50,000	NAD 1983 geographic
B00011	1985	50,000	NAD 1983 geographic
B00012	1985	50,000	NAD 1983 geographic
B00037	1985	50,000	NAD 1983 geographic
B00038	1985	50,000	NAD 1983 geographic
B00040	1985	50,000	NAD 1983 geographic
B00041	1985	50,000	NAD 1983 geographic
B00182	1989	50,000	NAD 1983 geographic
B00184	1989	50,000	NAD 1983 geographic
B00185	1989	50,000	NAD 1983 geographic
H04983	1929	20,000	NAD 1913 geographic
H04984	1929	20,000	NAD 1913 geographic
H04985	1929	20,000	NAD 1913 geographic
H04986	1929	20,000	NAD 1913 geographic
H04987	1929	40,000	NAD 1913 geographic
H04988	1929	40,000	NAD 1913 geographic
H04989	1929	40,000	NAD 1913 geographic
H04990	1929	40,000	NAD 1913 geographic
H04991*	1929	120,000	NAD 1913 geographic
H04992*	1929	120,000	NAD 1913 geographic
H04993*	1929	120,000	Undetermined
H05094	1930	10,000	NAD 1927 geographic
H05095	1930	10,000	NAD 1927 geographic
H05096*	1930	10,000	NAD 1927 geographic
H05171	1932	40,000	NAD 1927 geographic
H05921	1935	40,000	NAD 1927 geographic
H05944	1935	40,000	NAD 1927 geographic
H08567*	1960	160,000	NAD 1927 geographic
H11730	2007	4 meters	WGS 84 UTM Zone 10 N. (Meters)
H11731	2007	4 meters	WGS 84 UTM Zone 10 N. (Meters)
H11732	2007	4 meters	WGS 84 UTM Zone 10 N. (Meters)

*Surveys not used in the final DEM because they were superseded by newer surveys.

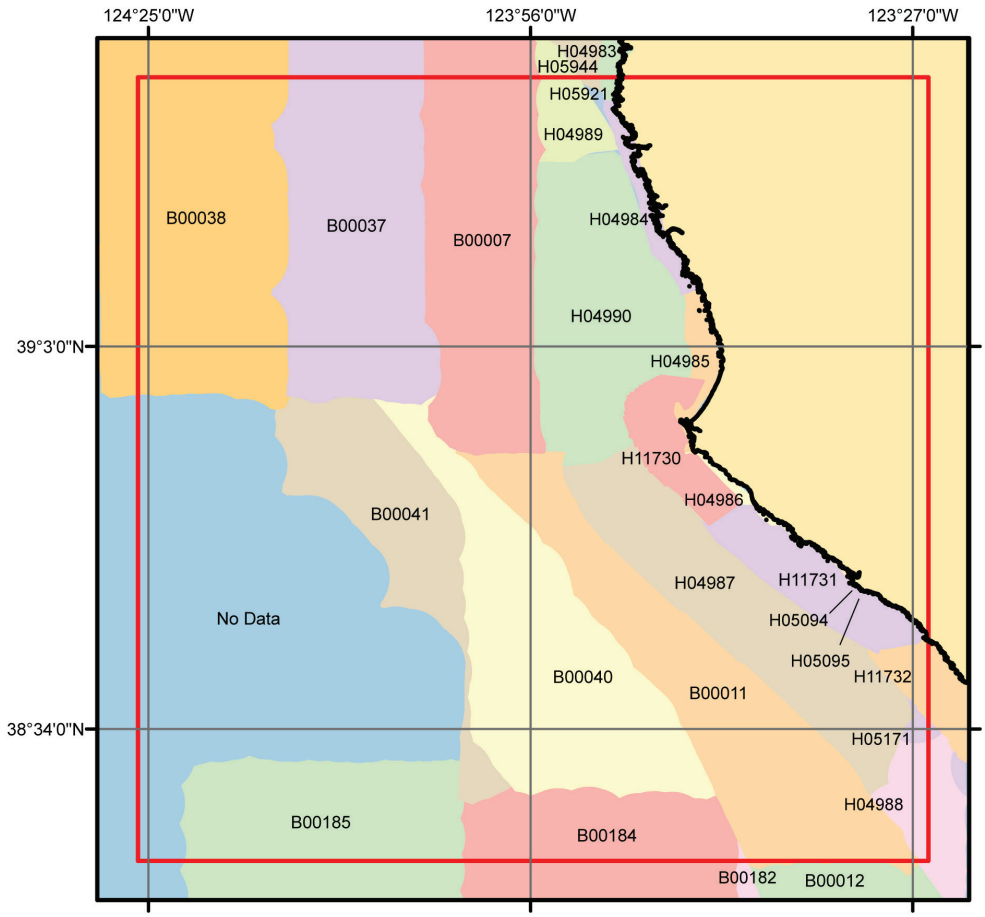

Figure 5. *Digital NOS hydrographic survey coverage in the Arena Cove region. DEM boundary in red.*

2) NGDC multibeam swath sonar surveys

A total of 28 multibeam swath sonar surveys were available for use in developing the Arena Cove DEM. The surveys were retrieved from the NGDC Multibeam Bathymetry Database (Table 5, Fig. 6). The NGDC Multibeam Bathymetry Database is comprised of original swath sonar data from surveys conducted mostly by the U.S. academic fleet. Most of the multibeam swath sonar surveys were transits rather than dedicated sea-floor surveys.

The data were gridded to 1 arc-second resolution using *MB-System*[5]. All multibeam surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum, which was assumed to be mean sea level (MSL). The data were converted to MHW using *VDatum* (see Sec. 3.2.1). Data errors were common in the multibeam surveys, due to noise along multibeam swath edges. In order to reduce the influence of these errors, the gridded data were manually edited in *QT Modeler* before being used in creating the gridded bathymetric surface (see Sec. 3.3.2) and the final DEM.

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

Table 5: Multibeam swath sonar surveys used in compiling the Arena Cove DEM.

Cruise ID	*Ship*	*Year*	*Institution*
AT07L14	Atlantis	2002	Woods Hole Oceanographic Institution (WHOI)
AT11L33	Atlantis	2005	WHOI
AT15L07	Atlantis	2006	WHOI
AT15L11	Atlantis	2006	WHOI
AVON08MV	Melville	1999	University of California, Scripps Institution of Oceanography (SIO)
AVON09MV	Melville	1999	SIO
AVON10MV	Melville	1999	SIO
AVON11MV	Melville	1999	SIO
AVON12MV	Melville	1999	SIO
CNTL04RR	Roger Revelle	2003	SIO
DRFT01RR	Roger Revelle	2001	SIO
EW0209	Maurice Ewing	2002	Columbia University, Lamont-Doherty Earth Observatory (LDEO)
EW9407	Maurice Ewing	1994	LDEO
EW9414	Maurice Ewing	1994	LDEO
EW9504	Maurice Ewing	1995	LDEO
EW9505	Maurice Ewing	1995	LDEO
FISK01LC	Laney Chouest	1995	US Navy
HEALY02	USCGC Healy	2001	WHOI
HLY0101	USCGC Healy	2001	LDEO
HLY03TA	USCGC Healy	2003	LDEO
LPRS02RR	Roger Revelle	2002	SIO
LWAD99MV	Melville	1999	SIO
NECR01RR	Roger Revelle	2000	SIO
Pioneer	Ocean Alert	1998	MBARI
REM-01MV	Melville	1993	SIO
SO108	Sonne	1996	University of Kiel, Germany, GEOMAR Forshungszentrum
Tran2sou	Ocean Alert	1998	MBARI
WEST15MV	Melville	1995	SIO

