Digital Elevation Models of Sitka, 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

In July of 2011, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed two integrated bathymetric–topographic digital elevation models (DEMs) centered on Sitka, Alaska region (Figs. 1 and 2) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). The nested 1/3 and 3 arc-second[1] coastal DEMs will be used as input for the Method of Splitting Tsunami (MOST) model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEMs were generated from diverse digital datasets in the region (grid boundaries and sources shown in Fig. 4) and designed to represent modern morphology. They will be used for tsunami forecasting as part of the tsunami 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 Sitka DEMs.

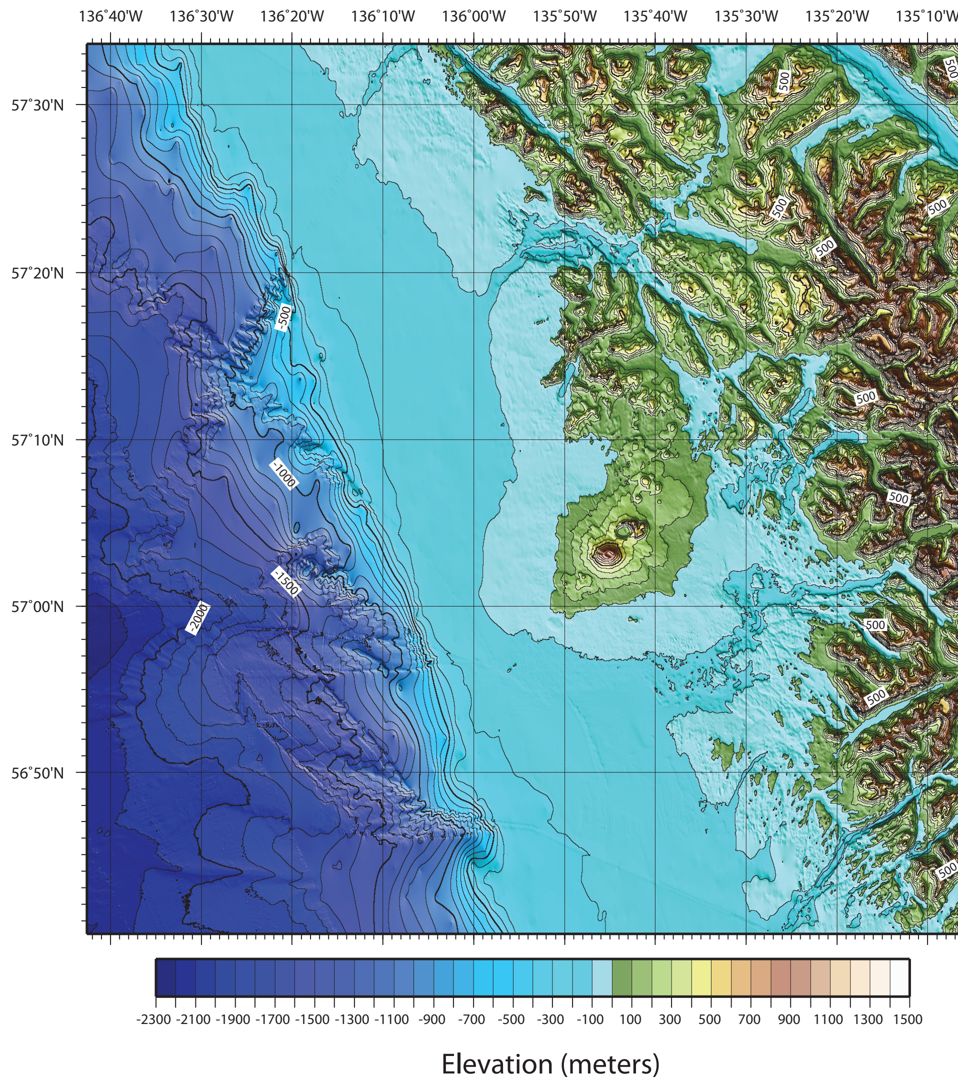

Figure 1. Shaded-relief image of the Sitka MHW 3 arc-second DEM. Contour interval is 100 meters. Image is in Mercator projection.

1. The Sitka DEMs are 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 Sitka, (57°3'11"N, 135°19'48"W) 1/3 arc-second of latitude is equivalent to 10.31 meters and 3 arc-seconds equals 92.8; 1/3 arc-second of longitude is equivalent to 5.61 meters and 3 arc-seconds equals 50.57.

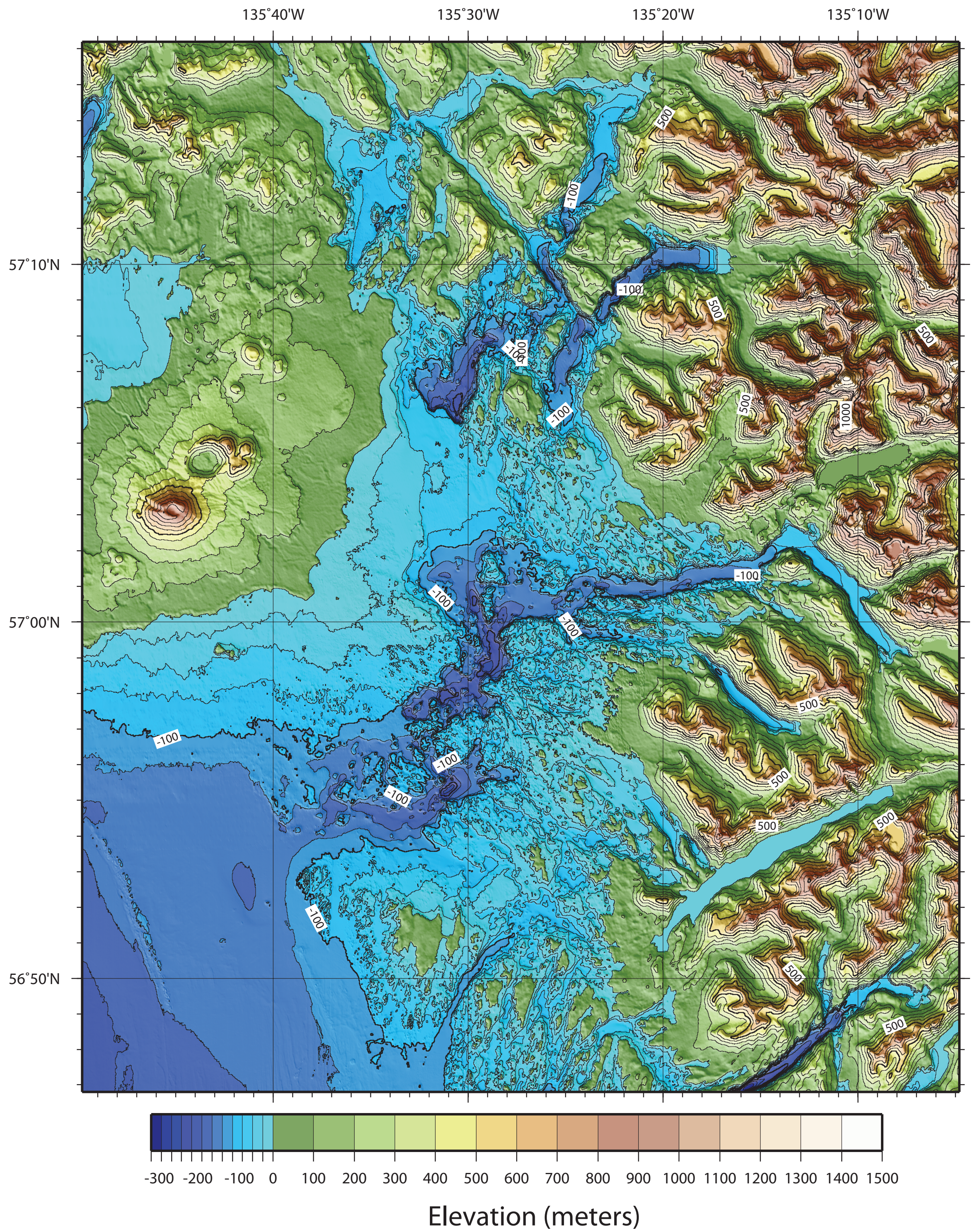

Figure 2. Shaded-relief image of the Sitka MHW 1/3 arc-second DEM. Contour interval is 100 meters for the topography and 25 meters for the bathymetry. Image is in Mercator projection.

2. Study Area

Sitka, Alaska is located in the Alexander Archipelago on Baranof Island and Japonski Island. The Sitka DEMs, centered on Sitka Harbor, were 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 (Table 1; Fig. 3).

