NOAA Technical Memorandum NESDIS NGDC-27

DIGITAL ELEVATION MODELS OF CRAIG, ALASKA: PROCEDURES, DATA SOURCES AND ANALYSIS

E. Lim
L.A. Taylor
B.W. Eakins
K.S. Carignan
R.R. Warnken
P.R. Medley

National Geophysical Data Center
Marine Geology and Geophysics Division
Boulder, Colorado
March 2009

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Environmental Satellite, Data, and Information Service

NOAA Technical Memorandum NESDIS NGDC-27

DIGITAL ELEVATION MODELS OF CRAIG, ALASKA: PROCEDURES, DATA SOURCES AND ANALYSIS

Elliot Lim[1]
Lisa A. Taylor[2]
Barry W. Eakins[1]
Kelly S. Carignan[1]
Robin R. Warnken[2]
Pamela R. Medley[1]

[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder

[2]NOAA, National Geophysical Data Center, Boulder, Colorado

National Geophysical Data Center
Marine Geology and Geophysics Division
Boulder, Colorado
March 2009

UNITED STATES DEPARTMENT OF COMMERCE

Gary Locke
Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Dr. Jane Lubchenco
Under Secretary for Oceans and Atmosphere/Administrator

National Environmental Satellite, Data, and Information Service

Mary E. Kicza
Assistant Administrator

NOTICE

Corresponding project contact:
Lisa A. Taylor
NOAA National Geophysical Data Center
Marine Geology and Geophysics Division
325 Broadway, E/GC 3
Boulder, Colorado 80305
Phone: 303-497-6767
Fax: 303-497-6513
E-mail: Lisa.A.Taylor@noaa.gov
http://www.ngdc.noaa.gov/mgg/inundation/tsunami/inundation.html

---

Also available from the National Technical Information Service (NTIS)
(http://www.ntis.gov)

Contents

List of Figures

List of Tables

Digital Elevation Models of Craig, Alaska: Procedures, Data Sources and Analysis

1. Introduction

In October 2008, 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 Craig, Alaska (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for the Tsunami Research (http://nctr.pmel.noaa.gov/). The 1 arc-second[1] and 1/3 arc-second 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. 2) 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 Craig DEMs.

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

1. In polar latitudes, longitude lines are spaced significantly closer together than latitude lines, approaching zero at the poles. While the DEMs are built upon grids of square cells in geographic coordinates, they are not square cells when converted to meters. At the latitude of Craig, Alaska (55º28’35”N, 133º8’54”W) 1 arc-second of latitude is equivalent to 30.68 meters; 1 arc-second of longitude equals 17.42 meters.

2. Study Area

Craig, Alaska is located at 55º28'35"N 133º8'54"W, on Craig Island, connected to the west coast of Prince of Wales Island. It is a part of the Alexander Archipelago and is approximately 56 miles northwest of Ketchikan and 220 miles south of Juneau. The Prince of Wales Island spans an area of more than 2,600 square miles and covers 990 miles of coastline. The islands in the area are the exposed peaks of submerged coastal mountains that rise steeply from the Pacific Ocean. The morphology is characterized by deep, fjord-like channels that separate the islands and cut them off from the mainland. In addition, forested mountains, deep U-shaped valleys, streams, lakes, and bays are prevalent in the area.

The town was named after Craig Miller who established a fish saltery on nearby Fish Egg Island in 1907 with the assistance of the local Haida natives. He went on to construct a cold storage plant and packing company at the present site of Craig, Alaska.

3. Methodology

The Craig DEMs 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. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum of 1983 (NAD 83) geographic and mean high water (MHW), for modeling of maximum flooding, respectively[2]. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1a: PMEL specifications for the 1 arc-second Craig DEM.

Grid Area	Craig, Alaska
Coverage Area	132.49 º to 134.31º W; 54.49º to 56.28º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	MHW
Vertical Units	Meters
Cell Size	1 arc-second
Grid Format	ESRI ASCII raster grid

Table 1b: PMEL specifications for the 1/3 arc-second Craig DEM.

Grid Area	Craig, Alaska
Coverage Area	133.00 º to 133.46º W; 55.30º to 55.63º 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

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

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 2) were obtained from several U.S. federal and academic agencies, including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), and NGDC; the U.S. Fish and Wildlife Service (USFWS); the U.S. Geological Survey (USGS); and the U.S. Army Corps of Engineers (USACE). Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 horizontal datum and to convert into ESRI *ArcGIS* shapefiles[3]. The shapefiles were then displayed with *ArcGIS* to assess data quality and manually edit datasets. Vertical datum transformations to MHW were also accomplished using *FME*, based upon data from the NOAA Craig tidal station, as no *VDatum* model software was available for this area.

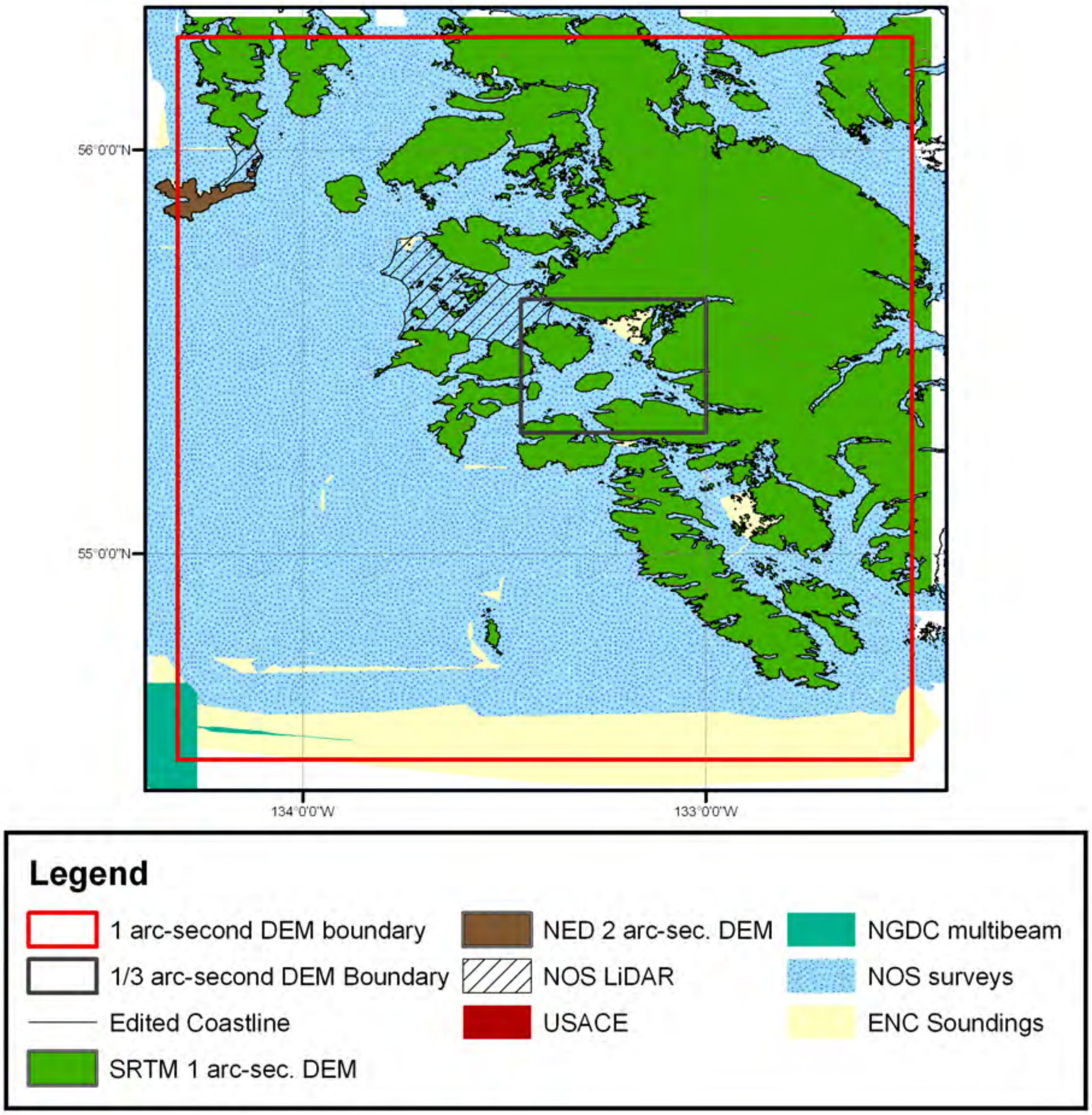

Figure 2. *Source and coverage of datasets used in compiling the Craig DEMs.*

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

3.1.1 Shoreline

Two digital coastline datasets of the Craig region were analyzed for inclusion in the Craig DEMs: NOAA ENC #17405 (1:40,000 scale) and USFWS statewide Alaska digital coastline. Comparisons between the two coastline datasets, NOS hydrographic surveys, Shuttle Radar Topography Mission (SRTM) topographic DEM and NOS hydrographic lidar showed that the USFWS coastline (Table 2) best fit the topographic and bathymetric data (Fig. 3) and was edited to create a “combined coastline” for the Craig DEMs.

ENC #17405 provided an extracted coastline covering a 16 km² area surrounding Craig. This coastline is at lower resolution and less complete than the SRTM topographic dataset and is not as accurate as the USFWS coastline. Therefore it was not used in building the Craig DEMs.

Table 2. Shoreline dataset used in compiling the Craig DEMs.

