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

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Contents

List of Figures

List of Tables

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

1. Introduction

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed two integrated bathymetric–topographic digital elevation models (DEMs) of San Diego, California (Fig. 1). The 1/3 arc-second[1] DEMs of San Diego, California referenced to North American Vertical Datum of 1988 (NAVD 88) and mean high water (MHW) were carefully developed and evaluated. The MHW DEM 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 DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3) and was transformed 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.

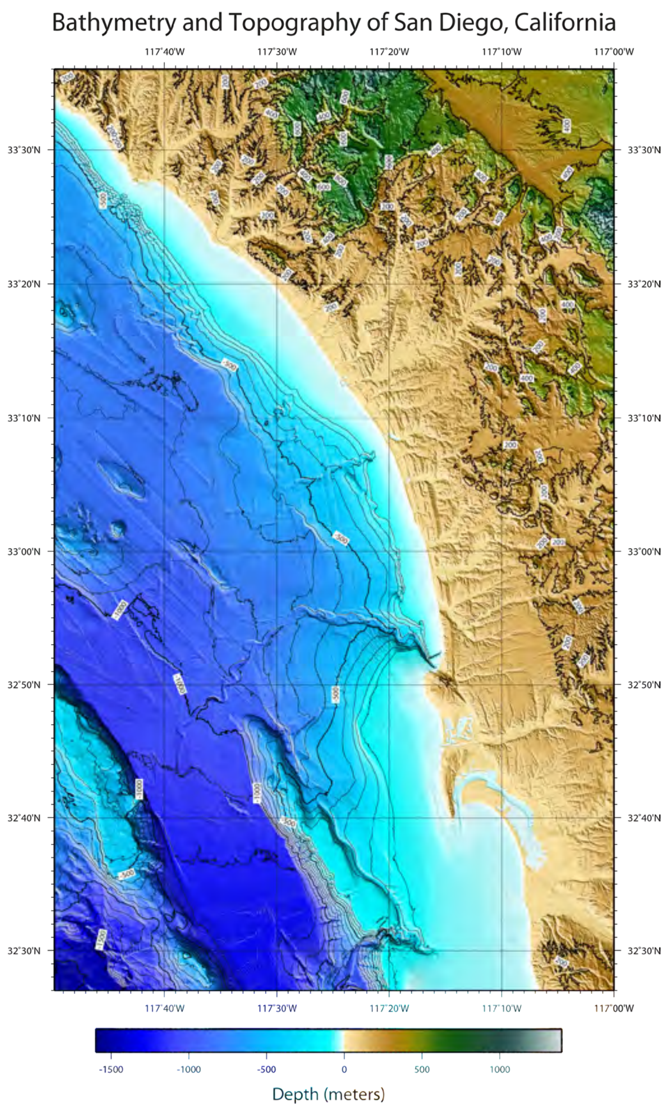

Figure 1. Shaded relief image of the San Diego NAVD 88 DEM. Projection is Mercator projection.

1. The San Diego , California DEMs were 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 Diego, California, (32° 42′ 54″ N, 117° 9′ 45″ W) 1/3 arc-second of latitude is equivalent to 10.27 meters; 1/3 arc-second of longitude equals 8.73 meters.

2. Study Area

The San Diego DEMs provide coverage of the southern coast of California. The DEMs border Mexico to the south and extends north to Laguna Beach, California (Fig. 2). San Diego is the eighth largest city in the United States and the second largest in California with a population of over 1.3 million. Recent research has suggested that while distant-generated tsunamis may pose less of a risk to severely damaging San Diego Harbor, tsunamis generated locally may cause larger waves and currents causing more damage (Barberopoulou et. al., 2010).

Figure 2. Map overview of the San Diego DEM region with inset image of entrance to San Diego Bay (Map: ESRI basemap. Image: Copyright © 2002-2012 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

3. Methodology

The San Diego 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 transformed 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 1. PMEL specifications for the 1/3 arc-second San Diego MHW DEM.

Grid Area	San Diego, California
Coverage Area	117.00º to 117.83º W; 33.60º to 32.45º 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. 3) were obtained from several U.S. federal, state and local agencies, and academic institutions including: NGDC; NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS) and Coastal Services Center (CSC); the U.S. Geological Society (USGS); the California State University at Monterey Bay Seafloor Mapping Laboratory (CSUMB); the Coronado Cays Home Owners Association (CCHOA); the U.S. Army Corps of Engineers (USACE); and the Scripps Institution of Oceanography, University of California at San Diego (SIO). 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 MHW were accomplished using NOAA's *VDatum* transformation tool. ESRI's online *World 2D* imagery was used to analyze and modify data. *QT Modeler* and *Gnuplot* were used to evaluate processing and gridding techniques.

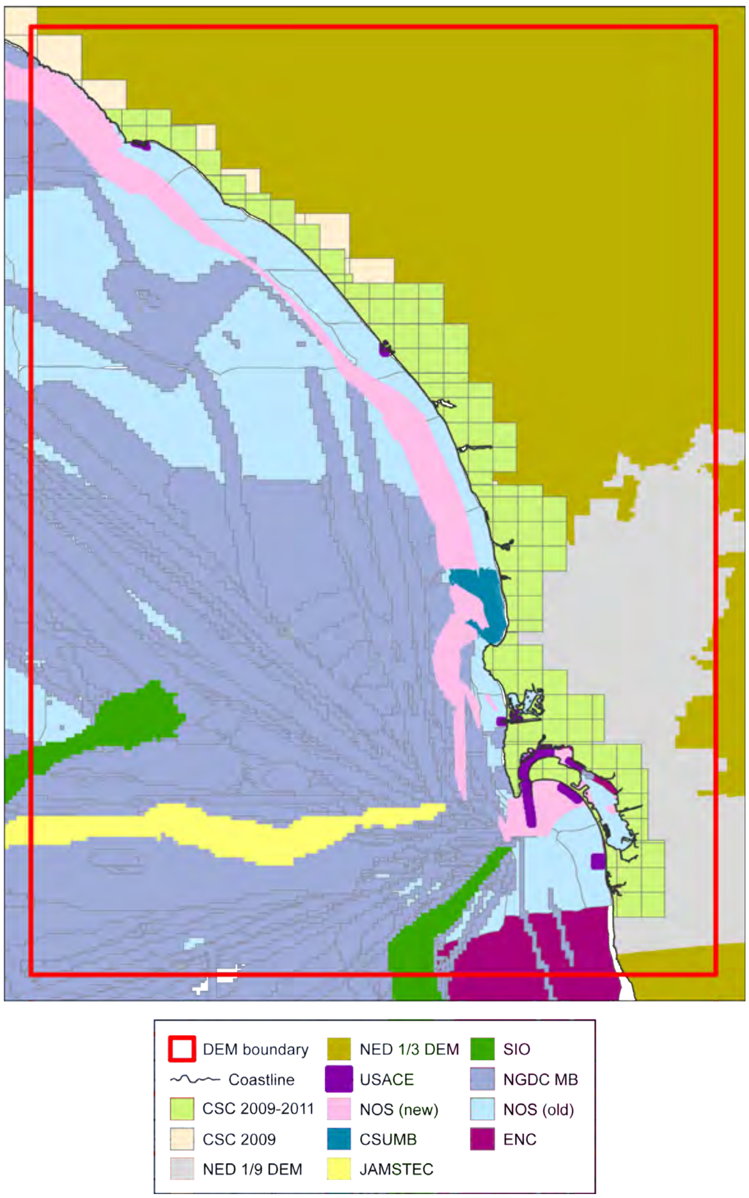

Figure 3. Source and coverage of the dataset used to compile the San Diego NAVD 88 DEM.

