NOAA Technical Memorandum NESDIS NGDC-47

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1. Introduction

In March of 2010, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed an integrated bathymetric–topographic digital elevation model (DEM) of Nikolski, Alaska (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for the 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 forecasting as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a description of the data sources and methodology used to develop the Nikolski DEM.

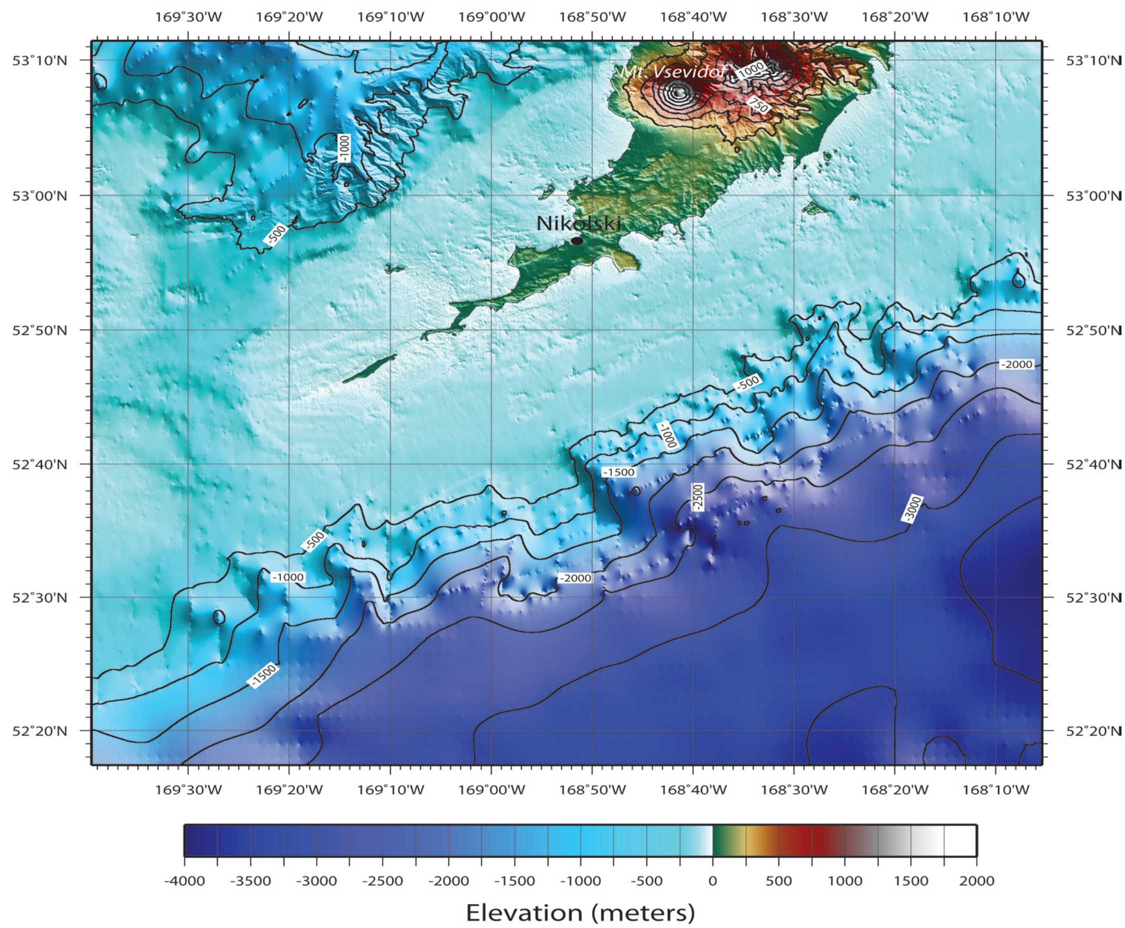

Figure 1. Shaded-relief image of the Nikolski 1 arc-second DEM. Contour interval is 250 meters. Image is in Mercator projection.

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 Nikolski, Alaska (52º57'0"N, 168º50'0"W) 1 arc-second of latitude is equivalent to 30.86 meters; 1 arc-second of longitude equals 18.41 meters.

2. Study Area

Nikolski, Alaska is located at 52º56'29"N 168º51'39"W, on Umnak Island in the Aleutian Islands. The island covers an area of 133 square miles and has a total population of 39. On a clear day, the horizon is dominated by Mount Vsevidof, a stratovolcano with the highest point on Umnak Island. Mount Vsevidof is approximately 10 kilometers wide at the base and steepens from 15 degrees to 30 degrees near the peak. A circular crater, 1.2 kilometers in diameter, is present at the summit. Its most recent eruption was caused by an earthquake on March 11, 1957.

3. Methodology

The Nikolski DEM was constructed to meet PMEL specifications (Table 1), based on input requirements for the development of reference inundation models (RIMs) and standby inundation models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum of 1983 (NAD 83) geographic[2] and mean high water (MHW), for modeling of maximum flooding. Data were gathered in an area slightly larger (~5%) than the DEM extents. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. PMEL specifications for the 1 arc-second Nikolski DEM.

Grid Area	Nikolski, Alaska
Coverage Area	169.66 º to 168.09º W; 52.29º to 53.19º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	Mean high water (MHW)
Vertical Units	Meters
Cell 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), and NGDC; the U.S. Fish and Wildlife Service (USFWS); the National Aeronautic Space Administration (NASA), and the U.S. Geological Survey (USGS). Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 horizontal datum and to convert into ESRI *ArcGIS* shapefiles[3]. The shapefiles 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 Unalaska, Dutch Harbor tide station.

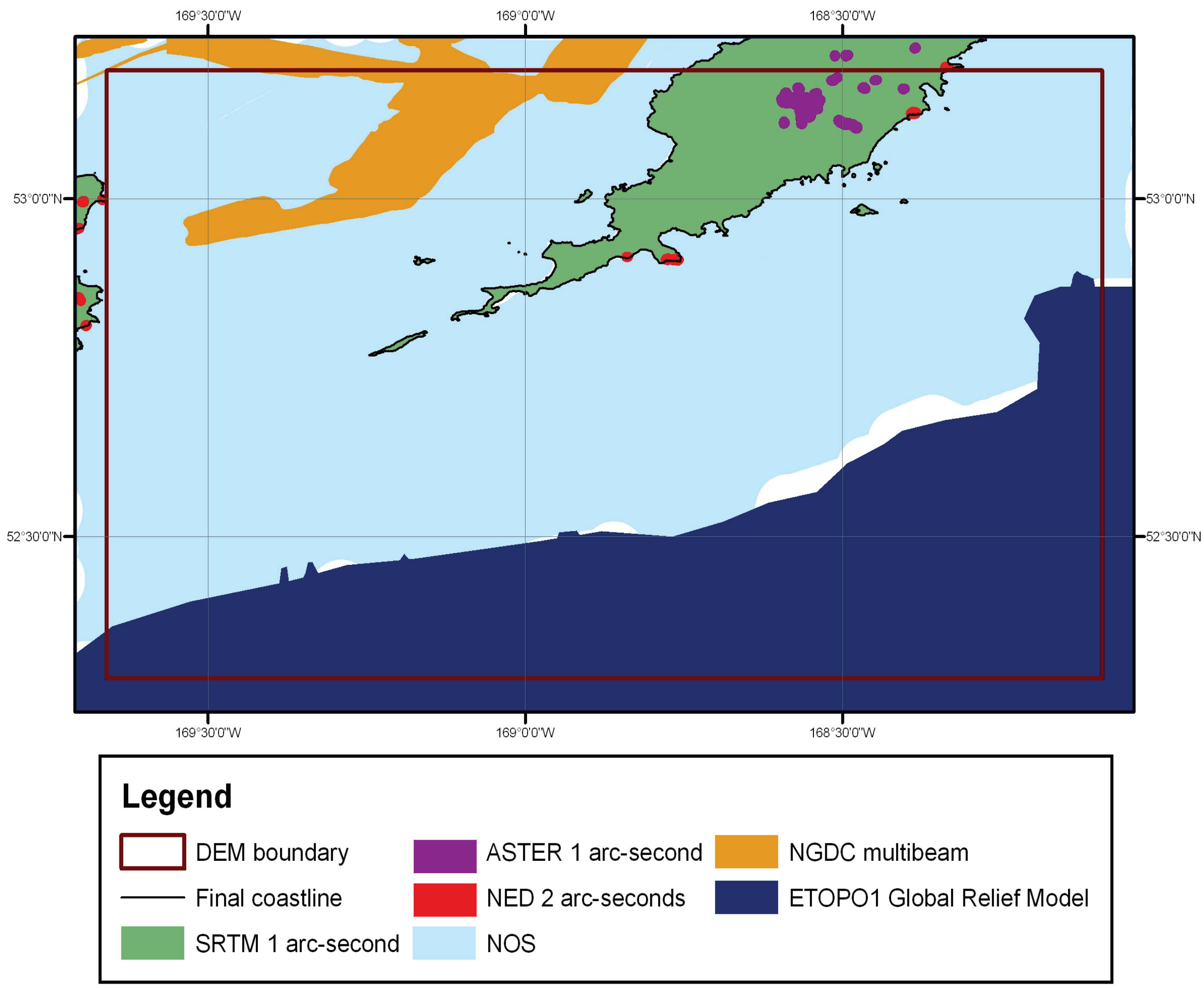

Figure 2. Source and coverage of datasets used in compiling the Nikolski DEM.