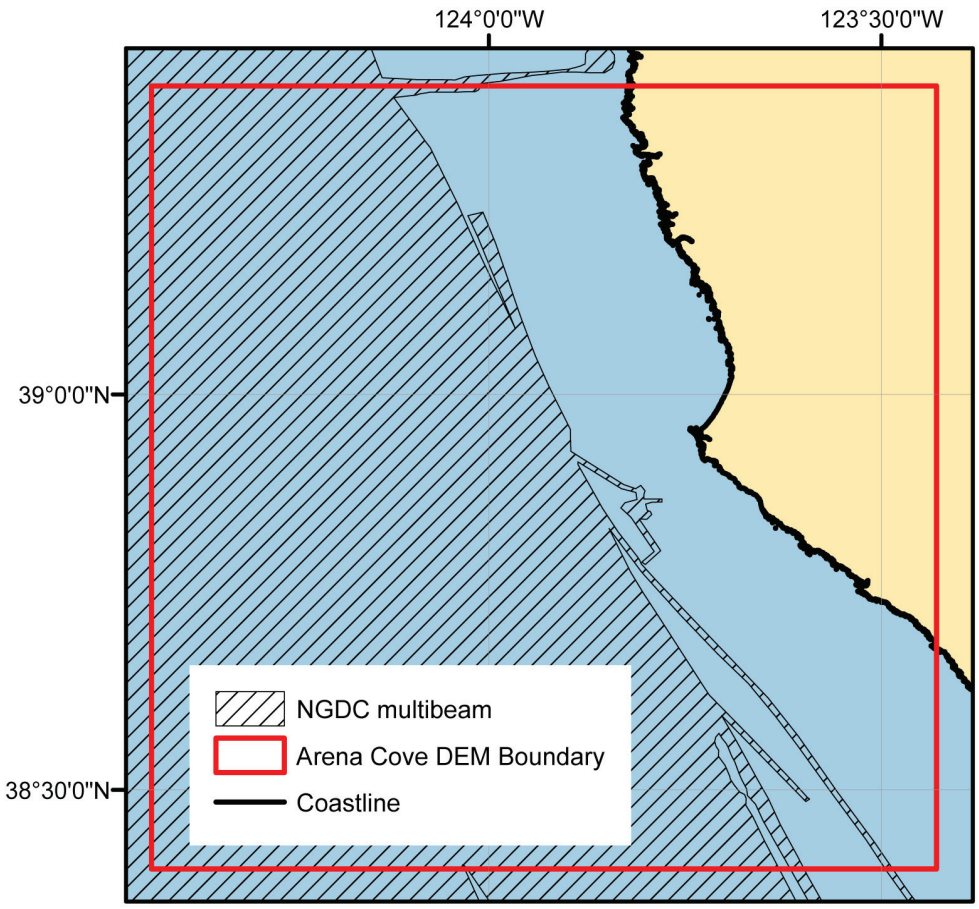

Figure 6. *Spatial coverage of multibeam swath sonar surveys from the NGDC Multibeam Bathymetry Database.*

3) CSUMB multibeam swath sonar surveys

Two near-shore multibeam swath sonar surveys were downloaded from California State University at Monterey Bay's web site as gridded data (Table 6; Fig. 7). This data were acquired, processed, archived, and distributed by CSUMB. The surveys were collected in 2001 and 2002, and were horizontally referenced to WGS 84 UTM Zone 10N and vertically referenced to MLLW. The files were converted to NAD 83 geographic using *FME* and to MHW using *VDatum*. The surveys were reviewed using *QT Modeler* and *ArcMap*.

Table 6: CSUMB Seafloor Mapping Lab multibeam swath sonar surveys used in compiling the Arena Cove DEM.

Survey ID	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Type*
Point Arena (ptarn)	2002	MLLW	WGS 84 UTM Zone 10N	2 meter grid
Point Cabrillo (ptcab)	2001	MLLW	WGS 84 UTM Zone 10N	1 meter grid

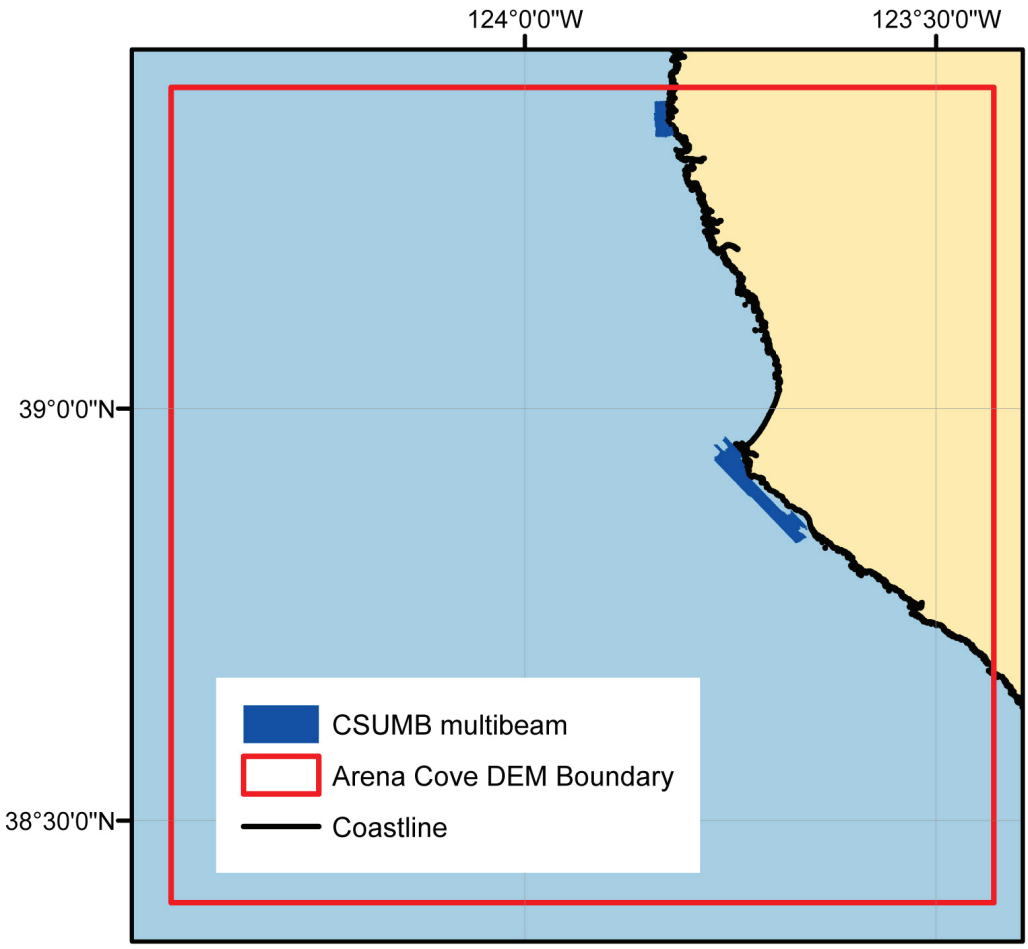

Figure 7. *Spatial coverage of the CSUMB multibeam swath sonar surveys used to compile the Arena Cove DEM.*

4) OCS Electronic Navigational Charts

Three ENCs were available from OCS for the Arena Cove area (Table 7; Fig. 8). The ENCs were downloaded from the OCS web site, and were referenced to NAD 83 geographic and MLLW. Near-shore point data, representing underwater rock hazards, were extracted from the ENCs. The data were reviewed and compared to the coastline and to the corresponding RNCs. In order to ensure that the rocks were represented in the DEM, elevation values (-1 in shallow water and -2 in slightly deeper water) were assigned to the extracted points in *ArcGIS.*

Table 7: ENCs available in the Arena Cove region.

