Digital Elevation Models of Keauhou and Kawaihae, Hawaii: Procedures, Data Sources and Analysis

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1. Introduction

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed two integrated bathymetric–topographic digital elevation models (DEMs) of Keauhou and Kawaihae, Hawaii (Figs. 1 and 2). The 1/3 arc-second[1] DEMs of Keauhou and Kawaihae, Hawaii referenced to mean high water (MHW) were carefully developed and evaluated. The DEMs will be used as input for the Method of Splitting Tsunami (MOST) model developed by Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The DEMs were generated from diverse digital datasets in the region (grid boundary and sources shown in Figs. 4 and 5) for tsunami inundation modeling, 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 summary of the data sources and methodology used in developing the DEMs.

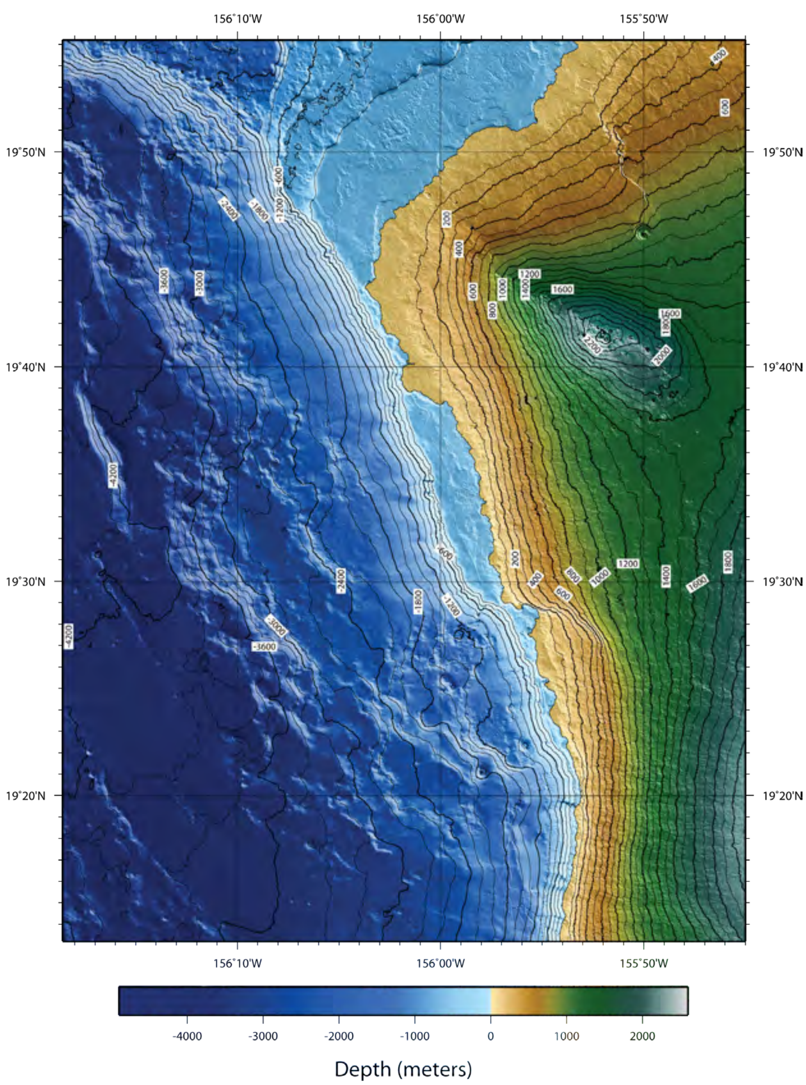

Figure 1. Bathymetric and topographic shaded-relief image of the Keauhou DEM. Contour interval is 100 meters for topography and 200 meters for bathymetry.

1. The Keauhou and Kawaihae, Hawaii DEMs were built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Keauhou, Hawaii, (19° 34′ 32″ N, 155° 57′ 38″ W) 1/3 arc-second of latitude is equivalent to 10.25 meters; 1/3 arc-second of longitude equals 9.72 meters. At the latitude of Kawaihae, Hawaii, (20° 2′ 14″ N, 155° 49′ 42″ W) 1/3 arc-second of latitude is equivalent to 10.25 meters; 1/3 arc-second of longitude equals 9.69 meters.

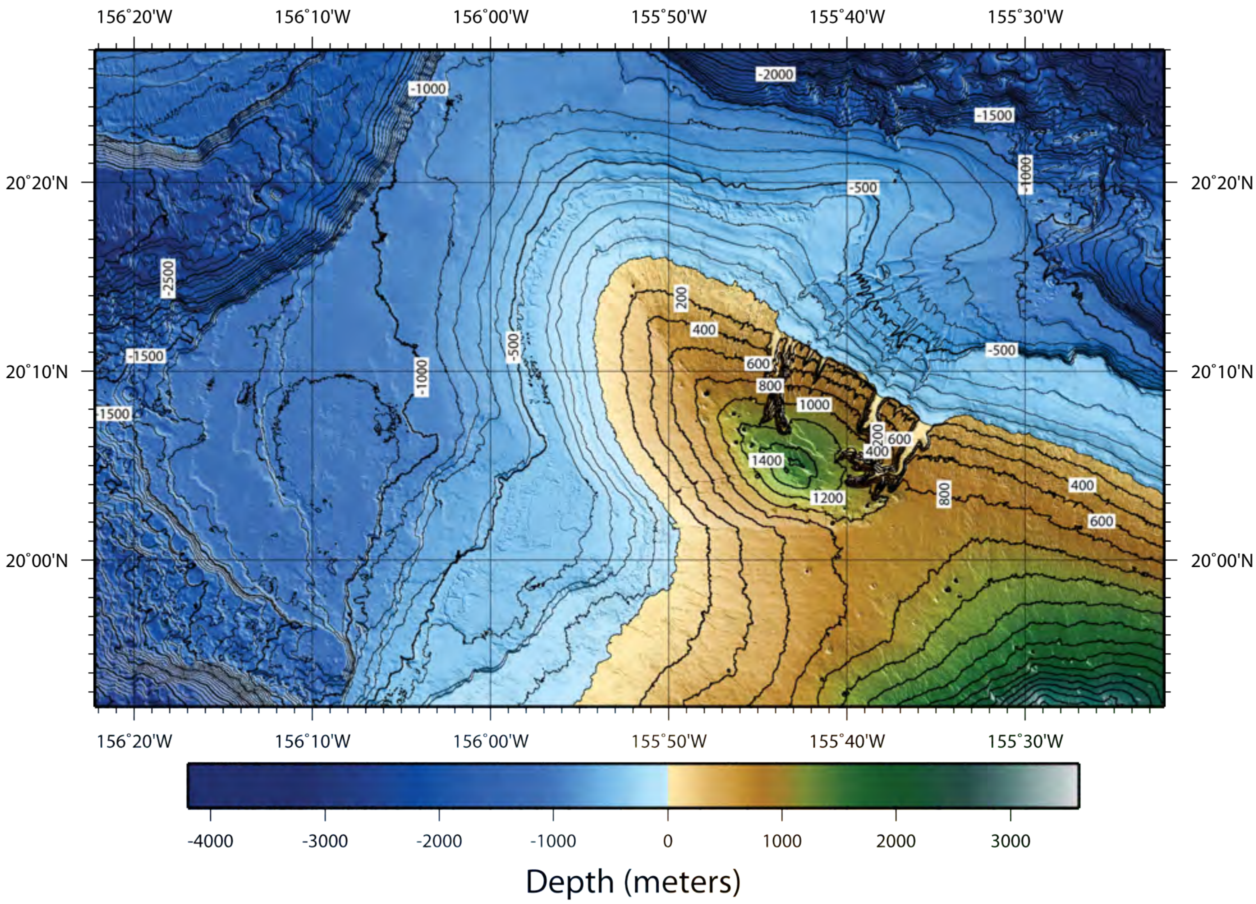

Figure 2. Bathymetric and topographic shaded-relief image of the Kawaihae DEM. Contour interval is 200 meters for topography and 100 meters for bathymetry.

2. Study Area

The Keauhou and Kawaihae DEMs provide coverage of the northwestern coast of the island of Hawaii, Hawaii is the southwestern most island of the main Hawaiian Island Chain (Fig. 3). Hawaii is at risk from tsunamis caused by both distant and local sources. Most tsunamis that affect the islands originate from distant areas where tectonic plates collide (subduction zones), such as Alaska's Aleutian Island chain, Japan, and the west coast of South America. But, regional shallow undersea earthquakes or landslides can generate local tsunamis, posing more danger for residents because of shorter warning times (i.e. hours to minutes notice).

