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

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Digital Elevation Models of Monterey, 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 bathymetric–topographic digital elevation models (DEMs) of Monterey, California (Fig. 1). First, a 1/3 arc-second DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was developed and evaluated using diverse digital datasets available for the region (grid boundary and sources shown in Fig. 3). Then, a 1/3 arc-second conversion grid was created, using \textit{VDatum} to represent the relationship between NAVD 88 and mean high water (MHW) vertical datums in the Monterey region. Finally, a 1/3 arc-second MHW DEM was developed by combining the NAVD 88 DEM and the vertical datum conversion grid. The MHW DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation 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 Monterey DEMs.

1. The Monterey DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Monterey, California (36°36.3′ N, 121°53.3′ W) 1/3 arc-second of latitude is equivalent to 10.275 meters; 1/3 arc-second of longitude equals 8.284 meters.

*Figure 1. Shaded-relief image of the Monterey NAVD 88 DEM. Contour interval is 200 meters. Image is in Mercator projection.*
2. **Study Area**

The Monterey 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 Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The DEMs cover the coastal region surrounding the town of Monterey, California, including Santa Cruz (Fig. 2). The DEMs also encompass a portion of the Monterey Bay National Marine Sanctuary. The region is home to many species of marine life, which provide recreation, educational, and economic benefits to the surrounding communities and offers research opportunities for the Monterey Bay Aquarium Research Institute in Moss Landing and the University of California Santa Cruz.

Table 1. Specifications for the Monterey DEMs

<table>
<thead>
<tr>
<th>Grid Area</th>
<th>Monterey, California Vers. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage Area</td>
<td>121.28° to 122.42° W; 35.70° to 37.20° N</td>
</tr>
<tr>
<td>Coordinate System</td>
<td>Geographic decimal degrees</td>
</tr>
<tr>
<td>Horizontal Datum</td>
<td>World Geodetic System of 1984 (WGS 84)</td>
</tr>
<tr>
<td>Vertical Datum</td>
<td>a) North American Vertical Datum of 1988 (NAVD 88)</td>
</tr>
<tr>
<td></td>
<td>b) Mean High Water (MHW)</td>
</tr>
<tr>
<td>Vertical Units</td>
<td>Meters</td>
</tr>
<tr>
<td>Grid Spacing</td>
<td>1/3 arc-second</td>
</tr>
<tr>
<td>Grid Format</td>
<td>ESRI Arc ASCII raster grid</td>
</tr>
</tbody>
</table>

![Figure 2. Footprint map of the Monterey region.](image)
3. **Source Elevation Data**

The best available bathymetric and topographic digital data were obtained by NGDC from the following U.S. federal and state agencies: NOAA’s NGDC and Coastal Service Center (CSC), U.S. Geological Survey (USGS), and California State University (CSU) Seafloor Mapping Laboratory (Fig. 3). 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.

![Data Source Coverage Diagram](image)

*Figure 3. Data sources used in building the 1/3 arc-second Monterey NAVD 88 DEM. DEM boundary outlined in gray.*
3.1 Data Sources and Processing

Coastline, bathymetric, and topographic digital datasets (Tables 2, 3 and 4) were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum 1983 (NAD 83)\(^2\) and NAVD 88. Datasets were assessed to determine data quality and were manually edited where needed. Vertical transformations were accomplished using NOAA’s VDatum software package (Section 3.2.2).

### 3.1.1 Coastline

The coastline dataset used in the development of the Monterey DEM was NGDC’s Monterey Vers. 1 DEM coastline (Table 2; Carignan et al., 2009). NGDC developed the Monterey Vers. 1 DEM from NOAA’s Office of Coast Survey (OCS) coastlines and the California Dept. of Fish and Game, Marine Region GIS Unit (CDFG). The Monterey Vers. 2 DEM is slightly larger than the Vers. 1 DEM, therefore NGDC hand-digitized the remainder of the coastline based on aerial imagery.

