Digital Elevation Model of Shemya, Alaska: Procedures, Data Sources and Analysis

Prepared for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research by the NOAA National Geophysical Data Center (NGDC)
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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 Shemya, 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. 4) and will be used for tsunami inundation modeling, as part of the tsunami forecast system SIFT (Short-term Inundation Forecasting for Tsunamis) 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 Shemya DEM.

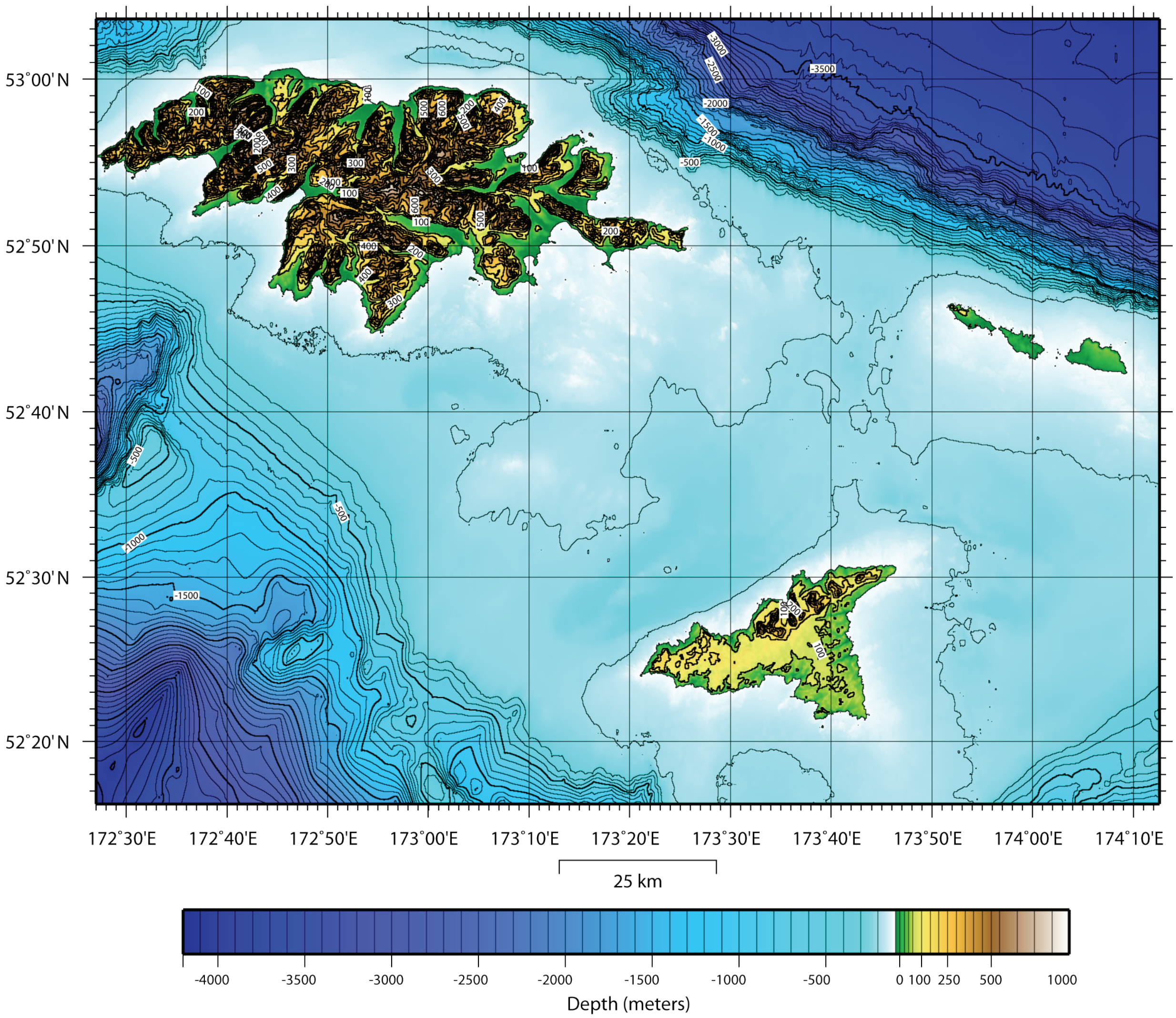

Figure 1. *Shaded-relief image of the Shemya, Alaska DEM. Bathymetric contour interval is 100 meters and topographic contour intervals are 25 meters at elevations below 600 meters and 100 meters for elevations above 600 meters.*

1. The Shemya DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Shemya, Alaska, (52° 43′ 00″ N, 174° 06′ 00″ E) 1 arc-second of latitude is equivalent to 30.91 meters; 1 arc-second of longitude equals 18.77 meters.

2. Study Area

Shemya, Alaska, is located on the eastern most island of the Semichi Island Group, part of the Near Islands, on the western end of the Aleutian Islands Chain of Alaska (Fig. 2). The DEM boundary encompasses: Shemya Island, Nizki Island, Alaid Island (the Semichi Islands); Agattu Island to the southwest; and the Attu Island to the west (Fig. 3). The topography of the five islands varies from low-lying, wave-cut platforms on the Semichi Islands to high relief and mountainous on Attu and Agattu Islands (Coats, 1956).

Recent studies on the geology of the Western Aleutian Chain describe the area as a transitional zone between oblique subduction and strike-slip motion of the Pacific Plate and North American Plate (Wilson et al., 2006) resulting in frequent seismic events. In 1965, Shemya recorded a tsunami of over 10 meters resulting from an 8.7 magnitude earthquake, the sixth largest earthquake in recorded history. The epicenter was located about 500 kilometers to the southeast in the Rat Islands.

Shemya served as a military base during World War II until the late 1990s, when Shemya Air Force Base was renamed Eareckson Air Station. The station currently operates as a radar, surveillance, weather, and aircraft refueling station with a population of approximately 30 full time residents. A U.S. Coast Guard LORAN station is located on Attu Island and has a population of around 20 residents.

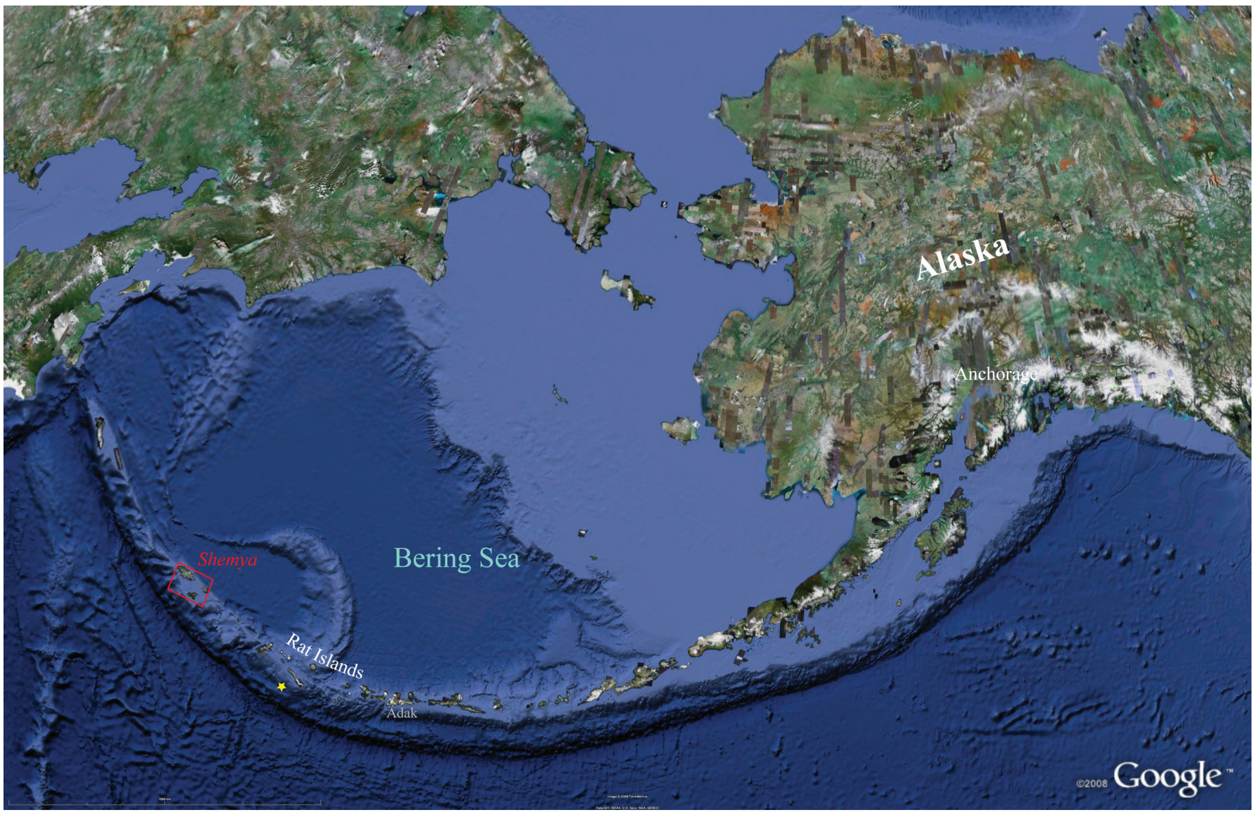

Figure 2. Google Earth image of Alaska's Aleutian Island Chain. The Shemya DEM boundary, shown as red box, is in lower left. The yellow star to the south of the Rat Islands marks the approximate location of the 1965 earthquake.

