NOAA Technical Memorandum NESDIS NGDC-23

DIGITAL ELEVATION MODEL OF KING COVE, ALASKA: PROCEDURES, DATA SOURCES AND ANALYSIS

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1. Introduction

In August 2008, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a revised bathymetric–topographic digital elevation model (DEM) centered on King Cove, Alaska (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). The 1 arc-second[1] coastal DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 2) and will be used for tsunami inundation modeling as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the King Cove DEM.

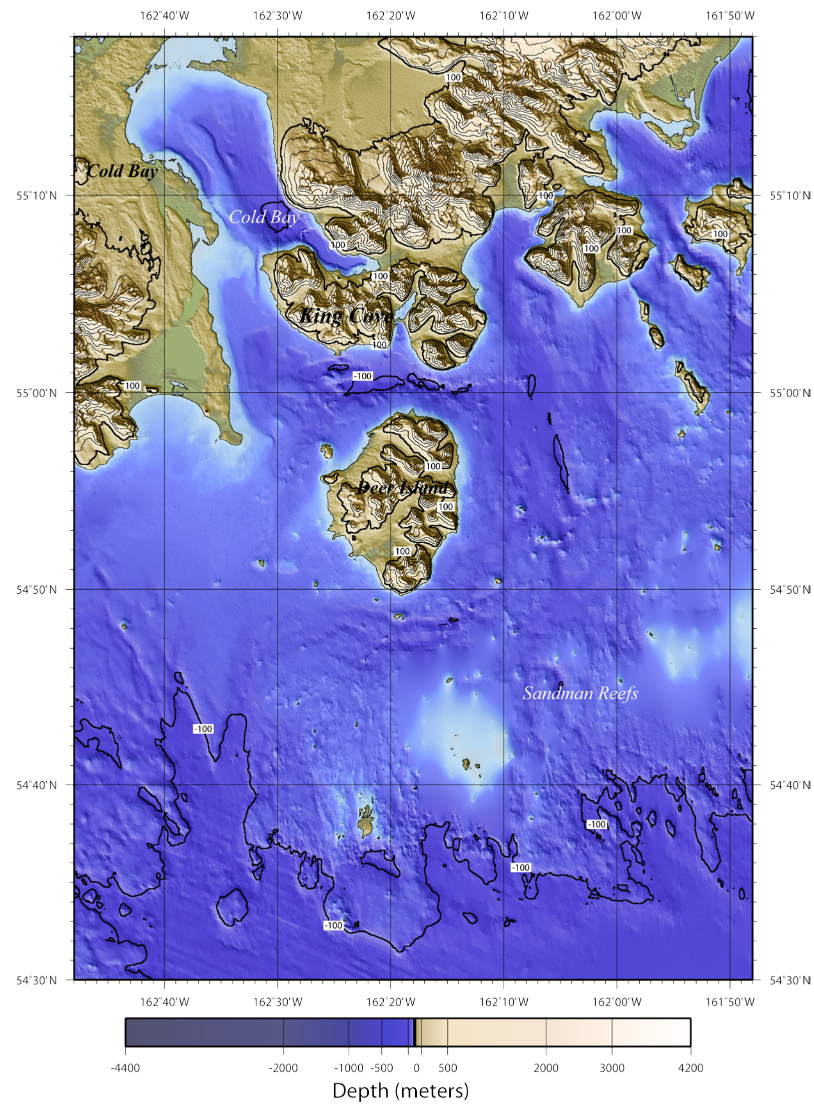

Figure 1. *Shaded relief image of the King Cove DEM. Contour interval is 100 meters. Image is in Mercator projection.*

1. In polar latitudes, longitude lines are spaced significantly closer together than latitude lines, approaching zero at the poles. While the DEM is built upon grids of square cells in geographic coordinates, they are not square cells when converted to meters. At the latitude of King Cove, Alaska (55°3′42′′ N, 160°18′37′′ W) 1 arc-second of latitude is equivalent to 30.92 meters; 1 arc-second of longitude equals 17.75 meters.

2. Study Area

King Cove is located on the south side of the Alaska Peninsula, on a sand spit fronting Deer Passage and Deer Island. It is 18 miles southeast of Cold Bay and 625 miles southwest of Anchorage at 55.06167° North Latitude and 162.31028° West Longitude. King Cove lies in the maritime climate zone with temperatures averaging 25 to 55 F, with extremes from -9 to 76 F. Snowfall averages 52 inches, and total annual precipitation is 33 inches. King Cove was founded in 1911 when Pacific American Fisheries built a salmon cannery there. Early settlers were Scandinavian, European, and Unangan fishermen.

3. Methodology

The King Cove, Alaska DEM was constructed to meet PMEL specifications (Table 1), based on input requirements for the development of Reference Inundation Models (RIMs) and Standby Inundation Models (SIMs) (V. Titov, pers. comm.) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum 1983 (NAD 83) and Mean High Water (MHW), for modeling of maximum flooding, respectively[2]. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1: PMEL specifications for the 1 arc-second King Cove, Alaska DEM.

Grid Area	King Cove, Alaska
Coverage Area	161.8 º to 162.8º W; 54.45º to 55.35º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
Grid Size	1 arc-second
Grid Format	ESRI ASCII raster grid

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

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 2) were obtained from several U.S. federal and academic agencies, including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), and NGDC; the National Geospatial-Intelligence Agency (NGA); the U.S. Fish and Wildlife Service (FWS); the U.S. Geological Survey (USGS); the U.S. Army Corps of Engineers (USACE); and Scripps Institution of Oceanography (SIO). Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to NAD 83 horizontal datum and to convert into ESRI (http://www.esri.com/) ArcGIS shape files[3]. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets. Vertical datum transformations to MHW were also accomplished using FME, based upon data from the NOAA King Cove tidal station, as no VDatum model software (http://vdatum.noaa.gov/) was available for this area.

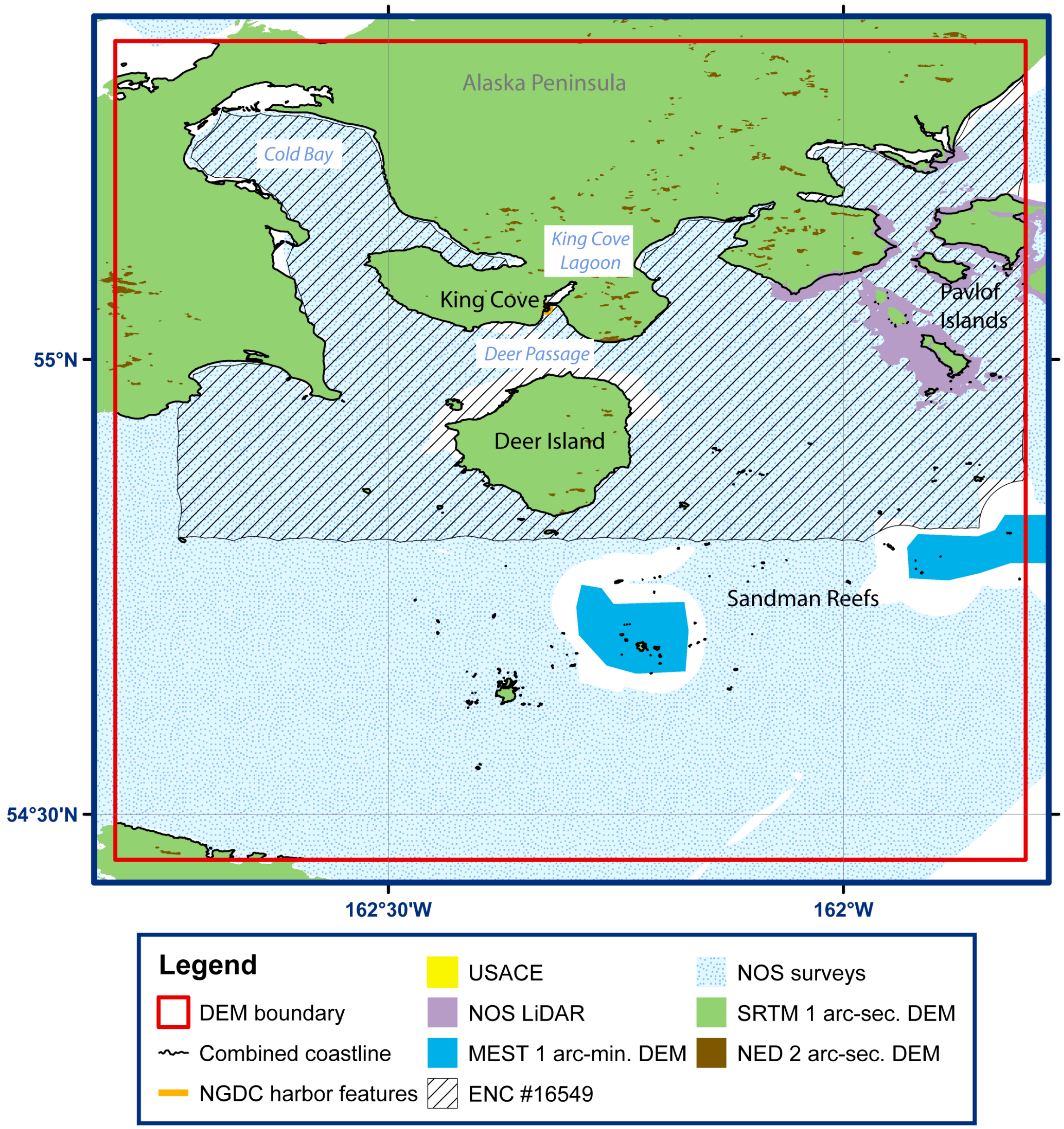

Figure 2. *Source and coverage of datasets used to compile the King Cove, Alaska DEM. White areas denote data gaps.*

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

3.1.1 Shoreline

Four digital coastline datasets of the King Cove region were analyzed for inclusion in the King Cove DEM: NOAA OCS electronic navigational charts #16520 and #16549; National Geospatial-Intelligence Agency (NGA[4]) High Water Line[2]; USGS geologic map derived shoreline; and U.S. Fish and Wildlife Service (FWS) statewide Alaska digital coastline. Comparisons between the different coastline datasets, NOS hydrographic surveys, SRTM topographic DEM, and raster nautical charts showed that the NGA and FWS coastlines (Table 2) best fit the topographic and bathymetric data (Fig. 3 and 4) and were used to create a 'combined coastline' for the King Cove DEM.