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

A coastline dataset of Southern California was obtained from NOAA's Office of Coast Survey *ENC Direct to GIS* online extraction tool (Table 2; http://www.nauticalcharts.noaa.gov/csdl/ctp/encdirect_new.htm). Coastline layers from the "coastal " and "approach" levels were extracted and clipped to 0.05 degrees (~ 5%) larger than the San Diego DEM boundary. The resulting shapefiles were merged and edited with *ArcGIS* tools. Piers and docks within the harbors and along the shoreline were deleted from the coastline. Using ESRI *ArcMap* editing tools, the coastline was modified based on *Google Earth* imagery to reflect the most current coastal morphology. An xyz file of the final edited 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).

Table 2. Shoreline dataset used in building the San Diego NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
OCS	1998 to 2009	Vector shore-line	1:5,000 to 1:100,000	WGS 84 geographic	MHW	http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the San Diego DEM included: NGDC multibeam swath sonar surveys, NOAA ENC soundings, and USACE and NOS hydrographic surveys, multibeam swath sonar surveys from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Scripps Institution of Oceanography (SIO), a bathymetric DEM from the California State University, Monterey Bay Seafloor Mapping Lab (CSUMB) and digitized contour data from the Coronado Cays Home Owners Association (CCHOA) (Table 3; Fig. 3). Datasets were originally horizontally referenced to WGS 84 geographic, NAD 83 geographic, WGS 84 UTM, or NAD 83 State Plane coordinates. The data are vertically referenced to mean lower low water (MLLW) or mean sea level (MSL).

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

Source	***Year***	***Data Type***	***Spatial Resolution***	***Original Horizontal Datum/Coordinate System***	***Original Vertical Datum***	***URL***
NGDC	1954 to 2010	NOS hydrographic survey soundings and Bathymetric Attributed Grid (BAG)	Ranges from .5 meter to 500 meters	NAD 83 geographic	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1982 to 2011	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
USACE	2008 to 2011	Hydrographic survey soundings	1 meter to 30 meter point spacing	California Lambert Zone VI (NAD 83) US Foot or NAD83 California State Plane, Zone VI, US Foot	MLLW	
JAMSTEC	2005-2006	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL	http://www.jamstec.go.jp/e/
SIO	2003 and 2005	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL	http://siox.sdsc.edu/
CSUMB	2001	Bathymetric DEM	2 meters	WGS 84 UTM Zone 11 North	MLLW	http://seafloor.csumb.edu/index.html
NOAA ENCs	2011 to 2012	Extracted NOAA electronic navigational chart soundings and contour lines	~ 25 meters up to ~400 meters point spacing and 6 foot contour lines	WGS 84 geographic	MLLW	http://nauticalcharts.noaa.gov/mcd/enc/

CCHOA	2010	Non-georeferenced hydrographic survey images	2 foot contour lines	Unknown	MLLW	
NGDC	2012	Digitized bathy-metric data	5 meter point spacing	N/A	NAVD 88	

1) NOS hydrographic survey data

Thirty-eight hydrographic surveys conducted between 1954 and 2010 were used in developing the San Diego NAVD 88 DEM (Table 4). Older hydrographic surveys within the San Diego region were not used as more recent data were available. The survey data were downloaded from NGDC's online NOS hydrographic database referenced to NAD 83 geographic horizontal datum and their original vertical datum, MLW or generally MLLW. The data were then transformed to NAVD 88 using *VDatum* and reviewed in *ArcGIS* for digitizing errors and compared with the USACE surveys if present and nautical charts.

Table 4. NOS hydrographic surveys used in compiling the San Diego NAVD 88 DEM.

Survey name	*Date*	*Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*
H11880	2008	10 meter BAG	NAD 83 UTM Zone 11	MLLW
H11879	2008	10 meter BAG	NAD 83 UTM Zone 11	MLLW
H11878	2008	10 meter BAG	NAD 83 UTM Zone 11	MLLW
H11877	2008	10 meter BAG	NAD 83 UTM Zone 11	MLLW
H11876	2008	10 meter BAG	NAD 83 UTM Zone 11	MLLW
H11875	2008	4 meter BAG	NAD 83 UTM Zone 11	MLLW
H11015	2001	10,000	NAD 1983	MLW
H09662	1976	20,000	NAD 1927	MLLW
H09470	1974	5,000	NAD 1927	MLLW
H09469	1974	10,000	NAD 1927	MLLW
H09468	1974	10,000	NAD 1927	MLLW
H09467	1974	10,000	NAD 1927	MLLW
H09277	1972	40,000	NAD 1927	MLLW
H09276	1972	10,000	NAD 1927	MLLW
H09275	1972	10,000	NAD 1927	MLLW
H09274	1972	5,000	NAD 1927	MLLW
H09253	1971 - 1972	40,000	NAD 1927	MLLW
H09252	1972	10,000	NAD 1927	MLLW

Survey name	***Date***	***Resolution***	***Original Horizontal Datum***	***Original Vertical Datum***
H09251	1971	10,000	NAD 1927	MLLW
H09250	1971	10,000	NAD 1927	MLLW
H09249	1971	10,000	NAD 1927	MLLW
H09248	1971	10,000	NAD 1927	MLLW
H09245	1971	5,000	NAD 1927	MLLW
H09114	1970	40,000	NAD 1927	MLLW
H09113	1970	40,000	NAD 1927	MLLW
H09112	1970	40,000	NAD 1927	MLLW
H09111	1970	40,000	NAD 1927	MLLW
H09108	1970	40,000	NAD 1927	MLLW
H09107	1970	10,000	NAD 1927	MLLW
H09106	1970	10,000	NAD 1927	MLLW
H09105	1970	10,000	NAD 1927	MLLW
H08980	1968	40,000	NAD 1927	MLLW
H08979	1968	20,000	NAD 1927	MLLW
H08978	1968	10,000	NAD 1927	MLLW
H08920	1970	10,000	NAD 1927	MLLW
H08135	1954	10,000	NAD 1927	MLLW
F00590	2010	10,000	NAD 83 UTM Zone 11	MLLW
F00513	2006	.5 to 1 meter BAG	NAD 83 UTM Zone 11	MLLW

2) NOAA NGDC multibeam database surveys

Fifty-three multibeam swath sonar surveys (Table 5) were used in developing the San Diego NAVD 88 DEM. The data are available from the NGDC multibeam sonar bathymetry database and are comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. Other multibeam surveys available in the DEM region were not used due to inconsistancies in overlapping data returns with other more recent surveys. The data used in the San Diego NAVD 88 DEM are referenced to a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be MSL.

The downloaded data were gridded to 1 arc-second resolution using *MB-System*[4] then transformed to NAVD 88 using *VDatum*. Further editing of the gridded data was done using *QT Modeler*. Editing of the individual survey data consisted of removing sound velocity errors and errors caused during ship course changes.

Table 5. Multibeam swath sonar surveys used in compiling the San Diego NAVD 88 DEM.