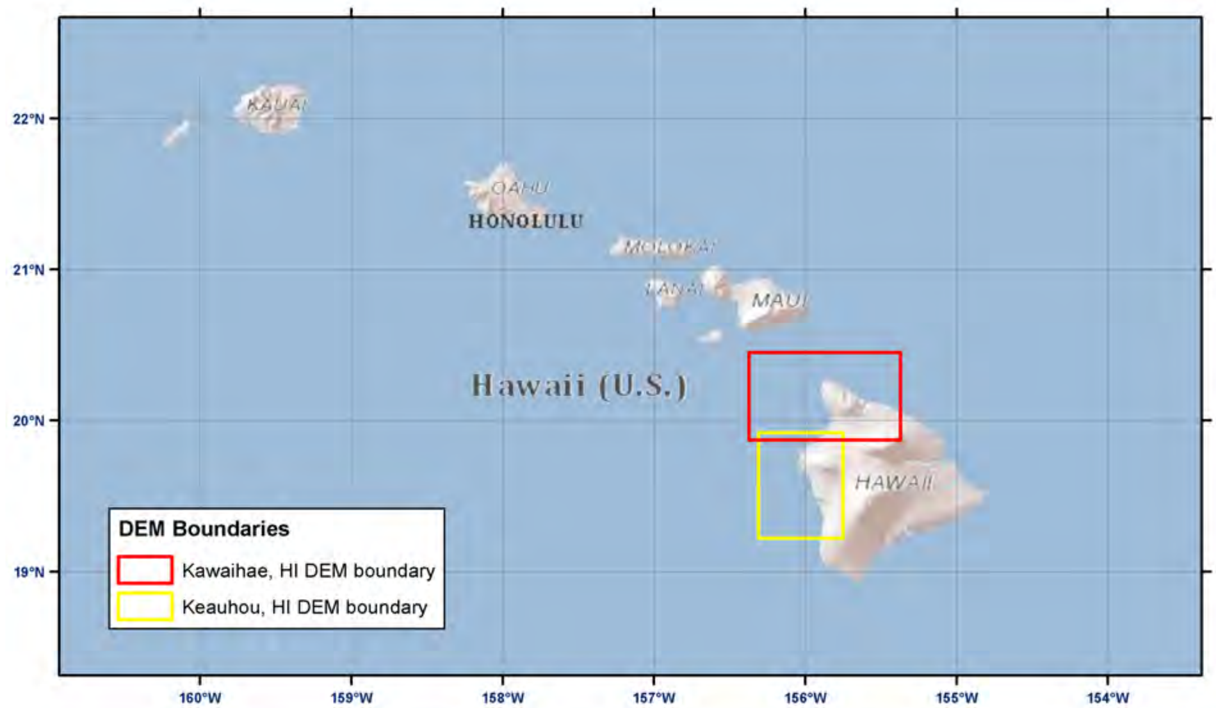

Figure 3. Map of the Hawaiian Islands Chain and locations of the Keauhou DEM, shown in yellow, and the Kawaihae DEM, shown in red.

3. Methodology

The Hawaii MHW 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 Center use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum of 1983[2] (NAD 83) and MHW, for modeling of maximum flooding. Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. PMEL specifications for the 1/3 arc-second Hawaii DEMs.

Grid Area	Keauhou, Hawaii	Kawaihae, Hawaii
Coverage Area	155.75º to 156.31º W; 19.22º to 19.92º N	155.37º to 156.37º W; 19.87º to 20.45º N
Coordinate System	Geographic decimal degrees	
Horizontal Datum	World Geodetic System of 1984 (WGS 84)	
Vertical Datum	Mean high water (MHW)	
Vertical Units	Meters	
Cell Size	1/3 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 DEMs. 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. 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. These DEMs are 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 DEMs, 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 (Figs. 4 and 5) were obtained from several U.S. federal, state and local agencies, and academic institutions including: NGDC; NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), Center for Coastal Monitoring and Assessment (CCMA); Coastal Services Center (CSC), and Pacific Services Center (PSC); the County of Hawaii Information Technology Division; the Federal Emergency Management Agency (FEMA); the U.S. Army Corps of Engineers Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX); the U.S. Army Corps of Engineers (USACE); and the State of Hawaii, Office of Planning, Department of Business, Economic Development, and Tourism (HI DBEDT). Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 geographic horizontal datum and to convert them into ESRI *ArcGIS* shapefiles[3]. The shapefiles were then displayed with *ArcGIS* and Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*) to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using NOAA's tide station information. ESRI's online *World 2D* imagery was used to analyze and modify data. *QT Modeler*, *Gnuplot* and Interactive Visualization System's *Fledermaus* software were used to evaluate processing and gridding techniques.

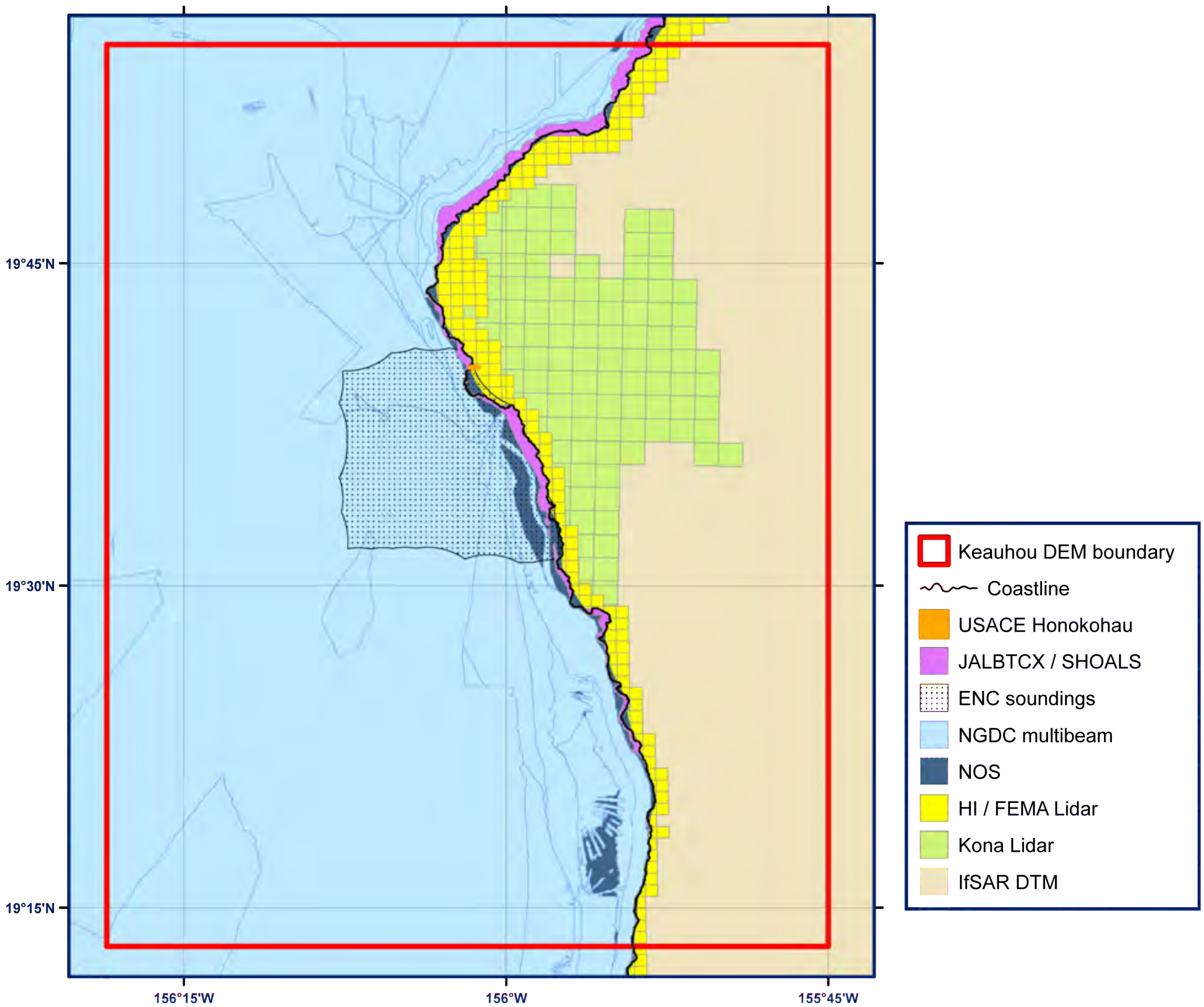

Figure 4. Spatial coverage of the datasets used in developing the Keauhou DEM.

3. *FME* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml) 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.