Table 2. Shoreline datasets used in compiling the King Cove, Alaska DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGA	2000	Satellite derived High Water Line	1:75,000 or smaller	WGS 84 geographic	~ High Water Line	See footnote 2
U.S. FWS	2006	Compiled coastline	Various	WGS 84 geographic	Undefined	

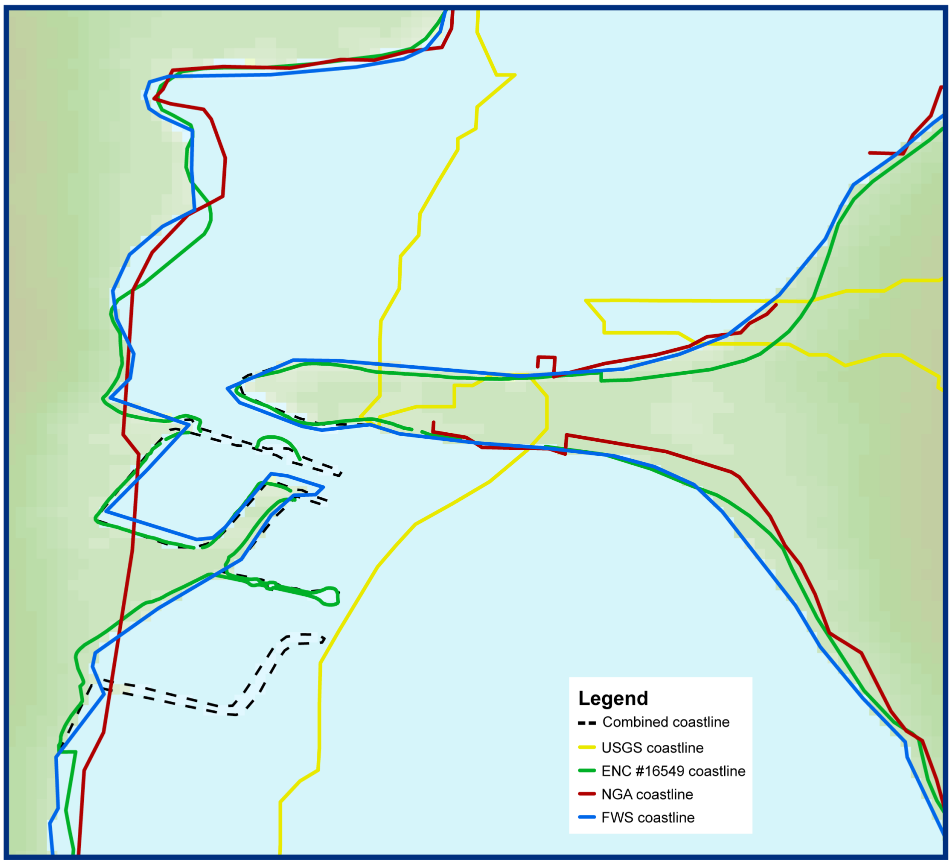

Figure 3. *Digital coastline datasets in the King Cove vicinity shown with SRTM topographic data.*

4.The NGA Office of Global Navigation, Maritime Division is in the process of developing a new version of World Vector Shoreline (WVS®) and in support of this effort has acquired a prototype Global Shoreline Data set. This new shoreline is an approximation of the High Water Line; it is NOT a Mean High Water Line since the source data have not been tide coordinated (http://gcmd.nasa.gov/records/GCMD_WVS_DMA_NIMA.html). The prototype Global Shoreline Data set (satellite derived High Water Line) in work at NGA has been acquired from orthorectified NASA, 2000 era, LANDSAT GeoCover (multi-spectral imagery). [Extracted from metadata]

1) **National Geospatial-Intelligence Agency High Water Line**
   The NGA Office of Global Navigation, Maritime Division developed the Global Shoreline Data set from digitized orthorectified NASA, 2000 era, LANDSAT GeoCover (multi-spectral imagery). This new shoreline is an approximation of the High Water Line with a resolution of 1:75,000 or smaller. The NGA coastline provided coverage of the DEM area excluding the area east of Belkofski Bay and had gaps in King Cove Harbor (Fig. 3). In the Cold Bay region the NGA coastline provided more detail than the FWS coastline.

2) **U.S. Fish and Wildlife Service**
   The U.S. Fish and Wildlife Service (FWS) has compiled a seamless digital coastline of the State of Alaska from a variety of sources, including: the National Hydrography Dataset, NOAA nautical charts, U.S. Fish and Wildlife Service, National Geographic Topo Software, U.S. Army Corps of Engineers, and Alaska Department of Natural Resources. This dataset was graciously provided to NGDC by Bret Christensen, U.S. Fish and Wildlife Service. Though efforts were made to obtain the highest resolution coastlines available, vertical datums were apparently not determined nor controlled in any way in compiling the FWS coastline; the horizontal datum of the compiled FWS coastline is WGS 84. The FWS coastline provides complete coverage of the DEM area and included features in King Cove Harbor that were not resolved in the NGA coastline (Fig. 3 and 4).

3) **NOAA OCS electronic navigational chart #16520 and #16549 extracted coastlines**
   Electronic navigational chart (ENC) #16520 provided an extracted coastline covering the western portion of the DEM to Belkofski Bay. When compared to the SRTM topographic dataset, this coastline at a scale of 1 to 300,000, is not as detailed as the NGA and the FWS coastlines. The OCS coastline is also shifted 100 to 300 meters to the north as compared to the SRTM dataset. The smaller scale nautical chart #16549, while providing more detail of harbor features, did not represent all features in the harbor and also varied from the topographic data by as much as 100 meters (Fig. 3). These data were not used in building the combined coastline for the DEM.

4) **USGS geologic map derived shoreline**
   The USGS developed a shoreline captured from geologic coverages, digitized from 1:63,360 topographic maps for parts of Cold Bay and 1:250,000-scale topographic maps. While providing complete coverage of the DEM area, the USGS coastline is less detailed than either the FWS or the NGA coastlines and is offset from the SRTM dataset and nautical chart #16549 in varying directions exceeding 500 meters. This dataset was not used in building the 'combined coastline' for the DEM.

To obtain the best digital MHW coastline, NGDC combined the NGA and FWS coastlines into a ‘combined coastline’. Where overlap occurred, the NGA coastline was usually excised, as the FWS coastline was typically more consistent with the NOS hydrographic survey data and SRTM topography. This ‘combined coastline’ was manually adjusted to fit the recent USACE surveys and project overview image at King Cove harbor (http://www.poa.usace.army.mil/CO/CoOrg/PnI_New/p&ione_2007.html#Kin) to reflect the north breakwater and in South Harbor to reflect both north and south breakwaters (Fig. 4). North of the town of Cold Bay the NGA coastline was used, as it more closely represented small inlet features shown on nautical chart #16549. The edits were done using ArcGIS. The combined coastline was subsampled to 10-meter spacing and converted to point data for use in the gridding process. It was also used as a coastal buffer for the bathymetric pre-surfacing algorithm (see Section 3.3.2) to ensure that interpolated bathymetric values reached “zero” at the coast. The combined coastline was also used to clip the SRTM topographic DEM, which contained elevation values, typically zero, over the open ocean (Section 3.1.3).