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

3.1.1 Shoreline

Two digital coastline datasets of the Nikolski region were analyzed for use in building the Nikolski DEM: NOAA ENCs and USFWS statewide Alaska digital coastline. Comparisons between the NOS hydrographic surveys, Shuttle Radar Topography Mission (SRTM) topographic DEM, RNCs, and ESRI's *World 2D* imagery indicated that both the USFWS and ENC coastlines (Table 2) were inconsistant with other datasets at the resolution of the DEM. The USFWS coastline was edited using the aforementioned datasets as reference to create a final coastline for the Nikolski DEM (Fig. 3).

ENCs provided an extracted coastline covering the study area. This coastline is less complete than the USFWS coastline and was not used in building the Nikolski DEM.

Table 2. Shoreline dataset used in compiling the Nikolski DEM.

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

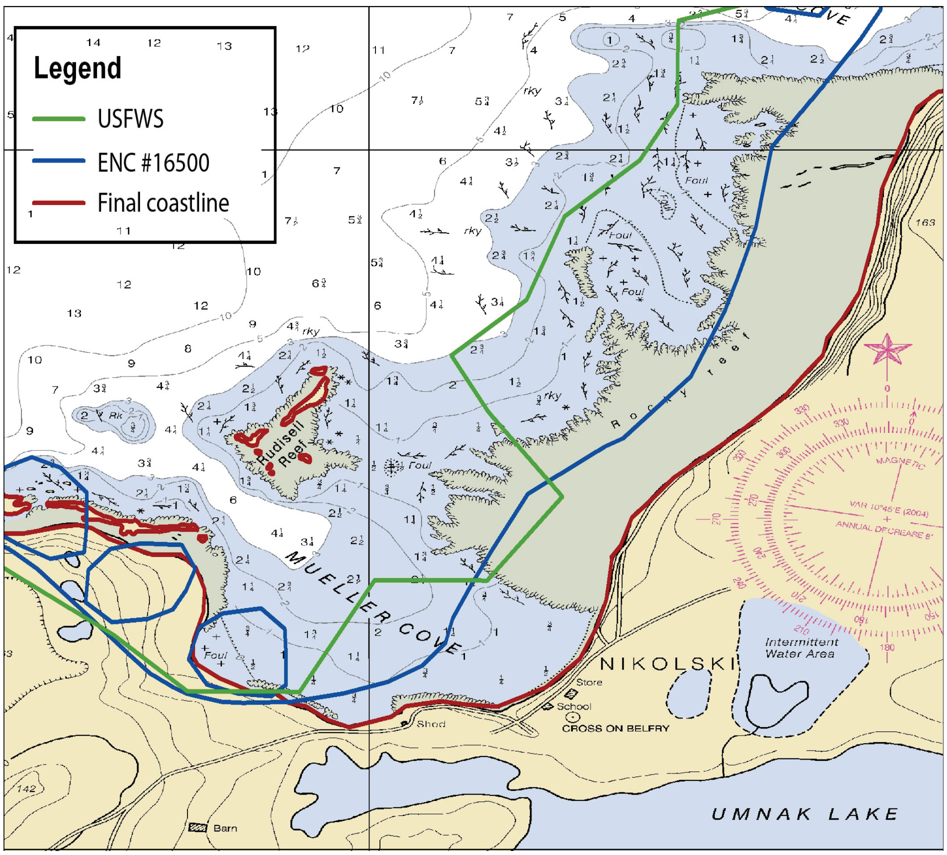

Figure 3. Digital coastline datasets in the Nikolski region. The ENC and USFWS coastlines are inconsistant with the 1:10,000 scale RNC of Nikolski. The USFWS coastline was edited using high-resolution RNCs and the SRTM topographic DEM as reference to create a final coastline.

1) U.S. Fish and Wildlife Service coastline

USFWS has compiled a seamless digital coastline of the State of Alaska from a variety of sources, including the National Hydrography Dataset, NOAA nautical charts, USFWS, National Geographic Topo Software, USACE, and Alaska Department of Natural Resources. This dataset was provided to NGDC by Bret Christensen, USFWS. Though efforts were made to obtain the highest resolution coastlines available, vertical datums were not determined nor controlled in any way in compiling the USFWS coastline; the horizontal datum of the compiled USFWS coastline is WGS 84. The USFWS coastline provides complete coverage of the DEM area.

2) NOAA Nautical Charts

Three NOAA nautical charts were available for the Nikolski region as georeferenced RNCs (Table 3). The charts were downloaded from NOAA's Office of Coast Survey web site (http://nauticalcharts.noaa.gov). The RNCs were used to reference coastline datasets and to assess the quality of bathymetric datasets in the region.

Table 3. NOAA nautical charts in the Nikolski region.

Chart	*Title*	*Edition*	*Edition Date*	*Format*	*Scale*
16500	Unalaska Island to Amukta Island	4th	2009	RNC/ENC	1:300,000
16501	Islands of Four Mountains	2nd	2007	RNC/ENC	1:80,000
16511	Inanudak and Nikolski Bays	7th	2004	RNC	1:10,000 and 1:40,000

To obtain the best digital MHW coastline, NGDC manually edited the USFWS coastline into a final coastline (Fig. 3). The USFWS coastline was chosen over the ENC due to its full coverage of the DEM. The USFWS coastline was edited to be consistent with the SRTM topography, NOS hydrographic survey data, and ESRI's *World 2D* imagery. The coastline around Nikolski Bay was manually adjusted to match RNC #16511 (1:10,000 scale, Fig. 3). The final coastline was sub-sampled to 10-meter spacing using NGDC's *GEODAS* software 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 Sec. 3.3.2) to ensure that interpolated bathymetric values reached "zero" at the coast. The final coastline was also used to clip the SRTM, ASTER, and National Elevation Dataset (NED) topographic DEMs, which contained elevation values, typically zero, over the open ocean (see Sec. 3.1.3).

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the Nikolski DEM included NOS hydrographic surveys, NGDC multibeam swath sonar surveys, and the ETOPO1 Global Relief Model (Table 4). Datasets were originally referenced to mean lower low water (MLLW) or mean sea level (MSL).

Table 4. Bathymetric datasets used in compiling the Nikolski DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1910 to 1940	NOS hydro-graphic survey soundings	Ranges from 10 meters to 1.5 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 83 geographic	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	2007	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NGDC ETOPO1	2008	Global Relief Model	1 arc-minute	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html

1) National Ocean Service hydrographic survey data

A total of 24 NOS hydrographic surveys conducted between 1910 and 1940 were available for use in the Nikolski DEM (Table 4; Fig. 4). The hydrographic survey data were downloaded from NGDC's NOS Hydrographic Survey Database using *GEODAS*[4], which transformed the surveys to NAD 83. The data were originally vertically referenced to MLLW and horizontally referenced to Early Alaska, Unalaska, or undetermined datums.

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 NOS Hydrographic Survey Database in their original datums (Table 5). The data were then converted to NAD 83 geographic using *FME* software. *FME* is an integrated collection of spatial extract, transform, and load tools for data transformation. A few NOS surveys contained gross horizontal inaccuracies and were manually shifted in *ArcGIS* to fit the final coastline. The surveys were subsequently clipped to a polygon 0.05 degrees (~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 Sec. 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 SRTM topographic data and the final coastline.

NOS survey #H03194 was discarded due to it's undetermined horizontal datum (Table 5).

4. NGDC's GEODAS 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 and NAD 13 to NAD 83 geographic. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

Table 5. Digital NOS hydrographic surveys used in compiling the Nikolski DEM.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum of Digital Records*
H03124[+]	1910	n/a	MLLW	Undetermined
H06265	1937	1:40,000	MLLW	Early Alaska
H06274	1937	1:20,000	MLLW	Early Alaska
H06286	1937	1:20,000	MLLW	Early Alaska
H06303	1937	1:20,000	MLLW	Early Alaska
H06377	1938	1:80,000	MLLW	Early Alaska
H06379	1938	1:20,000	MLLW	Early Alaska
H06380*	1938	1:20,000	MLLW	Early Alaska
H06381	1938	1:20,000	MLLW	Early Alaska
H06382	1938	1:20,000	MLLW	Early Alaska
H06383	1938	1:80,000	MLLW	Early Alaska
H06412	1938	1:20,000	MLLW	Early Alaska
H06413	1938	1:120,000	MLLW	Early Alaska
H06478	1939	1:120,000	MLLW	Early Alaska
H06503	1940	1:80,000	MLLW	Early Alaska
H06504	1939	1:20,000	MLLW	Early Alaska
H06505*	1939	1:20,000	MLLW	Early Alaska
H06526	1939	1:200,000	MLLW	Early Alaska
H06527	1939	1:240,000	MLLW	Unalaska
H06568	1940	1:80,000	MLLW	Early Alaska
H06569	1940	1:20,000	MLLW	Early Alaska
H06570	1940	1:20,000	MLLW	Early Alaska
H06610	1940	1:20,000	MLLW	Early Alaska
H06611	1940	1:20,000	MLLW	Early Alaska

* Geographic position manually adjusted in *ArcGIS* to fit combined coastline.
\+ Discarded survey.