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Data Type</th>
<th>Spatial Resolution</th>
<th>Original Horizontal Datum/Coordinate System</th>
<th>Original Vertical Datum</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGDC</td>
<td>2009</td>
<td>Poly Line</td>
<td>10 meters</td>
<td>WGS 84 geographic</td>
<td>MHW</td>
</tr>
</tbody>
</table>

### 3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Monterey DEM include 33 NOS hydrographic surveys, 32 CSU SeaFloor Mapping Lab multibeam sonar surveys, and two NGDC multibeam sonar surveys (Table 3; Fig. 3).

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Data Type</th>
<th>Spatial Resolution</th>
<th>Original Horizontal Datum/Coordinate System</th>
<th>Original Vertical Datum</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSU Seafloor Mapping Lab</td>
<td>2000 to 2008</td>
<td>Gridded Multibeam Sonar Surveys</td>
<td>1 to 10 meters</td>
<td>WGS 84 UTM Zone 10 N</td>
<td>MLLW or NAVD 88</td>
<td><a href="http://seafloor.csumb.edu/index.html">http://seafloor.csumb.edu/index.html</a></td>
</tr>
<tr>
<td>NGDC</td>
<td>1998</td>
<td>Multibeam swath sonar surveys</td>
<td>Raw sonar files gridded to 1 arc-second</td>
<td>WGS 84 geographic</td>
<td>Assumed NAVD 88 (meters)</td>
<td><a href="http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html">http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html</a></td>
</tr>
<tr>
<td>NGDC</td>
<td>1932 to 1989</td>
<td>NOS hydrographic survey soundings</td>
<td>Ranges from 10 meters to 1 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)</td>
<td>NAD 27 geographic or NAD 83 geographic</td>
<td>Mean Lower Low Water (MLLW)</td>
<td><a href="http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html">http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html</a></td>
</tr>
</tbody>
</table>

---

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (1984) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Many GIS applications treat the two datums as identical and do not transform data between them. The error introduced by not converting between the datums is insignificant for NGDC 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 waves 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 are identical and may be used interchangeably.
1) **California State Seafloor Mapping Laboratory multibeam sonar surveys**

Thirty-two near-shore multibeam sonar surveys were downloaded from the California State Seafloor Mapping Laboratory website as gridded data. The surveys were collected between 2000 and 2008, and referenced to WGS 84 UTM Zone 10N and either NAVD 88 (meters) or MLLW datums.

2) **National Geophysical Data Center multibeam swath sonar surveys**

Two multibeam swath sonar surveys from the NGDC multibeam bathymetry database were used in the development of the Monterey DEMs: Monterey and Sur. The database is comprised of the original swath sonar files of surveys conducted mostly by academic fleet. All surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be equivalent to NAVD 88. The data were gridded at 1 arc-second resolution using *MB-System*.

3) **National Ocean Service hydrographic surveys**

A total of 33 NOS hydrographic surveys conducted between 1932 and 1989 were used in developing the Monterey DEM. The hydrographic survey data were extracted from NGDC’s online hydrographic database originally referenced to Mean Lower Low Water (MLLW) and either NAD 27 geographic or NAD 83 geographic datums. As many of these surveys are superseded by newer data, NOS soundings were only retained where no other data were available. Data point spacing for the NOS surveys varied by collection date. In general, earlier surveys had greater point spacing than more recent surveys.

### 3.1.3 Topography

The topographic datasets used to build the Monterey NAVD 88 DEM included the following: CSC topographic lidar surveys and USGS 1/9 and 1/3 National Elevation Dataset (NED) DEM (Table 4; Fig. 3). CSC also provided NGDC with Interferometric SAR (IFSAR) data but this data were not used because the survey was first-return, containing elevation values of trees and buildings. This data is also proprietary and would not have been available for use in a public DEM.

Table 4. Topographic datasets used in compiling the Monterey NAVD 88 DEM.

