



**DIGITAL ELEVATION MODEL OF SANTA BARBARA, CALIFORNIA:
PROCEDURES, DATA SOURCES AND ANALYSIS**

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Marine Geology and Geophysics Division
Boulder, Colorado
March 2009

NOAA Technical Memorandum NESDIS NGDC-29

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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 Santa Barbara, California: Procedures, Data Sources and Analysis

1. INTRODUCTION

In December 2008, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a bathymetric–topographic digital elevation model (DEM) of Santa Barbara, California (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (<http://nctr.pmel.noaa.gov/>). The 1/3 arc-second¹ 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). It will be used for tsunami forecasting 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 Santa Barbara DEM.

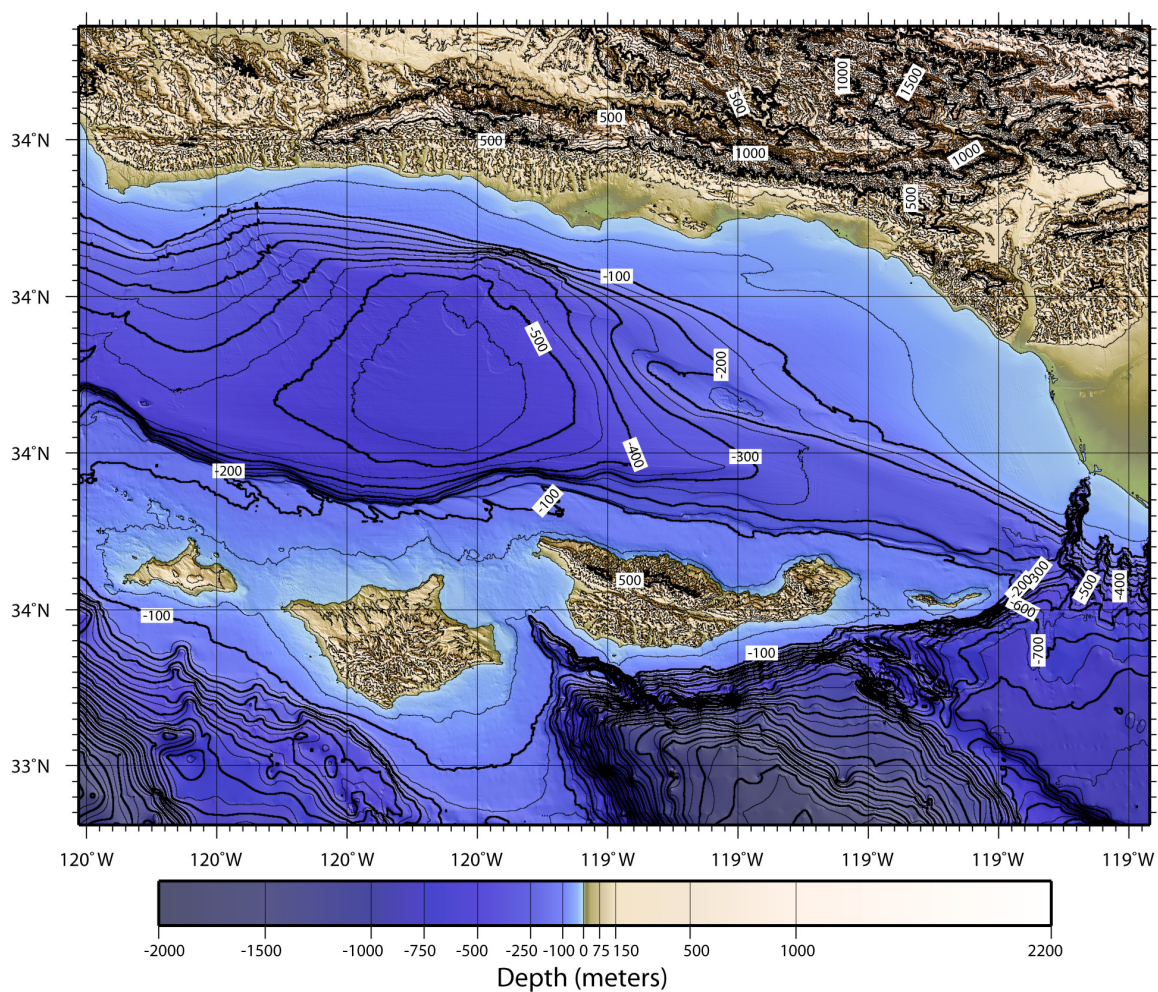


Figure 1. Shaded-relief image of the Santa Barbara DEM. Contour interval is 100 meters.

1. The Santa Barbara DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Santa Barbara, California (34° 25' 33" N, 119° 42' 51" W) 1/3 arc-second of latitude is equivalent to 10.271 meters; 1/3 arc-second of longitude equals 8.511 meters.

2. STUDY AREA

The Santa Barbara DEM covers the coastal region surrounding the town of Santa Barbara, California, from Port Hueneme in the southeast to Point Conception in the northwest, and includes the communities of Port Hueneme, Oxnard, Ventura, Carpinteria, Santa Barbara, Isla Vista, and Goleta (Fig. 2).

The Channel Islands National Marine Sanctuary is located at the southern boundary of the DEM. The Channel Islands are home to many species of marine life, providing recreation, educational, and economic benefits to the surrounding communities as well as research opportunities for the University of California, Santa Barbara. The coastline varies from sandy beaches to rocky sea cliffs. The Santa Clara River, the largest in Southern California, empties into the Pacific Ocean south of Oxnard. It flooded in 2005, causing heavy damage and loss of life.



Figure 2. Overview of the Santa Barbara region on NASA World Wind I-cubed image.

3. METHODOLOGY

The Santa Barbara DEM was constructed to meet PMEL specifications (Table 1), based on input requirements for the development of reference inundation models (RIMs) and standby inundation models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum of 1983 (NAD 83) and mean high water (MHW), for modeling of maximum flooding, respectively.² Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1: PMEL specifications for the Santa Barbara DEM.

Grid Area	Santa Barbara, California
Coverage Area	119.14° to 120.51° W; 33.77° to 34.62° N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	MHW
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the wave's passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEM, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal, state and local agencies and academic institutions including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), Coastal Services Center (CSC); the California State University Seafloor Mapping Laboratory (CSUMB); the U.S. Geological Survey (USGS); the U.S. Army Corps of Engineers (USACE); the California Department of Fish and Game (CDFG), and Ventura and Santa Barbara Counties. Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 horizontal datum and to convert them into ESRI *ArcGIS* shapefiles³. The shapefiles were then displayed with *ArcGIS* to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using *FME*, based upon data from the NOAA Santa Barbara Harbor, Rincon Island, and Bechers Bay tide stations (<http://tidesandcurrents.noaa.gov/>) and OCS's *VDatum* transformation tool. Applied Imagery's *Quick Terrain Modeler* software was used to evaluate processing and gridding techniques.

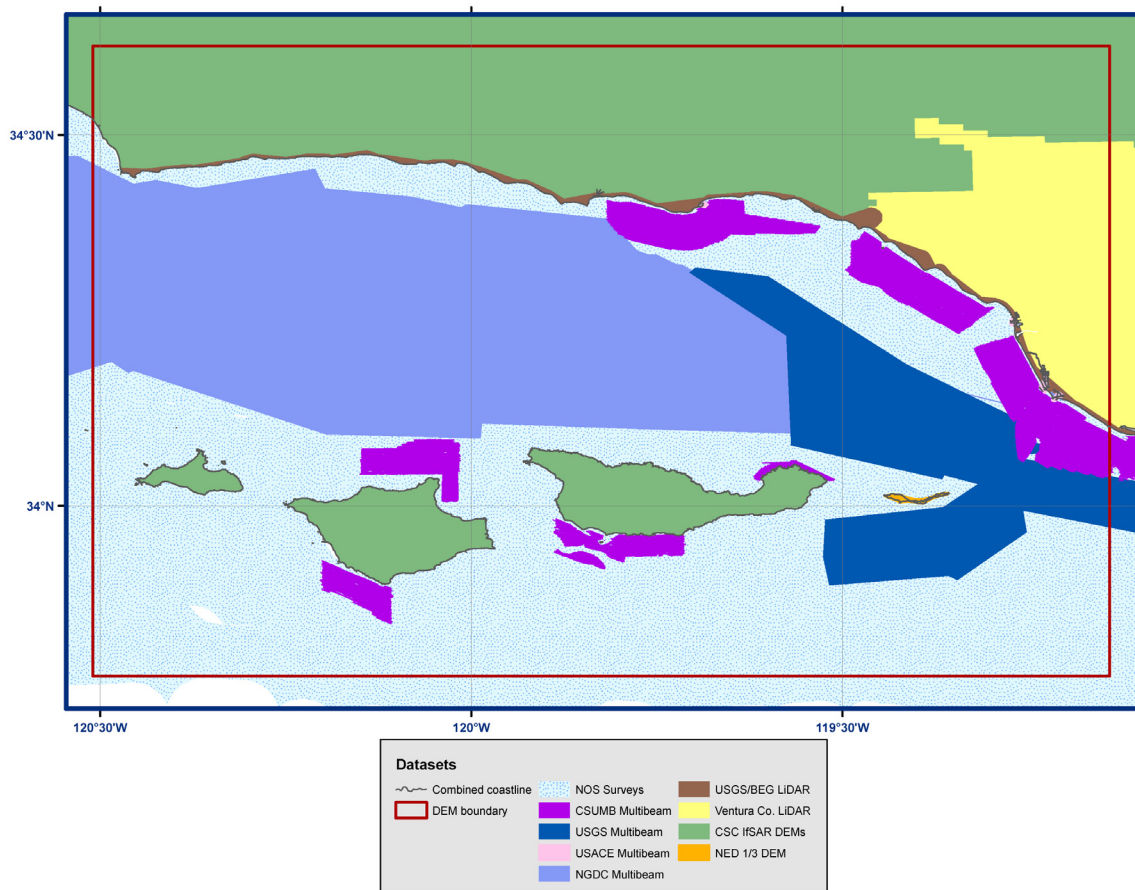


Figure 3. Source and coverage of datasets used in compiling the Santa Barbara DEM.

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

3.1.1 Shoreline

Coastline datasets of the Santa Barbara region were obtained from NOAA, CDFG's Marine Region GIS Unit, and the San Diego Association of Governments (SANDAG) (Table 2; Fig. 4). Of these four datasets, the OCS's Electronic Navigational Charts (ENCs)⁴ and the CDFG coastline were used to develop a "combined coastline" of the Santa Barbara region

Table 2: Shoreline datasets used in the Santa Barbara DEM.