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

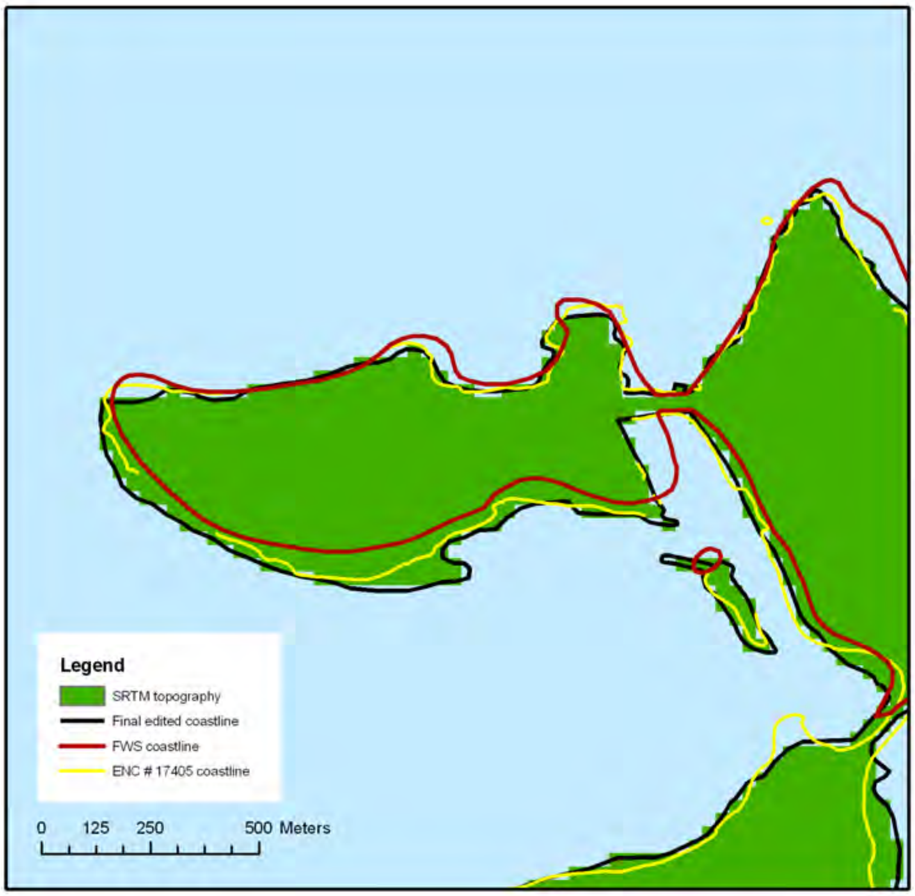

Figure 3. *Digital coastline datasets surrounding Craig Harbor. The ENC coastline is of lower resolution and is less accurate than the SRTM topographic data. It was not used in building the Craig DEMs.*

1) U.S. Fish and Wildlife Service coastline

USFWS has compiled a seamless digital coastline of the State of Alaska from a variety of sources, including: the National Hydrography Dataset, NOAA nautical charts, USFWS, National Geographic Topo Software, USACE, and Alaska Department of Natural Resources. This dataset was graciously provided to NGDC by Bret Christensen, USFWS. 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 USFWS coastline; the horizontal datum of the compiled USFWS coastline is WGS 84. The USFWS coastline provides complete coverage of the DEM areas.

To obtain the best digital MHW coastline, NGDC manually edited the USFWS coastline into a combined coastline (Fig. 3). The USFWS coastline was chosen over the ENC due to its full coverage of the DEMs. The USFWS coastline was edited to be consistent with the SRTM topography, NOS hydrographic survey data, and NOS hydrographic lidar. The coastline around Craig Harbor was manually adjusted to fit recent USACE survey data and to represent two breakwaters off the southeast tip of Craig Island (Fig. 4). The combined coastline was sub-sampled to 10-meter spacing using NGDC's *GEODAS* software and converted to point data for use in the gridding process. It was also used as a coastal buffer for the bathymetric pre-surfacing algorithm (see Sec. 3.3.2) to ensure that interpolated bathymetric values reached "zero" at the coast. The combined coastline was used to clip the SRTM and National Elevation Dataset (NED) topographic DEMs, which contained elevation values, typically zero, over the open ocean (see Sec. 3.1.3).

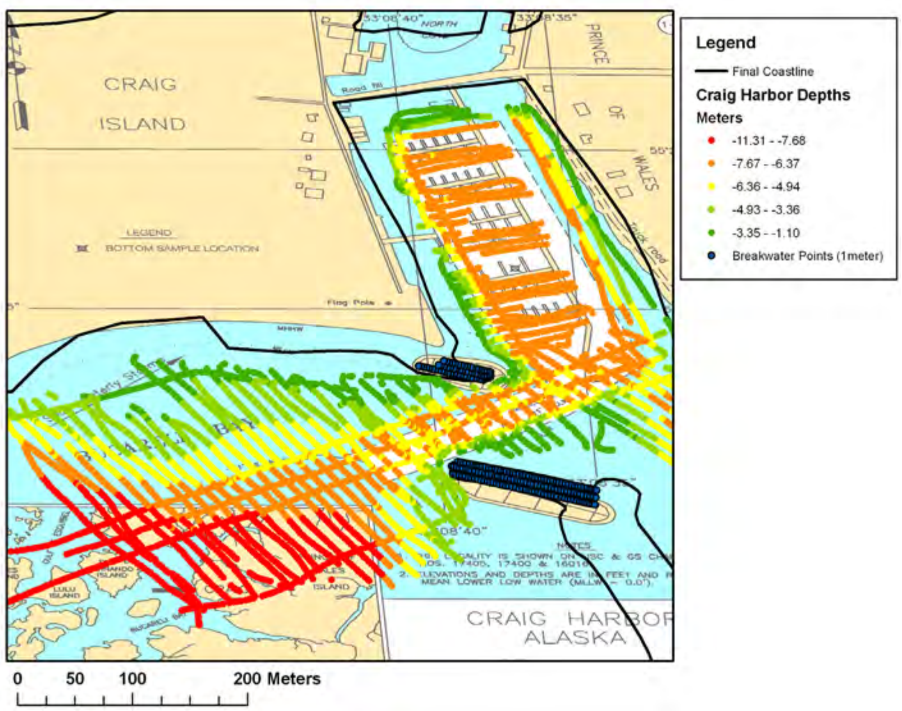

Figure 4. *Coastline in Craig Harbor (black line) shown with USACE hydrographic data and USACE project overview map.*

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the Craig DEMs included: NOS hydrographic surveys, one recent USACE harbor survey, NOAA ENC chart soundings, two NOS hydrographic lidar surveys, and NGDC multibeam swath sonar surveys (Table 3). Datasets were originally referenced to mean lower low water (MLLW) or mean sea level (MSL).

Table 3. Bathymetric datasets used in compiling the Craig DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1909 to 2003	NOS hydrographic survey soundings	Ranges from 10 meters to 1.5 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 27, NAD 83, Early Alaskan Datum, Undefined Datum	MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USACE	2003	Harbor survey	~2 to 10 meters	Alaska State Plane, zone 1, NAD 83 feet	MLLW (feet)	http://www.poa.usace.army.mil/en/hydro/King%20Cove/2006/
NOAA ENCs	2008	NOAA digitized nautical chart soundings	~500 to 1200 meters	WGS 84 geographic	MLLW (meters)	http://nauticalcharts.noaa.gov/mcd/enc/
NOS	2005	Hydrographic lidar surveys	5 meters	NAD 83 geographic	MLLW (meters)	
NGDC	2007	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html

1) National Ocean Service hydrographic survey data

A total of 158 NOS hydrographic surveys conducted between 1909 and 2003 were used in the Craig DEM development (Table 4; Fig. 5). The hydrographic survey data were originally vertically referenced to MLLW and horizontally referenced to NAD 27 or NAD 83 geographic and 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 combined coastline. The surveys were subsequently clipped to a polygon 0.05 degrees (~5%) larger than the 1 arc-second gridding area to support data interpolation across DEM boundaries.

After converting all NOS survey data to MHW (see Sec. 3.2.1), the data were displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and compared to the NED and SRTM topographic data and the combined coastline.

NOS survey #H11237 had incorrect bathymetry values, determined when checked against the smoothsheet and overlapping datasets. Further investigation revealed that the original soundings had been converted from fathoms to meters twice. *FME* was used to change each sounding in survey #H11237 to the correct value by multiplying the elevations by .5468 (1 meter = .5468 fathoms). NOS was contacted and they are in the process of revising the survey.