Cruise ID	*Year*	*Ship*	*Collecting Institution / Source*
981107RR	1998	Roger Revelle	University of California, Scripps Institution of Oceanography (UC/SIO)
A-3-98-SC	1998	Ocean Alert	U.S. Geological Society (USGS)
AT03L42	1999	Atlantis	Woods Hole Oceanographic Institution (WHOI)
AT03L49	2000	Atlantis	WHOI
AT07L09	2002	Atlantis	WHOI
AT11L19	2004	Atlantis	WHOI
AT15L11	2006	Atlantis	WHOI
AT3L13	1998	Atlantis	WHOI
AT3L20	1998	Atlantis	WHOI
AVON01MV	1999	Melville	UC/SIO
AVON12MV	1999	Melville	UC/SIO
BMRG01MV	1995	Melville	UC/SIO
BMRG09MV	1996	Melville	UC/SIO
BONZ02WT	1982	Thomas Washington	UC/SIO

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

Cruise ID	*Year*	*Ship*	*Collecting Institution / Source*
C199SC	1999	Coastal Surveyor	USGS
CALF01RR	1996	Roger Revelle	UC/SIO
CALF03RR	1996	Roger Revelle	UC/SIO
CERE04WT	1982	Thomas Washington	UC/SIO
CNTL02RR	2002	Roger Revelle	UC/SIO
CNTL03RR	2003	Roger Revelle	UC/SIO
CNTL04RR	2003	Roger Revelle	UC/SIO
CNTL06RR	2003	Roger Revelle	UC/SIO
CNTL08RR	2003	Roger Revelle	UC/SIO
CRGN01WT	1987	Thomas Washington	UC/SIO
DELV02RR	1996	Roger Revelle	UC/SIO
DRFT01RR	2001	Roger Revelle	UC/SIO
DRFT16RR	2002	Roger Revelle	UC/SIO
EW9415	1994	Maurice Ewing	Columbia University, Lamont-Doherty Earth Observatory (CU/LDEO)
EW9504	1995	Maurice Ewing	CU/LDEO
EX1101	2011	Okeanos Explorer	National Oceanic and Atmospheric Administration (NOAA)
HLY05TI	2005	USCGC Healy	Rolling Deck to Repository (R2R) Program
INSV01WT	1990	Thomas Washington	UC/SIO
JNUS01WT	1992	Thomas Washington	UC/SIO
KIWI01RR	1997	Roger Revelle	UC/SIO
KRUS06RR	2004	Roger Revelle	UC/SIO
LWAD99MV	1999	Melville	UC/SIO

Cruise ID	***Year***	***Ship***	***Collecting Institution / Source***
NECR01RR	2000	Roger Revelle	UC/SIO
NPAL98MV	1998	Melville	UC/SIO
NV9704MV	1997	Melville	UC/SIO
PACS03MV	1998	Melville	UC/SIO
RAPA00WT	1990	Thomas Washington	UC/SIO
REM01MV	1993	Melville	UC/SIO
REVT01RR	1996	Roger Revelle	UC/SIO
REVT02RR	1996	Roger Revelle	UC/SIO
RSCN01MV	1997	Melville	UC/SIO
SEAW02RR	2001	Roger Revelle	UC/SIO
SMNT01WT	1983	Thomas Washington	UC/SIO
TO9001WT	1990	Thomas Washington	UC/SIO
TO9002WT	1990	Thomas Washington	UC/SIO
TUNE09WT	1992	Thomas Washington	UC/SIO
WEST00MV	1993	Melville	UC/SIO
WEST15MV	1995	Melville	UC/SIO
WSFL01WT	1990	Thomas Washington	UC/SIO

3) USACE hydrographic surveys

Fourteen hydrographic surveys conducted between 2008 and 2011 were used in developing the San Diego NAVD 88 DEM (Table 6). The survey data were provided by USACE and referenced to NAD 83 California State Plane or California Lambert horizontal datum and their original vertical datum, MLLW. The data were then transformed to NAVD 88 using *VDatum* and reviewed in *ArcGIS* for digitizing errors and were compared with the more recent NOS surveys and nautical charts.

Table 6. USACE hydrographic surveys used in compiling the San Diego NAVD 88 DEM.

Survey	*Year*	*Scale*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*
DP0510CO_FT	2010	~1 meter point spacing	California Lambert Zone VI (NAD 83) US Foot	MLLW
IBDP1009CO_FT	2009	~1 meter point spacing	California Lambert Zone VI (NAD 83) US Foot	MLLW
MS1108CO_FT	2008	~3 meter point spacing	California Lambert Zone VI (NAD 83) US Foot	MLLW
OS0410CO_FT	2010	~1 meter point spacing	California Lambert Zone VI (NAD 83) US Foot	MLLW
SD0809CO_BP_SI_FT	2009	~1 meter point spacing with 30 meter line spacing	California Lambert Zone VI (NAD 83) US Foot	MLLW
SD0809CO_ENT_BP_FT	2009	~1 meter point spacing with 30 meter line spacing	California Lambert Zone VI (NAD 83) US Foot	MLLW
SD0809CO_SI_HI_FT	2009	~1 meter point spacing with 30 meter line spacing	California Lambert Zone VI (NAD 83) US Foot	MLLW
SDDP0809CO_FT	2009	~1 meter point spacing with 30 meter line spacing	California Lambert Zone VI (NAD 83) US Foot	MLLW
MSB1010po	2010	~1 meter point spacing	NAD83 California State Planes, Zone VI, US Foot	MLLW
MSB1110po	2010	~1 meter point spacing	NAD83 California State Planes, Zone VI, US Foot	MLLW
SD0611co_ Sta100_00to145_00_3Ft	2011	~1 meter point spacing	NAD83 California State Planes, Zone VI, US Foot	MLLW
SD0611co_ Sta60_00to100_00_3Ft	2011	~1 meter point spacing	NAD83 California State Planes, Zone VI, US Foot	MLLW
SD1010co_ Sta220_00to290_00_3Ft	2010	~1 meter point spacing	NAD83 California State Planes, Zone VI, US Foot	MLLW
SD1010co_ Sta380_00to430_00_3Ft	2010	~1 meter point spacing	NAD83 California State Planes, Zone VI, US Foot	MLLW

4) JAMSTEC multibeam database survey

One multibeam survey conducted between 2005 and 2006 was used in developing the San Diego NAVD 88 DEM (Table 7). The survey data were downloaded from JAMSTEC's online database referenced to WGS 84 geographic horizontal datum and assumed to be vertically referencd to MSL. The downloaded data were gridded to 1 arc-second resolution using *MB-System* then transformed to NAVD 88 using *FME.*

Table 7. JAMSTEC multibeam survey used in compiling the San Diego NAVD 88 DEM.

Cruise ID	*Year*	*Ship*	*Horizontal Datum*	*Original Vertical Datum*
MR05-05	2005-2006	R/V Mirai	WGS 84 geographic	assumed MSL

5) SIO multibeam database surveys

Two multibeam surveys conducted in 2003 and 2005 were used in developing the San Diego NAVD 88 DEM (Table 8). The survey data were downloaded from SIO's online database referenced to WGS 84 geographic horizontal datum and assumed to be vertically referencd to MSL. The downloaded data were gridded to 1 arc-second resolution using *MB-System* then transformed to NAVD 88 using *FME.* Further editing of the gridded data was done using *QT Modeler*.

Table 8. SIO multibeam surveys used in compiling the San Diego NAVD 88 DEM.

Cruise ID	*Year*	*Ship*	*Horizontal Datum*	*Original Vertical Datum*
SANQ01RR	2005	Roger Revelle	WGS 84 geographic	assumed MSL
CNTL07RR	2003	Roger Revelle	WGS 84 geographic	assumed MSL

6) CSUMB multibeam survey

One hydrographic surveys conducted in 2001 by CSUMB was used in developing the San Diego NAVD 88 DEM (Table 9). The survey data were downloaded from CSUMB's online database referenced to WGS 84 UTM Zone 11 North horizontal datum and vertical datum of MLLW. The data were transformed to NAVD 88 using *VDatum* and reviewed in *ArcGIS* for digitizing errors and compared with the more recent NOS surveys and nautical charts.

Table 9. CSUMB multibeam survey used in developing the San Diego NAVD 88 DEM.

Survey	*Year*	*Scale*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*
La Jolla	2001	2 meters	WGS 84 UTM Zone 11 North	MLLW

7) Extracted ENC soundings and contours

Six NOAA nautical charts were available from OCS within the San Diego DEM boundaries (Table 10). Sounding data were extracted using OCS's *ENCDirect to GIS* online tool for charts 18740, 18772, and 18773 in shapefile format. The data were referenced to WGS 84 geographic and MLLW. Transformation to NAVD 88 were accomplished using *VDatum*. Contour lines were extracted from charts 18772 and 18773, converted to point data and assigned the corrected elevation values for vertical datum of NAVD 88 and units of meters. Raster nautical charts were used as a reference to quality check gridded bathymetric data (see Section 3.3.2).