Chart	*Title*	*Edition*	*Edition Date*	*Format*	*Scale*
18626	Elk to Fort Bragg	15	2000	ENC and RNC	1:40,000
18620	Point Arena to Trinidad Head	23	2002	ENC and RNC	1:200,000
18640	San Francisco to Point Arena	25	2005	ENC and RNC	1:207,840

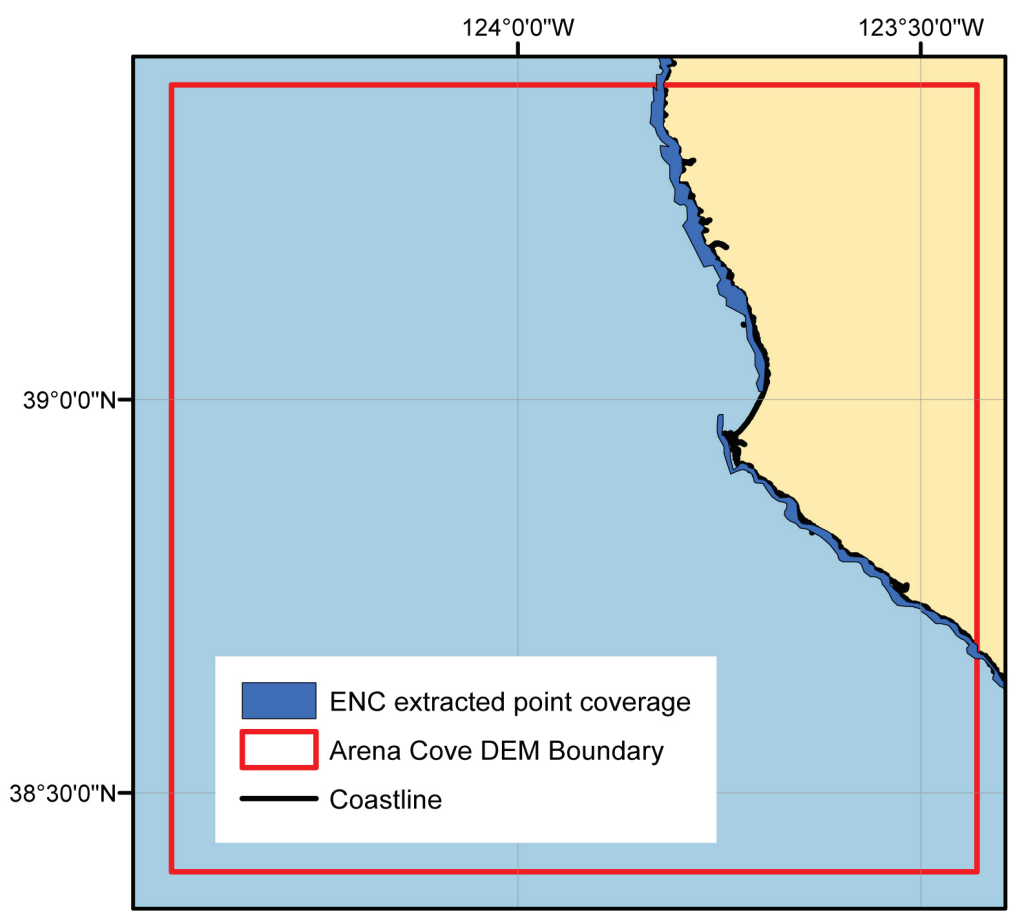

Figure 8. *Spatial coverage of points extracted from ENCs used in compiling the Arena Cove DEM.*

3.1.3 Topography

Three topographic datasets were used to build the Arena Cove DEM (Table 8; Fig. 9). The USGS National Elevation Dataset (NED) 1/3 arc-second DEM provided full coverage for the Arena Cove region. The 2002 CSC Airborne Lidar Assessment of Coastal Erosion (ALACE) project lidar dataset and the 2003 USGS Center for Lidar Information Coordination and Knowledge (CLICK) lidar dataset provided coverage along most of the Pacific coastline. NGDC evaluated but did not use the lower resolution Shuttle Radar Topography Mission (SRTM) Elevation 1 arc-second DEM available from USGS (http://seamless.usgs.gov).

Table 8: Topographic datasets used in compiling the Arena Cove DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
USGS	1999-2000	NED DEM	1/3 arc-second	NAD 83 geographic	NAVD 88 (meters)	http://ned.usgs.gov
CSC	2002	Non-bare-earth lidar	~1 meter	NAD 83 geographic	NAVD 88 (meters)	http://maps.csc.noaa.gov/TCM
USGS CLICK	2003	Non-bare-earth lidar	~0.5 meters	NAD 83 State Plane CA Zone II (feet)	NAVD 88 (feet)	http://lidar.cr.usgs.gov