Table 4. Digital NOS hydrographic surveys used in compiling the Craig DEMs.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum of Digital Records*
H03042*	1909	20,000	MLLW	Undetermined horizontal datum
H03042A*	1909	40,000	MLLW	Undetermined horizontal datum
H03416*	1912/13	20,000	MLLW	Undetermined horizontal datum
H03417*	1912	20,000	MLLW	Undetermined horizontal datum
H03427*	1912	10,000	MLLW	Undetermined horizontal datum
H03427I*	1912	20,000	MLLW	Undetermined horizontal datum
H03539*	1913	10,000	MLLW	Undetermined horizontal datum
H03540*	1913	20,000	MLLW	Undetermined horizontal datum
H03547*	1913	10,000	MLLW	Undetermined horizontal datum
H03666*	1914	10,000	MLLW	Undetermined horizontal datum
H03678*	1914	20,000	MLLW	Undetermined horizontal datum
H03679*	1914	10,000	MLLW	Undetermined horizontal datum
H03680*	1914	10,000	MLLW	Undetermined horizontal datum
H03691*	1914	20,000	MLLW	Undetermined horizontal datum
H03692*	1914	20,000	MLLW	Undetermined horizontal datum
H03692A*	1914/25	20,000	MLLW	Undetermined horizontal datum
H03795*	1915	10,000	MLLW	Undetermined horizontal datum
H03818*	1915	20,000	MLLW	Undetermined horizontal datum
H03819A*	1916	120,000	MLLW	Undetermined horizontal datum
H03819B*	1920	120,000	MLLW	Undetermined horizontal datum
H03880*	1915	20,000	MLLW	Undetermined horizontal datum
H03912*	1916	20,000	MLLW	Undetermined horizontal datum
H03930*	1916	10,000	MLLW	Undetermined horizontal datum
H03931*	1916	40,000	MLLW	Undetermined horizontal datum
H03932*	1916	20,000	MLLW	Undetermined horizontal datum
H03932A*	1917	20,000	MLLW	Undetermined horizontal datum
H03932I*	1916	10,000	MLLW	Undetermined horizontal datum
H03933*	1916	20,000	MLLW	Undetermined horizontal datum
H03940*	1916	20,000	MLLW	Undetermined horizontal datum
H04009*	1917	20,000	MLLW	Undetermined horizontal datum
H04191*	1920	20,000	MLLW	Undetermined horizontal datum
H04192*	1920	20,000	MLLW	Undetermined horizontal datum
H04203*	1921	20,000	MLLW	Undetermined horizontal datum
H04204*	1921	10,000	MLLW	Undetermined horizontal datum
H04208A*	1921	120,000	MLLW	Undetermined horizontal datum
H04208B*	1921	60,000	MLLW	Undetermined horizontal datum
H04209*	1921	20,000	MLLW	Undetermined horizontal datum
H04209I1*	1921	10,000	MLLW	Undetermined horizontal datum
H04209I2*	1921	10,000	MLLW	Undetermined horizontal datum
H04251*	1922	20,000	MLLW	Undetermined horizontal datum
H04259*	1922	20,000	MLLW	Undetermined horizontal datum
H04260*	1922	20,000	MLLW	Undetermined horizontal datum
H04261A*	1922/23	120,000	MLLW	Undetermined horizontal datum
H04261B*	1922/23	60,000	MLLW	Undetermined horizontal datum
H04264*	1922	20,000	MLLW	Undetermined horizontal datum
H04273*	1922	20,000	MLLW	Undetermined horizontal datum
H04274*	1922	50,000	MLLW	Undetermined horizontal datum

NOS Survey ID	Year of Survey	Survey Scale	Original Vertical Datum	Original Horizontal Datum of Digital Records
H04325*	1923	20,000	MLLW	Undetermined horizontal datum
H04326*	1923	20,000	MLLW	Undetermined horizontal datum
H04330*	1923	10,000	MLLW	Undetermined horizontal datum
H04441*	1924	10,000	MLLW	Undetermined horizontal datum
H04515*	1925	20,000	MLLW	Undetermined horizontal datum
H04516*	1925	40,000	MLLW	Undetermined horizontal datum
H04517A*	1925	20,000	MLLW	Undetermined horizontal datum
H04534*	1925	10,000	MLLW	Undetermined horizontal datum
H04535*	1925	20,000	MLLW	Undetermined horizontal datum
H04536*	1925	40,000	MLLW	Undetermined horizontal datum
H04594*	1925	20,000	MLLW	Undetermined horizontal datum
H04622A*	1926	20,000	MLLW	Undetermined horizontal datum
H04626A*	1926	40,000	MLLW	Undetermined horizontal datum
H04626AI*	1926	20,000	MLLW	Undetermined horizontal datum
H04761A*	1927	10,000	MLLW	Undetermined horizontal datum
H04773*	1927	10,000	MLLW	Undetermined horizontal datum
H04774*	1927	10,000	MLLW	Undetermined horizontal datum
H06283*	1937	20,000	MLLW	Early Alaska Datums
H06284*	1937	20,000	MLLW	Early Alaska Datums
H06285*	1937	20,000	MLLW	Early Alaska Datums
H06358*	1938	10,000	MLLW	Early Alaska Datums
H07095*	1946	2,500	MLLW	Early Alaska Datums
H07098*	1946	5,000	MLLW	Early Alaska Datums
H07987*	1957	10,000	MLLW	Early Alaska Datums
H08036*	1953	10,000	MLLW	Early Alaska Datums
H08037*	1953	10,000	MLLW	Early Alaska Datums
H08038*	1953	10,000	MLLW	Early Alaska Datums
H08064*	1953	20,000	MLLW	Early Alaska Datums
H08065A	1953/54	10,000	MLLW	NAD 27
H08065B	1953/54	10,000	MLLW	NAD 27
H08067*	1953/54	10,000	MLLW	Early Alaska Datums
H08112	1960	20,000	MLLW	NAD 27
H08127*	1954	10,000	MLLW	Early Alaska Datums
H08128*	1954	10,000	MLLW	Early Alaska Datums
H08130*	1954	10,000	MLLW	Early Alaska Datums
H08131*	1954	10,000	MLLW	Early Alaska Datums
H08132*	1954	10,000	MLLW	Early Alaska Datums
H08133	1954	10,000	MLLW	Early Alaska Datums
H08134*	1954	20,000	MLLW	Early Alaska Datums
H08149	1954	10,000	MLLW	Early Alaska Datums
H08150*	1954	10,000	MLLW	Early Alaska Datums
H08151*	1955	10,000	MLLW	Early Alaska Datums
H08230	1945/55	10,000	MLLW	Early Alaska Datums
H08231	1955	10,000	MLLW	Early Alaska Datums
H08232	1955	10,000	MLLW	Early Alaska Datums
H08244	1955	10,000	MLLW	Early Alaska Datums
H08245	1955	10,000	MLLW	Early Alaska Datums
H08286	1956	10,000	MLLW	Early Alaska Datums
H08287	1956	10,000	MLLW	Early Alaska Datums

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum of Digital Records*
H08288*	1956	10,000	MLLW	Early Alaska Datums
H08289*	1956	10,000	MLLW	Early Alaska Datums
H08290	1956	10,000	MLLW	Early Alaska Datums
H08325	1955	10,000	MLLW	NAD 27
H08326	1956/58	5,000	MLLW	Early Alaska Datums
H08359*	1957	10,000	MLLW	Early Alaska Datums
H08391	1957	10,000	MLLW	early Alaska Datums
H08392*	1957	10,000	MLLW	Early Alaska Datums
H08393	1957	10,000	MLLW	NAD 27
H08443	1958	10,000	MLLW	Early Alaska Datums
H08444	1958	40,000	MLLW	NAD 27
H08455*	1958/60	10,000	MLLW	NAD 27
H08456*	1958	10,000	MLLW	NAD 27
H08457	1958	10,000	MLLW	NAD 27
H08458	1958	10,000	MLLW	Early Alaska Datums
H08466*	1959	10,000	MLLW	Early Alaska Datums
H08531	1960	10,000	MLLW	Early Alaska Datums
H08532	1960	10,000	MLLW	Early Alaska Datums
H08533	1963	10,000	MLLW	Early Alaska Datums
H08604	1961	20,000	MLLW	Early Alaska Datums
H08605	1961	20,000	MLLW	Early Alaska Datums
H08640	1962	10,000	MLLW	Early Alaska Datums
H08653	1962	10,000	MLLW	Early Alaska Datums
H08654	1962	10,000	MLLW	Early Alaska Datums
H08688*	1965	10,000	MLLW	Early Alaska Datums
H08769	1963	10,000	MLLW	Early Alaska Datums
H08945	1967/71	10,000	MLLW	Early Alaska Datums
H08946*	1967/71	10,000	MLLW	Early Alaska Datums
H09084	1969	10,000	MLLW	Early Alaska Datums
H09085	1969	10,000	MLLW	Early Alaska Datums
H09092	1969	20,000	MLLW	NAD 27
H09192	1971	10,000	MLLW	NAD 27
H09193	1971	5,000	MLLW	NAD 27
H09194	1971	20,000	MLLW	NAD 27
H09215	1971	10,000	MLLW	Early Alaska Datums
H09216*	1971	10,000	MLLW	Early Alaska Datums
H09220	1971	10,000	MLLW	Early Alaska Datums
H09222	1971	5,000	MLLW	Early Alaska Datums
H09269	1972	10,000	MLLW	NAD 27
H09309	1972	10,000	MLLW	Early Alaska Datums
H09401	1973	10,000	MLLW	Early Alaska Datums
H09402	1973	10,000	MLLW	NAD 27
H09403	1973	10,000	MLLW	NAD 27
H09754	1978	5,000	MLLW	Early Alaska Datums
H09756*	1978	5,000	MLLW	Early Alaska Datums
H09757	1978	10,000	MLLW	Early Alaska Datums
H10818	1998	10,000	MLLW	NAD 83
H10949	2000	20,000	MLLW	NAD 83
H10950	2000	20,000	MLLW	NAD 83

NOS Survey ID	Year of Survey	Survey Scale	Original Vertical Datum	Original Horizontal Datum of Digital Records
H10951	2001	20,000	MLLW	NAD 83
H10959	2000	20,000	MLLW	NAD 83
H11058	2001	10,000	MLLW	NAD 83
H11099	2002	10,000	MLLW	NAD 83
H11160	2002	10,000	MLLW	NAD 83
H11161	2002	10,000	MLLW	NAD 83
H11162	2002	10,000	MLLW	NAD 83
H11163	2002	10,000	MLLW	NAD 83
H11164	2002	20,000	MLLW	NAD 83
H11165	2002	10,000	MLLW	NAD 83
H11237	2003	10,000	MLLW	NAD 83
H11238	2003	10,000	MLLW	NAD 83
H11240	2003	10,000	MLLW	NAD 83