Table 1. Specifications for the Sitka DEMs

Grid Area	3 arc-second Sitka, Alaska DEM	1/3 arc-second Sitka, Alaska DEM
Coverage Area	136.71º to 135.05º W; 56.67º to 57.56º N	135.83º to 135.08º W; 56.78º to 57.27º N
Grid Spacing	3 arc-second	1/3 arc-second
DEM Type	Structured	
Coordinate System	Geographic decimal degrees	
Horizontal Datum	World Geodetic System of 1984 (WGS 84)	
Vertical Units	Meters	
Vertical Datum	Mean High Water (MHW)	
Grid Format	ESRI Arc ASCII raster grid	

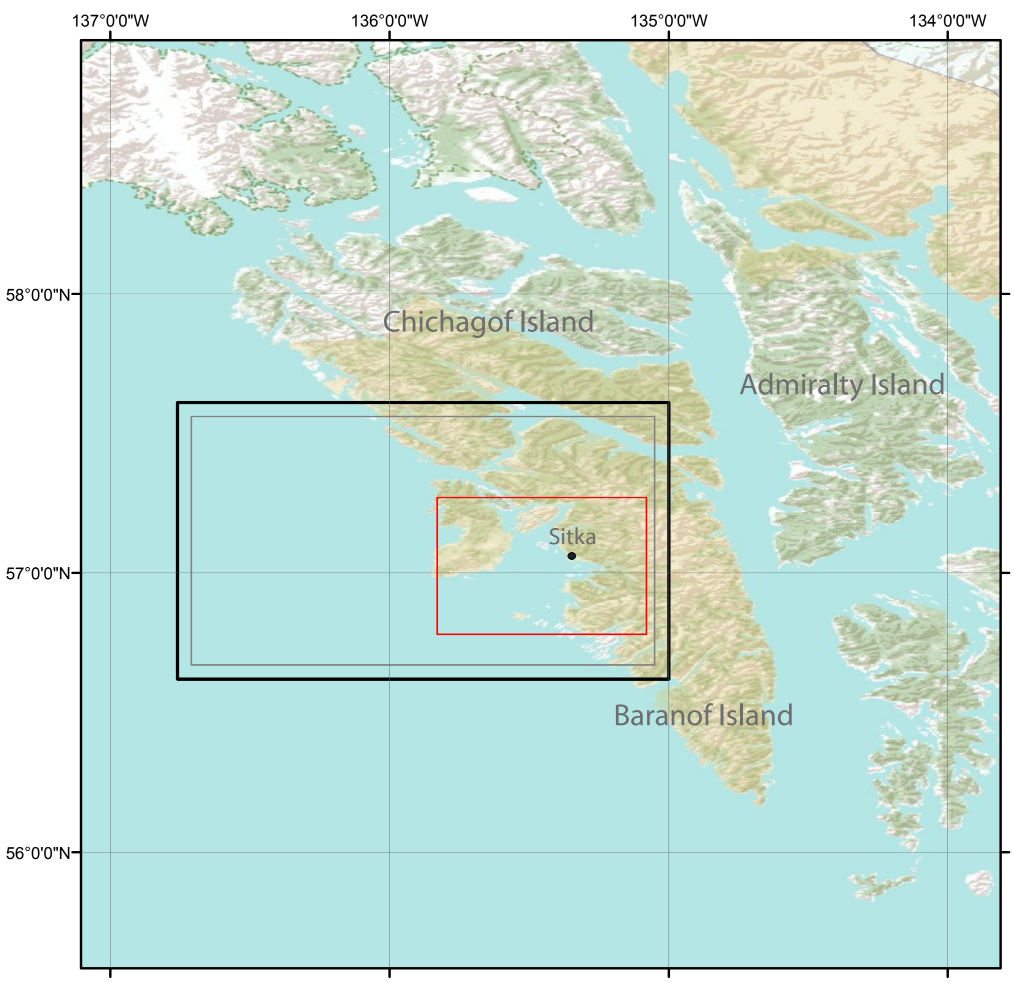

Figure 3. Overview of the Sitka DEM region. Red box represents the 1/3 arc-second bounding box. Gray box represents the 3 arc-second bounding box. Black box is the buffer 5% larger than the 3 arc-second extent for data collection.

3. Source Elevation Data

The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum 1983 (NAD 83)[2] geographic and mean high water (MHW). Data were gathered in an area slightly larger (5%) than the DEM extents. This data 'buffer' ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

3.1 Data Sources and Processing

Coastline, bathymetric, and topographic digital datasets (Tables 2, 3, and 4; Fig. 5) were obtained from the following U.S. federal and state agencies: NOAA's NGDC and Office of Coast Survey (OCS); the National Aeronautics and Space Administration (NASA); U.S. Army Corps of Engineers (USACE); and the University of Alaska Fairbanks (UAF). Data were visually displayed with Earth Systems Research Institute's (ESRI) *ArcGIS* to assess data quality and manually edit datasets. Datasets were shifted to NAD 83 geographic horizontal datum using ESRI's *ArcGIS* and *Proj. 4*. Vertical datum transformations were accomplished using a constant offset derived from the Sitka tide station #9451600 (see Sec 3.2.2).

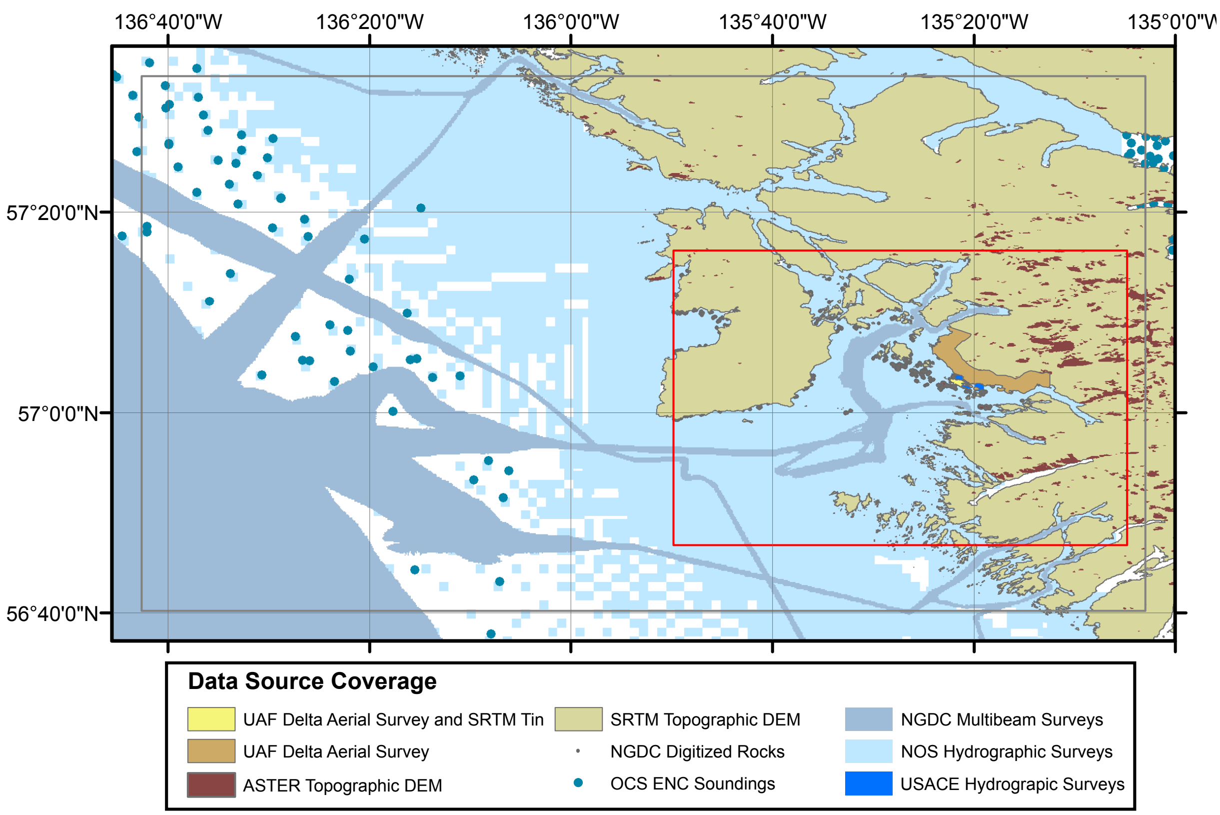

Figure 4. Data sources used in building the 3 and 1/3 arc-second Sitka MHW DEMs. White areas represent no data. Red box represents the 1/3 arc-second bounding box

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (1984) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Many GIS applications treat the two datums as identical and do not transform data between them. The error introduced by not converting between the datums is insignificant for NGDC 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 waves 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 geogprahic. At the scale of the DEM, WGS 84 and NAD 83 are identical and may be used interchangeably.

