NOAA Technical Memorandum NESDIS NGDC-36

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Marine Geology and Geophysics Division
Boulder, Colorado
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Elliot Lim[1]
Lisa A. Taylor[2]
Barry W. Eakins[1]
Kelly S. Carignan[1]
Pamela R. Grothe[1]
R. Jason Caldwell[1]
Dorothy Z. Friday[1]

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

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

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Gary Locke
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Dr. Jane Lubchenco
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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

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Contents

List of Figures

List of Tables

Digital Elevation Models of Pago Pago, American Samoa: Procedures, Data Sources and Analysis

1. Introduction

In September 2009, 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 Pago Pago, American Samoa, for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov). The coastal DEMs will be used as input for the Method of Splitting Tsunami (MOST) model development by PMEL to simulate tsunami generation, propagation, and inundation. A 3 arc-second DEM[1] (Fig. 1) was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 4) and will be used for tsunami modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) developed by PMEL for the NOAA Tsunami Warning Centers. To increase the forecasting accuracy of SIFT, a smaller 1/3 arc-second DEM (Fig. 2) was generated for the immediate area surrounding Pago Pago, where high-resolution multibeam bathymetric data were available. This report provides a summary of the data sources and methodology used in developing the Pago Pago DEMs.

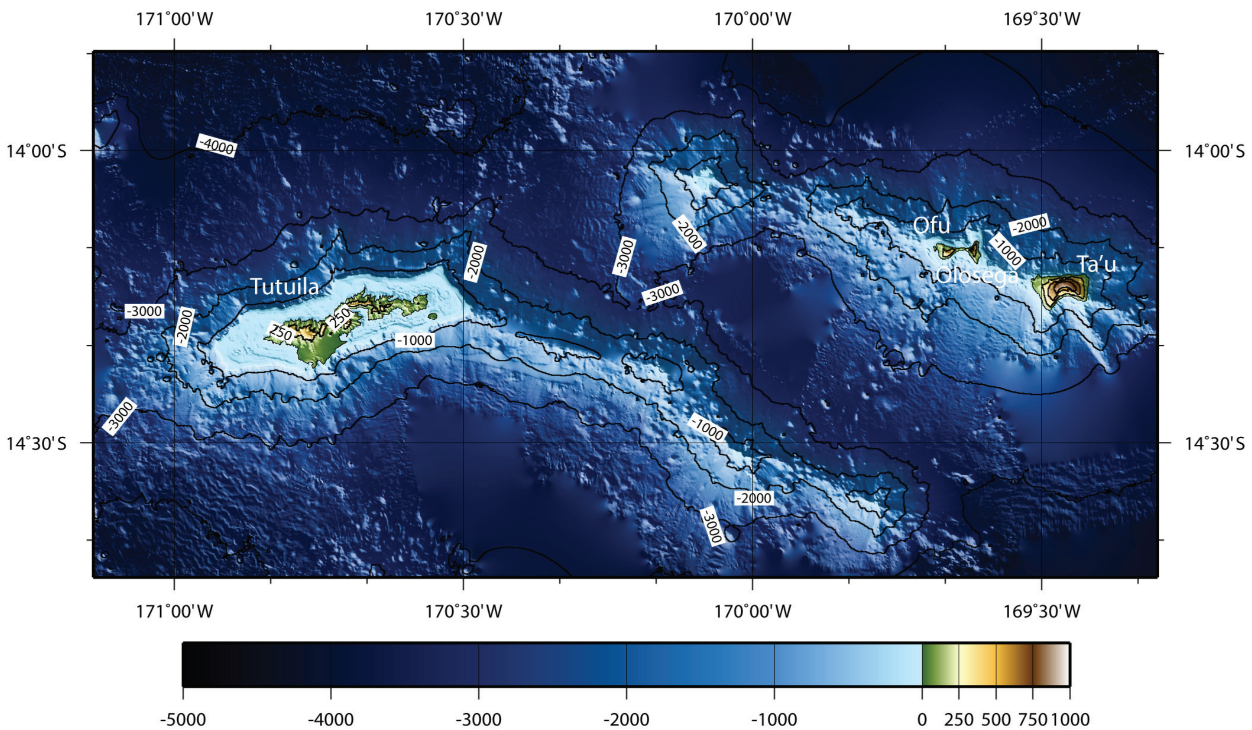

Figure 1. *Shaded-relief image of the 3 arc-second Pago Pago DEM. Contour interval is 1000 meters for bathymetry and 250 meters for topography.*

1. The Pago Pago DEMs are built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Pago Pago (14°17'S, 170°42'W) 1/3 arc-second of latitude is equivalent to 10.24 meters; 1/3 arc-second longitude equals 9.99 meters. Three arc-seconds of latitude is equivalent to 92.20 meters; 3 arc-seconds of longitude is equivalent to 89.92 meters.