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

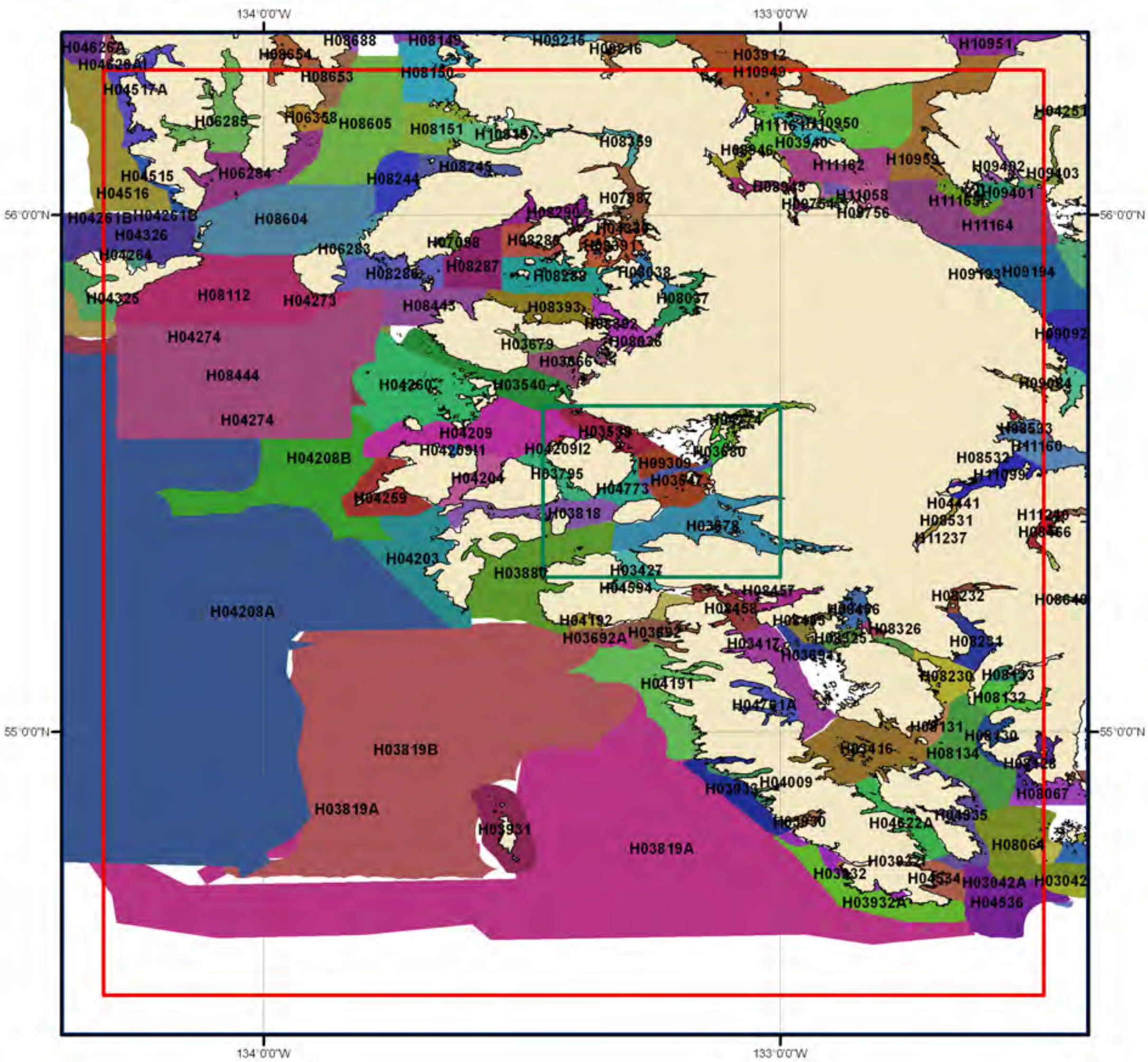

Figure 5. *Digital NOS hydrographic survey coverage in the Craig region. Red denotes boundary of 1 arc-second DEM;. green denotes boundary of 1/3 arc-second DEM; coastline in black.*

2) U.S. Army Corps of Engineers harbor survey

The USACE conducted a high-resolution hydrographic harbor survey of Craig Harbor in 2003 (Figs. 6 and 7). The survey was originally referenced to NAD 83 Alaska State Plane coordinates (feet) and MLLW vertical datum (feet). The resolution of the survey ranges from ~2 to 10 meters and the depth ranges from -1.1 to -11.3 meters at MHW.

Figure 6. *USACE project layout image for Craig Harbor.*
(http://www.poa.usace.army.mil/CO/CoOrg/PnI_New)

Figure 7. *An oblique photo of Craig taken on Apri 28, 2005 from the west. Provided by the USACE AK District web site. (http://www.poa.usace.army.mil/CO/CoOrg/PnI_New/craig%20hbr%20south%20cove%20R&H%2005.jpg)*

3) NOAA Electronic Navigational Chart soundings

Nautical charts #16016 and #17404 were available from OCS in Electronic Navigational Chart (ENC) [4] format and, as no bathymetric survey data were available for these areas, sounding data were extracted from these charts using *FME*.

ENC chart #16016 covers the area from Dixon Entrance to Cape St. Elias. Soundings range from ~3 kilometers to 6.5 kilometers apart, and depths range from -2166.24 meters to -6.44 meters. The scale for this dataset is 1:300,000.

ENC chart #17404 coverage stretches eastward from San Christoval Channel to Cape Lynch. Soundings range from ~20 meters to ~1200 meters apart, and depths range from -3.14 meters to -277.14 meters at MHW. The scale for this dataset is 1:40,000.

4) National Ocean Service hydrographic lidar surveys

NOS provided NGDC with two recent hydrographic lidar surveys located in the eastern and central part of the Craig 1 arc-second DEM (Fig. 8). The lidar surveys are referenced to NAD 83 geographic and MLLW. These surveys range from -.01 to -38.86 meters in elevation with a point spacing of 5 meters. The elevations on or near the shoreline were generally inconsistent with the SRTM dataset and were not used in building the Craig 1 arc-second DEM.

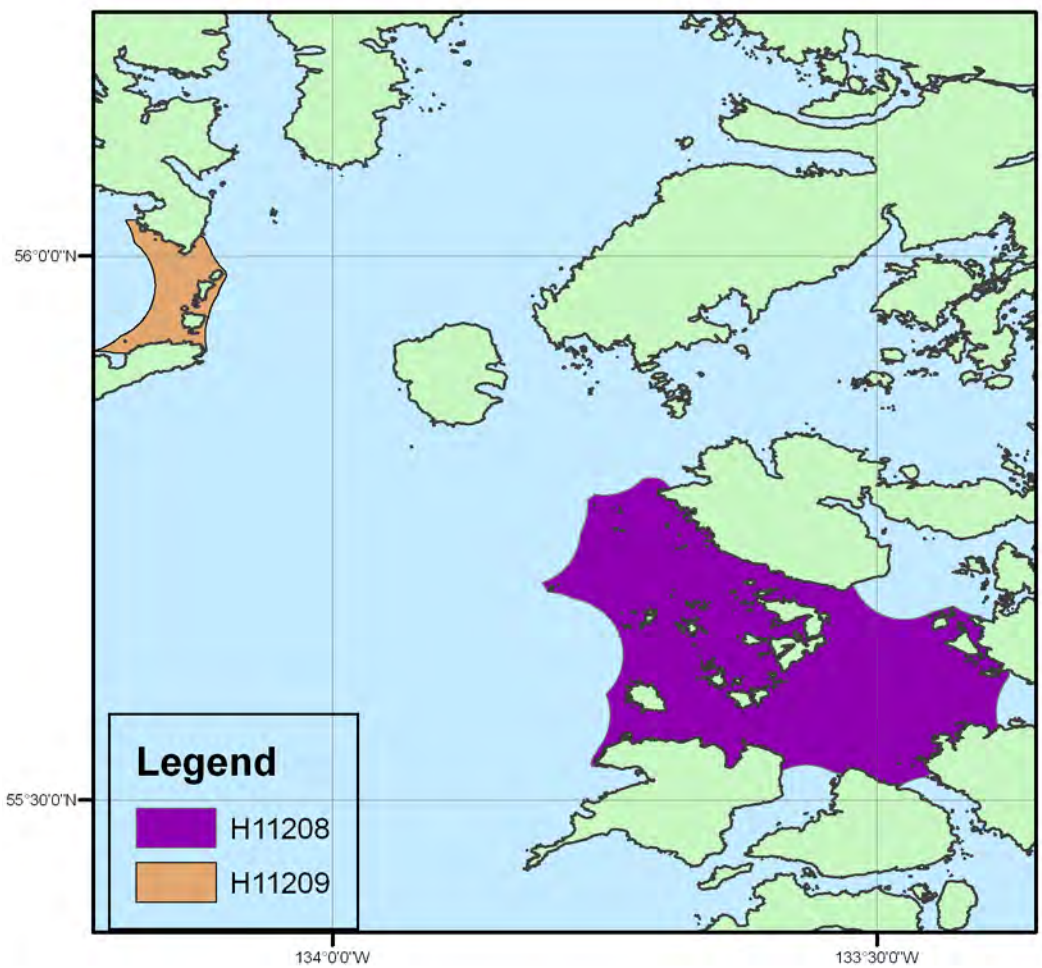

Figure 8. *NOS hydrographic lidar surveys in the Craig region. #H11209 is located on the north eastern border and #H11208 is in the central portion of the 1 arc-second Craig DEM.*

4. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site: http://nauticalcharts.noaa.gov/mcd/enc/]

5) Multibeam swath sonar files

Two multibeam swath sonar surveys (Table 5; Fig. 2) were available from the NGDC multibeam sonar bathymetry database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html) for use in the 1 arc-second Craig DEM. This database is comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. Most of the multibeam swath sonar surveys offshore were transits rather than dedicated sea-floor surveys. Both surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be equivalent to MSL.