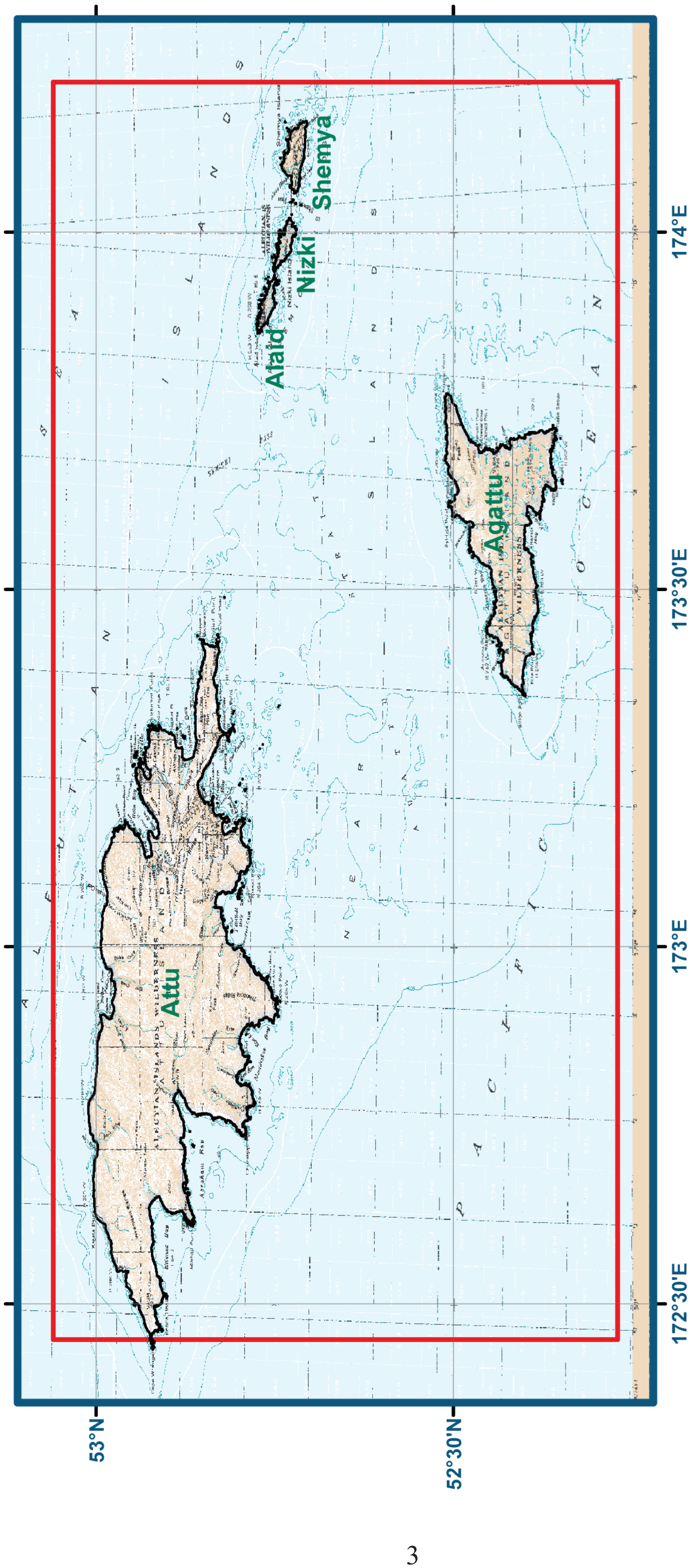

Figure 3. *USGS Attu topographic quadrangle with DEM boundary shown in red.*

3. Methodology

The Shemya, 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 Center 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: World Geodetic System 1984 (WGS 84) and Mean High Water (MHW), for modeling of maximum flooding, respectively. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1: PMEL specifications for the Shemya, Alaska, DEM.

Grid Area	Shemya, Alaska
Coverage Area	172.45º to 174.21º E; 52.27º to 53.06º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
Cell Size	1 arc-second
Grid Format	ESRI Arc ASCII grid

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 4) were obtained from several U.S. federal agencies including: NGDC; NOAA's Office of Coast Survey (OCS); the U.S. Fish and Wildlife Service (USFWS); and the U.S. Geological Survey (USGS). Safe Software's (http://www.safe.com/) *FME*[2] data translation tool package was used to shift datasets to NAD 83 horizontal datum and to convert them into ESRI (http://www.esri.com/) *ArcGIS* shapefiles. The shapefiles were then displayed with *ArcGIS* to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using *FME*, based upon data from the NOAA Shemya tide prediction table (http://co-ops.nos.noaa.gov/tide_pred.html). Applied Imagery's (http://www.appliedimagery.com/) *Quick Terrain Modeler* software was used to evaluate processing and gridding techniques.

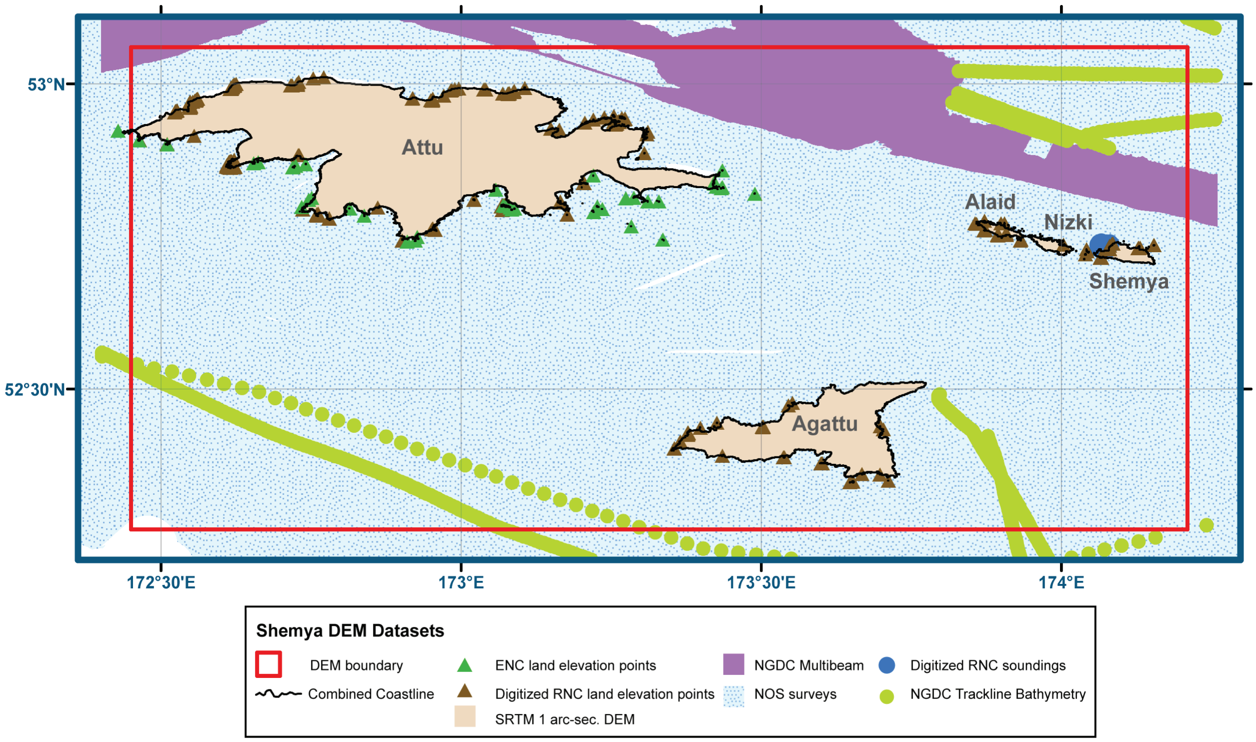

Figure 4. *Source and coverage of datasets used to compile the Shemya DEM.*

2. 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

Coastline datasets for the Shemya region were obtained from NOAA's Office of Coast Survey as Electronic Navigational Charts (ENCs; Table 2; Fig. 5) and were used to develop a 'combined coastline' of the Shemya region. NGDC reviewed but did not use the smaller scale U.S. Fish and Wildlife Service coastline, the National Geospatial-Intelligence Agency Prototype Global Shoreline Data, and the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS).

Table 2: Shoreline datasets used in the Shemya DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
OCS ENCs	1990 to 1997	Extracted coastline	Various	WGS 84 geographic (meters)	Mean High Water	http://w1.nauticalcharts.noaa.gov/mcd/enc/index.htm

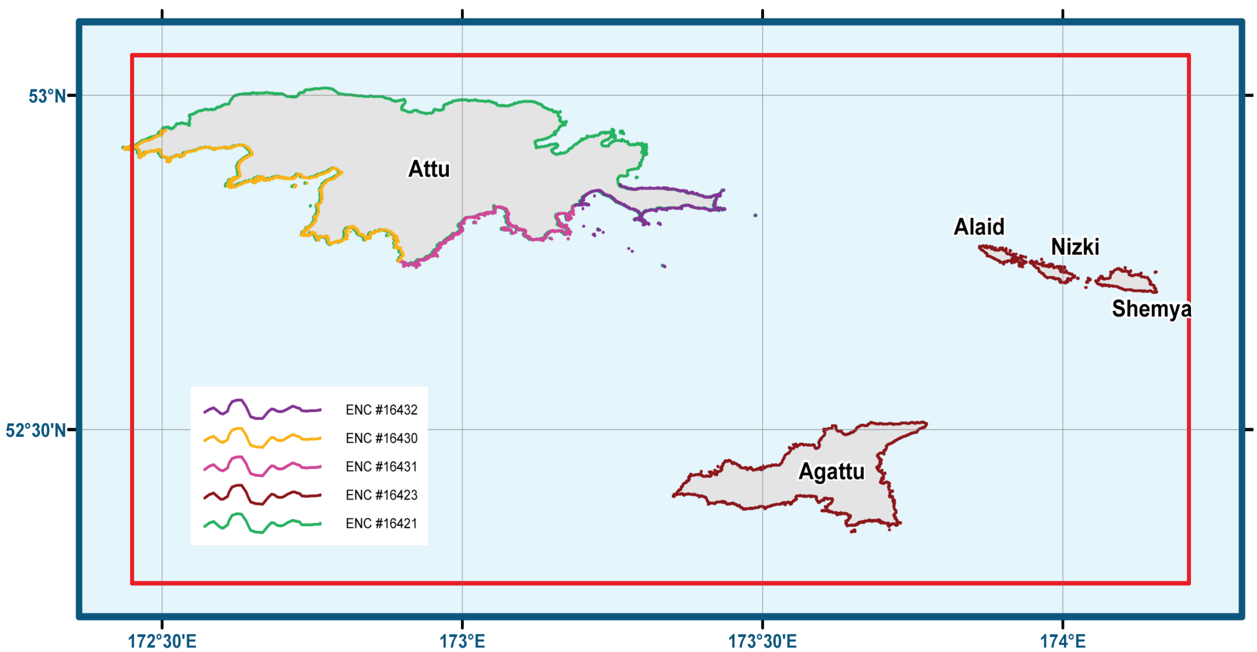

Figure 5. *Digital coastline datasets used in developing a 'combined coastline' of the Shemya region.*

1) OCS extracted Electronic Navigational Chart coastline

Six electronic navigational charts (ENCs) were available for the Shemya area (Table 3) and downloaded from NOAA's Office of Coast Survey website (http://nauticalcharts.noaa.gov/mcd/enc/index.htm). The ENCs are in S-57 format and include coastline data referenced to Mean High Water. The coastline shapefiles were extracted from ENCs #16430, 16431, and 16432 using *FME* and compared to large-scale RNCs and the SRTM topographic DEM. On the northern coast of Attu Island where large-scale ENCs or RNCs were not available, the smaller-scale ENC #16421 coastline was used; On Agattu and Shemya Islands, ENC #16423 was used. The extracted coastlines were merged using *ArcGIS* and used to create a 'combined coastline' of the Shemya region.