<i>Source</i>	<i>Year</i>	<i>Data Type</i>	<i>Spatial Resolution</i>	<i>Original Horizontal Datum/Coordinate System</i>	<i>Original Vertical Datum</i>	<i>URL</i>
NOAA ENCs	2007	Digital nautical charts	1:40,000 to 1:216,000	WGS 84 geographic	MHW	http://nauticalcharts.noaa.gov/mcd/enc/
CDFG Marine Region	1996	Digitized 1:24,000 USGS quads	1:24,000	NAD 83 geographic	Mean high tide	http://www.dfg.ca.gov/marine/

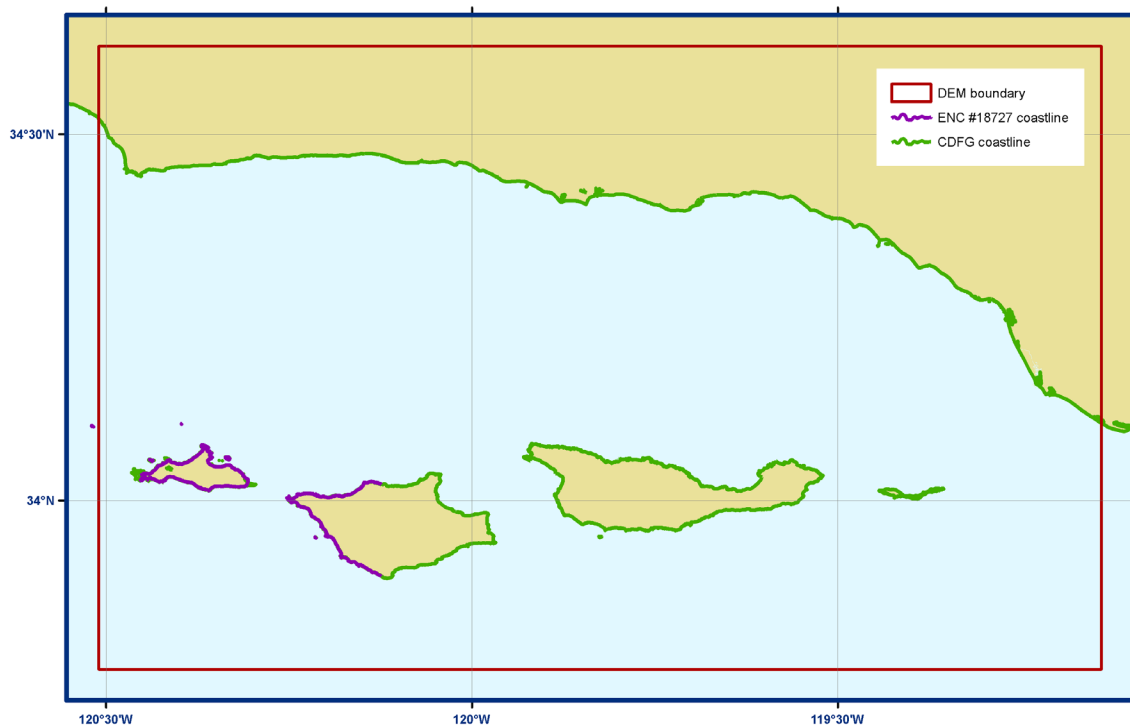


Figure 4. Digital coastline datasets used in developing a combined coastline of the Santa Barbara region.

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://nauticalcharts.noaa.gov/mcd/enc/>]

1) NOAA Electronic Navigational Charts

Four ENC's were available for the Santa Barbara area (Table 3) and downloaded from NOAA's OCS web site (<http://nauticalcharts.noaa.gov/mcd/enc/>). The ENC's are in S-57 format and include coastline data files referenced to MHW. The coastline from ENC #18727 was adjusted to match high-resolution topographic data on San Miguel Island and the western half of Santa Rosa Island, and used in the combined coastline for developing the Santa Barbara DEM.

Table 3: ENC's available in the Santa Barbara region.

<i>Chart #</i>	<i>Title</i>	<i>Edition</i>	<i>Year of Source data</i>	<i>Issue Date</i>	<i>Scale</i>
18700	Point Conception to Point Sur	6	2003	2008	1:216,116
18720	Point Dume to Purisima Point	8	2000	2008	1:232,188
18725	Port Hueneme to Santa Barbara	15	2003	2008	1:50,000
18727	San Miguel Passage	5	1992	2008	1:40,000

2) California Department of Fish and Game Marine Region GIS Unit coastline

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

The combined coastline was compared to the most recent high resolution topography datasets and modified to include coastal features including jetties, rocks, and sand bars. At the mouth of the Santa Clara River, current aerial photography from the California Coastal Records Project (<http://www.californiacoastline.org>) was used to determine the location and shape of the outlet and estuary (Fig. 5). Features such as bridges, piers, and docks were removed using *ArcMap* editing tools. The combined coastline was also compared to recent high resolution bathymetric data located in the harbor at Port Hueneme, Channel Islands, Ventura, and Santa Barbara and edited to ensure inclusion of complete bathymetric surveys. An xyz file of the combined coastline was generated using *GEODAS* for use in compiling the Santa Barbara DEM.



Copyright (C) 2002-2008 Kenneth & Gabrielle Adelman, California Coastal Records Project, <http://www.Californiacoastline.org>

Figure 5. 2008 aerial photos of the Santa Clara River mouth.

3.1.2 Bathymetry

Bathymetric datasets available for use in the compilation of the Santa Barbara DEM include 56 NOS hydrographic surveys; 12 CSUMB near-shore multibeam swath sonar surveys; one USGS multibeam swath bathymetric sonar survey covering the deeper areas within the Santa Barbara Channel; USACE multibeam data for the harbors at Santa Barbara, Ventura, Channel Islands Harbor, and Port Hueneme; and 10 multibeam swath sonar surveys downloaded from the NGDC multibeam bathymetry database (Table 4; Fig. 6).

Table 4: Bathymetric datasets used in compiling the Santa Barbara DEM.

<i>Source</i>	<i>Year</i>	<i>Data Type</i>	<i>Spatial Resolution</i>	<i>Original Horizontal Datum/ Coordinate System</i>	<i>Original Vertical Datum</i>	<i>URL</i>
NGDC	1930 to 2005	NOS hydrographic survey soundings	Ranges from 1 meter to 1 kilometer (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 27, NAD 83 geographic or NAD 83 UTM 11	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
CSUMB	2003 to 2008	Multibeam swath sonar	2 to 3 meters	WGS 84 UTM zone 10N and 11N	MLLW	http://seafloor.csumb.edu/
USGS	2004	Multibeam swath sonar	15 meters	WGS 84 geographic	MLLW	http://geopubs.wr.usgs.gov/open-file/of01-179/
USACE	2007 to 2008	Multibeam swath sonar	1 to 3 meter grids	NAD 83 California State Plane zone V (meters)	MLLW	http://www.spl.usace.army.mil/cms/index.php
NGDC	1989 to 1998	Multibeam swath sonar	5 meters	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html

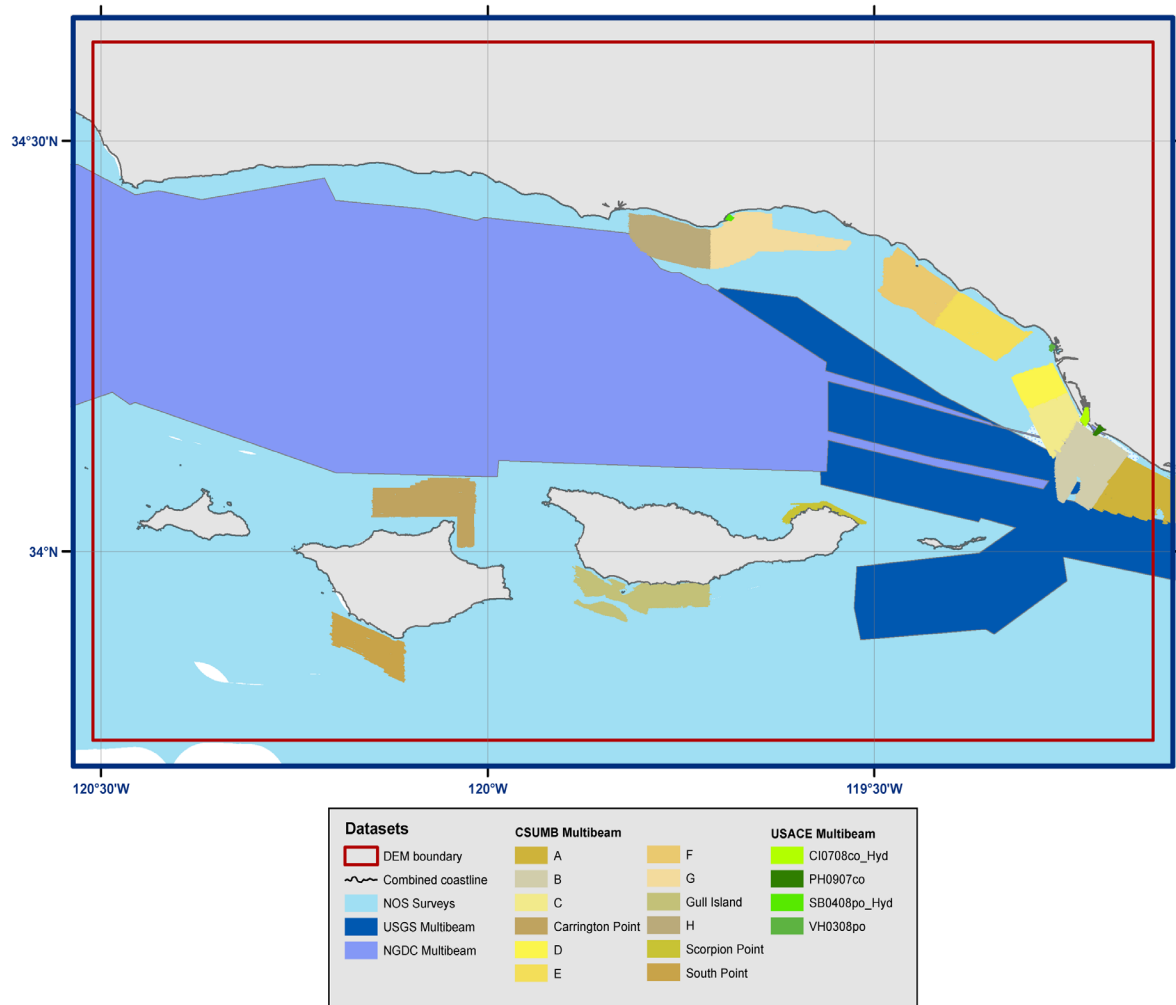


Figure 6. Spatial coverage of the bathymetric datasets used in compiling the Santa Barbara DEM.

1) National Ocean Service hydrographic survey data

A total of 56 NOS hydrographic surveys conducted between 1930 and 2005 were available for use in developing the Santa Barbara DEM. The hydrographic survey data were originally vertically referenced to mean lower low water (MLLW) and horizontally referenced to either NAD 27 or NAD 83 datums. Only 48 of the 56 surveys were used in building the Santa Barbara DEM, as some older surveys have been superseded (Table 5; Fig. 7).

Data point spacing for the NOS surveys varied by collection date. In general, earlier surveys had greater point spacing than more recent surveys. Surveys were extracted from NGDC's NOS Hydrographic Survey Database (<http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html>) referenced to NAD 83. The most recent survey, H11501, was provided by the NOS Pacific Hydrographic Branch in BAG format and convert to xyz using *CARIS Bathy DataBase 2.0*. The data were then converted to NAD 83 using *FME* software, an integrated collection of spatial extract, transform, and load tools for data transformation. The surveys were subsequently clipped to a polygon 0.05 degrees (~5%) larger than the Santa Barbara DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW using *VDatum* (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 the topographic and bathymetric datasets, the combined coastline, and NOS Raster Navigational Charts (RNCs). The surveys were clipped to remove soundings that overlap the more recent multibeam swath sonar surveys and where soundings from older surveys have been superseded by more recent NOS surveys.

Table 5: Digital NOS hydrographic surveys available within the Santa Barbara DEM boundary.