3.1.1 Coastline

NGDC used two coastlines to assist in building the Sitka DEMs: NGDC'S Southern Alaska Coastal Relief Model (CRM) coastline and UAF's Sitka Harbor and City of Sitka DEM coastline (Table 2; Fig. 5).

Table 2. Coastline datasets used in building the Sitka MHW DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*
NGDC	2009	Polyline	Various	WGS 84 geographic	Undefined
UAF	2011	Polyline	Various	WGS 84 geographic	MHHW

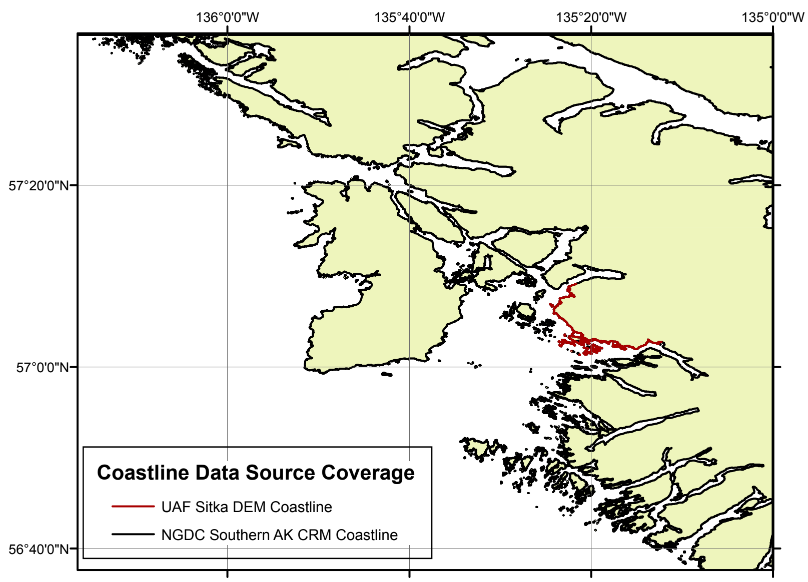

Figure 5. Coverage of the coastlines used in the development of the Sitka DEMs.

1) **NGDC's Southern Alaska Coastal Relief Model coastline**

   NGDC built a coastline for the Southern Alaska CRM from three different sources: U.S. Fish and Wildlife Services (FWS) coastline, the National Geospatial-Intelligence Agency (NGA) global shoreline, and the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS). The FWS coastline was used in the region of Sitka (Lim et al., 2009). The coastline was edited to match the available elevation data, RNCs and satellite imagery.

2) **UAF's Sitka DEM coastline**

   UAF built a small 8/15 arc-second DEM centered on Sitka, Alaska. UAF provided NGDC with their final coastline for use in building the DEM. The coastline was built from three different sources: a breakline from Delta Aerial Surveys, Inc. Triangular Irregular Network (TIN), hand-digitalization based on aerial imagery, and the FWS coastline. The UAF coastline was used in the vicinity of Sitka Harbor. The coastline was built to MHHW and was not changed to MHW because the difference from MHW to MHHW is only 0.24 meters, which would result in a horizontal difference less than the 10 meter cell size of the 1/3 arc-second DEM.

NGDC clipped the NGDC Southern AK CRM coastline to the buffer of the 3 arc-second extents, removed the region where the UAF coastline overlapped it and then merged the UAF coastline to the NGDC Southern AK CRM coastline to create a 'combined coastline'. The combined coastline was edited to match to the available data, RNCs, and satellite imagery, and offshore rocks.

3.1.2 Bathymetry

Bathymetric datasets available in the Sitka region included NOS hydrographic surveys, NGDC multibeam swath sonar surveys, OCS electronic navigational chart (ENC) soundings, and USACE hydrographic surveys (Table 3; Fig. 4).

Table 3. Bathymetric datasets used in building the Sitka DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*
NGDC	1903 to 2008	NOS hydrographic surveys	Ranges from 50 centimeters to 2 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	Undetermined, Early Alaska, NAD 1927 geographic, NAD 83 geographic, NAD 83 UTM Zone 8 N	Mean Lower Low Water (MLLW) (meters)
NGDC	2004 to 2009	Multibeam swath sonar surveys	Gridded at 30 meters	WGS 84 geographic	Assumed MSL (meters)
OCS		ENC point soundings	Varies	WGS 84 geographic	MLLW (meters)
USACE	2001 to 2008	Hydrographic harbor surveys	Ranges from 2 and 10 meters	NAD 83 Alaska State Plane, US foot	MLLW (feet)

1) National Ocean Service hydrographic survey data

A total of 97 NOS hydrographic surveys conducted between 1903 and 2010 were available in the Sitka region (see Appendix A). Older single-beam surveys were extracted as xyz files using *GEODAS* from NGDC's online NOS Hydrographic database with a buffer 0.05 degrees (~5%) larger than the Sitka DEM extents to support data interpolation along grid edges. New shallow-water multibeam surveys were downloaded as a bathymetric attributed grid (BAG) format from the NOS Hydrographic database. The hydrographic survey data were downloaded with vertical datums referenced to MLLW. The surveys were originally referenced to several horizontal datums (Table 3) but were transformed to NAD 83 geographic either during download by *GEODAS* or with *Proj.4*.

Data point spacing for the NOS surveys varies by collection date. In general, earlier surveys had greater point spacing than more recent surveys. BAG survey point spacing varied from 50 centimeters to 10 meters. The data were displayed in ESRI's *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets. The data were edited as necessary. The surveys were also compared to various topographic and bathymetric datasets, the combined coastline, and OCS Raster Nautical Charts (RNCs). Older sounding data were clipped to remove soundings that have been superseded by more recent surveys.

2) National Geophysical Data Center multibeam swath sonar survey data

Three multibeam swath sonar surveys were available from the NGDC Multibeam Bathymetry Database for use in building the Sitka DEMs (Table 4). This data base is comprised of the original swath sonar surveys conducted mostly by U.S. academic fleet. The data were gridded to 30 meters resolution using *MB-System*[3].

The surveys provided coverage for deep water in the 3 arc-second DEM. Data in shallow water were removed because newer and more accurate NOS BAG surveys were available for the same areas. Minor editing was performed in *ArcMap* to remove anamolous points and sound velocity errors at the edges of the surveys.

3. MB-System is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for MB-System is freely available (for free) by anonymous ftp (including "point and click" access through these web pages). A complete description is provided in web pages accessed through the web site. MB-System was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for MB-System development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994-1997), NOAA (2002-2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ [Extracted from MB-System web site.]

Table 4. NGDC multibeam swath sonar surveys used in building the Sitka DEMs.

Cruise ID	*Year*	*Ship*	*Original Horizontal Datum*	*Original Vertical Datum*	*Institution*
EW0408	2004	Maurice Ewing	WGS 84 geographic	Assumed MSL	Lamont-Doherty Observatory of Columbia Univeristy
KM0514	2005	Kilo Moana	WGS 84 geographic	Assumed MSL	University of Hawaii
HLY09TD	2009	Healy	WGS 84 geographic	Assumed MSL	United States Coast Guard

3) Office of Coast Survey Electronic Navigational Chart Soundings

Data coverage in the deep water between the NGDC multibeam surveys and NOS hydrographic surveys was sparse. Soundings from available ENC's were extracted to help fill in data holes where only sparse NOS hydrohraphic surveys existed.

4) U.S. Army Corp of Engineers hydrographic surveys

Three USACE hydrographic surveys were available from the Alaska District: Sitka Channel Rock Breakwaters, Sitka Crescent Bay Harbor, and Sitka Western Channel. The surveys had an original horizontal datum of NAD 83 Alaska State Plane, US feet, and an original vertical datum of MLLW. Point spacing varied by survey but typically had 10 meter or better spacing.

3.1.3 Topography

Five topographic datasets were used to build the Sitka DEMs: NASA SRTM and ASTER topographic DEMs, UAF Delta Aerial Survey and a TIN of Delta Aerial Survey and SRTM, and digitized elevations by NGDC (Table 5).

Table 5. Topographic datasets used in building the Sitka DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*
NASA SRTM	2004	Topographic DEM	1 arc-second	WGS 84 geographic	NAVD 88 (EGM 96 Geoid)
NASA ASTER	1999	Topographic DEM	1 arc-second	WGS 84 geographic	NAVD 88 (EGM 96 Geoid)
UAF Delta Aerial Survey	2011	Point	10 meters	WGS 84 geographic	MHHW
UAF TIN of Delta Aerial Survey and SRTM	2011	Point	5 meters	WGS 84 geographic	MHHW
NGDC Digitized Rocks	2011	Point	Varies	NAD 83 geographic	MHW

1) NASA Space Shuttle Radar Topography DEM

NASA obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of the Earth. SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000[4]. Data from this mission have been processed into 1 degree by 1 degree tiles as raster DEMs. The data have not been processed to bare-earth, but meet the absolute horizontal and vertical accuracies of 16 and 20 meters, respectively.

