NOAA Technical Memorandum NESDIS NGDC-45

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1. Introduction

In February of 2010, 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 Cordova, Alaska (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). The 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 boundary and sources shown in Fig. 3) and designed to represent modern morphology. They 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 Cordova DEMs.

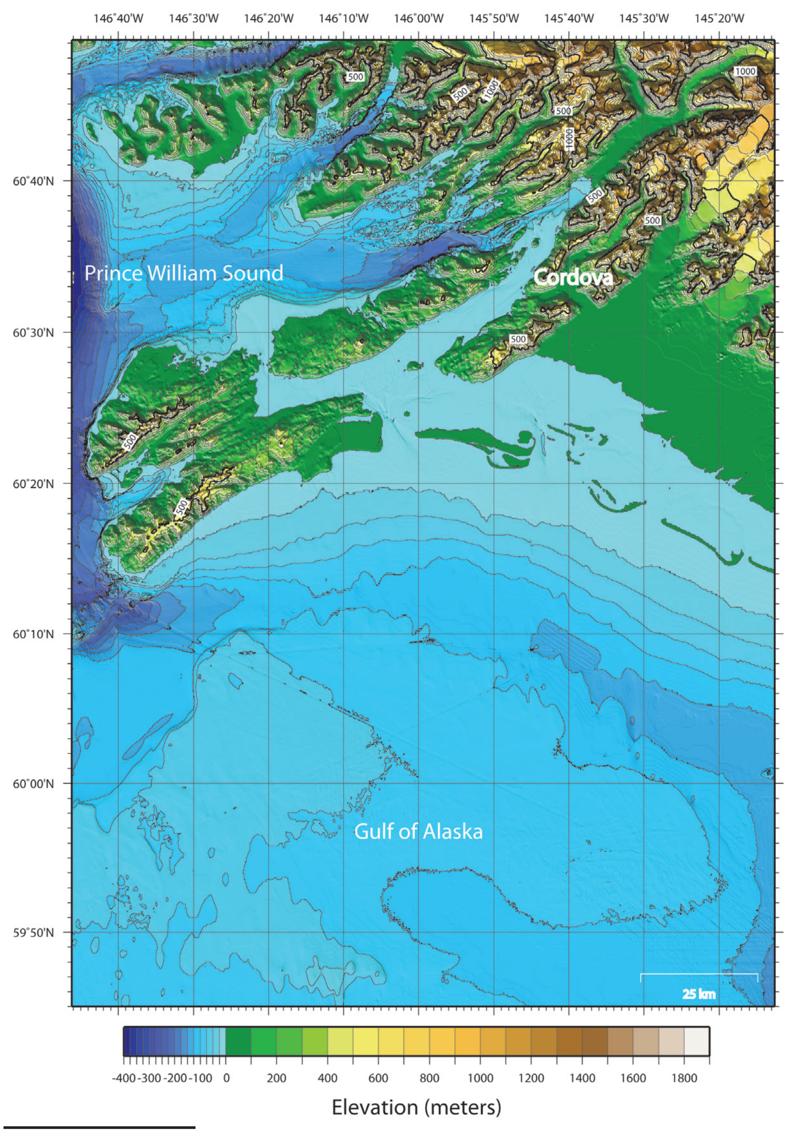

Figure 1. *Shaded-relief image of the Cordova region, derived from the 3 arc-second DEM. Bathymetric contour interval is 25 meters. Topographic contour interval is 100 meters.*

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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 Cordova, Alaska (60º 32' 34" N, 145º 45' 27" W) 1/3 arc-second of latitude is equivalent to 10.31 meters and 3 arc-second of latitude is equivalent to 92.79 meters; 1/3 arc-second of longitude equals 5.08 meters and 3 arc-second of longitude equals 45.74 meters.

2. Study Area

Cordova, Alaska is a small town on the east side of the Prince William Sound, with approximately 2,500 residents (Fig. 2). Cordova, along with most of Prince William Sound, has gradually been carved away by glaciation, creating many fjords and passageways, islands, and rocky shores.

The Prince William Sound region has frequent earthquakes, putting the residents of Cordova at risk for tsunamis. On March 27th, 1964, a powerful earthquake registering 9.2 on the Richter scale, generated tsunamis from tectonic uplift and local underwater slides. Over 100 residents in the region perished from the tsunamis. Cordova experienced wave heights up to 6 meters and about 1.7 million dollars in damage (http://wcatwc.arh.noaa.gov/64quake.htm). The earthquake caused major vertical displacements around Prince William Sound, with uplift reported up to 15 meters and maximum subsidence of 2.3 meters relative to mean sea level (http://www.drgeorgepc.com/Earthquake1964Alaska.html). These vertical displacements of the seafloor have reduced the accuracy and reliability of pre-1965 hydrographic surveys.

The Copper River Delta, located about 10 kilometers southeast of Cordova, is in a constant state of morphologic change. The river enters the Gulf of Alaska full of silt and sand, creating mud flats and sand dunes with criss-crossing channels. There are no recent surveys in the delta, which is only in the 3 arc-second DEM, and thus will not be accurately represented.

Figure 2. *Map of the region surrounding Prince William Sound, Alaska. Major geographical features identified. (http://www.alaska101.com/exploreAlaska/maps/princeWilliamSound.gif)*

3. Methodology

The Cordova DEMs were constructed to meet PMEL specifications (Tables 1a and 1b), 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[2] (NAD 83) geographic and mean high water (MHW), for modeling of maximum flooding. Data were gathered in an area slightly larger (~5%) than the DEM extents. The data "buffers" 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.

Table 1a. PMEL specifications for the 1/3 arc-second Cordova DEM.

Grid Area	Cordova, Alaska
Coverage Area	145.21º to 146.77º W; 60.49º to 60.82º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	MHW
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI ASCII raster grid

Table 1b. PMEL specifications for the 3 arc-second Cordova DEM.

Grid Area	Cordova, Alaska
Coverage Area	145.21º to 146.77º W; 59.75º to 60.82º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	MHW
Vertical Units	Meters
Cell Size	3 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 geographic is restricted to North America, while WGS 84 geographic 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. 3) were obtained from several U.S. federal agencies, including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), and NGDC; the U.S. Geological Survey (USGS); and the U.S. Army Corps of Engineers (USACE). Safe Software's *Feature Manipulation Engine (FME)* data translation tool package and ESRI's *ArcCatalog* data transformation tool were 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* or *ArcCatolog*, based upon data from the NOAA tide station #9454050 at Cordova (see Section 3.2.1).

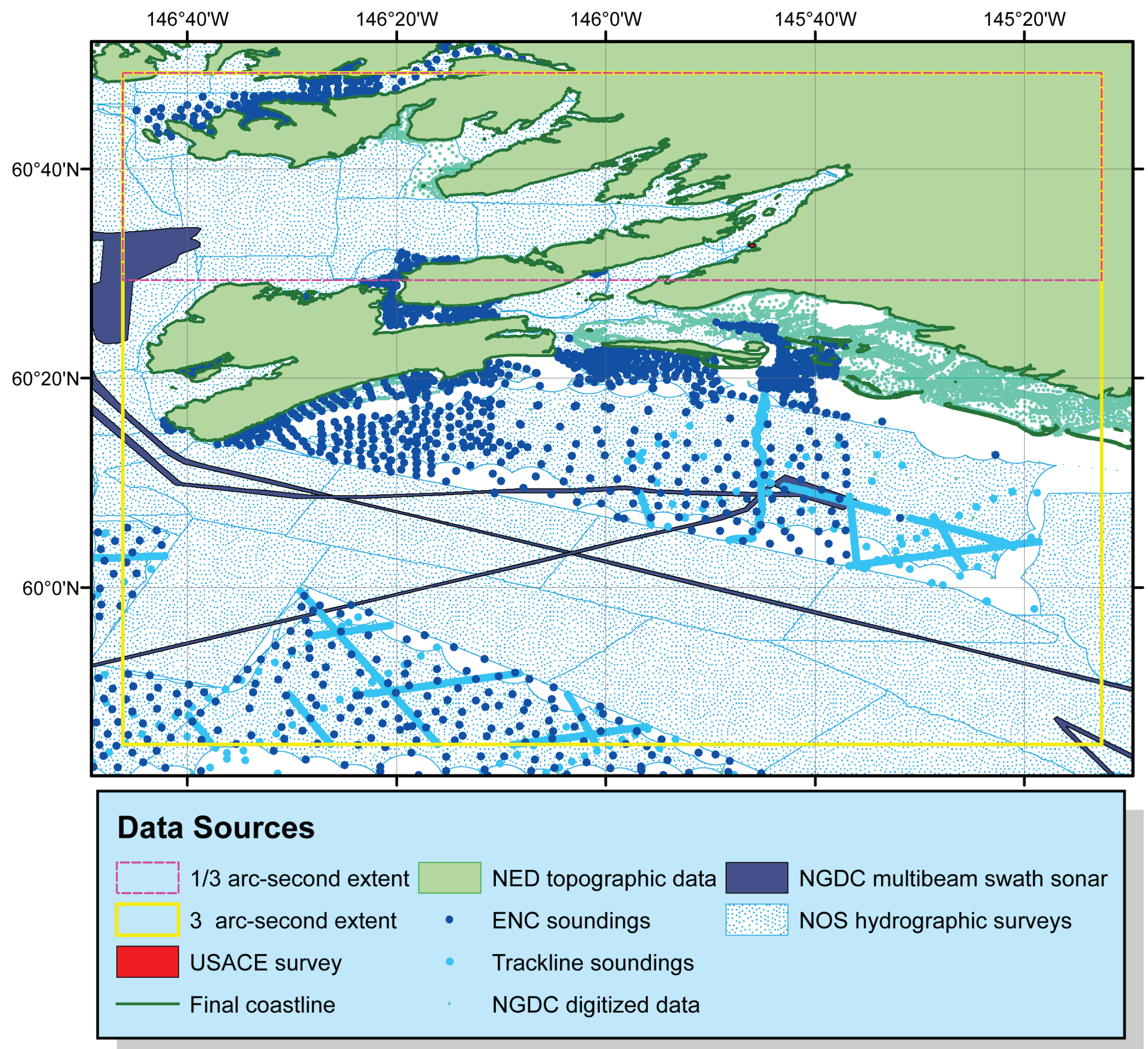

Figure 3. *Source and coverage of datasets used in building the Cordova DEMs. White areas represent data gaps.*

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

3.1.1 *Shoreline*

Coastline datasets of the Cordova region were available from NGDC, OCS, and the U.S. Fish and Wildlife Service (USFWS). The NGDC coastline of the Prince William Sound region was used as the final coastline (Table 2).