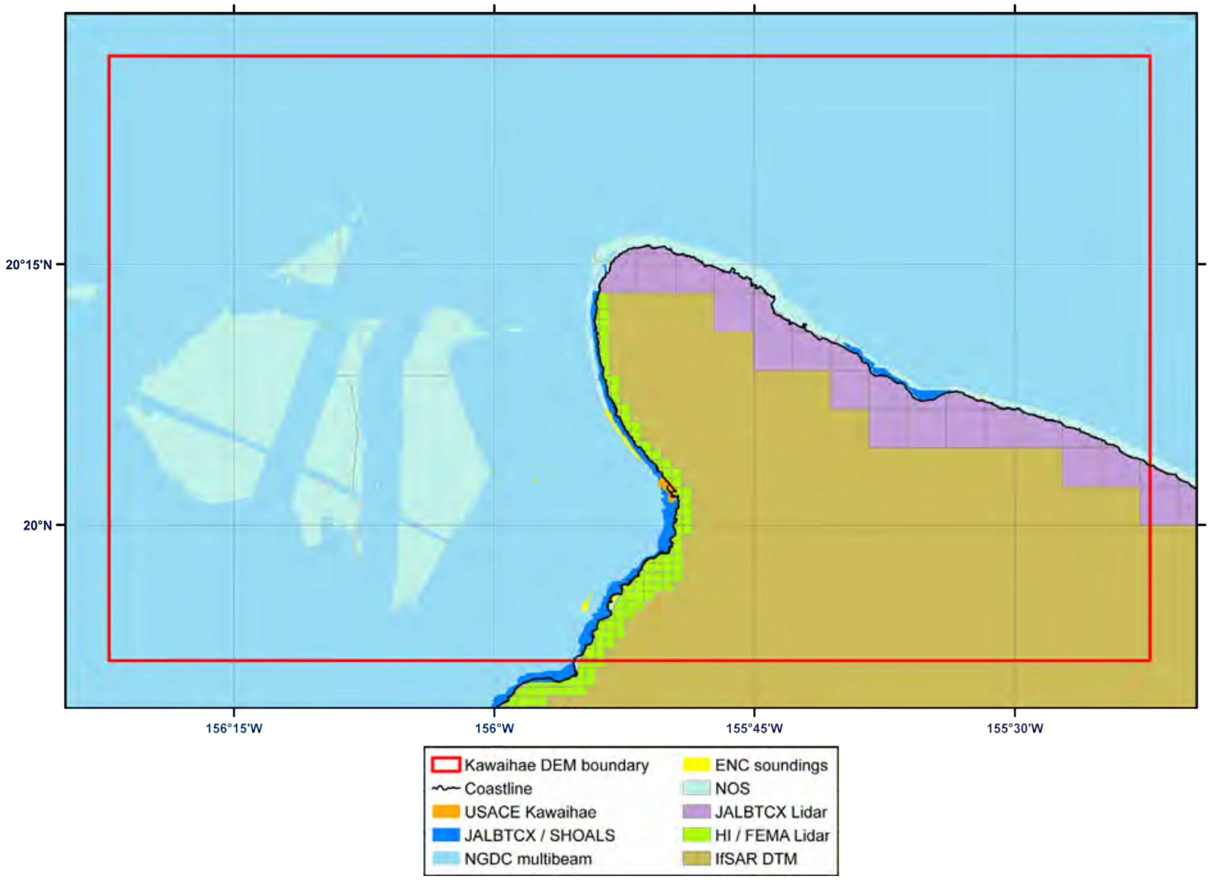

Figure 5. Spatial coverage of the datasets used in developing the Kawaihae DEM.

3.1.1 Coastline

A coastline dataset of the Island of Hawaii was obtained from NOAA's Center for Coastal Monitoring and Assessment (CCMA) Biogeography division. NGDC compared this shoreline to Electronic Nautical Chart (ENC) coastline data which showed the CCMA shoreline was more consistent with ESRI's *World 2D* imagery, *Google Earth* and IKONOS imagery (Table 2; Figs. 6 and 7).

The CCMA Hawaii shoreline was downloaded from the CCMA Biodiversity web page in shapefile format and transformed to NAD 83 geographic using *ArcCatalog*. The data were derived from IKONOS and Quickbird Satellite Imagery from 2004 to 2006. This shapefile was created from manual digitizing when mapping the coral reef habitats of the Main Eight Hawaiian Islands by visual interpretation and manual delineation of IKONOS and Quick Bird satellite imagery.

The CCMA shoreline was clipped to 0.05 degrees (~ 5%) larger than the Keauhou and Kawaihae DEM boundaries. Piers and docks within Keauhou and Kawaihae were deleted from the coastline. In Kailua Bay, the main wharf was not resolved in the CCMA shoreline; however, coastal photos online showed the section of the wharf closest to the shore has been built up from the seabed. The remainder of the wharf appears to be built up on pilings. Two coastlines sections were used in developing the Keauhou DEM at Kailua Bay. In developing a bathymetric surface, a coastline not including the wharf was used. This kept grid cell elevation values more consistant with nautical chart soundings and SHOALS data. A coastline including the nearshore section of the wharf was used in the final gridding process. Similarly, in Kawaihae Harbor, the jetties were not resolved in the shoreline data (Fig. 7). Using ESRI *ArcMap* editing tools, the coastline was modified based on *Google Earth* imagery to reflect the most current coastal morphology. An xyz file of the "combined coastline" with points every 10 meters was generated using NGDC's *GEODAS* software for use in creating a bathymetric surface (see Section 3.3.2).

Table 2. Shoreline dataset used in building the Hawaii DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
CCMA	2004 to 2006	Vector shoreline	1:6,000	NAD 83 UTM Zone 4 North (meters)	Unknown	http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd_07/welcome.html

Figure 6. Google Earth image of Kailua Bay and available coastline data for the Keauhou DEM region. Extracted ENC vector coastline in yellow, CCMA in red, and final edited coastline in blue.

Figure 7. Google Earth image of Kawaihae Harbor and available coastline data in the Kawaihai DEM region. Extracted ENC vector coastline in yellow, CCMA in red, and final edited coastline in blue.

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the Hawaii DEMs included: NGDC multibeam swath sonar surveys, U.S. Army Corps of Engineer Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) SHOALS lidar, NOAA ENC chart soundings, and USACE and NOS hydrographic surveys (Table 3; Figs. 4 and 5). Datasets were originally horizontally referenced to WGS 84 geographic, NAD 83 geographic, or NAD 83 State Plane coordinates. The data are vertically referenced to mean lower low water (MLLW) or mean sea level (MSL).

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

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
JALBTCX/ SHOALS	1999	Hydrographic lidar survey	~ 5 to 10 meters	WGS 84 geographic	MLLW	http://shoals.sam.usace.army.mil/hawaii/pages/Hawaii_Data.htm
NGDC	1995 to 2010	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NGDC	1968 to 1987	NOS hydrographic survey soundings	Ranges from 5 meters to 2 kilometers	NAD 83 geographic	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USACE	1998 to 2010	Hydrographic survey soundings	< 1 meter to 30 meter point spacing	NAD 83 HARN 1993 Hawaii State Plane Zone 1	MLLW	
NOAA ENC	2011	Extracted NOAA nautical chart soundings	~ 30 meters up to ~1 kilometer	WGS 84 geographic	MLLW	http://nauticalcharts.noaa.gov/mcd/enc/

1) USACE Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) hydrographic lidar surveys

JALBTCX conducted high-resolution hydrographic lidar surveys around Hawaii in 2001 (Table 4). These surveys were originally referenced to WGS 84 geographic and MLLW vertical datum (meters). The resolution of the surveys range from roughly 5 to 10 meters and the depths range from several meters above zero to ~ 30 meters below zero at MHW. Elevations above zero were filtered out except at Kawaihae Harbor where the elevations on the jetties were retained.

Table 4. JALBTCX / SHOALS hydrographic surveys used in compiling the Hawaii DEMs.

Survey name	*Date*	*Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*
Hawaii 6	2001	~ 5 to 10 meters	WGS 84 geographic	MLLW
Hawaii 7	2001	~ 5 to 10 meters	WGS 84 geographic	MLLW
Hawaii 8	2001	~ 5 to 10 meters	WGS 84 geographic	MLLW
Hawaii 9	2001	~ 5 to 10 meters	WGS 84 geographic	MLLW
Hawaii 10	2001	~ 5 to 10 meters	WGS 84 geographic	MLLW
Hawaii 11	2001	~ 5 to 10 meters	WGS 84 geographic	MLLW
Hawaii 12	2001	~ 5 to 10 meters	WGS 84 geographic	MLLW
Hawaii 13	2001	~ 5 to 10 meters	WGS 84 geographic	MLLW

2) NOAA NGDC multibeam database surveys

Twenty-eight multibeam swath sonar surveys (Table 5) were available from the NGDC multibeam sonar bathymetry database within the Hawaii DEM regions. This database is comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. One of the available surveys from 2004 was not used due to inconsistancies in overlapping data returns with other surveys. The surveys used in building the Hawaii DEMs are referenced to a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be MSL.

The downloaded data were gridded to 1 arc-second resolution using *MB-System*[4]. Further editing of the gridded data was done using *QT Modeler* and clipped to JALBTCX SHOALS bathymetric lidar surveys.

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

Cruise ID	*Year*	*Ship*	*Collecting Institution / Source*
AHI-06-05	2006	Ahi	National Oceanic and Atmospheric Administration (NOAA/NMFS)
AII8L11	1987	Atlantis II	University of Rhode Island (URI)
CNTL13RR	2003	Roger Revelle	University of California, Scripps Institution of Oceanography (UC/SIO)
DRFT13RR	2002	Roger Revelle	UC/SIO
EX0909	2009	Okeanos Explorer	National Oceanic and Atmospheric Administration (NOAA)
HI-06-05	2006	Hi'ialakai	NOAA/NMFS
HI-06-10	2006	Hi'ialakai	NOAA/NMFS
HI-06-14	2006	Hi'ialakai	NOAA/NMFS
KM0202	2002	Kilo Moana	University of Hawaii (UH)
KM0205	2002	Kilo Moana	UH
KM0317	2003	Kilo Moana	Rolling Deck to Repository (R2R) Program
KM0518	2005	Kilo Moana	R2R
KM0612	2006	Kilo Moana	R2R
KM0615	2006	Kilo Moana	R2R

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. [Extracted from MB-System web site; http://www.ldeo.columbia.edu/res/pi/MB-System/]

Cruise ID	*Year*	*Ship*	*Collecting Institution / Source*
KM0625	2006	Kilo Moana	R2R
KM0632	2006	Kilo Moana	R2R
KM0719	2007	Kilo Moana	R2R
KM0720	2007	Kilo Moana	R2R
Kohala	1998	Ocean Alert	Monterey Bay Aquarium Research Institute (MBARI)
KR2001	2001	Kairei	Japanese Agency for Marine-Earth Science and Technology (JAMSTEC)
LAN-92	1992	Laney Chouest	NOAA
Mahukona	1998	Ocean Alert	MBARI
NECRO05RR	2000	Roger Revelle	UC/SIO
TUNE03WT	1991	Thomas Washington	UC/SIO
TUNE04WT	1991	Thomas Washington	UC/SIO
YK1999	1999	Yokosuka	JAMSTEC
YK2002	2002	Yokosuka	JAMSTEC

3) NOS hydrographic survey data

Nineteen hydrographic surveys conducted between 1968 and 1987 were used in developing the Hawaii DEMs (Table 6). The survey data were downloaded from NGDC's online NOS hydrographic database referenced to NAD 83 geographic horizontal datum and their original vertical datum, MLLW. The data were then transformed to MHW using *FME* and reviewed in *ArcGIS* for digitizing errors and were compared with the SHOALS surveys and nautical charts.