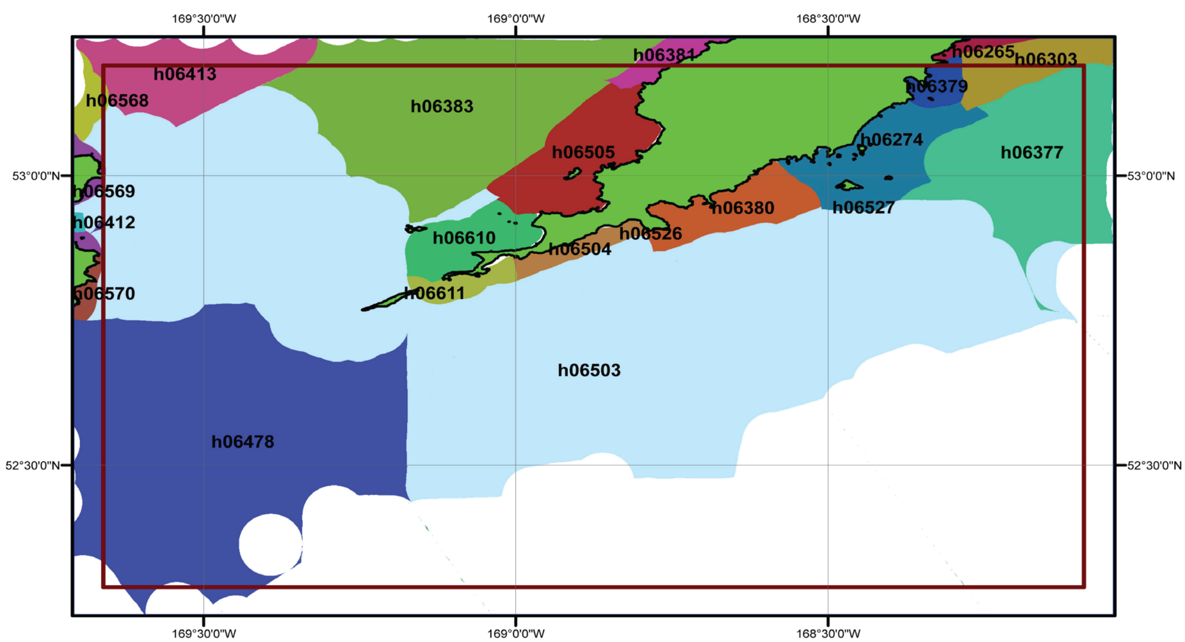

Figure 4. Digital NOS hydrographic survey coverage in the Nikolski region. Brown boundary denotes DEM extent; coastline in black.

2) Multibeam swath sonar files

Four multibeam swath sonar surveys (Table 6; Fig. 5) were available from the NGDC multibeam sonar bathymetry database for use in the Nikolski DEM. This database is comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. Most of the offshore multibeam swath sonar surveys were transits rather than dedicated sea-floor surveys. Both surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be equivalent to MSL.

The downloaded data were gridded to 1 arc-second resolution using *MB-System*[5]. The gridded data were converted to shapefiles and transformed to MHW using *FME*.

Table 6. Multibeam swath sonar surveys used in compiling the Nikolski DEM.

Cruise ID	***Ship***	***Year***	***Original Vertical Datum***	***Original Horizontal Datum***	***Institution***
EW0204	Maurice Ewing	2002	Assumed MSL	WGS 84 geographic	Columbia University, Lamont Doherty Earth Observatory
FOCI95	Surveyor	1995	Assumed MSL	WGS 84 geographic	NOAA
TN182	Thomas Thompson	2005	Assumed MSL	WGS 84 geographic	University of South Carolina
RNDB06WT	Thomas Washington	1988	Assumed MSL	WGS 84 geographic	Scripps Institution of Oceanography

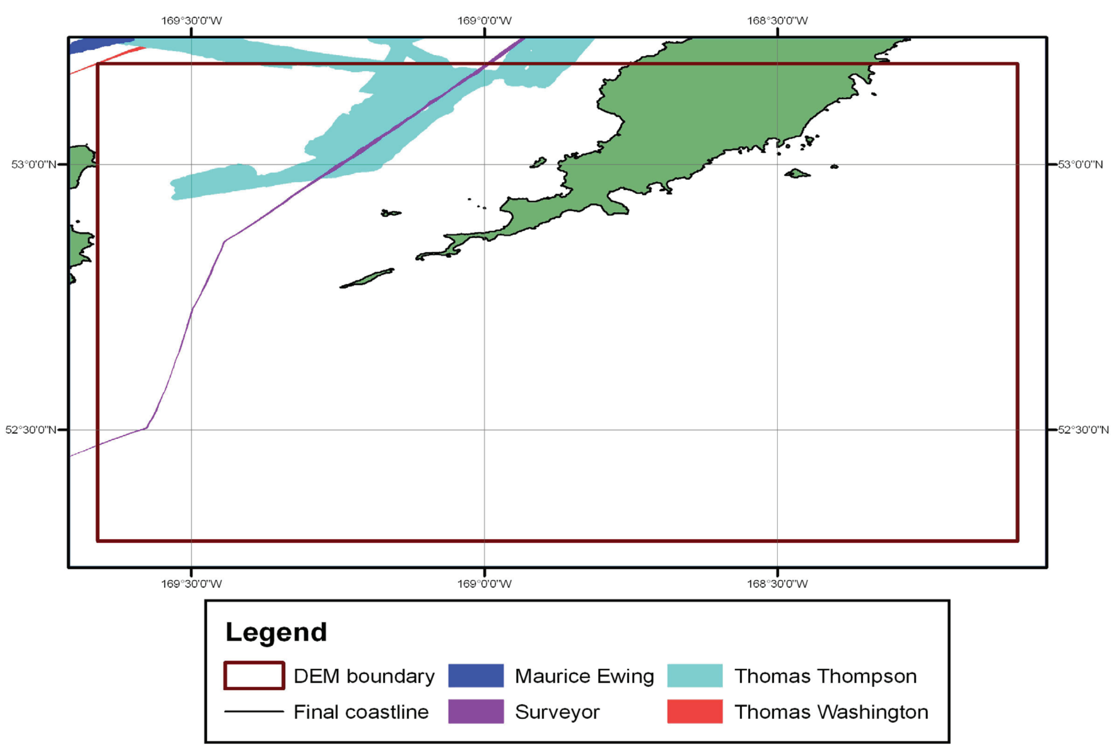

Figure 5. Source and coverage of multibeam bathymetry datasets used in compiling the Nikolski DEM.

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 signifi cant 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 MBSystem web site.]

3) ETOPO1 Global Relief Model

A portion of the 1 arc-minute (~2 kilometer cell size) ETOPO1 Global Relief Model was extracted using NGDC's GEODAS grid translator "Design-a-Grid" tool (http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html?dbase=grdet1). ETOPO1 is an integrated bathymetric–topographic grid, however, only the bathymetric values were used in creating a bathymetric surface. Figure 6 shows the bathymetric portion of the ETOPO1 grid that was used in building the Nikolski DEM. *FME* was used to convert the grid to MHW and transform it to a point shapefile. It was then edited to retain points in areas without direct depth measurements.