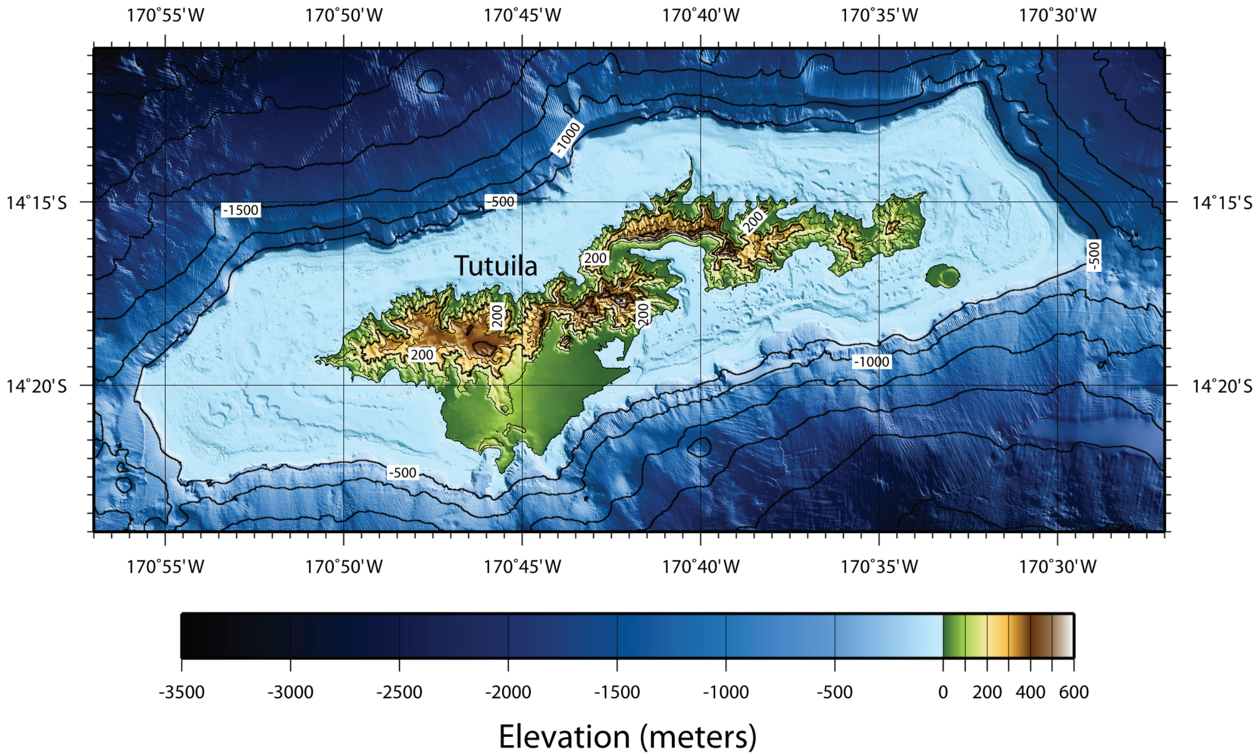

Figure 2. *Shaded-relief image of the 1/3 arc-second Pago Pago DEM. Contour interval is 500 meters for the bathymetry and 200 meters for the topography.*

2. Study Area

The Pago Pago DEMs encompass the American Samoa islands of Tutuila, Ofu, Olosega, and Ta'u (see Figs. 1, 2, and 4). American Samoa is an unincorporated territory of the United States and is located between 11 and 15 degrees south latitude and 171 and 169 degrees west longitude in the South Pacific Ocean. Tutuila is the largest island and covers an area of 55 square miles. Tutuila is the eroded summit of a large basaltic volcano that formed 1.54 to 1 million years ago during the Early Pleistocene era. Offshore, the island is characterized by a drowned coastline and underdeveloped fringing reefs. Inland areas feature lush, steep, and narrow valleys. Pago Pago, the capital of American Samoa, is home to roughly 11,500 people and is located in Pago Pago Harbor on the island of Tutuila (Fig. 3). Pago Pago Harbor is one of the world's largest natural harbors and was formed by submergence of the volcano's caldera.

Figure 3. *Photograph of Pago Pago Harbor.*
(Photo credit: Elliot Lim)

3. Methodology

The Pago Pago DEMs were constructed to meet PMEL specifications (Tables 1a and 1b), based on input requirements for the development of reference inundation models (RIMs) and standby inundation models (SIMs) (V. Titov, pers. comm.) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums of World Geodetic System of 1984 (WGS 84) and mean high water (MHW), respectively, 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 1a: PMEL specifications for the 3 arc-second Pago Pago DEM.