<i>NOS Survey ID</i>	<i>Year of Survey</i>	<i>Survey Scale</i>	<i>Original Vertical Datum</i>	<i>Original Horizontal Datum of Digital Records</i>
H05030*	1930	80,000/20,000	MLLW	NAD 27
H05419*	1933	5,000	MLLW	NAD 27
H05420	1933	10,000	MLLW	NAD 27
H05426	1933	10,000	MLLW	NAD 27
H05463*	1933	10,000	MLLW	NAD 27
H05498*	1933	10,000	MLLW	NAD 27
H05499*	1933	10,000	MLLW	NAD 27
H05502	1933	10,000	MLLW	NAD 27
H05503	1933	10,000	MLLW	NAD 27
H05624	1933	10,000	MLLW	NAD 27
H05625	1933	10,000	MLLW	NAD 27
H05626*	1933	10,000	MLLW	NAD 27
H05627	1933	10,000	MLLW	NAD 27
H05445	1933	20,000	MLLW	NAD 27
H05464*	1933	5,000	MLLW	NAD 27
H05508	1933	10,000	MLLW	NAD 27
H05775	1933	120,000	MLLW	NAD 27
H05425*	1933	10,000	MLLW	NAD 27
H05446	1933/34	40,000	MLLW	NAD 27
H05660	1934	20,000	MLLW	NAD 27
H05661	1934	5,000	MLLW	NAD 27
H05509	1934	10,000	MLLW	NAD 27
H05746	1934	40,000	MLLW	NAD 27
H05776	1934	120,000	MLLW	NAD 27
H05830	1934	40,000	MLLW	NAD 27
H05849	1934	40,000	MLLW	NAD 27
H05662	1935	10,000	MLLW	NAD 27
H05683	1935	20,000	MLLW	NAD 27
H05695	1935	20,000	MLLW	NAD 27

<i>NOS Survey ID</i>	<i>Year of Survey</i>	<i>Survey Scale</i>	<i>Original Vertical Datum</i>	<i>Original Horizontal Datum of Digital Records</i>
H05696	1935	10,000	MLLW	NAD 27
H05699	1935	20,000	MLLW	NAD 27
H05700	1935	20,000	MLLW	NAD 27
H05701	1935	20,000	MLLW	NAD 27
H05773	1935	40,000	MLLW	NAD 27
H05850	1935	40,000	MLLW	NAD 27
H05851	1935	80,000	MLLW	NAD 27
H05860	1935	40,000	MLLW	NAD 27
H05861	1935	80,000	MLLW	NAD 27
H06258	1937	80,000	MLLW	NAD 27
H06259	1937	80,000	MLLW	NAD 27
H09666	1976	5,000	MLLW	NAD 27
H09667	1976	10,000	MLLW	NAD 27
H09725	1977	20,000	MLLW	NAD 27
H09728	1977	20,000	MLLW	NAD 27
H09730	1977	20,000	MLLW	NAD 27
H09732	1977	20,000	MLLW	NAD 27
H09741	1978	10,000	MLLW	NAD 27
H09751	1978	5,000	MLLW	NAD 27
H09752	1978	20,000	MLLW	NAD 27
H09740	1978	5,000	MLLW	NAD 27
H10161	1984	20,000	MLLW	NAD 27
H10164	1984	20,000	MLLW	NAD 27
H10165	1984/85	10,000	MLLW	NAD 27
H10171	1985	20,000	MLLW	NAD 27
H11024	2001	10,000	MLLW	NAD 83
H11501	2005	5,000	MLLW	NAD 83 UTM 11 N meters

* survey not used in building the Santa Barbara DEM

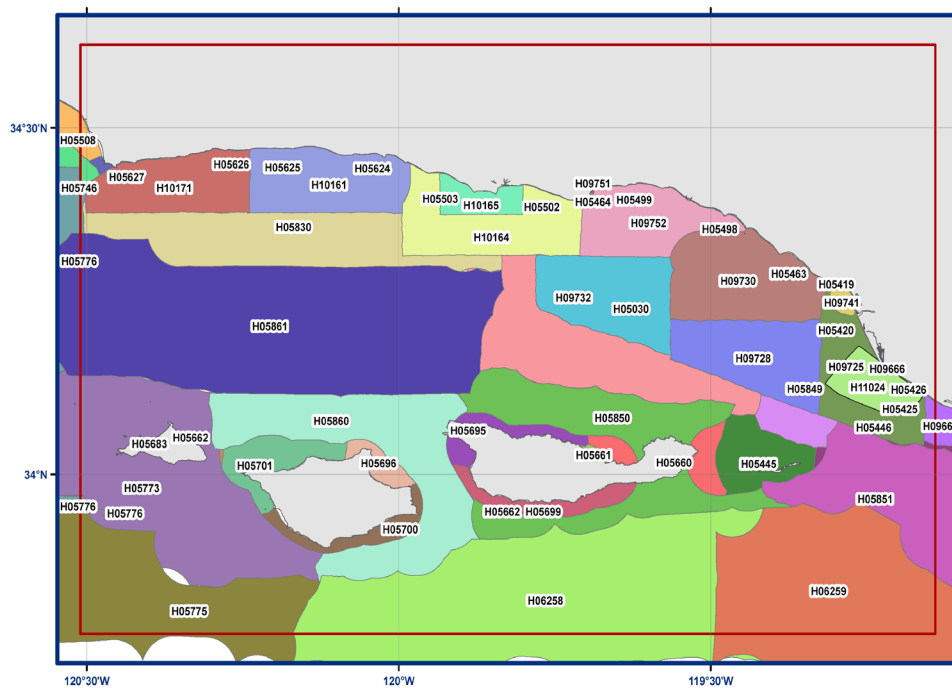


Figure 7. Digital NOS hydrographic survey coverage in the Santa Barbara region. DEM boundary in red.

2) California State University Seafloor Mapping Laboratory multibeam sonar surveys

Twelve near shore multibeam swath sonar surveys were downloaded from the CSUMB web site (<http://seafloor.csumb.edu/>) as gridded data or xyz files (Table 6, Fig. 8). The surveys were collected from 2003 to 2008, and referenced to WGS 84, UTM zone 10N, or zone 11N and MLLW vertical datum. The files were converted to NAD 83 and to MHW using the *VDatum* transformation tool. The surveys were reviewed and edited as necessary to remove anomalous data points using QT Modeler and *ArcMap*.

Table 6: CSUMB multibeam sonar surveys used in compiling the Santa Barbara DEM.

<i>Survey ID</i>	<i>Year</i>	<i>Original Vertical Datum</i>	<i>Original Horizontal Datum</i>	<i>Type</i>
Channel Islands Santa Rosa Island – Carrington Point	2003	MLLW	WGS1984 UTM zone 10N	3 meter grid
Channel Islands Santa Rosa Island – South Point	2003	MLLW	WGS1984 UTM zone 10N	3 meter grid
Channel Islands Santa Cruz Island – Gull Island	2003	MLLW	WGS1984 UTM zone 11N	3 meter grid
Channel Islands Santa Cruz Island – Scorpion Point	2006	MLLW	WGS1984 UTM zone 11N*	2 meter xyz
Santa Barbara Channel A	2008	MLLW	WGS1984 UTM zone 10N*	2 meter xyz
Santa Barbara Channel B	2008	MLLW	WGS1984 UTM zone 10N*	2 meter xyz
Santa Barbara Channel C	2008	MLLW	WGS1984 UTM zone 10N*	2 meter xyz
Santa Barbara Channel D	2008	MLLW	WGS1984 UTM zone 10N*	2 meter xyz
Santa Barbara Channel E	2007	MLLW	WGS1984 UTM zone 10N*	2 meter xyz
Santa Barbara Channel F	2007	MLLW	WGS1984 UTM zone 10N*	2 meter xyz
Santa Barbara Channel G	2007	MLLW	WGS1984 UTM zone 10N*	2 meter xyz
Santa Barbara Channel H	2007	MLLW	WGS1984 UTM zone 10N*	2 meter xyz

* xyz files are assumed to be in the same horizontal datum as the grids.

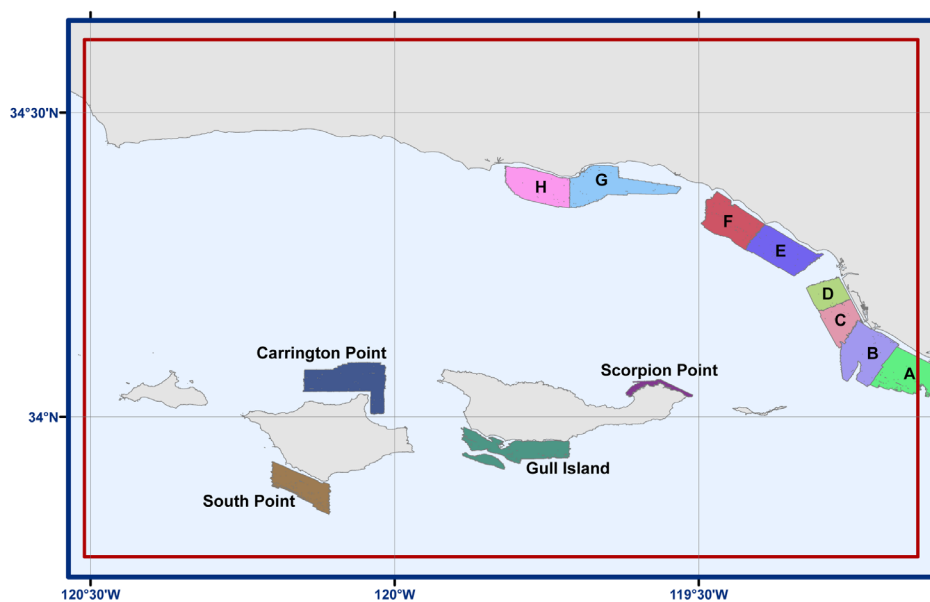


Figure 8. Spatial coverage of CSUMB multibeam swath sonar surveys used in compiling the Santa Barbara DEM.

3) U.S. Geological Survey multibeam swath sonar survey

The USGS conducted a multibeam swath sonar survey along the California coast within the DEM boundary (Fig. 9). The 15-meter gridded survey data were downloaded in ASCII xyz format from the USGS Data Catalog web site (<http://pubs.usgs.gov/of/2005/1153/>) in WGS 84 geographic horizontal datum and MLLW vertical datum. The data were converted from MLLW to MHW using the *VDatum* transformation tool.