Table 2. Shoreline dataset used in building the Cordova DEM.

Source	*Year*	*Data Type*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
FWS	2006	Compiled coastline	Various	WGS 84 geographic	Undefined
NOAA nautical charts	1997-1998	Inferred MHHW coastline	Digitized from 1:10000,1:30000 and 1:80000 scale charts	WGS 84 geographic	Inferred MHHW

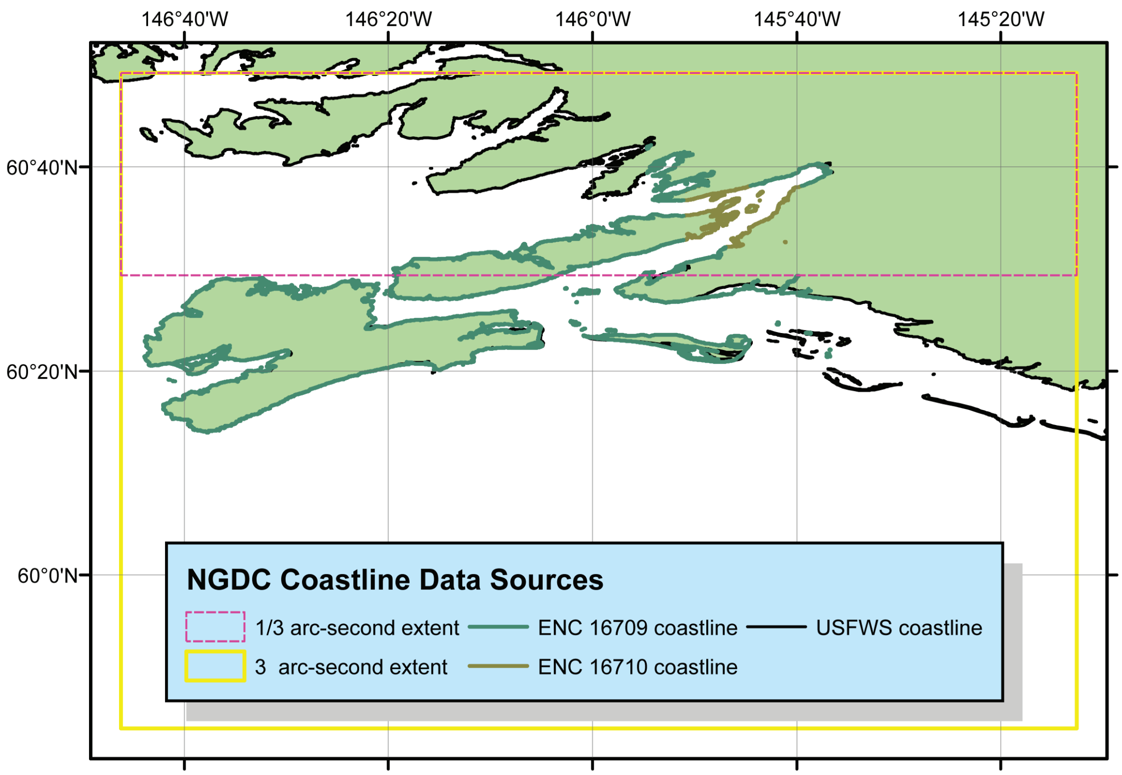

Figure 4. *Source and coverage of datasets used in creating the NGDC coastline of the Prince William Sound region.*

1) U.S. Fish and Wildlife Service

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

2) NOAA nautical charts

Six NOAA nautical charts were available for the Cordova area (see Table 7), and were downloaded from NOAA's Office of Coast Survey web site (http://www.nauticalcharts.noaa.gov/index.html). All charts are available as georeferenced Raster Nautical Charts (RNCs; digital images of the charts), which were used to assess the quality of bathymetric datasets. Most charts were also available as Electronic Navigational Charts (ENCs) that represent chart features as individual digital objects. The ENCs are in S-57 format and include coastline data files referenced to Mean High Water (MHW).

ENCs #16709 and #16710 provided detailed coastlines covering the area surrounding Cordova, Alaska. Both of the ENC coastline datasets contained many piers and other man made structures that had to be removed when building the final coastline. Satellite imagery from Google Earth (http://earth.google.com) and photographs of Cordova, Alaska, were referenced while manually adjusting the coastlines in the immediate vicinity of the harbors.

NGDC created a coastline of the Prince William Sound region, which incorporates the whole region of Cordova. The coastline is a compilation of NOAA ENCs #16706, #16709 and #16710 and the FWS coastline and edited to best fit the topographic and bathymetric data (Caldwell et al., 2009). NGDC clipped the coastline in *ArcMap* to 0.05 degrees larger than the Cordova DEM extents (Fig. 4). The final coastline was sub-sampled to 10-meter spacing using NGDC's *GEODAS* software and converted to xyz data for use in gridding the pre-surface bathymetric grid (see Sect. 3.3.2). It was also used to clip the pre-surfaced bathymetric grid and the National Elevation Dataset (NED) DEM, to prevent negative values on land and positive values over the open ocean.

3.1.2 Bathymetry

Bathymetric datasets used in building the Cordova DEM include: NOS hydrographic surveys, a USACE harbor survey, NOAA ENC and RNC chart soundings, multibeam swath sonar surveys, and trackline surveys (Table 3).

Table 3. Bathymetric datasets used in building the Cordova DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1903-2008	NOS hydrographic soundings	ranges from 1:2,500 to 1:600,00 (varies with scale or survey, depth, traffic, and probability of obstruction)	Early Alaska Datum, Valdez Datum, NAD 27, NAD 83, UTM06 NAD 83	MLLW (meters)	http://ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1970-1977	Trackline (single beam echo-sounder)	soundings between 250 meters apart to 2 kms apart	WGS 84 Geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/geodas/trackline.html
NGDC	2004	Multibeam Swath Sonar	raw MB files gridded to 8 arc-seconds	WGS 84 Geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NGDC	2009	Digitized Soundings	~10 to 100 meters	WGS 84 Geographic	Inferred MHW	
NOAA ENC	2008	NOAA digitized nautical chart soundings	~500 to 1200 meters	WGS 84 Geographic	MLLW (meters)	http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm
USACE	2006	Harbor Survey	~2 to 10 meters	Alaska State Plane, Zone 6, NAD 83 feet	MLLW (feet)	http://www.poa.usace.army.mil/en/hydro/

1) National Oceanographic Survey hydrographic survey data

A total of 61 NOS hydrographic surveys conducted between 1903 and 2008 were available for use in building the Cordova DEM (Table 4; Fig. 5). The hydrographic survey data were originally vertically referenced to MLLW and horizontally referenced to NAD 27 geographic, NAD 83 geographic, Valdez, Early Alaska, 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 (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in their original datums (Table 4). The data were then converted to NAD 83 using *FME* software, an integrated collection of spatial extract, transform, and load tools for data transformation; some NOS surveys 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 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 ENCs, and compared to the NED topographic data and NGDC's coastline. NOS surveys conducted prior to 1965 were clipped to newer surveys to minimize the influence of soundings taken prior to the 1964 earthquake.

Careful evaluation was needed when comparing the NOS point data with old RNCs. A shallow spot on the #16013 RNC showed a depth of 8 fathoms MLLW (~17 meters MHW) on a shoal but the data from survey F00261 showed a depth of ~23 meters. After reviewing the F00261 descriptive report, it was noted that the ~17 meter value from the #16013 RNC was incorrect (Fig. 6).

Table 4. Digital NOS hydrographic surveys available in the Cordova region.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
F00252	1983	2,500	Early Alaska	MLLW
F00261	1984	10,000	Early Alaska	MLLW
H02658	1903	20,000	Undetermined	MLLW
H02665	1903	600,000	Undetermined	MLLW
H02970	1908/1909	15,000	Valdez	MLLW
H02971	1908	40,000	Valdez	MLLW
H03024	1909	200,000	Valdez	MLLW
H03411	1912	20,000	Undetermined	MLLW
H03553	1913	20,000	Undetermined	MLLW
H03704	1914	20,000	Undetermined	MLLW
H03816	1915	20,000	Undetermined	MLLW
H03817	1915	20,000	Undetermined	MLLW
H03954	1916	20,000	Undetermined	MLLW
H03955	1916	20,000	Valdez	MLLW
H03958	1916	80,000	Valdez	MLLW
H03959	1916	10,000	Undetermined	MLLW
H05035	1930	10,000	Early Alaska	MLLW
H05454	1933	80,000	Early Alaska	MLLW
H07628	1947	40,000	Early Alaska	MLLW
H07725	1948	10,000	Early Alaska	MLLW
H08206	1955	10,000	Early Alaska	MLLW
H08852	1965	5,000	Early Alaska	MLLW
H08853	1965	10,000	Early Alaska	MLLW
H08854	1965	20,000	Early Alaska	MLLW
H08901	1966	10,000	NAD 27 geographic	MLLW
H09205	1971	40,000	NAD 27 geographic	MLLW
H09206	1971	40,000	NAD 27 geographic	MLLW
H09382	1973	40,000	Early Alaska	MLLW
H09383	1973	10,000	Early Alaska	MLLW
H09385	1973	20,000	Early Alaska	MLLW
H09386	1973	20,000	Early Alaska	MLLW
H09387	1973	20,000	Early Alaska	MLLW
H09423	1974	20,000	Early Alaska	MLLW
H09424	1974	20,000	NAD 27 geographic	MLLW
H09425	1974	40,000	Early Alaska	MLLW
H09636	1976	10,000	Early Alaska	MLLW
H09713	1977	10,000	Early Alaska	MLLW
H09829	1979	40,000	Early Alaska	MLLW
H09830	1979	40,000	Early Alaska	MLLW
H09831	1979	40,000	Early Alaska	MLLW
H10029	1982	10,000	Early Alaska	MLLW
H10038	1982	10,000	Early Alaska	MLLW
H10090	1983/1984	20,000	Early Alaska	MLLW