Table 6. NOS hydrographic surveys used in compiling the Hawaii DEMs.

Source	*Year*	*Scale*	*Original Horizontal Datum/ Coordinate System*	*Horizontal Datum/Coordinate System of Records*	*Original Vertical Datum*
B00090	1986	50,000	NAD 83	NAD 83	MLLW
B00098	1987	50,000	NAD 83	NAD 83	MLLW
B00099	1987	50,000	NAD 83	NAD 83	MLLW
B00101	1987	50,000	NAD 83	NAD 83	MLLW
H09015	1969	40,000	Early Hawaiian Island Datum	NAD 83	MLLW
H09016	1969	80,000	Early Hawaiian Island Datum	NAD 83	MLLW
H09017	1968	10,000	Early Hawaiian Island Datum	NAD 83	MLLW
H09018	1968 to1970	10,000	Early Hawaiian Island Datum	NAD 83	MLLW
H09019	1968	10,000	Early Hawaiian Island Datum	NAD 83	MLLW
H09129	1970	40,000	Early Hawaiian Island Datum	NAD 83	MLLW
H09131	1970	10,000	Early Hawaiian Island Datum	NAD 83	MLLW
H09132	1970	10,000	Old Hawaiian Datum	NAD 83	MLLW
H09234	1971	5,000	Old Hawaiian Datum	NAD 83	MLLW
H09235	1971	5,000	Old Hawaiian Datum	NAD 83	MLLW
H09974	1981	80,000	Old Hawaiian Datum	NAD 83	MLLW
H09975	1981	20,000	Old Hawaiian Datum	NAD 83	MLLW
H09983	1981	20,000	Old Hawaiian Datum	NAD 83	MLLW
H09985	1981	80,000	Early Hawaiian Island Datum	NAD 83	MLLW
H09986	1981	80,000	Early Hawaiian Island Datum	NAD 83	MLLW

4) USACE hydrographic surveys

Hydrographic survey data for Honokohau and Kawaihae Harbors was provided by USACE - Honolulu District - Civil Works Technical Branch (Table 7). The channel line and cross line data were referenced to NAD 83 HARN 1993 Hawaii State Plane Zone 1 horizontal datum and MLLW (feet) vertical datum. Transformations to WGS 84 geographic and MHW in meters were made using *FME*.

Table 7. USACE hydrographic surveys used in compiling the Hawaii DEMs.

Survey name	*Date*	*Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*
Honokohau Small Boat Harbor	2010	point spacing < 1 meters and line spacing ~6 meters	NAD 83 HARN 1993 Hawaii State Plane Zone 1	MLLW
Kawaihae Deep Draft Harbor	1998	point spacing < 3 meters and line spacing from 20 to 30 meters	NAD 83 HARN 1993 Hawaii State Plane Zone 1	MLLW
Kawaihae Small Boat Harbor	1998	point spacing < 2 meters and line spacing from 2 to 10 meters	NAD 83 HARN 1993 Hawaii State Plane Zone 1	MLLW

5) Extracted Nautical Chart soundings

Seven NOAA nautical charts were available from OCS within the Hawaii DEM boundaries (Table 8). Sounding data were extracted using OCS's ENCDirect to GIS online tool for charts #19327, 19330, and 19331 in shapefile format. The data were referenced to WGS 84 geographic and MLLW. Transformation to MHW were accomplished using *FME*. Raster nautical charts were used as a reference to quality check gridded bathymetric data (see Section 3.3.2).

Table 8. Nautical charts available in the Hawaii region.

Chart	*Title*	*Format*	*Edition*	*Issue Date*	*Scale*
19322	Harbors and Landings on the Northeast and Southeast Coast of Hawaii	RNC	8	2003	1:2,500
19326	Paauhau Landing	RNC	6	1999	1:5,000
19327	West Coast of Hawaii Cook Point to Upolu Point; Keauhou Bay; Honokohau Harbor	ENC and RNC	8	2011	1: 80,000
19329	Mahukona Harbor and Approaches	RNC	8	2003	1:5,000
19330	Kawaihae Bay-Island of Hawaii	ENC and RNC	7	2011	1:10,000
19331	Kailua Bay Island Of Hawaii	ENC and RNC	2	2010	1:5,000
19332	Kealakekua Bay to Honaunau Bay	RNC	8	1998	1:10,000

3.1.3 Topography

Topographic datasets in the Hawaii region were obtained from: NOAA's Pacific Services Center (PSC) and the State of Hawaii, Office of Planning, Department of Business, Economic Development, and Tourism (HI DBEDT) (Table 9; Figs. 4 and 5).

Table 9. Topographic datasets used in compiling the Hawaii DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
PSC	2005	IfSAR DTM	~ 5 meters	NAD 83 UTM Zone 5 North	NAVD 88	
State of Hawaii Civil Defense / FEMA	2006	Lidar DEMs	~ 3 feet	NAD 83 State Plane HI Zone 1 FIPS 5101 (feet)	Local Tidal	
HI DBEDT	2006	Lidar	~ 1 meter point spacing	NAD 83 UTM Zone 5 North (meters)	Local Tidal	
JALBTCX	2007	Lidar DEM	5 meter	NAD 83 geographic	Mean Sea Level	

1) **IfSAR DTM of Hawaii**

The IfSAR DTM of Hawaii provide the majority of the topographic coverage on the island. The dataset was provided by PSC as a raster digital terrain model (DTM) in NAD 83 UTM Zone 5 North horizontal datum and NAVD 88 (meters) vertical datum. *FME* was used to convert the raster to xyz format. Other higher resolution lidar data were available to replace the IfSAR data along the coast.

2) **State of Hawaii Civil Defense / FEMA Lidar**

Pacific Services Center (PSC) provided NGDC with the State of Hawaii Civil Defense topographic lidar dataset. The lidar was flown in 2006 in support of hurricane study for the Hawaiian Islands and was specified to include coverage from the coastline up to the 10 meter contour elevation with an average point spacing of 3 feet. The data were projected to NAD 83 State Plane Hawaii Zone 4 FIPS 5104 (feet), and referenced to a local tidal datum, assumed to be local mean sea level. Data were converted to xyz format and transformed to WGS 84 geographic using *FME*.

3) HI DBEDT Lidar

This lidar dataset covers the area surrounding the community of Kona from the shoreline and inland to Hainoa Crater (Fig. 4). The data were transformed from NAD 83 UTM coordinates and a local tidal datum to WGS 84 geographic and MHW using *FME*. The data tiles were then clipped to the coastline as needed to removed anomalous values over water. In Kailua Bay, the pier was resolved in the lidar data. Using images, it appears that the section of the pier closest to the shore is actually built up and was not removed from the dataset. Figure 8 shows an example of the HI DBEDT lidar dataset in Kailua Bay on the eastern side of Hawaii. Note the cross section of the data over the bay; data point elevations are around zero meters. This indicates water surface values; data set was clipped to the coastline to remove the water surface elevation points.