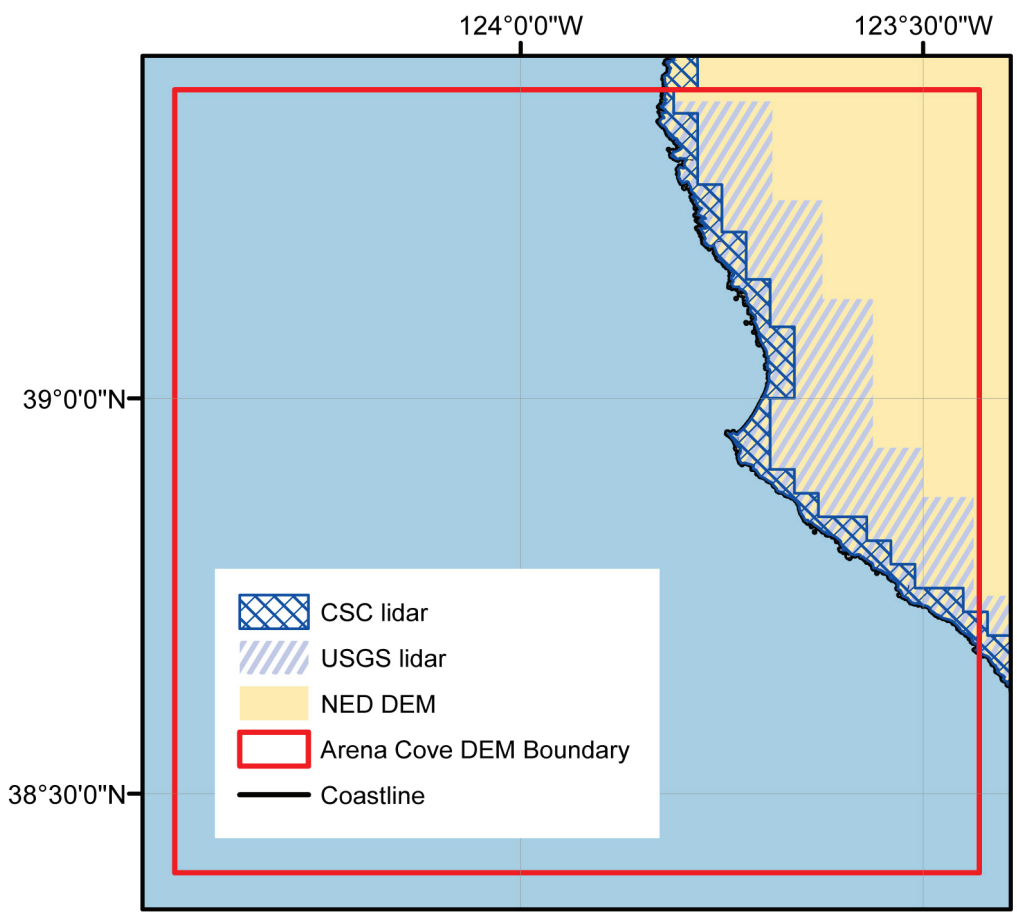

Figure 9. *Spatial coverage of topographic datasets used in building the Arena Cove DEM.*

1) USGS NED topographic 1/3 arc-second DEM

The USGS NED data are available for download as portions of a bare-earth raster DEM, and provide complete 1/3 arc-second coverage of the Arena Cove region[6]. The DEMs are horizontally referenced to NAD 83 geographic and vertically referenced to the North American Vertical Datum of 1988 (NAVD 88, meters). The data were converted from NAVD 88 to MHW in *FME* (see Sec. 3.2.1, Table 9). The elevations in the NED DEM have a vertical accuracy of +/- 7 to 15 meters, depending on the resolution of the source data used by the USGS. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov). The dataset was mostly derived from USGS topographic quadrangle maps and aerial photographs based on topographic surveys conducted in the 1970s and 1980s; it has been revised using data collected in 1999. The NED DEM includes "zero" elevation values over the open ocean, which were removed from the dataset by clipping it to the final coastline.

2) CSC ALACE lidar

The 2002 NASA/USGS ALACE project lidar dataset was downloaded from the CSC web site. The lidar dataset was horizontally referenced to NAD 83 geographic and vertically referenced to NAVD 88. The data were converted to MHW using *FME* (see Sec. 3.2.1, Table 9). The elevations in the lidar dataset have a vertical accuracy of +/- 0.2 meters, although the dataset was not processed to bare-earth and contained vegetation and building values, as well as elevation values over open water. All values over water were clipped out of the dataset, and the dataset was weighted evenly with the NED dataset in the final DEM in order to smooth the lidar closer to a bare-earth surface.

3) USGS CLICK lidar

The 2003 USGS CLICK lidar dataset was downloaded from the CLICK web site. The files were converted from NAD 83 State Plane California Zone II (feet) to NAD 83 geographic using *PROJ.4* software. *PROJ.4* is capable of very quickly batch processing large lidar xyz data files. The files were then median-averaged using the *GMT*[7] tool "blockmedian", and vertically shifted from NAVD 88 to MHW using *FME* (see Sec. 3.2.1, Table 9). The elevations in the lidar dataset have a vertical accuracy of ~0.15 meters, although the dataset was not processed to bare earth and contained vegetation and building values, as well as elevation values over open water. All values over water were clipped out of the dataset, and the dataset was weighted evenly with the NED dataset in the final DEM in order to smooth the lidar closer to a bare-earth surface.

6. 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 geographic, except for AK, which is NAD 27 geographic. 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 web site]

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

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Arena Cove DEM were originally referenced to a number of vertical datums including MLLW, MSL, and NAVD 88. The datasets were transformed to MHW to provide maximum flooding estimates for inundation modeling, and units were converted from feet to meters as appropriate.

1) **Bathymetric data**

   The NOS survey data, multibeam swath sonar surveys, and extracted ENC data were transformed to MHW using *VDatum*.

2) **Topographic data**

   The USGS NED 1/3 arc-second DEM, the USGS CLICK lidar dataset, and the CSC ALACE lidar dataset were converted from NAVD 88 to MHW using *FME* software, which was accomplished by adding a constant offset of -1.550 meters, as measured at the Arena Cove tide station (Table 9).

Table 9: Relationship between MHW and NAVD 88 used in the Arena Cove DEM

Vertical datum	*Difference to MHW**
NAVD 88	-1.550 meters

*Data obtained from Arena Cove tide station (#9416841), see Figure 17 for location.

3.2.2 Horizontal datum transformations

Datasets used to compile the Arena Cove DEM were originally referenced to WGS 84 UTM Zone 10N, WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, NAD 13 geographic, and NAD 83 State Plane California South Zone II. The relationships and transformational equations between these horizontal datums are well established. Data were converted to a horizontal datum of NAD 83 geographic using *GEODAS*, *PROJ.4*, *FME* or *ArcGIS*.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

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

- Elevations located over the open-ocean in the NED and lidar datasets.
- Noise along edges of multibeam swath sonar surveys.
- Topographic lidar datasets not processed to bare earth.
- Many near-shore rocks were not represented in the available datasets.
- Sparse NOS soundings.

3.3.2 Smoothing of bathymetric data

NOS hydrographic survey data are generally sparse relative to the resolution of the 1/3 arc-second Arena Cove DEM. This is especially true for deep-water surveys, where the NOS survey data have point spacing up to two kilometers apart. In order to reduce the effect of artifacts created in the DEM by the low-resolution NOS datasets, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing "pre-surface" bathymetric grid was generated using *GMT*.

The bathymetric point data were median-averaged using the *GMT* tool "blockmedian" to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Arena Cove 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 resulting grid was converted into an ESRI Arc ASCII grid file, and clipped to the final edited coastline (to eliminate values that were interpolated into land areas). The bathymetric surface was compared with original soundings to ensure grid accuracy (e.g., Fig. 10) and exported for use in the final gridding process (see Table 10). All large differences (> 10 meters) between the NOS dataset and the bathymetric surface (Fig. 10) are caused by data points located in deep water, where the NOS dataset is overlaid with higher quality NGDG multibeam data.