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Data Type</th>
<th>Spatial Resolution</th>
<th>Original Horizontal Datum/Coordinate System</th>
<th>Original Vertical Datum</th>
<th>URL</th>
</tr>
</thead>
</table>

1) **Coastal Service Center topographic lidar DEMs**

Two topographic surveys from CSC were used in building the Monterey DEM: 2004 National Geodetic Survey (NGS) Elkhorn Slough and 1998 Spring EC. Both surveys were downloaded at three meter raster DEMs in datums of NAD 83 geographic and NAVD 88. The 2004 NGS Elkhorn Slough was collected by NGS for environmental and ecological research and was classified as bare-earth. The 1998 Spring EC survey was collected as part of the 1996-2000 NOAA/USGS/NASA Airborne LiDAR Assessment of Coastal Erosion (ALACE) Project for the US Coastline, and contained only elevations of the shoreline and was not classified as bare-earth. The few trees and buildings that were included in the data were manually removed by NGDC.

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3: *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 (point and access through these web pages). A complete description is provided in web pages accessed through the web site. MB-System was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for MB-System development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994-1997), NOAA (2002-2004), and others. URL: [http://www.ldeo.columbia.edu/res/pi/MB-System/](http://www.ldeo.columbia.edu/res/pi/MB-System/) [Extracted from MB-System web site.]
2) **USGS NED topographic DEMs**

The USGS NED topographic DEM provides complete 1/3 arc-second coverage of the Monterey DEM region and the NED 1/9 DEM provided partial coverage in the DEM region. Where available, the NED 1/9 topographic DEM was used instead of the NED 1/3 DEM. The data were in a horizontal datum of NAD 83 geographic and a vertical datum of NAVD 88, and were available for download as raster DEMs on the USGS web site. The bare earth elevations of the NED 1/3 topographic DEM have a vertical accuracy of +/- 7 to 15 meters, respectively, but are most likely less than that in low elevation areas. The vertical accuracy of elevation values in the NED 1/9 topographic DEM are on the order of 1 meter. See the USGS Seamless web site for more specific source information.

### 3.2 Establishing Common Datums

#### 3.2.1 Horizontal datum transformations

Datasets used to build the Monterey NA VD 88 DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, or NAD 83 UTM Zone 10 N. The relationships and transformational equations between the geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using Proj4.4.

#### 3.2.2 Vertical datum transformations

Datasets used to build the Monterey NA VD 88 DEM were originally referenced to either MLLW or NAVD 88 or were assumed NAVD 88. All datasets referenced to MLLW were transformed to NAVD 88 using VDatum.

#### 3.2.3 Verifying transformations and consistency between datasets

After horizontal and vertical transformations were applied, datasets were checked for consistency and problems and errors were resolved before proceeding with subsequent gridding steps. All datasets were converted to xyz files using GDAL in preparation for gridding.

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4. Proj4 is a free software standard Unix filter function which converts geographic longitude and latitude coordinates into cartesian coordinate, $(\lambda,\phi) \rightarrow (x,y)$, by means of a wide variety of cartographic projection functions. [http://trac.osgeo.org/proj/](http://trac.osgeo.org/proj/)
4. **Digital Elevation Model Development**

4.1 **Smoothing of bathymetric data**

Hydrographic survey data are generally sparse relative to the resolution of the 1/3 arc-second Monterey DEMs. In order to reduce the effect of artifacts in the DEM by low-resolution bathymetric datasets, and to provide effective interpolation from the deep water into the coastal zone, a 1/3 arc-second-spacing ‘pre-surface’ bathymetric grid was generated using *Generic Mapping Tools (GMT)*\(^5\). The coastline elevation value was set to -1 meter to ensure a bathymetric surface below zero in areas where data are sparse or non-existent along the coast.