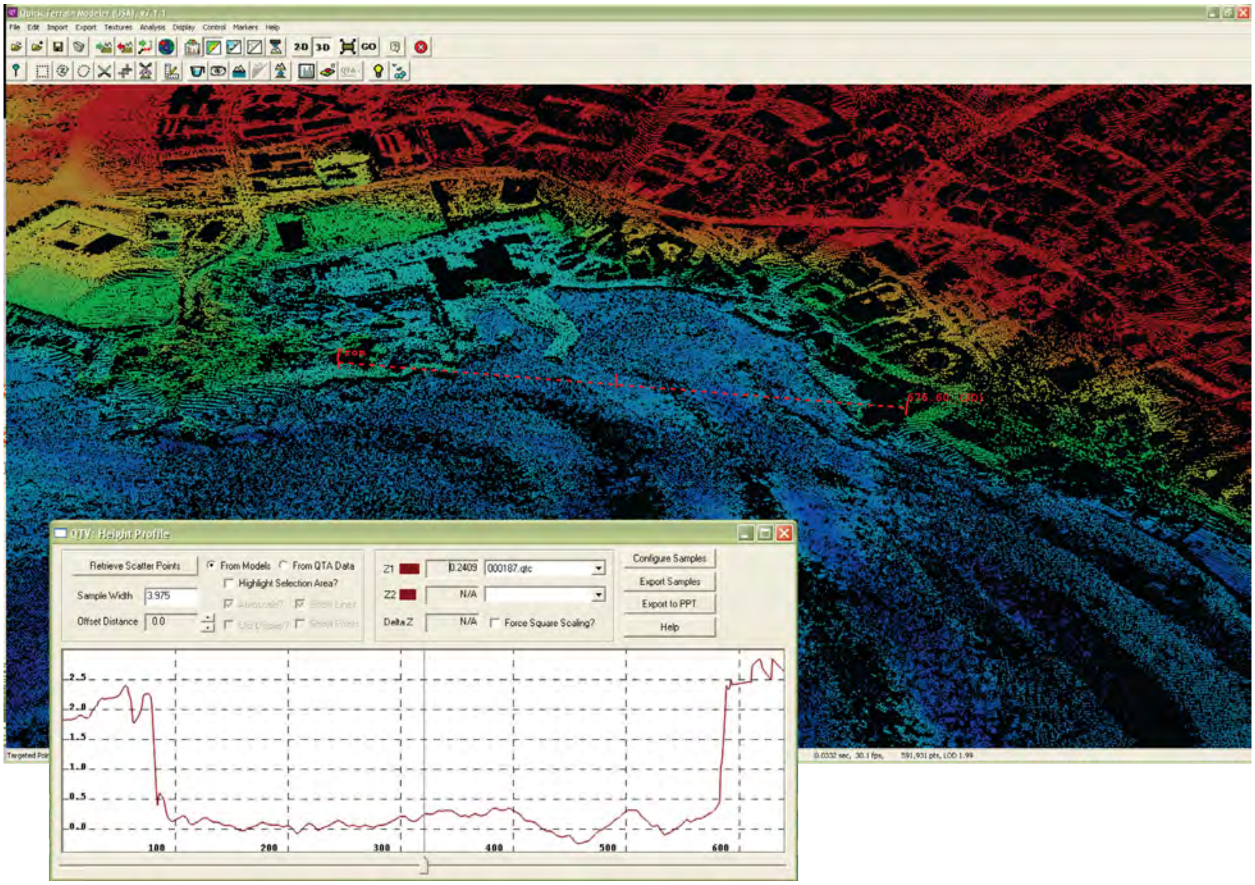

Figure 8. Image of HI DBEDT lidar in Kailua Bay displayed in QT Modeler with cross section of data along red line.

4) JALBTCX Hawaii lidar

PSC provided lidar data from 2007 of the northern shoreline of Hawaii (Fig. 5). These data were collected for Hawaii State Civil Defense for tsunami mapping. Topographic data were required between the zero and 15 meter contours, nominal, for the northern coastline of the islands of Hawaii (Big Island), Kauai, Maui, Molokai, and Oahu. The data were collected from the land water interface seaward to a depth of 40 meters or laser extinction, whichever came first.

One meter lidar data were downloaded gridded to 5 meters using an average grid method and referenced to NAD 83 geographic and mean sea level. The data were transformed to MHW and converted to xyz format using *FME*. Figure 9 shows a section of the data where possible shadows from steep topographic near shore may have caused anomalous returns in the lidar resulting in a small peninsula. This section of data was removed from the final datasets before gridding and after comparison with *Google Earth* imagery and overlapping IfSAR data (Fig. 10).

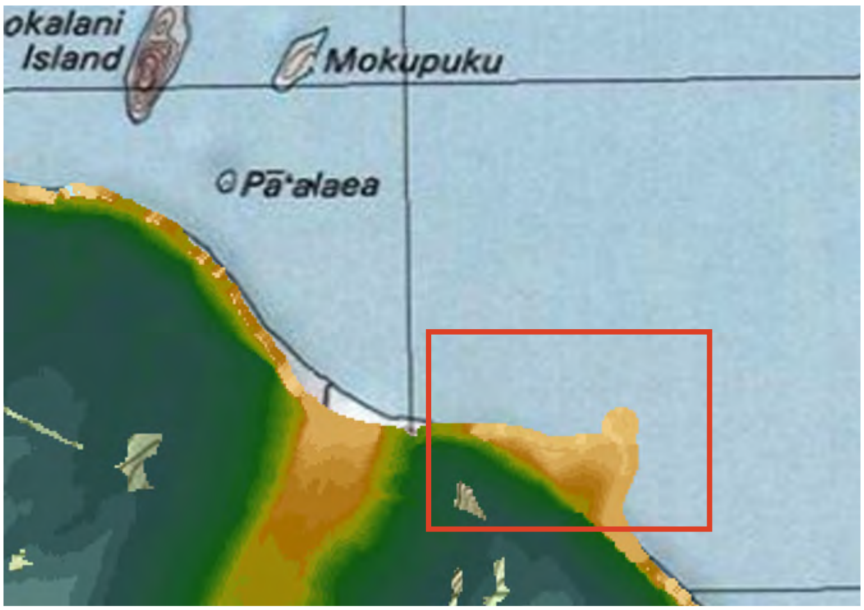

Figure 9. Section of JALBTCX lidar data on the north coast of Hawaii. Background is USGS topographic quad.

Figure 10. Same area as in Figure 9 in Google Earth imagery.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Hawaii DEM were originally referenced to a number of vertical datums including: Unknown local tidal datum, MLLW, MSL, and NAVD 88.

1) Bathymetric data

The multibeam surveys, the JALBTCX SHOALS data, NOS, USACE, and the nautical chart soundings were transformed from MSL, and MLLW to MHW, using a constant value. The relationships between the various vertical datums and MHW based on the tide station in the DEM region are listed in Table 10.

2) Topographic data

The IfSAR DTM and the lidar data were originally referenced to NAVD 88, local tidal datum, or MSL. For these DEMs, local tidal datum and MSL were assumed to be equal. Data referenced to NAVD 88 was also treated as MSL as NAVD 88 does not exist on the Hawaiian Island. Transformations from MSL to MHW were done using a constant value based on the Kawaihae tide station (Table 10).

Table 10. Relationships between MHW and other vertical datums in meters within the Hawaii DEM region.

	Kawaihae (ID 1617433) Elevations of tidal datums in reference to MLLW (meters)
MHHW	0.656
MHW	0.507
MSL	0.285
MTL	0.277
MLW	0.046
NAVD 88	n/a
MLLW	0.0
	Difference between datums (meters)
MSL to MHW	-0.222
MTL to MHW	-0.230
MLLW to MHW	-0.507

3.2.2 Horizontal datum transformations

Datasets used in compiling the Hawaii DEMs were originally referenced to: NAD 83 and WGS 84 geographic; NAD 83 UTM Zone 4 North (meters); and NAD 83 HARN 1993 State Plane Hawaii Zone, NAD 83 UTM Zone 5 North, NAD 83 State Plane Hawaii Zone 1 FIPS 5101 (feet) horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established and transformations to NAD 83 geographic were done using *FME* or *ArcGIS* software.

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 *QT 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 water in topographic datasets. Data required automated clipping to the combined coastline or manual editing.
- Inconsistent, overlapping bathymetric datasets. Lower-resolution datasets were clipped to higher-resolution data and all datasets were weighted based on quality and age in gridding process.

3.3.2 Smoothing of bathymetric data

In order to reduce the effect of artifacts in the form of lines of "pimples" in the 1/3 arc-second DEM due to variable resolution datasets, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing "pre-surface" grid was generated using *GMT*[5].

All bathymetric datasets were combined into a single file. Points extracted from the combined coastline were also included and assigned elevation values of zero meters to ensure that the offshore elevations remained negative. These point data were then smoothed using the *GMT* tool "blockmedian" onto a 1 arc-second grid. The *GMT* tool "surface" was 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). For the Kawaihae DEM, where SHOALS data coverage did not extend over the north shore of Hawaii, a 1/3 arc-second surface for the near shore region was also generated. This provided needed data points to reduce interpolation effects at the coast where dense topographic data abuts sparse bathymetric data.

The resulting surfaces were compared with original soundings to ensure grid accuracy, converted to xyz files for use in the final gridding process (see Table 11). The statistical analyses of the differences between the 1 arc-second bathymetric surface and bathymetric data files showed that the majority of the soundings are in good agreement with the bathymetric surface.

5. 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. [Extracted from GMT web site; http://gmt.soest.hawaii.edu/]

3.3.3 Building the 1/3 arc-second MHW DEM

MB-System was used to create 1/3 arc-second DEMs of Keauhou and Kawaihae, Hawaii. 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 11. Greatest weight was given to the the USACE hydrographic surveys. Least weight was given to the deep water NGDC multibeam and NOS sounding data.

