Digital Elevation Models of Bar Harbor, Maine: Procedures, Data Sources and Analysis

Prepared for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research by the NOAA National Geophysical Data Center (NGDC)
October 17, 2011

Friday, D.Z.[1], L.A. Taylor[2], B.W. Eakins[1], K.S. Carignan[1], P.R. Grothe[1], E. Lim[1], and M.R. Love[1]
1. Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder
2. NOAA, National Geophysical Data Center, Boulder, Colorado

Corresponding project contact:
Lisa A. Taylor
NOAA, National Geophysical Data Center
Marine Geology and Geophysics Division
325 Broadway, E/GC 3
Boulder, Colorado 80305
Phone: 303-497-6767
Fax: 303-497-6513
E-mail: Lisa.A.Taylor@noaa.gov
http://www.ngdc.noaa.gov/mgg/inundation/

Contents

1. Introduction 1
2. Study Area 2
3. Methodology 3
   3.1 Data Sources and Processing 4
      3.1.1 Coastline 5
      3.1.2 Bathymetry 6
      3.1.3 Topography 12
   3.2 Establishing Common Datums 13
      3.2.1 Vertical datum transformations 13
      3.2.2 Horizontal datum transformations 13
   3.3 Digital Elevation Model Development 14
      3.3.1 Verifying consistency between datasets 14
      3.3.2 Smoothing of bathymetric data 14
      3.3.3 Building the NAVD 88 DEM 15
      3.3.4 Building the MHW DEM 16
   3.4 Quality Assessment of the DEM 17
      3.4.1 Horizontal accuracy 17
      3.4.2 Vertical accuracy 17
      3.4.3 Slope map and 3-D perspectives 18
      3.4.4 Comparison with National Geodetic Survey geodetic monuments 20
      3.4.5 DEM comparison with source data files 21
4. Summary and Conclusions 21
5. Acknowledgments 21
6. References 22
7. Data Processing Software 22

List of Figures

Figure 1. Shaded-relief image of the Bar Harbor 1/3 arc-second MHW DEM. Contour interval is 15 meters for bathymetry and 100 meters for topography. 1
Figure 2. Overview of the Bar Harbor DEM region 2
Figure 3. Aerial photograph showing the town of Bar Harbor and surrounding coastline 3
Figure 4. Source and coverage of datasets used in compiling the Bar Harbor DEM. 4
Figure 5. Histogram of the differences between the recent NOS bathymetric data and the 1/3 arc-second pre-surfaced bathymetric grid 16
Figure 6. Slope map of the Bar Harbor DEM 18
Figure 7. Data contribution plot of the Bar Harbor DEM 19
Figure 8. Perspective view from the southeast of the 1/3 arc-second NAVD88 Bar Harbor DEM 19
Figure 9. Histogram of the differences between NGS geodetic monument elevations and the Bar Harbor DEM 20

List of Tables

Table 1. Specifications for the Bar Harbor DEM. 4
Table 2. Shoreline dataset used in developing the Bar Harbor DEM 5
Table 3. Bathymetric datasets used in compiling the Bar Harbor DEM 6
Table 4. Digital NOS hydrographic surveys available for use in the Bar Harbor DEM 7
Table 5. Topographic datasets used in compiling the Bar Harbor DEM. 11
Table 6. Data hierarchy used to assign gridding weight in *MB-System* 15

Digital Elevation Model of Bar Harbor, Maine: 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 Bar Harbor, Maine (Fig. 1). First, a 1/3 arc-second[1] 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. 4). Then, a 1/3 arc-second conversion grid was created to represent the relationship between the NAVD 88 and Mean High Water (MHW) vertical datums in the Bar Harbor 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 Bar Harbor DEMs.

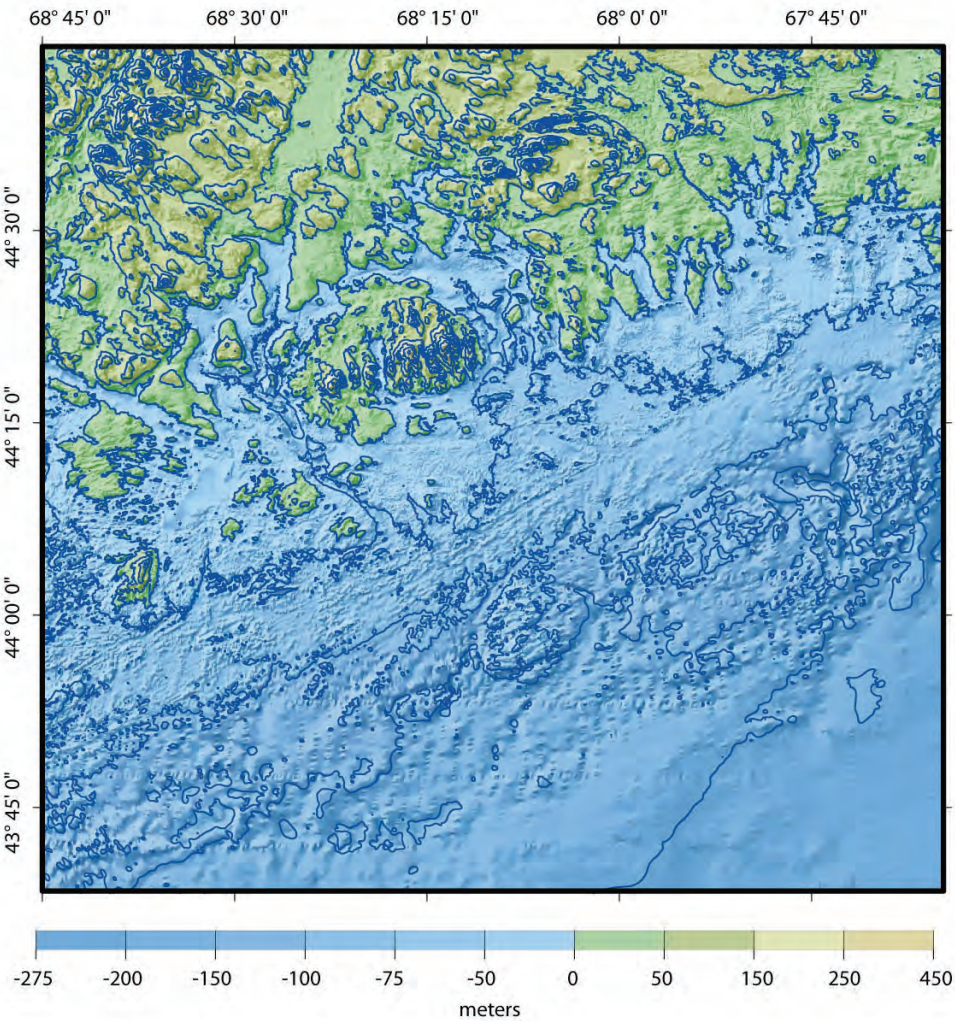

Figure 1. Shaded-relief image of the Bar Harbor 1/3 arc-second MHW DEM. Contour interval is 15 meters for bathymetry and 100 meters for topography.

1. The Bar Harbor DEMs are built upon a grid of cells that are square in geographic coordinates (latitiude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Bar Harbor, Maine (44°23' 9"N, 68°12'34"W) 1/3 arc-second of latitude is equivalent to 10.29 meters; 1/3 arc-second of longitude equals 7.8 meters.