Table 3: NOAA nautical charts available in the Shemya, Alaska, region.

Chart	*Title*	*Format*	*Edition*	*Issue Date*	*Scale*
16420	Near Islands Buldir Island to Attu Island	ENC and RNC	2	2007	1,300,000
16421	Near Islands from Ingenstrem Rocks to Attu Island	ENC and RNC	3	2008	1:160,000
16423	Shemya Island to Attu Island	ENC and RNC	3	2007	1:100,000
16430	Attu Island Theodore Pt. to Cape Wrangell	ENC and RNC	3	2005	1:40,000
16431	Temnac Bay	ENC and RNC	1	2005	1:20,000
16432	Massacre Bay	ENC and RNC	2	2005	1:25,000
16433	Sarana Bay to Holtz Bay;Chichagof Harbor	RNC	8	2003	1:20,000
16434	Agattu Island	RNC	6	2004	1:40,000
16435	Alaid and Nizki Islands	RNC	6	2004	1:20,000
16436	Shemya Island	RNC	10	1996	1:20,000

The 'combined coastline' was modified to include large offshore rocks and small islets shown on the larger-scale RNCs. An xyz file of the 'combined coastline' was generated using *GEODAS* (http://www.ngdc.noaa.gov/mgg/gdas/gx_announce.html) for use in compiling the Shemya DEM.

3.1.2 *Bathymetry*

Bathymetric datasets available for use in the compilation of the Shemya DEM include 51 NOS hydrographic surveys; one multibeam survey downloaded from the NGDC multibeam database; four NGDC trackline surveys; and soundings digitized from NOAA/OCS's RNCs (Table 4; Fig. 6).

Table 4: Bathymetric datasets used in compiling the Shemya DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1933 to 2005	NOS hydrographic survey soundings	Ranges from less than 10 m to 600 m (varies with scale of survey, depth, traffic, and probability of obstructions)	Early Alaska	Mean Lower Low Water	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	2005	Multibeam swath sonar	1 arc-second	WGS 84 geographic	assumed Mean Sea Level	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NGDC	1989 to 1998	Trackline bathymetry	Ranges from 150 meters to 1 km	WGS 84 geographic	assumed Mean sea Level	http://www.ngdc.noaa.gov/mgg/geodas/trackline.html
OCS RNC	1954 to 2000	digitized soundings	from several meters to tens of meters	WGS 84 geographic	Mean Lower Low Water	http://w1.nauticalcharts.noaa.gov/mcd/Raster/index.htm

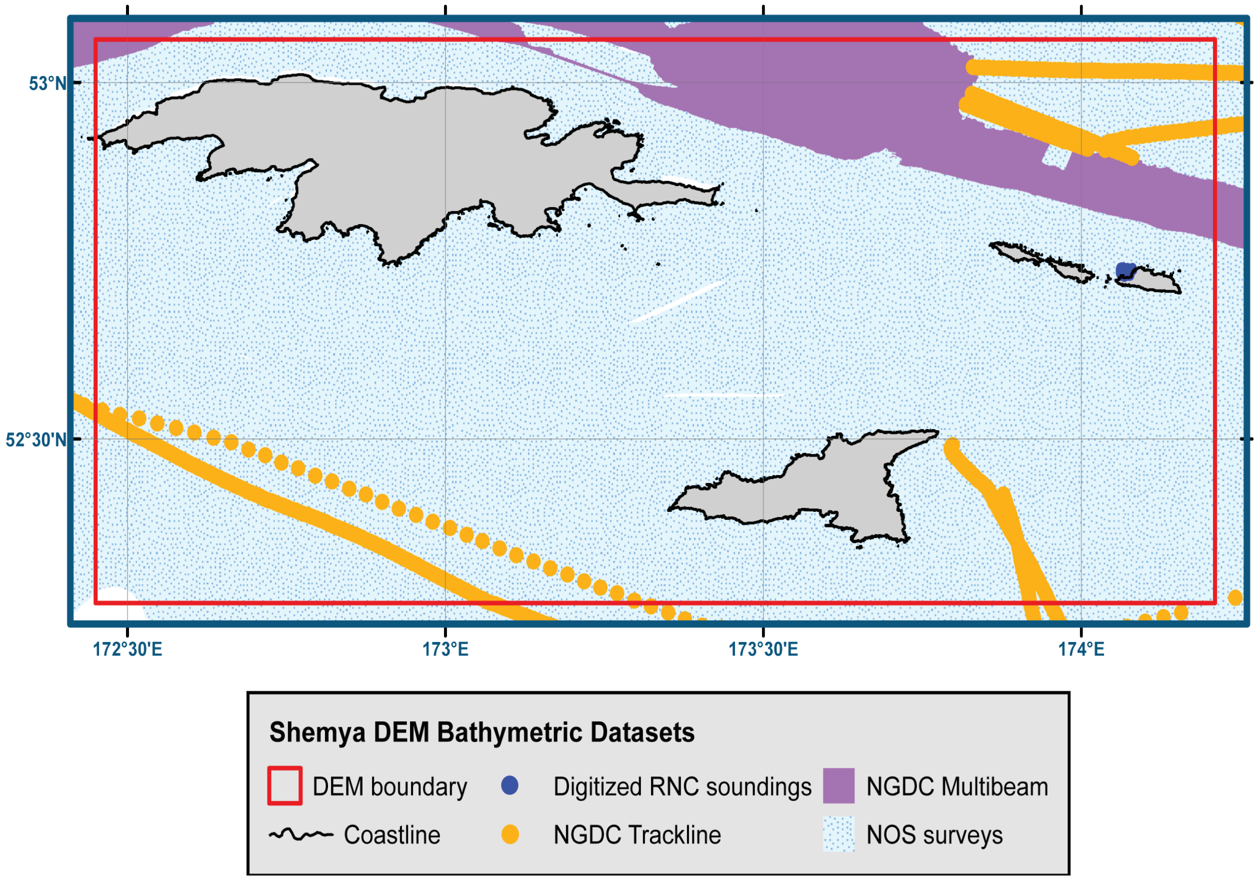

__Figure 6.__ Spatial coverage of the bathymetric datasets used in compiling the Shemya DEM.

1) NOS hydrographic survey data

A total of 51 NOS hydrographic surveys conducted between 1934 and 1952 were available for use in developing the Shemya DEM. The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) and horizontally referenced to Early Alaskan Datum. Forty-nine of the 51 surveys were used in building the Shemya DEM, as some older surveys have been superseded (Table 5; Fig. 7).

Data point spacing for the NOS surveys varied by scale. In general, small scale surveys had greater point spacing than large scale surveys. Surveys were extracted from NGDC's online NOS hydrographic database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html). The data were then converted to shapefiles using *FME* software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com). The surveys were subsequently clipped to a polygon 0.05 degree (~5%) larger than the Shemya DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW using a constant value based on the NOAA tide tables (see Section 3.2.1), the data were displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to the topographic and bathymetric datasets, the 'combined coastline', and NOS raster nautical charts (RNCs). Older surveys were clipped to remove soundings that have been superseded by more recent NOS surveys and multibeam data.

There is no defined transformation from Early Alaska to WGS 84. As a result, some surveys were offset from the 'combined coastline' by nearly 1 km. These offset surveys were manually adjusted to fit the 'combined coastline'.

Table 5: Digital NOS hydrographic surveys available within the Shemya DEM boundary.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum†*
H06926*	1934	5,000	mean lower low water	Early Alaska Datums
H06939	1943	20,000	mean lower low water	Early Alaska Datums
H06940	1943	10,000	mean lower low water	Early Alaska Datums
H06975	1944	2,400	mean lower low water	Early Alaska Datums
H06987	1944	10,000	mean lower low water	Early Alaska Datums
H07012	1944	5,000	mean lower low water	Early Alaska Datums
H07013	1944	10,000	mean lower low water	Early Alaska Datums
H07014	1944	10,000	mean lower low water	Early Alaska Datums
H07015	1944	20,000	mean lower low water	Early Alaska Datums
H07016	1944	20,000	mean lower low water	Early Alaska Datums
H07017	1944	20,000	mean lower low water	Early Alaska Datums
H07018	1944	40,000	mean lower low water	Early Alaska Datums
H06937	1944	20,000	mean lower low water	Early Alaska Datums
H06988	1944	5,000	mean lower low water	Early Alaska Datums
H06990	1944	10,000	mean lower low water	Early Alaska Datums
H06991	1944	20,000	mean lower low water	Early Alaska Datums
H06999	1944	10,000	mean lower low water	Early Alaska Datums
H07000	1944	20,000	mean lower low water	Early Alaska Datums
H06874	1945	40,000	mean lower low water	Early Alaska Datums
H06875	1945	10,000	mean lower low water	Early Alaska Datums
H07067	1945	2,500	mean lower low water	Early Alaska Datums
H07068	1945	5,000	mean lower low water	Early Alaska Datums
H07077	1945	2,500	mean lower low water	Early Alaska Datums
H07088	1945	20,000	mean lower low water	Early Alaska Datums
H06865	1945	10,000	mean lower low water	Early Alaska Datums
H06866	1945	20,000	mean lower low water	Early Alaska Datums
H06868	1945	20,000	mean lower low water	Early Alaska Datums
H06869	1945	40,000	mean lower low water	Early Alaska Datums