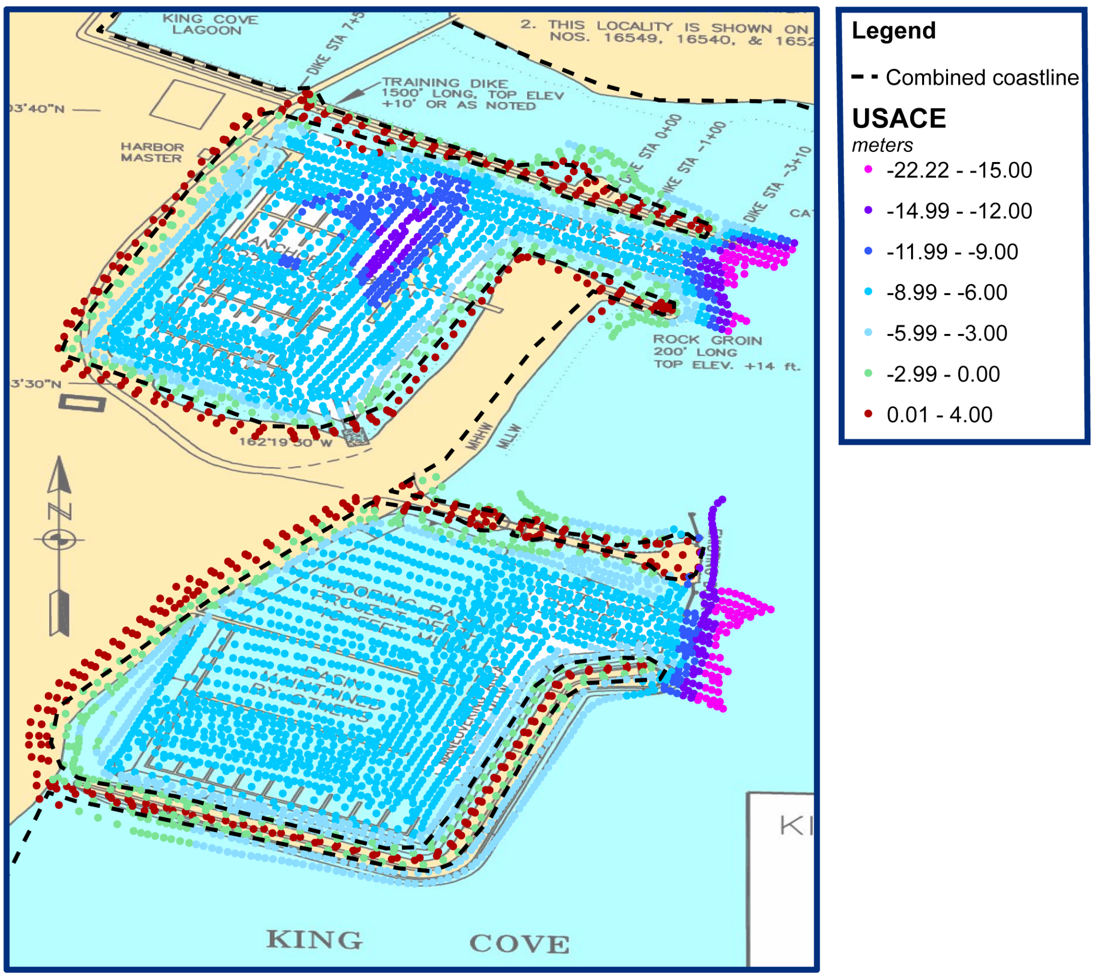

Figure 4. *‘Combined coastline’ (black dashed line) shown with USACE data and USACE project overview image.*

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the King Cove DEM include 45 NOS hydrographic surveys, two recent USACE harbor surveys, electronic navigational chart soundings, and an extracted subset of the Global Measured and Estimated Seafloor Topography (MEST) DEM (Table 3).

Table 3. Bathymetric datasets used in compiling the King Cove, Alaska DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1901 to 1956	Hydrographic survey soundings	Ranges from 10 meters to 1.5 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 27, Early Alaskan Datum, Undefined Datum	MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USACE	2006	Harbor survey	~2 to 10 meters	Alaska State Plane, Zone 7, NAD 83 feet	MLLW (feet)	http://www.poa.usace.army.mil/en/hydro/King%20Cove/2006/
OCS ENC #16549	2003	NGDC digitized nautical chart soundings	~500 to 1200 meters	WGS 84 geographic	MLLW (meters)	http://www.nauticalcharts.noaa.gov/
SIO	2007	Altimetry-derived seafloor estimate	1 arc-minute	WGS 84 geographic	MSL	http://topex.ucsd.edu/marine_topo/

1) NOS hydrographic survey data

A total of 45 NOS hydrographic surveys conducted between 1901 and 1956 were used in the King Cove DEM development (Fig. 5; Table 4). The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) and horizontally referenced to either “Early Alaska”, “Unalaska”, or “undetermined” datums. Frequently, in creating digital versions of early 20th century surveys, NOS was unable to determine the horizontal datum of the original survey. These surveys were adjusted to a more current ‘datum of records’, frequently NAD 27, by NOS (http://www.ngdc.noaa.gov/mgg/dat/geodas/docs/hyd93.txt) during the process of converting analog sounding to digital format.

Data point spacing for the surveys ranged from about 10 to 60 meters in shallow water to 1.5 kilometers in deep water. All surveys were extracted from NGDC’s online database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in their original datums (Table 4). The data were then converted to NAD 83 using FME software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com); some NOS surveys were manually shifted in ArcGIS to fit the combined coastline. The surveys were subsequently clipped to a polygon 0.05 degree (~5%) larger than the 1 arc-second gridding area to support data interpolation across DEM boundaries.

After converting all NOS survey data to MHW (see Section 3.2.1), the data were displayed in ESRI ArcMap and reviewed for digitizing errors against scanned original survey smooth sheets and compared to the NED and SRTM topographic data and the combined coastline. Survey #H06702 had two soundings digitized with incorrect depth values when compared to the corresponding smooth sheet and were corrected using ArcMap.

Table 4. Digital NOS hydrographic surveys used in compiling the King Cove, Alaska DEM.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H02557*	1901	10,000/20,000	mean lower low water	undetermined
H03305*	1911	40,000	mean lower low water	undetermined
H03305A	1911	20,000	mean lower low water	undetermined
H03305I	1925	20,000	mean lower low water	Unalaska Datum
H03654	1913/39	100,000	mean lower low water	undetermined
H04301*	1923/25	60,000	mean lower low water	undetermined
H04314*	1923/24	20,000	mean lower low water	undetermined
H04374*	1924	20,000	mean lower low water	undetermined
H04375*	1923/24	20,000	mean lower low water	undetermined
H04380*	1924	20,000	mean lower low water	undetermined
H04490*	1925	20,000	mean lower low water	undetermined
H04491*	1925	40,000	mean lower low water	undetermined
H04496	1925	20,000	mean lower low water	undetermined
H06143*	1936	40,000	mean lower low water	early Alaska Datum
H06280*	1937	10,000	mean lower low water	early Alaska Datum
H06281*	1937/39	20,000	mean lower low water	early Alaska Datum
H06384*	1938	10,000	mean lower low water	early Alaska Datum
H06385*	1938	20,000	mean lower low water	early Alaska Datum
H06437*	1939	20,000	mean lower low water	early Alaska Datum
H06482*	1939	10,000	mean lower low water	early Alaska Datum
H06484*	1938/39	40,000	mean lower low water	Unalaska Datum
H06485*	1940	40,000	mean lower low water	early Alaska Datum
H06486*	1939/40	80,000	mean lower low water	early Alaska Datum
H06487*	1940	20,000	mean lower low water	early Alaska Datum
H06488*	1939/40	20,000	mean lower low water	early Alaska Datum
H06586*	1940	40,000	mean lower low water	early Alaska Datum
H06587*	1940	20,000	mean lower low water	early Alaska Datum
H06588*	1940/42	20,000	mean lower low water	early Alaska Datum
H06589*	1940	20,000	mean lower low water	early Alaska Datum
H06590	1940	20,000	mean lower low water	early Alaska Datum
H06591	1940	20,000	mean lower low water	early Alaska Datum
H06592	1940	10,000	mean lower low water	early Alaska Datum
H06593*	1940	20,000	mean lower low water	early Alaska Datum
H06699	1941	40,000	mean lower low water	early Alaska Datum
H06702*	1941	20,000	mean lower low water	early Alaska Datum
H06703*	1941	20,000	mean lower low water	early Alaska Datum
H06704*	1941	5,000	mean lower low water	early Alaska Datum
H06716	1941	10,000	mean lower low water	early Alaska Datum
H06767*	1942	20,000	mean lower low water	early Alaska Datum
H06768*	1942	20,000	mean lower low water	early Alaska Datum
H06769*	1942	20,000	mean lower low water	early Alaska Datum
H06772	1942	20,000	mean lower low water	early Alaska Datum
H07030*	1945	5,000	mean lower low water	early Alaska Datum
H07031*	1945	5,000	mean lower low water	early Alaska Datum
H08301*	1956	20,000	mean lower low water	early Alaska Datum

* Geographic position manually adjusted in ArcGIS to fit combined coastline.