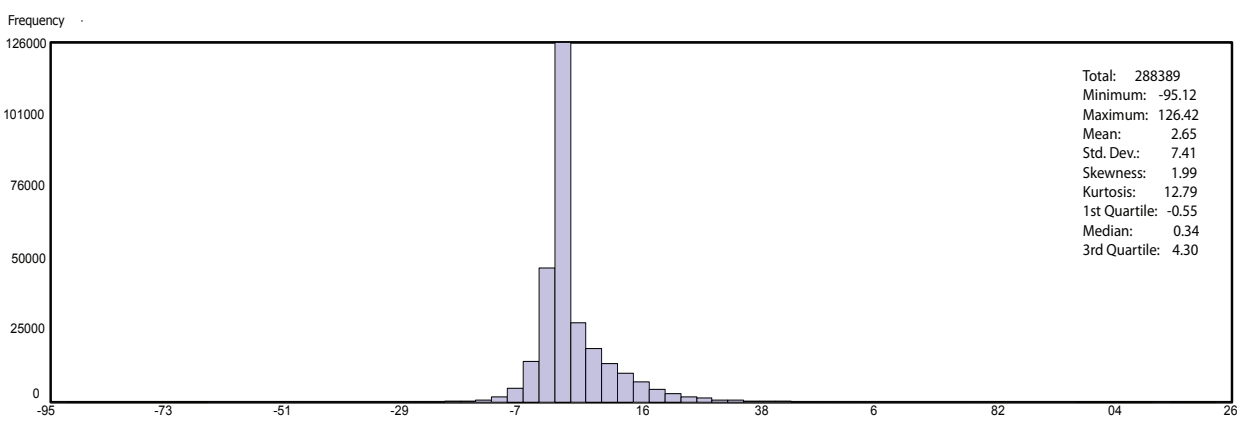

Figure 10. *Histogram of the differences between the pre-1990 NOS data and the bathymetric surface.*

3.3.3 Gridding the data with MB-System

MB-System was used to create the 1/3 arc-second Arena Cove DEM. The *MB-System* tool "mbgrid" was used to apply a tight spline tension to the Arena Cove 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 multibeam datasets and topographic data. Least weight was given to the coastline and less dense bathymetric point data. Gridding was performed in quadrants, with the resulting Arc ASCII grids seamlessly merged in *ArcCatalog* to create the final 1/3 arc-second Arena Cove DEM.

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

Dataset	*Relative Gridding Weight*
CSC topographic lidar	10
USGS CLICK lidar	10
USGS NED topographic grid	10
CSUMB multibeam surveys	10
NGDC multibeam surveys	10
NOS hydrographic surveys	1
Extracted ENC soundings	1
Combined coastline	1
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 Arena Cove DEM is dependent upon the cell size of the DEM and the horizontal accuracy of source datasets. Topographic features have an estimated accuracy of ten meters: topographic lidar data have an accuracy of less than two meters and NED topography is accurate within ten meters. Bathymetric features are resolved only to within a few hundred meters in deep-water areas. Shallow water areas, near-coastal regions, rivers, and harbors have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings, the positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys, and the possibility of man-made morphologic change (i.e., channel dredging and building of jetties).

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Arena Cove DEM is also dependent upon the accuracy of source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy of up to 15 meters; topographic lidar data have an accuracy of less than one meter, but are not bare-earth, and NED topography has a vertical accuracy between 7 and 15 meters. Bathymetric source data have an estimated accuracy between 0.1 meters and five percent of water depth, depending on the survey location and the survey date. Vertical bathymetric data values are most accurate when derived from recent, highly detailed GPS-navigated sonar surveys, and least accurate when derived from surveys performed manually in the early twentieth century. Gridding interpolation to determine deep-water values between sparse, poorly-located soundings degrades the vertical accuracy of some elevations.

3.4.3 Slope maps and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Arena Cove DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 11). The DEM was transformed to UTM Zone 10N coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary slope grids revealed suspect data points, which were corrected before recompiling the DEM. A data distribution plot of the Arena Cove DEM is shown in Figure 12. Figure 13 shows a perspective view from the southwest of the 1/3 arc-second Arena Cove DEM in its final version.

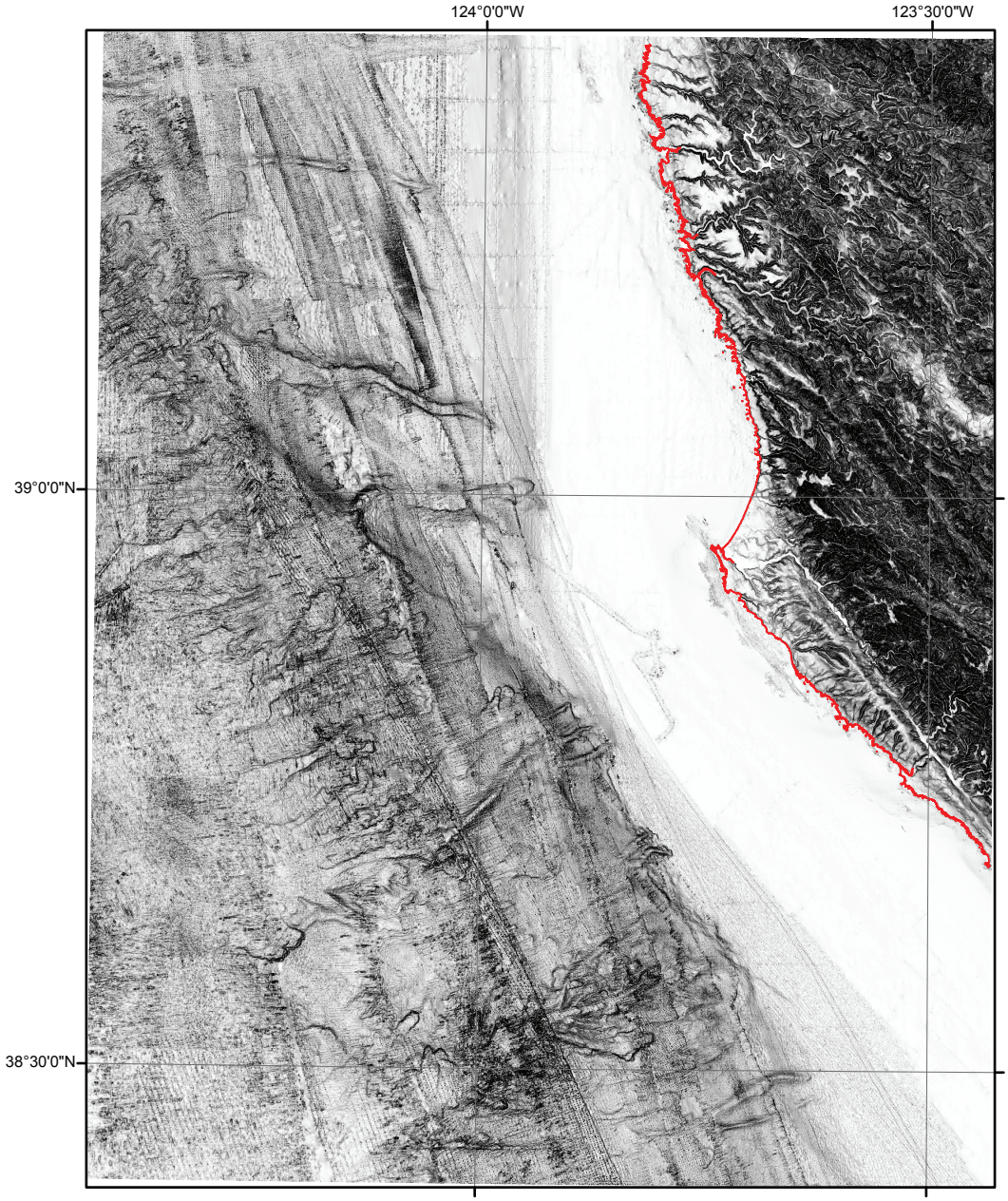

Figure 11. *Slope map of the Arena Cove DEM. Flat-lying slopes are white; dark shading denotes steep slopes; Arena Cove coastline in red.*