Table 11. Data hierarchy used to assign gridding weight in *MB-System*

Dataset	*Relative Gridding Weight for Keauhou DEM*	*Relative Gridding Weight for Kawaihae DEM*
NOS hydrographic soundings	-	.1
JALBTCX lidar	-	1
NGDC multibeam data	.1	1
HI DBEDT lidar	10	-
ENC soundings	10	-
Combined coastline	1	10
IfSAR DTM	10	1
Bathymetric 'pre-surfaced' data	10	1
HI / FEMA lidar	10	10
JALBTCX / SHOALS surveys	10	10
USACE hydrographic surveys	100	100

3.4 Quality Assessment of the DEM

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Hawaii DEMs are dependent upon DEM cell size and the datasets used to determine corresponding DEM cell values. Topographic features inland have an estimated horizontal accuracy of less than 10 meters based on the documented accuracy of the datasets. Lidar datasets have an accuracy of less than one meter. IfSAR DTM are 2 meters RMSE or better in areas of unobstructed flat ground. Gridded multibeam survey data have a positional accuracy of 10 meters. More recent JALBTCX / SHOALS bathymetric lidar data have accuracy of + / - 3 meters. USACE hydrographic surveys have a horizontal accuracy of 1 meter.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Hawaii DEMs are also highly dependent upon the source datasets contributing to grid cell values. Topographic datasets have vertical accuracies of less than 1 meter, derived from FEMA, HI DBEDT, and JALBTCX lidar data, and the IfSAR DTM has an accuracy of 1 meter RMSE or better in areas of unobstructed flat ground. Bathymetric values, derived from single and multibeam sounding measurements, are 0.3 meters in 0 to 20 meters of water, 1.0 meters 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 data degrades the vertical accuracy of elevations in deep water to about 5% of water depth. JALBTCX / SHOALS data have a vertical accuracy of 0.3 meter. USACE hydrographic surveys have a vertical accuracy of 0.5 foot.

3.4.3 Slope maps and 3-D perspectives

ESRI *ArcCatalog* was used to generate slope grids from the 1/3 arc-second Hawaii DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Figs. 11 and 12). The DEMs were transformed to NAD 83 UTM Zone 5 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Dark areas indicate steeper slopes while lighter areas indicate low slope.

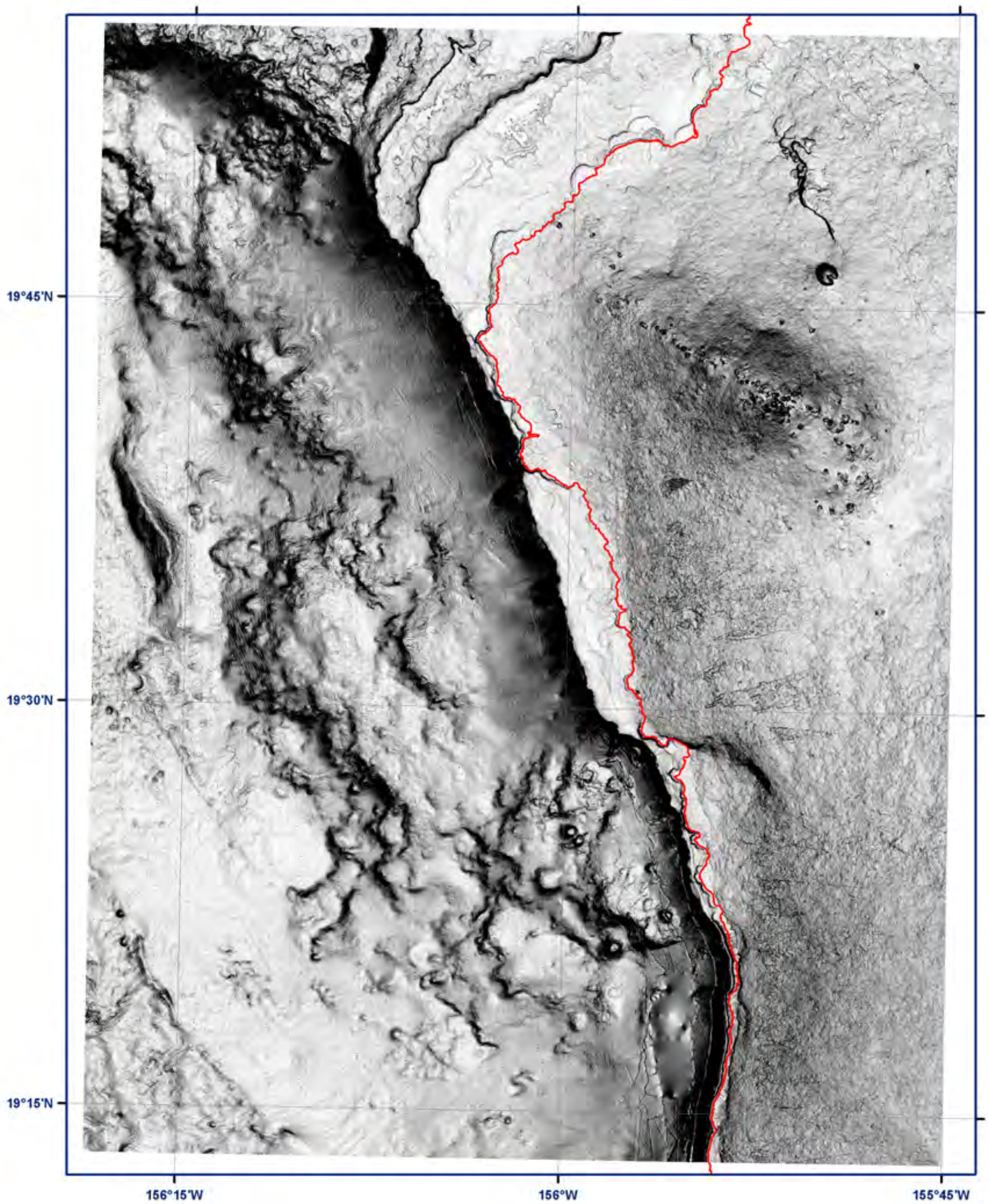

Figure 11. Slope map of the Keauhou DEM. Coastline in red.

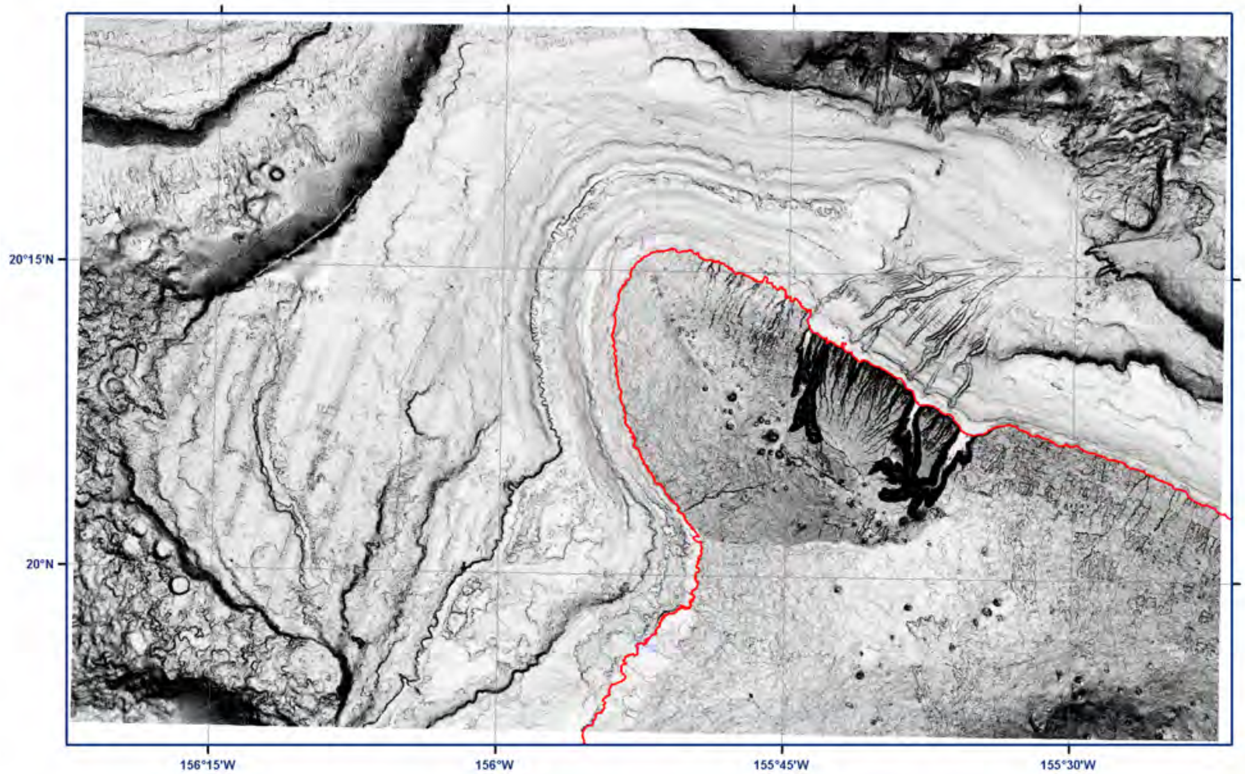

Figure 12. Slope map of the Kawaihae DEM. Coastline in red.

High-resolution perspective images were generated using *POV Ray,* providing three-dimensional viewing of the DEMs (Figs. 13 and 14). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEMs.