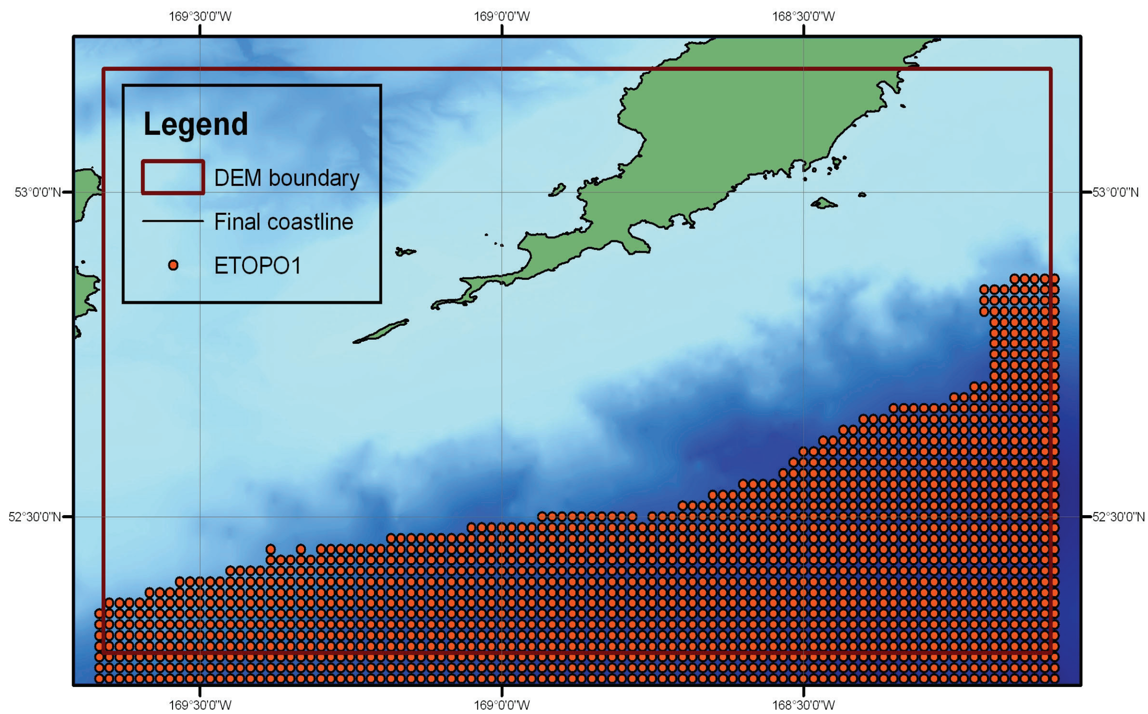

Figure 6. Coverage of the ETOPO1 Global Relief Model used in compiling the Nikolski DEM.

3.1.3 Topography

Three topographic datasets in the Nikolski region were obtained from the USGS and NASA: NED 2 arc-second, 1 arc-second SRTM, and 1 arc-second ASTER topographic DEMs (Fig. 7; Table 7).

Table 7. Topographic datasets used in compiling the Nikolski 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	NGVD 29 (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/
ASTER	2009	Topographic DEM	1 arc-second grid	WGS 84 geographic	WGS 84/EGM96 Geoid (meters)	http://asterweb.jpl.nasa.gov/

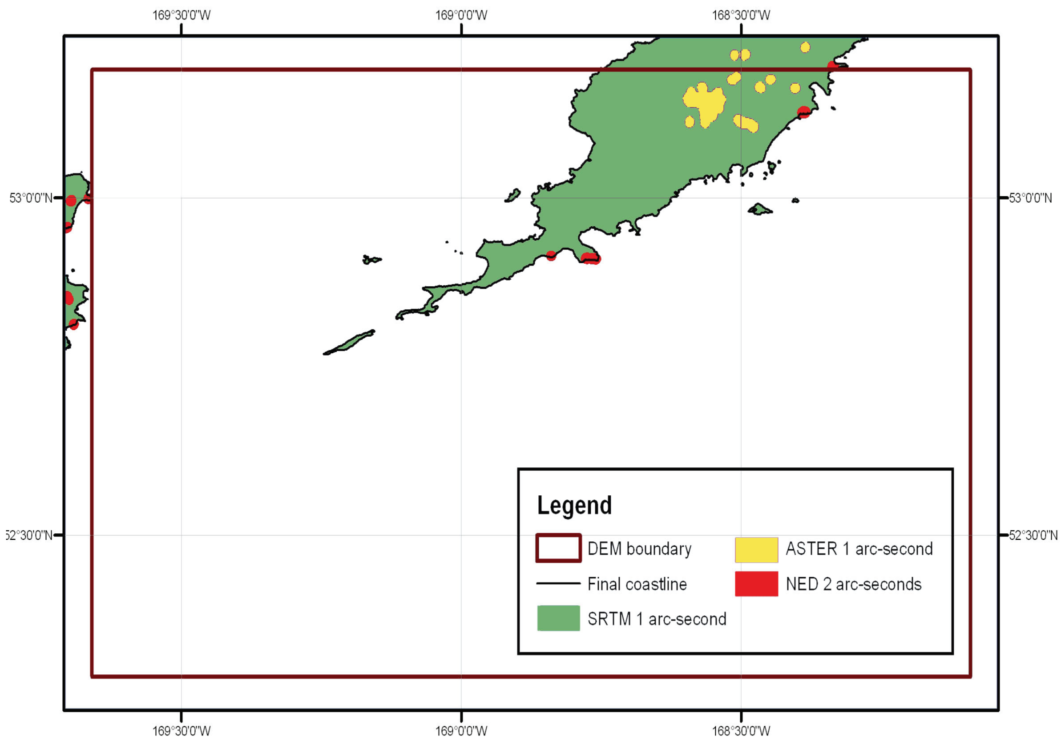

Figure 7. Source and coverage of topographic datasets used in compiling the Nikolski DEM.

1) U.S. Geological Survey National Elevation Dataset topography

USGS's NED provides complete 2 arc-second coverage of Alaska[6]**.** Data are in NAD 27 Alaska geographic coordinates and North American Vertical Datum of 1929 (NGVD 29) 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 along the coasts, only to fill in gaps within the SRTM data (e.g., Fig. 8). The NED data had values over the open oceans that were deleted by clipping to the final coastline.

2) NASA Space Shuttle Radar Topography Mission

The NASA SRTM obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth[7]. 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, edited to define the coastline, and are available from the USGS Seamless web site **(**http://seamless.usgs.gov/**)** as raster DEMs. The data have not been 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 Nikolski, there are numerous small areas with "no data" values necessitating the use of the lower-resolution NED topographic data in coastal areas (Fig. 8). The SRTM DEM also contains values over the open ocean, which were deleted by clipping to the final coastline.

6. The USGS National Elevation Dataset (NED; http://ned.usgs.gov/) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for 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 web site]

7. 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]

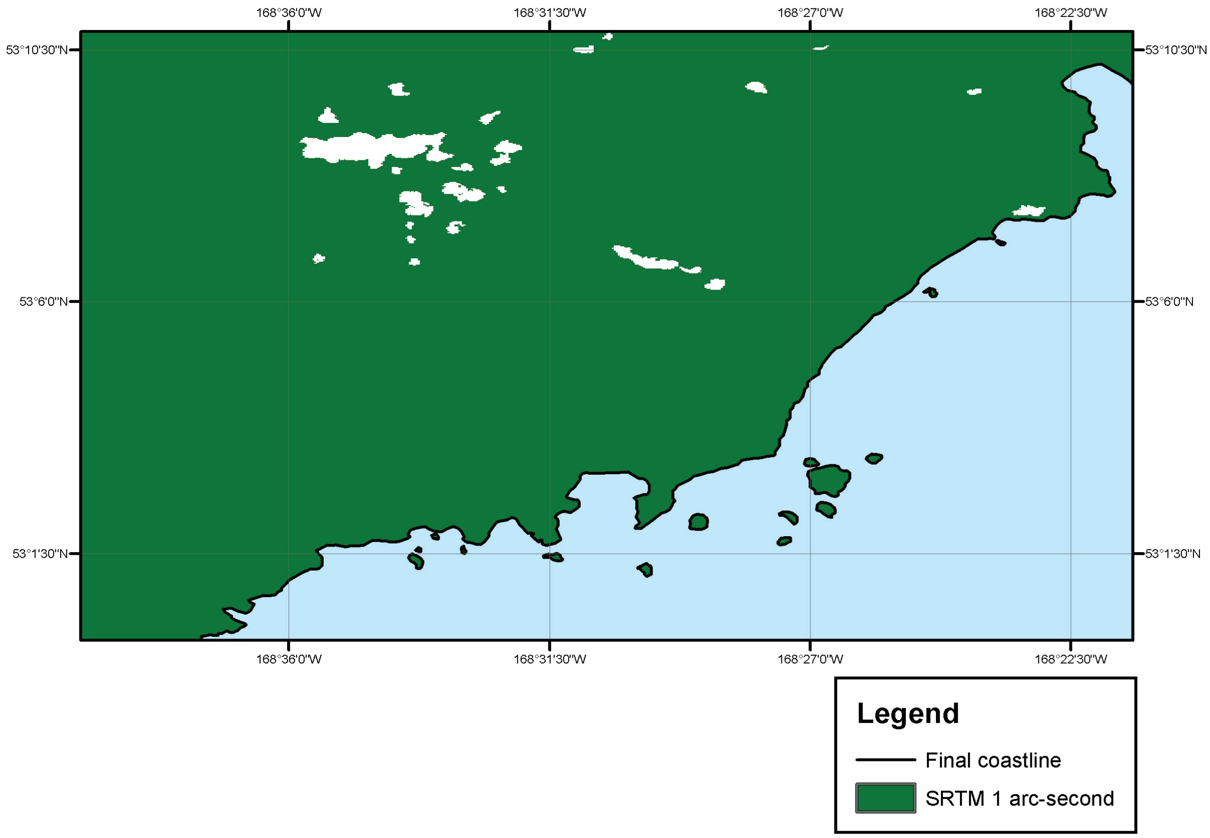

Figure 8. Examples of data gaps in the SRTM topographic DEM.