Grid Area	American Samoa
Coverage Area	171.14º to 169.30º W; 14.73º to 13.83º S
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	3 arc-second
Grid Format	ESRI Arc ASCII grid

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

Grid Area	Tutuila Island
Coverage Area	170.95º to 170.45º W; 14.40º to 14.18º S
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 Arc ASCII grid

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 4) were obtained from several U.S. federal agencies, academic institutions, and private companies including: NOAA NGDC and Coastal Services Center (CSC); Scripps Institution of Oceanography (SIO); Gaia Geo-Analytical; the U.S. Geological Survey (USGS); and the Naval Oceanographic Office (NAVOCEANO). NGDC reviewed, but did not use, data available from Fagetele Bay National Marine Sanctuary (FBNMS; http://dusk.geo.orst.edu/djl/samoa), because the datasets were available from the primary sources. Safe Software's (http://www.safe.com) *FME* data translation tool package was used to shift datasets to WGS 84 geographic horizontal datum and to convert them into ESRI (http://www.esri.com) *ArcGIS* shapefiles. The shapefiles were then displayed with *ArcGIS* to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using *FME* and *ArcGIS*, based upon data from NOAA tide station #1770000 at Pago Pago. Applied Imagery's *Quick Terrain Modeler* software (http://www.appliedimagery.com) was used for evaluating datasets before the final gridding process.

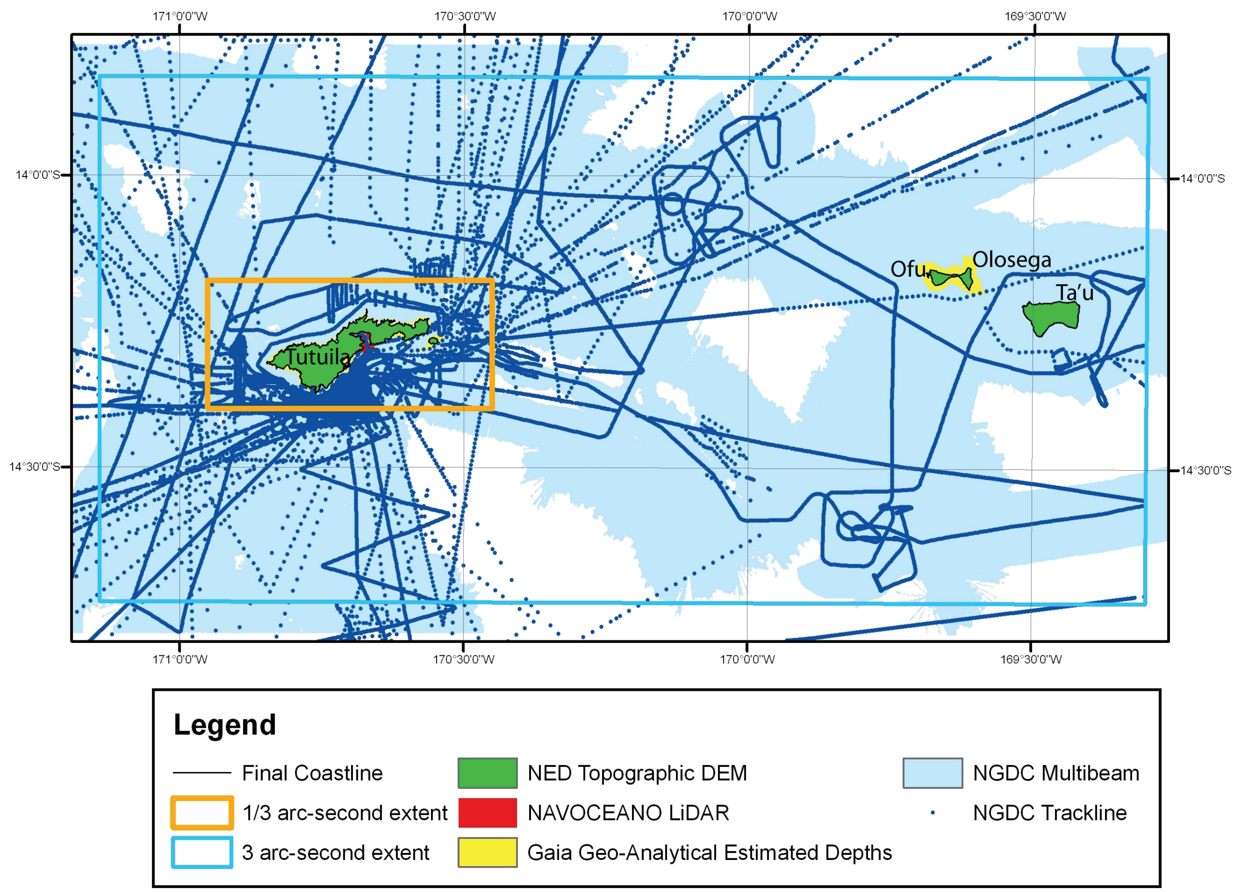

Figure 4. *Source and coverage of datasets available in the American Samoa region. Areas of no data are white.*

3.1.1 Shoreline

In 2002, NOAA Coastal Services Center (CSC) digitized a coastline of the American Samoa islands of Tutuila, Ofu, Olosega, and Ta'u (Table 2). The vectorized shorelines were derived from one meter, panchromatic 2002 IKONOS satellite imagery (e.g., Fig. 5). Areas of the coastline that were obscured by cloud cover in the IKONOS imagery were derived from USGS digital quadrangles by NOS/CSC.

NGDC digitized the coastline at Pago Pago International Airport to represent ponds along the runway (Fig. 6). The coastline was digitized using 2002 IKONOS satellite imagery, which has a resolution of approximately 1 meter.