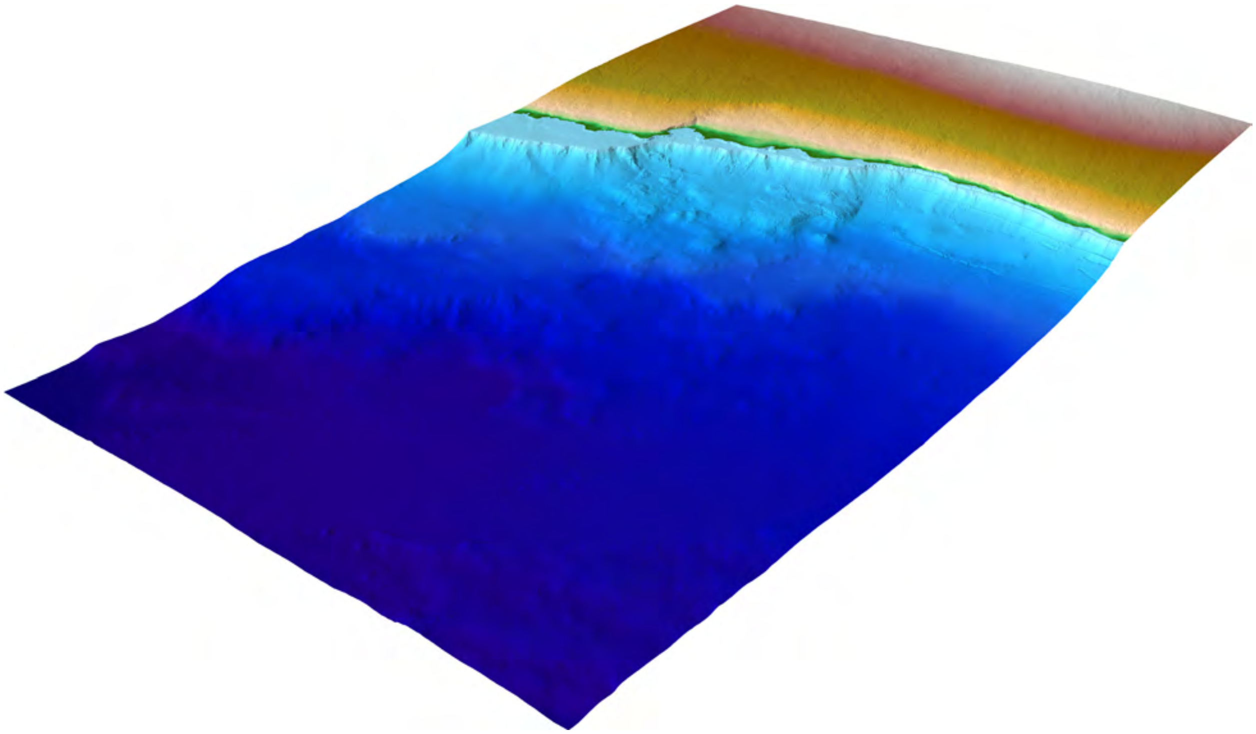

Figure 13. Perspective image of the Keauhou DEM. View is from the southwest.

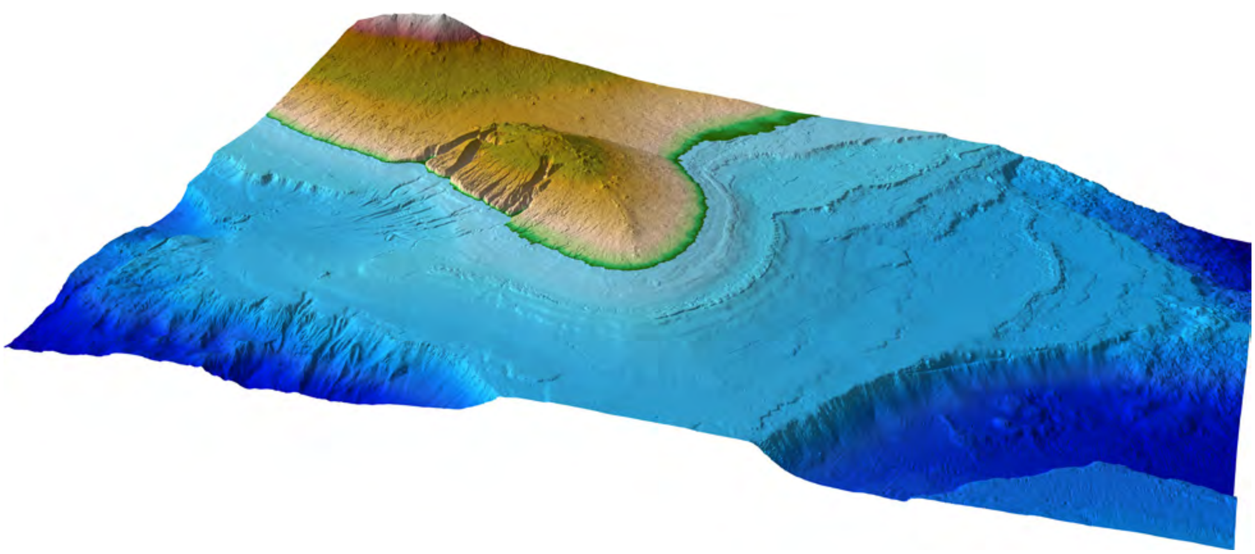

Figure 14. Perspective image of the Kawaihae DEM. View is from the northwest.

3.4.4 MHW DEM comparison with source data files

To ensure grid accuracy, the 1/3 arc-second Hawaii DEMs were compared to a sample of data files from each of the data sources. Comparisons of high resolution lidar data files to the DEMs showed small differences between source elevations and DEM elevations inland with large differences occuring along steep coastal terrain. Comparisons between two multibeam source data files showed the majority of the differences in elevation were small with larger differences occuring where several surveys overlap along the edges of data coverage. Comparisons between SHOALS data files and the DEMs were similar to those between multibeam data files and DEMs.

3.4.5 Comparison with National Geodetic Survey geodetic monuments

Shapefiles of the datasheets for NGS geodetic monuments located within the DEM boundaries were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/, see Figs. 15 and 16 for monument locations). Shapefile attributes give positions in NAD 83 geographic (typically sub-mm accuracy) and elevations at local tidal vertical datum. Histograms of the difference in elevation between the NGS monuments and the Keauhou and Kawaihae DEMs are shown in figures 17 and 18. Comparisons between the NGS monument elevations and the Keauhou DEM showed 69 of the 85 monuments to be less than 5 meters different. Of the other 16 elevations, 12 were scaled elevations which are positionally less accurate. Two of the remaining four were located on elevated structures, a post and lighthouse. Comparisons between the NGS monuments and the Kawaihae DEM showed 20 monument elevations had differences greater than 5 meters. Ten of these were scaled and nine of the remainder were located on hilltops, slopes, or ridgelines.

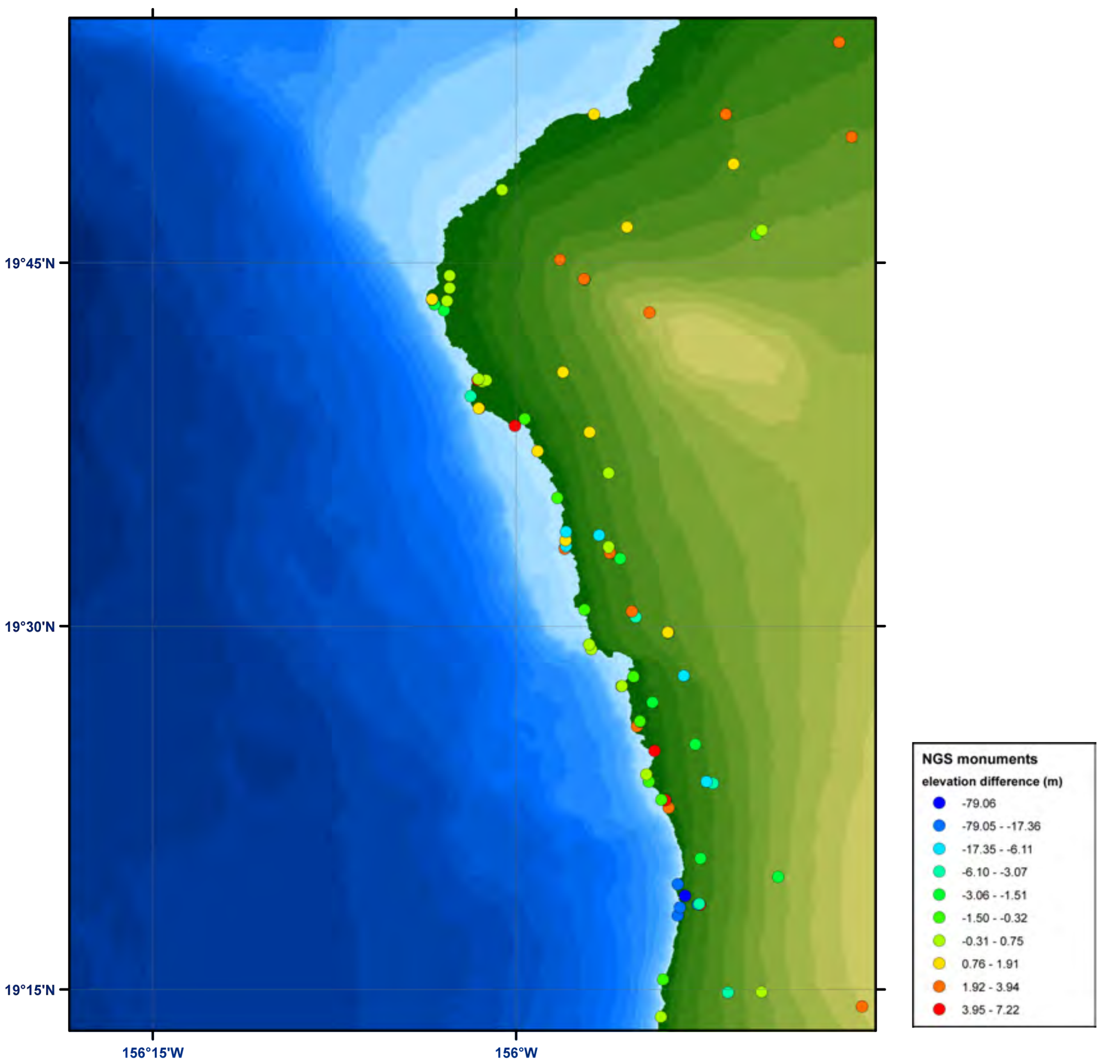

Figure 15. Map of NGS monument locations in the Keauhou DEM region and difference in the monument elevation and DEM elevation.

