NOAA Technical Memorandum NESDIS NGDC-58

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Marine Geology and Geophysics Division
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1. INTRODUCTION

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed a bathymetric–topographic digital elevation model (DEM) of Kachemak Bay, Alaska (Fig. 1). The 1/3 arc-second[1] DEM, referenced to Mean High Water (MHW), was developed and evaluated using diverse digital datasets available for the region (grid boundary and sources shown in Fig. 4). The 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 Kachemak Bay DEM.

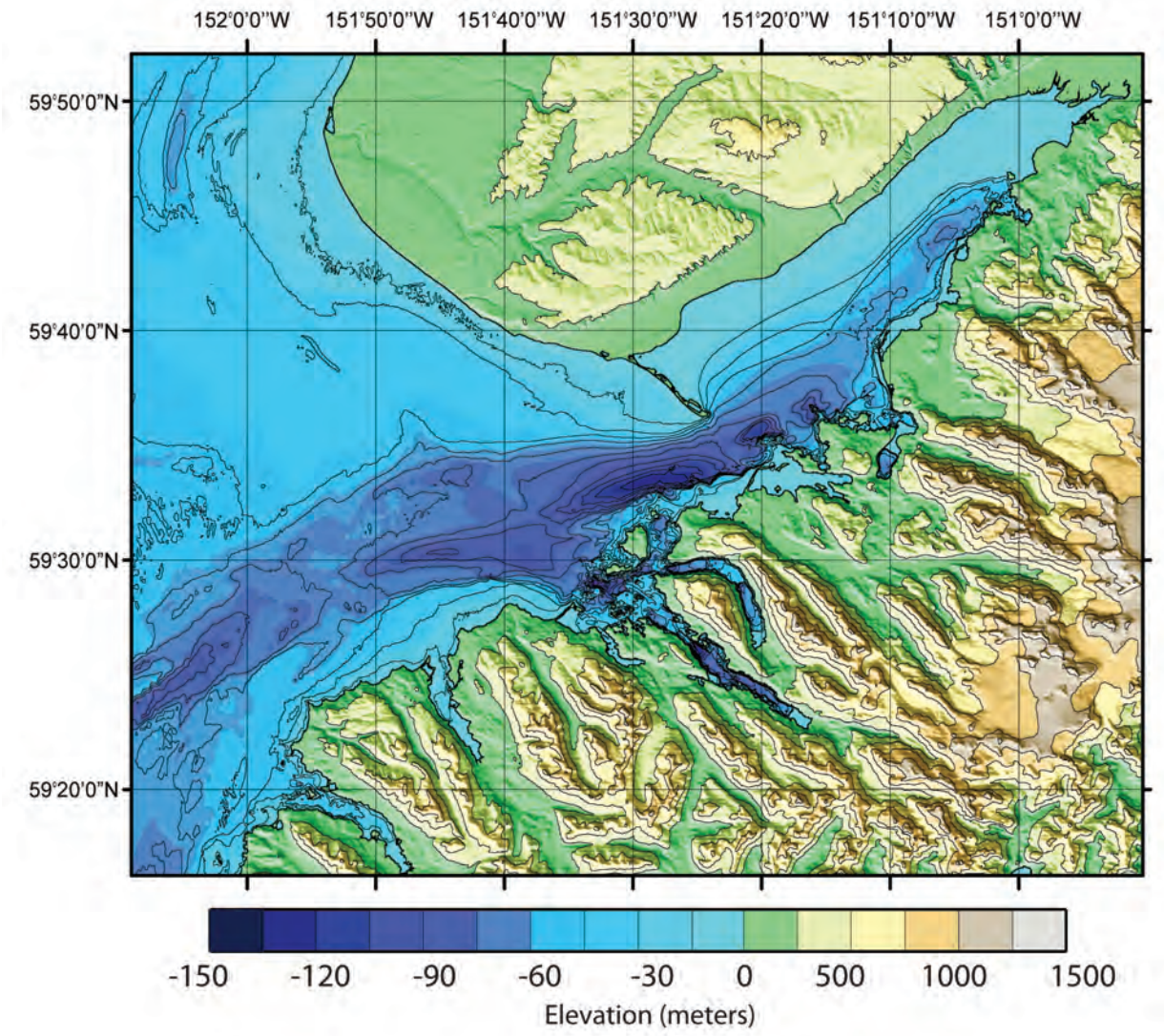

Figure 1. Shaded-relief image of the Kachemak Bay 1/3 arc-second DEM. Contour interval is 15 meters for bathymetry and 100 meters for topography.

1. The Kachemak Bay DEM is 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 Homer, Alaska, (59°38'35"N, 151°31'33"W) 1/3 arc-second of latitude is equivalent to 10.32 meters; 1/3 arc-second of longitude equals 5.22 meters.

2. Study Area

The Kachemak Bay DEM provides coverage of the area surrounding Homer, Alaska, including all of Kachemak Bay and the town of Seldovia. The DEM area is located along the southwestern Kenai Peninsula, west of the Kenai mountains, and approximately 100 miles south of Anchorage (Fig. 2). The area is tectonically active and at high risk of future tsunamis. The 9.2 magnitude Alaskan earthquake of 1964, for example, affected the area significantly; it changed the shoreline terrain and caused numerous tsunamis in the area.

The town of Homer was founded in the late nineteenth century as a mining town, and is currently known for its renowned fishing industry and its natural beauty. The town has about 4,000 year-round residents. From the town of Homer, a four mile long spit extends into Kachemak Bay, which affects the water circulation patterns in the bay (Fig. 3).

Figure 2. Overview of the Kachemak Bay DEM region. Black box represents approximate Kachemak Bay DEM extent. ESRI's online World 2D Imagery in background.

Figure 3. Aerial photograph showing the Homer spit. (Wikipedia Commons http://en.wikipedia.org/wiki/Homer_Spit)

3. METHODOLOGY

The Kachemak Bay 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 MHW. Data were gathered in an area slightly larger than the DEM extents. This data "buffer" ensured that gridding occurred 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 Kachemak Bay DEM.

Grid Area	Kachemak Bay, Alaska
Coverage Area	152.10º to 150.89º W; 59.32º to 59.82º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datums	Mean High Water (MHW)
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 Kachemak Bay National Estuarine Research Reserve (KBRR); the Kenai Peninsula Borough; the Alaska Department of Fish and Game (ADFG); the U.S. Army Corps of Engineers (USACE); the U.S. Fish and Wildlife Service (USFWS); the U.S. Geological Survey (USGS); the National Geospatial Intelligence Agency (NGA); and the National Aeronautics and Space Administration (NASA). Datasets were shifted to NAD 83 geographic horizontal 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. Vertical datum transformations were accomplished using a constant offset derived from the Homer tide station (see Sec. 3.2.1).

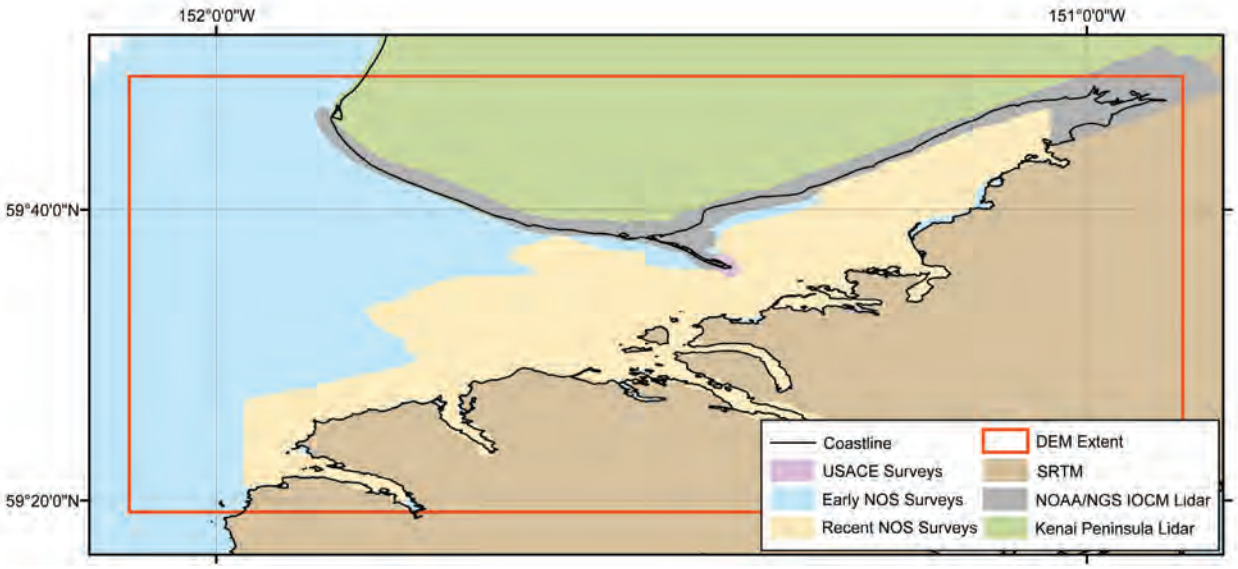

Figure 4. Source and coverage of datasets used in compiling the Kachemak Bay DEM.