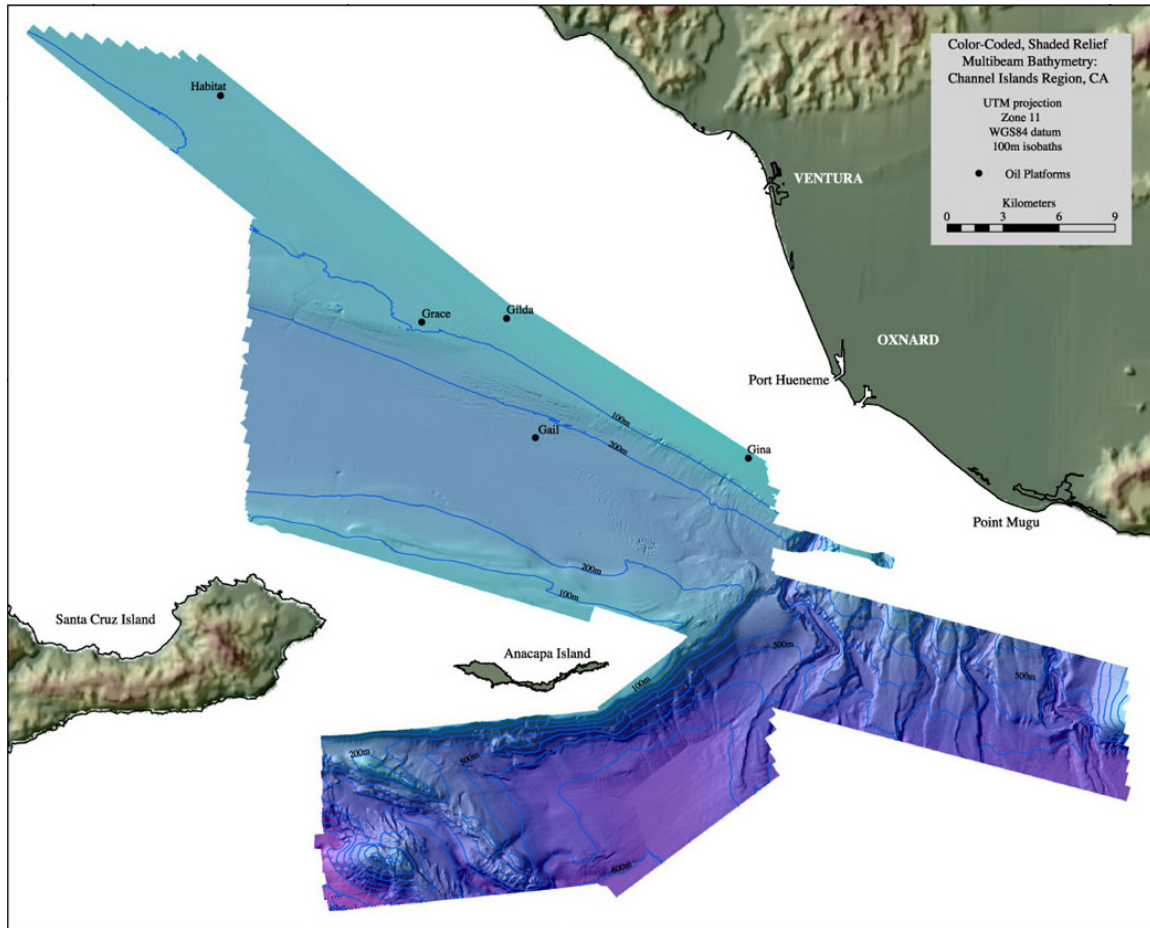


Figure 9. Shaded-relief image showing spatial coverage of the 2004 USGS multibeam swath sonar survey. Image taken from USGS Open File Report 2005-1153.

4) U.S. Army Corps of Engineers multibeam bathymetric surveys

USACE dredges and maintains the harbors at Santa Barbara, Ventura, and Port Hueneme (Fig.10). Four multibeam bathymetric surveys were provided to NGDC in gridded form for use in building the Santa Barbara DEM. The 1 to 3 meter resolution grids provide dense coverage at the entrance and within the harbors. The surveys were converted to point shapefiles and transformed to NAD 83 using *FME* and MHW using the *VDatum* tool.

Table 7: USACE multibeam bathymetric surveys used in compiling the Santa Barbara DEM.

<i>Survey</i>	<i>Date</i>	<i>Type</i>	<i>Resolution</i>	<i>Horizontal Datum</i>	<i>Vertical Datum</i>
Channel Islands Harbor	2008	Multibeam swath sonar	1 meter grid	NAD 83 California State Plane zone V	MLLW
Port Hueneme	2007	Multibeam swath sonar	3 meter grid	NAD 83 California State Plane zone V	MLLW
Santa Barbara Harbor	2008	Multibeam swath sonar	1 meter grid	NAD 83 California State Plane zone V	MLLW
Ventura Harbor	2008	Multibeam swath sonar	1 meter grid	NAD 83 California State Plane zone V	MLLW

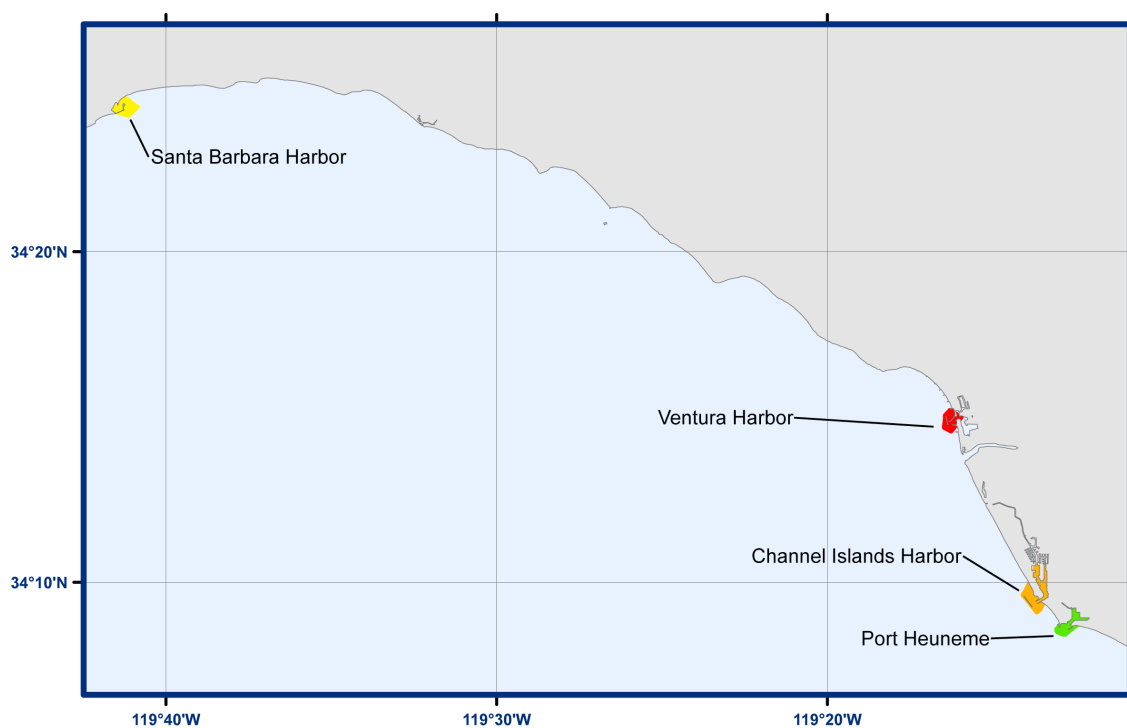


Figure 10. Spatial coverage of USACE multibeam bathymetric surveys used in compiling the Santa Barbara DEM.

5) NGDC multibeam swath sonar surveys

Ten multibeam swath sonar surveys from University of California/Scripps Institute of Oceanography (SIO), Monterey Bay Aquarium Research Institute (MBARI) and Columbia University/Lamont-Doherty Earth Observatory (CU/LDEO) were downloaded from the NGDC Multibeam Bathymetry Database (<http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html>; Table 8). The most recent survey, Channel, covers a large portion of the Santa Barbara Channel and supersedes the earlier nine surveys available (Fig. 11). This was the only survey used in compiling the Santa Barbara DEM. The survey was gridded using *MB-System* into smaller sections and converted to xyz format, then transformed from MSL to MHW using the *VDatum* tool. The eastern section of the survey approaches and enters the Port Hueneme Harbor. Elevations in this area were not consistent with the USACE survey or NOS survey H11024 and were removed using *FME* (Fig. 12).

Table 8: NGDC multibeam sonar surveys available in the Santa Barbara DEM region.

<i>Survey ID</i>	<i>Year</i>	<i>Original Vertical Datum</i>	<i>Institute</i>	<i>Ship</i>
CALF01RR	1996	Assumed MSL	SIO	Roger Revelle
CALF03RR	1996	Assumed MSL	SIO	Roger Revelle
Channel	1998	Assumed MSL	MBARI	Ocean Alert
EW9414	1994	Assumed MSL	CU/LDEO	Ewing
NPAL98MV	1998	Assumed MSL	SIO	Melville
REM01MV	1993	Assumed MSL	SIO	Melville
REM02MV	1993	Assumed MSL	SIO	Melville
RNDB18WT	1989	Assumed MSL	SIO	Thomas Washington
TUNE01WT	1991	Assumed MSL	SIO	Thomas Washington
WEST15MV	1995	Assumed MSL	SIO	Melville

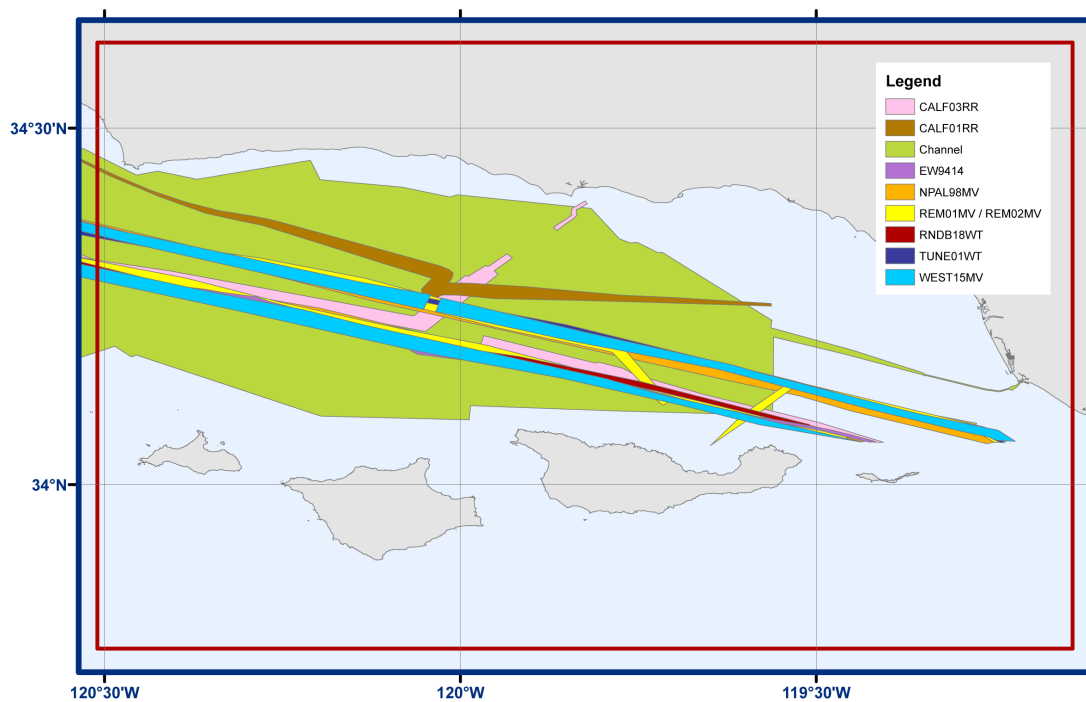


Figure 11. Spatial coverage of NGDC multibeam bathymetric data used in compiling the Santa Barbara DEM.