H06870	1945	10,000	mean lower low water	Early Alaska Datums
H06871	1945	40,000	mean lower low water	Early Alaska Datums
H06872	1945	10,000	mean lower low water	Early Alaska Datums
H06873	1945	2,400	mean lower low water	Early Alaska Datums
H07019	1945	40,000	mean lower low water	Early Alaska Datums
H06864	1946	20,000	mean lower low water	Early Alaska Datums
H06867	1946	20,000	mean lower low water	Early Alaska Datums
H07135	1946	80,000	mean lower low water	Early Alaska Datums
H07137	1946	60,000	mean lower low water	Early Alaska Datums
H07138	1946	10,000	mean lower low water	Early Alaska Datums
H07139	1946	20,000	mean lower low water	Early Alaska Datums
H07141	1946	80,000	mean lower low water	Early Alaska Datums
H07146	1946	40,000	mean lower low water	Early Alaska Datums
H07136	1946	60,000	mean lower low water	Early Alaska Datums
H07142	1946	10,000	mean lower low water	Early Alaska Datums
H07143*	1946	20,000	mean lower low water	Early Alaska Datums
H07144	1946	20,000	mean lower low water	Early Alaska Datums
H07145	1946	20,000	mean lower low water	Early Alaska Datums
H07624	1947	40,000	mean lower low water	Early Alaska Datums
H07626	1947	100,000	mean lower low water	Early Alaska Datums
H07634	1947	5,000	mean lower low water	Early Alaska Datums
H07597	1947	20,000	mean lower low water	Early Alaska Datums
H07994	1952	2,500	mean lower low water	Early Alaska Datums

* superceded survey not used in building the Shemya DEM
† digitized datum recorded as NAD 83 geographic or unknown

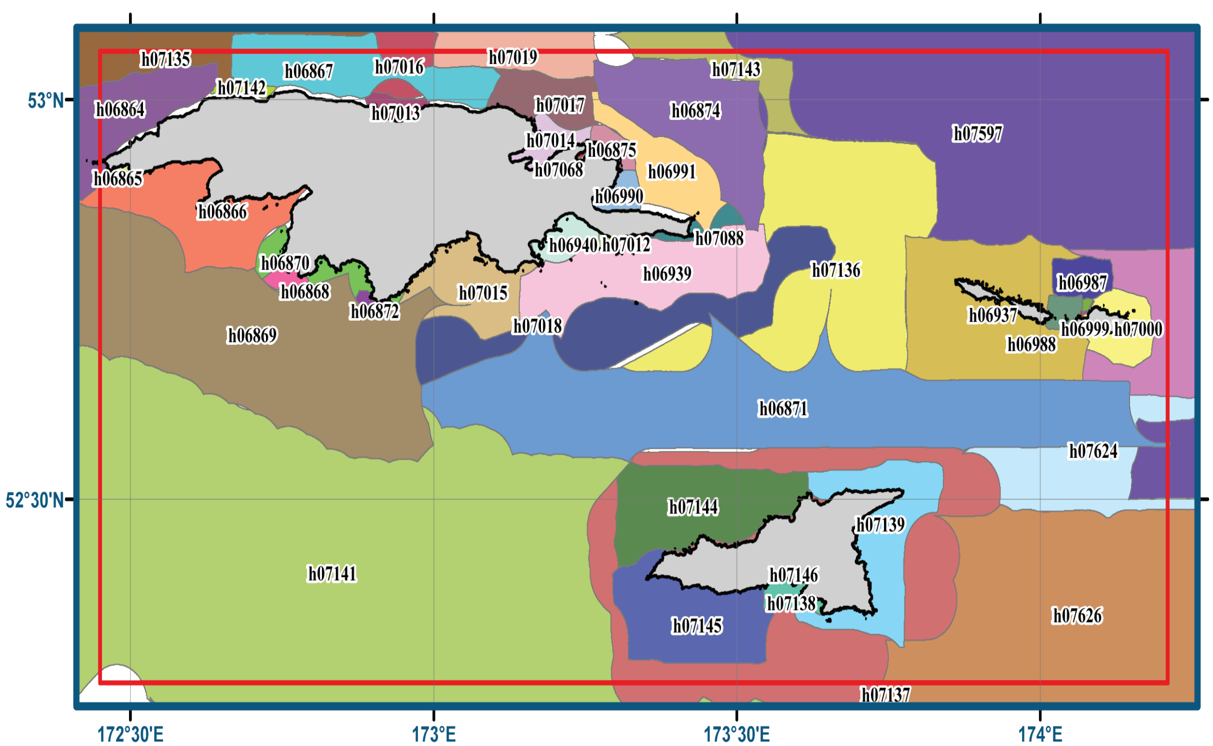

Figure 7. Digital NOS hydrographic survey coverage in the Shemya region. Some older surveys were not used as they have been superseded by more recent surveys. DEM boundary in red.

2) NGDC Multibeam swath sonar survey

A 2005 multibeam swath sonar survey was downloaded from the NGDC multibeam bathymetry database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html; Table 6). The survey is located along the northern side of the island group (Fig. 6). The data were gridded using *MB-System* (http://www.ldeo.columbia.edu/res/pi/MB-System) at 30 meter cell size and viewed in *QT Modeler* for quality analysis. The grid was then converted to xyz format and the elevations were transformed from MSL to MHW using *FME* for use in the final gridding process.

Table 6: NGDC multibeam swath sonar survey available in the Shemya region.

Survey ID	*Year*	*Original Vertical Datum*	*Institute*	*Ship*
TN182	2005	assumed Mean Sea Level	University of South Carolina	Thomas Thompson

3) NGDC Trackline surveys

Four trackline surveys were downloaded from the NGDC trackline bathymetry database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html; Table 7; Fig. 8). The survey data were converted to shapefile format, transformed from MSL to MHW, and clipped to the 2005 multibeam swath sonar survey. The resulting shapefiles were converted to xyz format to be used in the final gridding process using *FME*.

Table 7: NGDC trackline surveys available in the Shemya DEM region.

Survey ID	*Year*	*Original Vertical Datum*	*Institute*	*Ship*
SI933001	1972	assumed Mean Sea Level	U.S. Navy Naval Oceanographic Office	Silas Bent
L981AA	1981	assumed Mean Sea Level	USGS	Silas P . Lee
FARN0687	1987	assumed Mean Sea Level	U.K. Natural Environmental Research Council	Farnella
FARN0787	1987	assumed Mean Sea Level	U.K. Natural Environmental Research Council	Farnella

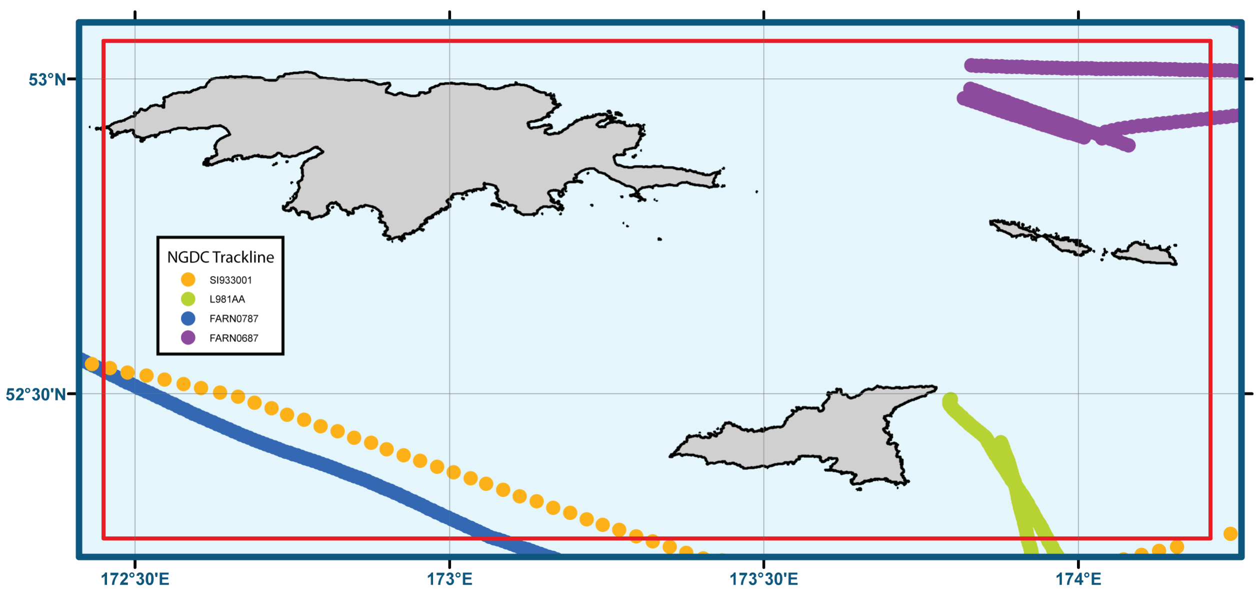

Figure 8. *Spatial coverage of NGDC trackline survey data used in compiling the Shemya DEM.*

4) OCS Raster Nautical Chart digitized soundings

In Shemya's Alcan Harbor, NGDC digitized the soundings on the 1:10,000 scale inset of RNC #16436, providing better data coverage and utilizing the more recent chart information (Figure 9). The NOS survey data in the harbor dated from the late 1940s and is sparse. The addition of the digitized soundings better defined the harbor. Sounding elevation values on the chart (fathoms) were converted to meters and the resulting shapefile was converted to xyz format for use in generating the bathymetric surface and in the final gridding process.