3.1.1 Coastline

Alaska shoreline data were obtained from USFWS (Table 2). The vector coastline was developed by USFWS in 2006 and combines the best available data from several other sources and organizations. In the Kachemak Bay area, the coastline closely matched the available topographic data, bathymetric data, and aerial imagery.

Table 2. Shoreline dataset used in developing the Kachemak Bay DEM.

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

1) United States Fish and Wildlife Service coastline

USFWS compiled a seamless digital vector coastline of the State of Alaska using their own data, along with data from six other sources, including: the USGS National Hydrography Dataset, NOAA's Electronic Navigational Charts (ENCs), *National Geographic* Topographic Software (derived from USGS topographic quadrangle maps), the U.S. Army Corps of Engineers, and the Alaska Department of Natural Resources. The USFWS coastline dataset was provided to NGDC in 2006 by Bret Christensen of the USFWS.

To further define the coastline for the Kachemak Bay DEM, NGDC clipped the USFWS coastline to the Kachemak Bay DEM extent and reviewed it by comparing it with SRTM topographic digital elevation models, lidar datasets, NOS hydrographic soundings, USACE hydrographic soundings, NOAA Raster Nautical Charts (RNCs), and ESRI's *World 2D* online imagery (Fig. 5). Small adjustments to the coastline were made as necessary. The comparison helped to ensure that features such as jetties and rocks were accurately reflected in the coastline. The final edited coastline was converted to xyz data with a ten meter point spacing, using NGDC's *GEODAS* software, for use in building a 'pre-surface' bathymetric grid (see Sec. 3.3.2).

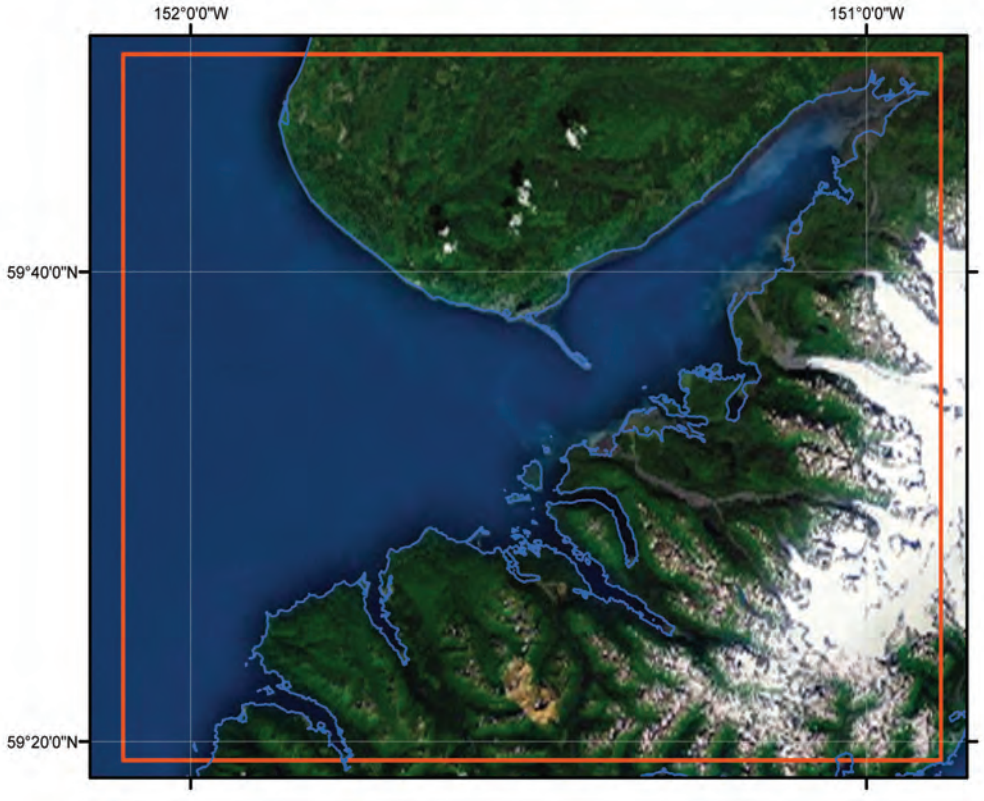

Figure 5. Overview of final coastline in blue. ESRI's online World 2D Imagery in background.

3.1.2 Bathymetry

Three bathymetric datasets were used to build the Kachemak Bay DEM (Table 3). These included twelve recent high-resolution NOS bathymetric surveys, six early NOS hydrographic surveys; and one hydrographic survey from the USACE Alaska District.

Table 4. Bathymetric datasets used in compiling the Kachemak Bay DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
Early NOS	1915 to 1983	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)	Early Alaska Datums; NAD 27 geographic	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
Recent NOS	2008-2009	Hydrographic survey bag data	4 to 8 meters	Universal Transverse Mercator (UTM) NAD 83, Zone 5	MLLW	http://www.hydropaloo-za.noaa.gov/
USACE	2008	Hydrographic survey xyz data	1 to 30 meters	State Plane Coordinate System NAD 27, Alaska Zone 4	MLLW	http://www.poa.usace.army.mil/en/hydro/

1) Early National Ocean Service hydrographic survey data

A total of 17 NOS hydrographic surveys conducted between 1915 and 1981 were available for use in building the Kachemak Bay DEM (Table 4; Fig. 6), though most of the surveys were superseded by newer data. Only six were used in the final DEM. 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.

The data point spacing of the surveys varies by scale. In general, small scale surveys have greater point spacing than large scale surveys. The data were converted to shapefiles, and were edited and clipped to the DEM buffer area in ESRI's *ArcGIS*. The surveys were compared to the original survey smooth sheets, other bathymetric datasets, the Kachemak Bay coastline, topographic data, and NOS raster nautical charts (RNCs). Some surveys were manually shifted to fit the coastline. 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 5. Early digital NOS hydrographic surveys available for use in developing the Kachemak Bay DEM.

NOS Survey ID	*Year of Survey*	*Area of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
H03802*	1915	Pt. Gore to Port Graham	1:60,000	Undetermined	MLLW
H05082*	1930	Nuka Passage	1:20,000	Early Alaska Datums	MLLW
H09569*	1980	Bear Cove and Vicinity	1:10,000	Early Alaska Datums	MLLW
H09840*	1979	Cape Starichkof	1:20,000	Early Alaska Datums	MLLW
H09876	1980	Bear Island to Millers Landing	1:20,000	Early Alaska Datums	MLLW
H09877	1981	Vukon Island to Glacier Spit	1:20,000	Early Alaska Datums	MLLW
H09878*	1980	Port Graham	1:10,000	Early Alaska Datums	MLLW
H09879	1980	Koyuktolik Bay to Point Pogbibshi	1:20,000	Early Alaska Datums	MLLW
H09884*	1980	Halibut Cove and Peterson Bay	1:10,000	Early Alaska Datums	MLLW
H09893*	1980	Sadie Cove to Tutka Bay	1:10,000	Early Alaska Datums	MLLW
H09900*	1980	Homer Spit	1:5,000	Early Alaska Datums	MLLW
H09941*	1981	Kasitsha Bay to Edred Passage	1:10,000	Early Alaska Datums	MLLW
H09958	1981	Entrance to Kachemak Bay	1:20,000	NAD 27 geographic	MLLW
H09967	1981	Diamond Creek to Laida Spit	1:20,000	NAD 27 geographic	MLLW
H10091	1983	Bluff Point to Flat Island	1:40,000	Early Alaska Datums	MLLW
H10421*	1981	Barabaloa Point to Point Pogibshi	1:20,000	NAD 27 geographic	MLLW
H10967*	1981	Seldovia Bay	1:5,000	NAD 27 geographic	MLLW

* Denotes surveys that have been superseded by more recent data.

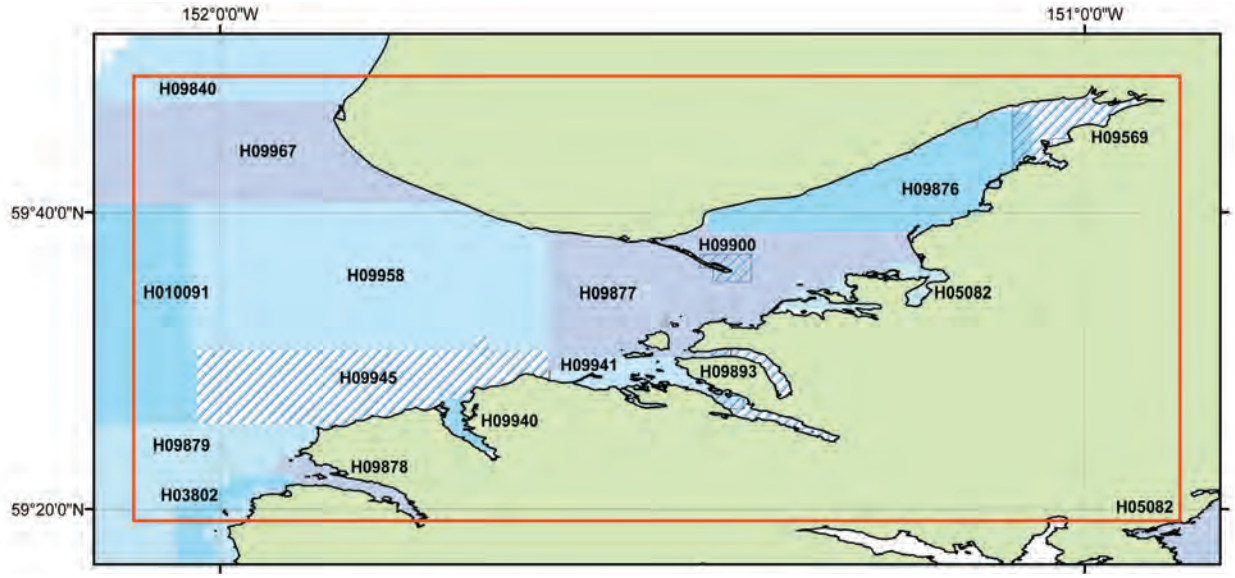

Figure 6. Early NOS hydrographic survey coverage in the Kachemak Bay region. Red box shows DEM extents.