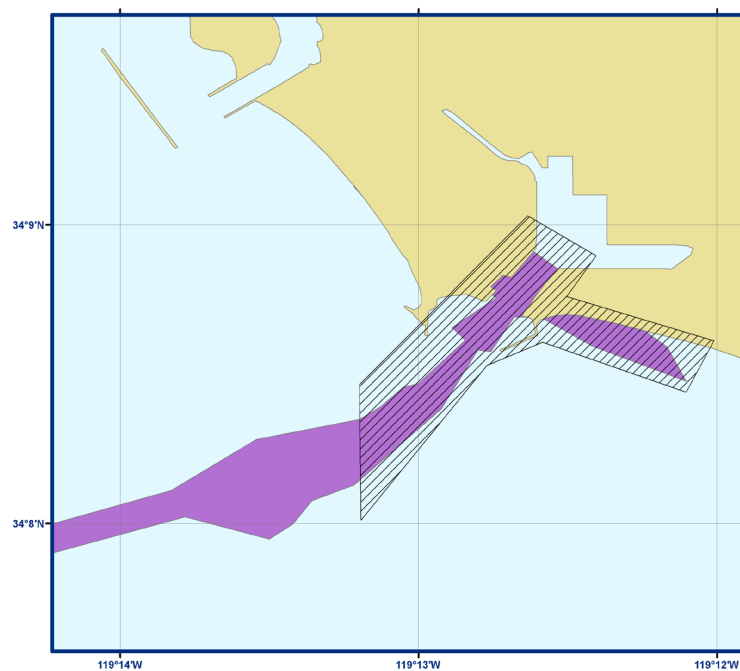


Figure 12. Detail of section of Channel multibeam bathymetric survey removed from the dataset.
Purple denotes survey coverage, cross hatched region was deleted.

3.1.3 Topography

Five topographic datasets in the Santa Barbara region were obtained from Ventura County, USGS, CSC, and OCS, and used to build the Santa Barbara DEM (Table 9; Fig. 13). NGDC evaluated, but did not use, the Shuttle Radar Topography Mission (SRTM) Elevation 1 arc-second DEM available from USGS or CSC lidar data from 1998. NGDC digitized some elevation points to supplement the available datasets at Santa Barbara, Ventura, Channel Islands, and Port Hueneme Harbors. The lidar data and topographic DEMs were referenced to North American Vertical Datum of 1988 (NAVD88).

Table 9: Topographic datasets used in compiling the Santa Barbara DEM.

<i>Source</i>	<i>Year</i>	<i>Data Type</i>	<i>Spatial Resolution</i>	<i>Original Horizontal Datum/Coordinate System</i>	<i>Original Vertical Datum</i>	<i>URL</i>
USGS/BEG	2005	Lidar	1 meter	NAD 83 UTM zone 11N (meters)	NAVD88	
Ventura County	2005	Bare-earth lidar	1 meter	NAD 83 California State Plane V (feet)	NAVD88	
CSC	2002/2003	IfSAR DEMs	3 meters	WGS 84 (geographic)	NAVD88	http://csc.noaa.gov/digitalcoast/
USGS	1999-2005	NED DEM	1/3 arc-second	NAD 83 (geographic)	NAVD88	http://ned.usgs.gov/
NGDC		Digitized elevation points	~2.5 meters	WGS 84 (geographic)	MHW	
NOAA ENC		Digital nautical charts		WGS 84 (geographic)	MHW	

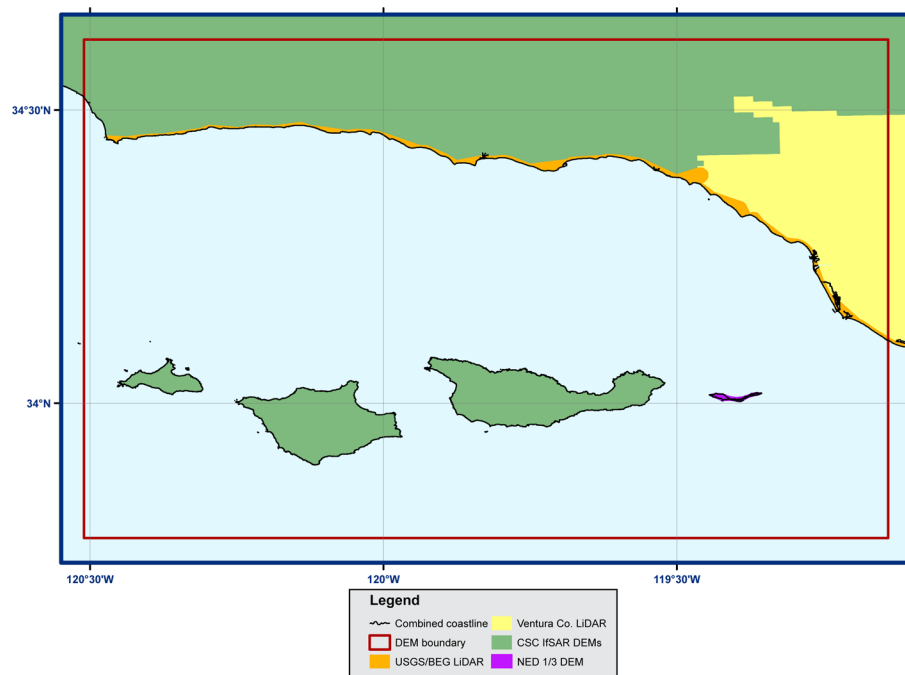


Figure 13. Spatial coverage of the topographic datasets used in compiling the Santa Barbara DEM.

1) U.S. Geological Survey/Bureau of Economic Geology bare-earth lidar

USGS provided NGDC with bare-earth coastal lidar data (Fig. 14) surveyed in October 2005 by the Bureau of Economic Geology (BEG), University of Texas at Austin. The data cover the California coastline from Point Mugu to Point Conception and was collected to monitor coastal change. The ASCII data files were converted to point shapefiles and used to adjust the combined coastline. Anomalous elevation values over water were clipped to the combined coastline with the exception of those in the Santa Clara River outlet (Fig. 15). Elevation values in the river channel were more effective at creating a shallow depth for the channel in the final DEM than removing the values in the channel.

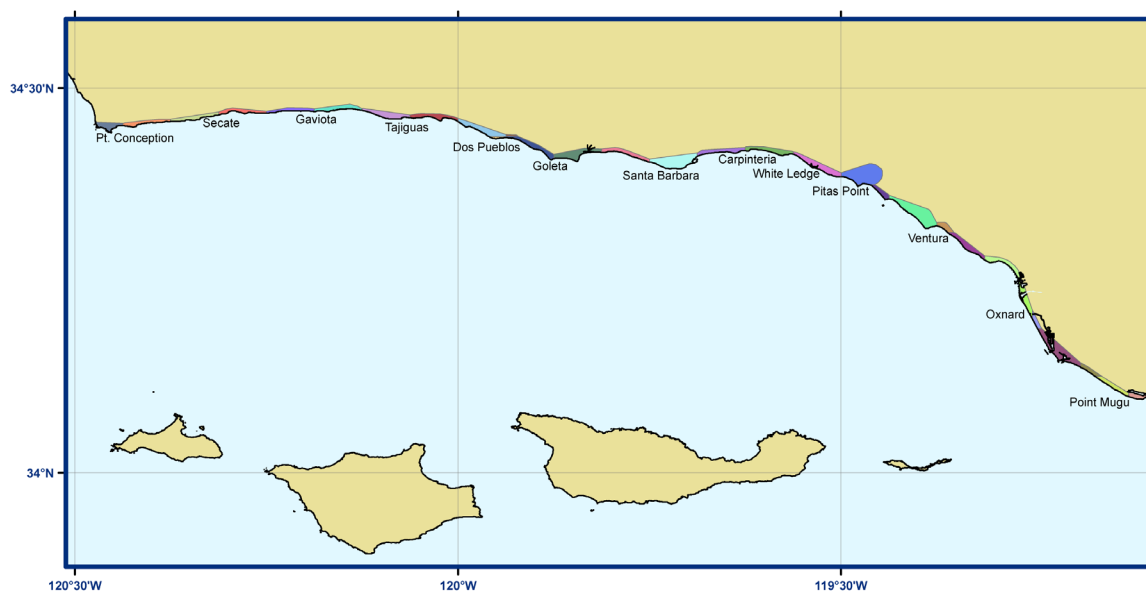


Figure 14. Spatial coverage of USGS/BEG lidar data used in compiling the Santa Barbara DEM.

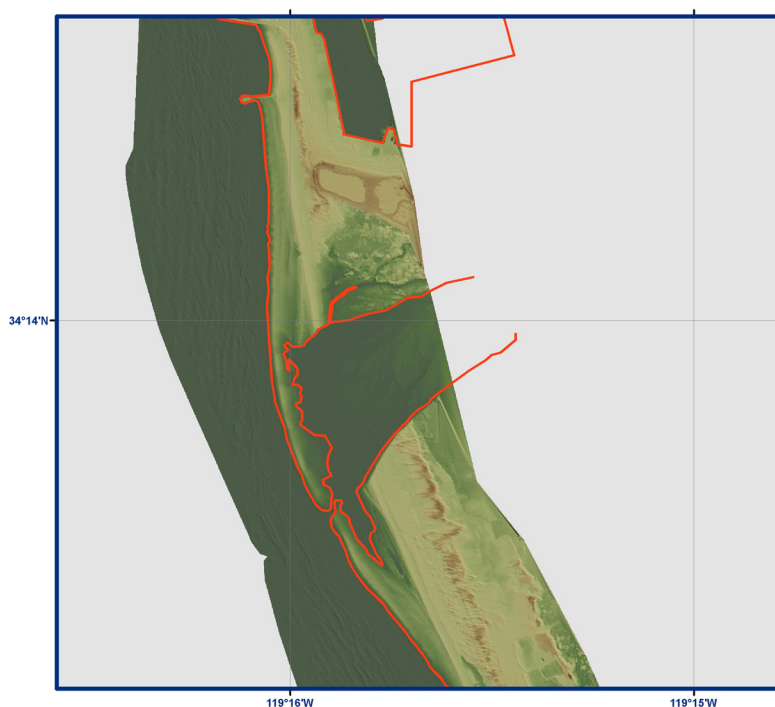


Figure 15. Surface model of unclipped USGS/BEG lidar data at the mouth of the Santa Clara River. Note returns from waves nearing beach.

2) Ventura County lidar

Ventura County provided NGDC with bare-earth lidar point data flown in February of 2005 (Fig. 16). The point data were transformed to NAD 83 and MHW with *FME* and clipped to the combined coastline except within the Santa Clara River channel. Data were not clipped in the channel because there were no bathymetric surveys available. The returns reflected a more accurate surface than if clipping it to the coastline (Fig. 17).

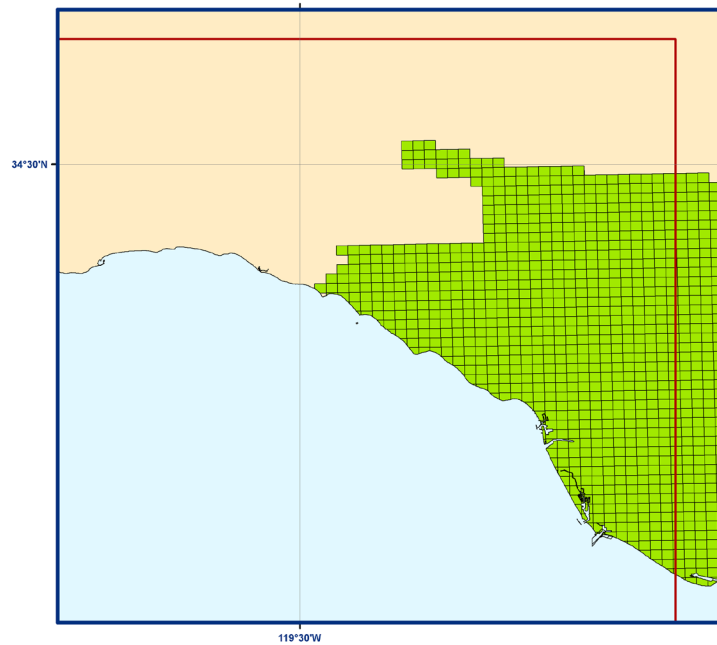


Figure 16. Spatial coverage of Ventura County lidar data used in compiling the Santa Barbara DEM.