Table 10. Nautical charts available in the San Diego region.

Chart	*Title*	*Format*	*Edition*	*Issue Date*	*Scale*
18740	San Diego to Santa Rosa Island	ENC and RNC	20	2011	234,270
18746	San Pedro Channel, Dana Point Harbor	ENC and RNC	5	2011	20,000
18758	Del Mar Boat Basin	ENC and RNC	10	2011	1:5,000
18765	Approaches to San Diego Bay;Mission Bay	ENC and RNC	2	2011	100,000
18772	Approaches to San Diego Bay	ENC and RNC	12	2011	20,000
18773	San Diego Bay	ENC and RNC	33	2012	12,000
18774	Gulf of Santa Catalina;Delmar Boat Basin-Camp Pendleton	ENC and RNC	3	2011	100,000

8) CCHOA Hydrographic survey images

The Coronado Cays Home Owners Association provided NGDC with digital copies of hydrographic surveys for the channels in the community. The images were aerial photos overlayed with bathymetric contour lines. An index map of the photos is provided in Figure 4. The individual images were converted from pdf format to tiff and georeferenced in ArcMap. The contours were digitized and converted to point data assigning corrected elevation values for a vertical datum of NAVD 88 and in units of meters.

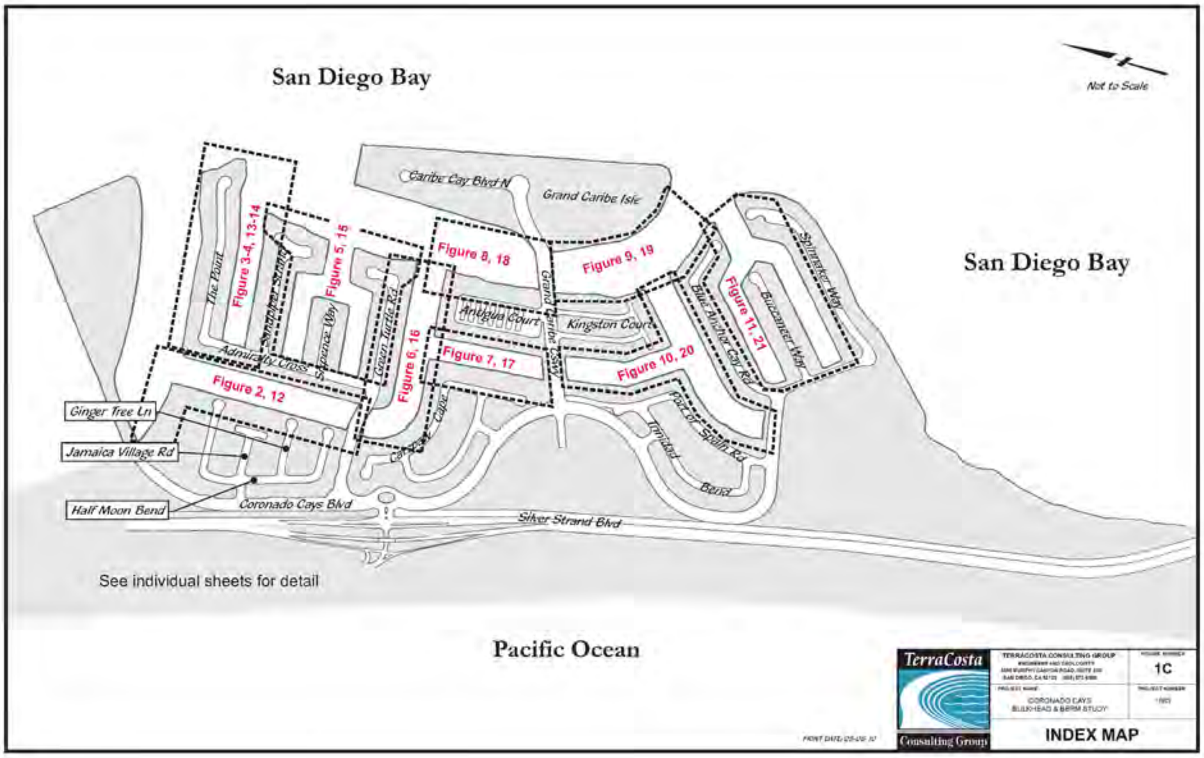

Figure 4. Index map of Coronado Cays survey data.

9) NGDC Digitized bathymetric data

No digital bathymetric data was available for lagoons located within the DEM boundary; Bataquitos, Hedionda, and San Dieguito. NGDC digitized contour points for these lagoons referencing online documentation for restoration plans and biological monitoring reports (Sec. 6).

3.1.3 *Topography*

Topographic datasets in the San Diego region were obtained from: NOAA's Coastal Service Center (CSC) and USGS (Table 11; Fig. 3).

Table 11. Topographic datasets used in compiling the San Diego NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
CSC 2009 - 2011 California Coastal LiDAR Project	2009 to 2011	Lidar	1 meter nominal ground spacing	WGS 84/ITRF 94	NAVD 88	http://www.csc.noaa.gov/dataviewer/index.html#
CSC March 2009 SIO Lidar	2009	Lidar	5 meter averaged gridded data	WGS 84/ITRF 94	NAVD 88	http://www.csc.noaa.gov/dataviewer/index.html#
USGS	varies	raster DEMs	1/9 and 1/3 arc-second	NAD 83 geographic	NAVD 88	http://seamless.usgs.gov/

1) **CSC - 2009 - 2011 California Coastal LiDAR Project**

The 2009-2011 lidar data was collected in conjunction with the State of California and provided by the California Coastal Conservancy for sea level rise, shoreline delineation and coastal planning purposes. The data were downloaded from the CSC online database in xyz format and reviewed in *QT Modeler*. This data is classified as bare-earth however contains some returns over water. These were removed from the dataset with *QT Modeler*. The metadata provided with the dataset states the minimum expected vertical accuracy as tested to meet or exceed the National Standard for Spatial Data Accuracy (NSSDA). When compared to GPS survey grade points in generally flat, non-vegetated areas, at least 95% of the positions had an error less than or equal to 18 cm (equivalent to root mean square error (rmse) of 9 cm if errors were normally distributed).

2) **CSC - March 2009 Scripps Institute of Oceanography (SIO) Lidar of the Southern California Coastline Lidar**

The 2009 lidar data was collected at different times of the year, over multiple years in narrow strips along shoreline to determine rates of shoreline change. The data were provided by Scripps Institute of Oceanography and available from CSC. The metadata provided with the dataset states that for each survey area (north and south), the mean elevation difference between the selected lidar points and their respective GPS points was used to estimate and remove elevation bias from the lidar. The standard deviation of the elevation differences provided estimates of the lidar precision. The bias was removed so that mean lidar elevations have a vertical accuracy of 0.10 m RMSE.

The data were downloaded from the CSC online database as 5 meter gridded rastered tiles. The raster tiles were clipped to the coastline to remove elevation values over water and converted to xyz point format. This lidar data was used only where the CSC 2009-2001 lidar data was not available along the coast.

3) USGS 1/3 and 1/9 arc-second topographic DEMs

USGS National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the San Diego DEM region. 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. *GDAL* was used to convert the rasters to xyz format. Other higher- resolution data were available to replace the NED data in many coastal areas.