The downloaded data were gridded to 1 arc-second resolution using *MB-System*. *MB-System* is an NSF-funded free software application specifically designed to manipulate multibeam swath sonar data. The gridded data were converted to shapefiles and transformed to MHW using *FME*.

Table 5. Multibeam swath sonar surveys used in compiling the Craig DEMs.

Cruise ID	*Ship*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Institution*
F0CI93	Surveyor	1993	Assumed MSL	WGS 84 geographic	NOAA
KMO514	Kilo Moana	2005	Assumed MSL	WGS 84 geographic	University of New Hampshire

3.1.3 Topography

Topographic datasets in the Craig region were obtained from the USGS: NED 2 arc-second gridded topography and 1 arc-second SRTM (Fig. 9; Table 6). NGDC also digitized harbor features not represented in either topographic dataset.

Table 6. Topographic datasets used in compiling the Craig 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	NGVD29 (meters)	http://ned.usgs.gov/
NASA SRTM	2000	Topographic DEM	1 arc-second grid	WGS 84 geographic	WGS 84/EGM96 Geoid (meters)	http://srtm.usgs.gov/

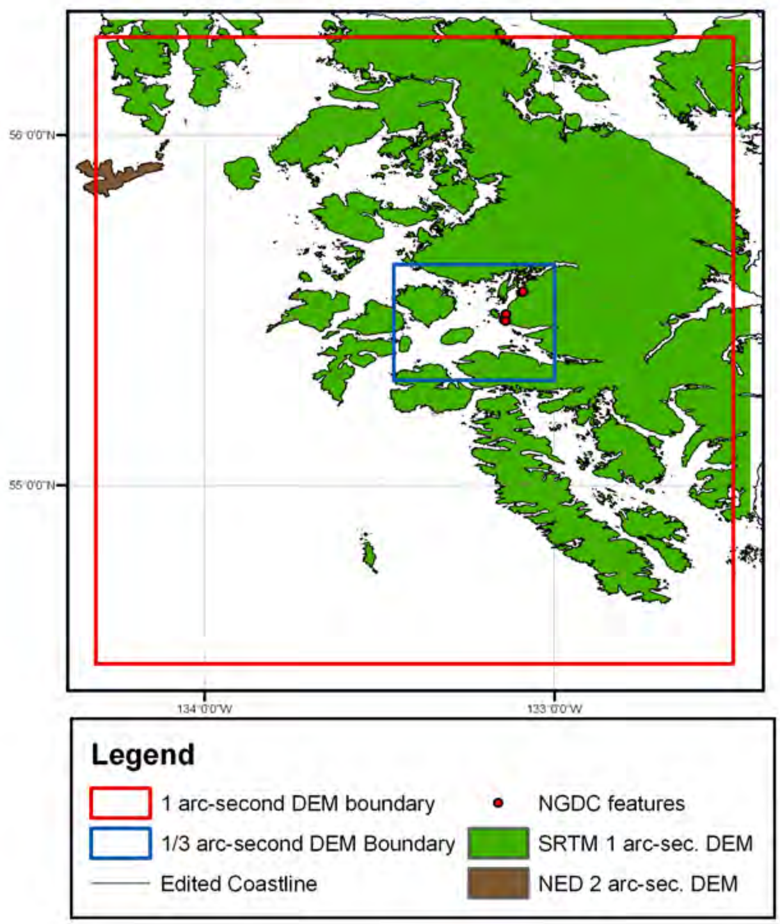

Figure 9. *Source and coverage of topographic datasets used in compiling the Craig DEMs.*

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

USGS's NED provides complete 2 arc-second coverage of Alaska[5]. Data are in NAD 27 Alaska geographic coordinates and North American Vertical Datum of 1929 (NGVD29) vertical datum (meters), and are available for download as raster DEMs. The extracted bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution (see the USGS Seamless web site for specific source information: http://seamless.usgs.gov). The dataset was derived from USGS quad maps and aerial photos based on surveys conducted in the 1970s and 1980s. The NED data were used only to fill in gaps within the SRTM data (e.g., Fig. 9). In addition, the NED data had values over the open oceans that were deleted by clipping to the coastline.

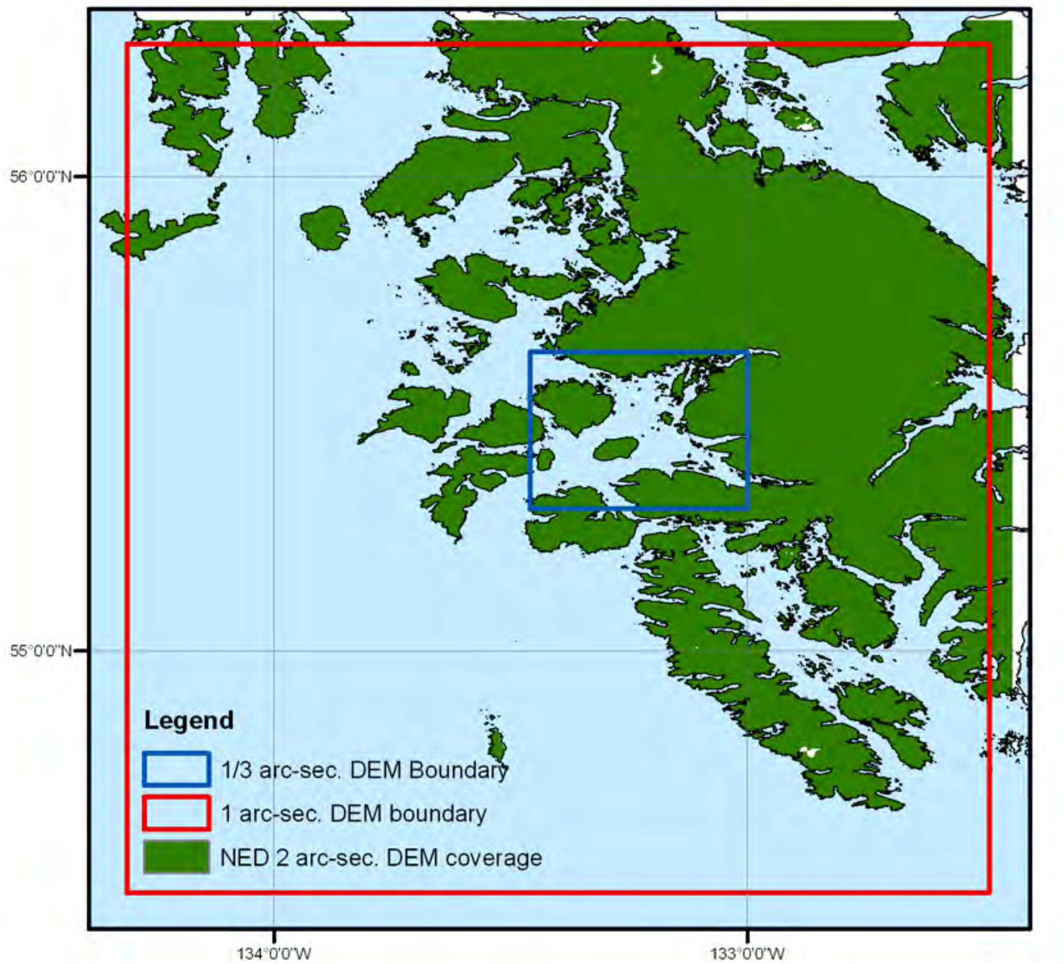

Figure 10. *Coverage of NED 2 arc-second topographic data in the Craig DEMs. Note: White areas denote data gaps.*

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

2) NASA Space Shuttle Radar Topography Mission

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

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

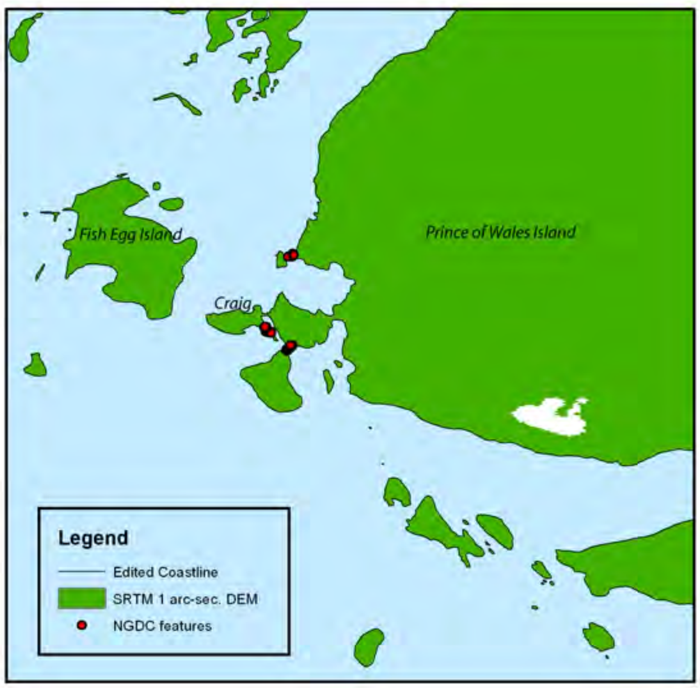

Figure 11. *Example of gap (white area) in the SRTM data coverage. Gaps were filled with topographic data from the NED DEM. Edited coastline in black. Blue represents zero values over the open ocean.*

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

3) NGDC digitized harbor features

Using a USACE project overview image as a reference, NGDC digitized a point shapefile to represent two main harbor features at Craig. The breakwater that forms the southeastern barrier of Craig Island and the breakwater that forms the barrier to the south of the Craig Harbor entrance were given elevation values of 1 meter, estimated from aerial photographs (e.g., Fig. 7).