2) Recent National Ocean Service hydrographic survey data

Twelve recent NOS surveys were available for use in the Kachemak Bay DEM (Table 5; Fig. 7). The surveys were collected as part of the Hydropalooza project— a large-scale NOAA project to map the Kachemak Bay seafloor and coastline. The recent NOS data are high-resolution sonar depictions of the bathymetry in Kachemak Bay.

Some of the surveys were not available for download from NGDC's online NOS hydrographic survey database and were obtained by hard drive from NOS. All of the recent NOS surveys required no editing, and were converted into xyz files for use in final gridding.

Table 6. Recent digital NOS hydrographic surveys used in developing the Kachemak Bay DEM.

NOS Survey ID	*Year of Survey*	*Area of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
H11933	2008	Kachemak Bay	1:10,000	NAD 83	MLLW
H11934	2008	Vicinity of Glacier Spit	1:10,000	NAD 83	MLLW
H11936*	2008	Not Specified	1:10,000	NAD 83	MLLW
H11938	2008	Kachemak Bay	1:10,000	NAD 83	MLLW
H12084*	2009	Not Specified	1:10,000	NAD 83	MLLW
H12085	2009	Not Specified	1:10,000	NAD 83	MLLW
H12086	2009	Not Specified	1:10,000	NAD 83	MLLW
H12087	2009	Southern Portion of Cook Inlet	1:10,000	NAD 83	MLLW
H12088	2008	Not Specified	1:10,000	NAD 83	MLLW
H12089	2008	Not Specified	1:10,000	NAD 83	MLLW
H12090	2008	Not Specified	1:10,000	NAD 83	MLLW
H12114	2008	Not Specified	1:10,000	NAD 83	MLLW

* Denotes Surveys that were not available from the NGDC online NOS hydrographic survey database for Kachemak Bay DEM.

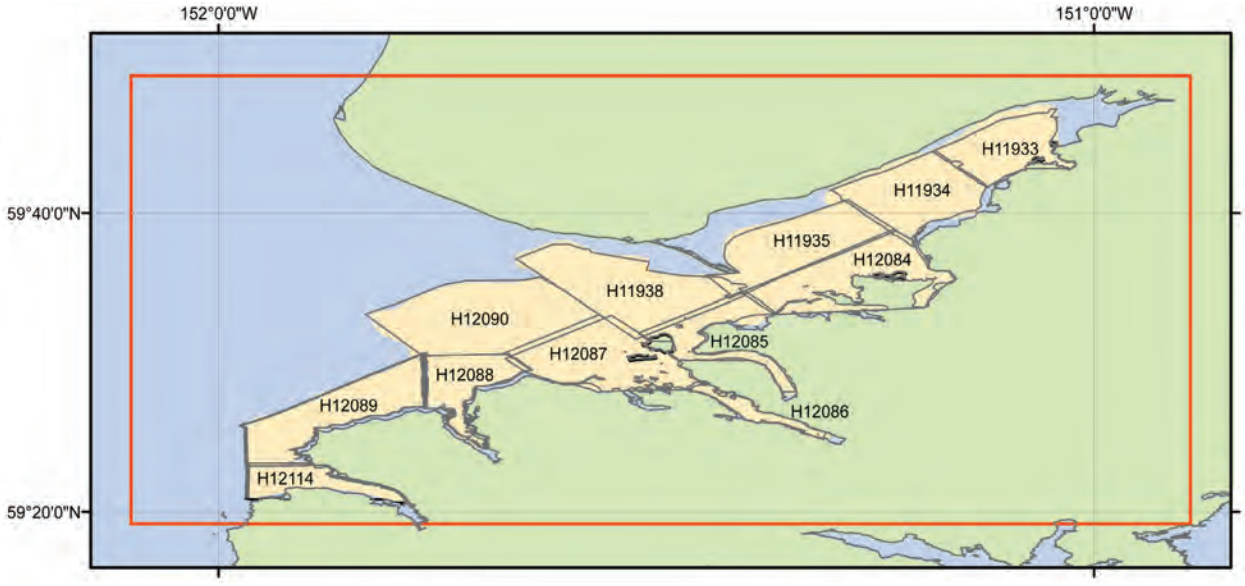

Figure 7. Recent NOS hydrographic survey coverage in the Kachemak Bay region. Red box shows DEM extent.

3) U.S. Army Corps of Engineers hydrographic surveys

Four hydrographic survey datasets were available from the USACE Alaska district website (Fig. 8), but only one of the USACE surveys was used in gridding the final Kachemak Bay DEM. The surveys provided depth information near the communities of Homer and Seldovia, and were horizontally referenced to Alaska State Plane NAD 27 Zone 4. Surveys that overlapped high resolution NOS surveys or lidar data were not used, leaving only the 'Homer Spit 1'(see Fig. 8) survey for use in the final DEM.

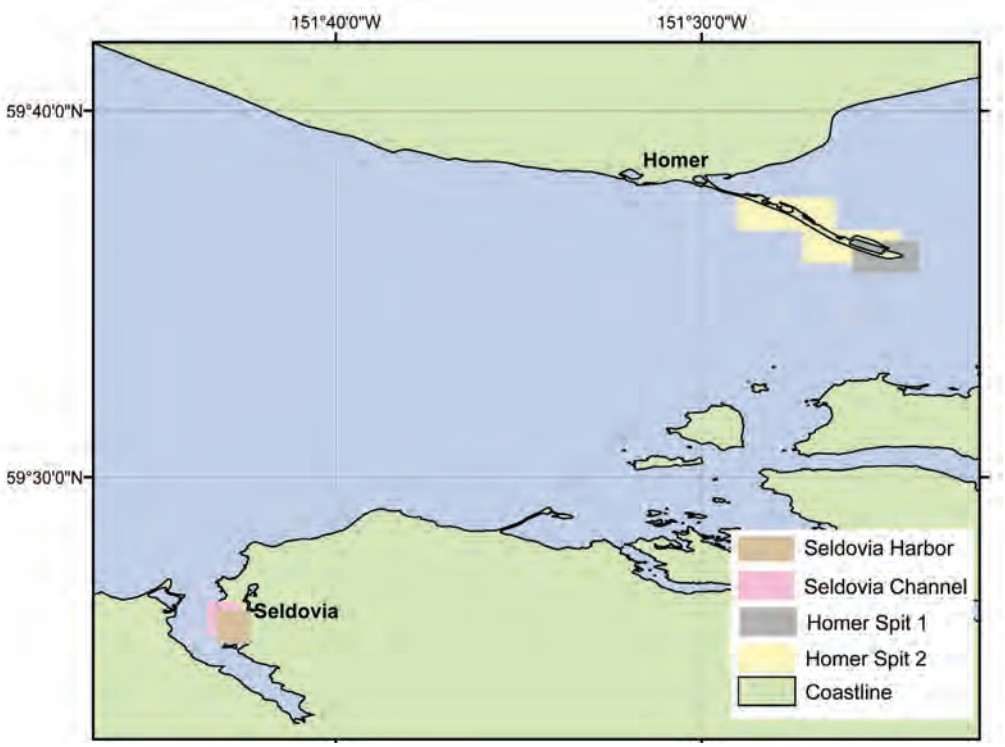

Figure 8. Spatial coverage of USACE hydrographic survey data in Kachemak Bay.

3.1.3 Topography

Three topographic datasets were used in building the Kachemak Bay DEM (Table 6; Fig. 9). The datasets included NOAA coastal lidar data, Kenai Peninsula lidar data (from a variety of organizations), and NGS/NASA SRTM data. ASTER data and USGS NED data were also assessed, but were not used in the final DEM because of data quality issues.