The USGS NED 1/9 arc-second DEM data were available for the southern portion of San Diego county (see Fig. 3). This dataset is generated from 2005 digital orthophotography provided by the City of San Diego and was collected to generate 2 foot contours and .25 foot pixel color orthophotos. The resulting data were used to develop a digital surface model (DSM) which has been reviewed and processed by USGS to be included in the 1/9 arc-second NED dataset. The data were converted from rasters to xyz format and clipped to the coastline using *QT Modeler*.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the San Diego NAVD 88 DEM were originally referenced to a number of vertical datums including: MLLW, MLW, MSL, and NAVD 88.

1) Bathymetric data

The multibeam surveys, NOS, USACE, and the nautical chart soundings were transformed from MLLW, MLW, and MSL to NAVD 88 using NOAA's *VDatum* transformation tool. The relationships between the various vertical datums and NAVD 88 based on the tide stations in the DEM region are listed in Table 12.

2) Topographic data

The CSC lidar and the USGS DEMs were originally referenced to NAVD 88. No vertical transformation was needed.

Table 12. Relationships between NAVD 88 and other vertical datums in meters at the San Diego tide station.

	San Diego (ID 9410170) Elevations of tidal datums in reference to MLLW (meters)
MHHW	1.745
MHW	1.519
MSL	0.896
MTL	0.902
MLW	0.285
NAVD 88	0.132
MLLW	0.0
	Difference between datums (meters)
MHW to NAVD 88	-1.387
MSL to NAVD 88	-0.764
MLLW to NAVD 88	0.132

3.2.2 Horizontal datum transformations

Datasets used in compiling the San Diego NAVD 88 DEM were originally referenced to: NAD 83 and WGS 84 geographic; WGS 84/ITRF 94; California Lambert Zone VI (NAD 83) US Foot; NAD83 California State Plane, Zone VI, US Foot; or WGS 84 UTM Zone 11 North horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established and transformations to NAD 83 geographic were done using *FME* or *ArcGIS* software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in 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 coastline or manual editing.
- Inconsistent, overlapping bathymetric datasets. Lower-resolution and older datasets were clipped to higher-resolution data and all datasets were weighted based on quality and age in gridding process.

3.3.2 Smoothing of bathymetric data

In order to reduce the effect of artifacts in the form of lines of "pimples" in the 1/3 arc-second DEM due to variable resolution datasets, and to provide effective interpolation into the coastal zone, 1 and 1/3 arc-second-spacing "pre-surface" grids were generated using *GMT*[5].

All bathymetric datasets were combined into a single file. Points extracted from the combined coastline were also included and assigned elevation values of zero meters to ensure that the offshore elevations remained negative. These point data were then smoothed using the *GMT* tool "blockmedian" onto a 1 arc-second grid. The *GMT* tool "surface" was applied to interpolate values for cells without data values. The *GMT* grid created by "surface" was converted into an ESRI Arc ASCII grid file using the *MB-System* tool "mbm_grd2arc". 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). A 1/3 arc-second surface was generated for the near shore areas. This provided needed density of bathymetric data points to reduce interpolation effects at the coast where dense topographic data abuts sparse bathymetric data.

The resulting surfaces were compared with original soundings to ensure grid accuracy, converted to xyz files for use in the final gridding process (see Table 13). The statistical analyses of the differences between the 1 arc-second bathymetric surface and bathymetric data files showed that the majority of the soundings are in good agreement with the bathymetric surface.

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

3.3.3 Building the 1/3 arc-second NAVD 88 DEM

MB-System was used to create a 1/3 arc-second NAVD 88 DEM of San Diego. 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 CSC lidar and USACE, CSUMB, and digitized features datasets. Least weight was given to the low resolution NED DEMs, older NOS hydrographic surveys, and deep water multibeam.

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

Dataset	*Relative Gridding Weight*
USACE hydrographic surveys	100
CSC 2009-2011 lidar	100
NGDC digitized features	100
CSUMB multibeam	100
Newer NOS hydrographic surveys	10
CCHOA contour data	10
OCS ENC soundings	10
CSC 2009 lidar	1
Bathymetric 'pre-surfaced' data	1
JAMSTEC multibeam	0.1
NGDC multibeam data	0.1
SIO multibeam	0.1
USGS NED 1/9 DEM	0.1
USGS NED 1/3 DEM	0.1
Old NOS hydrographic surveys	0.1

3.3.4 Developing the Mean High Water DEM

The MHW DEM was created by adding “NAVD 88 to MHW” conversion grid to the NAVD 88 DEM.

1) Developing the conversion grid

Using extents slightly larger (~ 5 percent) than the specified DEM extents, 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 *GDAL* and *Python*. 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 San Diego NAVD 88 DEM. Figure 5 shows the conversion grid with the difference in elevation between NAVD 88 and MHW.

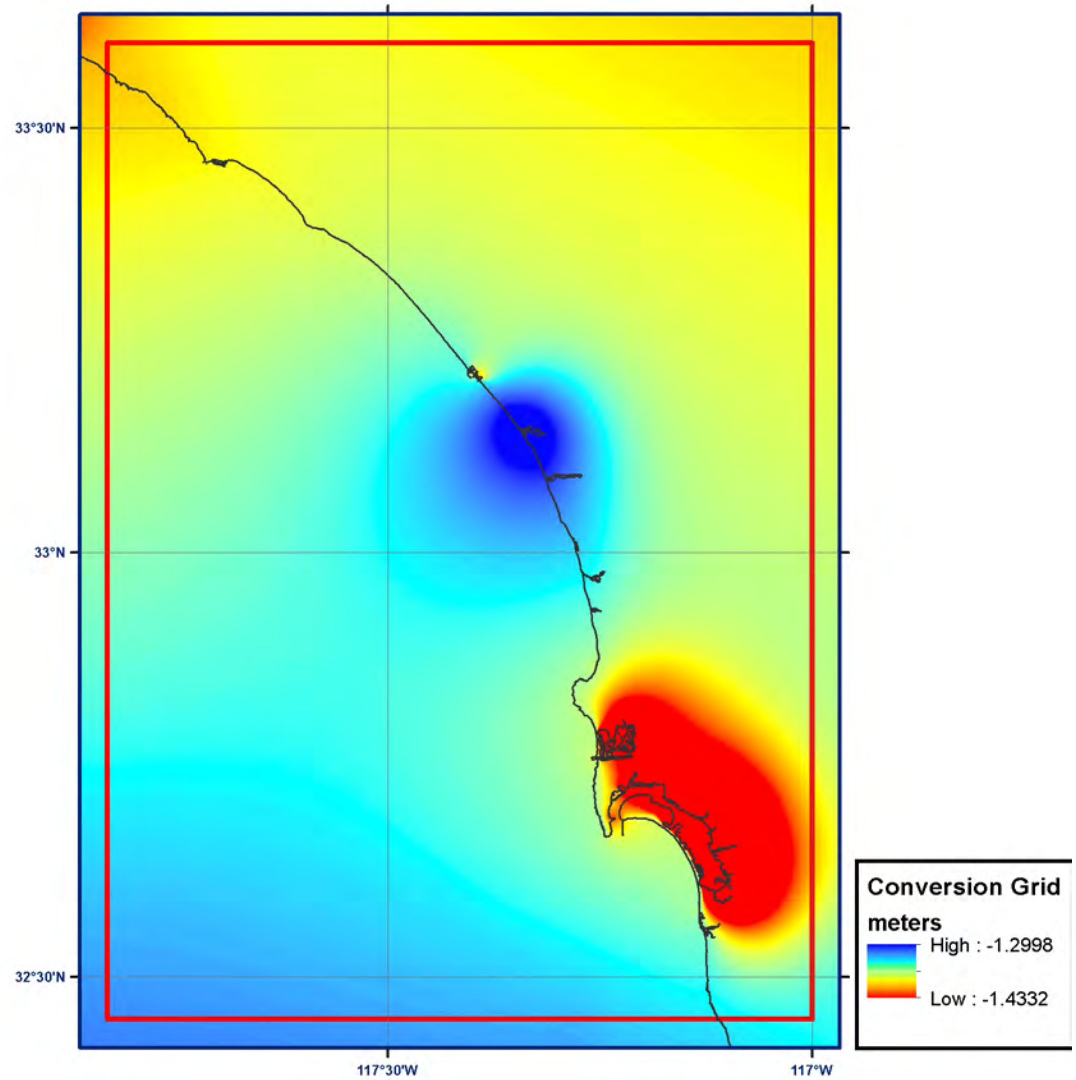

Figure 5. Image of the NAVD 88 to MHW conversion grid for the San Diego DEM area.