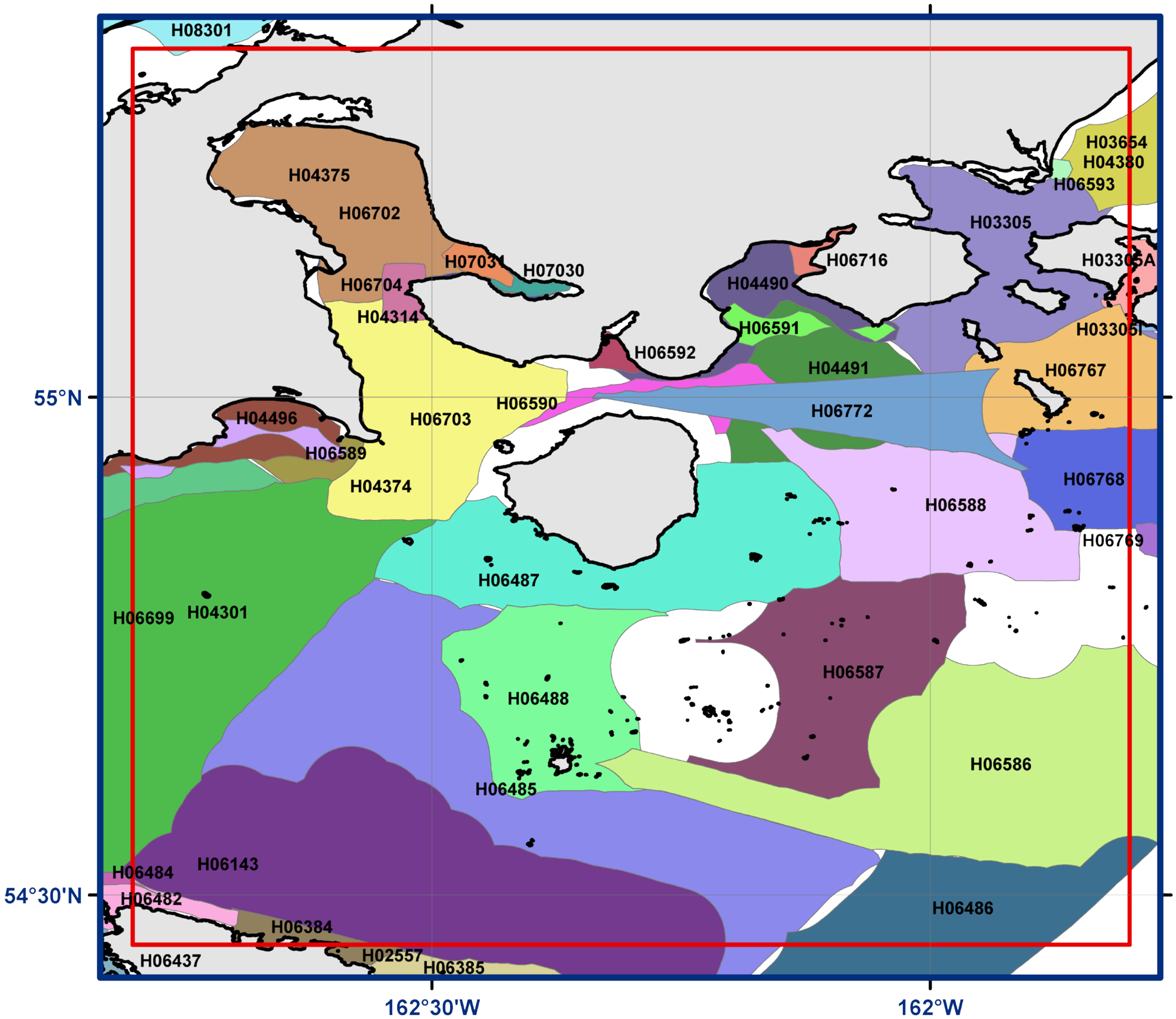

Figure 5. *Digital NOS hydrographic survey coverage in the King Cove region. Red denotes boundary of 1 arc-second DEM with the combined coastline in black.*

2) USACE harbor surveys

USACE conducted or contracted harbor surveys in King Cove Harbor and in South Harbor in 2006 (Figs. 6 and 7). The two surveys contain both bathymetric and topographic data. The surveys were originally referenced to NAD 83 Alaska State Plane coordinates and MLLW vertical datum. The resolution of the two surveys range from ~2 to 10 meters and from 2.7 to 22.2 meters depth at MHW.

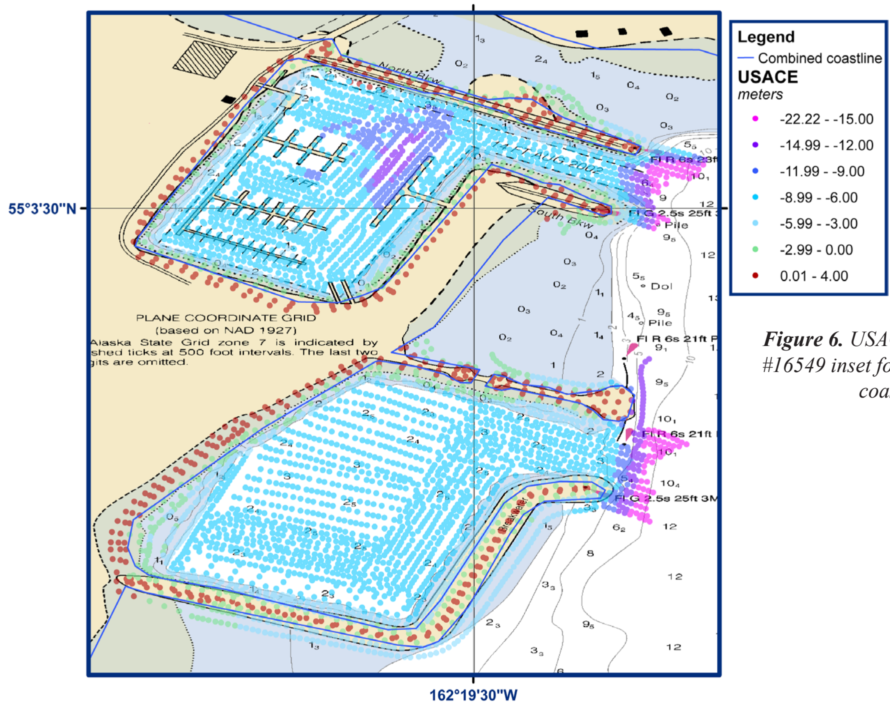

Figure 6. USACE survey data points and RNC #16549 inset for King Cove Harbor. Combined coastline shown in blue.

Figure 7. A 2006 highly oblique photo of King Cove Harbor taken from USACE AK District website. (http://www.poa.usace.army.mil/CO/CoOrg/PnI_New/p&ione_2007.html#Kin).

3) OCS Electronic Navigational Chart soundings

OCS nautical chart #16549 was available in electronic navigation chart format and, as no bathymetric survey data were available for the area, sounding data were extracted from this chart using FME. Coverage stretches eastward from Cold Bay through Deer Passage, including King Cove and King Cove Lagoon, east to Pavlof Islands. Soundings range from ~20 meters to ~1200 meters apart, and depths range from 1.96 meters to 148.16 meters at MHW.

4) Measured and Estimated Seafloor Topography (MEST)

Two areas within the DEM boundary where no survey data were available are located southeast of Deer Island in the Sandman Reefs (Fig. 2). Figure 9 shows the western most of the two un-surveyed areas surrounded by NOS soundings. Bathymetric values for these areas, approximately 18 square kilometers, were extracted from the 'Measured and Estimated Seafloor Topography' 1-minute DEM (Smith and Sandwell, 1997; http://topex.ucsd.edu/marine_topo/).

The grid has a 1 minute cell size with data in WGS 84 geographic coordinates and MSL. These data are exceptionally coarse at the resolution of the 1 arc-second King Cove DEM; however, they provide the only digital constraints on the bathymetry in the Sandman Reefs region. Extracted bathymetric data are generally shallower than overlapping measured bathymetric values (e.g., NOS hydrographic soundings and multibeam swath sonar survey data) and are considered to be of low accuracy.

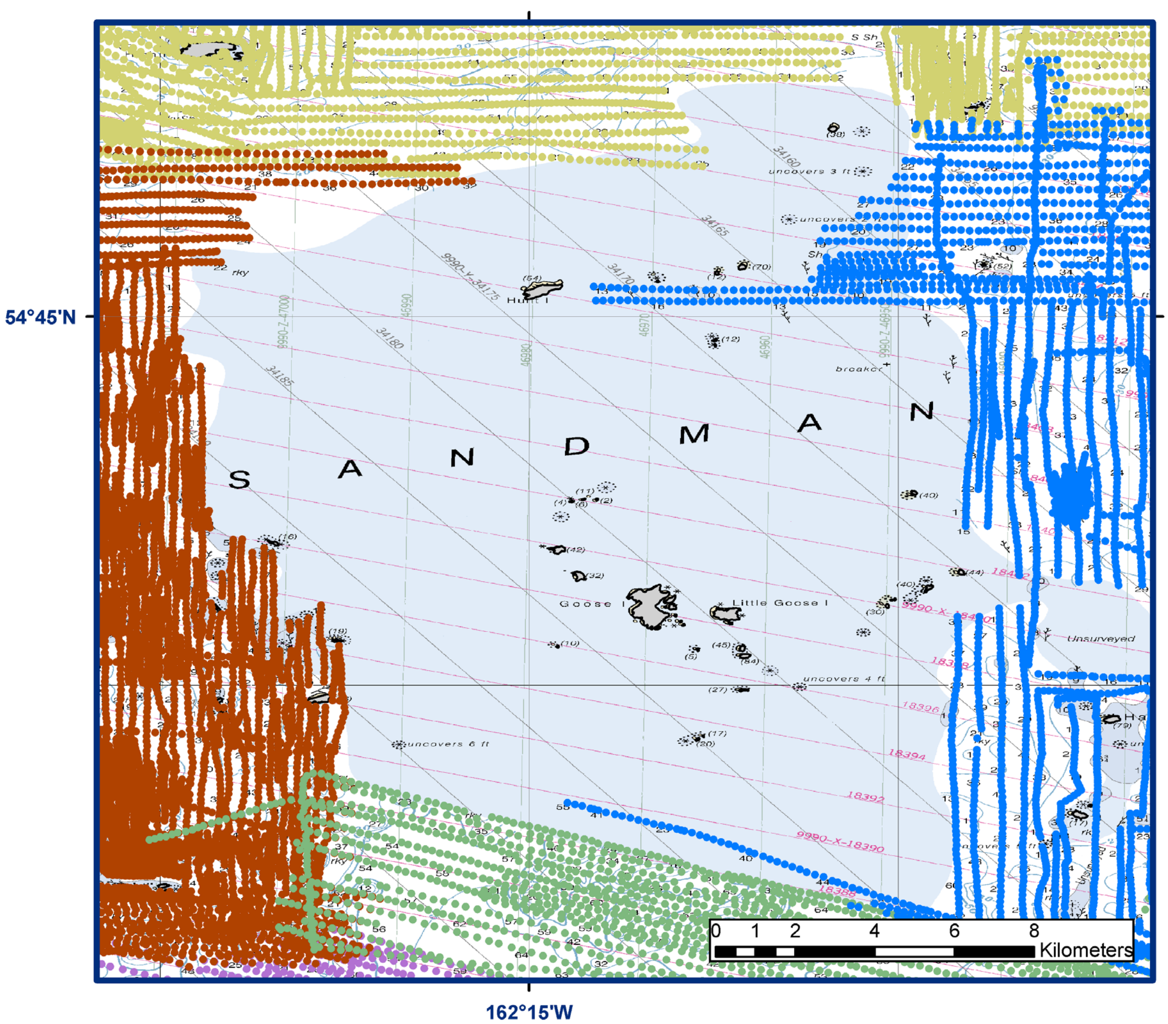

Figure 8. *NOS hydrographic survey sounding data, shown as multicolored points, surrounding unsurveyed western Sandman Reefs area as shown on RNC #16547.*