Table 7. Topographic datasets used in compiling the Kachemak Bay DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NOAA	2008	Lidar	5-7 meters	NAD 83 geographic	NAVD 88	http://www.csc.noaa.gov/digitalcoast/data/index.html
Multiple	2010	Lidar	4 feet	State Plane Alaska Zone 4 NAD 83 feet	NAVD 88	n/a
NASA	1999	SRTM	1 arc-second	WGS 84	NAVD 88 (EGM 96 Geoid)	http://edcsns17.cr.usgs.gov/EarthExplorer/

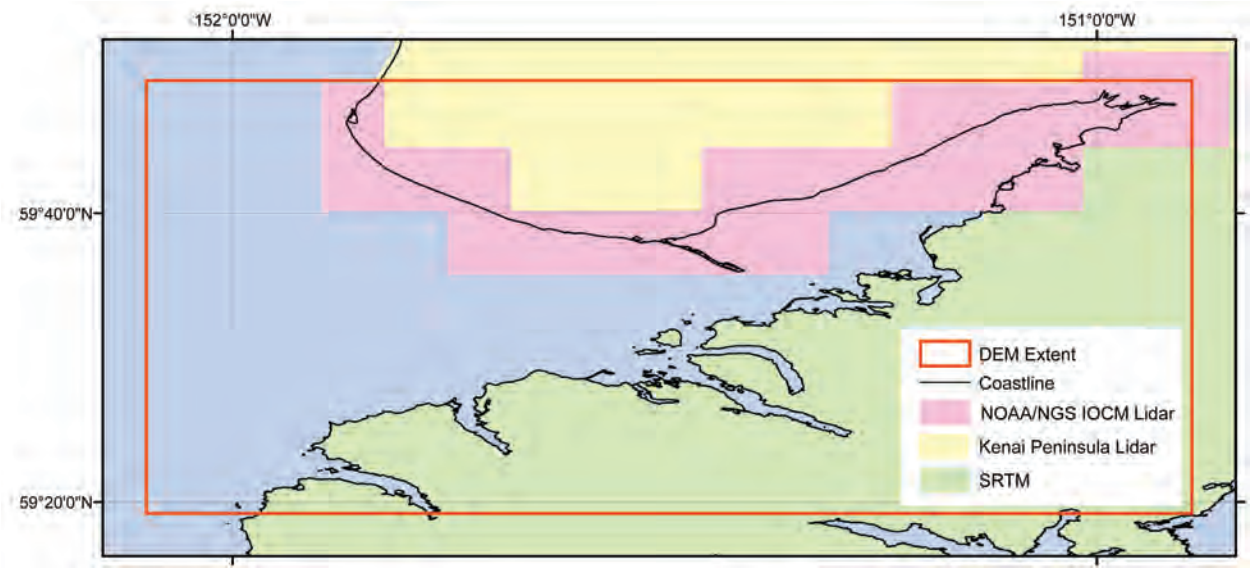

Figure 9. Source and coverage of topographic datasets used in compiling the Kachemak Bay DEMs.

1) NOAA Integrated Ocean and Coastal Mapping Kenai Peninsula Lidar

In the summer of 2008, NOAA funded and obtained a coastal lidar dataset of the area surrounding Homer, Alaska and Kachemak Bay. The data provide coverage of the coastline along the northern half of Kachemak Bay, from Anchor Point towards the head of the bay (See Fig. 9). The data were processed to bare earth and provided to NGDC as NAD 83 ascii raster files via NOAA's CSC website. The data were transformed into xyz format for use in gridding the final DEM.

2) Kenai Peninsula Lidar

In 2008, the Kenai Watershed Forum led an effort to acquire detailed lidar data of a large area of the Kenai peninsula. The resulting Kenai peninsula lidar dataset provides coverage of the land area north of Kachemak Bay (See Fig. 9). The data were collected by Aero-metric, Inc., under contract with the USGS. Funding and processing were provided by the Kenai Watershed Forum, the Kenai Peninsula Borough, the Alaska State Department of Natural Resources, the University of Alaska at Fairbanks Geophysical Institute, the U.S. Environmental Protection Agency, Resource Data, Inc., and USFWS, among others.

The data were provided to NGDC by Steve Baird at the Kachemak Bay Research Reserve and Chris Clough at the Kenai Peninsula Borough GIS department. The data were provided to NGDC as a high resolution (4 foot cell size) ESRI raster grid in Alaska State Plane Zone 4 NAD 83 feet. The grid was reprojected to WGS 84 geographic and sampled to 5 meter resolution in ArcMap, converted to xyz points, transformed to meters, and used for gridding the final DEM.

3) Shuttle Radar Topography Mission InSAR data

The SRTM was a joint international project run by the National Geospatial Intelligence Agency (NGA) and NASA[4]. In 2000, the SRTM project obtained global elevation data at 1 arc-second resolution using an interferometric synthetic aperture radar (InSAR) system. One SRTM raster grid tile was downloaded from the SRTM website for use in the Kachemak Bay DEM; the data were used to provide coverage along the southern half of Kachemak Bay, where lidar data was unavailable (See Fig. 9). The SRTM dataset provided the best coverage option when compared to ASTER and NED datasets, which did not provide reliable information near the coastline.

4. The SRTM data sets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA – previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies, to generate a near-global digital elevation model (DEM) of the Earth using radar interferometry. The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60 meter long baseline. A description of the SRTM mission can be found in Farr and Kobrick (2000). Synthetic aperture radars are side-looking instruments and acquire data along continuous swaths. The SRTM swaths extended from about 30 degrees off-nadir to about 58 degrees off-nadir from an altitude of 233 km, and thus were about 225 km wide. During the data flight the instrument was operated at all times the orbiter was over land and about 1000 individual swaths were acquired over the ten days of mapping operations. Length of the acquired swaths range from a few hundred to several thousand km. Each individual data acquisition is referred to as a "data take." SRTM was the primary (and pretty much only) payload on the STS-99 mission of the Space Shuttle Endeavour, which launched February 11, 2000 and flew for 11 days. Following several hours for instrument deployment, activation and checkout, systematic interferometric data were collected for 222.4 consecutive hours. The instrument operated almost flawlessly and imaged 99.96% of the targeted landmass at least one time, 94.59% at least twice and about 50% at least three or more times. The goal was to image each terrain segment at least twice from different angles (on ascending, or north-going, and descending orbit passes) to fill in areas shadowed from the radar beam by terrain. This 'targeted landmass' consisted of all land between 56 degrees south and 60 degrees north latitude, which comprises almost exactly 80% of Earth's total landmass. [Extracted from SRTM online documentation; http://srtm.usgs.gov/]

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation of the Kachemak Bay DEM were originally referenced to a number of vertical datums including MLW, MLLW, EGM 96 Geoid, and NAVD 88. All datasets were transformed to MHW using a constant offset transformation based on the Homer tide station values (Fig.10). The locations and tidal relationships of Kachemak Bay area tide stations (http://tidesandcurrents.noaa.gov/) are provided in Table 7. Only the Homer tide station values were used in the transformation process because of the central location of the station within the DEM extent. Also, it was the only tide station that provided information about the relationship between MHW and NAVD 88.

1) Bathymetric data

The early and recent NOS hydrographic surveys and USACE hydrographic surveys were transformed from MLLW and MLW to NAVD 88 using the difference values from the Homer tide station (Table 7).

2) Topographic data

All lidar datasets were transformed from NAVD 88 to MHW using the difference value from the Homer tide station. SRTM data were transformed from the EGM 1996 Geoid to the NAVD 88 Geoid 2009 using a geoid height transformation grid acquired from NGA (http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm96/egm96.html) and NOAA's Vertical Transformation tool *VDatum*. The SRTM data were then transformed to MHW using the difference value from the Homer tide station.

Table 8. Tide stations in the Kachemak Bay area and relationships between vertical datums in meters.

Tide Station	*Name*	*Difference NAVD 88 to MHW*	*Difference MLLW to MHW*	*Difference MLW to MHW*	*Latitude*	*Longitude*
9455437	Port Graham	n/a	4.941	4.427	59.35	-151.83
9455500	Seldovia	n/a	5.252	4.771	59.44	-151.72
9455557	Homer	3.834	5.328	4.825	59.60	-151.42
9455595	Bear Cove	n/a	5.404	4.893	59.73	-151.02
9455606	Anchor Point	n/a	5.366	4.834	59.77	-151.87
		Average	5.2582	4.75		