For U.S. regions, the data have 1 arc-second spacing and are referenced to WGS 84/EGM 96 Geoid. While providing complete coverage of the Sitka DEM region, there are numerous small areas with "no data" values. These areas are above an elevation where tsunami inundation occurs and thus will not affect the modeling results. The holes were filled with ASTER topographic DEM values. The SRTM DEM also contains values over the open ocean, which were deleted prior to gridding by clipping the DEM to the combined coastline.

2) NASA Advanced Spaceborne Thermal Emission Reflection Radiometer Topographic DEM

ASTER provides complete 1 arc-second topographic coverage of Alaska. The data are horizontally referenced to WGS 84 geographic coordinates and are vertically referenced to WGS 84/EGM 96 Geoid[5]. The raster dataset is available for download as 1 degree by 1 degree tiles. The extracted non-bare-earth elevations have a vertical accuracy of +/- 20 meters and horizontal accuracy of +/- 30 meters, both at the 95% confidence level.

The ASTER data contain values over the open ocean, which were deleted by clipping the raster files to the combined coastline. The ASTER data were only used to fill "no data" regions within the SRTM dataset. The ASTER data were not used as the primary topographic dataset due to the improper representation of topography in areas along the immediate coastline.

3) UAF Delta Aerial Survey

UAF provided NGDC with their processed xyz data of the Delta Aerial Survey Inc. Digital Terrain Model (DTM). The data were collected by Delta Aerial Surveys, Inc. for the City and Borough of Sitka. The data were photogrammetrically derived, referenced to the Alaska State Plane, Zone 1 Projection, NAD 83 horizontal datum in U.S. survey feet. The elevation values are referenced to MLLW vertical datum. UAF manually extracted xyz values from the provided 3D point shapefile geometry, transformed the data to WGS 84 geographic, meters and then MHHW using the Sitka tide station.

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

5. ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). ASTER is a cooperative effort between NASA, Japan's Ministry of Economy,Trade and Industry (METI) and Japan's Earth Remote Sensing Data Analysis Center (ERSDAC). ASTER is being used to obtain detailed maps of land surface temperature, reflectance and elevation. The three EOS platforms are part of NASA's Science Mission Directorate and the Earth-Sun System, whose goal is to observe, understand, and model the Earth system to discover how it is changing, to better predict change, and to understand the consequences for life on Earth. METI and NASA announced the release of the ASTER Global Digital Elevation Model (GDEM) on June 29, 2009. The GDEM was created by stereo-correlating the 1.3 million scene ASTER visible and near-infrared (VNIR) archive, covering the Earth's land surface between 83N and 83S latitudes. The GDEM is produced with 30 meter postings, and is formatted in 1 x 1 degree tiles as GeoTIFF files. Each GDEM file is accompanied by a Quality Assessment file, either giving the number of ASTER scenes used to calculate a pixel's value, or indicating the source of external DEM data used to fill the ASTER voids [Extracted from NASA JPL ASTER website]

4) UAF TIN of Delta Aerial Survey and SRTM

The Delta Aerial Survey DTM covered 1/3 of Japonski Island. The SRTM data did not match closely with the Delta Aerial Survey DTM, making it difficult to incorporate both datasets into the DEM. To overcome these differences and to create the most accurate surface, UAF built a 5 meter horizontal resolution TIN from elevation points from the Delta Aerial Survey, contour lines from CAD drawings provided by the Alaska Department of Transportation and Public Facilities (ADOT & PF), and SRTM points (Fig. 6). The final TIN was quality checked with documented mean elevation values of certain features, such as the Sitka Airstrip.

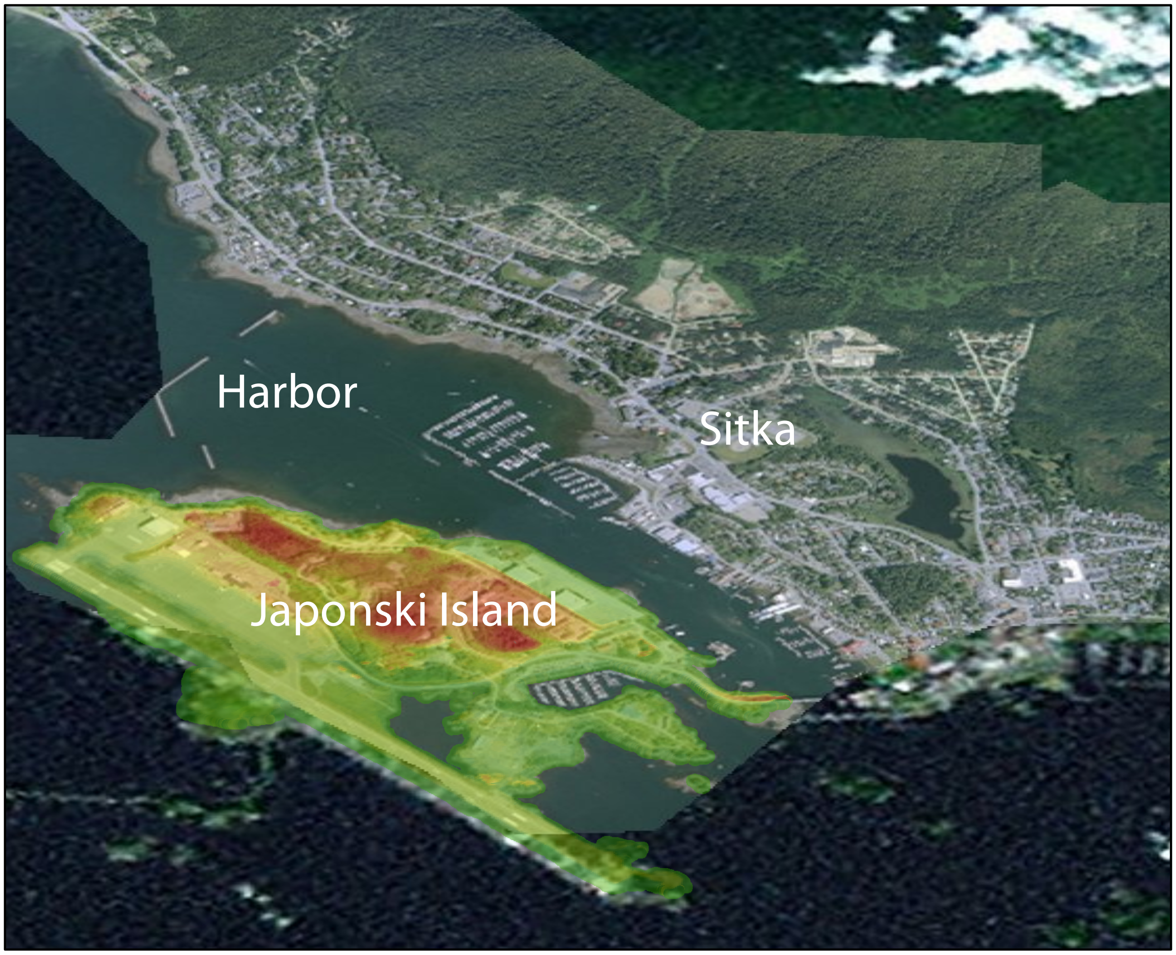

Figure 6. UAF TIN of Japonski Island. Elevation values range from 0.23 m (green) to 25.81 m (red).

3.2 Establishing Common Datums

3.2.1 Horizontal datum transformations

Datasets used to build the Sitka MHW DEMs were downloaded or obtained referenced to the Early Alaska Datums, NAD 1927 geographic, NAD 83 geographic, and NAD 83 UTM Zone 8 N, NAD 83 Alaska State Plane US Feet, WGS 84 geographic, or were undetermined. The relationships and transformational equations between these geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using *Proj.4* software or *ArcGIS's* reproject tool. Undetermined surveys were checked in *ArcMap* and manually adjusted according to original survey smooth sheets.

3.2.2 Vertical datum transformations

1) Bathymetric data

Bathymetric datasets used to build the Sitka DEMs were referenced to MLLW and MSL. All datasets were transformed to MHW to provide the maximum flooding for inundation modeling. Vertical datum transformations to MHW were accomplished by adding a constant offset, based on data from NOAA tide station #9451600, located at Sitka Harbor (Table 6).

2) Topographic data

Topographic datasets used to build the Sitka DEMs were referenced to NAVD 88 and MHHW. There is no relationship between NAVD 88 and MHW in this region. Data referenced to NAVD 88 were assumed to be MSL. Vertical datum transformations to MHW were accomplished by adding a constant offset, based on data from NOAA tide station #9451600, located at Sitka Harbor.