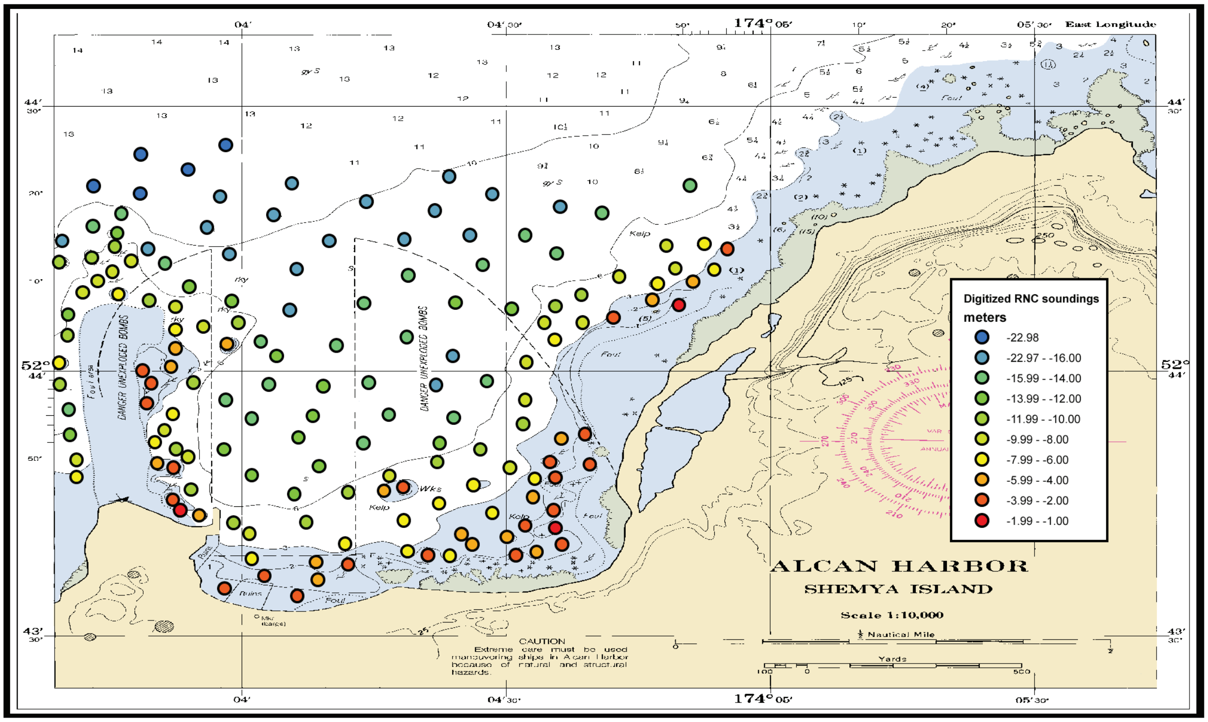

Figure 9. Location of soundings digitized by NGDC from the 1:10,000 scale inset on RNC #16436.

3.1.3 *Topography*

Three topographic datasets in the Shemya region were obtained from the U.S. Geological Survey (USGS) and NOAA's Office of Coast Survey and used to build the Shemya DEM (Table 8; Fig. 10); NED 2 arc-second is not available from USGS within the DEM boundary. NGDC reviewed but did not use the 1 arc-second Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM; http://www.gdem.aster.ersdac.or.jp/), a product of the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA), as low and zero elevations did not correspond to large scale nautical charts or SRTM topography. The ASTER GDEM was used to verify topographic contours at higher elevations (Sec. 3.4.4). NGDC digitized additional elevation points to supplement the available topographic datasets.

Table 8: Topographic datasets used in compiling the Shemya DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
SRTM	2000	topographic DEM	3 arc-second	WGS 84 geographic	assumed MSL	http://seamless.usgs.gov/
OCS ENC	1990 to 1996	extracted land elevation points	varies	WGS 84 geographic	mean high water	http://w1.nauticalcharts.noaa.gov/mcd/enc/index.htm
OCS RNC	1996	digitized land elevation points	varies	WGS 84 geographic	mean high water	http://w1.nauticalcharts.noaa.gov/mcd/Raster/index.htm

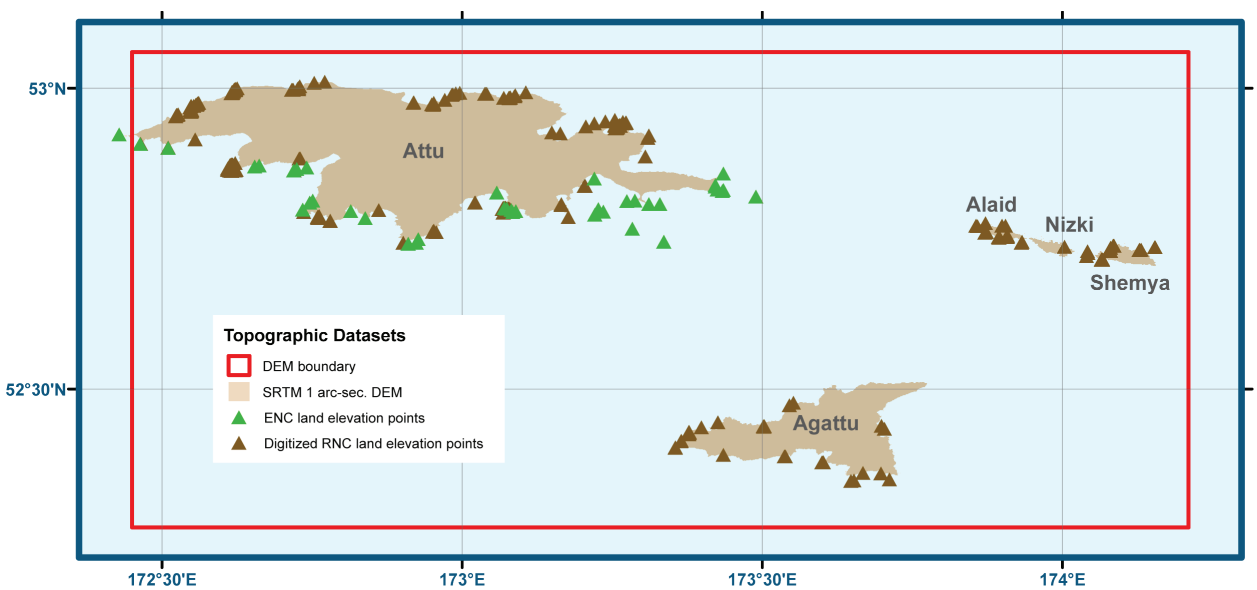

Figure 10. *Spatial coverage of the topographic datasets used in compiling the Shemya DEM.*

1) NASA Shuttle Radar Topography Mission 3 arc-second DEM

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[3]. The SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February 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 have not been processed to bare earth, but meet the absolute horizontal and vertical accuracies of 20 and 16 meters, respectively.

For the farthest west group of the Aleutian Islands, the data have 3 arc-second spacing and are referenced to the WGS 84/EGM96 Geoid. While providing complete coverage of the Shemya and Agattu Islands, there are numerous small areas with "no data" values on the island of Attu (Fig. 11). In order to create a 1 arc-second Shemya DEM, NGDC has resampled the 3 arc-second data to 1 arc-second and transformed to *ESRI* shapefile format removing points with elevations below zero. The SRTM data contained elevation values over the open ocean, which were deleted by clipping to the 'combined coastline'.

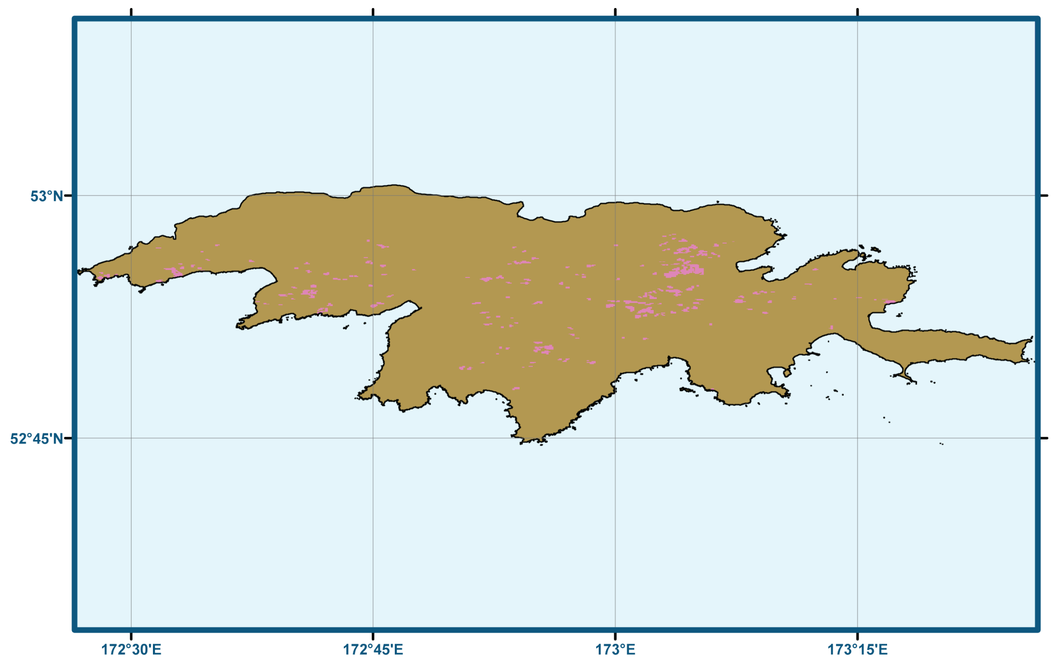

Figure 11. *SRTM 3 arc-second DEM data coverage on the island of Attu shown in tan and gaps in the SRTM DEM shown in pink. Values over open ocean are shown in light blue.*

3. 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]

2) OCS Electronic Navigational Chart (ENC) extracted land elevation points

Many of the offshore rocks and islets were not fully resolved in the SRTM topographic elevation dataset. To include these features in the Shemya DEM, land elevation points were extracted from ENCs #16430, 16431, and 16432 (Fig. 10). ENC land elevation data are referenced to MHW and WGS 84 geographic and are located along the southern coast of Attu Island. Data were converted to xyz format for use in the final gridding process using *FME*.

3) OCS Raster Nautical Chart (RNC) digitized land elevation points

Offshore rocks and islets not fully resolved in the SRTM topographic elevation dataset and not available as ENC land elevations were digitized by NGDC referencing the large scale RNCs (see Table 3). Elevations on the charts are referenced to MHW and in units of feet. *ESRI ArcCatalog* tools were used to assign geographic coordinates to the points; *FME* was used to convert data to xyz format and transform elevations to meters. Figure 12 shows three digitized points located on the smaller islands in Shemya Pass between Shemya and Nizki Islands.