The point data were median-averaged using the *GMT* command ‘blockmedian’ to create a 1/3 arc-second grid 0.05 degrees (~5%) larger than the Monterey DEM gridding region. The *GMT* command ‘surface’ was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created was converted into an ESRI Arc ASCII grid file, and clipped to the final coastline to eliminate data interpolation into land areas. The resulting surface was compared with original bathymetric soundings to ensure grid accuracy and then exported as an xyz file for use in the final gridding process (Table 5).

4.2 **Building the NAVD 88 DEM**

*MBS-System* was used to create the 1/3 arc-second Monterey NAVD 88 DEM. The *MBS-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 5. The resulting binary grid was converted to an Arc ASCII grid using the *MBS-System* tool ‘mbm_grd2arc’ to create the final 1/3 arc-second Monterey NAVD 88 DEM. Figure 4 illustrates cells in the DEM that have interpolated values (shown as white) versus data contributing to the cell value (shown as gray).

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Relative Gridding Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSUMB Multibeam</td>
<td>100</td>
</tr>
<tr>
<td>NGDC Multibeam</td>
<td>100</td>
</tr>
<tr>
<td>USGS NED 1/9 Topographic DEM</td>
<td>10</td>
</tr>
<tr>
<td>CSC Lidar</td>
<td>10</td>
</tr>
<tr>
<td>NOS Hydrographic Surveys</td>
<td>1</td>
</tr>
<tr>
<td>USGS NED 1/3 Topographic DEM</td>
<td>1</td>
</tr>
<tr>
<td>Pre-surface bathymetric grid</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5. Data hierarchy used to assign gridding weight in *MBS-System*.

\(^5\) *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. URL: [http://gmt.soest.hawaii.edu/](http://gmt.soest.hawaii.edu/) [Extracted from *GMT* web site.]
4.3 Building the MHW Structured DEM

The Monterey MHW DEM was created by adding a ‘NAVD 88 to MHW’ conversion grid to the NAVD 88 DEM.

4.3.1 Developing the conversion grid

Using extents slightly larger (~5%) than the Monterey project area, 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 command ‘surface’ applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-grid was then converted to an intermediate xyz file using the GMT command ‘grd2xyz’. Conversion values from NAVD 88 to MHW at each xyz point were generated using VDatum and the null values were removed.

The median-averaged xyz file was then interpolated with the GMT command ‘surface’ to create the 1/3 arc-second ‘NAVD 88 to MHW’ conversion grid with the extents of the buffered Monterey project area, representing the differences between the datums onshore to the DEM extents (Fig. 6).
4.3.2 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. The resulting xyz files were filtered to remove any null values and then were merged together to form a single xyz file of the NOS hydrographic survey data with a vertical datum of NAVD 88. A second xyz file of NOS data was created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 xyz files were computed.

To verify the conversion grid methodology, the difference xyz file was used to generate a histogram using Gnuplot\(^6\) to evaluate the performance of the 1/3 arc-second conversion grid by comparing the ‘NAVD 88 to MHW’ grid to the combined difference xyz files from the VDatum project area (Figure 6). Errors in the vertical datum conversion method will reside for the most part in the ‘NAVD 88 to MHW’ conversion grid, as the topographic data are already referenced to NAVD 88. Errors in the source datasets will require rebuilding just the NAVD 88 DEM.

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6. Gnuplot is an open-source command-driven interactive function plotting program. It can be used to plot functions and data points in both two- and three-dimensional plots in many different formats. It is designed primarily for the visual display of scientific data.
4.3.3 Creating the MHW structured DEM

Once the NA VD 88 DEM was completed and assessed for errors, the conversion grid was added to the NA VD 88 DEM using the GMT command ‘grdmath’. The resulting MHW DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI World 2D imagery.

4.4 Quality Assessment of the DEMs

4.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Monterey DEMs is dependent upon the datasets used to determine corresponding DEM cell values and the cell size of the DEM, making the highest accuracy possible 1/3 arc-seconds (about 10 meters). The horizontal accuracy is 3 to 10 meters where topographic datasets contribute to the DEM cell value. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings, potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys, and by the morphologic change that occurs in this dynamic region.