2. Study Area

The Bar Harbor DEM provides coverage of over 100 miles of rocky coastline in Maine, and includes coverage of the town of Bar Harbor, Mount Desert Island, Acadia National Park and much of the nearby mainland-- inlcuding Blue Hill, Ellsworth, Winter Harbor, and Gouldsboro (Fig. 2).

The town of Bar Harbor (Fig. 3) is known as a luxurious yet isolated tourist destination. Its high-end resort and spa offerings are paired with mountain hiking trails, protected lands, and boating opportunities. The town has about 5,000 year-round residents and is located about 250 miles away from Boston, Massachusetts— north of Portland, Maine.

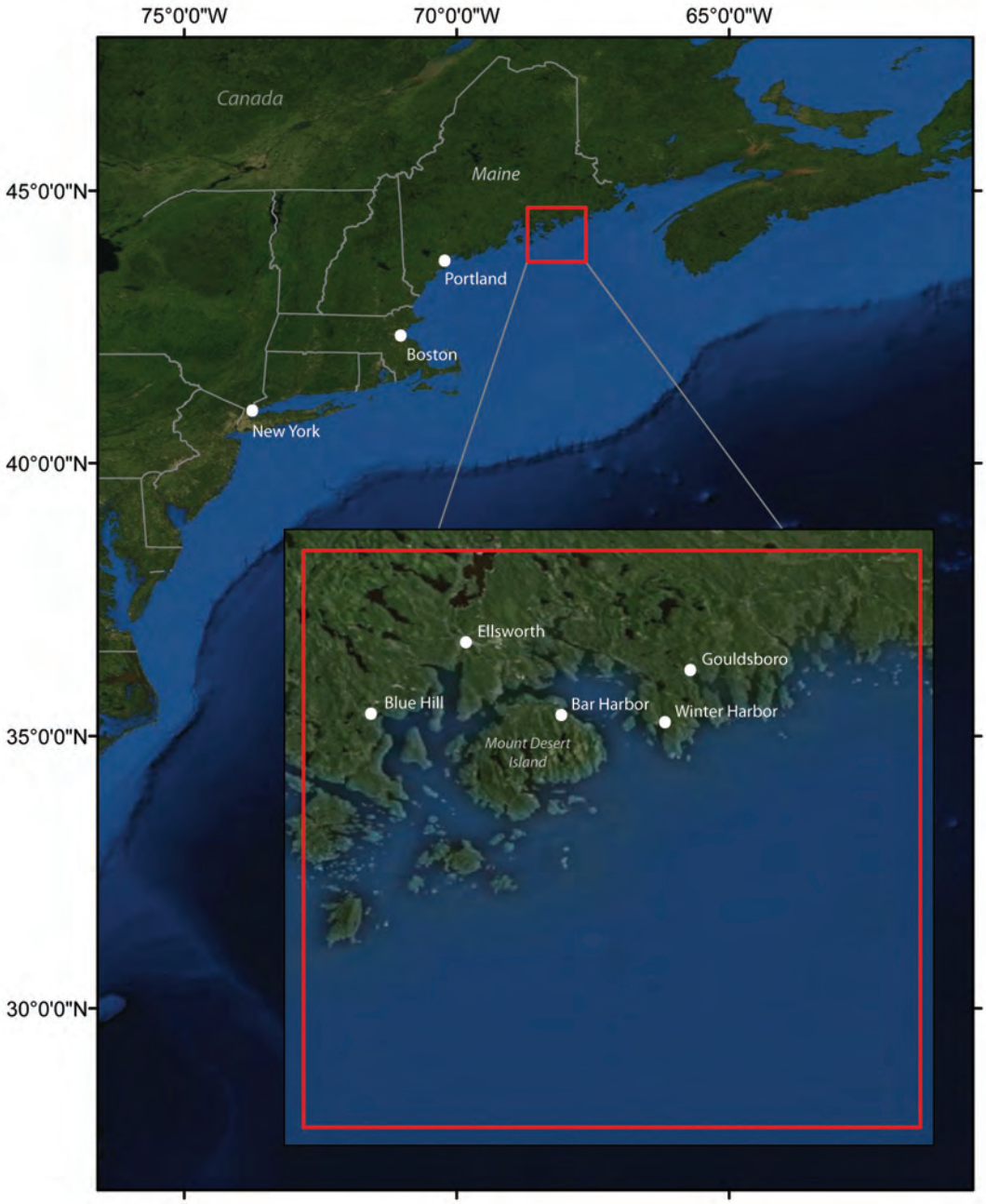

Figure 2. Overview of the Bar Harbor DEM region. Red box represents approximate Bar Harbor DEM extent. ESRI's online World 2D Imagery in background.

Figure 3. Aerial photograph showing the town of Bar Harbor and surrounding coastline. (Wikipedia Commons, photo by Matthew Field http://www.photography.mattfield.com)

3. Methodology

The Bar Harbor 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 (Short-term Inundation Forecasting for Tsunamis) 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 NAVD88. Data were gathered in an area slightly larger than the DEM extents. This data "buffer" ensured that gridding occured 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: Specifications for the Bar Harbor DEM.

Grid Area	Bar Harbor, Maine
Coverage Area	68.70º to 67.62º W; 43.69º to 44.69º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datums	a) Mean High Water (MHW) b) North American Vertical Datum of 1988 (NAVD 88)
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc 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 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. 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 were obtained from federal, state, and local agencies and institutions (Fig. 4) including: NGDC; NOAA's National Ocean Service (NOS), National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Coastal Services Center (CSC); the U.S. Geological Survey (USGS); the Maine Office of GIS (MEGIS); the University of New Brunswick (UNB); the City of Bar Harbor; and Acadia National Park. Datasets were shifted to NAD 83 geographic horizontal datum and NAVD 88 vertical datum using ESRI's *ArcGIS*, *Proj.4*, and NOAA's *Vertical Datum* (*VDatum)* transformation tool. Data were visually displayed with *ArcGIS* and Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*), to assess quality and manually edit datasets.