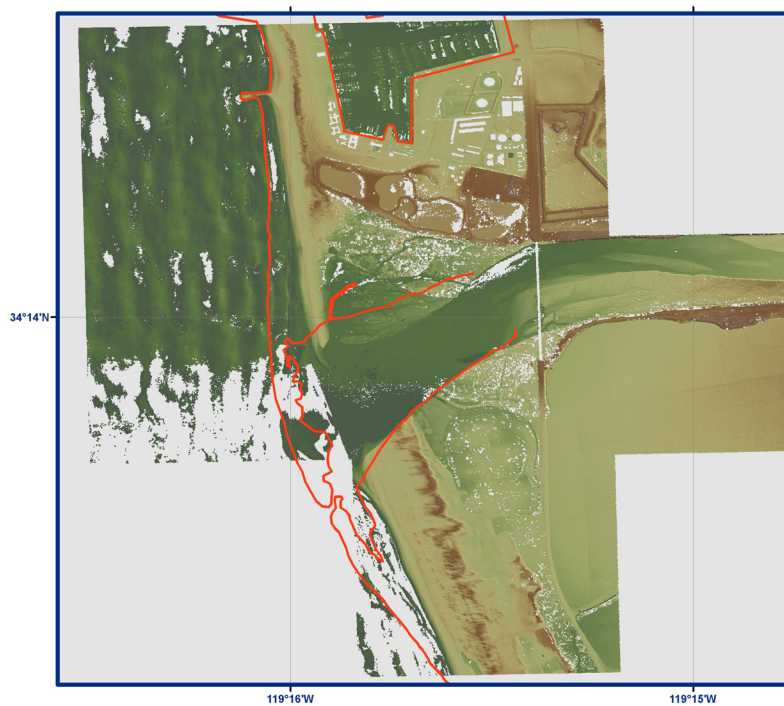


Figure 17. Surface model of unclipped Ventura County lidar data at the mouth of the Santa Clara River.
Note returns from waves nearing beach.

3) Coastal Services Center IfSAR DEMs

Interferometric Synthetic Aperture Radar (IfSAR) DEMs were downloaded from the CSC web site covering Santa Barbara County and the Channel Islands. The dataset was developed to support watershed analysis in the Southern California coastal environment. The DEMs were clipped to the coastline and transformed to MHW using *ArcCatalog* tools, and converted to xyz format with *FME*. The dataset is not processed to bare earth and was not edited prior to building the Santa Barbara DEM. The IfSAR data were used primarily for inland areas of Santa Barbara County and the Channel Islands, excluding Anacapa Island. DEM data encompassing Anacapa Island contained topographic values inconsistent with the rest of the dataset (Fig. 18).

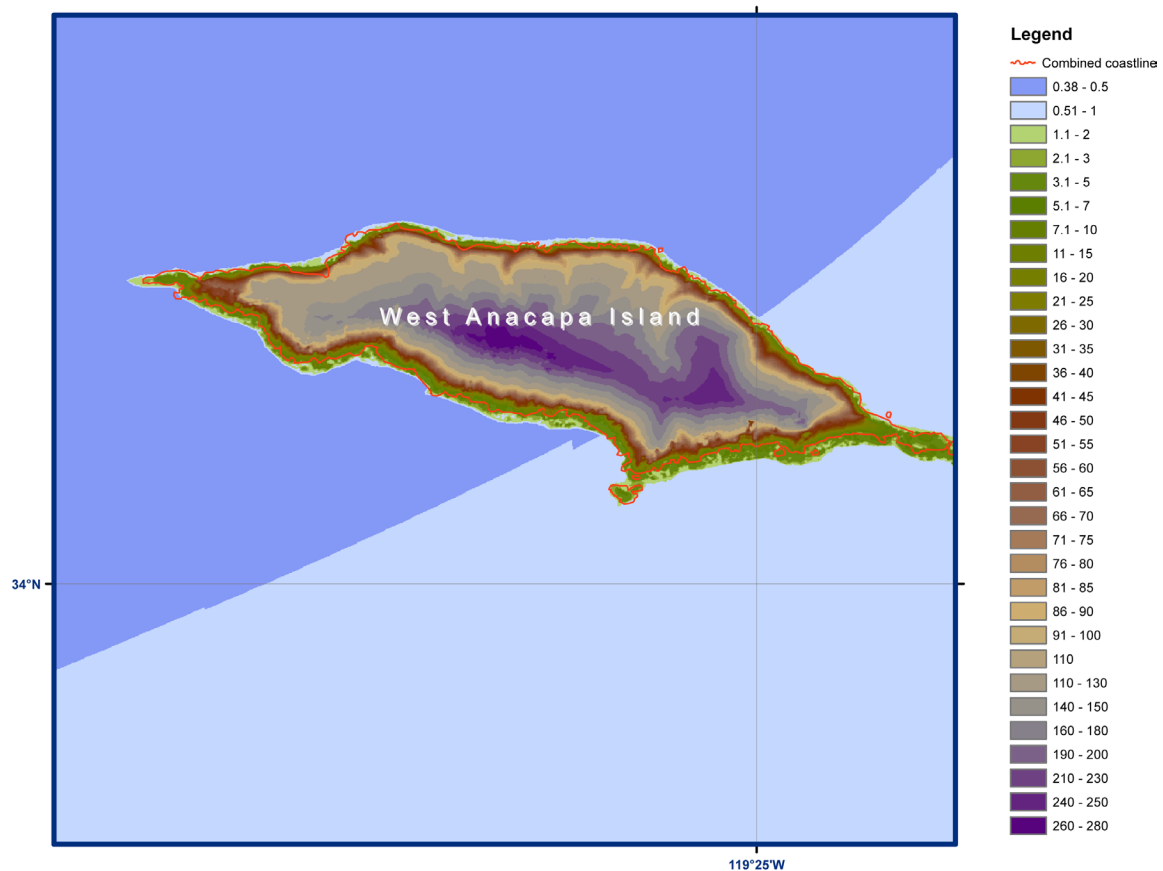


Figure 18. CSC IfSAR DEM of West Anacapa Island. Blue shades over ocean have elevation at MHW of .38 to 1 meter.

4) U.S. Geological Survey NED topographic DEM

USGS's National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the Santa Barbara region⁵. Data are in NAD 83 geographic coordinates and NAVD88 vertical datum (meters), and are available for download as raster DEMs. The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution (see the USGS Seamless web site for specific source information: <http://seamless.usgs.gov>). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys; it has been revised using data collected in 1999 and 2005. The NED data were used on Anacapa Island as a substitution for the higher resolution IfSAR data available throughout the DEM region. The NED DEM included "zero" elevation values over the open ocean, which were removed from the dataset by clipping to the combined coastline. The data were then converted to xyz points and filtered to remove "zero" elevations within the combined coastline.

5) NGDC digitized elevation points

To represent the jetties at Santa Barbara, Ventura, Channel Islands, and Port Hueneme Harbors (Fig. 19), NGDC created digital representations of the features using *ArcMap* and assigned elevations. The elevation for the Santa Barbara breakwater was set at 2.5 meters. The elevations for the features at Port Hueneme and Channel Islands harbors were set at 2.5 meters and features at Ventura Harbor were set at 4.5 and 5.5 meters, referencing the USACE's Enterprise Coastal Inventory Database (<http://chl.erdg.usace.army.mil/chl.aspx?p=s&a=Projects;246>). The point spacing for all digitized features is ~2.5 meters to ensure an even surface on the tops of the features.

5. 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 Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc-second), and elevation units (meters). The horizontal datum is NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc-second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site]



Figure 19. Location of the harbor features digitized by NGDC to represent the jetties and breakwaters shown on Google Earth with USACE overlay of features. A) Santa Barbara breakwater. B) Ventura Harbor jetties and breakwater. C) Port Hueneme and Channel Islands Harbor jetties and breakwaters.

6) NOAA Electronic Navigational Chart extracted land elevation points

Many of the offshore rocks and islets in the Channel Islands were not fully resolved in the digital topographic elevation datasets. To include these features, land elevation points were extracted from ENC #18727 and digitized referencing RNCs #18728 and #18729 (Fig. 20). ENC land elevation data are referenced to MHW and WGS 84. RNC elevation data are in units of feet and were converted to meters before incorporating into the final gridding process.

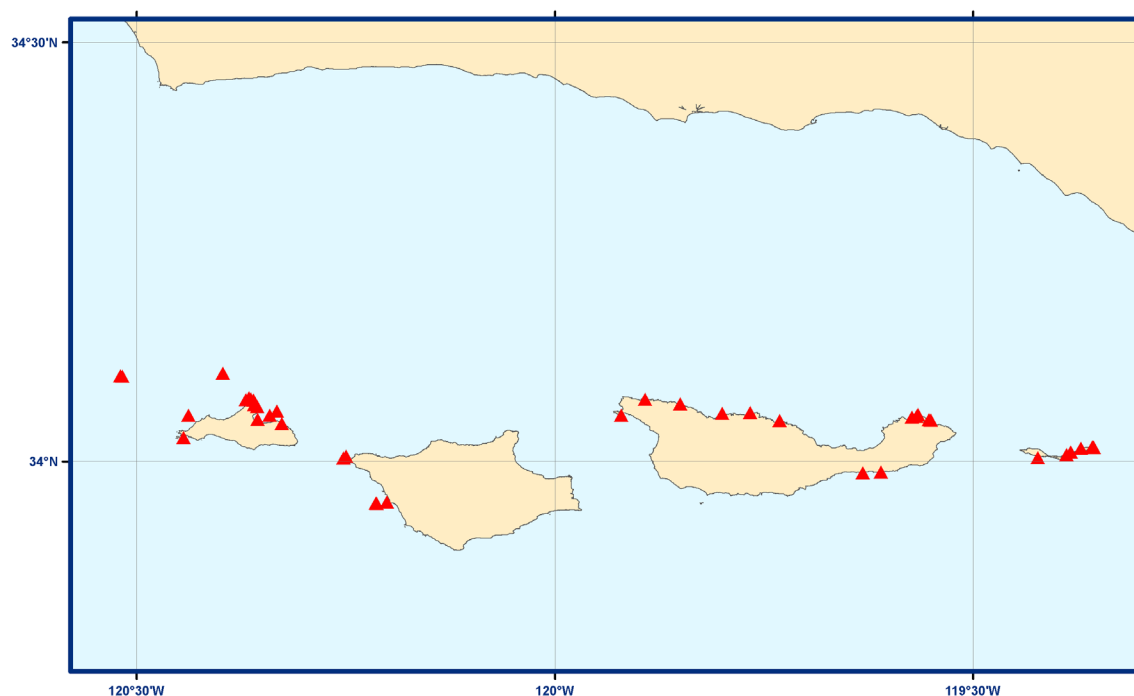


Figure 20. Location of extracted and digitized land elevations shown as red triangles in the Channel Islands region.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Santa Barbara DEM were originally referenced to a number of vertical datums including MLLW, mean sea level (MSL), and NAVD88. All datasets were transformed to MHW to provide maximum flooding for inundation modeling.

1) Bathymetric data

The NOS hydrographic surveys, and multibeam swath sonar surveys were transformed from MLLW and MSL to MHW, using the *VDatum* transformation tool (Fig. 21).