Table 6. Relationship between MHW and other vertical datums in the Sitka region.*

Vertical Datum	*Difference to MHW (meters)*
MLLW	2.791
MSL/NAVD 88⁺	1.181
MHHW	-0.237

* Datum relationships determined by tidal station #9451600 at Sitka, Alaska
⁺ NAVD 88 assumed to equivalent to MSL

3.2.3 Verifying transformations and consistency between datasets

After horizontal and vertical transformations were applied, datasets were checked for consistency. Problems and errors were resolved before proceeding with subsequent gridding steps. All datasets were converted to xyz files using *GDAL*[6] in preparation for gridding.

4. Digital Elevation Model Development

4.1 Smoothing of bathymetric data

Bathymetric survey data, especially older NOS hydrographic surveys, are generally sparse relative to the resolution of the 1/3 and 3 arc-second Sitka DEMs. In order to reduce the effect of artifacts in the DEM by low-resolution bathymetric datasets, and to provide effective interpolation from the deep water into the coastal zone, bathymetric pre-surfaces, or grids, were generated using using *Generic Mapping Tools (GMT)*[7].

A 1/3 arc-second pre-surface grid was compiled for the 1/3 arc-second DEM and a 3 arc-second 'pre-surface' grid was compiled for the 3 arc-second DEM. The 'pre-surface' grids were built from the bathymetric data (Table 3), which were converted to xyz files and combined into a single file, along with points extracted every ten meters from the final coastline. To provide a slightly more negative buffer along the entire coastline, the extracted coastline points were assigned values of -1 meter to ensure that the offshore elevation soundings remained negative.

The point data were median-averaged using the *GMT* command 'blockmedian' to create a 1/3 and 3 arc-second grid 0.05 degrees (~5%) larger than the Sitka DEM gridding regions. The *GMT* command 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The netcdf grid created was converted into an ESRI Arc ASCII grid file, and clipped to the coastline to eliminate data interpolation into land areas. The resulting surface was statistically compared with original soundings to ensure grid accuracy and then converted as an xyz file for use in the final gridding process.

6. *GDAL* is a translator library for raster geospatial data formats that is released under an X/MIT style Open Source license by the Open Source Geospatial Foundation. As a library, it presents a single abstract data model to the calling application for all supported formats. It also comes with a variety of useful commandline utilities for data translation and processing.

7. *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.]

4.2 Building the DEMs

MB-System was used to create the 1/3 and 3 arc-second square-cell DEMs. 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 7. The resulting netcdf grid was converted to an Arc ASCII grid using the *MB-System* tool 'mbm_grd2arc' to create the final 1/3 and 3 arc-second Sitka DEMs. Figure 7 illustrates cells in the DEMs that have interpolated values (shown in white) along with cells that have data contributing to the cell value (shown in gray).

Table 7. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
NGDC Digitized Features	100
NOS Bag Surveys	10
UAF Topographic xyz Points	10
USACE Hydrographic Surveys	1
NOS Hydrographic Surveys	1
NGDC Multibeam Swath Sonar Surveys	1
SRTM and ASTER Topographic DEMs	1
OCS ENC Soundings	0.1
Pre-surface bathymetric grid	0.1

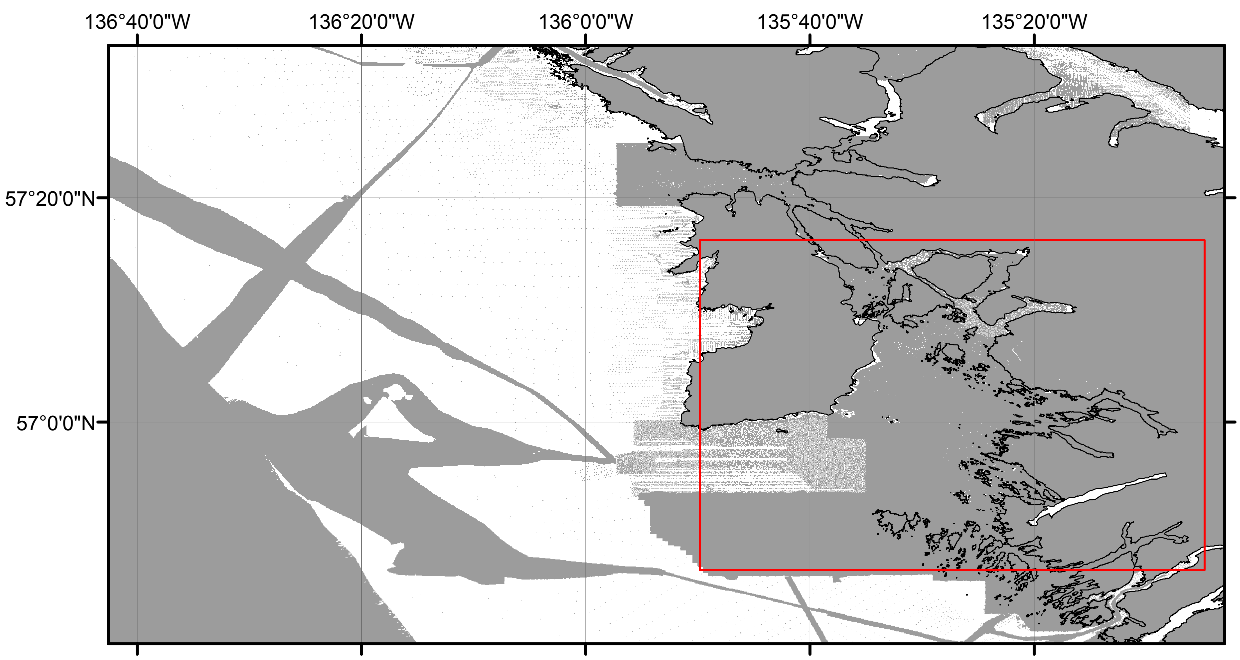

Figure 7. Data density grid of the Sitka DEMs; areas where source data contributed to the cells are illustrated in gray; areas where grid interpolation was necessary are illustrated in white. Red box denotes extents for the 1/3 arc-second MHW DEM.

4.3 Quality Assessment of the DEMs

4.3.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Sitka DEMs is dependent upon the datasets used to determine corresponding DEM cell values and the cell size of the DEM. The horizontal accuracy is no better than 10 meters for the 1/3 arc-second DEM and 90 meters for the 3 arc-second DEM. For topographic features where SRTM and ASTER data contribute to the cell value, the horizontal accuracy is between 20 and 30 meters in the 1/3 arc-second DEM. Bathymetric features are resolved only to within a few hundreds of meters in deep-water areas. Shallow, near-coastal regions 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.

4.3.2 Vertical accuracy

Vertical accuracy of the Sitka DEMs is also highly dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy between 16 meters for the SRTM DEM, 20 meters for the ASTER DEM, and approaching sub-meter accuracy for areas of the UAF provided data. Bathymetric values have an estimated accuracy of between 0.1 meters and 5% of water depth. Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations.

4.3.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Sitka DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 8 and 9). The DEMs were transformed to UTM Zone 8 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. Three-dimensional viewing of the UTM-transformed DEMs was accomplished using ESRI *ArcScene.* Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEMs. Figures 10 and 11 show perspective view images of the 1/3 and 3 arc-second Sitka DEMs in their final version.

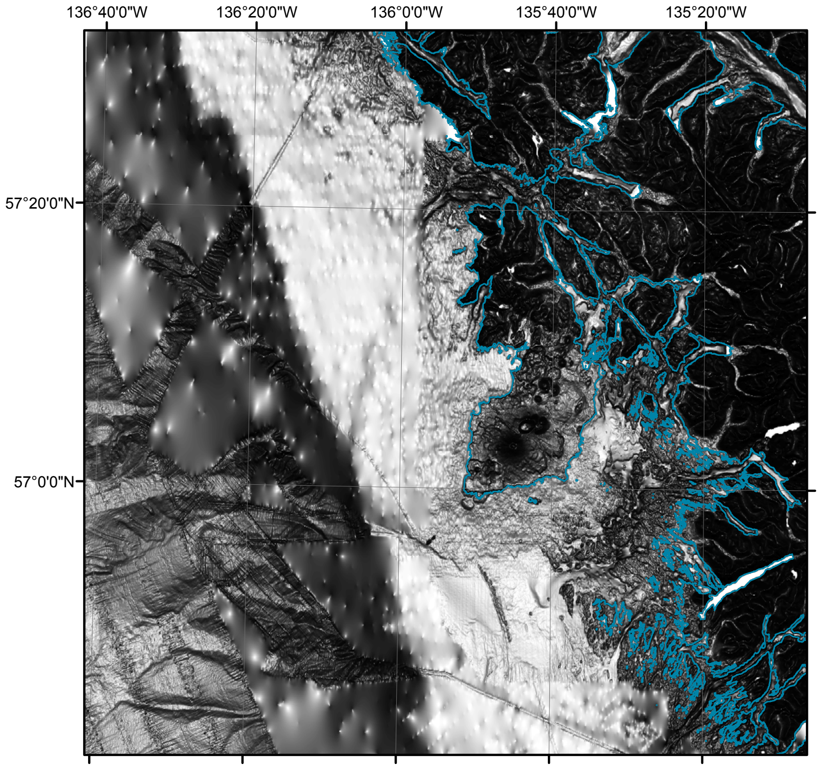

Figure 8. Slope map of the Sitka 3-arc-second DEM. Flat-lying slopes are white; dark shading denotes steep slopes. Combined coastline in blue.