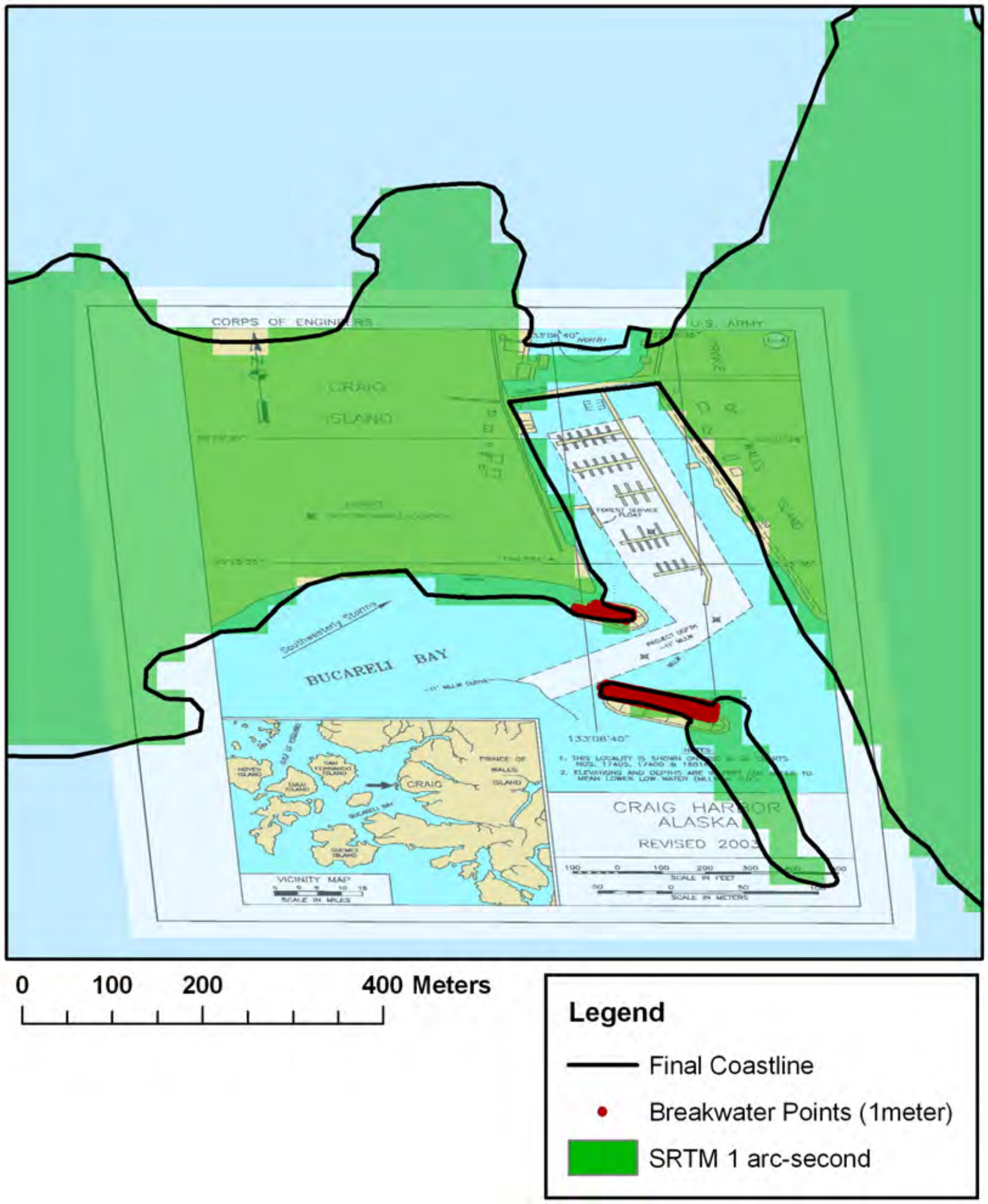

Figure 12. *Detail of Craig Harbor with USACE project overview georeferenced image underlying SRTM topographic data.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Craig DEMs were originally referenced to a number of vertical datums including: MLLW, MSL, WGS 84/EGM96 Geoid, and NGVD29. All datasets were transformed to MHW to provide the maximum flooding for inundation modeling.

1) **Bathymetric data**

The NOS hydrographic surveys, the USACE survey data, NOS lidar surveys, and the nautical chart soundings were transformed from MLW and MLLW to MHW, using *FME* software, by adding a constant offset measured at the NOAA Craig tidal station (Table 7). The multibeam swath sonar grid was transformed from MSL to MHW by adding a constant offset of -1.215 meters (Table 7).

2) **Topographic data**

The NED and SRTM DEMs were originally referenced to NGVD29 and WGS 84/EGM96 Geoid vertical datums, respectively. There are no survey markers in the vicinity of Craig that relate these two geodetic datums to the local tidal datums. Thus, it was assumed that both datums are essentially equivalent to MSL in this area (Table 7). Conversion to MHW, using *FME* software, was accomplished by adding a constant value of -1.215 meters.

Table 7. Relationship between MHW and other vertical datums in the Craig region.*

Vertical datum	*Difference to MHW*
MTL	-1.212
NGVD29 +	-1.215
WGS 84/EGM96 Geoid +	-1.215
MSL	-1.215
MLW	-2.424
MLLW	-2.842

* Datum relationships determined by tidal station #9451600 at Craig, Alaska.
+ Assumed to be equivalent to MSL.

3.2.2 Horizontal datum transformations

Datasets used in compiling the Craig DEMs were originally referenced to Early Alaska, “undetermined”, and NAD 27, NAD 83, or WGS 84 geographic horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established. The NAD 27 geographic data were converted to a horizontal datum of NAD 83 geographic using *FME* software. The NOS surveys referenced to Early Alaska or “undetermined” horizontal datums were manually shifted in *ArcGIS* to fit the combined coastline.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

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

- Data values over the open ocean in the NED and SRTM topographic DEMs. Each dataset required automated clipping to the combined coastline.
- Lack of good bathymetric data in the southern quarter of the 1 arc-second DEM.
- Lack of good bathymetric data near the coastline.
- Positional uncertainty of NOS surveys with Early Alaska or "undetermined" horizontal datums.

3.3.2 Smoothing of bathymetric data

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

The NOS hydrographic point data, in xyz format, were combined with the USACE surveys, ENC sounding, NOS hydrographic lidar, and NGDC multibeam swath sonar bathymetry data into a single file. Points extracted every 10 meters from the combined coastline were also included and assigned negative values of -1 meter to ensure that the offshore elevations remained negative; this was necessary due to the sparseness of the bathymetric data near the coast. These point data were then smoothed using the *GMT* tool "blockmedian" onto a 3 arc-second grid. The *GMT* tool "surface" was then applied to interpolate values for cells without data values. The *GMT* grid created by "surface" was converted into an ESRI Arc ASCII grid file using the *MB-System* tool "mbm_grd2arc". Conversion of this Arc ASCII grid file into an Arc raster permitted clipping of the grid with the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with the original soundings to ensure grid accuracy (e.g., Fig. 13), converted to a shapefile, and then exported as an xyz file for use in the final gridding process (see Table 8). The statistical analysis of the differences between the 1 arc-second bathymetric surface and one of the NOS surveys showed that the majority of the NOS soundings are in good agreement with the bathymetric surface. The few exceptions where the difference reached a few meters are attributed to rugged bathymetry where two or more closely positioned points were averaged to obtain the elevation of one grid cell.

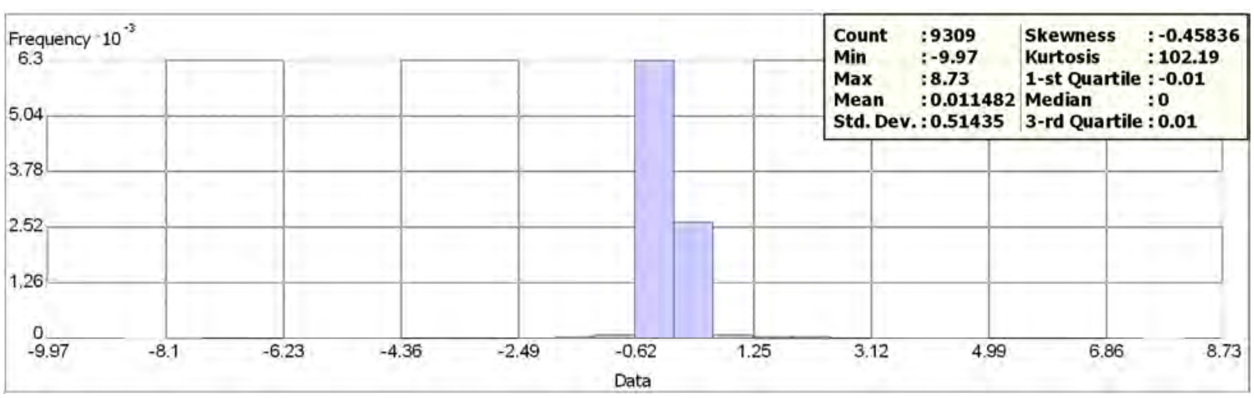

Figure 13. *Histogram of the difference between NOS hydrographic survey H03547 and the 1 arc-second pre-surfaced bathymetric grid.*

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

MB-System was used to create 1 arc-second and 1/3 arc-second DEMs of Craig, Alaska. The *MB-System* tool "mbgrid" applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the "mbgrid" gridding algorithm, as relative gridding weights, is listed in Table 8. Greatest weight was given to the high-resolution USACE and NOS hydrographic lidar datasets. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid.