3.1.3 Bathymetry-Topography

One bathymetric-topographic dataset was available for King Cove, Alaska: NOS Hydrographic LiDAR (Fig. 8; table 5).

Table 5. Bathymetric-topographic datasets used in compiling the King Cove, Alaska DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NOS	2005	Hydrographic LiDAR surveys	5 meters	NAD 83 geographic	MLLW (meters)	

1) NOS Hydrographic LiDAR

NOS provided NGDC with six recent hydrographic LiDAR surveys located in the eastern part of the DEM (Fig. 8). The LiDAR surveys are referenced to NAD 83 and MLLW. These surveys range from -63 to 47 meters in elevation and have point spacing of 5 meters. The lower elevations on and near the shoreline are consistent with the SRTM dataset, higher elevations are less accurate.

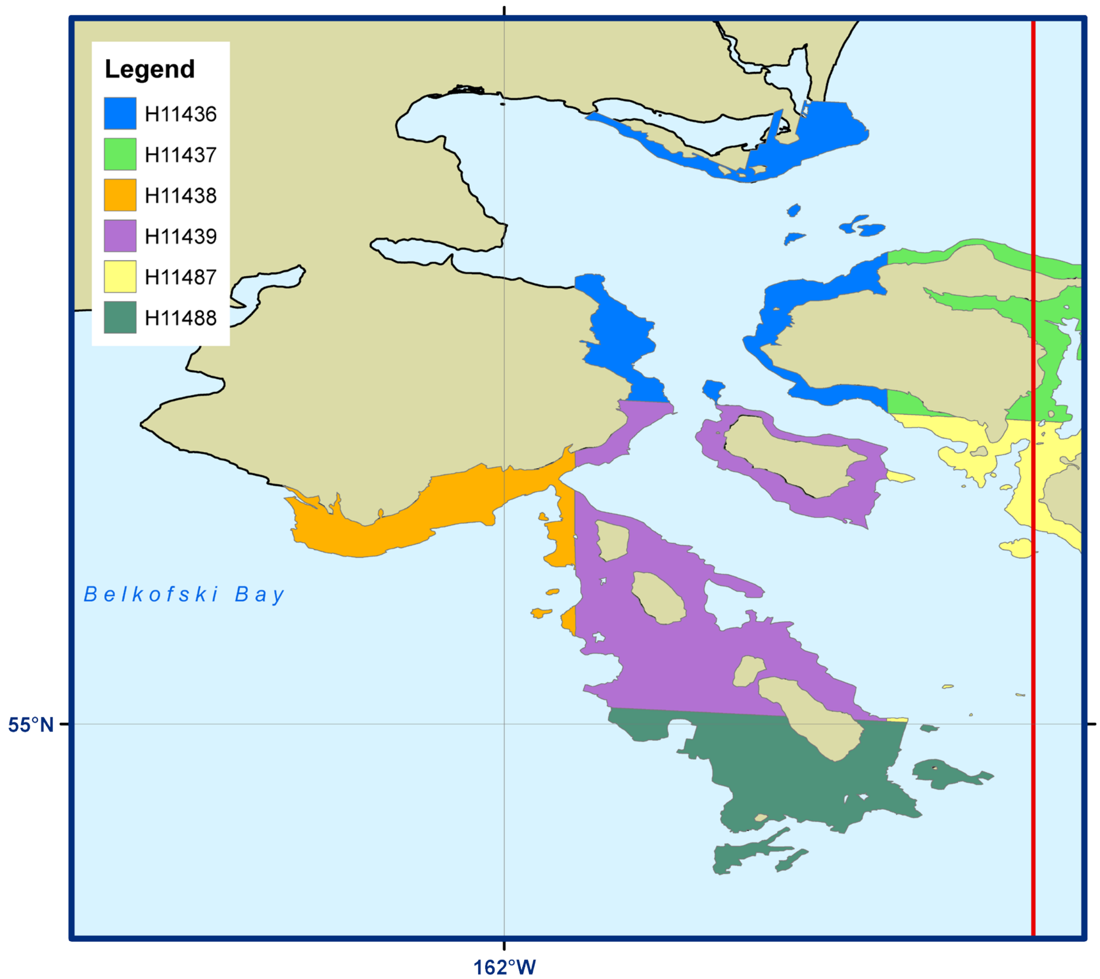

Figure 9. *NOS hydrographic LiDAR surveys located on the eastern border of the King Cove DEM (boundary shown in red).*

3.1.4 *Topography*

Topographic datasets for King Cove were obtained from the U.S. Geological Survey: National Elevation Dataset 2 arc-second gridded topography, and 1 arc-second NASA space shuttle radar topography (Fig. 10, Table 5). NGDC also digitized harbor features not represented in either topographic dataset.

Table 6. Topographic datasets used in compiling the King Cove, Alaska DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
USGS NED	2006	Topographic DEM	2 arc-second grid	NAD 27 geographic	NGVD29 (meters)	http://ned.usgs.gov/
NASA SRTM	2000	Topographic DEM	1 arc-second grid	WGS 84 geographic	WGS 84/ EGM96 Geoid (meters)	http://srtm.usgs.gov/
NGDC	2008	digitized harbor features	10 meter point spacing	WGS 84 geographic	MHW	

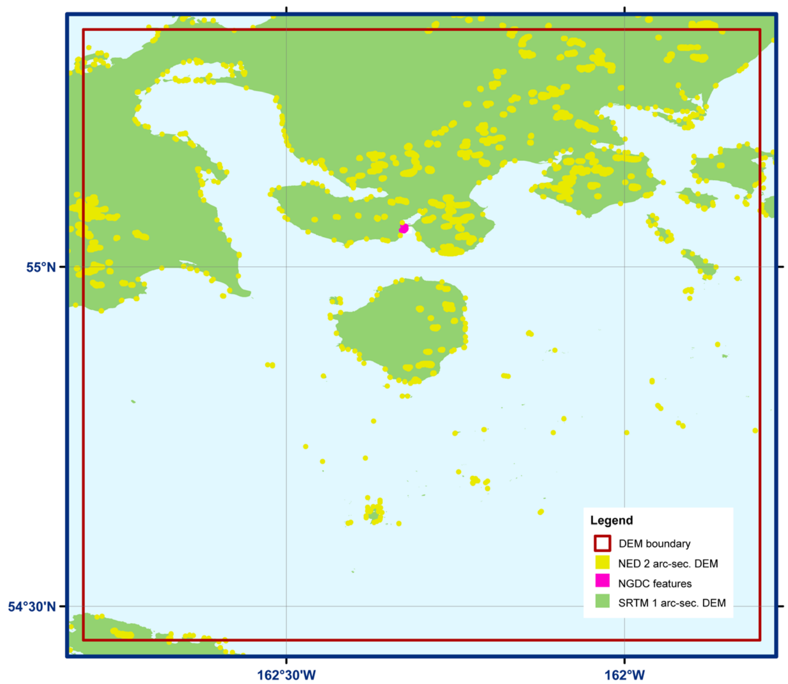

Figure 10. *Source and coverage of topographic datasets used in compiling the King Cove DEM.*

1) **USGS NED topography**

The U.S. Geological Survey's (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provides complete 2 arc-second coverage of Alaska[5]. Data are in NAD 27 Alaska geographic coordinates and NGVD29 vertical datum (meters), and are available for download as raster DEMs. The extracted bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov/). The dataset was derived from USGS quad maps and aerial photos based on surveys conducted in the 1970s and 1980s. The NED data were used only to fill in gaps within the SRTM data (e.g. Fig. 10).

5. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Alaska. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED website]

2) NASA space shuttle radar topography

The NASA Shuttle Radar Topography Mission (SRTM) obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth[6]. The SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. Data from this mission have been processed into 1 degree × 1 degree tiles that have been edited to define the coastline, and are available from the USGS Seamless web site (http://seamless.usgs.gov/) as raster DEMs. The data are not processed to bare earth, but meet the absolute horizontal and vertical accuracies of 20 and 16 meters, respectively.