Table 2: Shoreline datasets used in compiling the Pago Pago DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
CSC	2002	Vector	~ 1 meter	WGS 84 geographic	MHW	http://dusk.geo.orst.edu/djl/samoa/
NGDC	2009	Digitized coastline	N/A	WGS 84 geographic	N/A	

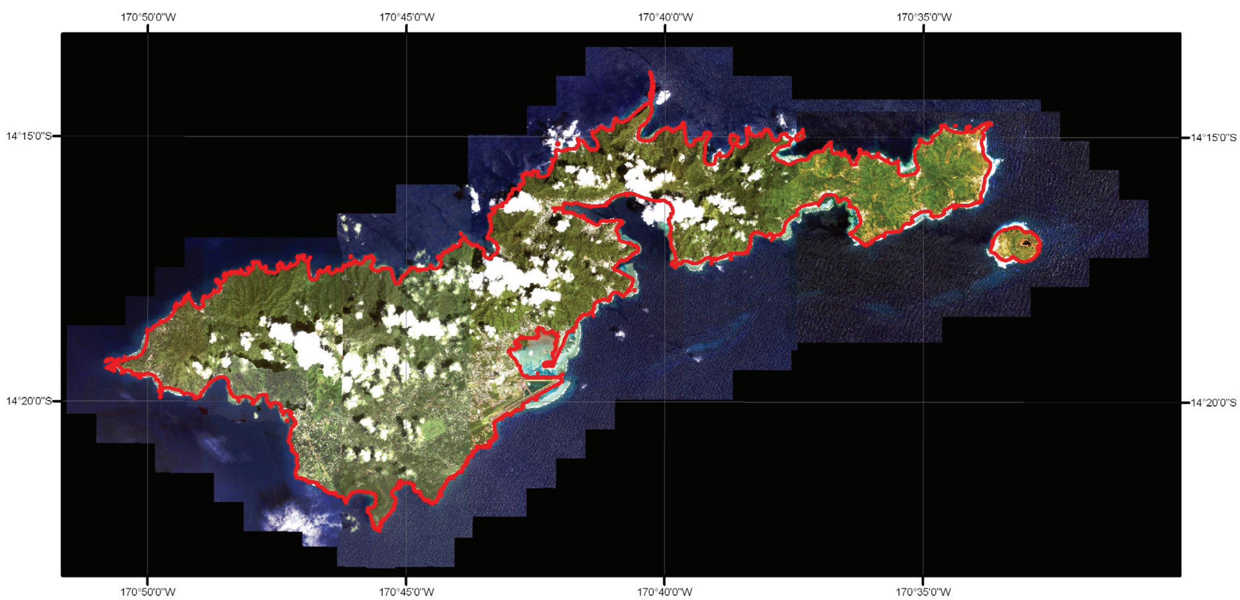

Figure 5. *IKONOS satellite imagery of Tutuila Island. CSC coastline in red.*

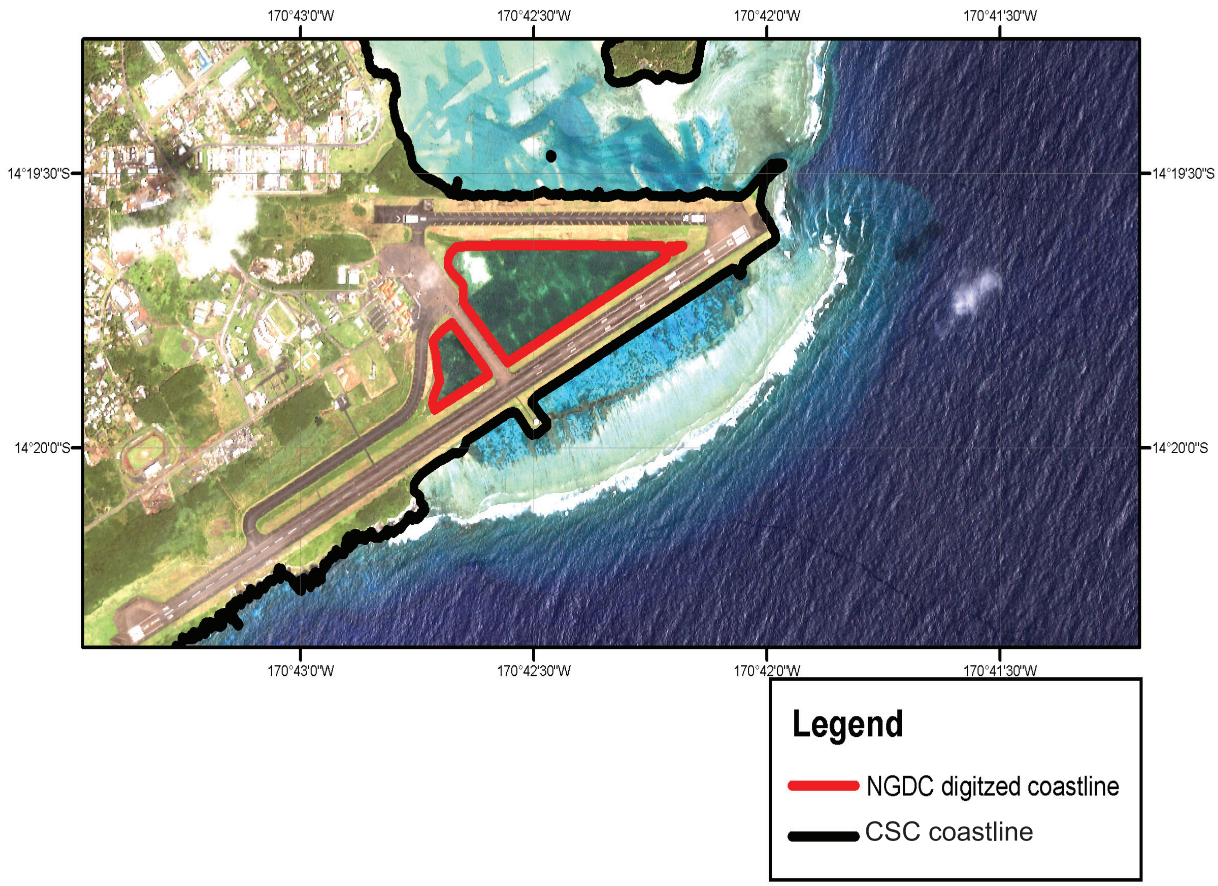

Figure 6. *NGDC-digitized coastline. Coastline was digitized to represent elevations below zero along the runway at Pago Pago International Airport. IKONOS satellite imagery in background.*

3.1.2 *Bathymetry*

Bathymetric datasets available for the compilation of the Pago Pago DEMs included: fifteen multibeam swath sonar surveys from the NGDC Multibeam Bathymetry Database, estimated depths derived from satellite imagery from Gaia Geo-Analytical, and 26 trackline geophysics surveys (Table 3; Fig. 7). The NOS hydrographic survey (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) available for the region (H09188) was not used in DEM development because it was superseded by more recent, higher-resolution data.

Table 3: Bathymetric datasets used in compiling the Pago Pago DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1996 to 2005	Multibeam swath sonar	Raw MB files gridded to 1 and 3 arc-seconds	WGS 84 geographic	Assumed mean sea level (MSL)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
Gaia Geo-Analytical	2008	Estimated depths from satellite imagery	~ 5 meters	WGS 84 geographic	Assumed MSL	http://dusk2.geo.orst.edu/djl/samoa
NGDC	1962 to 1998	Trackline (single beam echo-sounder)	Soundings up to 100's of meters along profiles spaced kilometers apart	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/geodas/trackline.html
NGDC	2009	Digitized points	N/A	WGS 84 geographic	N/A	