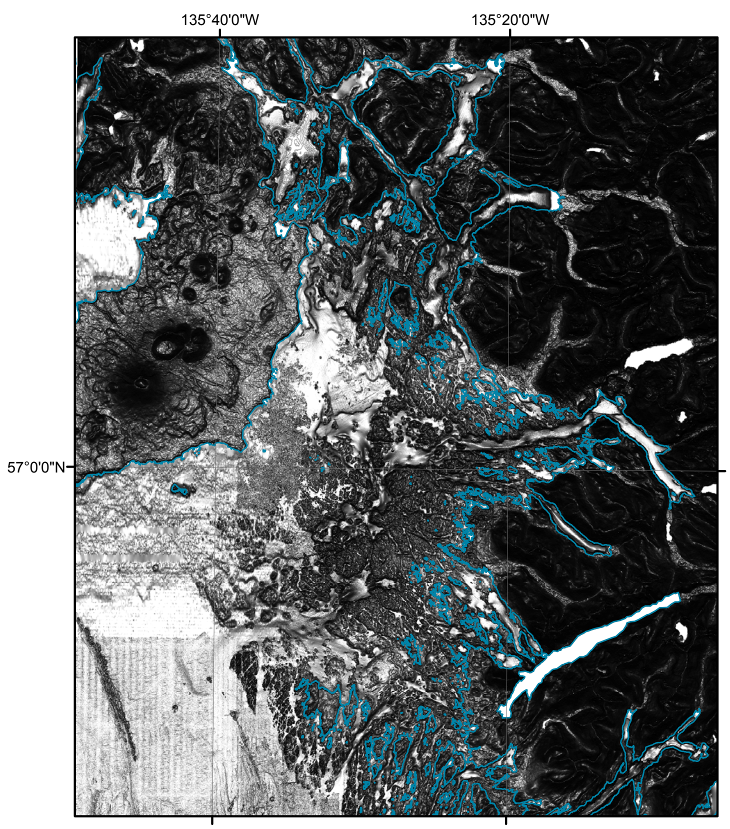

Figure 9. Slope map of the Sitka 1/3 arc-second DEM. Flat-lying slopes are white; dark shading denotes steep slopes. Combined coastline in blue.

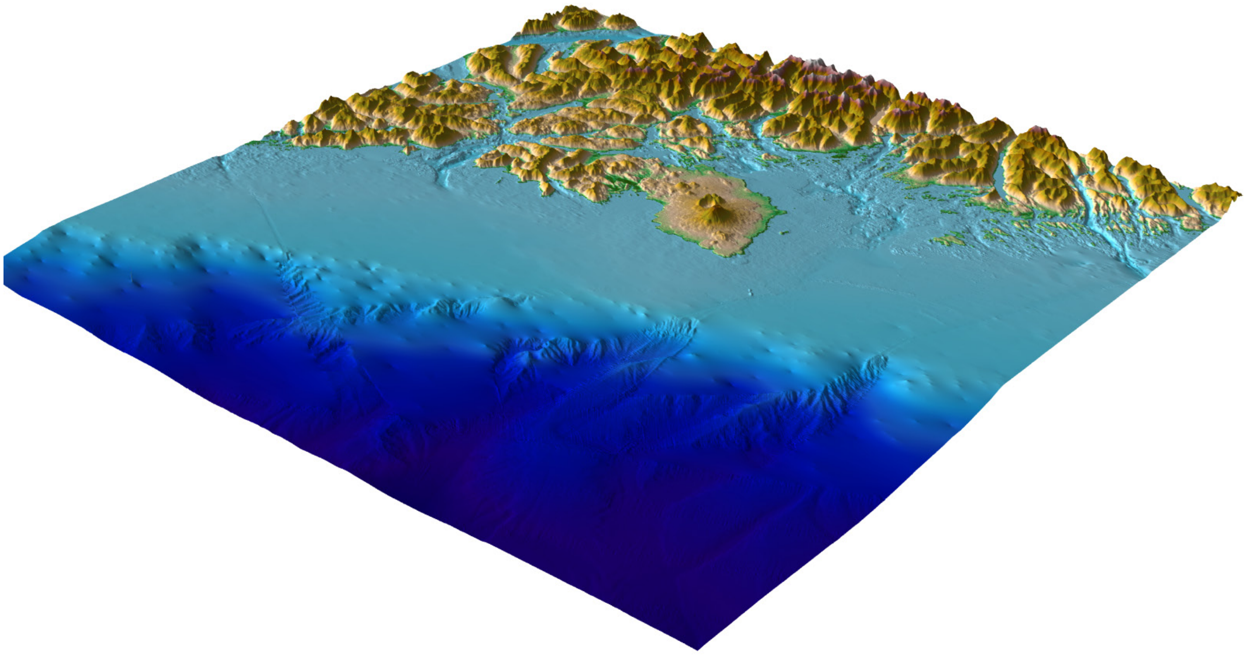

Figure 10. Perspective view from the southwest of the 3 arc-second Sitka DEM. Vertical exaggeration is 2 times.

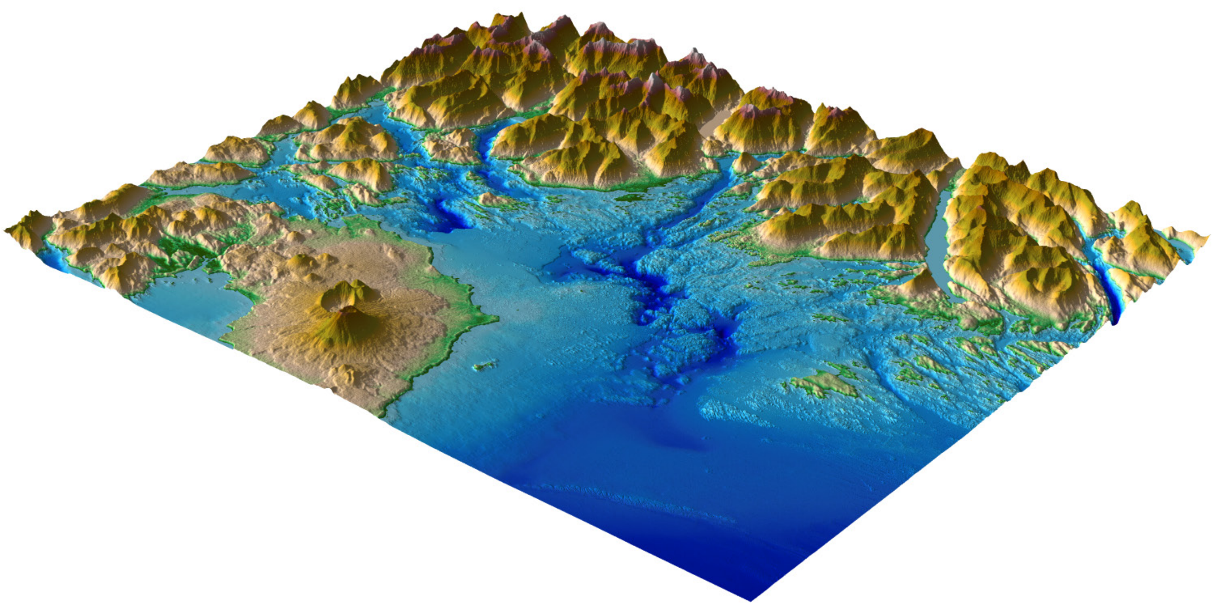

Figure 11. Perspective view from the southwest of the 1/3 arc-second Sitka DEM. Vertical exaggeration is 2 times.

4.3.4 *Comparison of the DEMs with source data files*

To ensure grid accuracy, the Sitka DEMs were compared to source data files. All bathymetric and topographic source data were compared to the Sitka DEMs using *Python*, *GDAL*, and *Gnuplot*[8]. Histograms of the differences between individual datasets and the Sitka DEMs mostly cluster around zero. Largest differences between source datasets and the DEM resulted from the averaging of multiple data points in steep terrain.

4.3.5 *Comparison with USGS and NOAA contour elevations*

The Sitka DEM elevation values were compared with NOAA nautical charts and USGS topographic maps by using contour lines. Contour lines were created from the DEM using *ArcMap's* 3D Analyst contour tool. Contours are in general agreement with NOAA's nautical charts and USGS's topographic maps (e.g. Figs. 12 and 13).