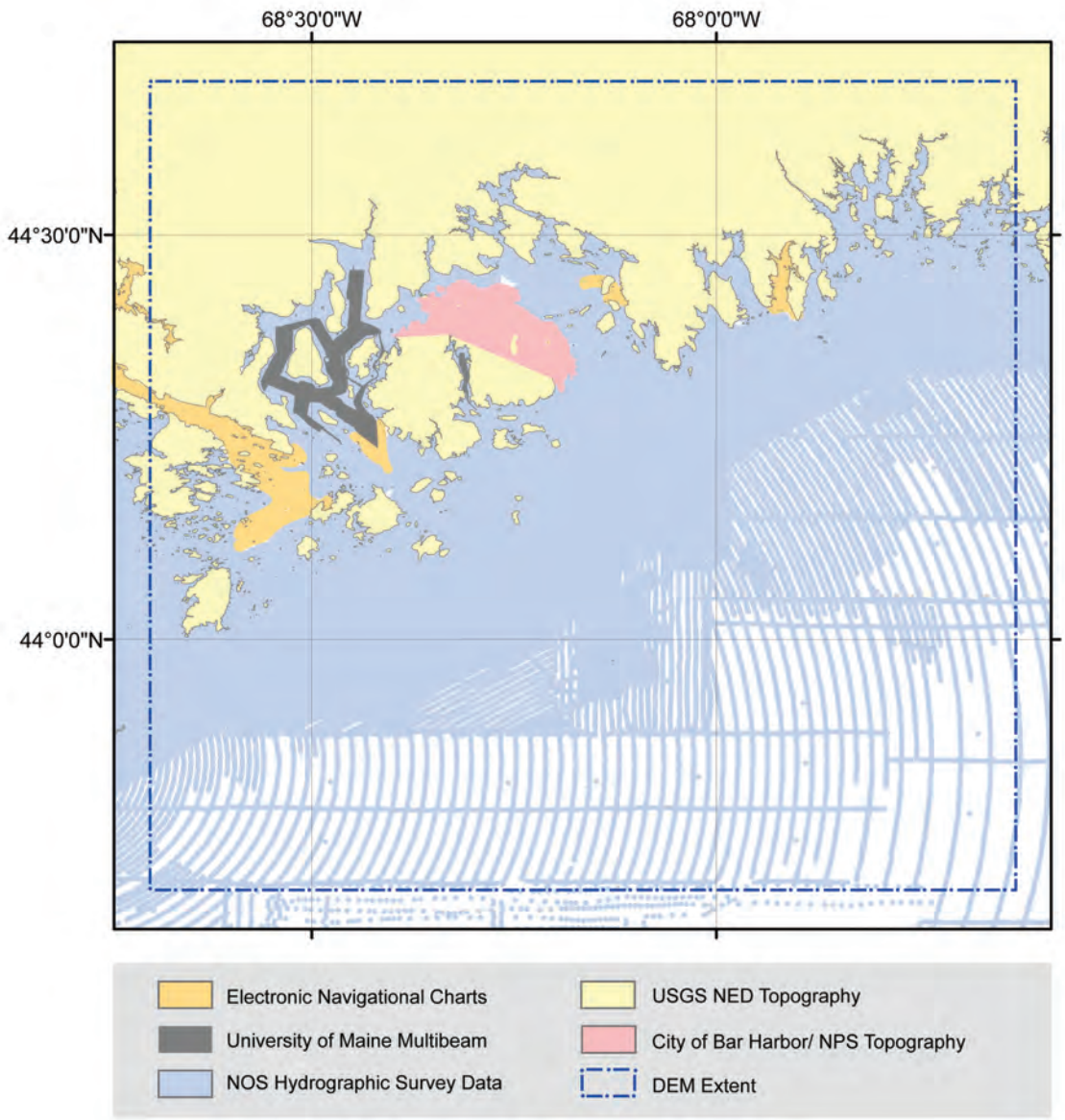

Figure 4. Source and coverage of datasets used in compiling the Bar Harbor DEM.

3.1.1 Coastline

Shoreline data for the state of Maine was obtained from MEGIS (Table 2).

Table 2. Shoreline dataset used in developing the Bar Harbor DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*
MEGIS	2006	Compiled Vector Coastline	Various	WGS 84 Geographic	Undefined

1) Maine GIS Coastline

MEGIS modified USGS 1:24000 hydrography digital line graph (DLG) quadrangle files to produce a digital representation of the Maine coastline. MEGIS reformatted the DLG file in ESRI coverages and projected them into the Maine State Plane Coordinate System, NAD 83. The coastline was extracted from the coverage files and then edited into a simple polygon. The coverages were re-projected into NAD 83 meters.

NGDC compared the coastline with USGS topographic data, aerial imagery, and nautical charts in order to determine a best-fit coastline for modeling purposes. The final edited coastline was converted to xyz data with ten meter point spacing, using NGDC's *GEODAS* software, for use in building a 'pre-surface' bathymetric grid (see Sec. 3.3.2).

3.1.2 Bathymetry

Bathymetric datasets used to build the Bar Harbor DEM included NOS hydrographic surveys obtained from NGDC, two multibeam swath sonar surveys acquired from the Ocean Mapping Group (OMG) at the University of New Brunswick (UNB), Canada, and extracted points from NOS Electronic Navigational Charts (ENCs, Table 3).

Table 3. Bathymetric datasets used in compiling the Bar Harbor DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1869 to 1999	Hydrographic survey xyz data	Ranges from less than 10 m to 600 m (varies with scale of survey, recency of survey, and distance from shore)	Standard American Datum; NAD 13, 27, 83 geographic	Mean Lower Low Water (MLLW) and Mean Low Water (MLW)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
OMG UNB Multibeam	2009	Multibeam Survey Data	2 meters	WGS 84	Mean Sea Level (MSL)	http://www.omg.unb.ca/Maine/index.html
ENC	2008 to 2009	Extracted Soundings	Digitized from 1:40,000 scale RNC, point spacing 50 to 100 meters	NAD 83 Geographic	MLLW	charts.noaa.gov/ENCs/ENCs.shtml

1) Early National Ocean Service hydrographic survey data

A total of 126 NOS hydrographic surveys conducted between 1869 and 1999 were available in the Bar Harbor DEM region (Table 4), The surveys were extracted from NGDC's online NOS hydrographic database using *GEODAS*[3]. The hydrographic survey data were downloaded vertically referenced to mean lower low water (MLLW) and horizontally referenced to NAD 83 geographic. After download, the NOS surveys were merged together and clipped to the Bar Harbor DEM extent buffer.

The data point spacing of the surveys varies by scale. In general, small scale surveys had greater point spacing than large scale surveys. The data were converted to a shapefile and compared and edited based on other bathymetric datasets, the original survey smooth sheets, topographic data, NOS raster nautical charts (RNCs), and the original NOS survey smooth sheets. Older surveys were clipped or removed to eliminate data that were overlapped by more recent bathymetric data.

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

Table 4. Early digital NOS hydrographic surveys available for use in developing the Bar Harbor DEM.

Survey ID	*Year*	*Scale/ Vertical Accuracy*	*Original Vertical Datum*	*Provided Horizontal Datum*	*Name*
F00253	1983	5,000	MLLW	North American Datum 1927	Two Bush Channel
F00407	1994	10,000	MLLW	North American Datum 1983	Penobscot Bay
F00448	1988	10,000	MLLW	North American Datum 1983	Belfast to Bucksport
H00933	1867	40,000	MLW	North American Datum 1927	Seguin Island to Cape Elizabeth
H00983	1868	10,000	MLW	Standard American Datum	Fox Island Thoroughfare East Side
H01028	1869	20,000	MLW	North American Datum 1913	Isle Au Haut Bay
H01029	1869	10,000	MLW	United States Standard Datum 1901	Hurricane Island Sound and Vicinity
H01059	1870	10,000	MLW	North American Datum 1913	Moose-A-Bec Reach
H01060	1870	10,000	MLW	North American Datum 1913	Moose-A-Bec Reach Eastern
H01061	1870	10,000	MLW	Undetermined	Indian River
H01073	1870	10,000	MLW	Undetermined	Fox Island Bay and Vicinity
H01142	1871	10,000	MLW	Undetermined	East Side of Fox Islands and Seal Bay
H01143	1871	20,000	MLW	North American Datum 1927	Camden to Belfast Bay
H01245A	1905	10,000	MLW	United States Standard Datum 1901	Sands Point to Barletti
H01245B	1905	10,000	MLW	United States Standard Datum 1901	Sands Point to Barletti
H01259	1873	20,000	MLW	North American Datum 1913	Castine Harbor
H01261	1873	10,000	MLW	North American Datum 1927	East from Fox Island to Buck Island
H01321	1875	10,000	MLW	North American Datum 1913	East Penobscot Bay
H01400A	1905	10,000	MLW	United States Standard Datum 1901	Merchants Row and Deer Island
H01400B	1905	10,000	MLW	North American Datum 1913	Merchants Row and Deer Island II
H01401	1878	10,000	MLW	North American Datum 1913	Blue Hill and Placentia Bays
H01406	1878	10,000	MLW	United States Standard Datum 1901	Isle au Haut Bay
H01433A	1905	10,000	MLW	North American Datum 1913	Pond Island to Newbury Neck
H01433B	1905	10,000	MLW	Undetermined	Pond Island to Newbury Neck II
H01434	1879	10,000	MLW	Undetermined	Western Blue Hill Bay
H01435A	1879	10,000	MLW	Undetermined	Goose Cove
H01435B	1879	10,000	MLW	Undetermined	Goose Cove II
H01436A	1905	10,000	MLW	Undetermined	Upper Part of Frenchman's Bay
H01436B	1905	10,000	MLW	Undetermined	Upper Part of Frenchman's Bay II
H01474A	1880	10,000	MLW	Undetermined	Franklin Bay
H01474B	1880	10,000	MLW	Undetermined	Franklin Bay II
H01474C	1880	10,000	MLW	North American Datum 1927	Franklin Bay III