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

Dataset	*Relative Gridding Weight*
SRTM topographic DEM	10
USACE surveys	1000
NOS hydrographic surveys	10
Final coastline at 0 meters elevation	1
USGS NED topographic DEM	100
ENC soundings	100
NOS lidar surveys	1000
NGDC hydrographic sonar multibeam	10
NGDC digitized features	10
Pre-surfaced bathymetric grid	1

3.4 Quality Assessment of the DEMs

3.4.1. Horizontal accuracy

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

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the DEMs are also highly dependent upon the source datasets contributing to grid cell values. Island interiors have vertical accuracies of between 10 and 15 meters, derived from the NED topographic data (estimated vertical accuracy of 10 meters) and the SRTM topographic data (vertical accuracy better than 16 meters but typically about 10 meters). Bathymetric values are derived from a wide range of input data, consisting of single and multibeam sounding measurements from the early 20^{th} centuries to recent: modern NOS standards are 0.3 m in 0 to 20 m of water, 1.0 m in 20 to 100 m of water, and 1% of the water depth in 100 m of water. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water to about 5% of water depth.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the 1 arc-second Craig DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 14). The DEM was transformed to UTM zone 8N coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the DEMs (Figs. 15 and 16) was accomplished using *POV Ray*. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM.

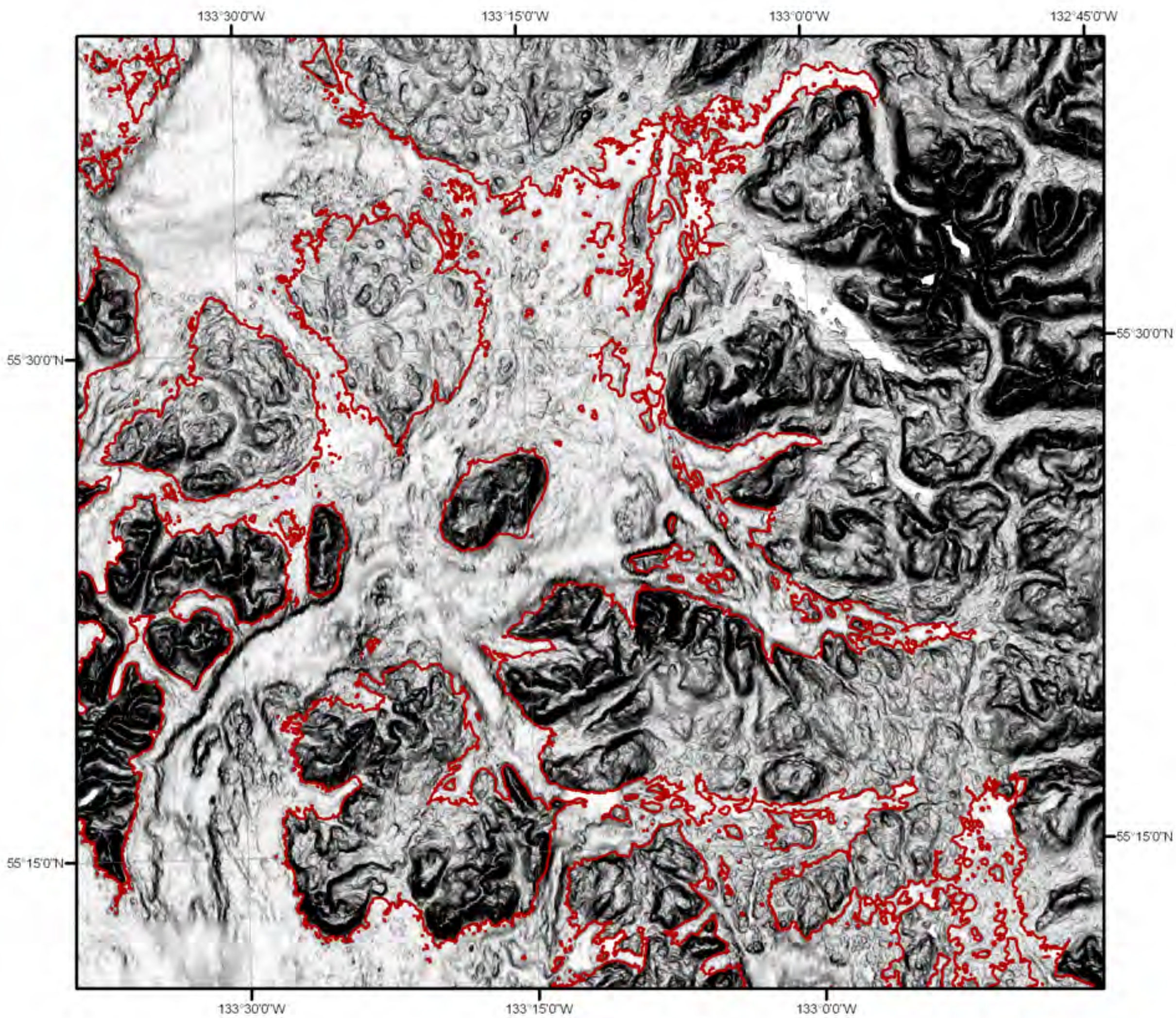

Figure 14. *Slope map of the 1 arc-second Craig DEM in the vicinity of Craig, Alaska. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

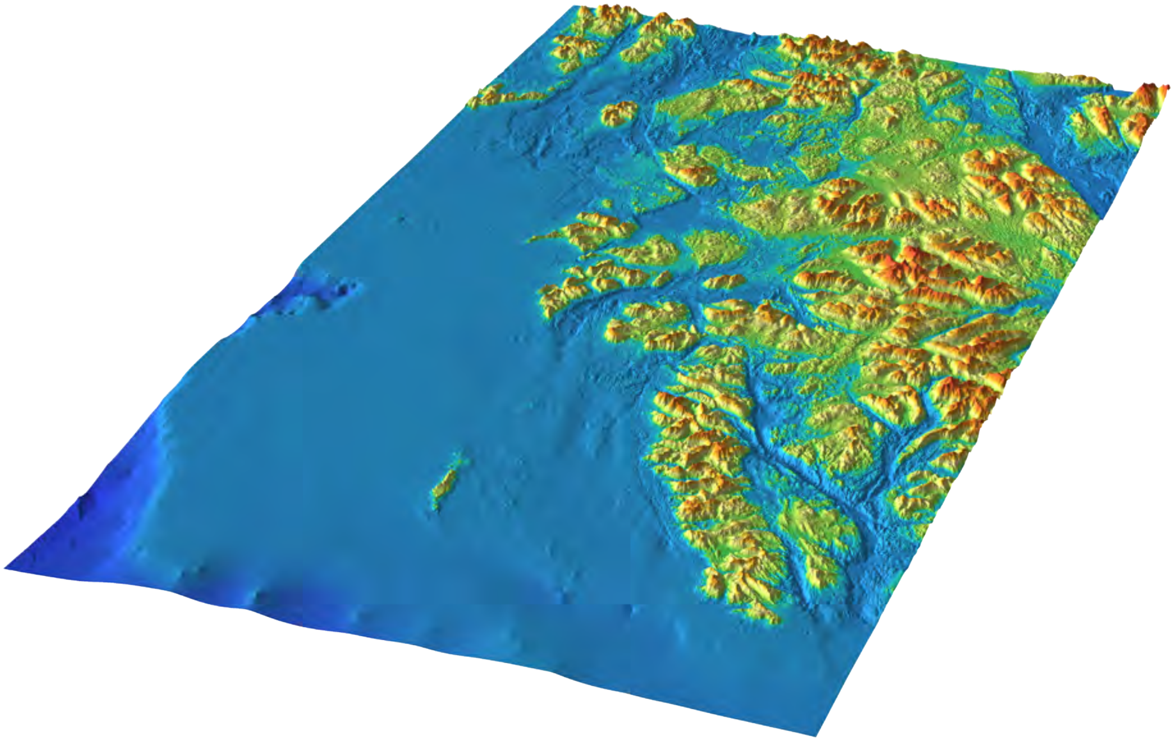

Figure 15. *Perspective view from the southeast of the 1 arc-second Craig DEM. Vertical exaggeration–times 2.*

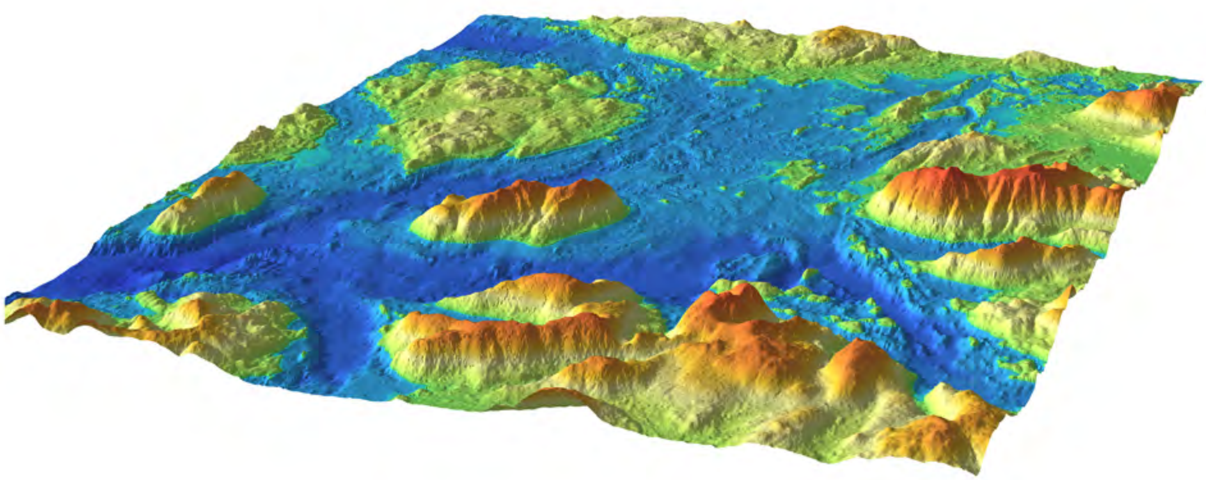

Figure 16. *Perspective view from the southeast of the 1/3 arc-second Craig DEM. Vertical exaggeration–times 2.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the 1/3 arc-second Craig DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas. A histogram of the difference between selected SRTM data points and the 1/3 arc-second Craig DEM is shown in Figure 17.