For U.S. regions, the data have 1 arc-second spacing and are referenced to the WGS 84/EGM96 Geoid. While providing near complete coverage of the Aleutian Islands in the vicinity of King Cove, there are numerous small areas with "no data" values (e.g., Fig. 11), necessitating use of the lower-resolution NED topographic data in these areas. The SRTM DEM also contains values over the open ocean, which were deleted by clipping to the combined coastline.

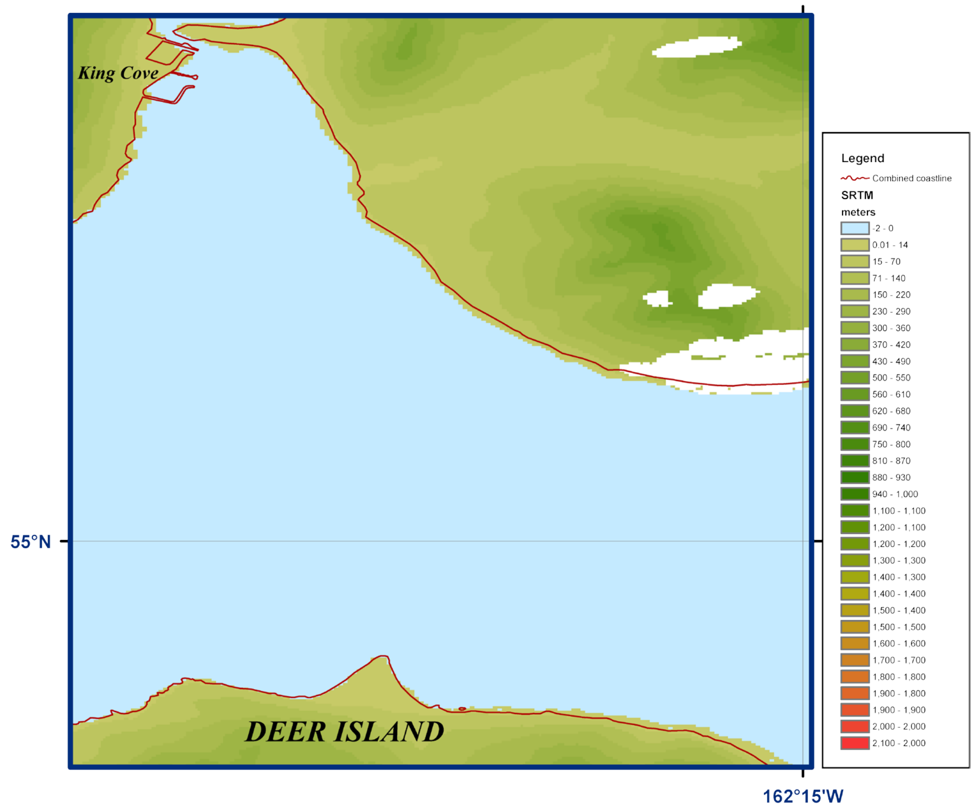

Figure 11. *Example of gaps (white areas) in SRTM data coverage. Gaps were filled with topographic data from the NED DEM. Combined coastline in red.*

6. 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]

3) NGDC digitized harbor features

Using the USACE project overview image as a reference, NGDC digitized a point shapefile to represent the two main harbor features at King Cove: the breakwater that forms the southern barrier of King Cove Lagoon entrance, the rock groin just south of the breakwater at the anchorage harbor, and the southern most breakwater at the mooring basin (referred to as Babe Newman in USACE documents, Fig. 12). Elevations applied to points were obtained from the USACE project overview image.

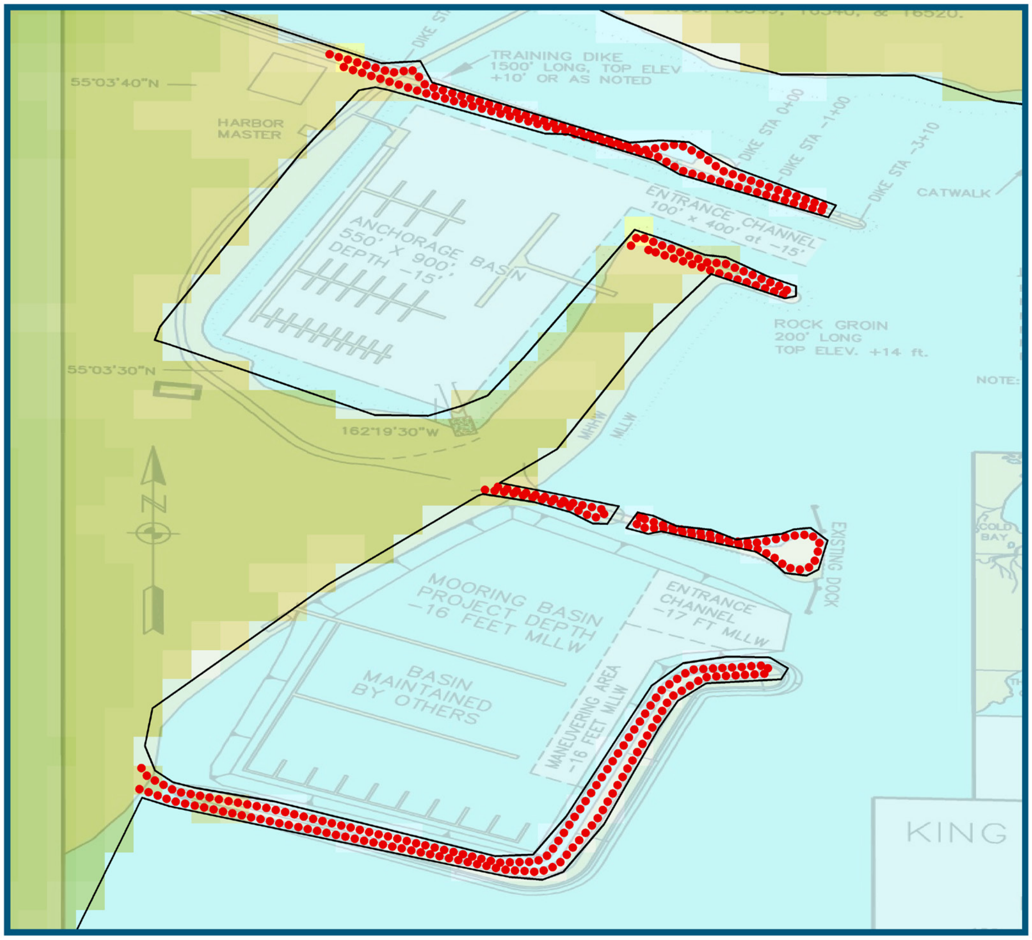

Figure 12. *Detail of King Cove Harbor with USACE project overview georeferenced image underlying SRTM topographic data.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the King Cove DEM were originally referenced to a number of vertical datums including: Mean Lower Low Water (MLLW), Mean Sea Level (MSL), WGS 84/EGM96 Geoid, and North American Vertical Datum of 1929 (NGVD29). All datasets were transformed to MHW to provide the maximum flooding for inundation modeling.

1) Bathymetric data

The NOS hydrographic surveys, the USACE survey data, NOS LiDAR surveys, and the nautical chart soundings were transformed from MLLW to MHW, using FME software, by adding a constant offset measured at the NOAA King Cove tidal station (see Table 6).

2) Topographic data

The NED and SRTM DEMs were originally in NGVD29 and WGS 84/EGM96 Geoid vertical datums, respectively. There are no survey markers in the vicinity of King Cove that relate these two geodetic datums to the local tidal datums. Thus, it was assumed out of necessity that both datums are essentially equivalent to MSL in this area (Table 6). Conversion to MHW, using FME software, was accomplished by adding a constant value of -0.747 meters.

Table 7. Relationship between Mean High Water and other vertical datums in the King Cove region.*

Vertical datum	*Difference to MHW*
MTL	-0.73
NGVD29 +	-0.747
MSL	-0.747
MLW	-1.46
MLLW	-1.869

* Datum relationships determined by tidal station #9459881 at King Cove, Alaska.
+ Assumed to be equivalent to MSL.

3.2.2 Horizontal datum transformations

Datasets used to compile the King Cove DEM were originally referenced to Early Alaska, Unalaska, NAD 27, NAD 83, and WGS 84 horizontal datums. The relationships and transformational equations between these horizontal datums are well established, with the exception of the Unalaska datum. All data were converted to a horizontal datum of NAD 83/WGS 84 using FME software, with the exception of many of the NOS surveys, which were manually shifted in ArcGIS to fit the combined coastline.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shape files were checked in ESRI ArcMap and Quick Terrain Modeler for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shape files were then converted to xyz files in preparation for gridding. Problems included:

- Data values over the open ocean in the NED and SRTM topographic DEMs. Each dataset required automated clipping to the combined coastline.
- Lack of good bathymetric data in the southeastern part of the DEM and in the vicinity of the Sandman Reefs.
- Lack of good bathymetric data near the coastline.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the 1 arc-second grid: in both deep water and near shore, the NOS survey data have point spacing up to 1.5 kilometers apart. In order to reduce the effect of artifacts in the form of lines of "pimples" in the 1 arc-second DEM due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 3 arc-second-spacing 'pre-surface' or grid was generated using GMT, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The NOS hydrographic point data, in xyz format, were combined with the USACE surveys, ENC soundings, and the estimated seafloor topography data into a single file, along with points extracted every 10 meters from the combined coastline—to provide a slightly negative (-2 meters) buffer along the entire coastline. The negative value of -2 meters was assigned to the coastline to make sure that the offshore elevations remain negative; this was necessary due to the sparseness of the bathymetric data near the coast. These point data were smoothed using the GMT tool 'blockmedian' onto a 3 arc-second grid. The GMT tool 'surface' was then applied to interpolate cells without data values. The GMT grid created by 'surface' was converted into an ESRI Arc ASCII grid file using the MB-System tool 'mbm_grd2arc'. Conversion of this Arc ASCII grid file into an Arc raster permitted clipping of the grid with the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with the original soundings to ensure grid accuracy (e.g., Fig. 13), converted to a shape file, and then exported as an xyz file for use in the final gridding process (see Table 7). The statistical analysis of the differences between the 3 arc-second bathymetric surface and one of the NOS surveys (see Fig. 13) showed that the majority of the NOS soundings are in good agreement with the bathymetric surface. The few exceptions where the difference reached tens of meters are in areas of rugged terrain where two or more closely positioned points were averaged to obtain the elevation of for one grid cell.