Survey ID	*Year*	*Scale/ Vertical Accuracy*	*Original Vertical Datum*	*Provided Horizontal Datum*	*Name*
H01528	1882	10,000	MLW	Undetermined	Pigeon Hill Bay and Approaches
H01567A	1887	10,000	MLW	Undetermined	Narraguagus Bay
H01567B	1887	10,000	MLW	Undetermined	Narraguagus Bay II
H01574	1883	10,000	MLW	Undetermined	Mud Hole Channel and Vicinity
H01608	1884	10,000	MLW	Undetermined	Pleasant Bay Entrance to Guard Point
H01610	1884	10,000	MLW	Undetermined	Harrington Bay and River
H01644	1885	10,000	MLW	Undetermined	Pleasant River
H01684	1885	10,000	MLW	Undetermined	Chandlers Bay
H01836	1888	40,000	MLW	Undetermined	Matinicus Rock to Seguin Island
H02763	1905	10,000	MLW	Undetermined	Entrance to Flanders Bay
H02782	1906	20,000	MLW	Undetermined	Blue Hill Bay to Eggemoggin Reach
H06564	1940	120,000	MLW	North American Datum 1927	East of Cape Ann
H06565	1940	120,000	MLW	North American Datum 1927	Gulf of Maine
H06566	1940	20,000	MLW	North American Datum 1927	Gulf of Maine, Cashes Ledge
H06675	1941	10,000	MLW	North American Datum 1927	Sheepscott Bay and Kennebec River
H06730	1941	20,000	MLW	North American Datum 1927	South of Seguin Island
H06839	1943	10,000	MLW	North American Datum 1927	Sheepscot River
H06840	1943	10,000	MLW	North American Datum 1927	Sheepscot River and Booth Bay
H06841	1943	10,000	MLW	North American Datum 1927	Upper Sheepscot River
H06842	1943	10,000	MLW	North American Datum 1927	Northern Half Damariscotta River
H06843	1943	10,000	MLW	North American Datum 1927	Damariscotta River and Johns River
H06844	1943	10,000	MLW	North American Datum 1927	Boothbay Harbor, Lineken & Johns Bays
H06853	1943	10,000	MLW	North American Datum 1927	Muscongus Bay and Sound
H06854	1944	10,000	MLW	North American Datum 1927	Muscongus Bay and Sound
H06858	1943	20,000	MLW	North American Datum 1927	Booth Bay and Mouth of Sheepscot River
H06861	1944	20,000	MLW	North American Datum 1927	Muscongus Bay
H06964	1944	10,000	MLW	North American Datum 1927	Medomak River
H06965	1944	10,000	MLW	North American Datum 1927	Muscongus Bay
H06967	1944	10,000	MLW	North American Datum 1927	Friendship and Franklin Island
H06968	1944	10,000	MLW	North American Datum 1927	Howard Point to Thomaston
H06969	1944	10,000	MLW	North American Datum 1927	Franklin Island to Burnt Island
H06982	1945	20,000	MLW	North American Datum 1927	Approaches to Penobscot Bay
H06984	1944	10,000	MLW	North American Datum 1927	Burnt Island to Mosquito Head
H06992	1944	10,000	MLW	North American Datum 1927	Inshore Monhegan Island

Survey ID	*Year*	*Scale/ Vertical Accuracy*	*Original Vertical Datum*	*Provided Horizontal Datum*	*Name*
H07054	1945	10,000	MLW	North American Datum 1927	Metinic Island and Green Island
H07055	1945	10,000	MLW	North American Datum 1927	Seal Island and Woodenball Island
H07056	1945	20,000	MLW	North American Datum 1927	Matinucus Island to Isle au Haut
H07057	1945	20,000	MLW	North American Datum 1927	Southwest of Matinicus Island
H07058	1945	20,000	MLW	North American Datum 1927	Jericho Bay
H07150	1946	10,000	MLW	North American Datum 1927	Isle Au Hau
H07151	1946	10,000	MLW	North American Datum 1927	Bass Harbor
H07152	1946	10,000	MLW	North American Datum 1927	Jericho Bay
H07153	1946	20,000	MLW	North American Datum 1927	Approaches to Blue Hill Bay
H07198	1947	10,000	MLW	North American Datum 1927	Belfast Harbor
H07199	1947	10,000	MLW	North American Datum 1927	Bar Harbor
H07643	1948	10,000	MLW	North American Datum 1927	Winter Harbor
H07772	1949	10,000	MLW	North American Datum 1927	Jericho Bay
H07773	1949	10,000	MLW	North American Datum 1927	Marshall Island
H07774	1949	10,000	MLW	North American Datum 1927	Long Island
H07830	1950	10,000	MLW	North American Datum 1927	Camden and Rockport Harbors
H07831	1950	1:10,000	MLW	North American Datum 1927	Rockland Harbor and Approaches
H07832	1950	20,000	MLW	North American Datum 1927	Monroe Island
H07833	1950	10,000	MLW	North American Datum 1927	Approaches to Blue Hill Bay
H07834	1950	10,000	MLW	North American Datum 1927	Blue Hill Bay and Jericho Bay
H08029	1953	10,000	MLW	North American Datum 1927	Mount Desert Island
H08030	1953	10,000	MLW	North American Datum 1927	Little Cranberry and Baker Islands
H08031	1953	40,000	MLW	North American Datum 1927	Vicinity of Mount Desert Rock
H08109	1950	10,000	MLW	North American Datum 1927	Bass Harbor and Approaches
H08110	1953	10,000	MLW	North American Datum 1927	Blue Hill Harbor
H08114	1953	10,000	MLW	North American Datum 1927	Cod Ledge
H08167	1954	10,000	MLW	North American Datum 1927	Matinicus Island and Vicinity
H08168	1954	20,000	MLW	North American Datum 1927	Vicinity of Matincus Island
H08169	1954	60000	MLW	North American Datum 1927	Mohegan Island to Matinicus Rock
H08175	1954	10,000	MLW	North American Datum 1927	Tenants Harbor
H08176	1954	20,000	MLW	North American Datum 1927	Two Bush Channel
H08177	1954	20,000	MLW	North American Datum 1927	Approaches to West Penobscot Bay
H08178	1954	20,000	MLW	North American Datum 1927	Stand-In Point to Lang Island