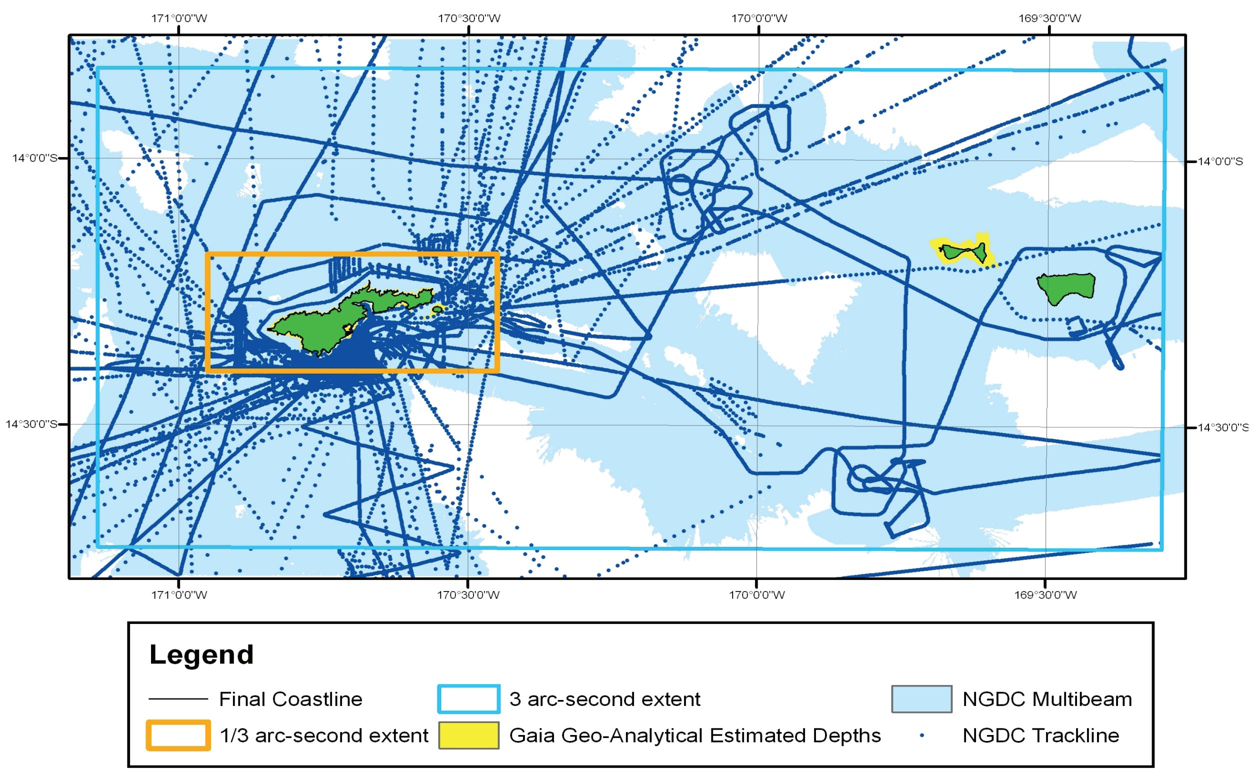

Figure 7. *Spatial coverage of bathymetric datasets available in the American Samoa region. Areas of no data are white. Topography is green.*

1) NGDC multibeam swath sonar surveys

Fifteen multibeam swath sonar surveys were available from the NGDC Multibeam Bathymetry Database for use in building the Pago Pago DEMs (Table 4; Fig. 8). This database is comprised of the original swath sonar data from surveys conducted mostly by the U.S. academic fleet. Using *MB-System*[2], the data were gridded by survey to 1 and 6 arc-second cell size for the 1/3 and 3 arc-second DEMs, respectively. After assessing individual survey quality, the gridded data were transformed to MHW (see Sec. 3.2.1) and converted to shapefiles for editing in *ArcMap*. Prior to gridding of the preliminary bathymetric surfaces and final grids, NGDC edited out noise along the swath edges and then converted the files to xyz format using *FME*.

Table 4: Multibeam swath sonar surveys used in compiling the Pago Pago DEMs.

Cruise ID	***Ship***	***Year***	***Original Vertical Datum***	***Original Horizontal Datum***	***Institution***
AHI-04-02	Ahi	2002	Assumed MSL	WGS 84 geographic	NOAA Pacific Islands Fisheries Science Center
AHI-06-02	Ahi	2002	Assumed MSL	WGS 84 geographic	NOAA Pacific Islands Fisheries Science Center
AVON02MV	Melville	1999	Assumed MSL	WGS 84 geographic	SIO
AVON03MV	Melville	1999	Assumed MSL	WGS 84 geographic	SIO
BMRG08MV	Melville	1996	Assumed MSL	WGS 84 geographic	SIO
BMRG09MV	Melville	1996	Assumed MSL	WGS 84 geographic	SIO
COOK15MV	Melville	2001	Assumed MSL	WGS 84 geographic	SIO
DRFT09RR	Roger Revelle	2002	Assumed MSL	WGS 84 geographic	SIO
DRFT10RR	Roger Revelle	2002	Assumed MSL	WGS 84 geographic	SIO
HI-06-02	Hi'ialakai	2002	Assumed MSL	WGS 84 geographic	NOAA Pacific Islands Fisheries Science Center
KIWI05RR	Roger Revelle	1997	Assumed MSL	WGS 84 geographic	SIO
KIWI12RR	Roger Revelle	1998	Assumed MSL	WGS 84 geographic	SIO
KMO506	Kilo Moana	2005	Assumed MSL	WGS 84 geographic	SIO
USF2001samoa	Bellows	2001	Assumed MSL	WGS 84 geographic	University of South Florida
USF2002samoa	Bellows	2002	Assumed MSL	WGS 84 geographic	University of South Florida