2) Assessing accuracy of conversion grid

The "NAVD 88 to MHW" conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from 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*. Errors in the vertical datum conversion method will reside for the most part in the "NAVD 88 to MHW" conversion grid, topographic data are already in NAVD 88. Errors in the source datasets will require rebuilding just the NAVD 88 DEM.

3) Creating the MHW DEMs

Once the NAVD 88 DEM was complete and assessed for errors, the conversion grid was added using *ArcCatalog*. The resulting MHW DEM was reviewed and assessed using raster nautical charts, USGS topographic maps, aerial imagery from the California Coastal Records Project, and ESRI *World 2D* imagery. Problems encountered were determined to reside in source datasets, which were corrected before building a new NAVD 88 DEM.

3.4 Quality Assessment of the DEM

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the San Diego DEM 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, 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 CSC lidar data, and the NED 1/3 arc-second 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 map, 3-D perspective, and data contribution plot

ESRI *ArcCatalog* was used to generate a slope grid from the 1/3 arc-second NAVD 88 San Diego DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig.6). The DEM was transformed to NAD 83 UTM Zone 11 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.

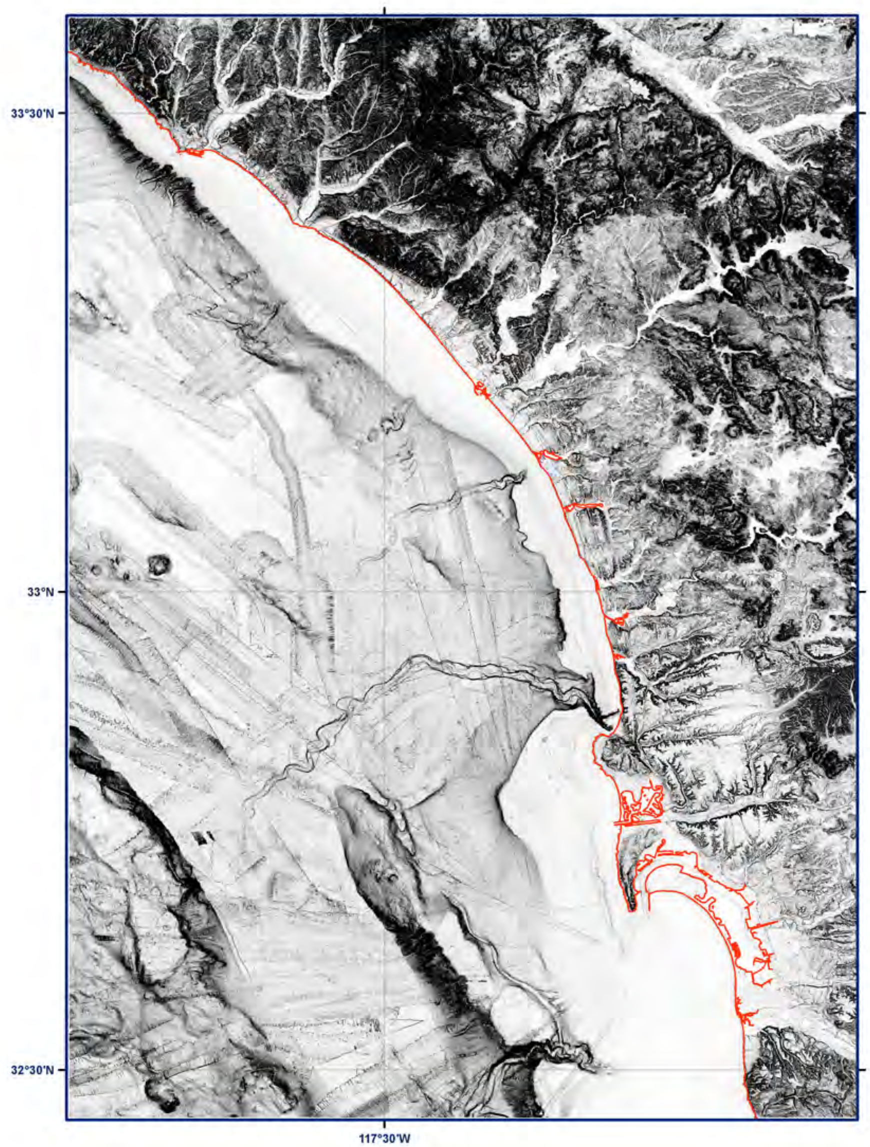

Figure 6. Slope map of the San Diego NAVD 88 DEM.

A high-resolution perspective image was generated using *POV Ray,* providing three-dimensional viewing of the DEM (Fig. 7). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM.

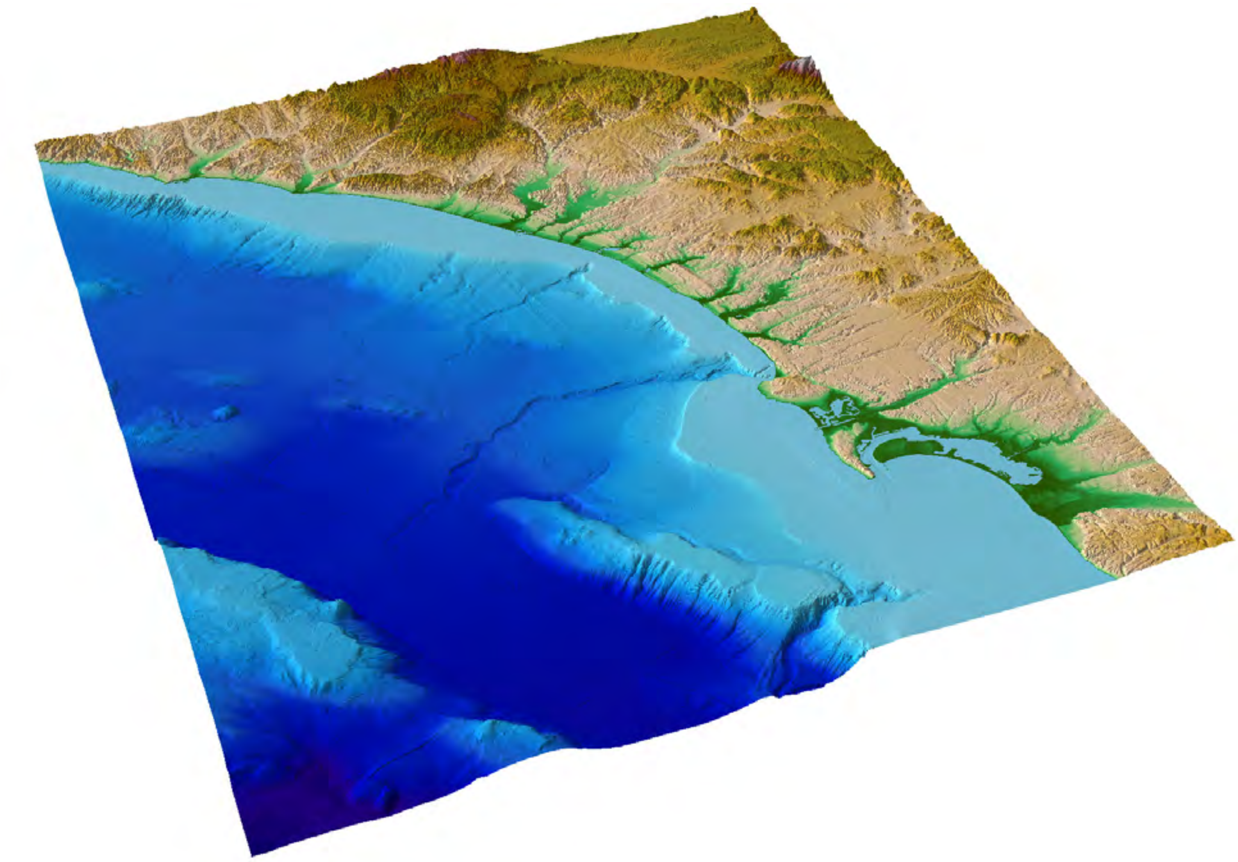

Figure 7. Perspective image of the San Diego NAVD 88 DEM. View is from the southwest, vertical exaggeration is 2 times.