3) METI/NASA Advanced Spacedborne Thermal Emission and Reflection Radiometer (ASTER)

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) was developed jointly by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). ASTER is an imaging instrument flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). ASTER is being used to obtain detailed maps of land surface temperature, reflectance, and elevation. It covers land surfaces between 83°N and 83°S and is comprised of 22,600 1°-by-1° tiles. Tiles that contain at least 0.01% land area are included. The ASTER GDEM is in GeoTIFF format with geographic lat/long coordinates and a 1 arc-second (approximately 30 m) grid. It is referenced to the WGS84/EGM96 geoid. Pre-production estimated accuracies for this global product were 20 m at 95 % confidence for vertical values and 30 m at 95 % confidence for horizontal values[8].

The ASTER GDEM was used only to fill data gaps for inland areas (Fig 7), because the ASTER GDEM contained inconsistencies along the coastline when compared to the SRTM and ESRI's *World 2D* imagery (Fig. 9).

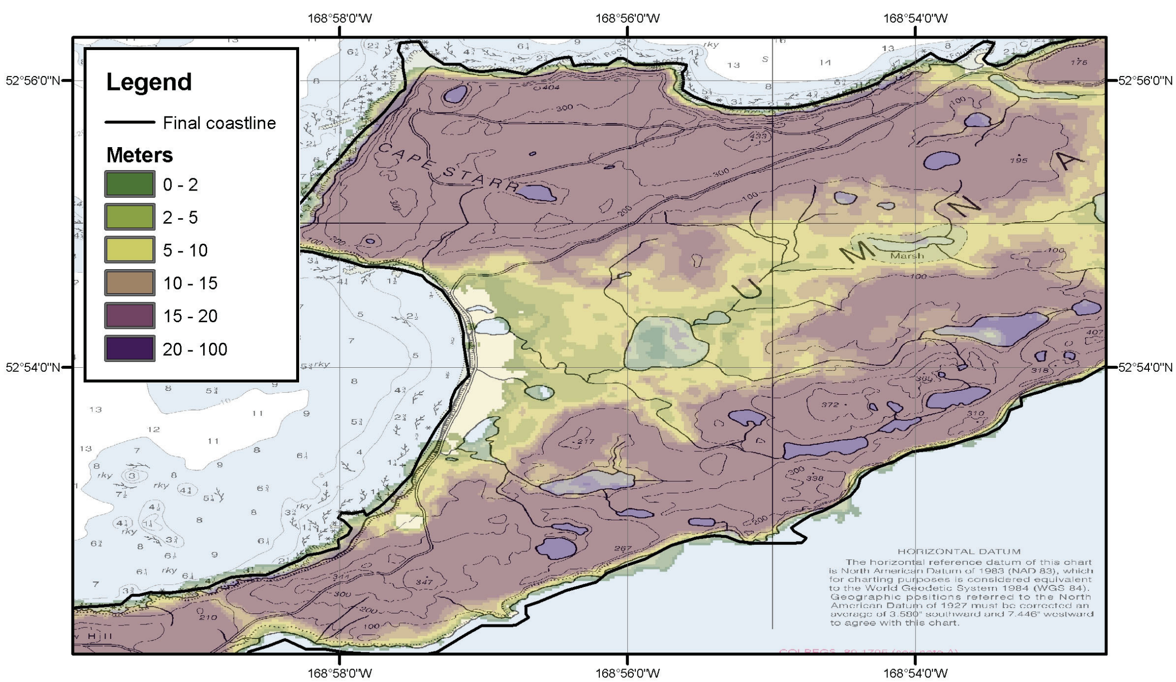

Figure 9. The ASTER GDEM contained inconsistencies along the zero contour when compared to the final coastline.

8. The ASTER GDEM was contributed by METI and NASA to the Global Earth Observation System of Systems (GEOSS) and is available to users via electronic download from the Earth Remote Sensing Data Analysis Center (http://www.ersdac.or.jp/eng/index.E.html) of Japan and NASA's Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/).

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Nikolski DEM were originally referenced to a number of vertical datums including: MLLW, MSL, WGS 84/EGM96 Geoid, and NGVD 29. All datasets were transformed to MHW to provide maximum flooding in inundation modeling.

1) **Bathymetric data**

The NOS hydrographic surveys were transformed from MLLW to MHW, using *FME* software, by adding a constant offset measured at the NOAA Unalaska, Dutch Harbor tide station #9462620 (http://tidesandcurrents.noaa.gov/). The NGDC swath sonar multibeam and bathymetric values extracted from the ETOPO1 Global Relief Model were transformed from MSL to MHW by adding a constant offset of -0.696 meters (Table 8).

2) **Topographic data**

The NED DEM was originally referenced to NGVD 29 and the SRTM and ASTER DEMs were referenced to the WGS 84/EGM96 Geoid vertical datum. There are no survey markers in the vicinity of Nikolski that relate these two geodetic datums to the local tidal datums. Thus, it was assumed that both datums are essentially equivalent to MSL in this area. Conversion to MHW, using *FME* software, was accomplished by adding a constant value of -0.696 meters (Table 8).

Table 8. Relationship between MHW and other vertical datums in the Nikolski region.*

Vertical datum	*Difference to MHW*
MSL	-0.696
NGVD29 +	-0.696
WGS 84/EGM96 Geoid +	-0.696
MLLW	-1.132

* Datum relationships determined by tide station #9462620 at Unalaska, Dutch Harbor.
+ Assumed to be equivalent to MSL.

3.2.2 Horizontal datum transformations

Datasets used in compiling the Nikolski DEM were originally referenced to NAD 27 and NAD 83 or WGS 84 geographic horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established. Some NOS surveys were manually shifted in *ArcGIS* to fit the final coastline.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in ESRI *ArcMap*, *Fledermaus,* 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 shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Data values over the open ocean in the NED, SRTM, and ASTER topographic DEMs. Each dataset required automated clipping to the final coastline.
- Lack of bathymetric data coverage in the southeast quarter of the DEM
- SRTM topographic DEM containing data gaps over the land
- ASTER topographic DEM inconsistent with other topographic datasets at the coast
- Positional uncertainty of NOS surveys with Early Alaska or undetermined horizontal datums

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 7 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 1 arc-second-spacing "pre-surface" or grid was generated using *GMT*[9], an NSF-funded shareware software application designed to manipulate data for mapping purposes.

The NOS hydrographic point data, in xyz format, were combined with the ETOPO1 Global Relief Model and NGDC multibeam swath sonar bathymetry data into a single file. Points extracted every 10 meters from the final coastline were also included and assigned negative values of -1 meter to ensure that the offshore elevations remained negative; this was necessary due to the sparseness of the bathymetric data near the coast. These point data were then smoothed using the *GMT* tool "blockmedian" onto a 1 arc-second grid 0.05 degrees (~5%) larger than the Nikolski DEM boundary. The *GMT* tool "surface" was then applied to interpolate values for cells without data values. The netcdf 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 final coastline (to eliminate data interpolation into land areas). The resulting surface was compared with the original soundings to ensure grid accuracy (e.g., Fig. 11), converted to a shapefile, and then exported as an xyz file for use in the final gridding process (see Table 9). The statistical analysis of the differences between the 1 arc-second bathymetric surface and one of the NOS surveys showed that the majority of the NOS soundings are consistent with the bathymetric surface. The few exceptions occur in steep bathymetry where several closely positioned points were averaged to obtain the elevation of one grid cell.

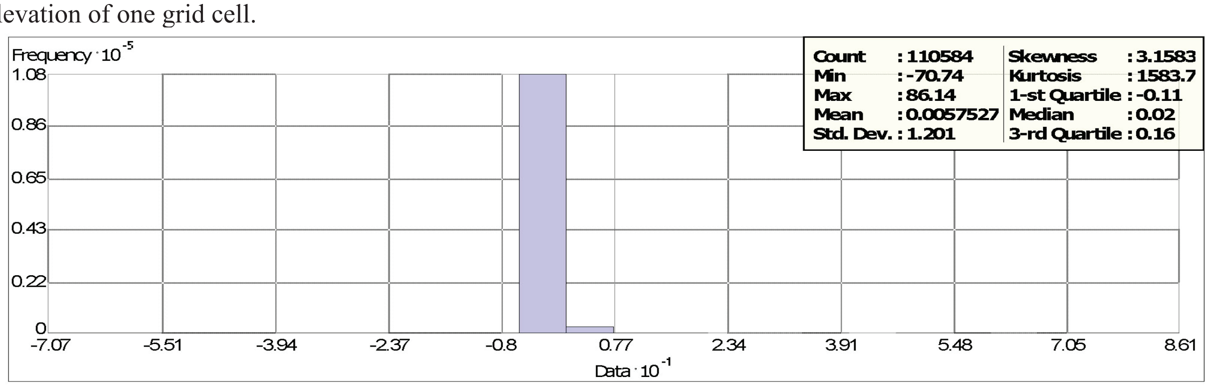

Figure 10. Histogram of the differences between NOS hydrographic surveys and the 1 arc-second pre-surfaced bathymetric grid.