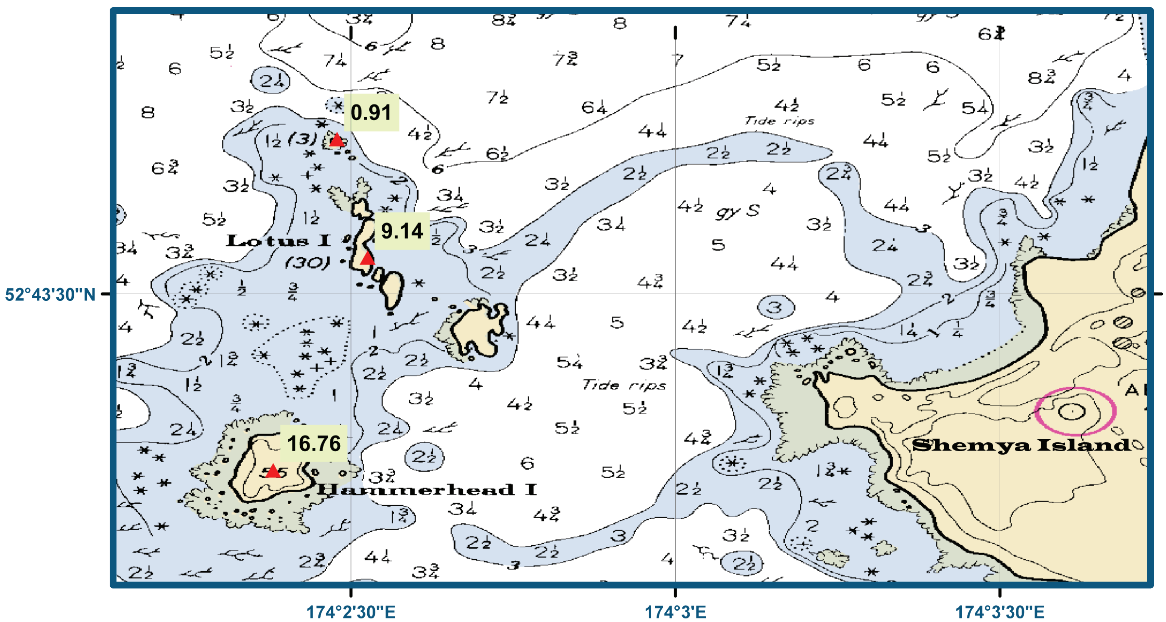

Figure 12. *Digitized RNC land elevation points, shown as red triangles, on the small islands in Shemya Pass. The assigned elevations in meters are shown in the light green boxes.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Shemya DEM were originally referenced to a number of vertical datums including Mean Lower Low Water (MLLW), Mean Sea Level (MSL), and WGS 84/EGM96 Geoid. All datasets were transformed to MHW to provide the maximum flooding for inundation modeling. Transformations to MHW were based on tide predictions at Alcan Harbor on Shemya Island[4] (Stephen Gill, pers. comm.).

1) **Bathymetric data**

   The NOS hydrographic surveys, NGDC trackline surveys, and the NGDC multibeam sonar survey were transformed from MLLW and MSL to MHW, using a constant based on a NOAA CO-OPS tide predictions for Alcan Harbor on Shemya Island (http://co-ops.nos.noaa.gov/tides09/; Table 9).

2) **Topographic data**

   The USGS SRTM 3 arc-second DEM was originally referenced to WGS 84/EGM96 Geoid vertical datum. There are no survey markers in the vicinity of Shemya that relate this geodetic datum to the local tidal datums. Thus, it was assumed that this datum is essentially equivalent to MSL in this area. Conversion to MHW, using *ArcCatalog* tools, was accomplished by adding a constant offset of -0.518 meters (Table 9), the difference between MSL and MHW using tidal predictions at Alcan Harbor.

Table 9. Relationship between Mean High Water and other vertical datums used in the Shemya DEM.

MSL to MHW	-0.518 meters
MLLW to MHW	-1.036 meters

3.2.2 Horizontal datum transformations

Datasets used to compile the Shemya DEM were originally referenced to Early Alaska and WGS 84 geographic horizontal datums. The NOS surveys referenced to Early Alaska horizontal datums were manually shifted in *ArcGIS* to fit the combined coastline and the raster nautical charts.

4. The Diurnal Range of tide is listed 3.4 ft. Since is is a primarily a Diurnal Tide, that means that Mean Higher High Water (MHHW) and Mean High Water (MHW) are approximately equivalent elevations. Thus, at Shemya, MHW is 3.4 ft. above MLLW. Local Mean Sea Level (LMSL) would be approximately at 1.7 ft., the same as MTL at this location. These data are based upon tide station measurements long ago - there have been no recent tide station occupations by NOAA.

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 *ArcMap* for consistency between datasets. 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:

- Lack of any high resolution topographic data required resampling SRTM dataset.
- Data values over the ocean in the SRTM topographic dataset. The SRTM dataset required automated clipping to the 'combined coastline'.
- Digital, measured bathymetric values from NOS surveys date back over 70 years. More recent data, such as the multibeam surveys, differed from older NOS data by as much as 100 meters vertically. The older NOS survey data were excised where more recent bathymetric data exists.
- NOS data in Early Alaska datum, which required manual shifting in *ArcMap* to align with 'combined coastline'.

3.3.2 Smoothing of bathymetric data

The older NOS hydrographic survey data are generally sparse at the resolution of 1 arc-second in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the form of lines of "pimples" in the DEM due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing 'pre-surface' bathymetric 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 clipped to remove overlap with the NGDC multibeam data and then combined with trackline data, digitized soundings, and points extracted from the combined coastline—to provide a buffer along the entire coastline. The coastline elevation value was set to -1.0 meter to ensure a bathymetric surface below zero in areas where bathymetric data are sparse or non-existent.

The point data were median-averaged using the *GMT* tool 'blockmedian' to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Shemya DEM gridding region. The *GMT* tool 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by 'surface' was converted into an ESRI Arc ASCII grid file, and clipped to the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy and exported as an xyz file for use in the final gridding process (Table 10). Figure 13 shows a histogram of NOS survey H07088 compared to the 1 arc-second pre-surfaced bathymetric grid. Differences cluster around zero with only 20 out of 5869 points varying more than 2 meters from the bathymetric surface. These few points are located at the coastline and in shallow, rocky areas.

Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the NOS hydrographic surveys. In areas where more recent data were available, the older surveys were either edited or not used.

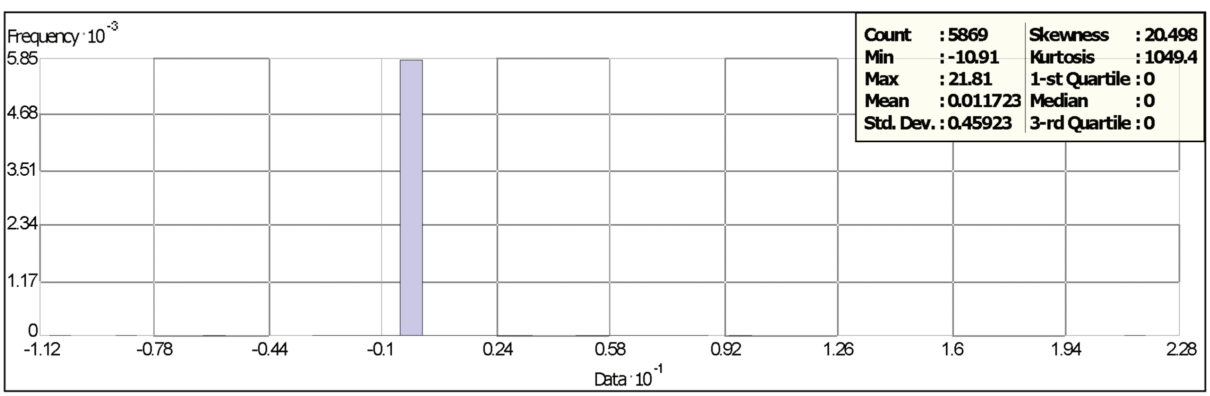

Figure 13. *Histogram of the differences between NOS hydrographic survey H07088 and the 1 arc-second pre-surfaced bathymetric grid*

3.3.3 Gridding the data with MB-System

MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/) was used to create the 1 arc-second Shemya DEM. *MB-System* is an NSF-funded share-ware software application specifically designed to manipulate submarine multibeam sonar data, though it can utilize a wide variety of data types, including generic xyz data. 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 10. Greatest weight was given to the RNC digitized sounding data and NGDC multibeam survey. Least weight was given to the combined coastline and pre-surfaced 1 arc-second bathymetric grid.

Table 10. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
RNC digitized soundings	100
NGDC multibeam survey	100
NGDC trackline bathymetry	10
ENC extracted land elevations	10
NOS hydrographic surveys	10
USGS SRTM topographic DEM	10
RNC digitized land elevations	10
Pre-surfaced bathymetric grid	1
Combined Coastline	1

3.4 Quality Assessment of the DEM

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Shemya 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 SRTM DEM. Bathymetric features are resolved only to within a few hundred meters in deep-water areas. Shallow, near-coastal regions, rivers, 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 for the Shemya DEM is highly dependent upon the source datasets contributing to DEM cell values. Elevation values within the island interiors, derived from the SRTM topographic data, have vertical accuracies of between 10 and 15 meters. Bathymetric values were derived from the wide range of sounding measurements from the early 20th century to recent, GPS-navigated multibeam swath sonar survey. 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, 3-D perspective, and data contribution plot

ESRI *ArcCatalog* was used to generate a slope grid from the Shemya DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 14). The DEM was transformed to UTM Zone 59 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids using *Quick Terrain Modeler* and *Fledermaus* revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1 arc-second Shemya DEM in its final version. Figure 15 shows a perspective rendering of the final DEM. Figure 16 shows a data contribution plot of the Shemya DEM.