NOS Survey ID	Year of Survey	Survey Scale	Original Horizontal Datum	Original Vertical Datum of Digital Records
H10139	1984	40,000	Early Alaska	MLLW
H11200	2003	20,000	NAD 83 geographic	MLLW
H11201	2003	20,000	NAD 83 geographic	MLLW
H11202	2003	20,000	NAD 83 geographic	MLLW
H11203	2003	20,000	NAD 83 geographic	MLLW
H11204	2003	20,000	NAD 83 geographic	MLLW
H11492*	2005	10,000	UTM06 NAD 83 geographic	MLLW
H11496*	2005	10,000	UTM06 NAD 83 geographic	MLLW
H11497*	2005	10,000	UTM06 NAD 83 geographic	MLLW
H11498*	2005	10,000	UTM06 NAD 83 geographic	MLLW
H11499*	2005	10,000	UTM06 NAD 83 geographic	MLLW
H11500*	2005	10,000	UTM06 NAD 83 geographic	MLLW
H11608*	2006	10,000	UTM06 NAD 83 geographic	MLLW
H11609*	2006	10,000	UTM06 NAD 83 geographic	MLLW
H11611*	2006	10,000	UTM06 NAD 83 geographic	MLLW
H11637*	2007	20,000	UTM06 NAD 83 geographic	MLLW
H11742*	2007	10,000	UTM06 NAD 83 geographic	MLLW
H11752*	2008	10,000	UTM06 NAD 83 geographic	MLLW

*indicates NOS shallow-water multibeam sonar survey

Note: Some earlier surveys were referenced to horizontal datums with no known conversions to NAD 83 geographic. These surveys were manually adjusted in ArcGIS to fit the final coastline.

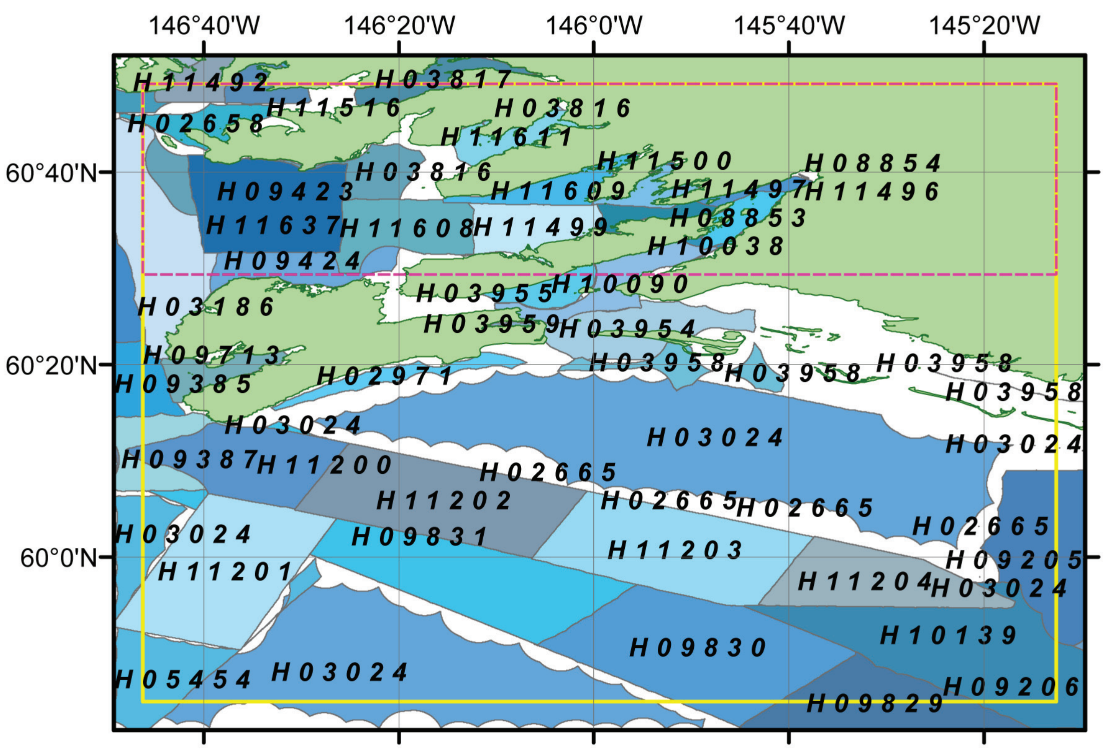

Figure 5. Digital NOS hydrographic survey coverage in the Cordova region. Yellow box denotes the boundary of 3 arc-second DEM;. pink box denotes the boundary of 1/3 arc-second DEM.

2) **NGDC trackline surveys**

Five trackline surveys (Table 5, Fig. 6) were available from the NGDC Marine Trackline Geophysics Database for use in building the Cordova DEMs. The Marine Trackline Geophysics Database contains bathymetry, magnetics, gravity, and seismic navigation data collected during marine cruises from 1953 to present. All of the surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be MSL. The data were downloaded as xyz files and were then converted to shapefiles and transformed to MHW using *FME* software. Only soundings where no data were available were used in building the Cordova DEMs (Fig. 6).

Table 5. Trackline surveys used in building the Cordova DEMs.

Survey ID	*Institution*	*Year*
conmals	NOAA NOS	1972
f186ga	USGS	1986
g175eg	USGS	1975
l677eg	USGS	1977
s877eg	USGS	1977
yaq703	Oregon State University (OSU)	1970

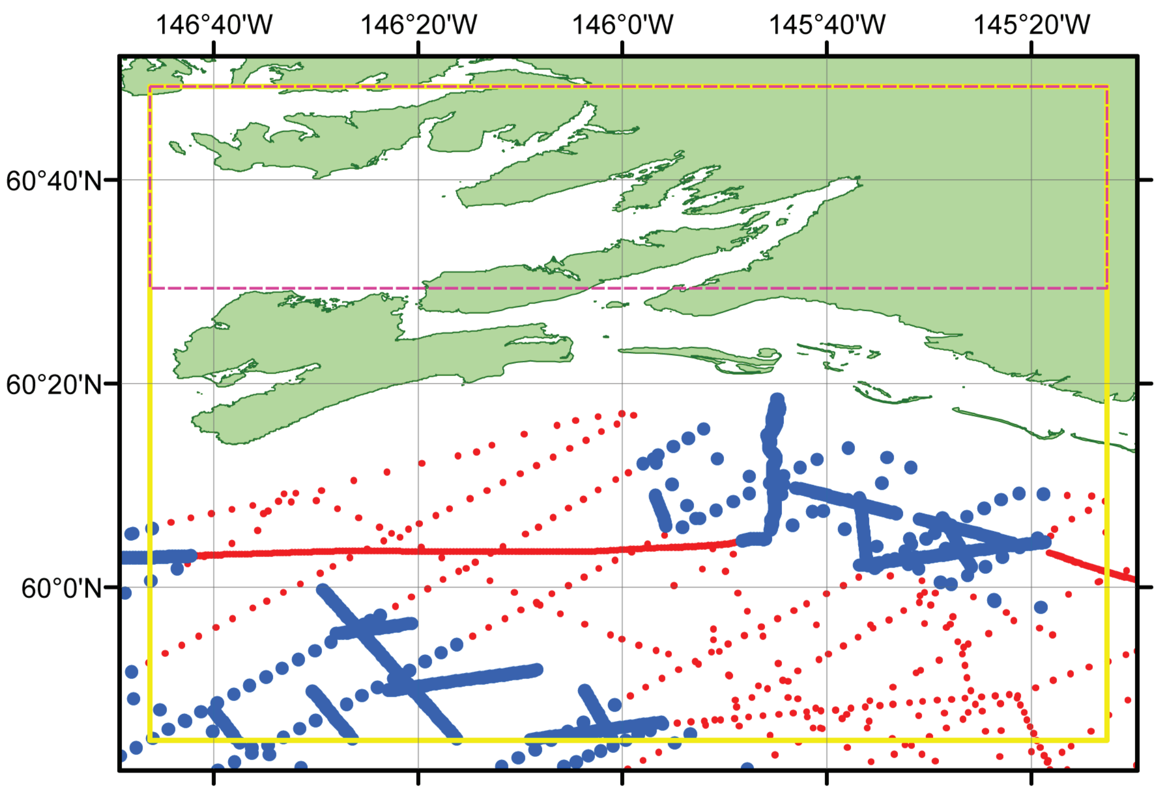

Figure 6. *Available trackline data. Soundings in blue were used in building the Cordova DEMs, soundings in red were superseded by newer, higher-resolution data and were not used.*

3) Multibeam swath sonar surveys

One multibeam swath sonar survey (Table 6, see Fig. 3) was available from the NGDC Multibeam Bathymetry Database for use in building the Cordova DEMs. The NGDC database is comprised of the original swath sonar files of surveys conducted mostly by U.S. academic fleet.

Most of the NGDC multibeam swath sonar survey was a transit rather than a dedicated seafloor survey. The survey has a horizontal datum of WGS 84 geographic and undefined vertical datum, assumed to be equivalent to MSL.

The downloaded data were gridded at 1 arc-second using the *MB-System*[4] tool 'mbgrid' to apply a tight spline tension. *MB-System* is an NSF-funded free software application specifically designed to manipulate multibeam swath sonar data. The gridded data were converted to MHW using *ArcCatalog* by adding a constant offset measured at the Cordova tide station (see Sect. 3.2.1).

The outer beams of the survey displayed a general upwards curvature. NGDC used *MB-System's* 'mbclean' tool to automatically remove the last outer eight pings from each side of the survey to smooth the edges (Fig. 7).

Table 6. Multibeam swath sonar survey used in building the Cordova DEMs.