Survey ID	*Year*	*Scale/ Vertical Accuracy*	*Original Vertical Datum*	*Provided Horizontal Datum*	*Name*
H08198	1955	120,000	MLW	North American Datum 1927	Cashes Ledge to Mount Desert Rock
H08200	1955	120,000	MLW	North American Datum 1927	North of Georges Bank
H08259	1955	10,000	MLW	North American Datum 1927	Muscle Ridge Channel
H08504	1956	20,000	MLW	North American Datum 1927	Schoodic Peninsula
H08509	1959	20,000	MLW	North American Datum 1927	Narraguagus Bay
H08510	1959	20,000	MLW	North American Datum 1927	Off Narraguagus Bay
H08513	1958	10,000	MLW	North American Datum 1927	Gouldsboro Bay Prospect Harbor
H08514	1957	10,000	MLW	North American Datum 1927	Prospect Harbor
H08667	1962	60,000	MLW	North American Datum 1927	Southeast Petiti Manan Island
H08668	1962	60,000	MLW	North American Datum 1927	NE Portion- Gulf of Maine
H08669	1962	60,000	MLW	North American Datum 1927	Mound Desert Rock
H10097	1983	10,000	MLW	North American Datum 1927	Spruce Head to Lincolnville
H10098	1983	10,000	MLW	North American Datum 1927	Isle Harbor to Lime Island
H10101	1983	10,000	MLW	North American Datum 1927	Lasell Island to Robinson Rock and North Haven Island
H10109	1983	10,000	MLW	North American Datum 1927	Belfast Bay to Great Spruce Head
H10130	1984	10000	MLW	North American Datum 1927	Fort Point Cove to Moose Point
H10131	1984	10,000	MLW	North American Datum 1927	Approaches to the Penobscot River
H10134	1984	10,000	MLW	North American Datum 1927	Orland River to Fort Point Cove
H10136	1984	10,000	MLW	North American Datum 1927	Bangar to Snub Point
H10146	1984	20,000	MLW	North American Datum 1927	Snub Point to Treat Hill
H10157	1984	10,000	MLLW	North American Datum 1927	Verona Park to Treat Hill
H10173	1985	10000	MLLW	North American Datum 1927	Penobscot Bay
H10177	1985	10000	MLLW	North American Datum 1927	East Penobscot Bay
H10178	1985	10000	MLLW	North American Datum 1927	Penobscot Bay
H10820	1998	10000	MLLW	North American Datum 1983	Two Bush Channel
H10867	1999	10000	MLLW	North American Datum 1983	Penobscot Bay
H10868	1999	10000	MLLW	North American Datum 1983	Sandy Point to Fort Point

2) OMG UNB Multibeam swath sonar surveys

Two multibeam swath sonar surveys, collected by the Ocean Mapping Group at the University of New Brunswick, Canada in 2009 (Figure 4; Table 3), were used in creating the Bar Harbor DEM. The surveys provided coverage of Blue Hill Bay and Somes Sound— both located around Mount Desert Island. The data were collected for subtidal morphology research.

Information about the project was provided to NGDC by the scientific project leads— Joe Kelley at the University of Maine and Laura Brothers at the USGS Coastal and Marine Science Center offices in Woods Hole, MA. Laura Brothers provided the data to NGDC in *Fledermaus* grid formats via secure file transfer protocol (SFTP). The two-meter resolution data were transformed to xyz points using *Fledermaus* and *ArcMap* ; the data were converted from MSL to NAVD88 using *VDatum* software.

3) Electronic navigational chart soundings

NGDC used FME software to extract bathymetric soundings from ENCs in the Bar Harbor area. The soundings provided depth information in areas where other bathymetric data were unavailable. The ENCs were downloaded from NOAA's Office of Coast Survey website horizontally referenced to NAD 83 geographic. The extracted soundings were transformed from a vertical datum of MLLW to NAVD 88 using *VDatum*.

3.1.3 Topography

The topographic datasets used in building the Bar Harbor DEM included the USGS National Elevation Dataset (NED) DEM and a stereophotogrammetry survey of the eastern side of Mount Desert Island acquired by Kappa Mapping, Inc. on behalf of the City of Bar Harbor and Acadia National Park (Table 5; Fig. 4).

Table 5. Topographic datasets used in compiling the Bar Harbor DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
USGS	1999-2000	NED	10 Meters	WGS 84	NAVD 88	http://ned.usgs.gov/
City of Bar Harbor and Acadia National Park	2004	Triangulated Irregular Network (TIN)	1:14,400	Universal Transverse Mercator (UTM) Zone 19	NAVD 88	http://www.kappamap.com/

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

The USGS NED data were available for download as portions of a bare-earth raster DEM, and provided complete 1/3 arc-second coverage of the Bar Harbor region. The DEMs were horizontally referenced to NAD 83 geographic and were vertically referenced to NAVD 88. The elevations in the NED DEM had a vertical accuracy of +/- 7 to 15 meters, depending on the resolution of the source data used by the USGS. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov). The dataset was mostly derived from USGS topographic quadrangle maps and aerial photographs based ontopographic surveys conducted in the 1970s and 1980s; in some areas it has been revised using data collected in 1999. The NED DEM included elevation with "zero" values over the open ocean, which were removed from the dataset by clipping it to the final coastline.

2) City of Bar Harbor/ Acadia National Park stereophotogrammetry

The entire town of Bar Harbor (including portions of Acadia National Park) was flown for stereo black and white aerial coverage on May 1, 2004. Photo scale is at 1:14,400 (1"=1200') which is suitable for 1"=200' mapping with 5' contours, based on National Map Accuracy Standards (NMAS). Limited planimetric (roads, hydrography, buildings,etc.) and topographic (breaklines, mass points, spot elevations) features were stereo compiled to produce a Triangular Irregular Network (TIN). From this TIN, 5' contours were generated. Contours were edited for cartographic completeness and labeled.

NGDC acquired the contours and the TIN via SFTP from Claire Kiedrowski at Kappa Mapping, Inc. and Karen Anderson at Acadia National Park, respectively. The TIN nodes were extracted and converted to meters using *ArcGIS*. The nodes were then exported as an xyz file for use in the final gridding process.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation of the Bar Harbor DEM were originally referenced to a number of vertical datums including MLW, MSL, and MLLW. All datasets were transformed to NAVD 88 using NOAA's Vertical Transformation tool *VDatum*.

1) **Bathymetric data**

   The NOS hydrographic surveys and OMG UNB multibeam surveys were transformed from MLLW, MLW, and MSL to NAVD 88 using *VDatum* software.

2) **Topographic data**

   The USGS NED DEM and the City of Bar Harbor/Acadia National Park stereophotogrammetry survey were both delivered to NGDC in NAVD 88.

3.2.2 Horizontal datum transformations

Datasets used in the compilation of the Bar Harbor DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, and UTM NAD 83 Zone 19. The relationships and transformational equations between these geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using *Proj.4*, *ArcGIS*, and *VDatum* software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied to the source datasets, the resulting transformed data were viewed in *ArcMap* and *QT Modeler* for consistency. Any problems or errors were identified and resolved before proceeding with subsequent gridding steps. Once evaluated, compared, and corrected, the data were converted into final xyz files in preparation for the DEM gridding process. Problems included:

- Obvious anomalous points within datasets.
- Inconsistent overlapping datasets. Earlier data were eliminated in these areas.
- Some topographic data contained values over the ocean. The values were clipped from the datasets using the Bar Harbor coastline.