The data contribution plot in Figure 8 depicts the DEM cells constrained by source data and cells with elevation values derived from interpolation.

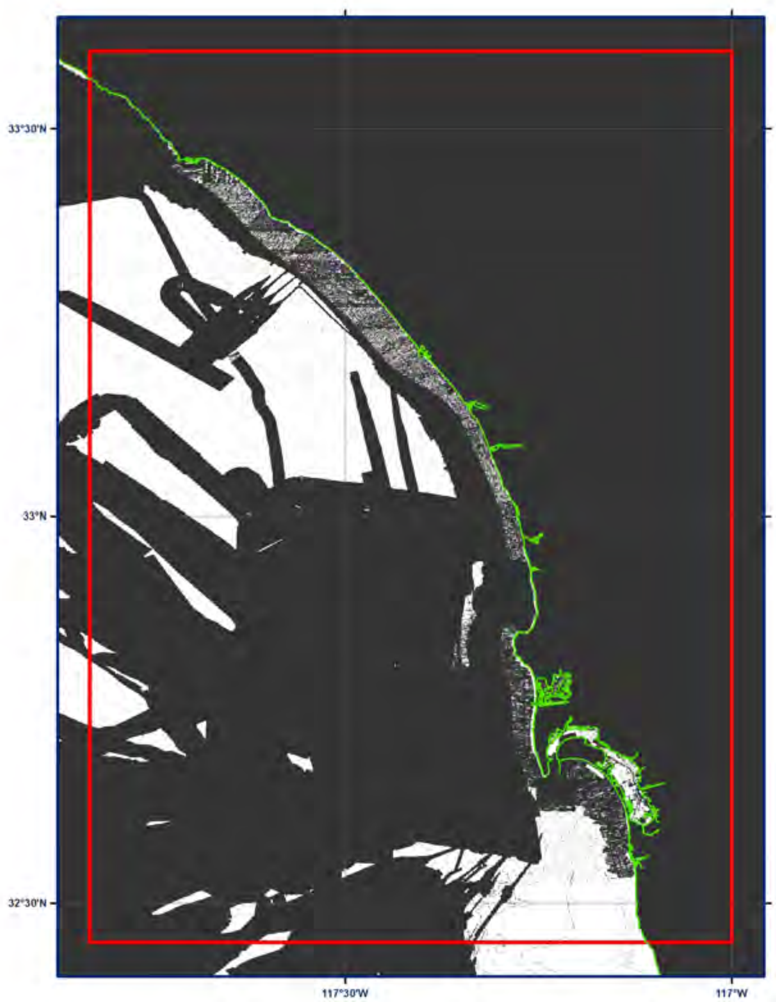

Figure 8. Data contribution plot of the San Diego NAVD 88 DEM. Black depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. DEM boundary in red, coastline in green.

3.4.4 NAVD 88 DEM comparison with source data files

To ensure grid accuracy, the 1/3 arc-second San Diego NAVD 88 DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas. Entire bathymetric datasets were used for comparing the deep-water NOS surveys and the near- shore CSUMB survey to the DEM. Large differences between the CSUMB survey data and the NAVD 88 DEM occur in areas near steep canyons and terrain (Fig. 9).

A random sample of data files were used for comparing the high-resolution lidar topographic files to the DEM. Figure 10 shows a representative histogram of the differences between the DEM and the data. The largest differences between the CSC lidar and the NAVD 88 DEM were located along areas at the coast where the dataset overlaps other high-resolution lidar and at the data boundaries. The largest differences between the NED 1/3 DEM and the NAVD 88 DEM were located the dataset overlaps high-resolution lidar.

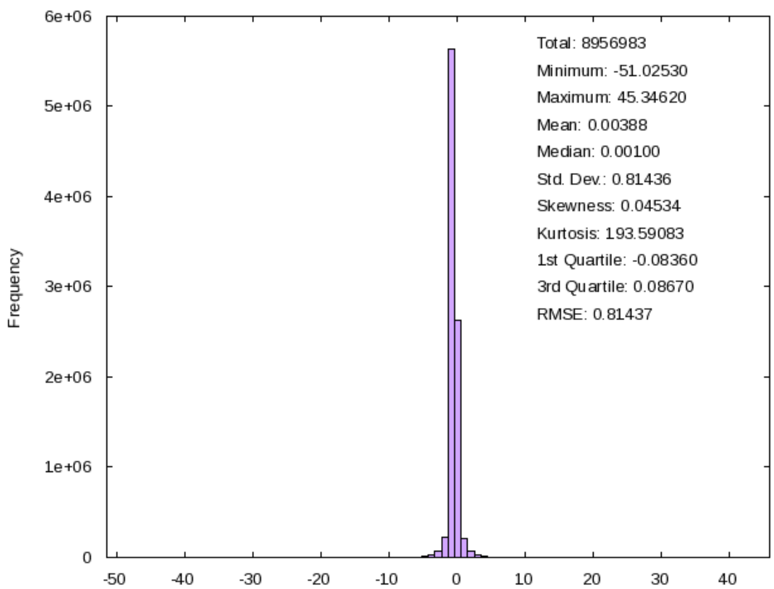

Figure 9. Histogram of the differences between the CSUMB multibeam data compared to the San Diego NAVD 88 DEM.

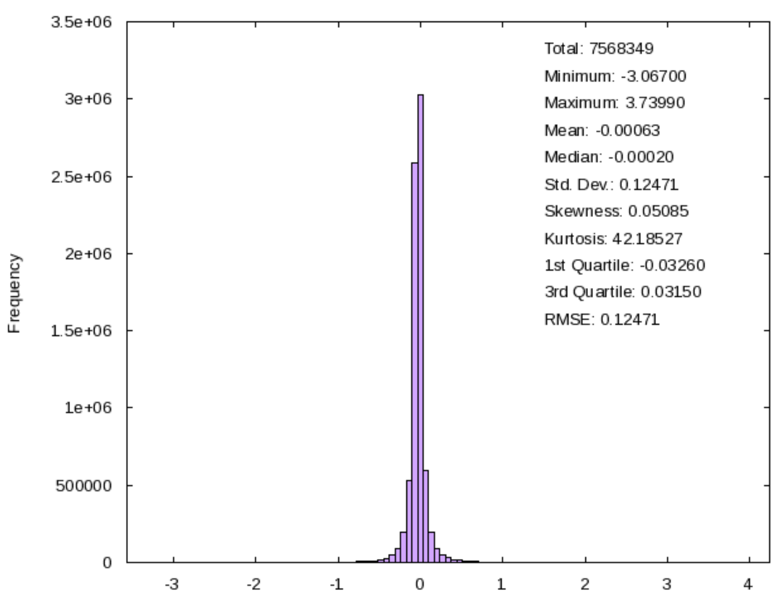

Figure 10. Histogram of the differences between a random selection of the CSC 2009-2011 lidar data compared to the San Diego NAVD 88 DEM.