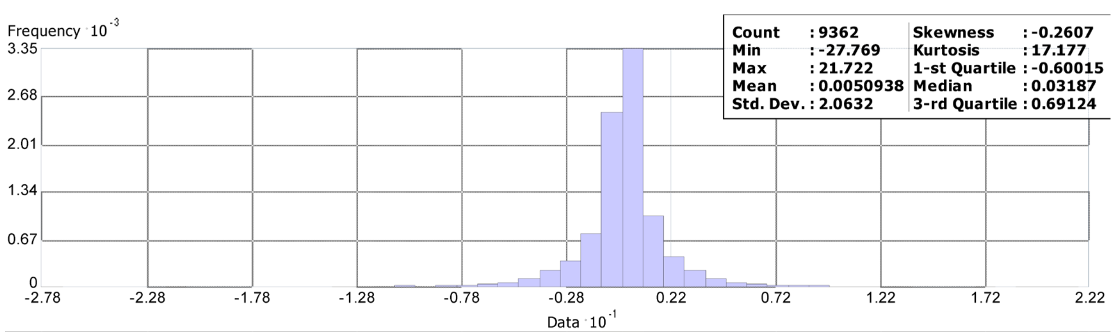

Figure 13. *Histogram of the difference between NOS hydrographic survey H06586 and the 1 arc-second NOS pre-surfaced bathymetric grid.*

3.3.3 Building the 1 arc-second DEM with MB System

MB-System was used to create a 1 arc-second King Cove DEM. The MB-System tool 'mbgrid' applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 7. Greatest weight was given to the high-resolution topographic SRTM and NGDC harbor feature datasets. Least weight was given to the pre-surfaced 3 arc-second bathymetric grid.

Table 8. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
SRTM topographic DEM	1,000
USACE surveys	100
NOS hydrographic surveys	10
Combined coastline at 0 meters elevation	100
USGS NED topographic DEM	1
ENC #16549 soundings	1
NOS LiDAR surveys	1
MEST bathymetric DEM	1
NGDC digitized features	1000
Pre-surfaced bathymetric grid	0.1

3.4 Quality Assessment of the DEM

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the King Cove DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features in island interiors have an estimated horizontal accuracy of 50 to 75 meters, based on the documented accuracy of the NED and SRTM DEMs. Bathymetric features in areas covered by early 20th-century NOS hydrographic soundings—along the margins of the DEM—are resolved only to within a few tens of meters in shallow water, and to a few hundred meters in deep-water areas; their positional accuracy is limited by the sparseness of soundings, and potentially large positional accuracy of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the DEM is also highly dependent upon the source datasets contributing to grid cell values. Island interiors have vertical accuracies of between 10 and 15 meters, derived from: the NED topographic data, which have an estimated vertical accuracy of 10 meters; and the SRTM topographic data, which have a vertical accuracy better than 16 meters but are typically about 10 meters. Gridding interpolation to determine bathymetric values between sparse, poorly located, early 20th-century NOS hydrographic soundings degrades the vertical accuracy of elevations in deep water to about 5% of water depth. Bathymetry vicinity of Sandman Reefs, derived largely from the low-resolution estimated seafloor topography, is shoal biased by several meters.

3.4.3 3-D perspective and slope map

ESRI ArcCatalog was used to generate a slope grid from the 1 arc-second King Cove DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 14). The DEM was transformed to UTM 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. Three-dimensional viewing of the UTM-transformed DEM (e.g., Fig. 15) was accomplished using ESRI ArcScene. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM.

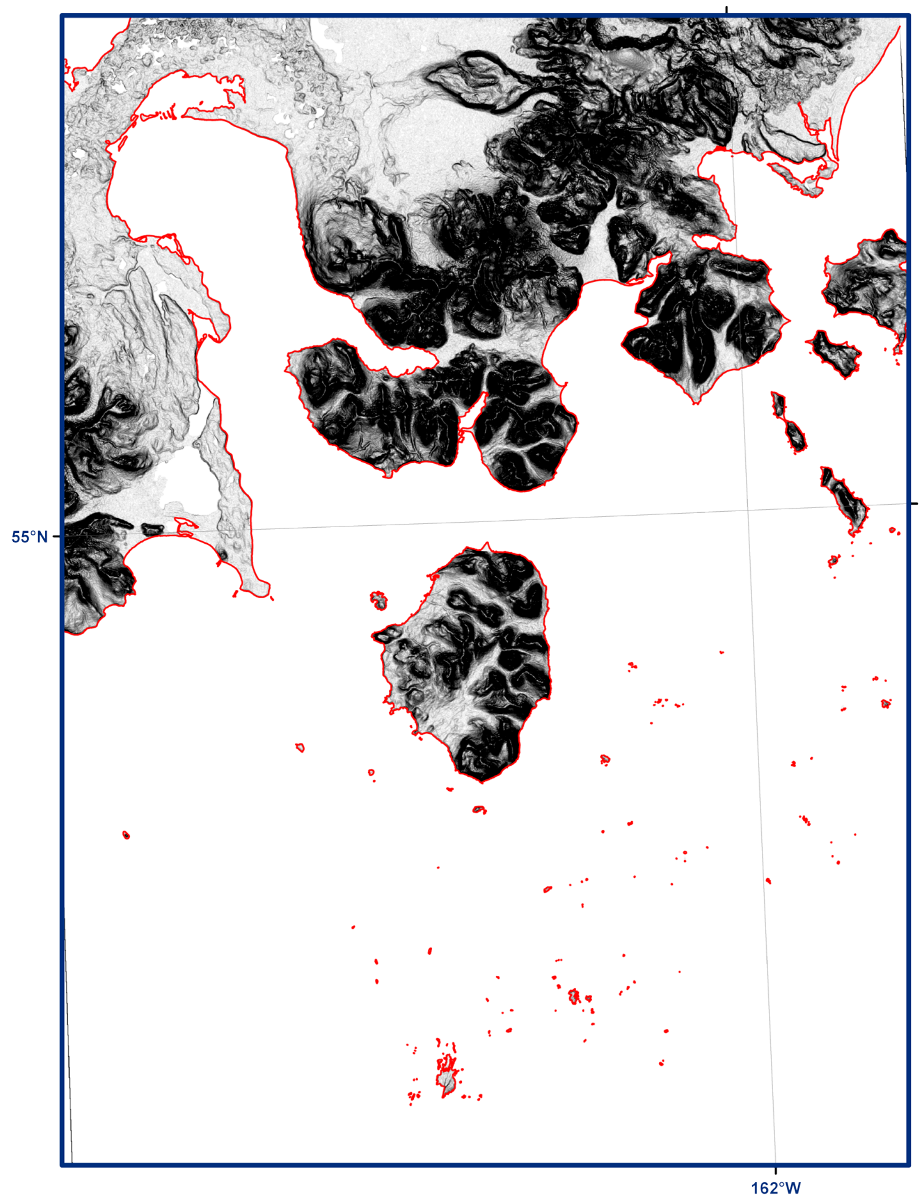

Figure 14. *Slope map of the 1 arc-second King Cove DEM in the vicinity of King Cove, Alaska. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