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

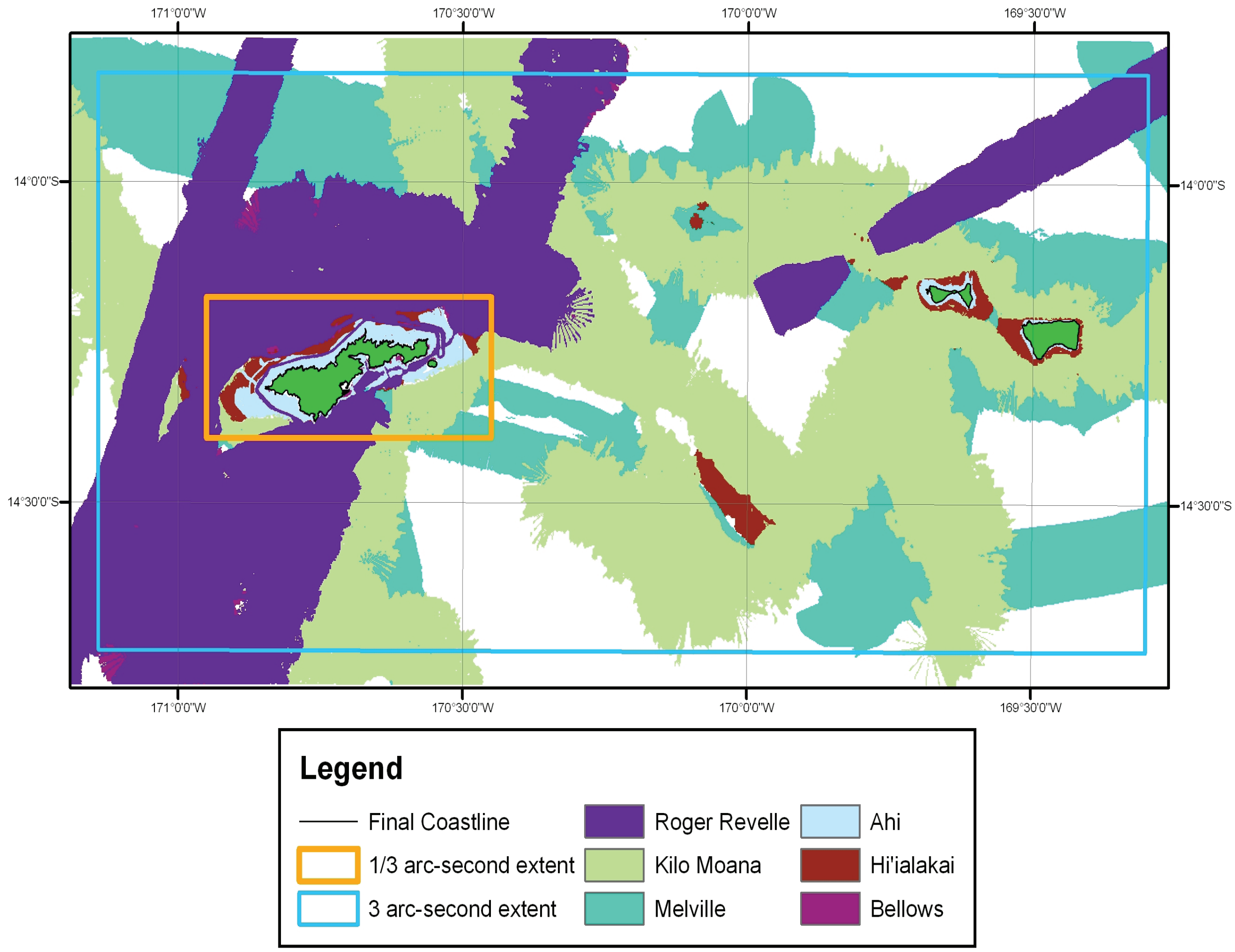

Figure 8. *Coverage of multibeam swath sonar surveys used in compiling the Pago Pago DEMs. Topography shown in green.*

2) NGDC Trackline surveys

Twenty-three single-beam echo-sounder surveys were available from the NGDC Marine Geophysical Trackline Database for use in building the Pago Pago DEMs (Table 5; Fig. 9). This database is comprised of bathymetry, magnetics, gravity, and seismic navigation data collected along ship tracks during marine cruises from 1953 to present. The bathymetric data were downloaded as xyz files in WGS 84 and MSL, and converted to MHW using *FME*.

The tracklines are spaced tens of kilometers apart and were only used where there were no high-resolution multibeam bathymetric data. Trackline data were not used in building the 1/3 arc-second DEM.

Table 5: Trackline surveys used in compiling the 3 arc-second Pago Pago DEM.

Cruise ID	*Ship*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Institution*
82031602	Kana Keoki	1985	Assumed MSL	WGS 84 geographic	University of Hawaii
AMPHH03AR	Argo	1980	Assumed MSL	WGS 84 geographic	SIO
CK80-1	Machias	1983	Assumed MSL	WGS 84 geographic	University of Hawaii
CK80-2	Machias	1983	Assumed MSL	WGS 84 geographic	University of Hawaii
ELT31	Eltanin	1979	Assumed MSL	WGS 84 geographic	Lamont-Doherty Earth Observatory
ERDC02WT	T. Washington	1974	Assumed MSL	WGS 84 geographic	SIO
GECS-FMV	Melville	1974	Assumed MSL	WGS 84 geographic	SIO
MW8701	Moana Wave	1987	Assumed MSL	WGS 84 geographic	University of Hawaii
MW8702	Moana Wave	1987	Assumed MSL	WGS 84 geographic	University of Hawaii
NBP98-6A	Nathaniel Palmer	1998	Assumed MSL	WGS 84 geographic	SIO
NOVA02AR	Argo	1967	Assumed MSL	WGS 84 geographic	SIO
NOVA06HO	Horizon	1967	Assumed MSL	WGS 84 geographic	SIO
NOVA07AR	Argo	1967	Assumed MSL	WGS 84 geographic	SIO
NOVA08AR	Argo	1967	Assumed MSL	WGS 84 geographic	SIO
PPTU03WT	T. Washington	1985	Assumed MSL	WGS 84 geographic	SIO
SOTW10WT	T. Washington	1972	Assumed MSL	WGS 84 geographic	SIO
SOTW11WT	T. Washington	1972	Assumed MSL	WGS 84 geographic	SIO
STYX02AZ	Agassiz	1968	Assumed MSL	WGS 84 geographic	SIO
STYX05AZ	Agassiz	1968	Assumed MSL	WGS 84 geographic	SIO
WS79-1	Machias	1979	Assumed MSL	WGS 84 geographic	University of Hawaii
V1814	Vema	1962	Assumed MSL	WGS 84 geographic	Lamont-Doherty Earth Observatory
V1906	Vema	1963	Assumed MSL	WGS 84 geographic	Lamont-Doherty Earth Observatory
V3610	Vema	1980	Assumed MSL	WGS 84 geographic	Lamont-Doherty Earth Observatory