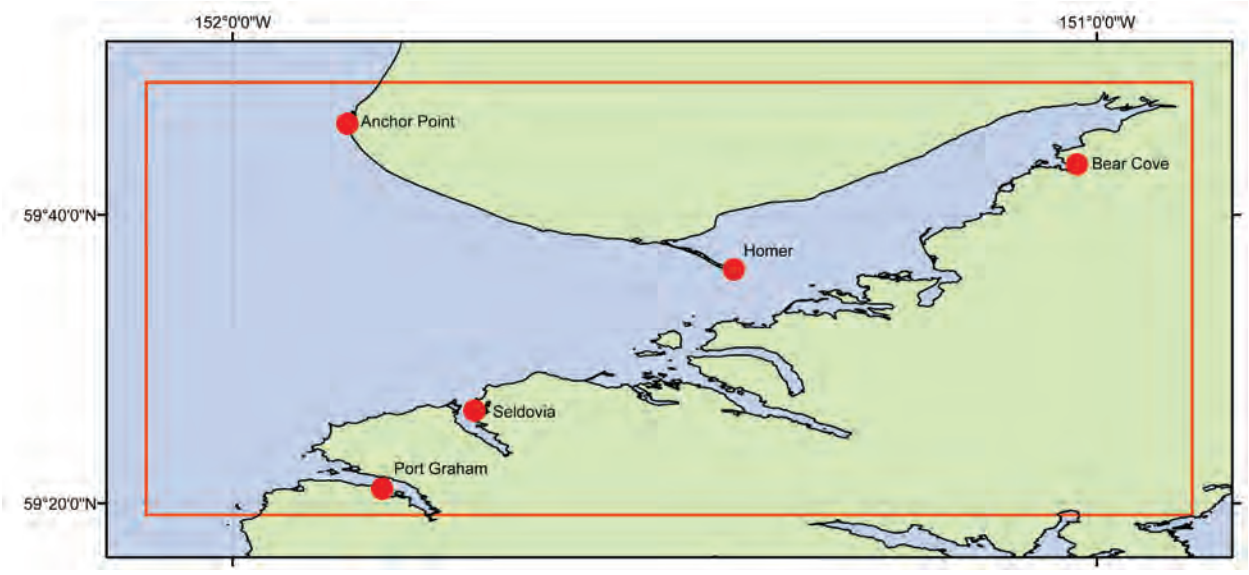

Figure 11. Locations of NOAA tide stations in the Kachemak Bay area.

3.2.2 Horizontal datum transformations

Datasets used in the compilation of the Kachemak Bay DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, Universal Transverse Mercator (UTM) NAD 83 Zone 5, Alaska State Plane Zone 4 NAD 27, and Alaska State Plane Zone 4 NAD 83. 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 and 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 small errors and anomalous points within datasets.
- Inconsistent overlapping NOS datasets. Earlier data were eliminated in these areas.
- Some topographic lidar data contained water-return values over the ocean, which needed to be clipped from the datasets using the Kachemak Bay coastline.
- Inconsistencies between lidar data and SRTM data. The SRTM data are older and lower quality data. A small buffer was used between the two datasets to allow for interpolation between them. This prevented the appearance of a "step" or "wall" in the final DEM where the datasets meet near the head of Kachemak Bay.
- Inconsistencies between the USACE hydrographic survey and early NOS surveys. Early NOS surveys were clipped out where they overlapped the more recent USACE survey.

3.3.2 Smoothing of bathymetric data

The early NOS hydrographic survey data are generally sparse at the resolution of the Kachemak Bay DEM, especially in the deep water areas near the mouth of Kachemak Bay. To reduce the effect of artifacts due to this, a 1/3 arc-second 'pre-surface' bathymetric grid in MHW vertical datum was generated using *GMT*[5], 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 Kachemak Bay coastline—to provide a breakline along the entire coastline. The coastline elevation values were set to -0.2 meters, 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 Kachemak Bay DEM region. The *GMT* grid created by 'surface' was clipped to the Kachemak Bay coastline, and the resulting surface was compared with original bathymetric soundings to ensure grid accuracy.

Examples of the comparisons are shown in Figures 11 and 12, which show histograms of the early NOS data and recent NOS data, respectively, compared to the 1/3 arc-second pre-surfaced bathymetric grid. Differences cluster around zero with a range of -11 to +9 meters when compared to the bathymetric surface. Points with the largest differences are located either in deep water, or in areas where dense data contain multiple elevation values per cell, which were averaged to create the bathymetric surface value. The final bathymetric surface was converted into xyz files for use in building the Kachemak Bay DEM (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.]

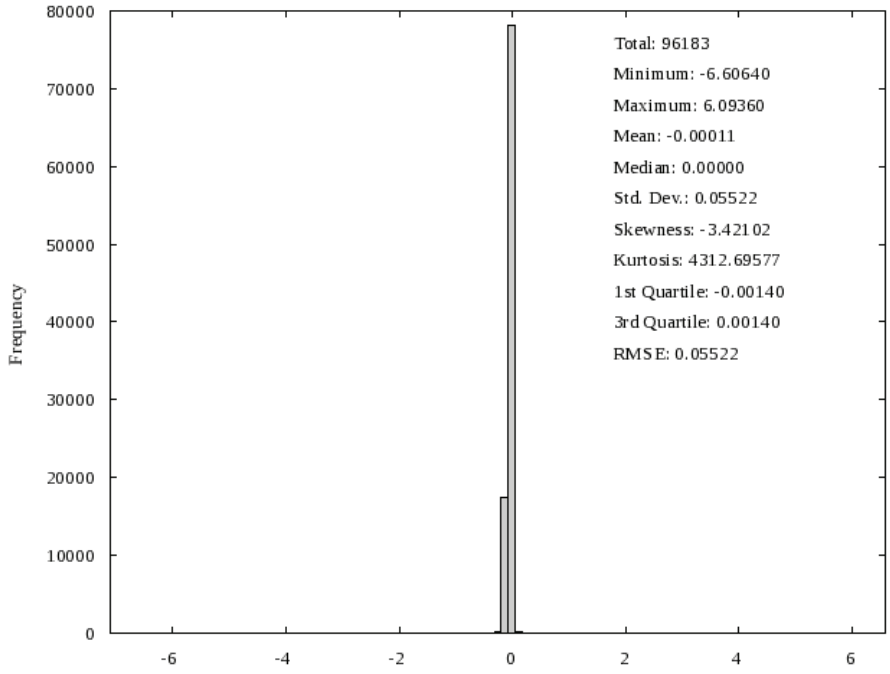

Figure 12. Histogram of the differences between the early NOS bathymetric data and the 1/3 arc-second pre-surfaced bathymetric grid.

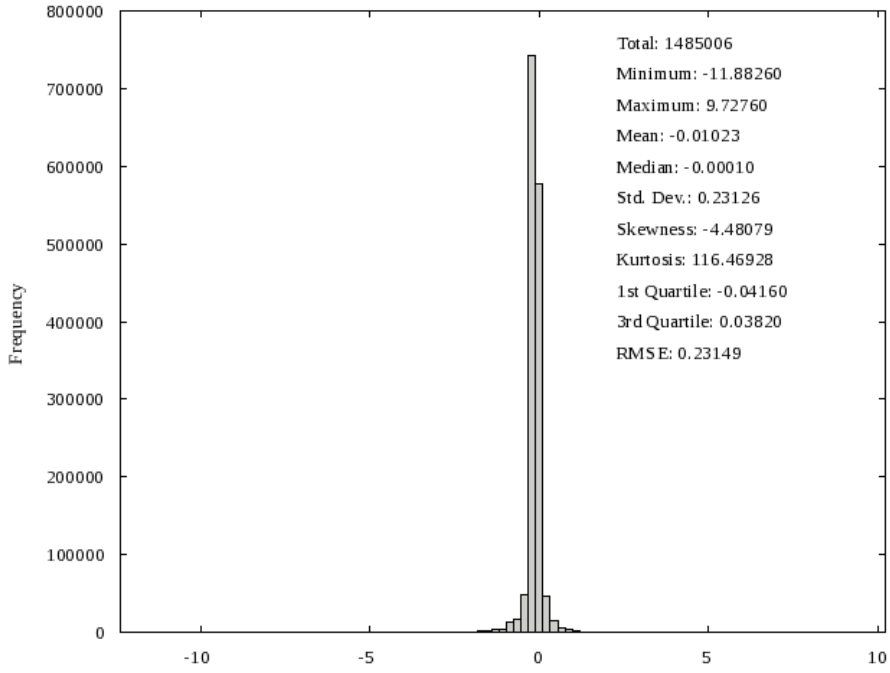

Figure 13. Histogram of the differences between the recent NOS bathymetric data and the 1/3 arc-second pre-surfaced bathymetric grid.

3.3.3 Building the DEM

MB-System[6] was used to create the 1/3 arc-second Kachemak Bay 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 8. The greatest weights were assigned to the lidar datasets, the pre-surfaced bathymetric grid, and the recent high-resolution NOS surveys. The least weight was given to the SRTM data, the USACE hydrographic soundings, and early NOS surveys.

Table 9. Data hierarchy used to assign gridding weight in *MB-System.*

Dataset	*Relative Gridding Weight*
NOAA/NGS Kenai Lidar	100
USGS Lidar DEM	100
Recent NOS Surveys	10
Pre-Surfaced Bathymetric Grid	10
Early NOS Surveys	1
USACE Hydrographic Surveys	1
SRTM Topographic DEM	1

3.4 Quality Assessment of the DEM

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Kachemak Bay DEM is dependent upon the DEM cell size and the accuracy of source datasets. Topographic features have an estimated horizontal accuracy of 10-30 meters: lidar data have an accuracy of less than five meters, but DEM cell size is 10 meters; SRTM data are accurate to approximately 30 meters. Bathymetric features are resolved to only within a few tens of meters in deep-water areas. Recent NOS surveys and shallow, near-coastal regions and harbor 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 Kachemak Bay DEM is also dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy less than 1 meter for bare-earth lidar data and up to 20 meters for non bare-earth SRTM 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 Kachemak Bay DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 13). The DEM was transformed to NAD 83 UTM Alaska 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 14 shows a data contribution plot of the Kachemak Bay DEM (the data contribution plot does not include information about the buffer area). Analysis of preliminary grids using *QT Modeler* and *Fledermaus* revealed suspect data points, which were corrected before recompiling the DEM. Figure 15 shows a color perspective image of the 1/3 arc-second Kachemak Bay DEM in its final version.