3.3.2 Smoothing of bathymetric data

The early NOS hydrographic survey data are generally sparse at the resolution of the Bar Harbor DEM, especially in the deep water areas near the mouth of Bar Harbor. To reduce the effect of artifacts due to this, a 1/3 arc-second 'pre-surface' bathymetric grid in NAVD 88 vertical datum was generated using *GMT*[4], an NSF-funded software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

To create the bathymetric surface, all bathymetric datasets were converted into xyz points, and were combined with points extracted from the Bar Harbor coastline—to provide a breakline along the entire coastline. The coastline elevation values were set to zero, to ensure the bathymetric surface approached zero relative to MHW in areas where bathymetric data are sparse or non-existent.

The point data were then median-averaged using the *GMT* tool 'blockmedian'. The *GMT* tool 'surface' was used to apply a tight spline tension to interpolate elevations for cells without data values, and to create 1/3 arc-second grid, 0.05 degrees (~5%) larger than the Bar Harbor DEM region. The *GMT* grid created by 'surface' was clipped to the Bar Harbor coastline and converted into an xyz file for use in building the final grid (See Sec. 3.3.3).

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

3.3.3 Building the NAVD 88 DEM

MB-System[5] was used to create the 1/3 arc-second Bar Harbor DEM. 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 6. The greatest weights were assigned to the multibeam datasets and the recent City of Bar Harbor stereophotogrammetry surveys. The least weight was given to the ENC extracted points, the NOS hydrographic soundings, and the USGS NED data

Table 6. Data hierarchy used to assign gridding weight in *MB-System*.

Dataset	*Relative Gridding Weight*
OMG/UNB Multibeam Surveys	100
Bar Harbor/Acadia National Park Surveys	100
NOAA NOS Hydrographic Surveys	10
USGS NED Data	10
ENC Extracted Points	1
Pre-Surfaced Bathymetric Grid	1

5. *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. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ [Extracted from *MB-System* web site.]

3.3.4 *Building the MHW DEM*

The MHW DEM was created by adding an "NAVD 88 to MHW" conversion grid to the NAVD 88 DEM.

1) Developing the conversion grid

Using extents slightly larger (~ 5 percent) than the Bar Harbor DEM, an empty xyz file of the grid area was created at 1/3 arc-second resolution. The elevation value at each of the points was set to zero. Conversion values from NAVD 88 to MHW at each xyz point were generated using *VDatum* and the null values were removed. The xyz file was then interpolated with the *GMT* tool 'surface' to create the 1/3 arc-second 'NAVD 88 to MHW' conversion grid with the extent of the Bar Harbor DEM, interpolating values inland to represent the differences between the two datums onshore (Fig. 5).

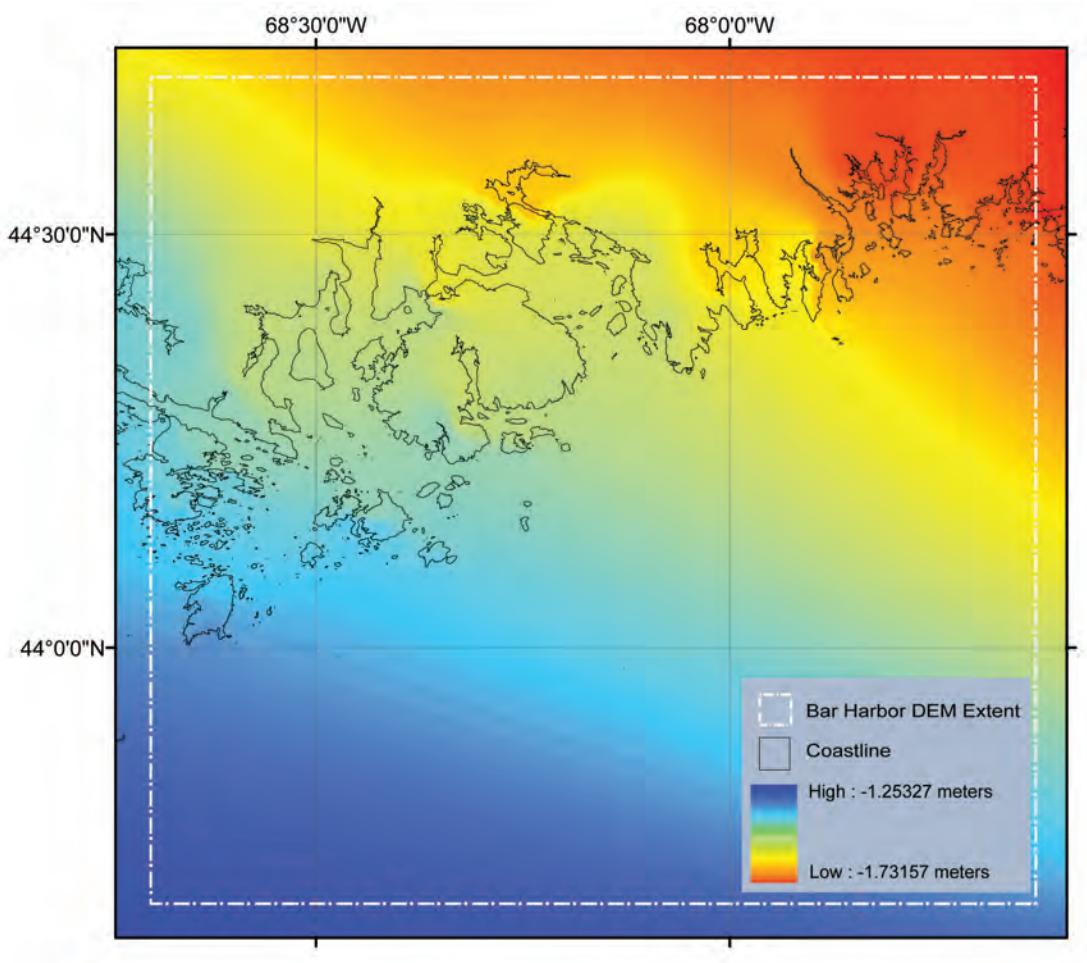

Figure 5. Image showing the Bar Harbor vertical conversion grid.

3.4 Quality Assessment of the DEM

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Bar Harbor DEM is dependent upon the DEM cell size and the accuracy of source datasets. Topographic features have an estimated horizontal accuracy of 10 meters: USGS NED data have a horizontal accuracy of 10 meters and the Bar Harbor/Acadia National Park stereophotogrammetry surveys have an accuracy of 10 meters, but with larger point spacings in some areas. Bathymetric features are resolved to only within a few tens of meters in deep-water areas. Recent NOS surveys and shallow, near-coastal multibeam surveys have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings and potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values in the Bar Harbor DEM is also dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy of 1-2 meters for the Bar Harbor/Acadia National Park stereophotogrammetry surveys and up to 15 meters for the NED DEMs. Bathymetric values have an estimated accuracy between 0.1 meters and 5% of water depth. The bathymetric depth values used in building the DEM were derived from a wide range of sounding measurements, from the early twentieth century NOS surveys to recent, high-resolution, GPS-navigated bathymetric surveys. Gridding interpolation— used to determine bathymetric values between sparse, poorly located NOS soundings— may degrade the vertical accuracy of elevations in deep water.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Bar Harbor 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 Maine Zone 4 coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Figure 7 shows a data contribution plot of the Bar Harbor DEM. Analysis of preliminary grids using *QT Modeler* and *Fledermaus* revealed suspect data points, which were corrected before recompiling the DEM. Figure 8 shows a color perspective image of the 1/3 arc-second Bar Harbor NAVD 88 DEM in its final version.