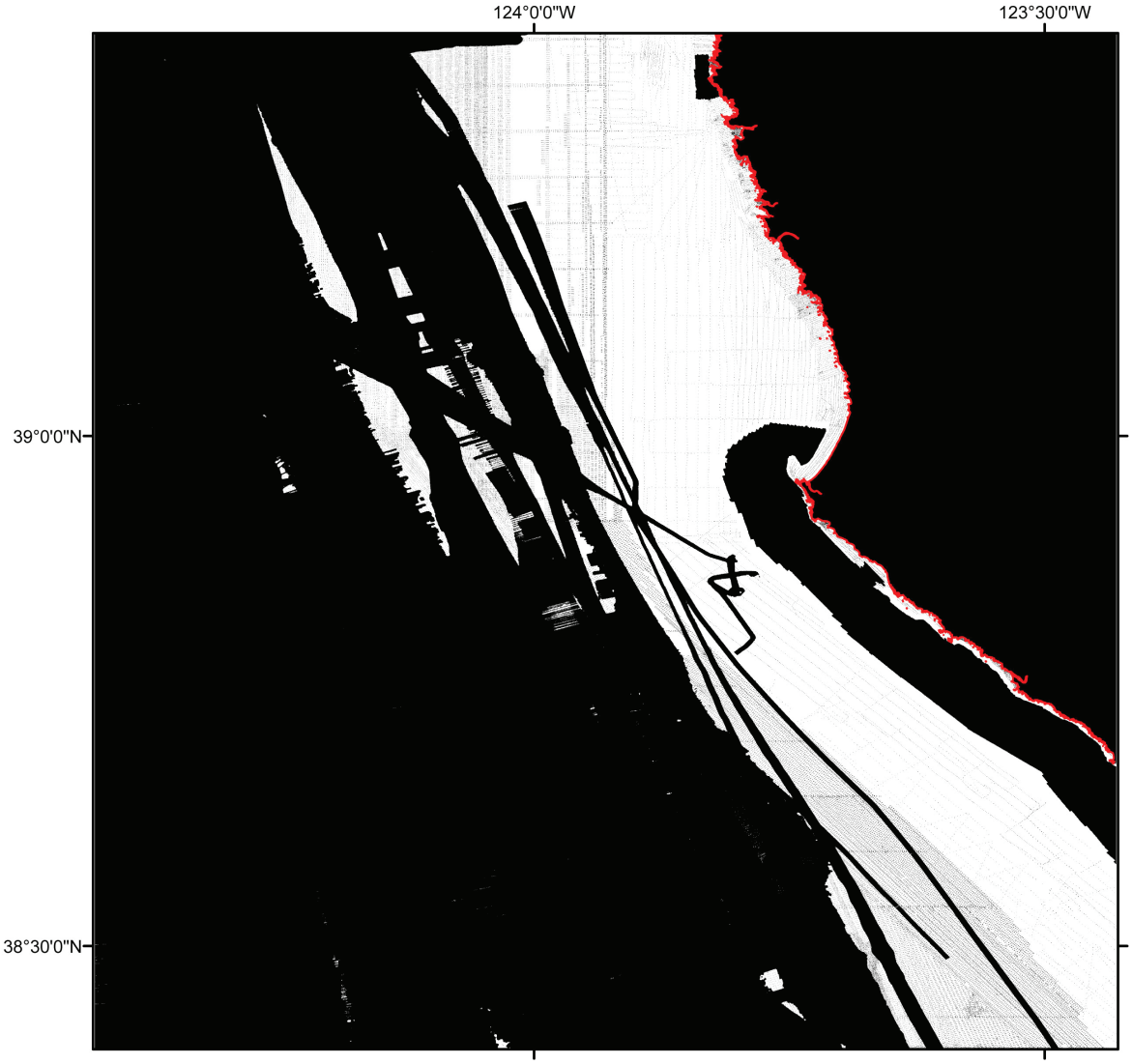

Figure 12. *Data distribution plot of the Arena Cove DEM. Areas where source data were available are depicted in black and grey; areas where grid interpolation was necessary are depicted in white; Arena Cove coastline in red.*

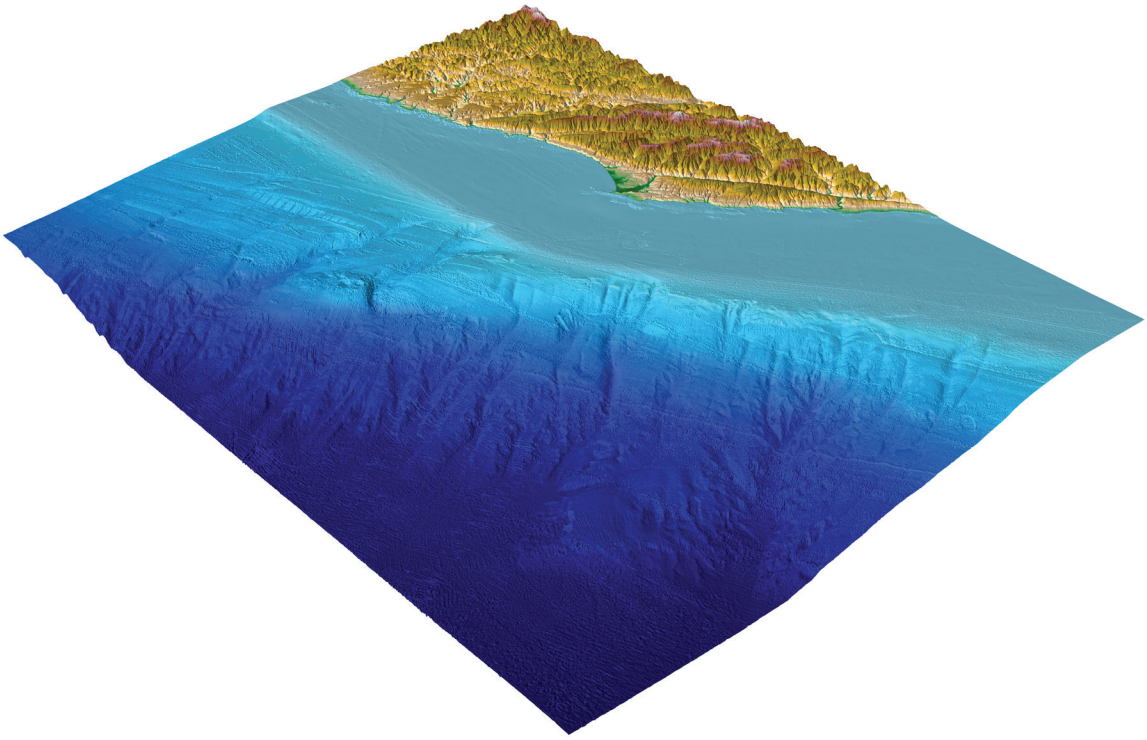

Figure 13. *Perspective view from the southwest of the Arena Cove DEM. Three times vertical exaggeration.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Arena Cove DEM was compared to a selection of source data files using *Fledermaus*. Sample comparisons are shown in Figures 14-17. Largest differences between source datasets and the DEM resulted from the averaging of multiple source datasets where data coverage overlapped, particularly in regions of steep slopes (e.g., USGS CLICK lidar, Fig. 14) and deep water (e.g., NOS data, Fig. 15). The USGS CLICK lidar (Fig. 14) also contains non-bare-earth elevation values, which contribute to large differences from the DEM where the lidar data incorporates trees and buildings. Multibeam datasets, which had strong contributions to the grid and dense data coverages, showed the smallest differences from the DEM (e.g., Figs. 16 and 17). This was especially true for the CSUMB multibeam dataset, which did not overlap any other datasets and covered a very small area (Fig. 17). The largest differences in the multibeam data (>20 meters, Fig. 16) are located in water depths greater than 2000 meters.