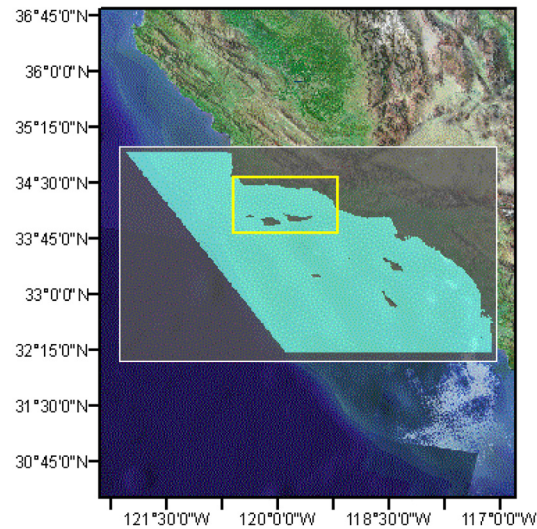


Figure 21. Image of generalized coverage of *VDatum* transformation tool for the Southern California region. Santa Barbara DEM boundary in yellow.

2) Topographic data

The USGS NED 1/3 arc-second DEM, lidar data, and the CSC IfSAR DEMs were originally referenced to NAVD88. As the *VDatum* transformation tool is not available further inland, conversion to MHW using *FME* software and *ArcCatalog*, was accomplished by adding a constant offset of -1.394 meters (Table 10), the average difference from NAVD88 to MHW at the Santa Barbara Harbor, Rincon Island, and Bechers Bay tide stations (#9411340, #9411270, and #9410962; Fig.27).

Table 10. Relationship between MHW and other vertical datums used in the Santa Barbara DEM.

	<i>Santa Barbara Harbor</i>	<i>Rincon Island</i>	<i>Bechers Bay</i>	<i>Average</i>
MSL to MHW	-0.563	-0.573	-0.532	-0.556
NAVD88 to MHW	-1.384	-1.404		-1.394
MLLW to MHW	-1.413	-1.434	-1.346	-1.398

3.2.2 Horizontal datum transformations

Datasets used in compiling the Santa Barbara DEM were originally referenced to WGS 84 geographic, WGS 84 UTM zone 10 and zone 11N, NAD 83 California State Plane V (feet or meters), NAD 83 UTM zone 1N, NAD 83 geographic, or NAD 27 geographic horizontal datums. The relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of NAD 83 geographic using *FME* software or *ArcGIS* tools.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in *ArcMap* for consistency between datasets. 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:

- Suspect topographic elevations located close to shore.
- Data values over the ocean and rivers in the topographic datasets. The datasets required automated clipping to the combined coastline.
- Topographic IfSAR dataset not processed to bare earth.
- Digital, measured bathymetric values from NOS surveys date back over 70 years. More recent data, such as the multibeam surveys differ from older NOS data by as much as 100 meters vertically. The older NOS survey data were excised where more recent bathymetric data exists.

3.3.2 Smoothing of bathymetric data

The older NOS hydrographic surveys are generally sparse at the resolution of 1/3 arc-second DEM in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the form of lines of “pimples” in the DEM due to this low resolution dataset and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing “pre-surface” bathymetric grid was generated using *GMT*, an NSF-funded shareware software application designed to manipulate data for mapping purposes.

The NOS hydrographic point data, in xyz format, were clipped to remove overlap with the USGS, USACE, CSUMB, and NGDC multibeam data and then combined with points extracted from the combined coastline to provide a buffer along the entire coastline. The coastline elevation value was set at -1.0 m to ensure a bathymetric surface below zero in areas where bathymetric data are sparse or nonexistent.

The point data were median-averaged using the *GMT* tool “blockmedian” to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Santa Barbara DEM gridding region. The *GMT* tool “surface” was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by “surface” was converted into an ESRI Arc ASCII grid file, and clipped to the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy (e.g., Fig. 22) and exported as an xyz file for use in the final gridding process (see Table 11).

Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the NOS hydrographic surveys. Coastal erosion and development, and changes in the harbor structure and design have modified the coastline. In areas where more recent data were available, the older surveys were either edited or removed.

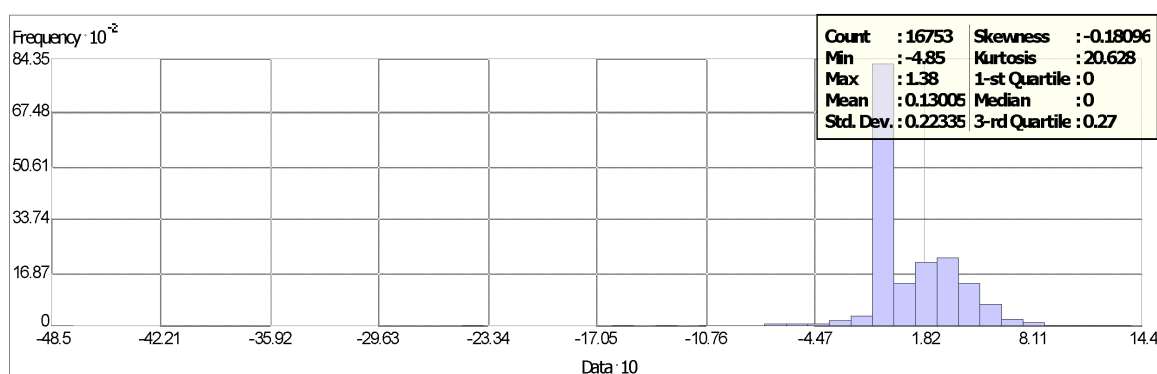


Figure 22. Histogram of the differences between NOS hydrographic survey H09730 and the 1 arc-second pre-surfaced bathymetric grid.

3.3.3 Gridding the data with MB-System

MB-System was used to create the 1/3 arc-second Santa Barbara DEM. *MB-System* is an NSF-funded shareware software application specifically designed to manipulate submarine multibeam sonar data, though it can utilize a wide variety of data types, including generic xyz data. The *MB-System* tool “mbgrid” was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the “mbgrid” gridding algorithm, as relative gridding weights, is listed in Table 11. Greatest weight was given to the USACE multibeam data, the land elevation data, and harbor features. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid. Gridding was performed in quadrants with the resulting Arc ASCII grids seamlessly merged in *ArcCatalog* to create the final 1/3 arc-second Santa Barbara DEM.

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

<i>Dataset</i>	<i>Relative Gridding Weight</i>
USGS/BEG coastal lidar	1000
CSC topographic IfSAR DEMs	100
USGS NED topographic DEM	100
Ventura County topographic lidar	100
ENC land elevations and NGDC digitized topographic harbor features	10,000
Combined coastline	1
USGS multibeam survey	100
CSUMB multibeam surveys	1000
NOS hydrographic surveys	10
USACE multibeam surveys	10,000
NGDC multibeam survey	100
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 Santa Barbara DEM is dependent upon DEM cell size and the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of 10 meters; USGS/BEG lidar, Ventura County lidar, and CSC topographic IfSAR data have accuracy better than 2 meters; NED topography is accurate to within about 10 meters. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of subaerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings, potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys, and by the morphologic change that occurs in this dynamic coastal region.

3.4.2 Vertical accuracy

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

3.4.3 Slope maps and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Santa Barbara DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 23). The DEM was transformed to UTM zone 11 coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the DEM was accomplished using *QT Modeler*. Figure 24 shows a perspective rendering generated using *ArcMap*. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Santa Barbara DEM in its final version.

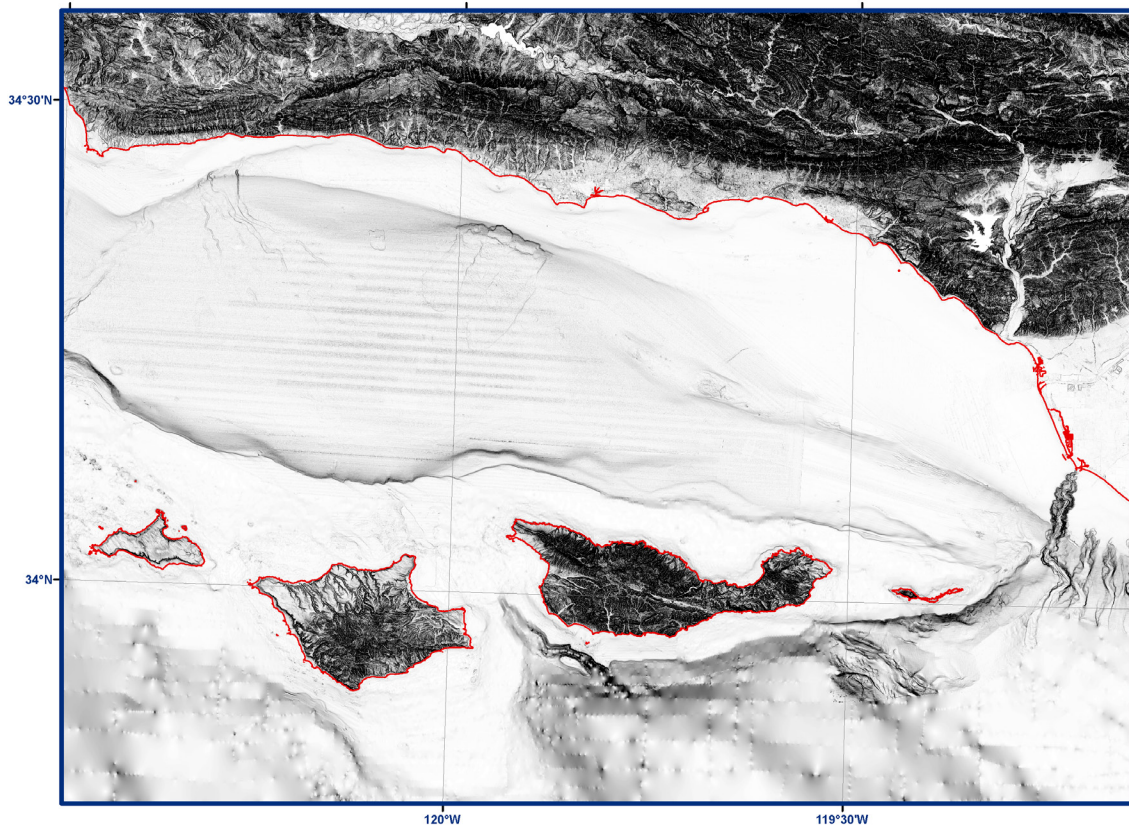


Figure 23. Slope map of the Santa Barbara DEM. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.