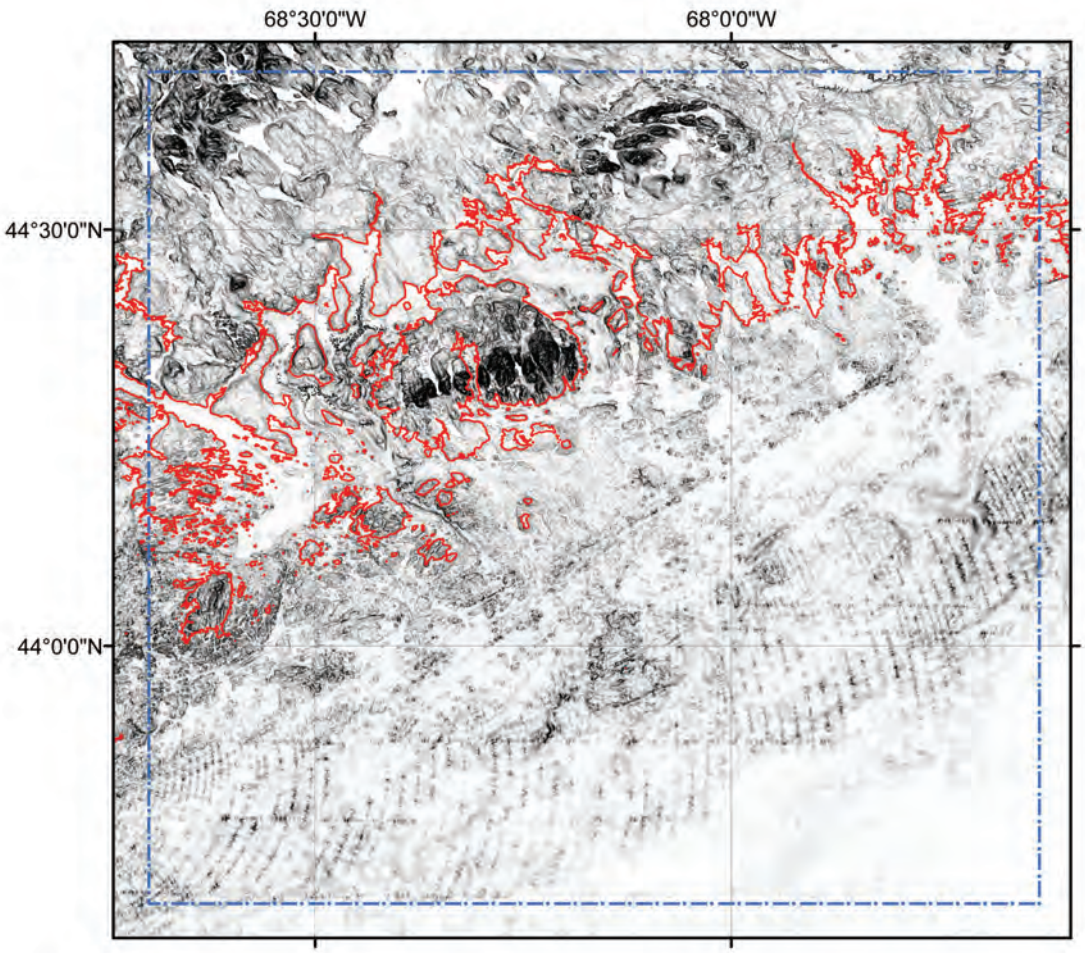

Figure 6. Slope map of the Bar Harbor DEM. Flat-lying slopes are shown in white; dark shading indicates steep slopes; coastline shown in red, DEM extent shown in blue.

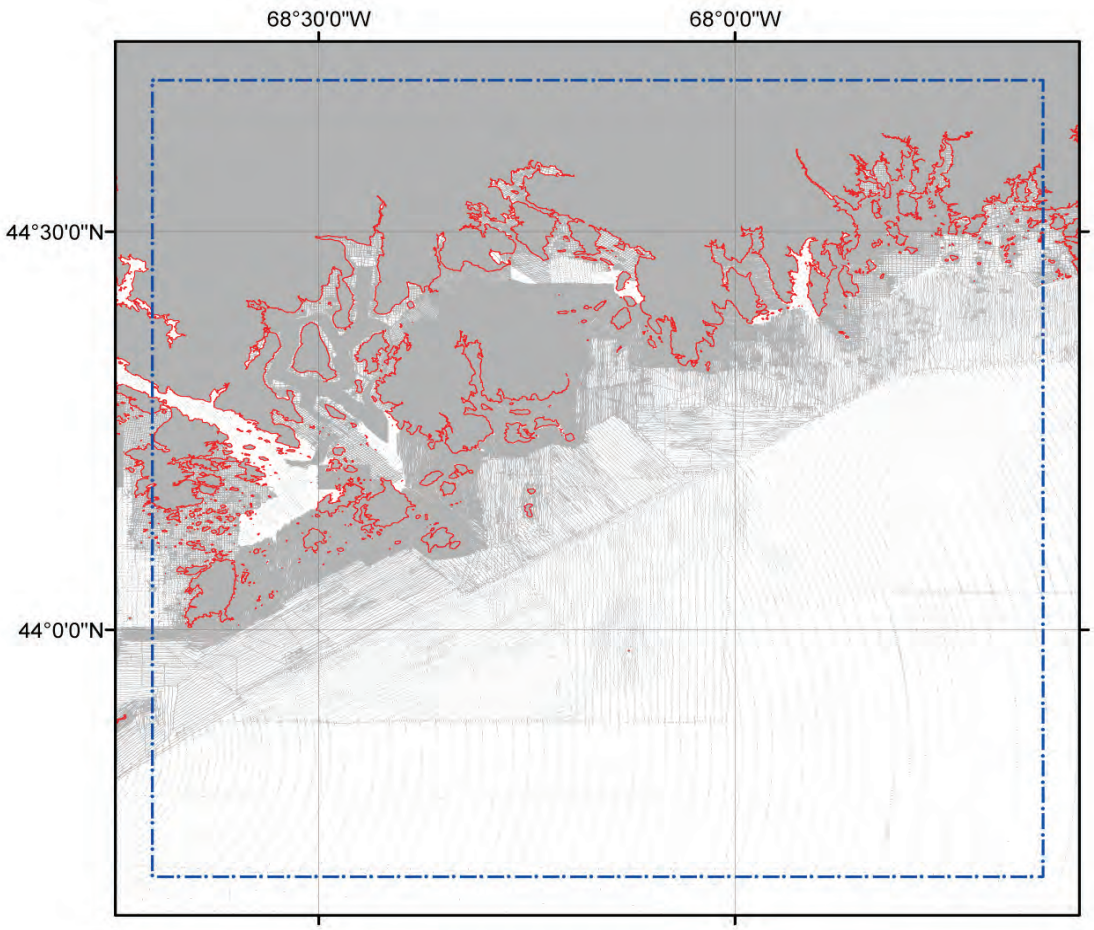

Figure 7. Data contribution plot of the Bar Harbor DEM. Gray represents DEM cells that are constrained by source data; white represents cells with elevation values that were derived from interpolation; coastline shown in red, DEM extent in blue.