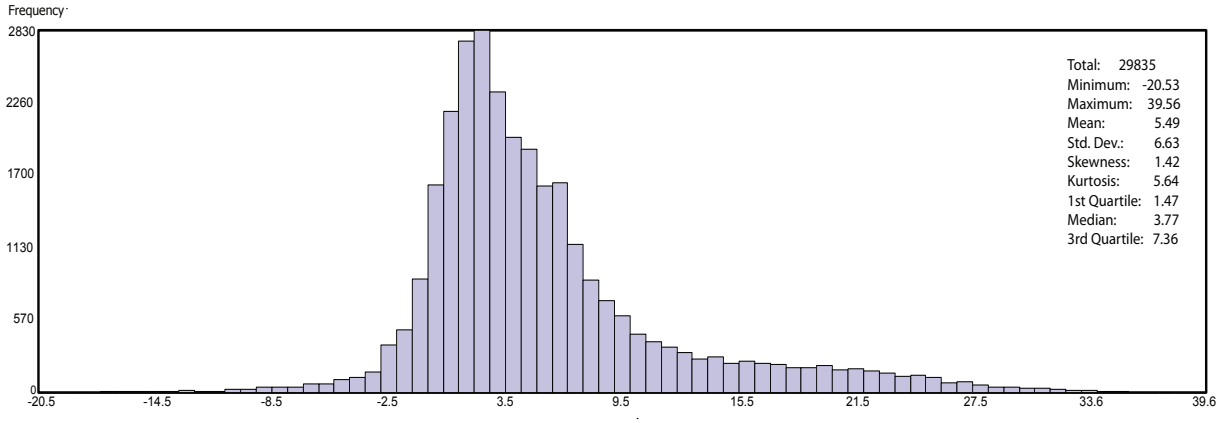

Figure 14. *Histogram of the differences between a section of the USGS CLICK lidar survey and the Arena Cove DEM.*

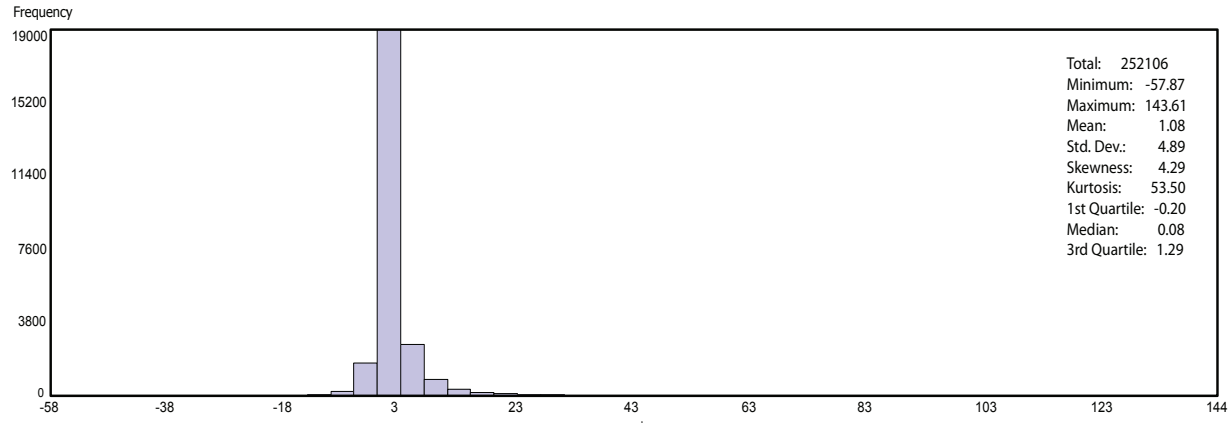

Figure 15. *Histogram of the differences between the pre-1990 NOS data and the Arena Cove DEM.*

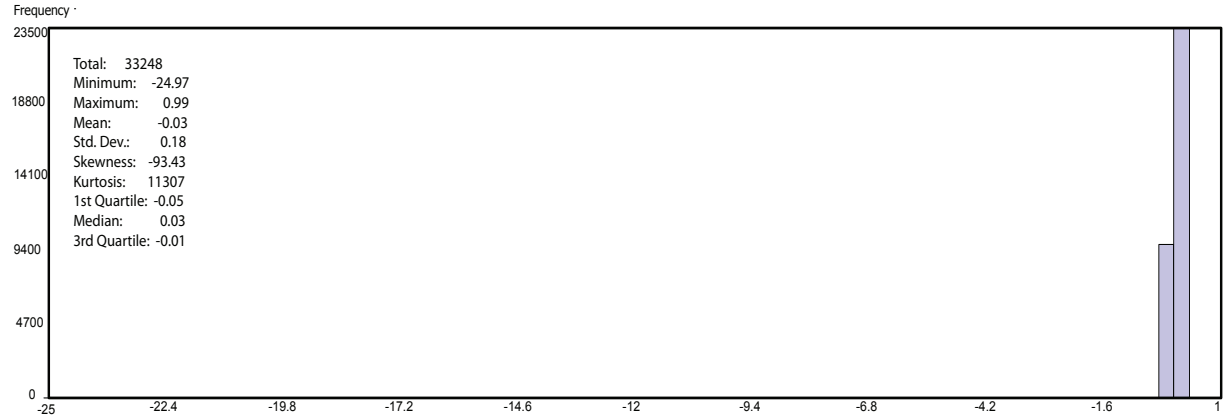

Figure 16. *Histogram of the differences between a section of the NGDC multibeam data and the Arena Cove DEM.*