Survey ID	*Ship*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Institution*
EW0409	Ewing	2004	Assumed Mean Sea Level	WGS 84 geographic	Columbia University

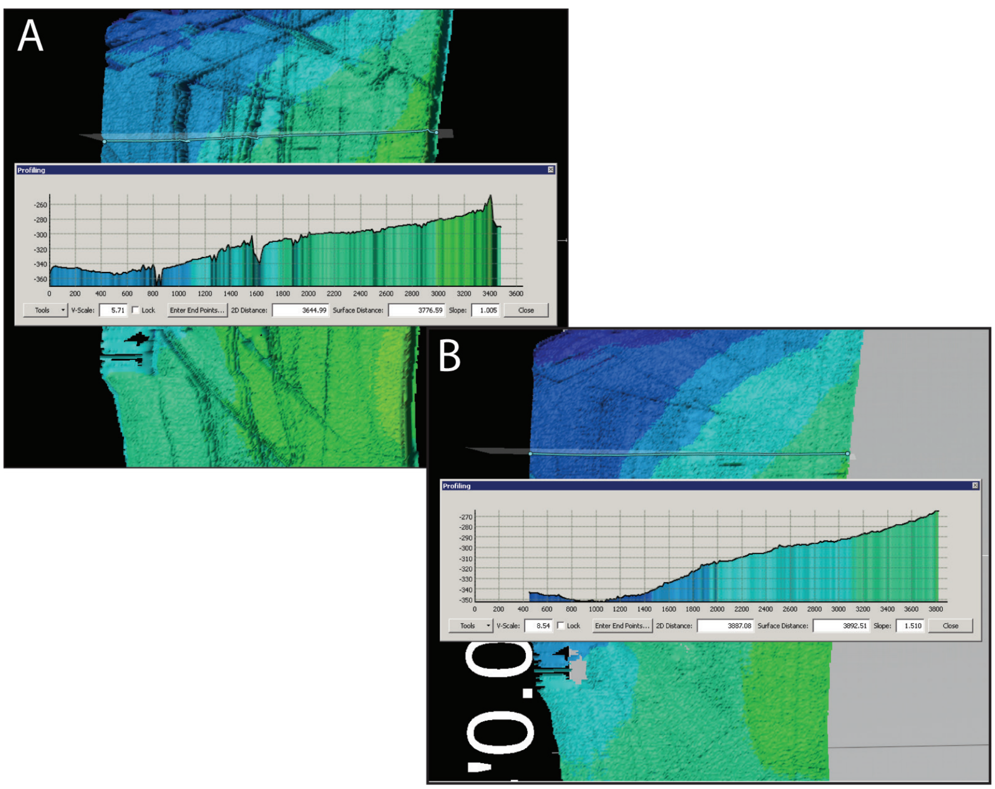

Figure 7. *Cross-sections of a portion of the multibeam survey. A) Before the survey was edited. B) After the outer 8 pings were removed using 'mbclean'.*

4. 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.]

4) NGDC Digitized Soundings

The Copper River Delta region, approximately 10 kilometers southeast of Cordova, had only old sparse NOS data and very few ENC soundings, leaving virtually no data to represent the current morphology. The delta is in a constant state of change and it should be noted that the DEM likely does not accurately reflect the correct depths or elevations of the delta and its mud flats. NGDC digitized depths in the channels from 5 to 20 feet based on Coast Pilot 9, satellite imagery (ESRI's World Imagery 2D Layer) and RNC #16709, to most accurately represent the modern morphology (Fig. 8).

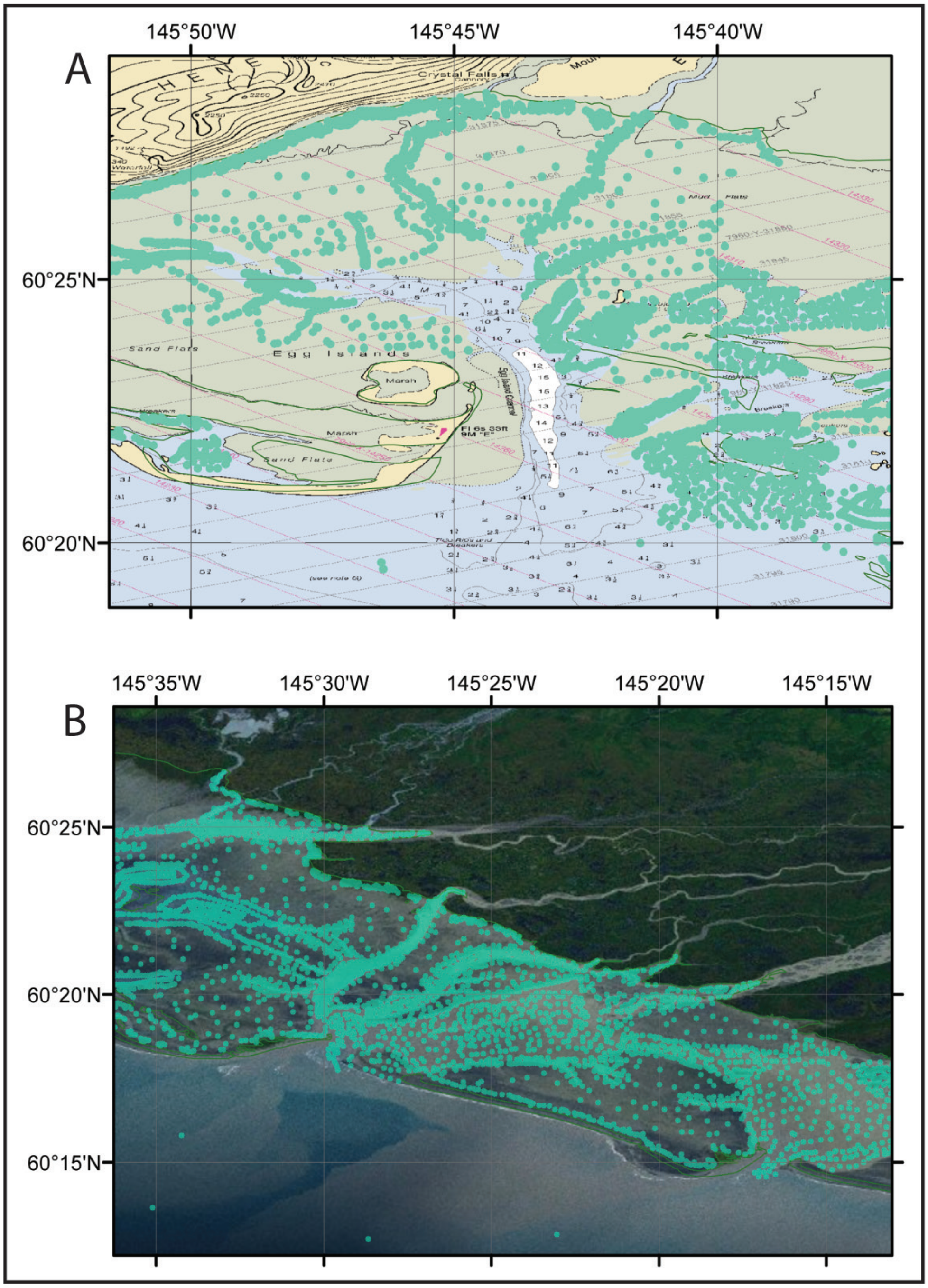

Figure 8. *NGDC digitized soundings in the Copper River Delta to help maintain negative depths in the DEM and represent modern morphology.*
A) Location of digitized soundings (green) in the channels based on RNC #16709.
B) Location of digitized soundings (green) in the channels based on satellite imagery.

5) NOAA Electronic Navigational Chart soundings

Nautical charts #531, #16700, #16708 and #16709 were available from NOAA's Office of Coast Survey in ENC chart format. As no digital bathymetric survey data were available in some of these areas, sounding data were extracted from these charts using *FME*. The point spacing and vertical resolution of the ENCs vary by the scale of the charts. Table 7 lists all available ENCs and RNCs of the Cordova region.

Table 7. NOAA nautical charts available of the Cordova region.

Chart	Title	Edition	Edition Date	Format	Scale
531	Gulf of Alaska, Strait of Juan de Fuca to Kodiak Island	13th	2008	ENC and RNC	1:2,100,000
16700	Prince William Sound	2nd	2008	ENC and RNC	1:200,000
16708	Prince William Sound, Port Fialgo and Valdez Arm	15th	2008	ENC and RNC	1:79,291 with 1:40,000 inset
16709	Prince William Sound, Eastern Entrance	11th	2008	ENC and RNC	1:80,000
16710	Orca Bay and Inlet Channel Islands to Cordova	6th	2008	ENC and RNC	1:30,000
16013	Cape St. Elias to Shumagin Islands	30th	2008	RNC	1:969,761

6) USACE harbor surveys

USACE conducted a high-resolution hydrographic harbor survey of Cordova Harbor in 2006 (Fig. 9). The survey was originally referenced to NAD 83 UTM Zone 3 Alaska State Plane coordinates (feet) and MLLW vertical datum (feet). The horizontal spacing of the surveys ranges from ~2 to 10 meters with depths ranging from -0.12 to -13.61 meters at MHW.

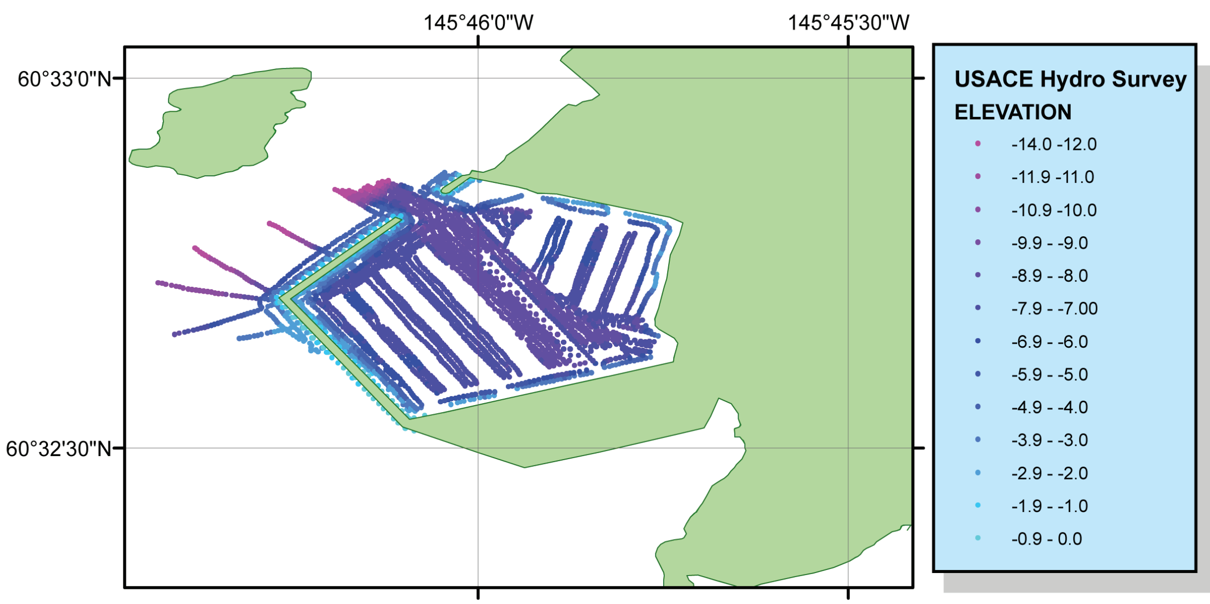

Figure 9. *Coverage of the USACE hydrographic survey used in building the Cordova DEMs.*

3.1.3 *Topography*

One topographic dataset of the Cordova region was obtained from the USGS: NED 2 arc-second gridded topography (Table 8; See Fig. 3). Advanced Spaceborne Thermal Emission and Reflection (ASTER) data were also downloaded and evaluated but were not used in gridding due to anomalies errors along the coast.