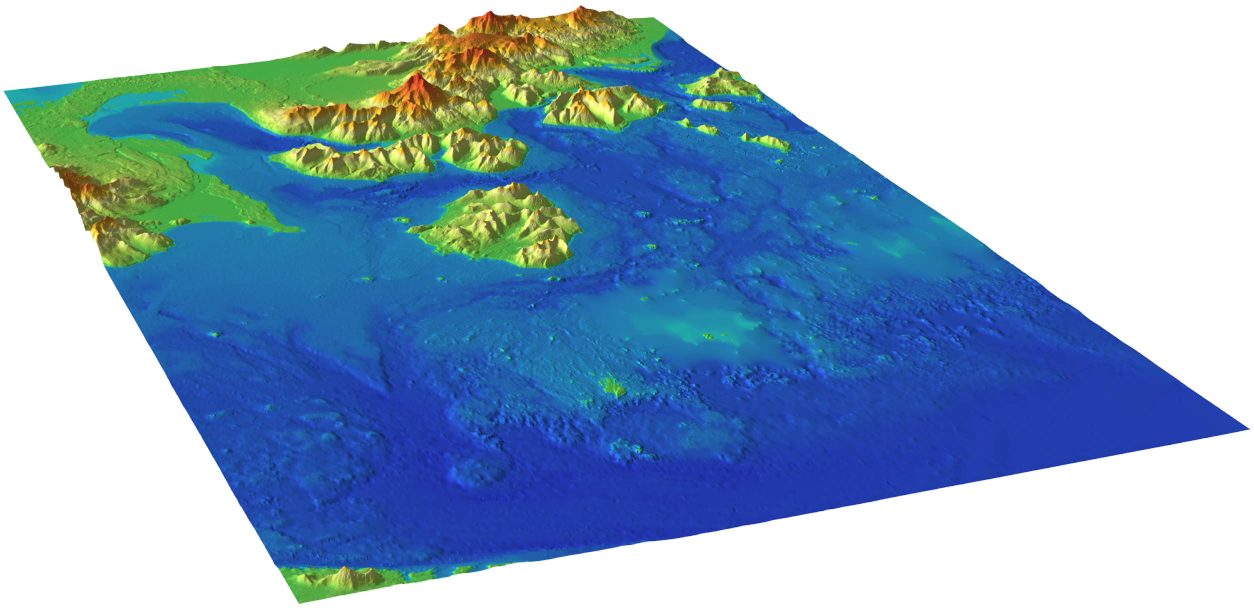

Figure 15. *Perspective view from the southeast of the 1 arc-second King Cove DEM. Combined coastline in blue; vertical exaggeration–times 2.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the 1 arc-second King Cove DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas. A histogram of the difference between selected SRTM data points and the King Cove DEM is shown in Figure 16. The largest differences occur in regions of highly variable, steep coastal relief where multiple, closely spaced points were averaged to a single cell value.

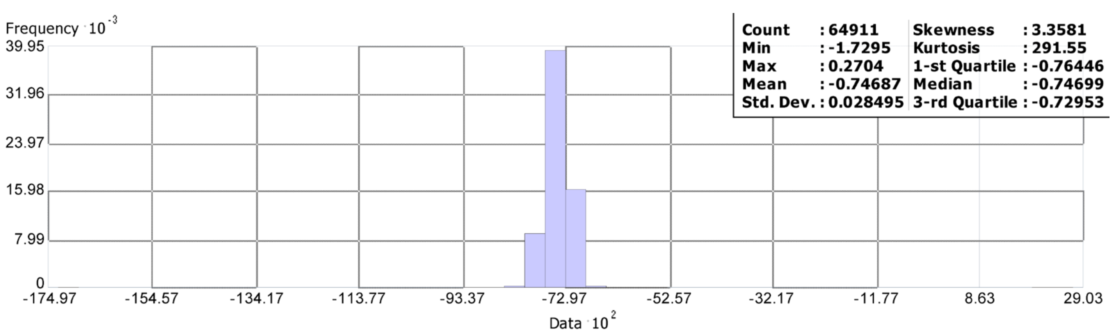

Figure 16. *Histogram of the difference between part of SRTM topographic dataset and the 1 arc-second King Cove DEM. The largest differences occur in regions of highly variable, steep coastal relief where multiple, closely spaced points were averaged to a single cell value.*

3.4.5 *Comparison with USGS topographic elevations*

Topographic elevations were extracted from online digital images of USGS topographic quadrangles at TopoZone (http://www.topozone.com) which give position and elevation in WGS 84 and NGVD29 vertical datum (in feet). Elevations were converted to meters and shifted to MHW vertical datum (see Table 8) for comparison with the 1 arc-second King Cove DEM (see Fig. 16 for locations). Significant differences exist between the King Cove DEM and the USGS topographic elevations: from -254 to -8.5 meters, with a negative value indicating that the DEM is less than the topographic quadrangle elevation (Fig. 17). Much of the difference results from horizontal offsets between the poorly resolved positional information taken from the online quadrangles, and the corresponding feature in the DEM. Such offsets range up to 254 meters.

From a vertical perspective, topographic elevations, typically at localized high points though the DEM, are lower than USGS topographic quadrangle elevations (Fig. 18). These differences may be attributable to the fact that the SRTM and NED topographic data, used to constrain the sub aerial parts of the DEM, represent averages of land elevations over 30 × 30 meter, and 60 × 60 meter square areas, respectively, while the topographic quadrangle elevations represent local maximum heights.

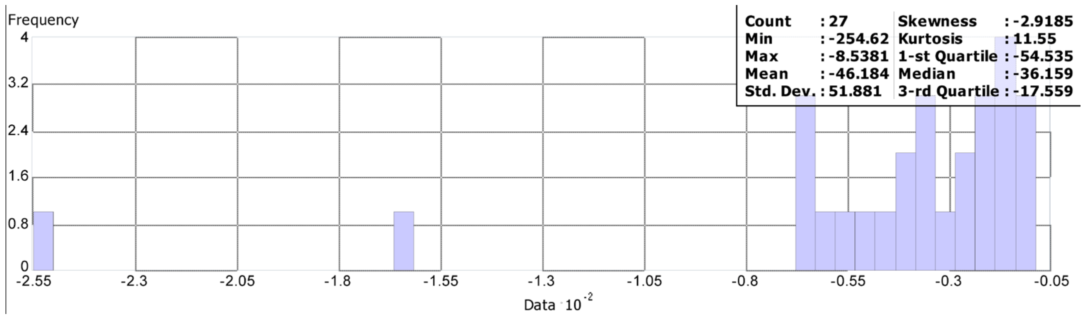

Figure 17. *Histogram of the differences between the USGS topographic benchmarks elevations and the 1 arc-second King Cove DEM. The pronounced negative values (DEM less than topographic elevations) result partly from horizontal offsets of features, typically local highs, but may also result from comparing average elevation over an area with a local maximum.*

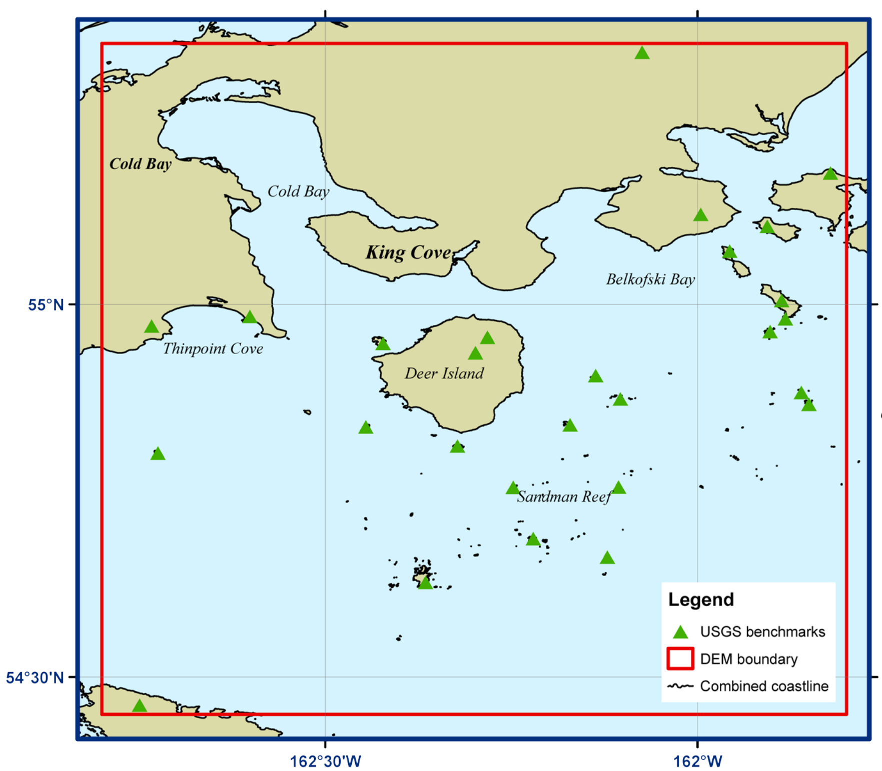

Figure 18. *Location of USGS topographic benchmarks used in quality assessment of King Cove DEM.*

4. Summary and Conclusions

A combined topographic–bathymetric digital elevation model of the King Cove, Alaska area, with cell spacing of 1 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 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, FME, GMT, Quick Terrain Modeler, and MB-System software.

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

- Conduct bathymetric surveys in the region to the north of the Deer Island, at the entrance to King Cove, and in the Sandman Reefs area which currently have no digital measured bathymetric data.
- Obtain digital versions of NOAA nautical chart #16547 that has not yet been digitized.
- Establish, via survey, the relationships between tidal and geodetic datums in the King Cove region.

5. Acknowledgments

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6. References

Electronic Navigational Chart #16549, 3rd Edition, 2008. Alaska Peninsula Cold Bay and Approaches. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16547, 9th Edition, 2004. Sanak Island and Sandman Reefs. Scale 1:81,326. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #16520, 3rd Edition, 2007. Unimak and Akutan Passes. Scale 1:300,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Smith, W. H. F., and D. T. Sandwell, Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277, p. 1957-1962, 26 Sept., 1997.

Coast Pilot 9, 25th Edition, 2007. Alaska Peninsula. U.S. Department of Commerce, NOAA, National Ocean Service.

7. Data Processing Software

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

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

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

GMT v. 4.1.1 – Generic Mapping Tools, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.0.9, shareware developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

Quick Terrain Modeler v.6.0.1, developed by Johns Hopkins University Applied Physics Laboratory, licensed by Applied Imagery, Silver Spring, Maryland, http://www.appliedimagery.com/