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 1 arc-second Nikolski DEM

MB-System was used to create a 1 arc-second DEM of Nikolski, Alaska. 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 9. Greatest weight was given to the NGDC swath sonar multibeam. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid.

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

Dataset	*Relative Gridding Weight*
NGDC hydrographic sonar multibeam	100
NOS hydrographic surveys	10
SRTM topographic DEM	10
USGS NED topographic DEM	1
ASTER topographic DEM	1
ETOPO Global Relief Model	1
Final coastline at 0 meters elevation	1
Pre-surfaced bathymetric grid	.01

3.4 Quality Assessment of the DEMs

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Nikolski DEM is dependent upon the DEM cell size and source datasets. Topographic features have an estimated horizontal accuracy of 30 meters; SRTM and ASTER data are accurate to approximately 30 meters, while the NED dataset is accurate to approximately 60 meters. Bathymetric features in areas covered by early twentieth century NOS hydrographic soundings—along the margins of the DEM—are resolved only to within a few tens of meters in shallow water, and hundreds of 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

The vertical accuracy of elevation values for the Nikolski DEM is also dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy of of between 10 and 20 meters, derived from the NED topographic data (estimated vertical accuracy of 10 meters), the SRTM topographic data (vertical accuracy better than 16 meters but typically about 10 meters), and ASTER topographic data (20 meters at 95% confidence). Bathymetric values are derived from a wide range of input data, consisting of single and multibeam sounding measurements from the early 20th centuries to recent: modern NOS standards are 0.3 m in 0 to 20 m of water, 1.0 m in 20 to 100 m of water, and 1% of the water depth in 100 m of water. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water to about 5% of water depth.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Nikolski DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 12). The DEM was transformed to UTM zone 2N 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 DEMs (Figs. 15 and 16) was accomplished using *POV Ray*. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM.

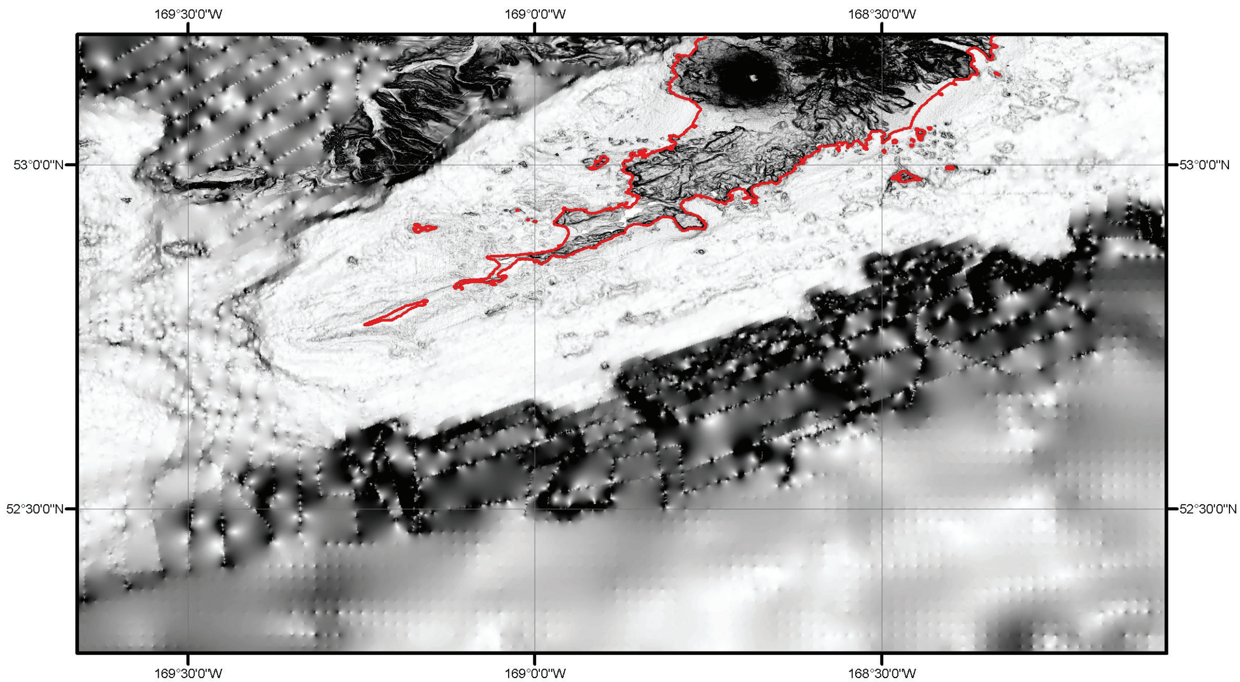

Figure 11. Slope map of the Nikolski DEM. Flat-lying slopes are white; dark shading denotes steep slopes; final coastline in red.

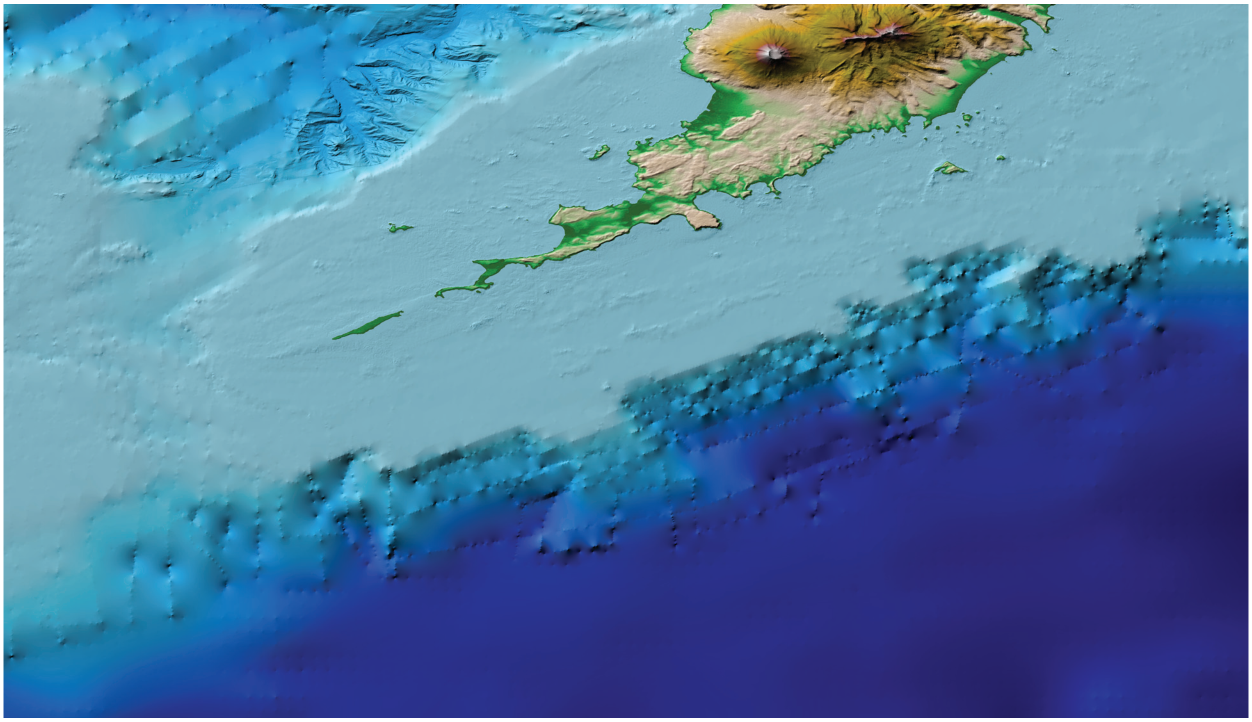

Figure 12. Color, shaded-relief image of the Nikolski DEM. Vertical exaggeration–times 2.