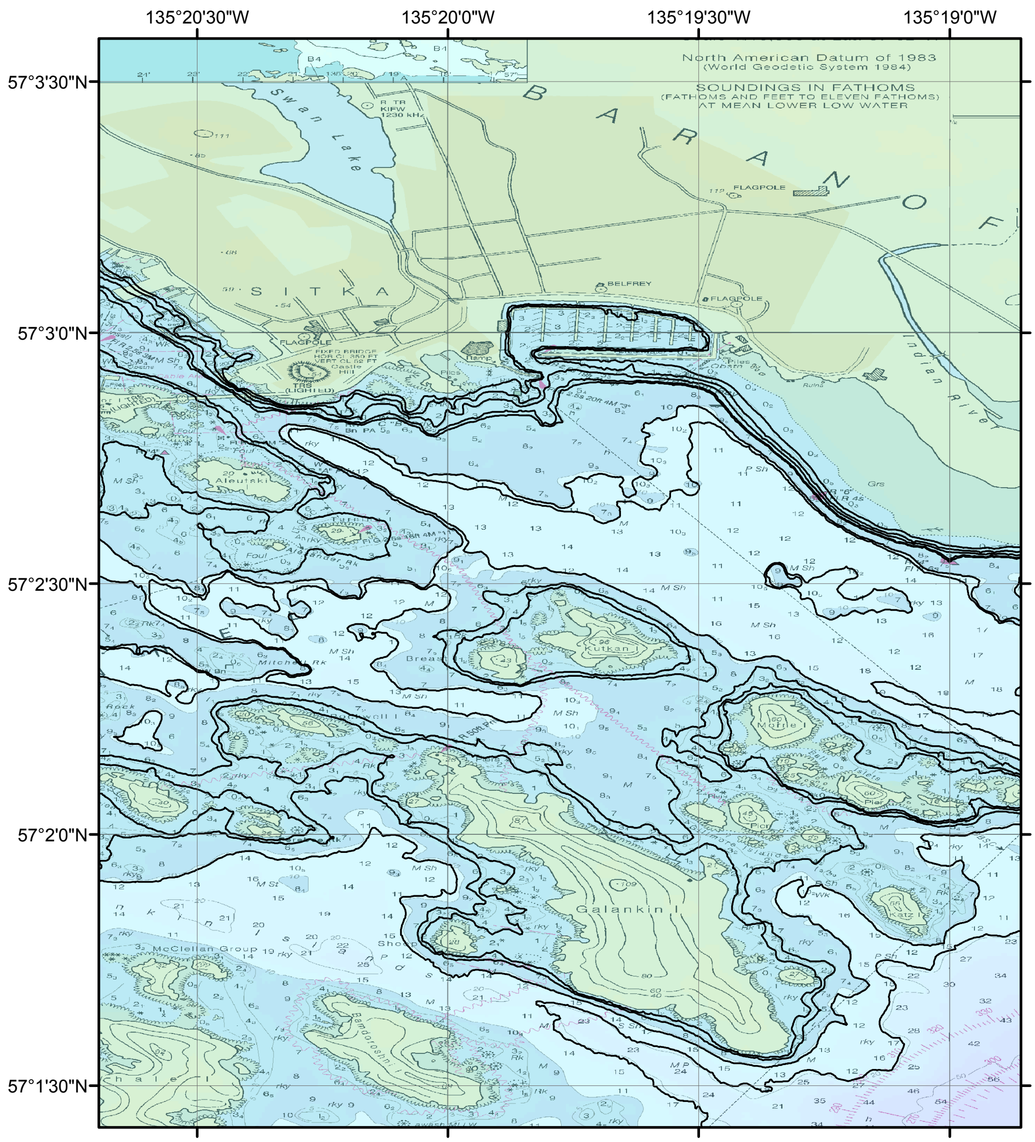

Figure 12. Bathymetric contour lines around Sitka Harbor from the Sitka 1/3 arc-second DEM (in black) overlying NOAA RNC #17327. Contour lines are in general aggreement with the contours from the RNC.

7. *Gnuplot* is a portable command-line driven graphing utility for linux, OS/2, MS Windows, OSX, VMS, and many other platforms. The source code is copyrighted but freely distributed. It was originally created to allow scientists and students to visualize mathematical functions and data interactively, but has grown to support many non-interactive uses such as web scripting. It is also used as a plotting engine by third-party applications like Octave. *Gnuplot* has been supported and under active development since 1986. *Gnuplot* supports many types of plots in either 2D and 3D. It can draw using lines, points, boxes, contours, vector fields, surfaces, and various associated text. It also supports various specialized plot types [Extracted from *Gnuplot* website].

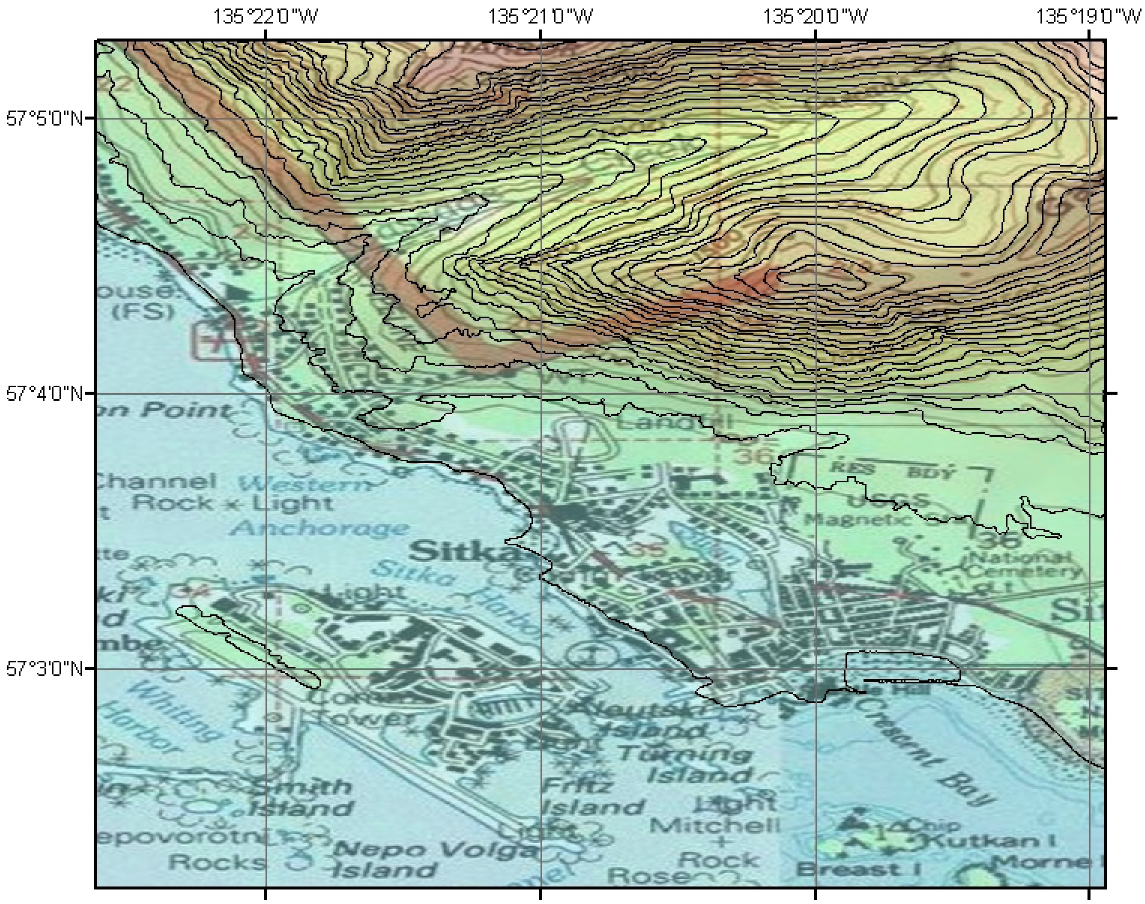

Figure 13. Topographic contour lines around Sitka Harbor from the Sitka 1/3 arc-second DEM (in black) overlying USGS topographic map. Contour lines are in general aggreement with the contours from the topographic map.

5. Summary and Conclusions

Two integrated bathymetric–topographic DEMs of Sitka, Alaska, with cell sizes of 1/3 arc-second and 3 arc-seconds, were developed for the PMEL NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state, and local agencies were obtained by NGDC, shifted to common horizontal and vertical datums, evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI *ArcGIS*, *FME*, *GMT*, *Quick Terrain Modeler*, *MB-System*, *GDAL*, *Proj.4*, and *Gnunplot* software.