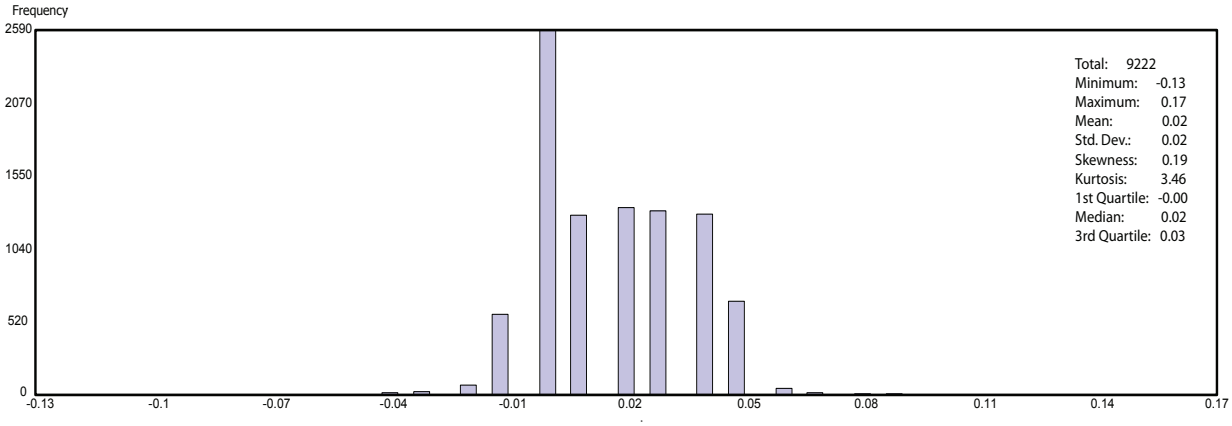

Figure 17. *Histogram of the differences between a section of the CSUMB multibeam data and the Arena Cove DEM.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 340 NOAA's National Geodetic Survey (NGS) geodetic monuments were extracted from online shapefiles of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 geographic and elevations in NAVD 88.

Elevations were shifted to the MHW vertical datum by adding a constant offset using *FME* (see Table 9), and were compared with the Arena Cove DEM (see Fig. 17 for monument locations). Elevation differences between the Arena Cove DEM and the NGS geodetic monuments range from -92.29 to 118.77 meters, with the majority of the NGS monument values within five meters of the DEM value (Fig. 18). Negative values indicate that the monument elevation is less than the DEM value. Of 340 total monuments, very few showed significant deviations from the DEM. Markers that showed deviation were located primarily along high elevation inland valleys and riverbanks, where NED data is least reliable. Other large discrepancies occurred where monuments are located on buildings, towers, and bridges, or have gone missing since their installation.

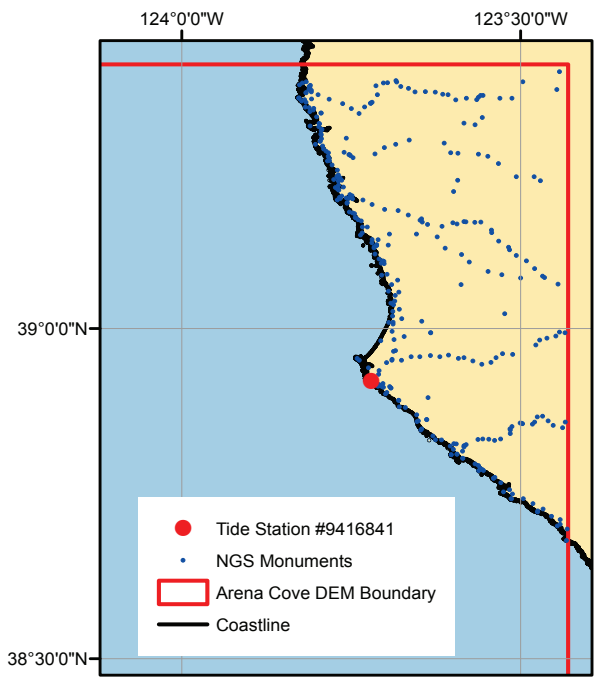

Figure 18. *NGS geodetic monument locations for the Arena Cove DEM.*

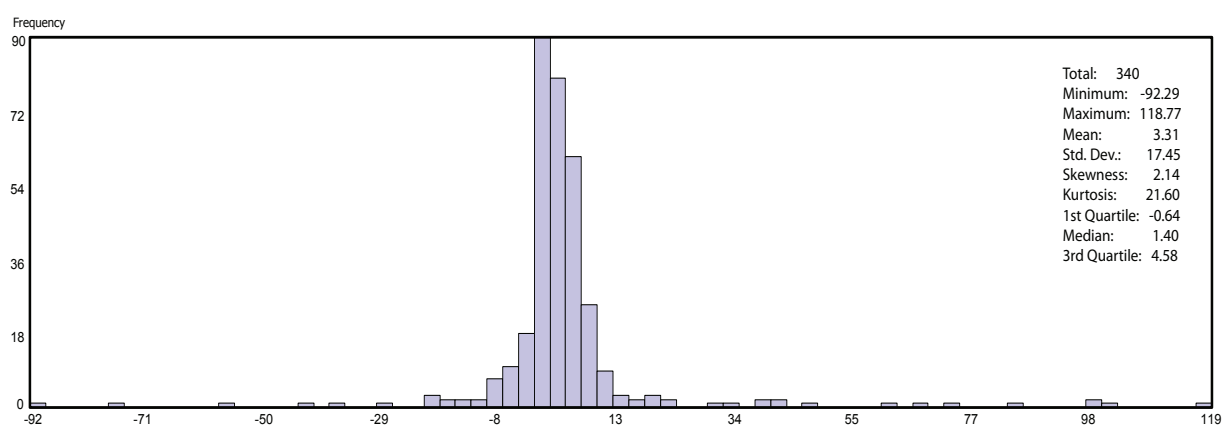

Figure 19. *Histogram of the differences between NGS geodetic monument elevations and the Arena Cove DEM.*

4. Summary and Conclusions

An integrated bathymetric–topographic digital elevation model of the Arena Cove, California region, with a cell size 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 and state 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*, *PROJ.4*, and *Quick Terrain Modeler* software.

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

- Conduct high-resolution NOS hydrographic surveys in areas where existing bathymetric data is sparse.
- Conduct bathymetric–topographic lidar surveys of the entire coast.
- Process CSC and USGS topographic lidar data to bare earth.
- Survey and map rocks along the coastline.

5. Acknowledgments

The creation of the Arena Cove DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL), and Carrie Bretz (CSUMB).

6. References

Nautical Chart #18620 (ENC and RNC), 23rd Edition, 2002. Point Arena to Trinidad Head. Scale 1: 200,000. U.S. Department of Commerce, NOAA, National Ocean Service, Office of Coast Survey.

Nautical Chart #18626 (ENC and RNC), 15th Edition, 2000. Elk to Fort Bragg. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Office of Coast Survey.

Nautical Chart #18640 (ENC and RNC), 25th Edition, 20075 San Francisco to Point Arena. Scale 1:207,840. U.S. Department of Commerce, NOAA, National Ocean Service, Office of Coast Survey.

7. Data Processing Software

ArcGIS v. 9.3, developed and licensed by ESRI, Redlands, California, http://www.esri.com

ESRI World Imagery, ESRI ArcGIS Resource Centers, http://www.esri.com

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

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

GEODAS v. 5 – Geophysical Data System, shareware 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, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu

MB-System v. 5.1.1, 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

PROJ.4, shareware developed by Gerald Evenden of the USGS and maintained by Frank Warmerdam, http://trac.osgeo.org/proj

Quick Terrain Modeler v. 6.0.6, Lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com

VDatum – Vertical Datum Transformation Tool, California- San Francisco Bay Vicinity, Version 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