6. *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.]

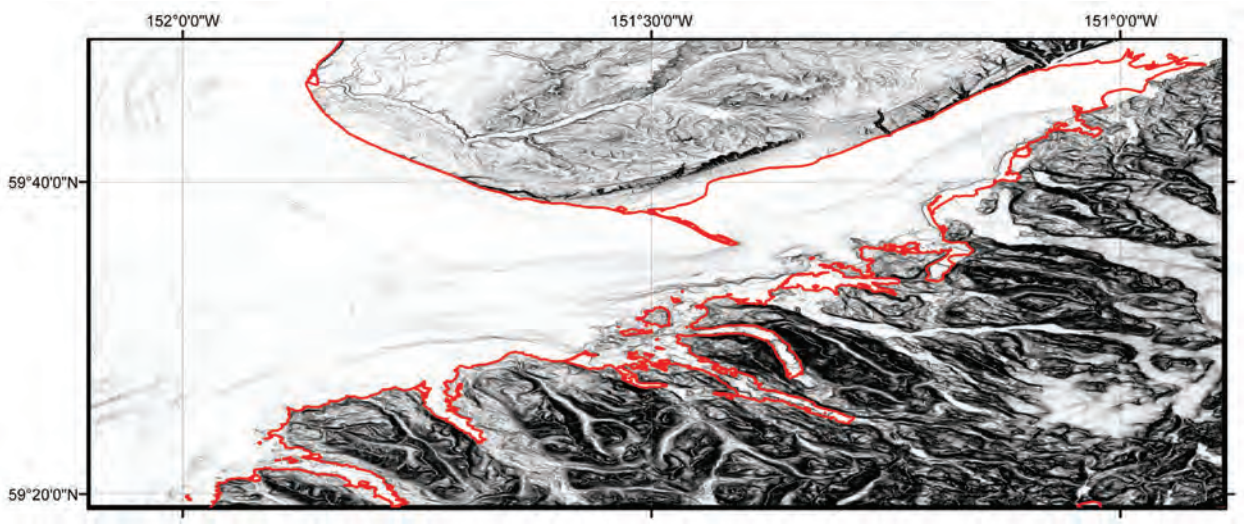

Figure 14. Slope map of the Kachemak Bay DEM. Flat-lying slopes are shown in white; dark shading indicates steep slopes; coastline shown in red.

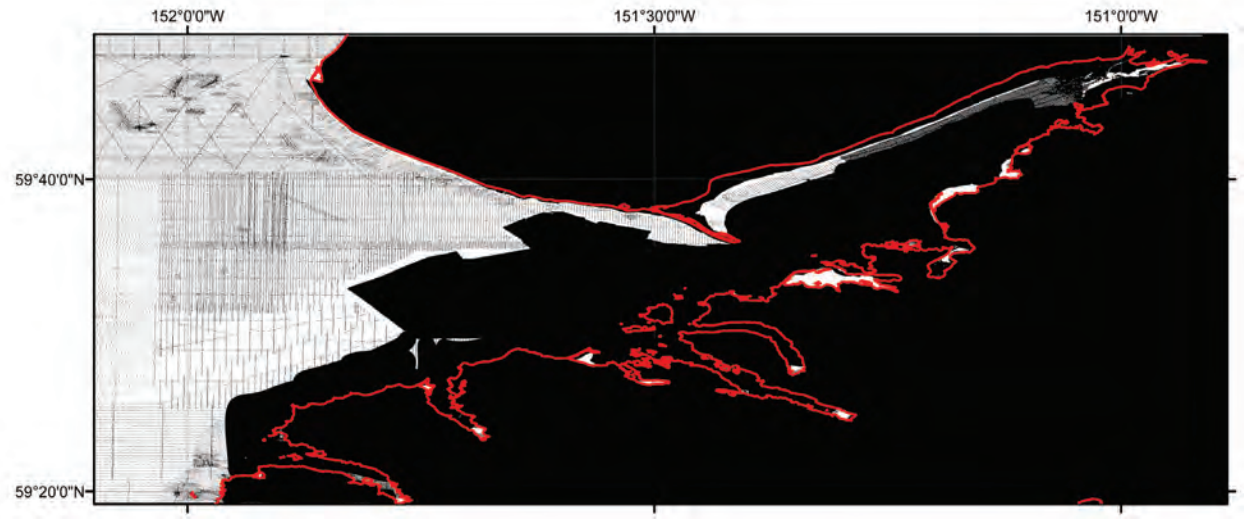

Figure 15. Data contribution plot of the Kachemak Bay DEM. Black represents DEM cells that are constrained by source data; white represents cells with elevation values that were derived from interpolation; coastline shown in red.

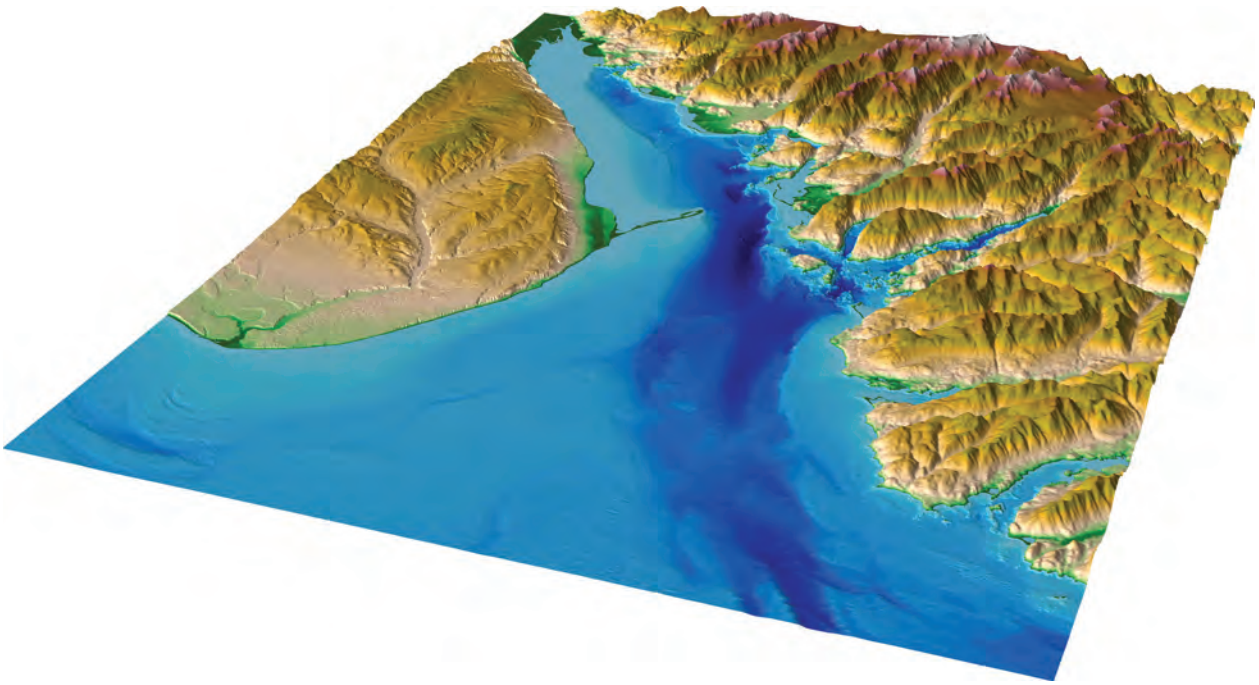

Figure 16. Perspective view from the west of the 1/3 arc-second Kachemak Bay DEM. Vertical exaggeration— times 2.

3.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 43 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (see Fig. 16 for monument locations). The associated shapefile attributes provided monument postions in NAD 83 geographic, and elevations in NAVD 88. These elevation data were transformed to MHW and compared to the Kachemak Bay DEM (Fig. 17). Differences between the DEM and the monument elevations range from negative three to nine meters, with a mean of 0.14 meters. Differences of one to two meters occur where the NGS monuments are found in ditches near the road, or on poles that extend slightly from the ground. Four monuments differed from the DEM by more than four meters, and all were all located on docks, buildings, or walls.