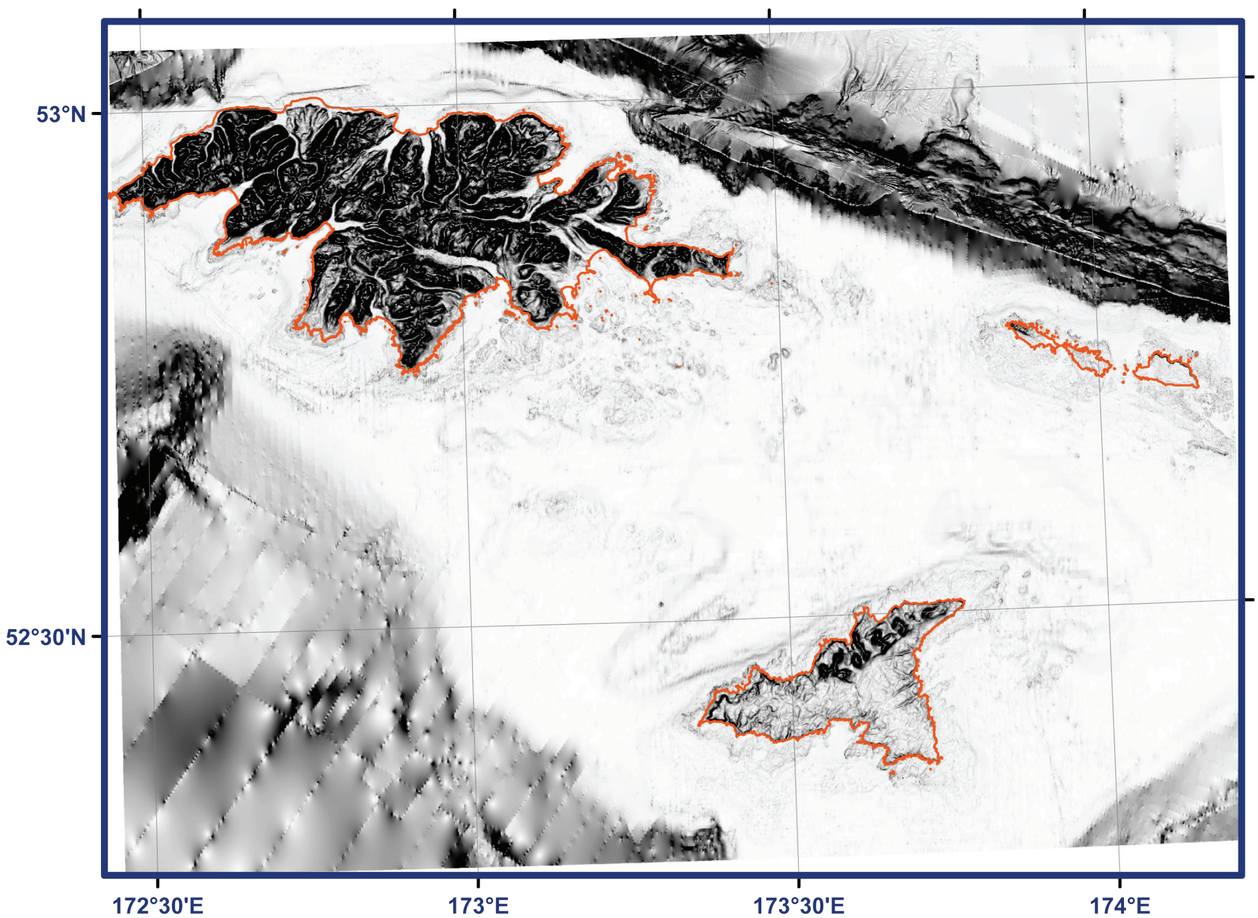

Figure 14. *Slope map of the Shemya DEM. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

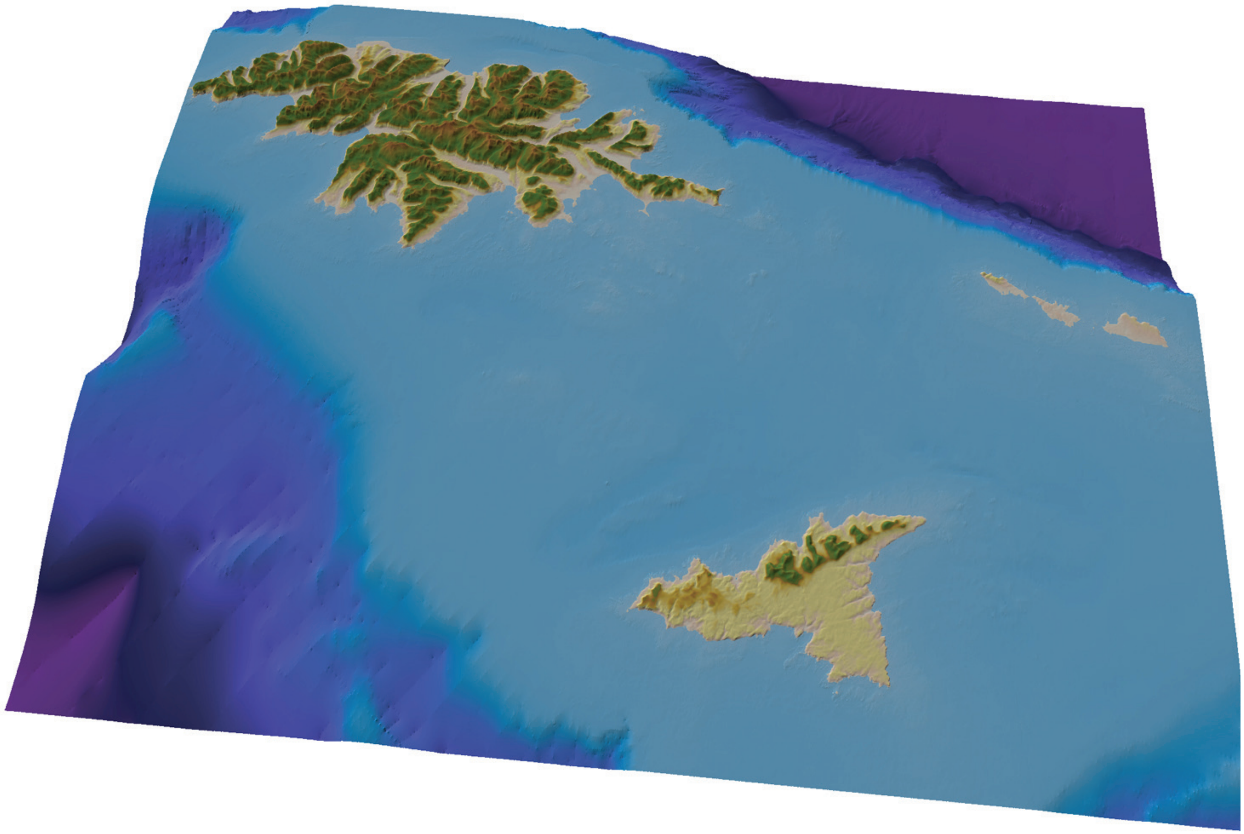

Figure 15. *Perspective view from the south of the Shemya DEM. Vertical exaggeration 2 times.*

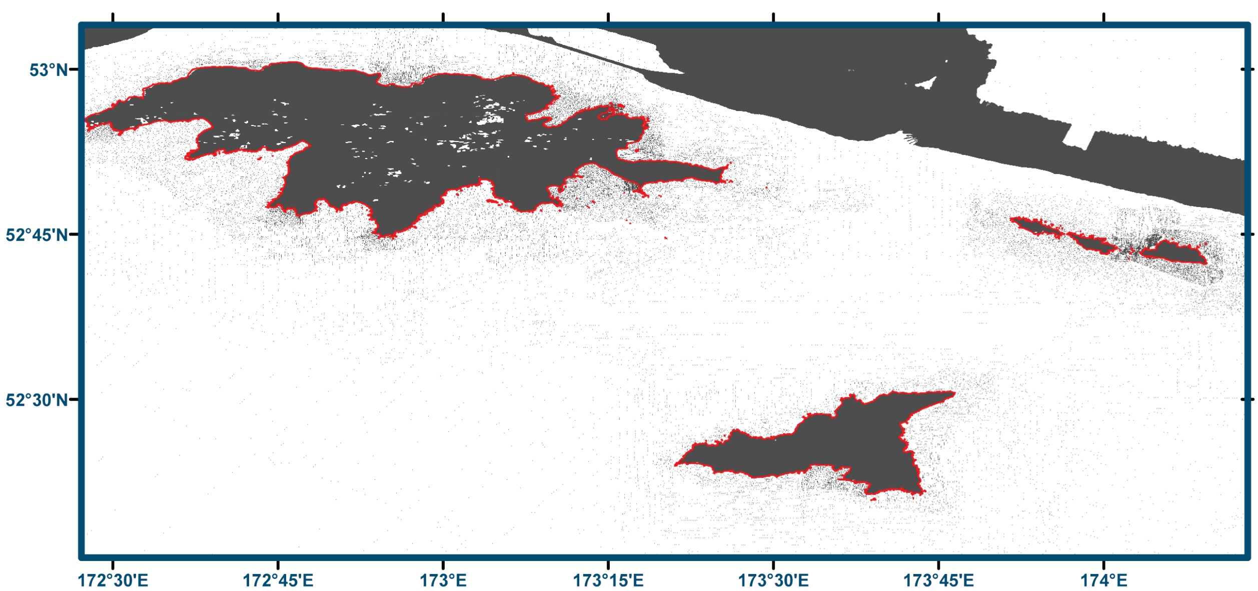

Figure 16. *Data contribution plot of the Shemya DEM. Gray depicts DEM cells constrained by source data. White depicts cells with elevation values derived from interpolation. Coastline in red.*

3.4.4 Comparison with topographic and bathymetric contours

Contours generated from the Shemya DEM were compared to bathymetric and topographic contours from different maps to qualitatively assess elevation values. Figure 17 shows the Attu USGS 1:250,000 topographic quadrangle map of western Attu Island displayed with the Shemya DEM topographic contours overlaid. Land features on the map are well represented in the DEM contours.

Contours derived from the ASTER global digital elevation model (GDEM) were used to evaluate the topography of the Shemya DEM. The ASTER GDEM is referenced to WGS 84/EGM96 geoid and can be downloaded in 1° by 1° tiles from the WIST website (https://lpdaac.usgs.gov/lpdaac/get_data/wist). Figure 18 shows a comparison of the contours derived from each.

Bathymetric contours from the DEM were also compared to contours extracted from 1:160,000 scale ENC #16421 (Fig. 19) and were generally consistent.