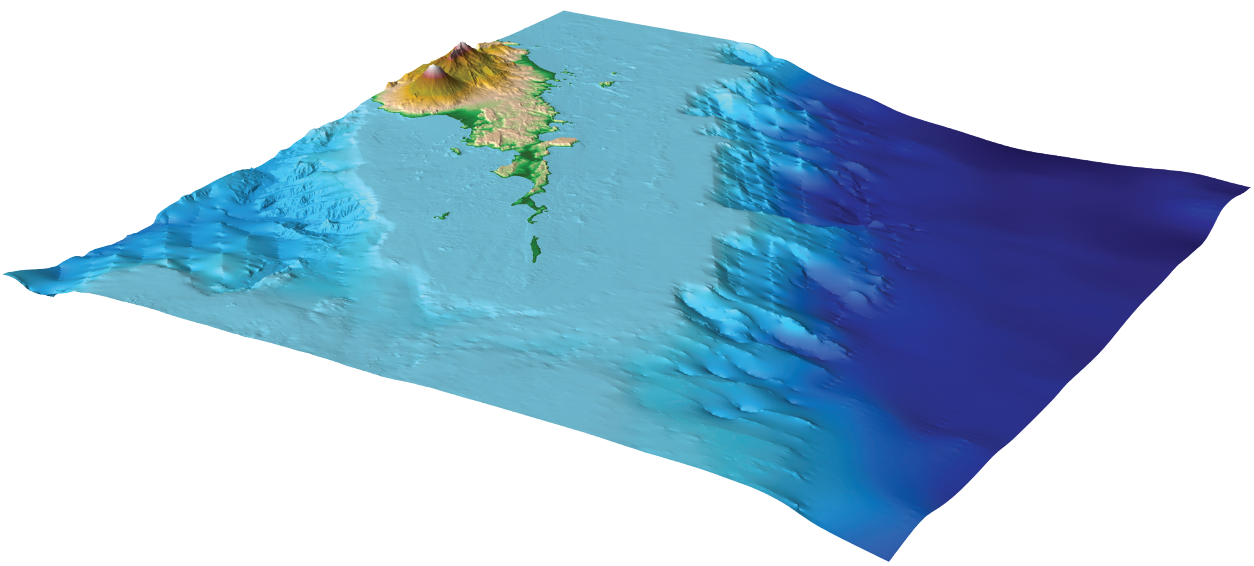

Figure 13. Perspective view from the southwest of the Nikolski DEM. Vertical exaggeration–times 2.

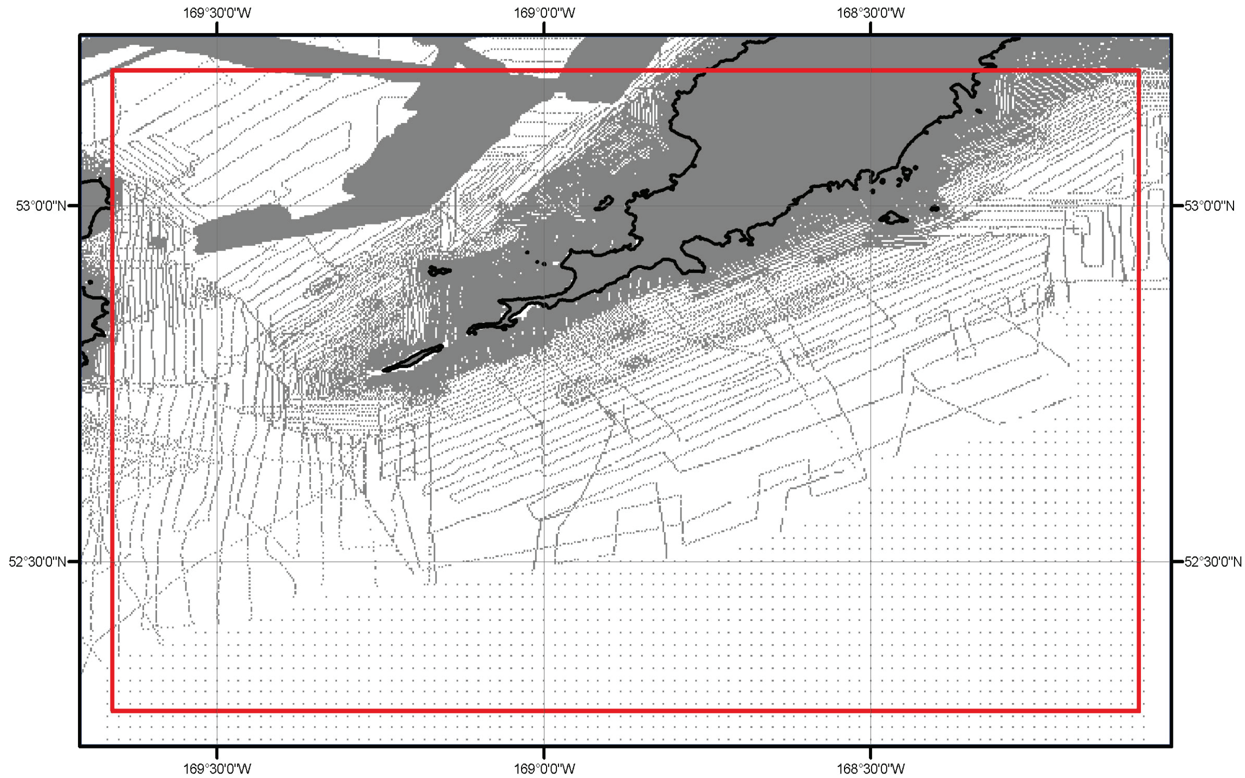

Figure 14. Data contribution plot to the Nikolski DEM. Grey depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. Coastline is shown in black; DEM boundary in red.

3.4.4 Comparison with source data files

To ensure grid accuracy, the Nikolski 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. Histograms of the differences between the SRTM topography, ASTER topography, and NOS hydrographic surveys and the Nikolski DEM are shown in Figures 15-17. Differences cluster around zero. A few points, in regions of steep topography and bathymetry, had discrepencies in the DEM that exceeded 40 meters (Fig 16).

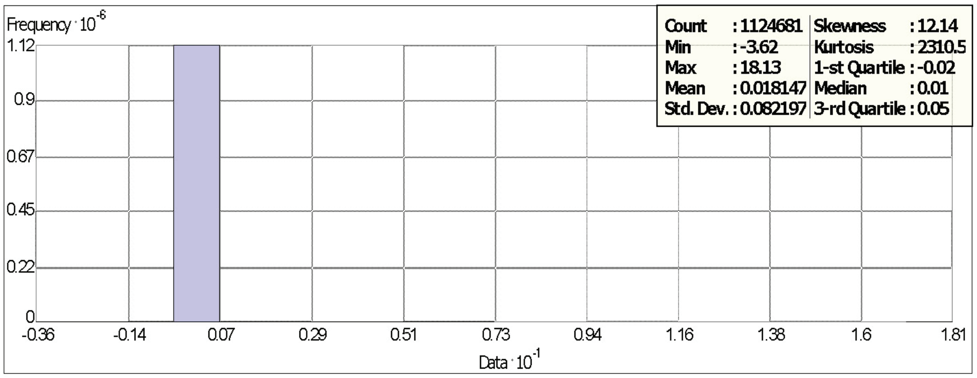

Figure 15. Histogram of the differences between the SRTM topographic dataset and the Nikolski DEM.

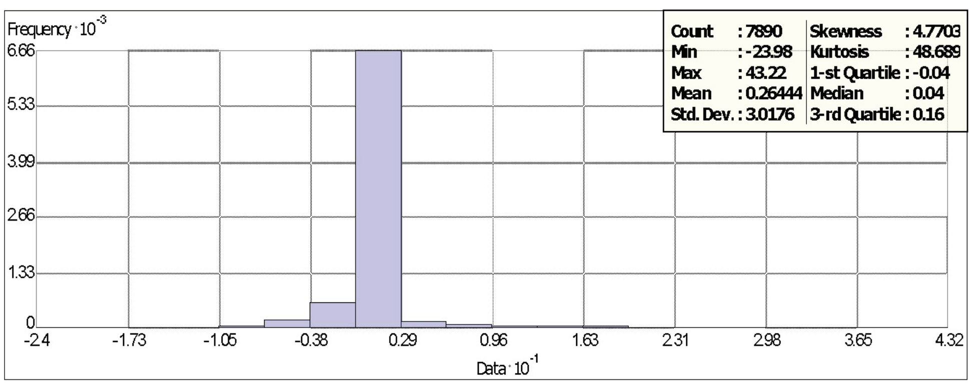

Figure 16. Histogram of the differences between the ASTER topographic dataset and the Nikolski DEM.

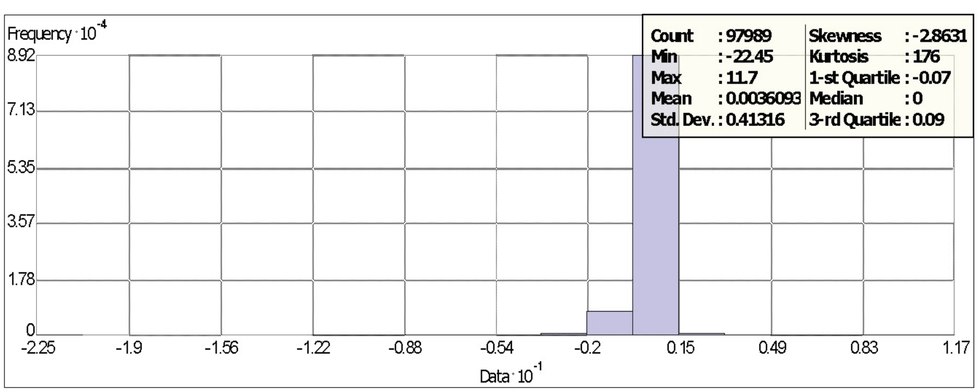

Figure 17. Histogram of the differences between the NOS hydrographic surveys and the Nikolski DEM.