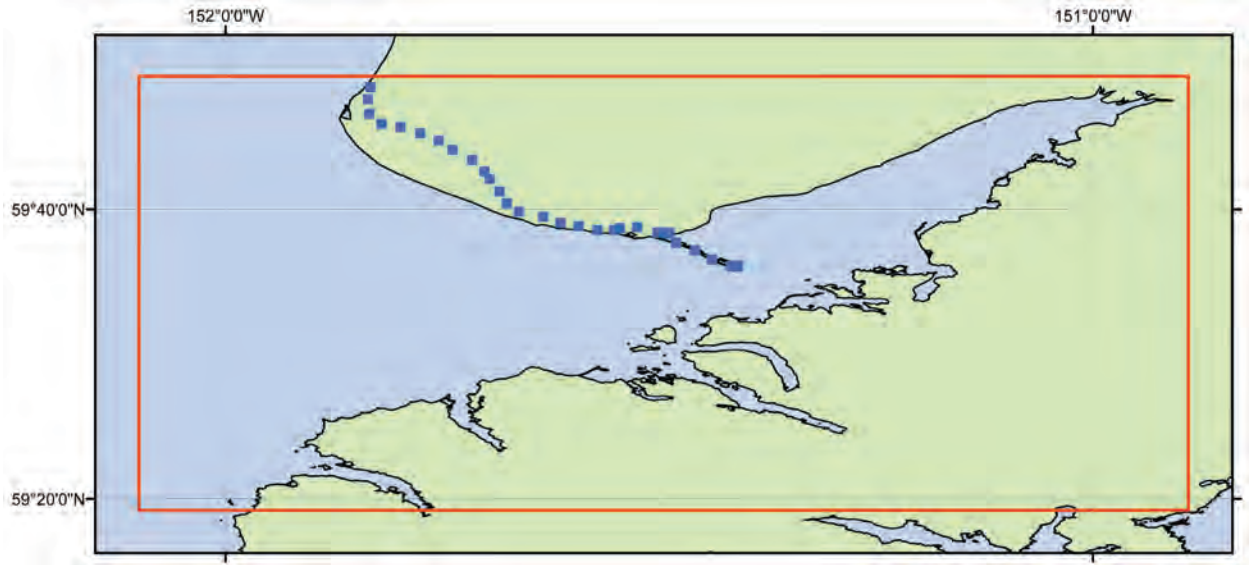

Figure 17. Location of NGS geodetic monuments in the Kachemak Bay region.

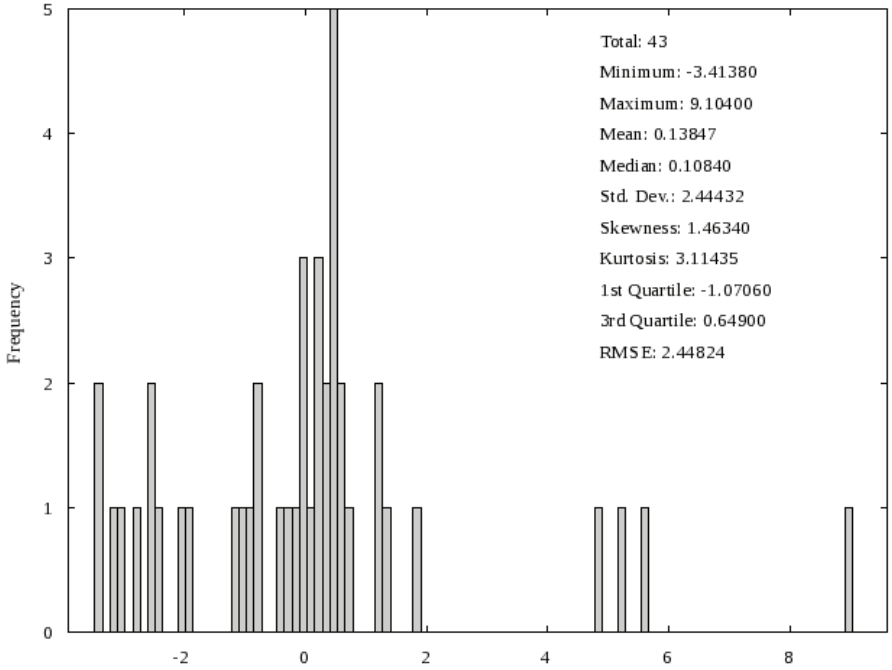

Figure 18. Histogram of the differences between NGS geodetic monument elevations and the Kachemak Bay DEM.

3.4.5 Comparison with older DEMs

In 2004, PMEL created several DEMs of the Kachemak Bay area for tsunami research purposes. These DEMs are available from NGDC at http://www.ngdc.noaa.gov/dem/ and were used in a 2005 State of Alaska Department of Natural Resources Division of Geological and Geophysical Resources study. The final report from this study can be found at http://www.dggs.alaska.gov/webpubs/dggs/ri/text/ri2005_002.PDF. The 2004 DEMs provided eight arc-second and three arc-second bathymetric coverage of large sections of Kachemak Bay, and one arc-second bathymetric-topographic DEM coverage of the communities of Homer and Seldovia.

In order to compare the 2010 Kachemak Bay DEM with the 2004 PMEL DEMs, NGDC resampled the 2010 Kachemak Bay DEM to lower resolutions and differenced the 2010 DEM with the 2004 DEMs. The DEMs differed greatly in some areas, and subtle improvements in quality were evident. Examples from the one arc-second DEM comparisons can be seen in Figure 18.

The comparison on the left shows the end of the Homer spit. Part A shows a portion of the 2004 Homer DEM, while Part B shows a portion of the 2010 Kachemak Bay DEM, and Part C shows the difference grid. Notable changes along the Homer spit occurred at the mouth of the harbor (red area in Part C), where the newer DEM (Part B) does a better job of depicting the channel due to newly obtained USACE data. The comparison on the right is of Seldovia Harbor. Part D shows a portion of the 2004 Homer DEM, while Part E shows a portion of the 2010 Kachemak Bay DEM, and Part F shows the difference grid. Notable changes in Seldovia harbor occur where the horizontal locations of the jetties and breakwaters are more accurately represented in the 2010 DEM, and also along the coast, where the data flows more smoothly toward the zero elevation. These improvements in the DEM are a result of high-quality recent NOS surveys that were obtained in 2008 and 2009 as part of the Hydropalooza project (http://www.hydropalooza.noaa.gov/).

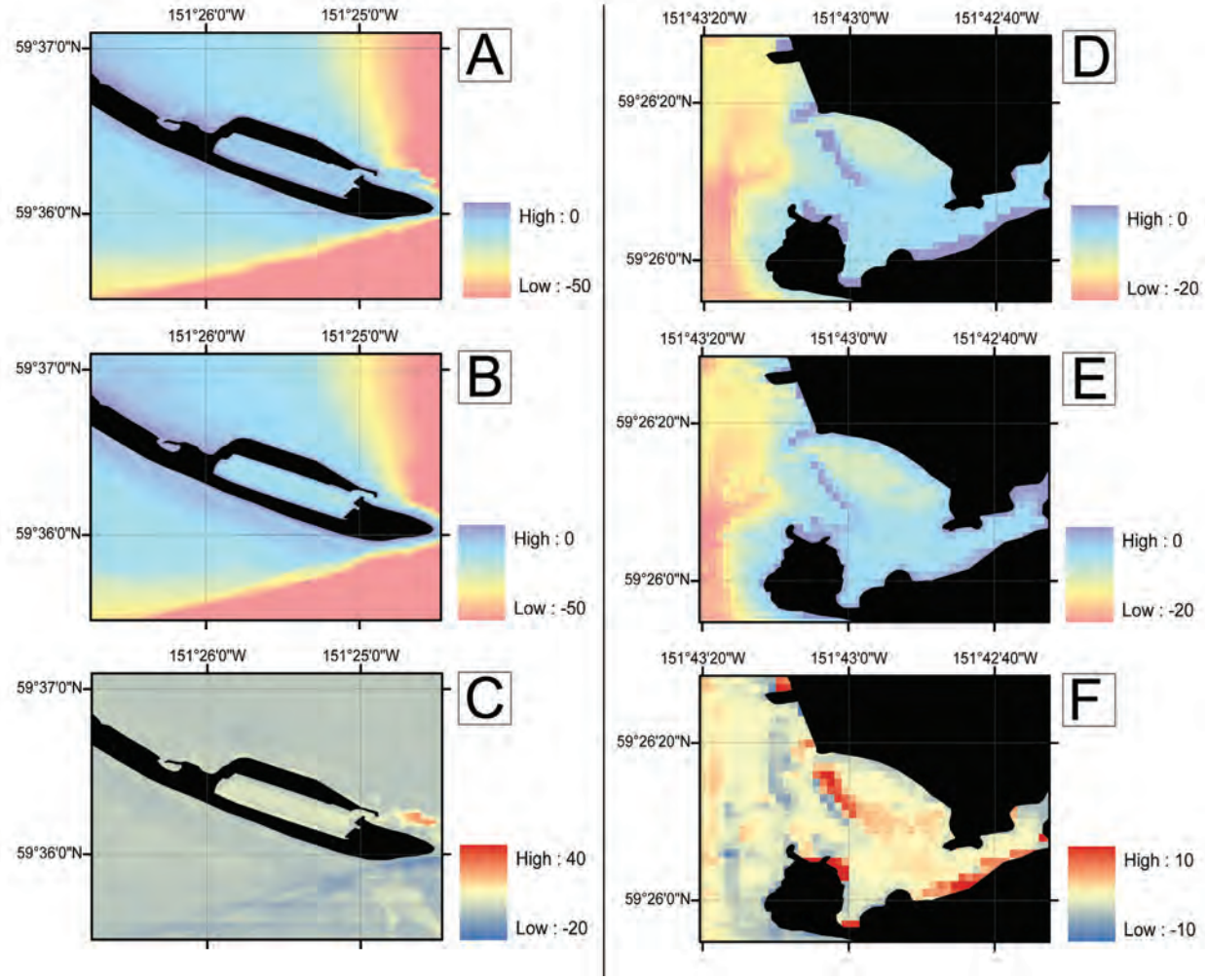

Figure 19. Comparisons of 2010 Kachemak Bay DEM and 2004 PMEL Homer DEMs. Coastline and land area shown in black.