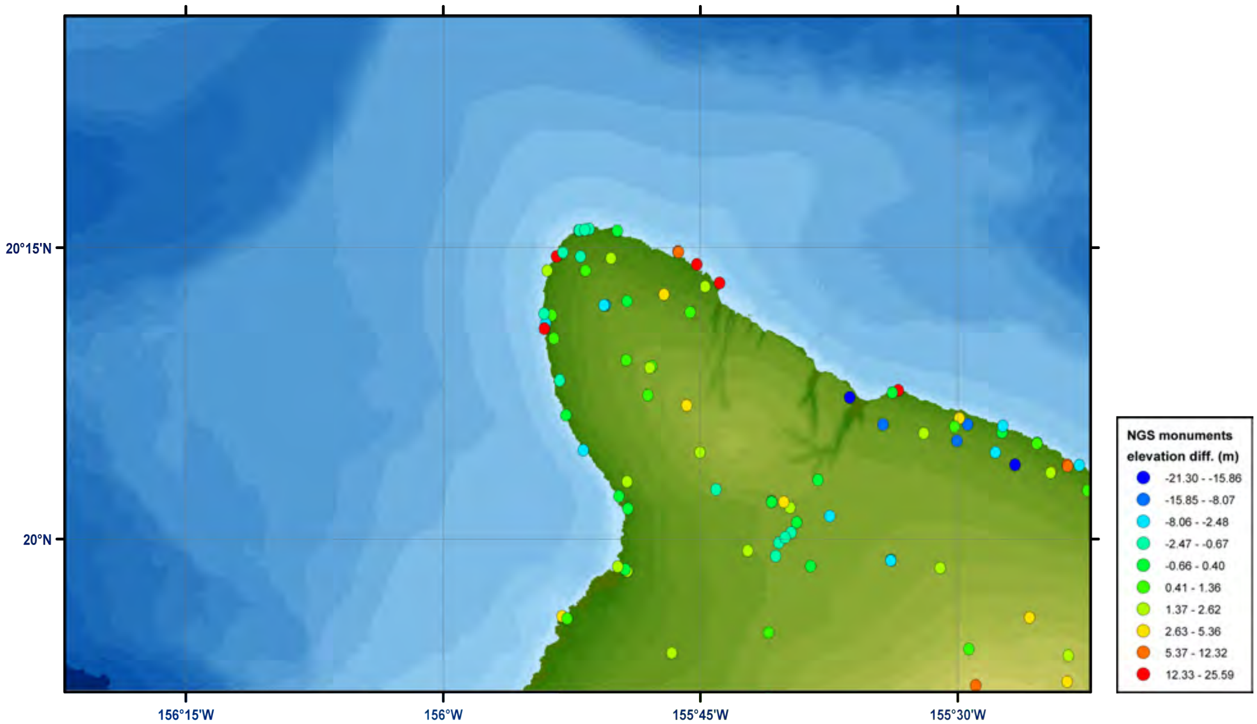

Figure 16. Map of NGS monument locations in the Keauhou DEM region and difference in the monument elevation and DEM elevation.

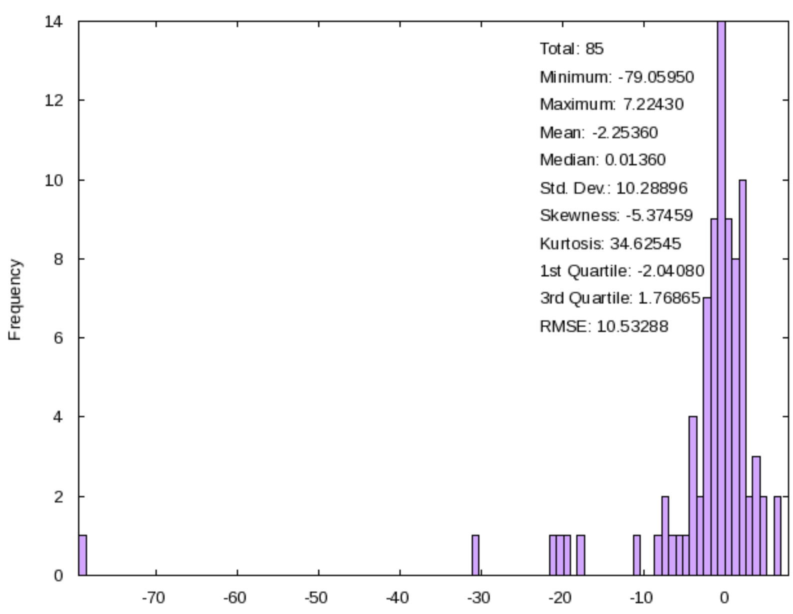

Figure 17. Histogram of the differences in elevation between the NGS monuments and the Keauhou DEM.

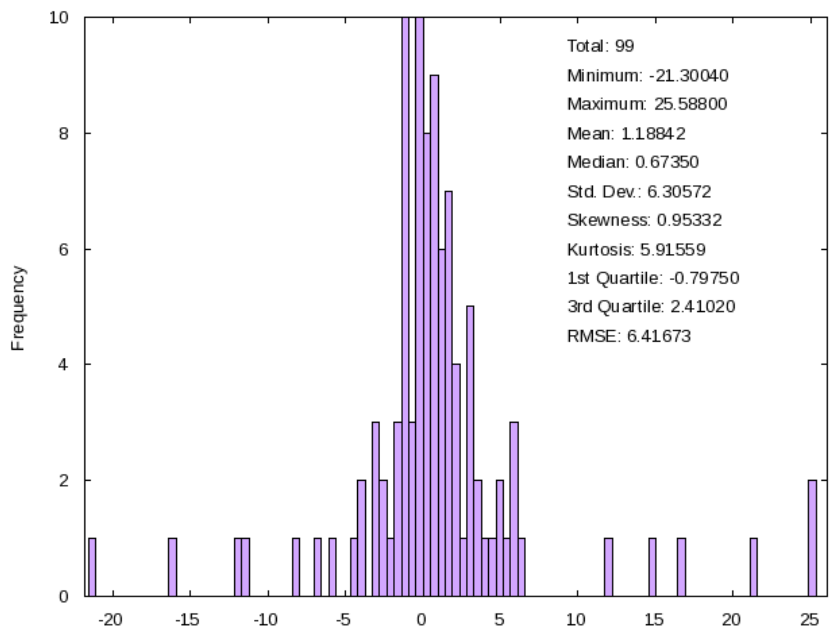

Figure 18. Histogram of the differences between the NGS monuments and the Kawaihae DEM.

4. Summary and Conclusions

Two integrated bathymetric–topographic DEMs of Keauhou and Kawaihae, Hawaii with cell size of 1/3 arc-second, vertically referenced to MHW were developed for the PMEL NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state and local agencies, and academic institutions 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*, *Fledermaus*, *FME*, *GDAL*, *GMT*, *Gnuplot*, *GEODAS*, *Quick Terrain Modeler*, *MB-System*, and *VDatum* software.

The recommendation to improve the DEMs, based on NGDC's research and analysis, is listed below:

- Conduct additional bathymetric–topographic lidar surveys along the shoreline not covered by SHOALS dataset.

5. Acknowledgments

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6. References

Raster Nautical Chart #19322, 8th Edition, 2003. Harbors and Landings on the Northeast and Southeast Coast of Hawaii. Scale 1:2,500. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Raster Nautical Chart #19326, 6th Edition, 1999. Paauhau Landing. Scale 1:5,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #19327, 8th Edition, 2011. West Coast of Hawaii, Cook Point to Upolu Point; Keauhou Bay; Honokohau Harbor. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Raster Nautical Chart #19329, 8th Edition, 2003. Mahukona Harbor and Approaches. Scale 1:5,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #19330, 7th Edition, 2011. Kawaihae Bay - Island of Hawaii. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #19331, 2nd Edition, 2010. Kailua Bay - Island of Hawaii. Scale 1:5,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Raster Nautical Chart #19332, 8th Edition, 1998. Kealakekua Bay to Honaunau Bay. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 10 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/

ESRI World Imagery (ESRI_Imagery_World_2D) – ESRI ArcGIS Resource Centers http://resources.esri.com/arcgisonlineservices/

FME 2011 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/.

Fledermaus v. 7.2.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/

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

GEODAS v. 5.0.11 – Geophysical Data System, freeware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/.

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

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

MB-System v. 5.1.0 – 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/.

Persistence of Vision Pty. Ltd (POV Ray) v. 3.6 – Persistence of VisionTM Raytracer. Persistence of Vision Pty., Williamstown, Victoria, Australia, http://www.povray.org/

Quick Terrain Modeler v. 7.1.1 – Lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.