Table 8. Topographic dataset used in building the Cordova DEMs.

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/

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

The U.S. Geological Survey's (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provides complete 2 arc-second coverage of Alaska[5]. Data are in NAD 27 geographic coordinates and National Geodetic Vertical Datum 29 (NGVD29; 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 quadrangle maps and aerial photos based on surveys conducted in the 1970s and 1980s.

Evaluation of the NED data indicated three issues that required quality control. First, the NED data had values over the open ocean that were deleted by clipping to the coastline (Fig. 10a). Second, the NED data had missing data along the coast which were interpolated using a smoothing process (see Sect. 3.3.3; Fig. 10b). Last, the NED data in this region were misaligned with other datasets by approximately one grid cell (60 meters) to the south. This resulted in a preponderance of steep slopes on south facing shores (Fig, 10c). To rectify the issue, the data were shifted northward by 60 meters prior to using the data in the DEM development.

5. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Alaska. The dataset provides seamless coverage of the United States, Hawai'i, Alaska, 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 Alaska, which is NAD 27. The vertical datum is NAVD 88, except for Alaska, which is NGVD 29. 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]

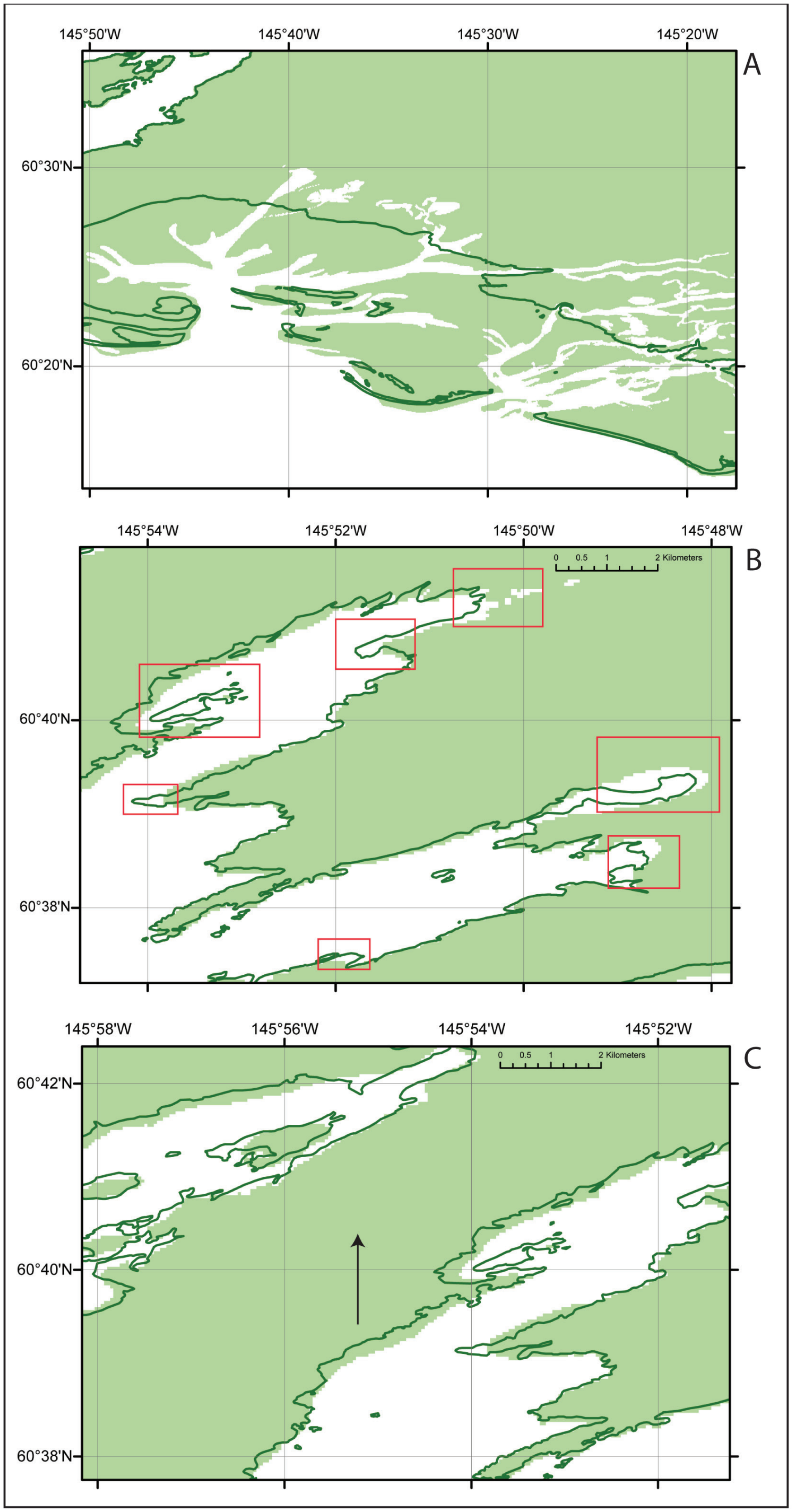

Figure 10. *Problems in the USGS NED raster data. A) Data over the open ocean, which were removed by clipping the raster to the coastline. B) Data gaps along the coast, which were filled in using interpolation. C) Data were offset by ~2 arc-second to the south, which required a northward shift of the data before gridding.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in building the Cordova DEMs were originally referenced to a number of vertical datums including: MLLW, MSL, and NGVD 29. All datasets were transformed to MHW to provide the maximum flooding for inundation modeling. Vertical datum transformations to MHW were accomplished using *FME* and *ArcGIS*, based upon data from NOAA tide station # 9454050 located at Cordova Harbor.

1) Bathymetric data

The NOS hydrographic surveys, the USACE harbor survey, and the ENC soundings were transformed from MLLW to MHW, using *FME* software, by adding a constant offset of -3.56 meters, measured at the NOAA Cordova tide station. The multibeam swath sonar survey and trackline surveys were transformed from MSL to MHW by adding a constant offset of -1.50 meters (Table 9).

2) Topographic data

The NED DEM was originally referenced to NGVD 29 vertical datum. There are no survey markers in the vicinity of Cordova that relate these two geodetic datums to the local tidal datums. Thus, it was assumed that the datum is essentially equivalent to MSL in this area (Table 9). The data were converted to MHW using *ArcGIS*, by adding a constant offset of -1.50 meters.

Table 9. Relationship between MHW and other vertical datums in the Cordova region.*

Vertical datum	*Difference to MHW*
MSL/NGVD 29+	-1.50
MLLW	-3.56

* Datum relationships determined by tidal station #9454050 at Cordova, Alaska.
\+ NGVD 29 assumed to be equivalent to MSL.

3.2.2 Horizontal datum transformations

Datasets used to build the Cordova DEMs were originally referenced to Early Alaska, Valdez, undetermined, NAD 83 Alaska State Plane (feet), NAD 83 UTM Zone 6N geographic (meters), and NAD 27 geographic, NAD 83 geographic, and WGS 84 geographic horizontal datums. The relationships and transformational equations between the Alaska State Plane, UTM, and geographic horizontal datums are well established. These data were converted to a horizontal datum of NAD 83 geographic using *FME* software. The NOS surveys referenced to Early Alaska, Valdez and undetermined horizontal datums 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 and rasters were checked in ESRI *ArcMap* and *Quick Terrain Modeler* for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated datasets were then converted to xyz files in preparation for gridding. Problems included:

- Data values over the open ocean in the NED topographic DEMs. The dataset required automated clipping to the final coastline.
- NED data were misaligned approximately one cell (2 arc-seconds) southward and required shifting to the north.
- The 2 arc-second NED data were coarse for a 1/3 arc-second DEM.
- Limited bathymetric data available near the Copper River delta.
- Sparse bathymetric data in the southern region of the 3 arc-second DEM.
- Many areas with no bathymetric data near the coastline, particularly in and near retreating glaciers.
- Misaligned NOS surveys with Early Alaska, Valdez, or undetermined horizontal datums.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the Cordova DEMs. In both deep water and near shore, some NOS survey data have point spacing up to 1.5 kilometers apart. Where no NOS data exists, even more sparse ENC and trackline data were used to fill gaps. In order to reduce the effect of artifacts in the DEMs due to low resolution datasets, and to provide effective interpolation into the coastal zone, bathymetric pre-surfaces or grids were generated using *GMT*[6], an NSF-funded share-ware software application designed to manipulate data for mapping purposes.

A 1 arc-second pre-surface grid was compiled for the 1/3 arc-second DEM and a 9 arc-second 'pre-surface' grid was compiled for the 3 arc-second DEM . The grids were built from NOS hydrographic surveys, USACE hydrographic survey, ENC soundings, trackline surveys, and NGDC multibeam swath sonar survey data. The data were converted to xyz files and combined into a single file, along with points extracted every 10 meters from the final coastline. To provide a slightly negative buffer along the entire coastline, the extracted coastline points were assigned 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 in most areas. These point data were then smoothed using the *GMT* tool 'blockmedian' onto a 1 and 9 arc-second grid. The *GMT* tool 'surface' was then applied to interpolate values for cells without data values. The netcdf grids created by 'surface' were converted into an ESRI Arc ASCII grid file using the *MB-System* tool 'mbm_grd2arc'. Conversion of the Arc ASCII grid files into an Arc raster permitted clipping of the grid with the final coastline to eliminate data interpolation into land areas.