Recommendations to improve the Sitka DEMs, based on NGDC's research and analysis, include:

- Conduct high-resolution shallow-water bathymetric multibeam surveys in areas where early 19th century survey data are the only available data.
- Conduct bathymetric–topographic lidar surveys of all near-shore regions to allow for a smooth transition from the bathymetric data to the topographic data and accurate representation of off-shore rocks.
- Conduct deep-water multibeam seafloor surveys where early 19th century survey data are the only available data.

6. Acknowledgments

The developement of the Sitka DEMs was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL). The authors would also like to thank Peter Hickman from UAF.

7. References

Hickman, P.J., E. Suleimani, and D. Nicolsky, 2011: Digital Elevation Model of Sitka Harbor and the City of Sitka, Alaska: Procedures, Data Sources, and Analysis.

Nautical Chart #17320 (RNC), 18th Edition, 2008. Coronation Island to Lisianski Strait. Scale 1:217,828. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17322 (RNC), 10th Edition, 2005. West Coast of Chichagof Island Khaz Bay. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17323 (RNC), 12th Edition, 2006. Salisbury Sound Peril Strait and Hoonah Sound. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17324 (RNC), 15th Edition, 2007. Sitka Sound to Salisbury Sound Inside Passage. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17325 (RNC), 9th Edition, 2006. South and West Coasts of Kruzof Island. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17326 (RNC), 16th Edition, 2007. Baranof Island Crawfish Inlet to Sitka. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17327 (RNC), 23rd Edition, 2008. Sitka Harbor and Approaches. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17328 (RNC), 7th Edition, 2003. Baranof Island Snipe Bay to Crawfish Inlet. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17338 (RNC), 14th Edition, 2005. Peril Straight Hoonah Sound to Chatham Straight. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

8. Data Processing Software

ArcGIS v. 10.0 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/.

FME 2010 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/.

GDAL v. 1.7.1 – Geogrpahic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://gdal.org/.

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

GMT v. 4.3.4 – Generic Mapping Tools, freeware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/.

Gnunplot v. 4.2, free software developed and maintained by Thomas Williams, Colin Kelley, Russell Lang, Dave Kotz, John Campbell, Gershon Elber, Alexander Woo, http://www.gnuplot.info/.

MB-System v. 5.1.0 – 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/.

Proj4 v. 4.7.0, free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/.

Python v. 2.4.3, Python is a remarkable pwerful dynamic programming lanuage that is used in a wide variety of application domains. Python is free software, http://python.org/.

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.

Appendix A. NOS Hydrographic Surveys

Table A1. NOS hydrographic surveys available in the Sitka, AK region

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Survey Type*	*Original Vertical Datum*	*Original Horizontal Datum*
F00250*	1983	5,000	Point	MLLW	North American Datum 1927
H02665	1903	600,000	Point	MLLW	Undetermined
H02857	1906	10,000	Point	MLLW	Undetermined
H02858	1906	20,000	Point	MLLW	Undetermined
H02859	1906	10,000	Point	MLLW	Undetermined
H04431*	1924	20,000	Point	MLLW	Undetermined
H04432	1924	80,000	Point	MLLW	Undetermined
H04524	1925	20,000	Point	MLLW	Undetermined
H04528	1925	80,000	Point	MLLW	Undetermined
H04529	1925	100,000	Point	MLLW	Undetermined
H04530	1925	20,000	Point	MLLW	Undetermined
H04539	1925	20,000	Point	MLLW	Undetermined
H04842	1928	20,000	Point	MLLW	Undetermined
H04843	1928	20,000	Point	MLLW	NAD 1927
H04846	1928	20,000	Point	MLLW	NAD 1927
H04847	1928	20,000	Point	MLLW	Undetermined
H06351*	1938	1,000	Point	MLLW	Early Alaska Datums
H06352	1938	5,000	Point	MLLW	Early Alaska Datums
H06353	1938	5,000	Point	MLLW	Early Alaska Datums
H06354*	1938	10,000	Point	MLLW	Early Alaska Datums
H06355	1938	10,000	Point	MLLW	Early Alaska Datums
H06655	1941	20,000	Point	MLLW	Early Alaska Datums
H06666	1941	10,000	Point	MLLW	Early Alaska Datums
H06667	1941	20,000	Point	MLLW	Early Alaska Datums
H06743	1941	40,000	Point	MLLW	Early Alaska Datums
H06764*	1942	5,000	Point	MLLW	Early Alaska Datums
H06947	1943	10,000	Point	MLLW	Early Alaska Datums
H06948	1943	10,000	Point	MLLW	Early Alaska Datums
H07096	1945	10,000	Point	MLLW	Early Alaska Datums
H07097	1945	5,000	Point	MLLW	Early Alaska Datums
H07163*	1945	1200	Point	MLLW	Early Alaska Datums
H07189	1947	10,000	Point	MLLW	Early Alaska Datums
H07190	1947	10,000	Point	MLLW	Early Alaska Datums

NOS Survey ID	***Year of Survey***	***Survey Scale***	***Survey Type***	***Original Vertical Datum***	***Original Horizontal Datum***
H07191	1947	10,000	Point	MLLW	Early Alaska Datums
H07193	1947	10,000	Point	MLLW	Early Alaska Datums
H07673*	1952	5,000	Point	MLLW	Early Alaska Datums
H07674	1948	5,000	Point	MLLW	Early Alaska Datums
H07675	1948	5,000	Point	MLLW	Early Alaska Datums
H07676	1948	10,000	Point	MLLW	Early Alaska Datums
H07787	1949	10,000	Point	MLLW	Early Alaska Datums
H07788	1949	1:10,000	Point	MLLW	NAD 1927
H07860*	1950	10,000	Point	MLLW	Early Alaska Datums
H07861	1950	10,000	Point	MLLW	Early Alaska Datums
H07930	1951	5,000	Point	MLLW	Early Alaska Datums
H07931	1951	10,000	Point	MLLW	Early Alaska Datums
H07985	1952	5,000	Point	MLLW	Early Alaska Datums
H07986	1952	10,000	Point	MLLW	Early Alaska Datums
H07988	1952	10,000	Point	MLLW	Early Alaska Datums
H07989	1952	10,000	Point	MLLW	Early Alaska Datums
H08501	1959	1,000	Point	MLLW	Early Alaska Datums
H09054	1969	10,000	Point	MLLW	NAD 1927
H09055	1969	10,000	Point	MLLW	NAD 1927
H09056	1969	10,000	Point	MLLW	NAD 1927
H09121	1970	20,000	Point	MLLW	NAD 1927
H09122	1970	20,000	Point	MLLW	NAD 1927
H09125	1970	10,000	Point	MLLW	NAD 1927
H09126	1970	10,000	Point	MLLW	Early Alaska Datums
H09127	1970	10,000	Point	MLLW	Early Alaska Datums
H11105	2002	10,000	Point	MLLW	NAD 83
H11106	2002	10,000	Point	MLLW	NAD 83
H11108	2002	10,000	Point	MLLW	NAD 83
H11109	2002	10,000	Point	MLLW	NAD 83
H11110	2002	10,000	Point	MLLW	NAD 83
H11111	2002	10,000	Point	MLLW	NAD 83
H11112	2003	10,000	Point	MLLW	NAD 83

NOS Survey ID	***Year of Survey***	***Survey Scale***	***Survey Type***	***Original Vertical Datum***	***Original Horizontal Datum***
H11113	2003	10,000	Point	MLLW	NAD 83
H11114	2004	10,000	Point	MLLW	NAD 83
H11115	2004	10,000	Point	MLLW	NAD 83
H11116	2004	10,000	Point	MLLW	NAD 83
H11117	2003	10,000	Point	MLLW	NAD 83
H11118	2004	10,000	Point	MLLW	NAD 83
H11119	2004	10,000	Point	MLLW	NAD 83
H11120	2003	10,000	Point	MLLW	NAD 83
H11121	2002	5,000	Point	MLLW	NAD 83
H11131	2002	10,000	Point	MLLW	NAD 83
H11134	2003	20,000	Point	MLLW	NAD 83
H11354	2004	10,000	Point	MLLW	NAD 83
H11122	2005	10 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11123	2004	5 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11124	2004	0.5 - 5 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11126	2009	5 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11127	2006	0.5 - 5 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11128	2006	10 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11130	2004	2 - 5 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11135	2005	10 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11270	2005	10 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11271	2005	10 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11427	2005	3 - 5 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11428	2005	5 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11538	2006	3 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11539	2006	3 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11540	2006	3 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11677	2007	10 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11844	2008	8 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11845	2008	8 meters	BAG	MLLW	NAD 83 UTM Zone 8 N
H11846	2008	4 meters	BAG	MLLW	NAD 83 UTM Zone 8 N

*indicates data were not used due to poor quality or overlapped by more recent surveys