3.4.5 Comparison with USGS topographic contours

Topographic elevations were obtained from the USGS Nikolski quadrangle (http://agdc.usgs.gov/data/usgs/to_geo.html). The quadrangle gives positions and elevations in NAD 83 and NGVD 29 vertical datum (in feet) and has a scale of 1:250,000 with a 200-foot contour interval.

To be consistent with the USGS *Nikolski* quadrangle, the Nikolski DEM was converted from meters into feet. A contour map of Mt. Vsevidof with a 1000-foot interval was created and compared against the USGS topographic quadrangle (Fig. 18). Although the figures show that minor differences exist between the Nikolski DEM and the USGS topographic contours, the morphology of the terrain is captured in the DEM.

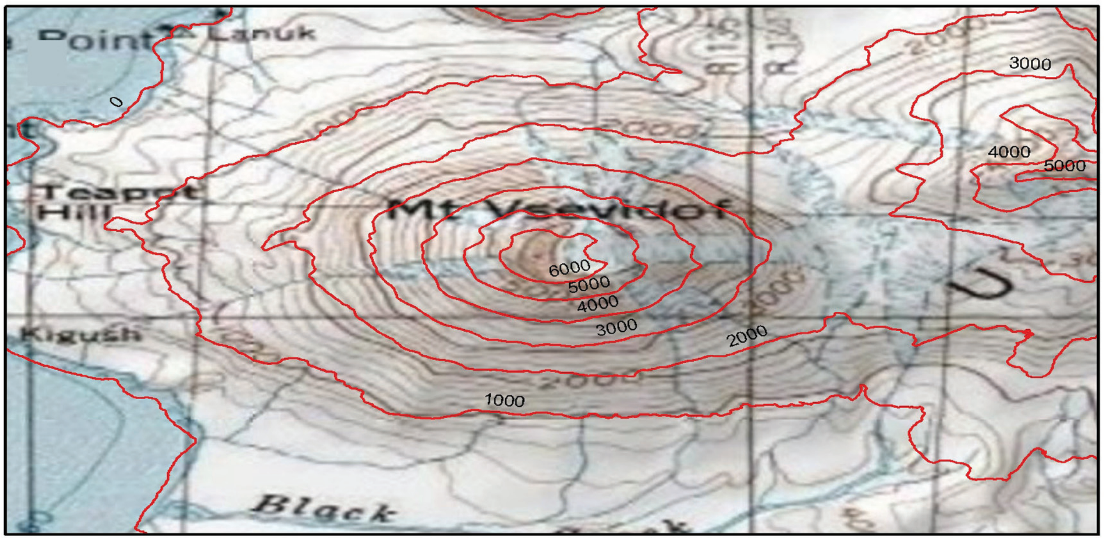

Figure 18. Comparison between USGS topography contours and the Nikolski DEM topographic contours. Brown lines and numbers represent 200 ft. contours from the USGS topographic map. Red lines represent 1000 ft. contours derived from the Nikolski DEM.

3.4.6 Comparison with National Geodetic Survey geodetic monuments

NGS datasheets were downloaded in shapefile format from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format, attributes provided monument positions in NAD 83 and elevations in NAVD88 (in meters). Datasheets for the Nikolski DEM region did not include elevation data, however superseded elevation information referenced to NGVD29 was available for select locations. NGDC used these points to assess the accuracy of the Nikolski DEM (Fig 19; Fig 20).

Differences between the DEM and the monument elevations range from -9.32 to 8.29 meters, with a standard deviation of ± 4.4 meters (Fig 20). Differences in elevations occured where monuments are located on steep topography.

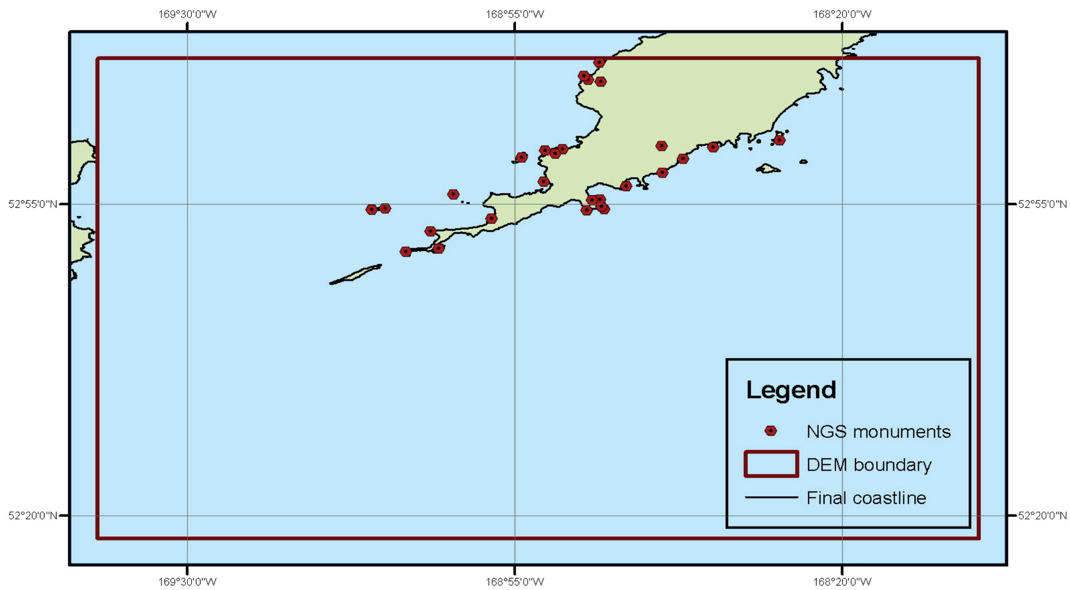

Figure 19. Locations of NGS monuments in the Nikolski region. Only those with elevation attributes are shown.

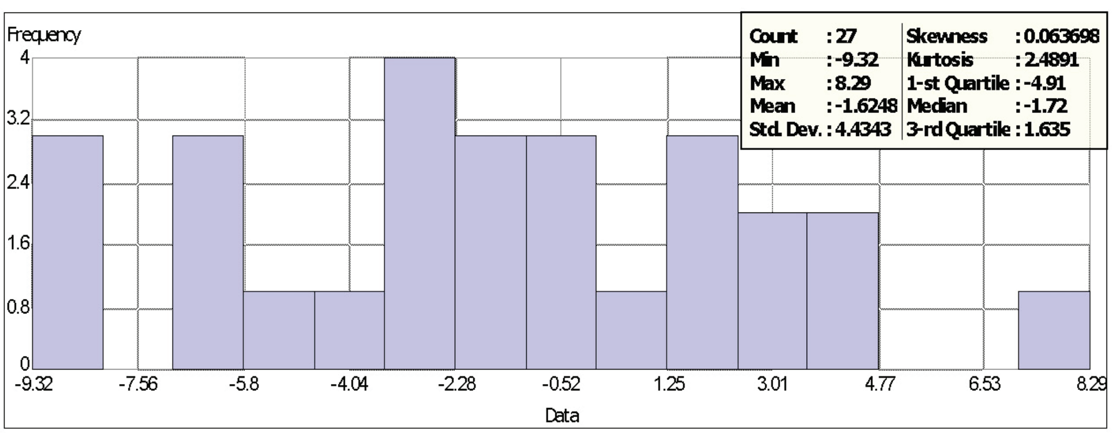

Figure 20. Histogram of the differences between the NGS monuments and the Nikolski DEM.

4. Summary and Conclusions

An integrated bathymetric-topographic DEM of the Nikolski, Alaska region, with cell size of 1 arc-second, was developed for the 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 *ArcGIS*, *ESRI World Imagery*, *FME*, *GMT*, *Quick Terrain Modeler*, and *MB-System* software.

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

- Conduct bathymetric surveys in the southern half of the DEM area
- Obtain more recent bathymetric and topographic data in the area immediately around Nikolski
- Establish the relationships between tidal and geodetic datums in the Nikolski region
- Determine the relationship between Early Alaska and NAD 83 geographic horizontal datums
- Conduct lidar surveys for coastal areas

5. Acknowledgments

The creation of the DEMs were funded by NOAA Center for Tsunami Research at PMEL. The authors thank Nazila Merati and Vasily Titov (PMEL), and Bret Christensen (USFWS).

6. References

Electronic Navigational Chart #16500, 4th Edition, 2009. Unalaska Island to Amukta Island. Scale 1:300,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #16501, 2nd Edition, 2007. Islands of Four Mountains. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16511, 7th Edition, 2004. Inanudak and Nikolski Bays. Scale 1:40,000. 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/.

FME 2009 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/

Fledermaus v. 7.0 - developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/.

GEODAS v. 5 – Geophysical Data System, free software 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, free software 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, free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

Persistance of Vision Pty. Ltd., (2004), Persistence of VisionTM Raytracer. Persistance of Vision Pty., Williamstown, Victoria, Australia, http://www.povray.org/

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/