4.4.2 Vertical accuracy

Vertical accuracy of the Monterey DEMs are also highly dependent upon the source datasets contributing to DEM cell values. Topographic lidar and the NED 1/9 topographic DEM have an RMSE of less than 30 cm. USGS NED 1/3 topographic DEM has a stated vertical accuracy of 7 to 15 meters but we find it to be much less for low-lying coastal regions. Bathymetric areas have an estimated accuracy of between 0.1 m 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 bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations.

4.4.3 Slope map and 3-D perspectives

ESRI ArcCatalog was used to generate a slope grid from the Monterey NA VD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 7). The DEM was transformed to UTM Zone 10 North coordinates (horizontal units in meters) in ArcCatalog for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM was accomplished using ESRI ArcScene. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 8 shows a perspective view image of the 1/3 arc-second Monterey NA VD 88 DEM in its final version.
Figure 7. Slope map of the Monterey NAVD 88 DEM. Flat-lying slopes are white; dark shading denotes steep slopes.
Figure 8. Perspective view from the southwest of the Monterey NAVD 88 DEM. Two times vertical exaggeration.
4.4.4 Comparison of the NAVD 88 structured DEM with source data files

To ensure grid accuracy, the Monterey NAVD 88 DEM was compared to source data files. All bathymetric and topographic source data were compared to the Monterey NAVD 88 DEM using Python, GDAL, and Gnuplot. Histograms of the differences between individual datasets and the Key West DEM mostly cluster around zero.

4.4.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of 1195 NOAA NGS geodetic monuments (Fig. 9) were extracted from online shapefiles of NGS Geodetic monument datasheets, which give monument positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Monuments with conditions noted as ‘GOOD’ or ‘MONUMENTED’ were only included in the analysis. Monument elevations were compared with elevations of the Monterey NAVD 88 DEM. Differences between the Monterey NAVD 88 DEM and the NGS geodetic monument elevations range from -110 to 492 meters, with the majority of them being with +/-1 meter (Fig. 10). Negative values indicate that the monument elevation is less than the DEM elevation. After examination, it was determined that those monuments with the largest deviations do not represent ground surface as they are located on top of a light house, on a bridge, or at the apex of other structures.

![Figure 9. Location of NGS geodetic monuments in the Monterey region.](image)
5. **SUMMARY AND CONCLUSIONS**

Two 1/3 arc-second bathymetric–topographic DEMs of the Monterey region, one vertically referenced to NAVD 88 and the other to MHW, were developed for the purpose of modeling tsunami inundation and to support other coastal management activities. The best available digital data from U.S. federal, state, and local agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation.

Recommendations to improve the Monterey DEMs, based on NGDC’s research and analysis, include:

- Conduct high-resolution shallow-water bathymetric multibeam surveys in the southern DEM region to replace early 19th century surveys.
- Conduct bare-earth bathymetric-topographic lidar surveys of the near-shore regions to allow for a smooth transition from the bathymetric data to the topographic data.

6. **ACKNOWLEDGMENTS**

The development of the Monterey DEMs was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Lindsey Wright, Marie Eble, and Vasily Titov (PMEL).

7. **REFERENCES**


8. **DATA PROCESSING SOFTWARE**

ArcGIS v. 10.0 – developed and licensed by ESRI, Redlands, California, [http://www.esri.com/](http://www.esri.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/](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.hawaii.edu/.

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

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

Proj4 v. 4.7.0, free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/.

Python v. 2.4.3, Python is a remarkable powerful dynamic programming language that is used in a wide variety of application domains. Python is free software, http://python.org/.

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University’s Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.

VDatum Transformation Tool, California - Monterey Bay to Morro Bay V. 01, – developed and maintained by NOAA’s National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/