The pre-surface grids were compared with the original soundings to ensure grid accuracy, and then exported as xyz files for use in the final gridding process (Table 10). The statistical analysis of the differences between the 1/3 arc-second bathymetric surfaces at Cordova and NOS survey H11752 and the USACE harbor survey, show that the majority of the NOS soundings are in good agreement (Figs. 11 and 12) with the bathymetric surface. The few exceptions where the differences reached up to 8 meters are attributed to rugged bathymetry where two or more closely positioned points were averaged to obtain the elevation of one grid cell.

6. GMT is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from GMT web site.

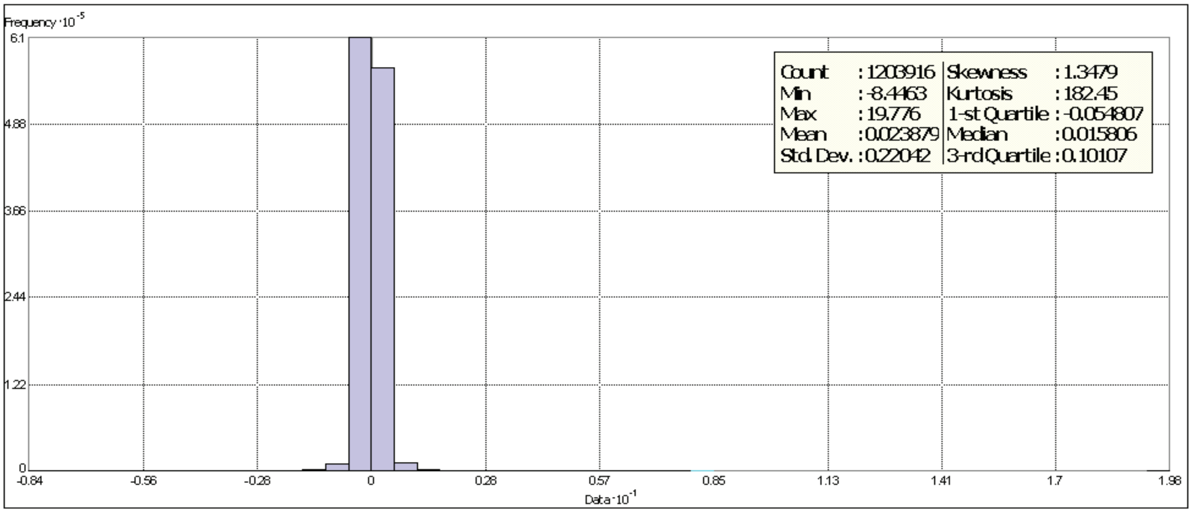

Figure 11. *Histogram of the differences between NOS hydrographic survey H11752 and the 1 arc-second pre-surfaced bathymetric grid.*

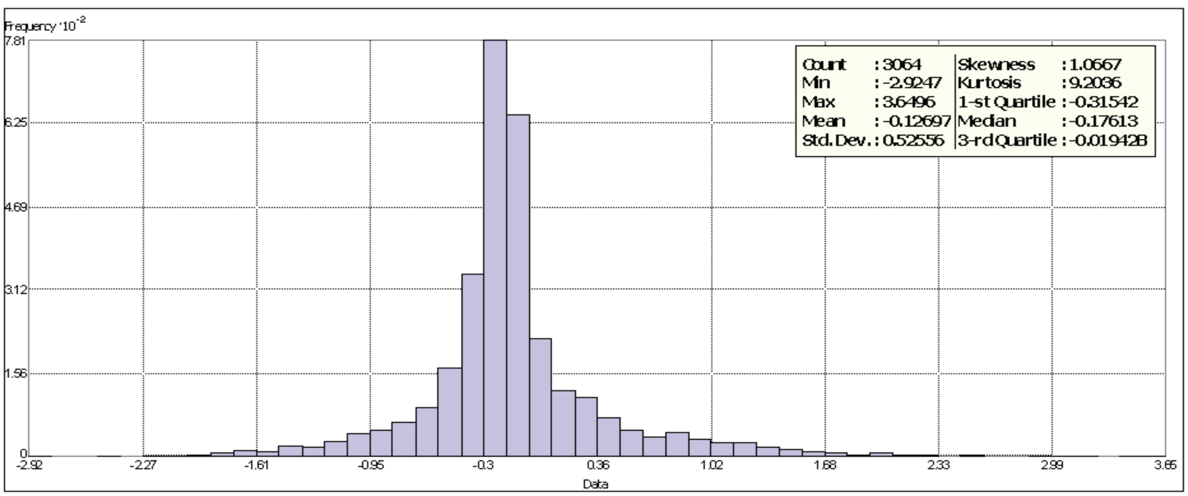

Figure 12. *Histogram of the differences between the USACE harbor survey and the 1 arc-second pre-surface bathymetric grid.*

3.3.3 Smoothing of topographic data

The resolution of the NED data (2 arc-seconds) was coarse compared to the 1/3 arc-second grid and led to unrepresentative slopes where zero values at the coast interpolated to the nearest NED point data. To better approximate the local topography in the high-resolution grids, the *GMT* tool 'surface' was applied using two datasets: (a) the 2 arc-second NED data points clipped to the coastline and then to extents slightly larger (~ 5 percent) than the 1/3 arc-second high-resolution grid and (b) points at 0 meters elevation extracted every 10 meters from the final coastline. These point data were then smoothed onto a 1/3 arc-second grid using the 'surface' tool. The resultant Arc ASCII grid was converted to a raster and then clipped again to the final coastline to eliminate data interpolation into bathymetric regions. The surface was then compared with the original NED data to ensure grid accuracy, converted to a shapefile, and then exported as an xyz file for use in the final gridding process.

3.3.4 Building the 1/3 arc-second and 3 arc-second DEMs with MB-System

MB-System was used to create 1/3 and 3 arc-second DEMs of Cordova. The *MB-System* tool 'mbgrid' was used to applied 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 high-resolution datasets and digitized features. Least weight was given to the pre-surfaced bathymetric grids and trackline soundings.

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

Dataset	*Relative Gridding Weight*
USACE surveys	10
USGS NED topographic DEM	10
ENC soundings	10
NGDC digitized features	10
NOS hydrographic surveys	10
NGDC hydrographic sonar multibeam	10
Pre-surfaced bathymetric grid	0.1
Trackline soundings	0.1

3.4 Quality Assessment of the DEMs

3.4.1 Horizontal accuracy

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

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the DEMs are also highly dependent upon the source datasets contributing to grid cell values. Topographic datasets have vertical accuracies of between 10 and 15 meters. Bathymetric values are derived from a wide range of input data, consisting of single and multibeam sounding measurements from the early 20th century to recent GPS-navigated sonar surveys. Modern NOS standards are 0.3 meters in 0 to 20 meters of water, 1.0 meter in 20 to 100 meters of water, and 1% of the water depth in 100 meters 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 1/3 and 3 arc-second DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Figs. 13 and 14). The DEMs were transformed to NAD 83/UTM Zone 6 coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grids; 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,* a shareware tool for generating three-dimensional graphics (http://www.povray.org). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEMs.

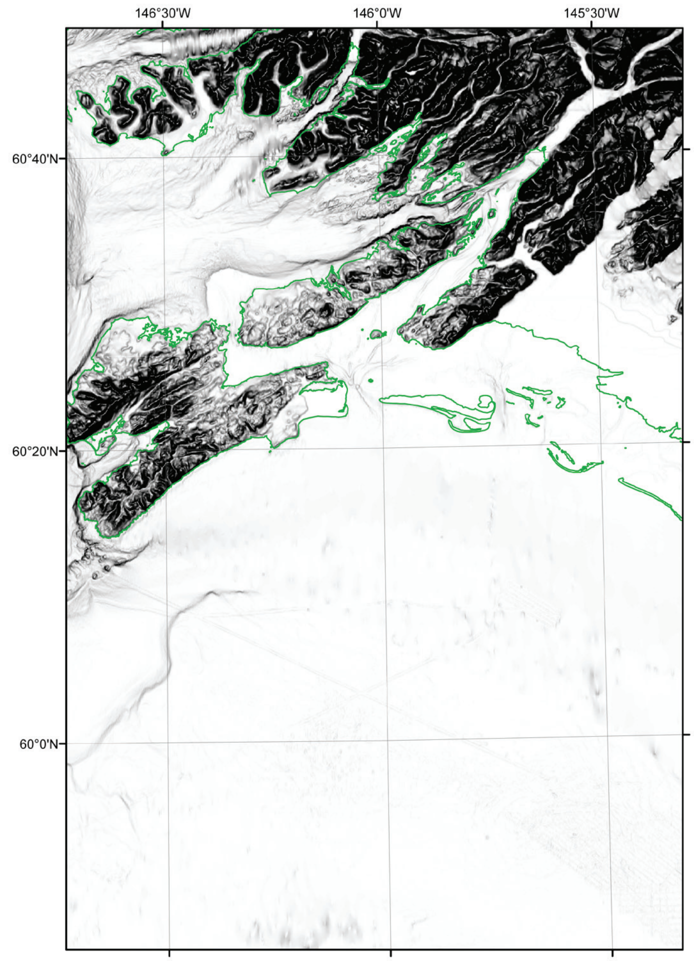

Figure 13. Slope map of the 3 arc-second Cordova DEM. Flat-lying slopes are white; dark shading denotes steep slopes; final coastline in green.