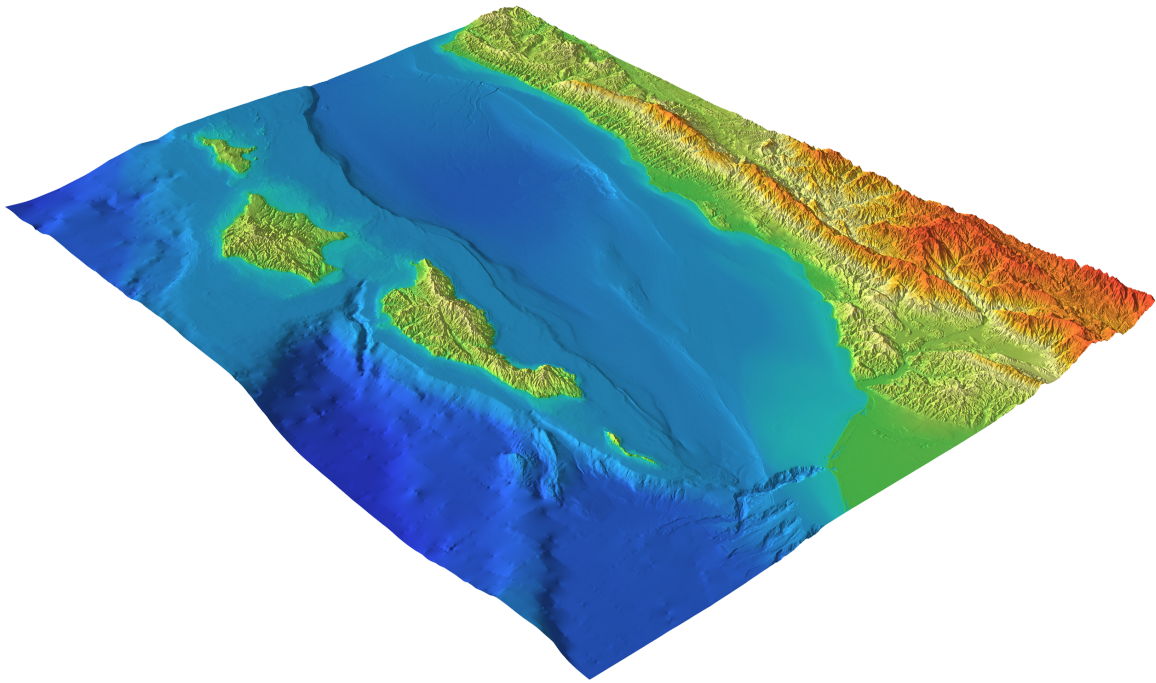


Figure 24. Perspective view from the southwest of the Santa Barbara DEM. Vertical exaggeration-times 2.

3.4.4 Comparison with source data files

To ensure grid accuracy, the Santa Barbara DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the differences between a USGS/BEG topographic lidar survey area and the Santa Barbara DEM is shown in Figure 25. Differences cluster around zero, elevation points with large difference values generally occurring in steep terrain.

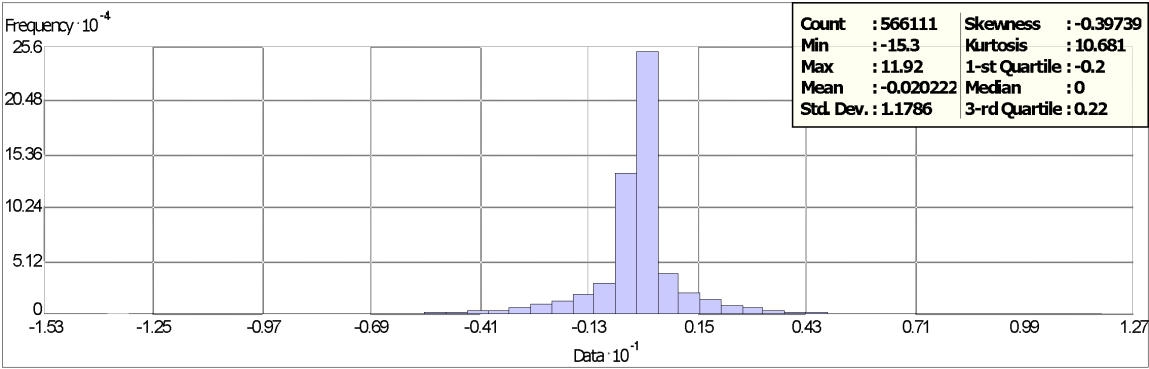


Figure 25. Histogram of the differences between one USGS/BEG lidar survey area and the Santa Barbara DEM.

3.4.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of 1175 geodetic monuments were extracted from the NOAA NGS web site (<http://www.ngs.noaa.gov/>) in shapefile format (see Fig. 27 for monument locations). Shapefile attributes give monument positions in NAD 83 (typically sub-mm accuracy) and elevations in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 10) for comparison with the Santa Barbara DEM (Fig. 26). Differences between the Santa Barbara DEM and the NGS geodetic monument elevations range from -442 to 508 meters, the majority of which are within ± 2 meters. Negative values indicate that the DEM monument elevation is less than the monument elevation. Only 110 monuments out of 1175 total showed significant deviations from the DEM. These discrepancies are generally caused by the rough local terrain, where significant changes in relief occur on the scale of less than 10 meters. Larger discrepancies occurred where monument elevations are incorrect in the NGS database.

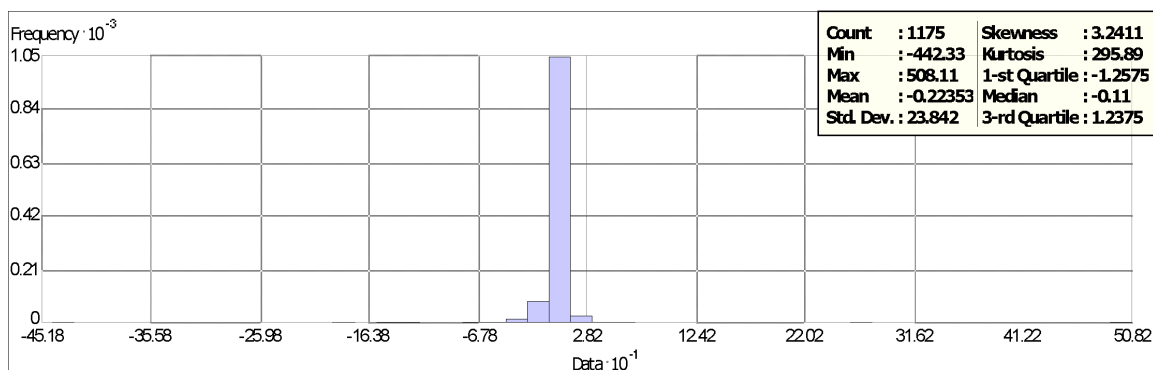


Figure 26. Histogram of the differences between NGS geodetic monument elevations and the Santa Barbara DEM.

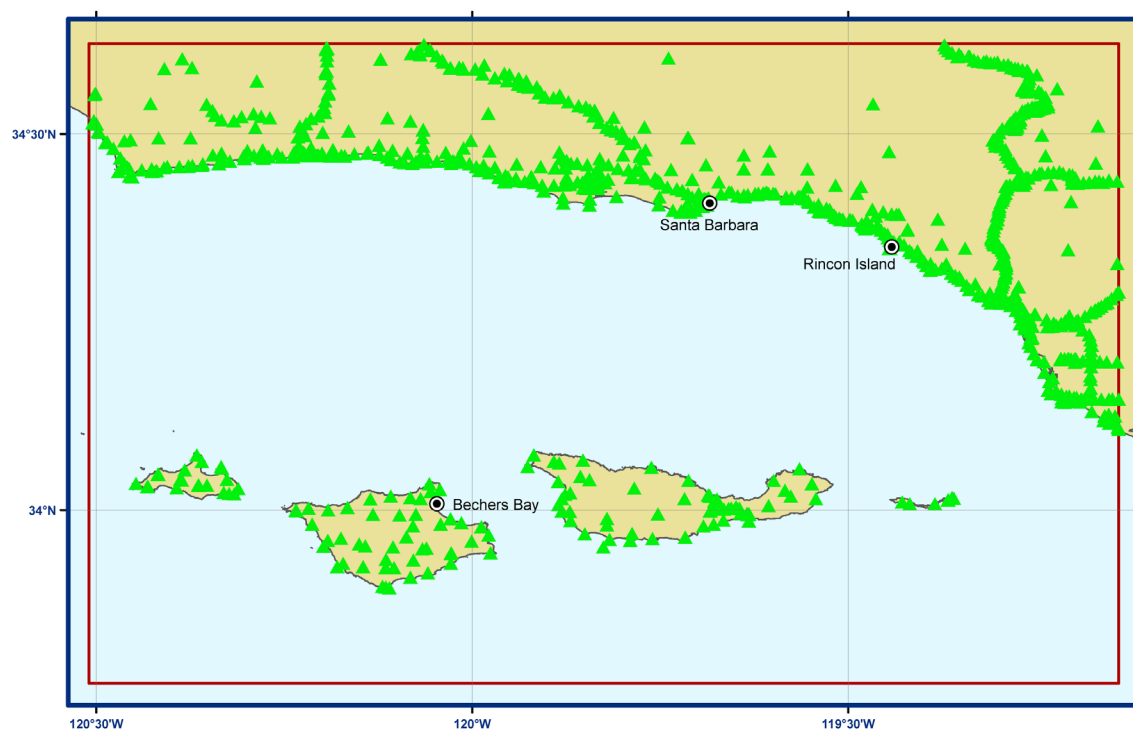


Figure 27. Location of NGS geodetic monuments, shown as green triangles, and the NOAA tide stations, shown as black circles.

4. SUMMARY AND CONCLUSIONS

A bathymetric–topographic DEM of the Santa Barbara, California region, with cell size of 1/3 arc-second, 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*, *CARIS*, *GMT*, *MB-System* and *Quick Terrain Modeler* software.

Recommendations to improve the Santa Barbara DEM, based on NGDC’s research and analysis, are listed below:

- Conduct hydrographic surveys for near-shore areas, especially in harbors.
- Conduct bathymetric–topographic lidar surveys of entire region.
- Conduct deep-water multibeam surveys for region south of Channel Islands.
- Process IfSAR DEMs to bare earth.

5. ACKNOWLEDGMENTS

The creation of the Santa Barbara DEM was funded by NOAA PMEL. The authors thank Nazila Meratia and Vasily Titov (PMEL), Patrick Barnard (USGS, Santa Cruz), Peter Darnell (USGS, Menlo Park), Roger Adams (City of Ventura), Karen Mendoza (Ventura County, Watershed Protection District), Zacharias Hunt (County Geographic Information Officer, Santa Barbara County), Alan Nichols and Brooks Hubbard (USACE Los Angeles District Office), and Susan Jordan (California Coastal Protection Network). Multibeam data used in this study were acquired, processed, archived, and distributed by the Seafloor Mapping Laboratory of California State University, Santa Barbara Bay.

6. REFERENCES

- Nautical Chart #18700 (ENC), 6th Edition, 2008. Point Conception to Point Sur. Scale 1: 216,116. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #18720 (ENC), 8th Edition, 2008. Point Dume to Purisima Point. Scale 1:232,188. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #18725 (ENC), 15th Edition, 2008. Port Hueneme to Santa Barbara. Scale 1:50,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #18727 (ENC), 5th Edition, 2008. San Miguel Passage. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #18721 (RNC), 11th Edition, 2008. Santa Cruz Island to Purisima Point. Scale 1:100,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #18724 (RNC), 1st Edition, 2008. Port Hueneme. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #18728 (RNC), 9th Edition, 2008. Santa Cruz Channel. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #18729 (RNC), 13th Edition, 2008. Anacapa Passage. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. DATA PROCESSING SOFTWARE

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

CARIS Bathy DataBase 2.0, bathymetric data processing software developed and licensed by CARIS, Fredericton, NB, Canada, <http://www.caris.com/>

FME 2008 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, <http://www.safe.com/>

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

GMT v. 4.1.4 – Generic Mapping Tools, freeware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, <http://gmt.soest.hawaii.edu/>

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

Quick Terrain Modeler v. 6.0.1 – lidar processing software developed by John Hopkins University's Applied Physics Laboratory and maintained and licensed by Applied Imagery, <http://www.appliedimagery.com/>