3.4.5 Comparison with National Geodetic Survey geodetic monuments

A shapefile of the datasheets for NGS geodetic monuments located within the DEM boundary was extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/, see Fig. 12 for monument locations). Shapefile attributes give positions in NAD 83 geographic and elevations at local tidal vertical datum. A histogram of the difference in elevation between the NGS monuments and the San Diego NAVD 88 DEM are shown in figure 11. Comparisons between the NGS monument elevations and the San Diego DEM showed 1032 of the 1290 monuments to be less than 5 meters different. Of the other 258 elevations, 216 were scaled elevations which are positionally less accurate, 50 of the horizontally adjusted monuments were greater than 5 meters difference compared to the DEM elevation values, and of the remaining 2, one had an incorrect position recorded and the other was located on a bridge.

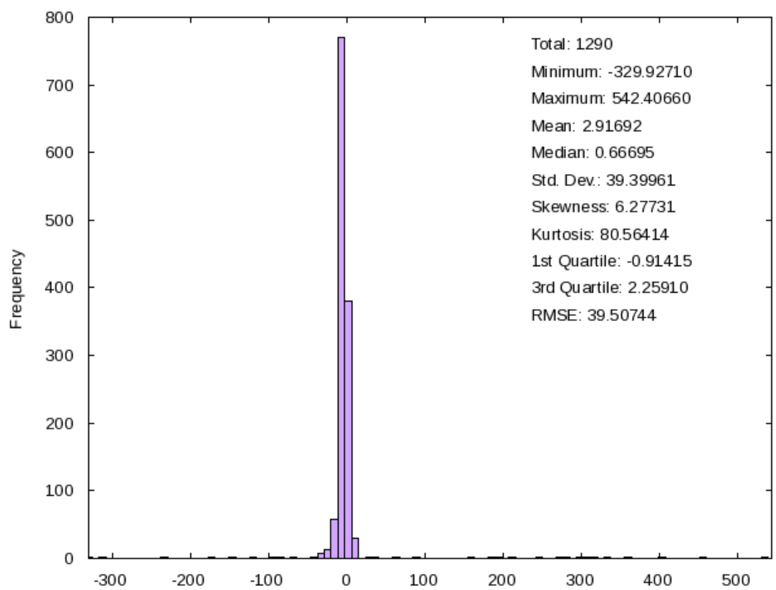

Figure 11. Histogram of the differences between the NGS geodetic monuments and the San Diego NAVD 88 DEM.

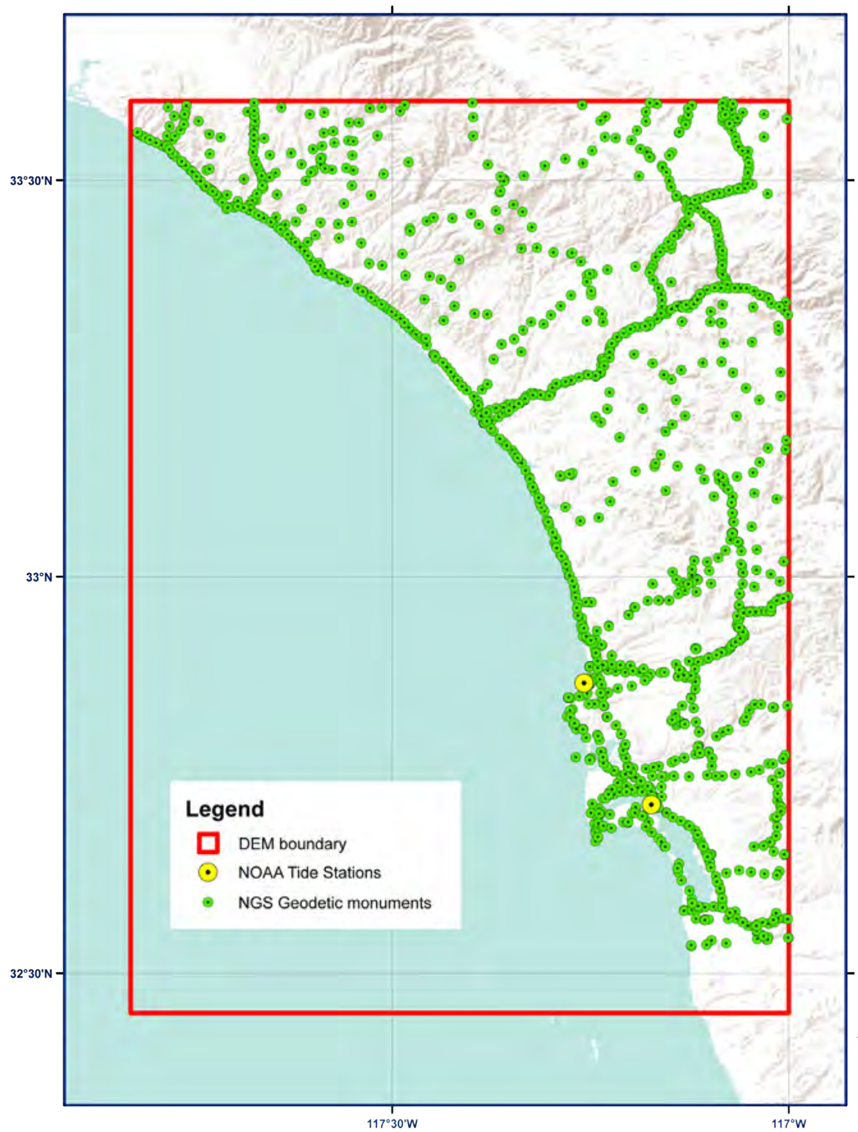

Figure 12. Locations of NGS geodetic monuments and NOAA tide stations in the San Diego DEM region.

4. Summary and Conclusions

An integrated bathymetric–topographic DEM of San Diego, California with cell size of 1/3 arc-second, vertically referenced to MHW was 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*, *FME*, *GDAL*, *GMT*, *Gnuplot*, *GEODAS*, *Quick Terrain Modeler*, *MB-System*, and *VDatum* software.

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

- Conduct shallow water bathymetric-topographic lidar surveys is South San Diego Bay.
- Conduct shallow water hydrographic surveys for lagoons along the coast.

5. Acknowledgments

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Barberopoulou, Aggeliki, Mark R. Legg, Burak Uslu. Reassessing the tsunami risk in major ports and harbors of California: San Diego. Natural Hazards 2010 58:479-496. DOI 10.1007/s11069-010-9681-8.

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Electronic Navigational Chart #18746, 5th Edition, 2011. San Pedro Channel, Dana Point Harbor. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #18758, 10th Edition, 2011. Del Mar Boat Basin. Scale 1:5,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #18765, 2nd Edition, 2011. Approaches to San Diego Bay; Mission Bay. Scale 1:100,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #18772, 12th Edition, 2011. Approaches to San Diego Bay. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #18773, 33rd Edition, 2012. San Diego Bay. Scale 1:12,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #18774, 3rd Edition, 2011. Gulf of Santa Catalina; Del Mar Boat Basin-Camp Pendleton. Scale 1:100,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

San Dieguito Wetlands Restoration Project - Final Restoration Plan. Southern California Edison Company. 2005. http://asset.sce.com/Documents/Environment%20-%20Power%20Generation/san_dieguito_final_restoration_plan.pdf. Accessed February 14, 2012.

7. Data Processing Software

ArcGIS v. 10 – 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 2011 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/.

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

GEODAS v. 5.0.11 – Geophysical Data System, freeware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/.

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

Gnuplot v. 4.2 – shareware 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 – 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/.

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