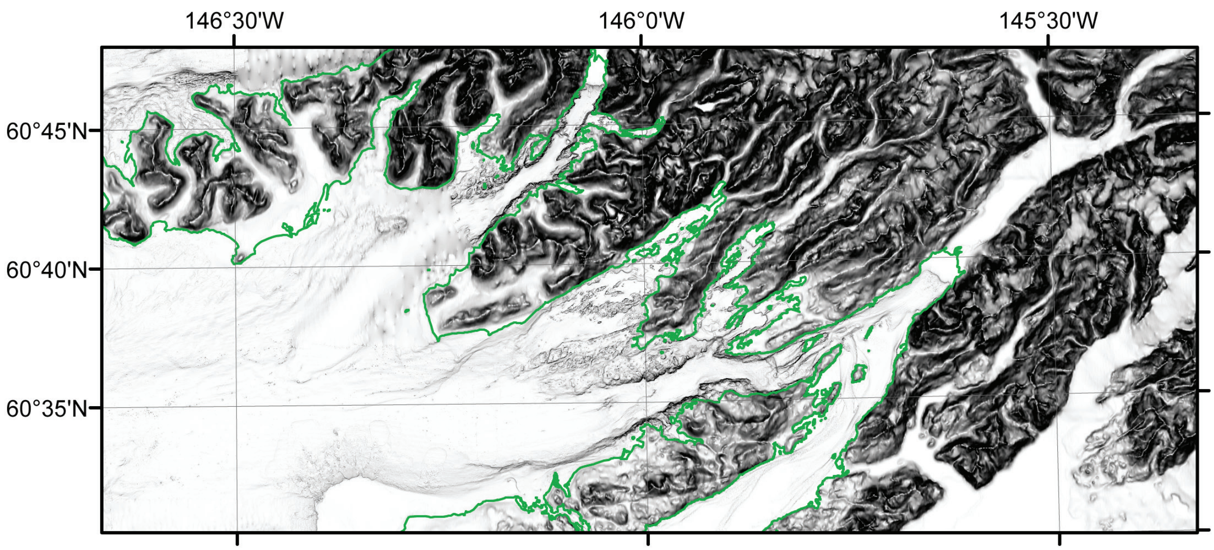

Figure 14. Slope map of the 1/3 arc-second Cordova DEM. Flat-lying slopes are white; dark shading denotes steep slopes; final coastline in green.

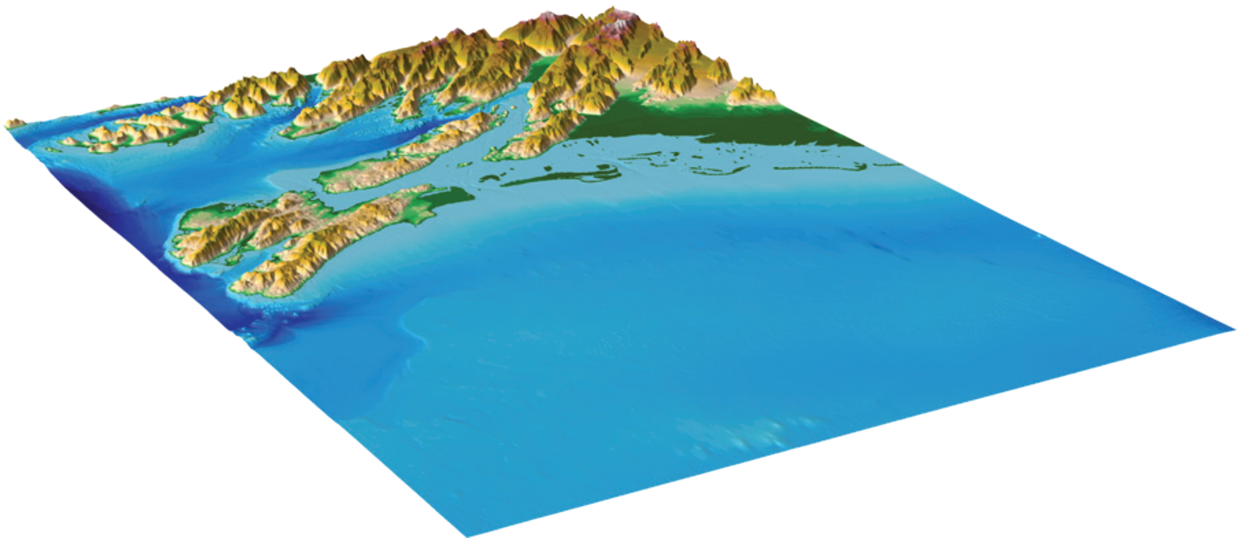

Figure 15. *Perspective view from the southwest of the 3 arc-second Cordova DEM. Vertical exaggeration is 2 times.*

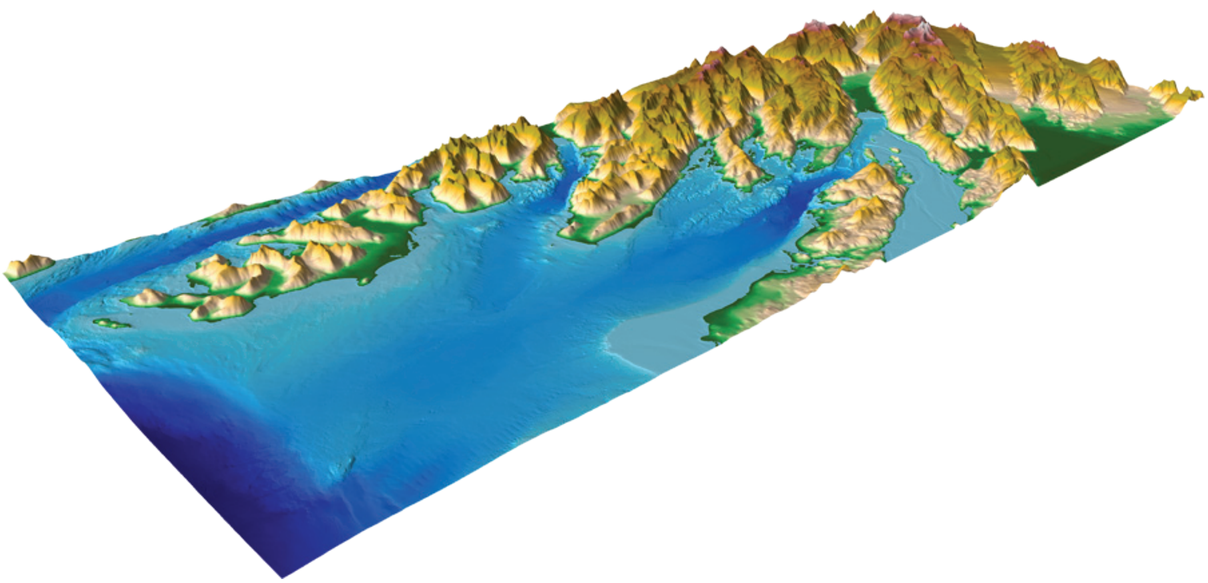

Figure 16. *Perspective view from the southwest of the 1/3 arc-second Cordova DEM. Vertical exaggeration is 2 times.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the 1/3 and 3 arc-seconds Cordova DEMs were compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas. A histogram of the differences between selected NED data points and the 3 arc-second Cordova DEM is shown in Figure 17; a histogram between the NGDC multibeam swath sonar survey and the 3 arc-second Cordova DEM is shown in Figure 18; and a histogram of the differences between NOS survey H11752 and the 1/3 arc-second Cordova DEM is shown in Figure 19. The data sources show relatively good agreement with the DEMs. Minor differences are most likely due to averaging of data in steep topography/bathymetry.

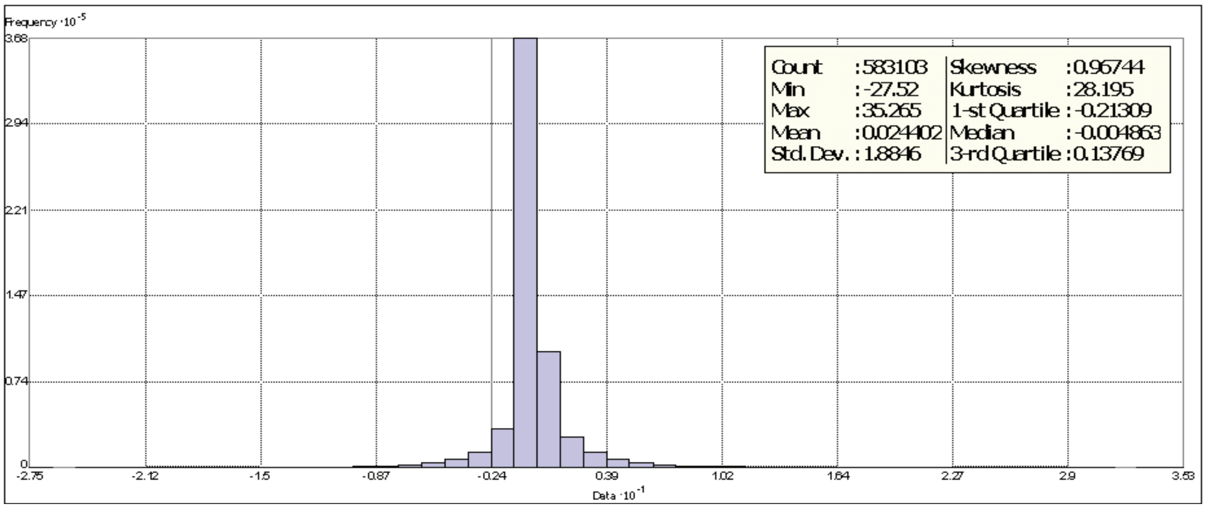

Figure 17. *Histogram of the differences between the NED topographic dataset and the 3 arc-second Cordova DEM.*