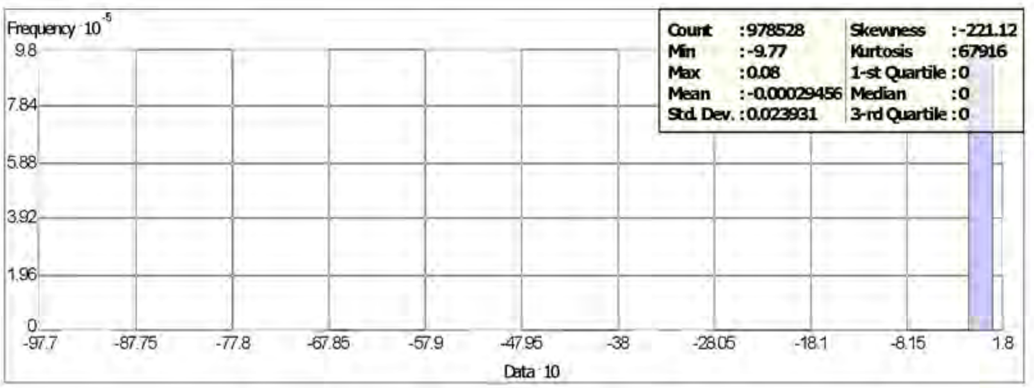

Figure 17. *Histogram of the difference between the SRTM topographic dataset and the 1/3 arc-second Craig DEM.*

3.4.5 Comparison with USGS topographic elevations

Topographic elevations were obtained from the USGS topographic *Craig* quadrangle (http://agdc.usgs.gov/data/usgs/to_geo.html). The quadrangle gives positions and elevations in NAD 83 and NGVD29 vertical datum (in feet) and has a scale of 1:63,360 with a 100-foot contour interval.

To be consistent with the USGS *Craig* quadrangle, the 1/3 arc-second Craig DEM was converted from meters into feet. A contour map with a 100-foot interval was created of San Juan Bautista Island (Fig. 18B). The contour map was then compared against the USGS topographic quadrangle (Fig. 18A). Although the figures show that minor differences exist between the 1/3 arc-second Craig DEM and the USGS topographic elevations, the morphology of the island is accurately captured in the DEM.

Topographic elevations at localized high points in the DEM are lower than USGS topographic quadrangle elevations (Fig. 18). These differences may be attributable to the fact that the SRTM and NED topographic data, used to constrain the subaerial parts of the DEM, represent averages of land elevations over 30 × 30 meter, and 60 × 60 meter square areas, respectively, while the topographic quadrangle elevations represent local maxima.

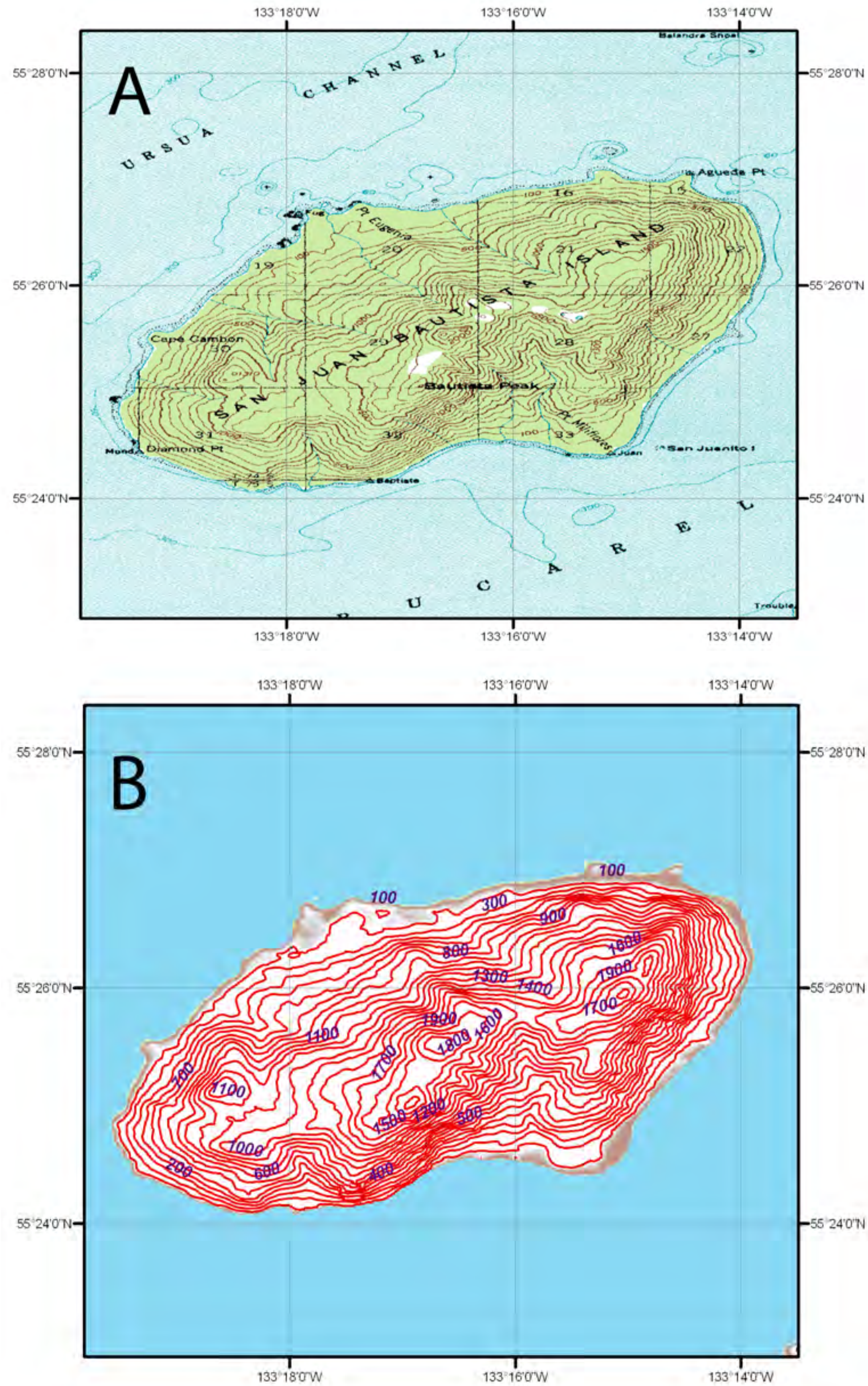

Figure 18. *Comparison between USGS topography contours and the 1/3 arc-second Craig DEM topographic contours. A) Brown lines and numbers represent 100 ft. contours from the USGS topographic map. B) Red lines and purple numbers represent 100 ft. contours from the 1/3 arc-second Craig DEM.*

4. Summary and Conclusions

Two integrated topographic–bathymetric DEMs of the Craig, Alaska area, with cell size of 1 arc-second and 1/3 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*, and *MB-System* software.

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

- Conduct bathymetric surveys in the southern quarter of the 1 arc-second DEM area.
- Obtain more recent data in the area immediately around Craig.
- Establish, via survey, the relationships between tidal and geodetic datums in the Craig region.
- Determine the relationship between Early Alaska and NAD 83 geographic horizontal datums.

5. Acknowledgments

The creation of the DEMs were funded by NOAA Center for Tsunami Research at PMEL. The authors thank Nazila Meratia and Vasily Titov (PMEL), Bret Christensen (USFWS), and Gary Nelson and Brooke McMahon (NOS Pacific Hydrographic Branch).

6. References

Electronic Navigational Chart #16016, 7th Edition, 2007. Dixon Entrance to Cape St. Elias. Scale 1:300,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #17404, 10th Edition, 2008. San Christoval Channel to Cape Lynch. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17403, 14th Edition, 2006. Davidson Inlet and Sea Otter Sound. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17404, 13th Edition, 2006. San Christoval Channel to Cape Lynch. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17405, 15th Edition, 2006. Ulloa Channel to San Christoval Channel. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17406, 7th Edition, 2004. Bakers Noyes and Lulu Islands. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17407, 15th Edition, 2003. Northern Part of Tlevak Strait and Ulloa Channel. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17408, 8th Edition, 2003. Central Dall Island and Vicinity. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17426, 15th Edition, 2006. Kasaan Bay Prince of Wales Island. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #17431, 11th Edition, 2004. North End of Cordova Bay and Hetta Inlet. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

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

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

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

GMT v. 4.3.0 – Generic Mapping Tools, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.1.0, 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/

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/