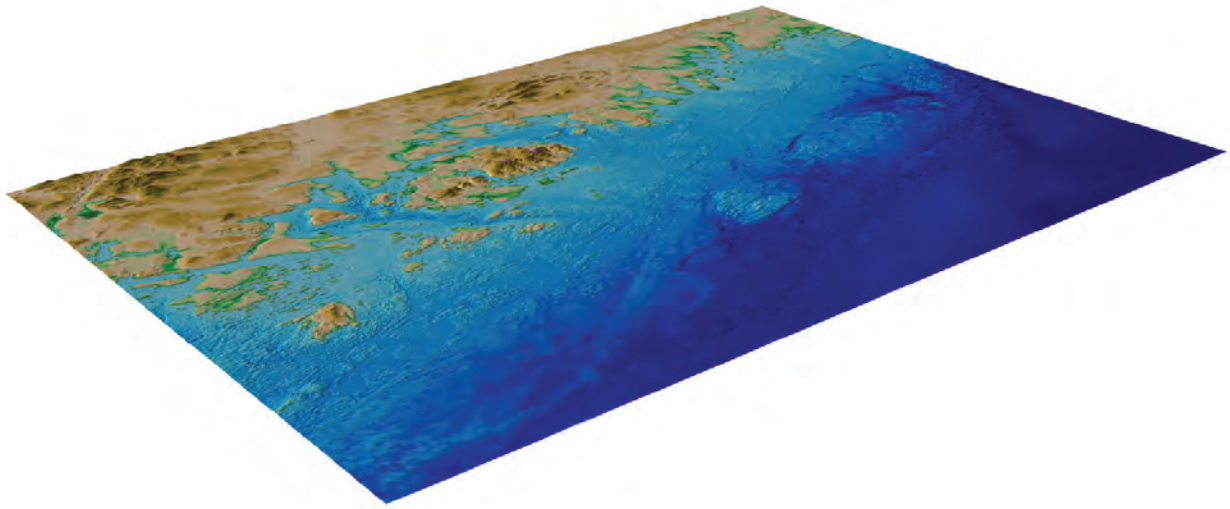

Figure 8. Perspective view from the southeast of the 1/3 arc-second NAVD88 Bar Harbor DEM. Vertical exaggeration— times 2.

3.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 428 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format. The associated shapefile attributes provided monument postions in NAD 83 geographic, and elevations in NAVD 88. The monument elevations were compared with the final Bar Harbor DEM values (Fig. 9). Differences between the DEM and the monument elevations range from -20.5 to four meters, with a mean of 2.22 meters. Differences of one to two meters occurred where the NGS monuments are found in ditches near the road; larger differences occurred when the monuments were found on buildings or on poles that extend from the ground.

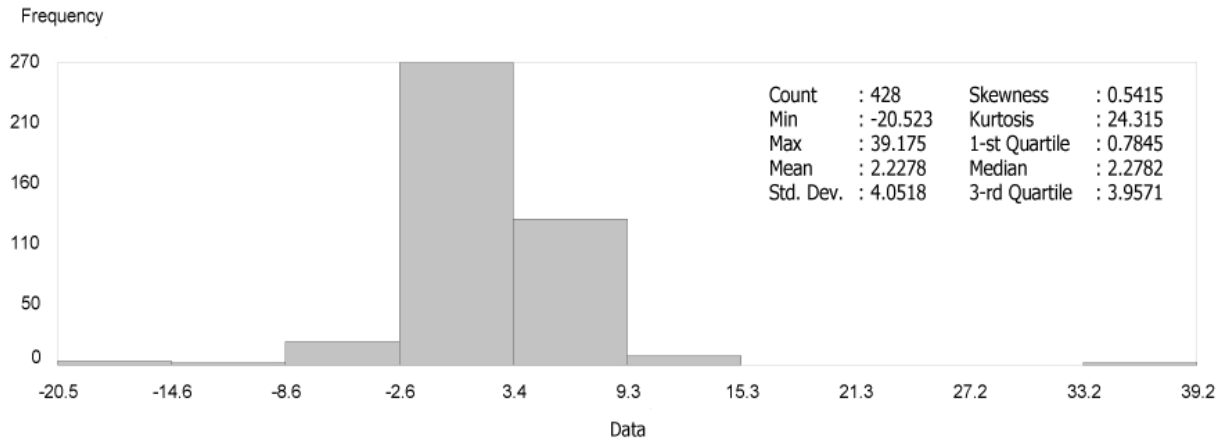

Figure 9. Histogram of the differences between NGS geodetic monument elevations and the Bar Harbor DEM.

3.4.5 DEM comparison with source data files

To ensure grid accuracy, the Bar Harbor NAVD 88 DEM was compared to source data files. All bathymetric and topographic source data were compared to the Bar Harbor NAVD 88 DEM using Python, GDAL, and Gnuplot. Histograms of the differences between individual datasets and the Bar Harbor NAVD 88 DEM mostly cluster around zero. Largest differences between source datasets and the DEM resulted from the averaging of multiple topographic source datasets where data coverage overlapped.

4. Summary and Conclusions

An integrated bathymetric–topographic digital elevation model of the Bar Harbor, Maine region, with a cell size of 1/3 arc-second, was developed for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state, local, and academic agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI *ArcGIS*, ESRI *ArcGIS World Imagery 2-D*, *Fledermaus*, *GMT*, *MB-System*, *QT Modeler*, and *VDatum* software.

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

- Incorporate coastal lidar surveys into the DEM.
- Conduct high-resolution bathymetric surveys in deep water areas surrounding Bar Harbor.

5. Acknowledgments

The creation of the Bar Harbor DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Marie Eble, and Vasily Titov (PMEL); Laura Brothers (USGS Woods Hole); Claire Keidrowski (Kappa Mapping, Inc.); Joseph Kelley (University of Maine); John E. Hughes Clarke (University of New Brunswick); Karen Anderson (Acadia National Park); and Steven Weed (Town of Bar Harbor).

6. References

Nautical Chart # 13312 (RNC), 22nd Edition, August 2006. Frenchman and Bluehill Bays and Approaches. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13313 (RNC), 20th Edition, July 2004. Approches to Blue Hill Bay. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13315 (RNC and ENC), 11th Edition, 2002. Deer Island Thorofare and Casco Passage. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13316 (RNC), 23rd Edition, September 2011. Blue Hill Bay and Blue Hill Harbor. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13318 (RNC), 18th Edition, August 2002. Frenchman Bay and Mount Desert Island. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13321 (RNC), 9th Edition, March 2003. Southwest Harbor and Approaches. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13322 (RNC), 9th Edition, February 2002. Winter Harbor. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13323 (RNC), 8th Edition, September 2004. Bar Harbor and Mount Desert Island. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13324 (RNC and ENC), 14th Edition, November 2003. Tibbett Narrows to Schoodic Island. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 10.0 – 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/.

Fledermaus v. 6.7.0 and 7.0.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/.

GEODAS v. 5 – Geophysical Data System, freeware developed and maintained by Dan Metzger, NOAA National