3.4.6 DEM comparison with source data files

To ensure grid accuracy, the Kachemak Bay DEM was compared to several source datasets. Examples are shown in figures 19 through 21.

The Kenai lidar dataset (Fig. 19) varied from the Kachemak Bay DEM by a median of zero meters, ranging from a minimum difference of -9.56 meters to a maximum difference of 40.59 meters. These minimum and maximum differences occurred where the Kenai data set overlapped the NOAA/NGS lidar dataset, which showed small differences from the Kenai lidar dataset in some areas. The entire NOAA/NGS lidar dataset (Fig. 20) overlapped the Kenai lidar dataset, and so its differences from the DEM are distributed with a median of -0.004 meters, a minimum difference of -29.65 meters and a maximum difference of 32.16 meters.

The USACE hydrographic survey data (Fig. 21) varied from the Kachemak Bay DEM by a median of -0.005 meters, with a minimum difference of -17.62 meters and a maximum difference of 4.56 meters. The largest differences in the USACE data occurred where the data bordered early NOS datasets. Early NOS datasets and recent NOS datasets (not shown) also indicated consistency with the final grid.

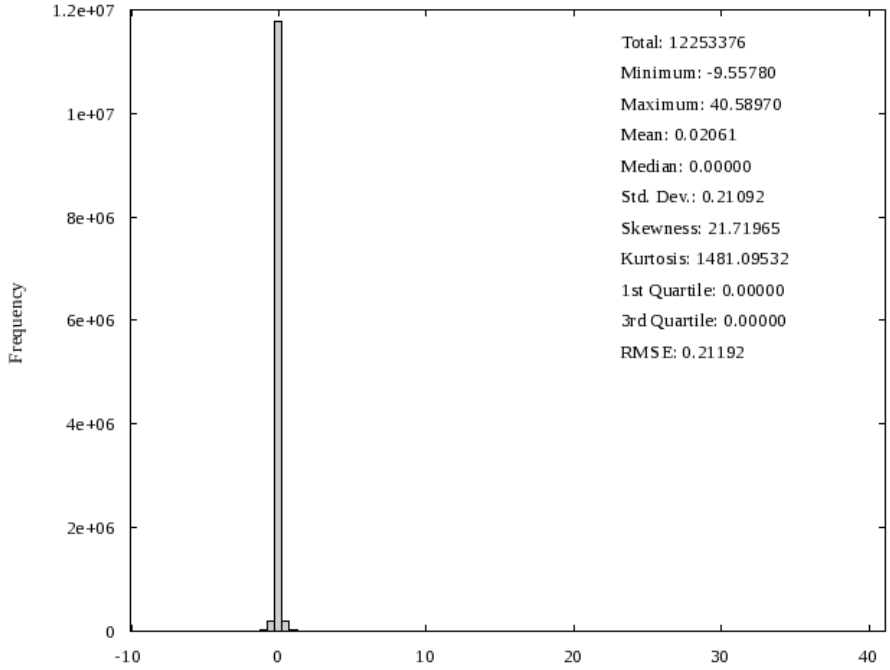

Figure 20. Histogram of the differences between a portion of the USGS Kenai lidar dataset and the Kachemak Bay DEM.

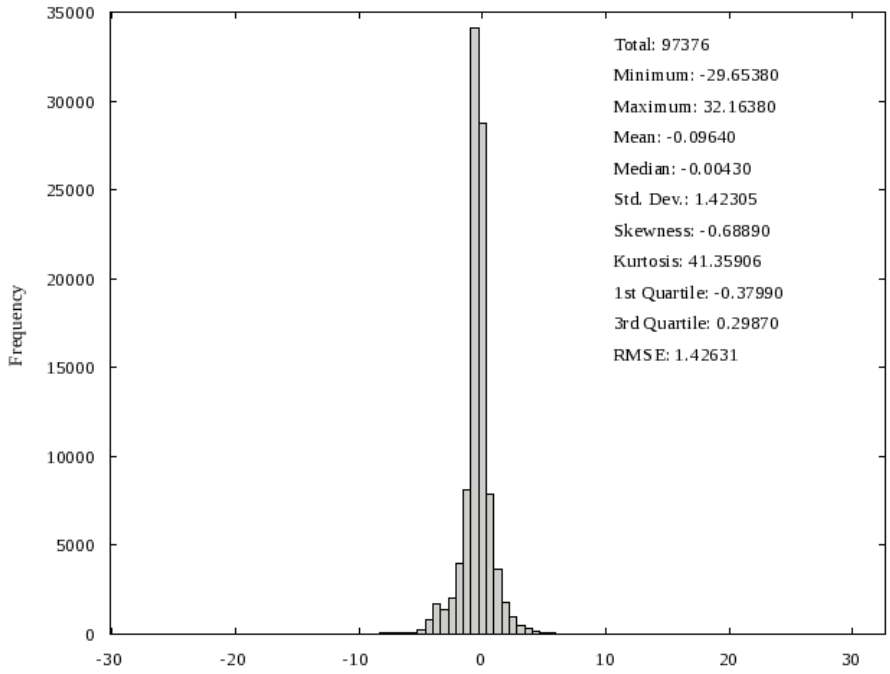

Figure 21. Histogram of the differences between the NOAA coastal lidar data and the Kachemak Bay DEM.

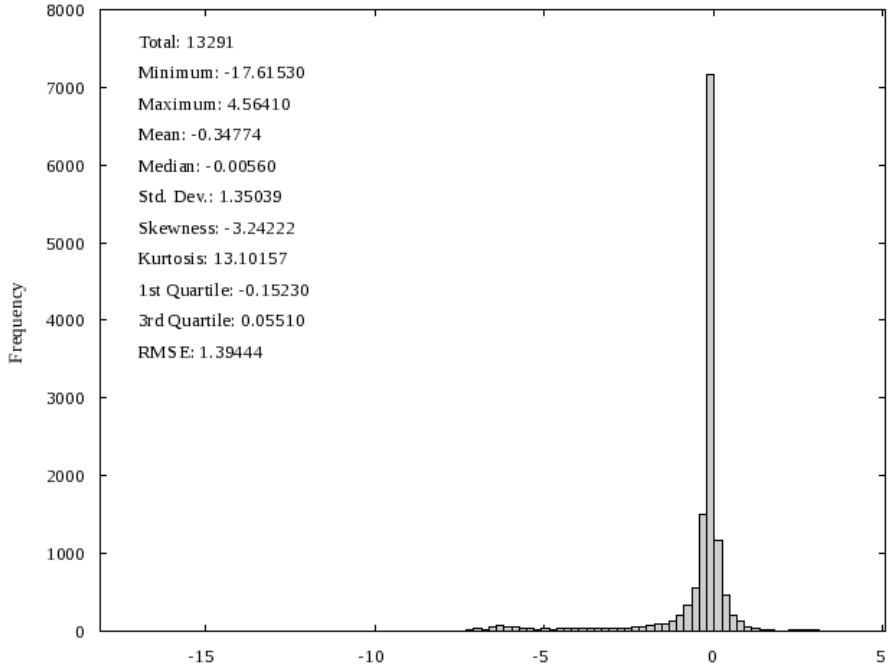

Figure 22. Histogram of the differences between the USACE hydrographic survey data points and the Kachemak Bay DEM.

4. Summary and Conclusions

An integrated bathymetric–topographic digital elevation model of the Kachemak Bay, Alaska 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 Kachemak Bay DEM, based on NGDC's research and analysis, are listed below:

- Conduct lidar surveys along the southern coast of Kachemak Bay.
- Conduct high-resolution bathymetric surveys in deep water areas near the mouth of Kachemak Bay.
- Extend *VDatum* tidal conversion coverage to include Alaska.

5. Acknowledgments

The creation of the Kachemak Bay DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL); Steve Baird (Kachemak Bay National Estuarine Research Reserve); and Chris Clough (Kenai Peninsula Borough GIS Division).

6. References

Nautical Chart # 16645 (RNC), 18th Edition, 2002. Gore Point to Anchor Point. Scale 1:82,662. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16646 (RNC), 13th Edition, 2007. Ports of Southeastern Cook Inlet. Scales 1:30,000; 1:20,000; 1:15,000; and 1:7,500. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16647 (RNC), 3rd Edition, 2001. Cape Elizabeth to Anchor Point. Scale 1:100,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.3.1 – 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 Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/.

GMT v. 4.3.4 – Generic Mapping Tools, freeware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.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. 7.0.2 – 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, Version 2.3.2— 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/welcome.html.

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