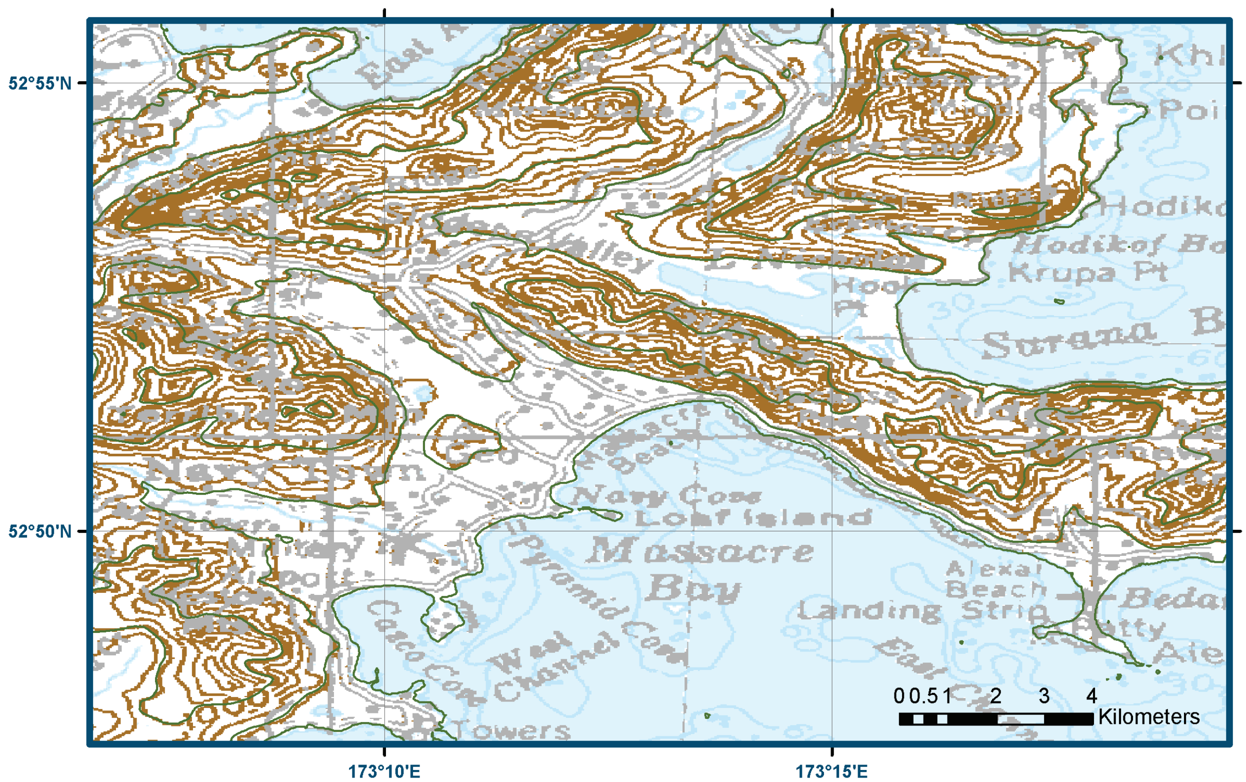

Figure 17. *Comparison of the Attu USGS topographic quadrangle contours, shown in green, and the Shemya DEM topographic contours, shown in brown.*

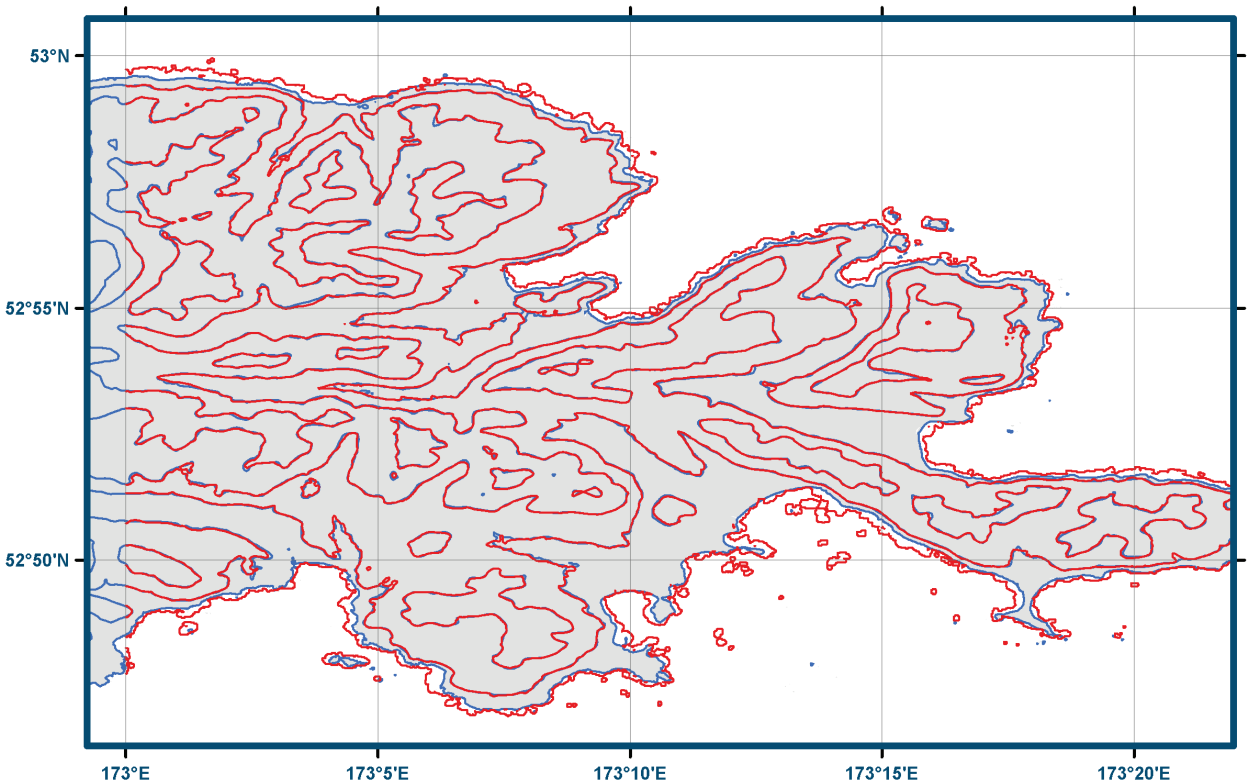

Figure 18. *Comparison of ASTER GDEM contours, shown in red, to Shemya DEM topographic contours, shown in blue, on the eastern half of Attu Island. Note discrepencies occur principally at the coast , where the ASTER GDEM is particularly noisy.*

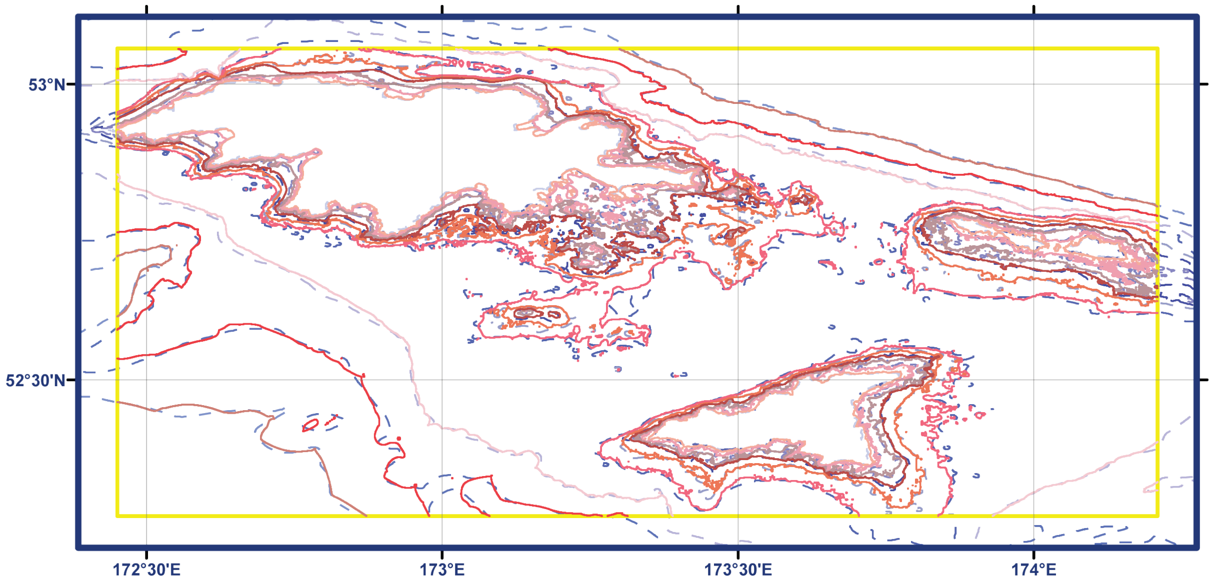

Figure 19. *Comparison of the extracted bathymetric contours from the 1:160,000 scale ENC #16421, shown as blue dashed lines, and the Shemya DEM bathymetric contours, shown in red. The DEM boundary is shown in yellow.*

4. Summary and Conclusions

A bathymetric–topographic digital elevation model of the Shemya, Alaska, region, with cell size 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*, *Fledermaus*, *GMT*, *MB-System* and *Quick Terrain Modeler* software.

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

- Conduct hydrographic surveys in near-shore areas, especially in Alcan Harbor on Shemya Island and Massacre Bay on Attu Island.
- Conduct bathymetric–topographic coastal LiDAR surveys of Semichi Islands.
- Conduct deep water multibeam surveys for region south of Attu and Agattu Islands.

5. Acknowledgments

The creation of the Shemya DEM was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Chris Chamberlin and Vasily Titov (PMEL) and Stephen Gill (NOAA/NOS).

6. References

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Nautical Chart #16420 (ENC and RNC), 2nd Edition, 2007. Near Islands, Buldir Island to Attu Island. Scale 1: 1,300,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16421 (ENC and RNC), 3rd Edition, 2008. Near Islands from Ingenstrem Rocks to Attu Island. Scale 1:160,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16423 (ENC and RNC), 3rd Edition, 2007. Shemya Island to Attu Island. Scale 1:100,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16430 (ENC and RNC), 3rd Edition, 2005. Attu Island, Theodore Point to Cape Wrangell. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16431 (ENC and RNC), 1st Edition, 2005. Tenmac Bay. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16432 (ENC and RNC), 2nd Edition, 2005. Massacre Bay. Scale 1:25,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16433 (RNC), 8th Edition, 2003. Sarana Bay to Holtz Bay, Chichagof Harbor. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16434 (RNC), 6th Edition, 2004. Agattu Island. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16435 (RNC), 6th Edition, 2004. Alaid and Nizki Islands. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

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Wilson, Frederic H., S. Mohadjer, and D. M. Grey, Reconnaissance Geologic Map of Western Aleutian Islands, Alaska, 2006. U.S. Geological Survey Open-File Report 2006-1302.

7. Data Processing Software

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

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

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

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

GMT v. 4.1.4 – 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. 6.0.1 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.