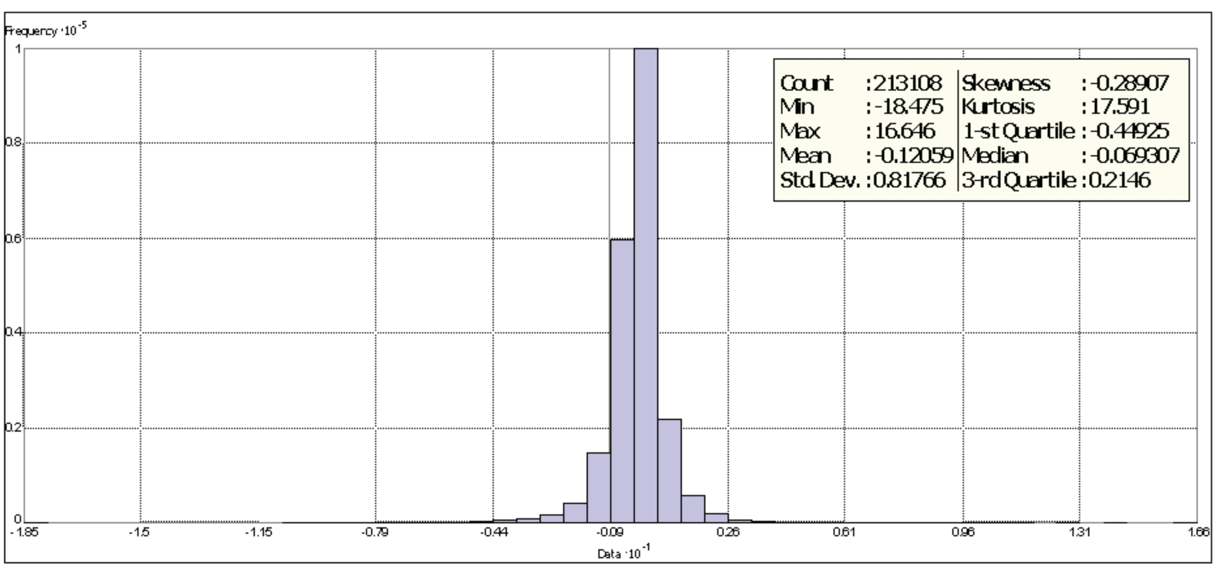

Figure 18. *Histogram of the differences between the NGDC multibeam swath sonar survey and the 3 arc-second Cordova DEM.*

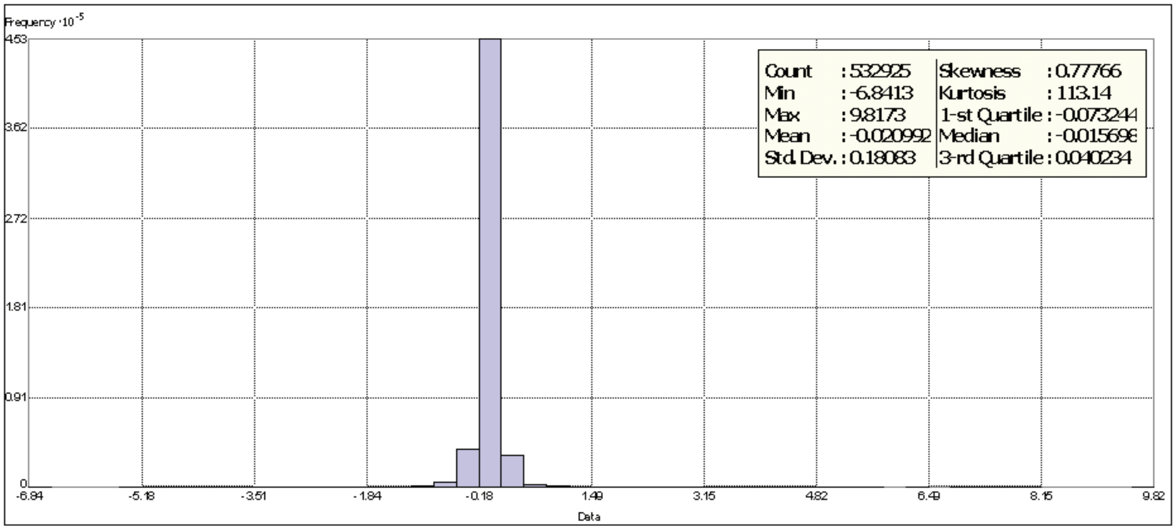

Figure 19. *Histogram of the differences between NOS survey H11752 and the 1/3 arc-second Cordova DEM.*

3.4.5 *Comparison with USGS topographic elevations*

USGS topographic quadrangle Cordova C-5 SW was downloaded for the Cordova vicinity (http://agdc.usgs.gov/data/usgs/to_geo.html). The Cordova quadrangle gives position and elevation in NAD 83 and NGVD 29 vertical datum (in meters) and has a scale of 1:25,000 with a 20-meter contour interval.

A contour map with a 20-meter interval was created using the 1/3 arc-second DEM. The contour map was then compared against the USGS topographic quadrangle contours (Fig. 20). Although the figures show that differences exist between the 1/3 arc-second DEM and the USGS topographic map contours, the morphology of the regions surrounding Cordova is preserved. The NED topographic data at 2 arc-seconds is coarse for a 1/3 arc-second DEM making the DEM contours appear smoothed compared to the USGS contours.

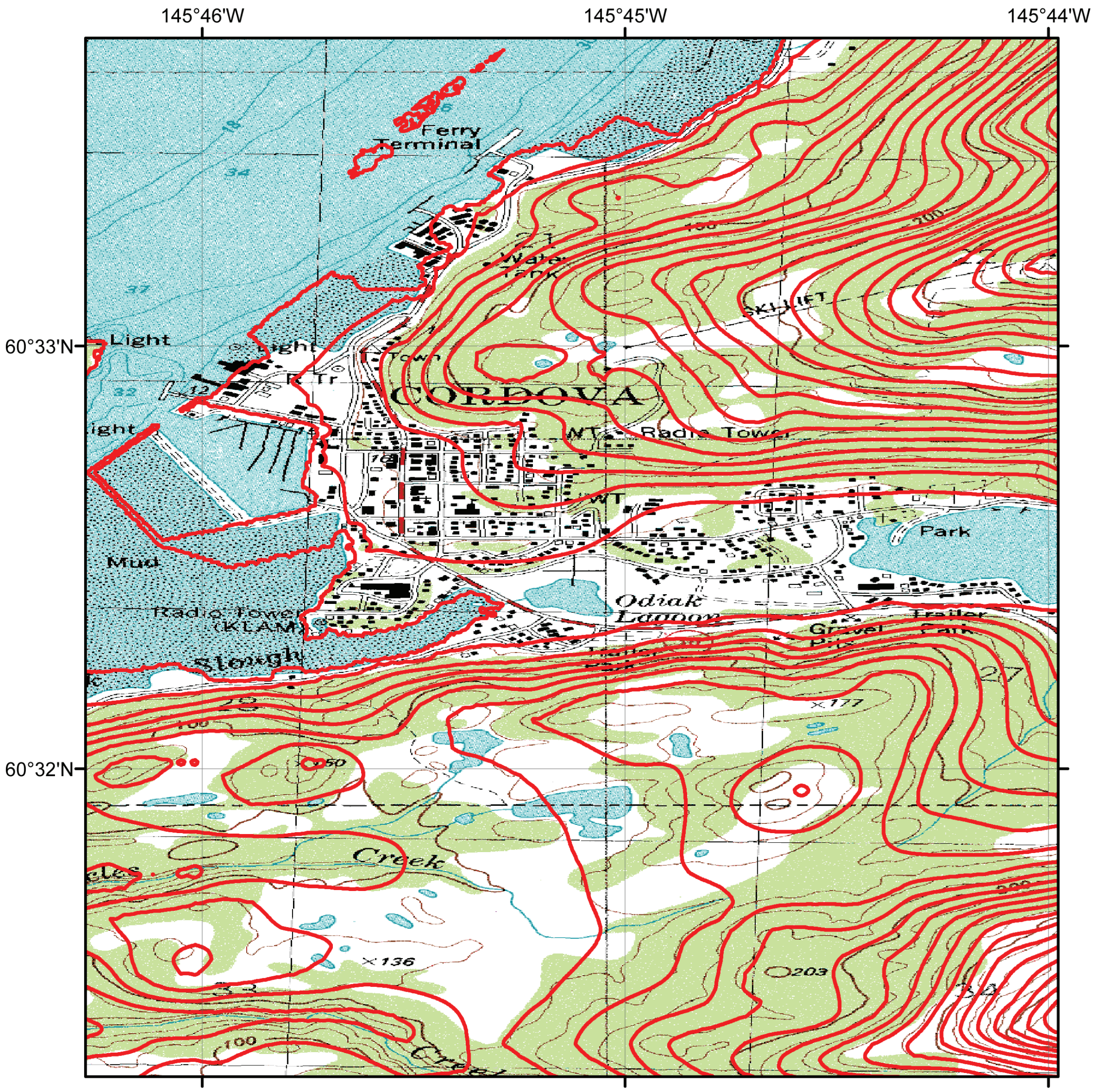

Figure 20. *Comparison between USGS topographic contours and the 1/3 arc-second Cordova DEM topographic contours. Brown lines and numbers represent 20 meter contours from the USGS topographic map. Red lines represent 20 meter contours from the 1/3 arc-second Cordova DEM.*

4. Summary and Conclusions

Two integrated bathymetric-topographic DEMs of Cordova, Alaska, with cell sizes of 1/3 arc-second and 3 arc-second, were developed for the 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 *ArcGIS*, *FME*, *GMT*, *Quick Terrain Modeler*, *Fledermaus* and *MB-System* software.

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

- Conduct new bathymetric surveys in the southern region of the 3 arc-second DEM area where digital sounding data are sparse or non-existent.
- Conduct high-resolution topographic surveys of Cordova.
- Obtain more recent data in the Copper River delta.
- Determine the relationship between Early Alaska and NAD 83/WGS 84 geographic horizontal datums.

5. Acknowledgments

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Nautical Chart #531 (ENC and RNC), 13th Edition, 2008. Gulf of Alaska, Strait of Juan de Fuca to Kodiak Island. 1:2,100,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16013 (RNC), 30th Edition, 2008. Cape St. Elias to Shumagin Islands. 1:969,761 with 1:400,000 inset. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16700 (ENC and RNC), 2nd Edition, 2008. Prince William Sound. 1:200,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16708 (ENC and RNC), 15th Edition, 2008. Prince William Sound, Port Fidalgo and Valdez Arm. 1:79,291 with 1:40,000 inset. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16709 (ENC and RNC), 11th Edition, 2008. Prince William Sound, Eastern Entrance. 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #16710 (ENC and RNC), 6th Edition, 2008. Orca Bay and Inlet Channel Islands to Cordova. 1:30,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.3, developed and licensed by ESRI, Redlands, California, http://www.esri.com/

ESRI Imagery World 2D Online World Imagery 2D – ESRI ArcGIS Resource Centers, http://resources.arcgis.com/

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

FME 2009 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.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. 4.3.0 – 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/