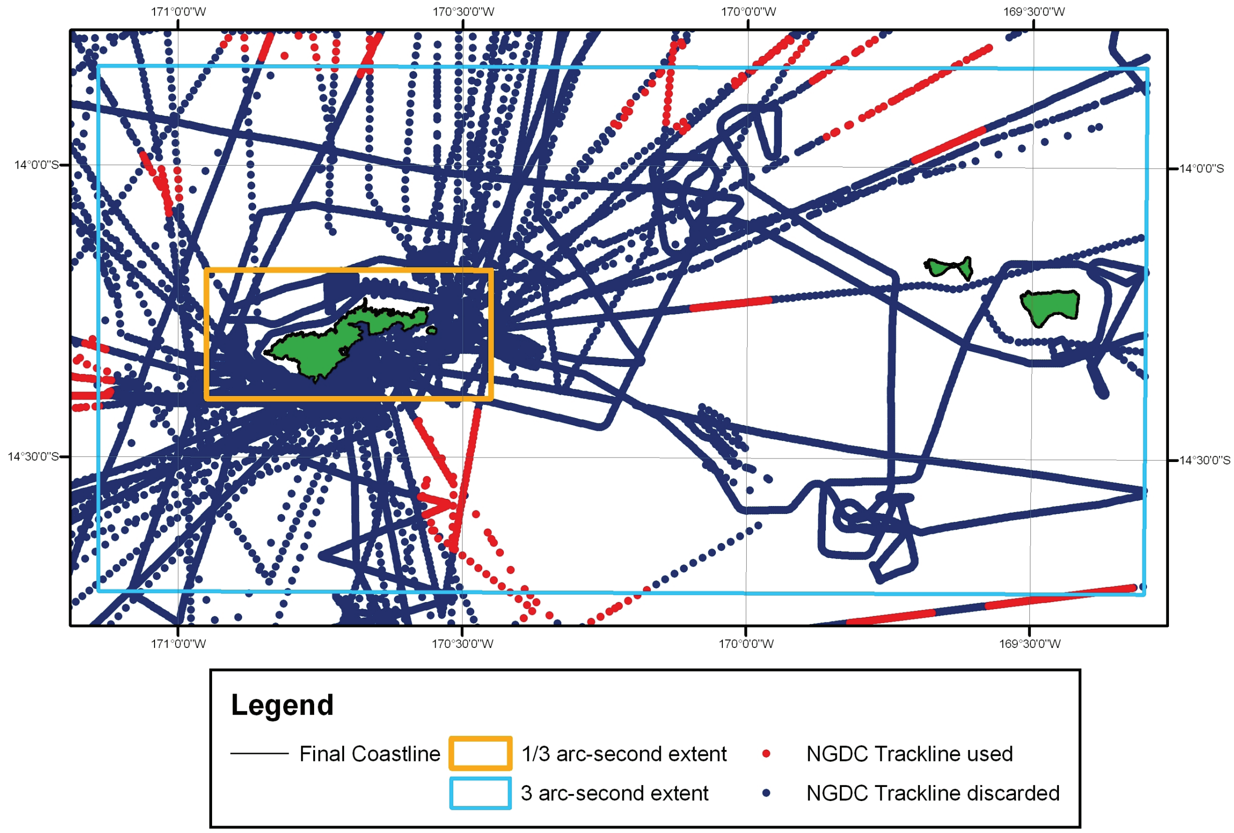

Figure 9. *Spatial coverage of trackline surveys in the Pago Pago region. Trackline data shown in dark blue were not used in the final DEM gridding, as there were high-resolution multibeam bathymetric data available in those areas. Topography shown in green.*

3) Gaia Geo-Analytical estimated depths

Kyle Hogrefe of Gaia Geo-Analytical, in affiliation with Oregon State University (OSU), completed a master thesis on a depth analysis of Tutuila using high-resolution satellite imagery (*Hogrefe, 2008*). Mr. Hogrefe graciously provided NGDC with the resulting data (Fig. 10).

Mr. Hogrefe derived bathymetry from the 2002 multispectral IKONOS satellite imagery provided by the National Center for Coastal Monitoring and Assessment (NCCMA). Bathymetry values shallower than 25 meters were derived by gauging the relative attenuation of blue and green spectral radiance as a function of depth. *Environment for Visualizing Images 4.5* was used to analyze and process the image. Data editing and integration were performed using *ArcGIS 9.2*. Corrections were made for atmospheric absorption and scattering.

Since no vertical datum was documented, NGDC assumed the data were essentially equivalent to MSL. The raster files were converted to shapefiles and transformed to MHW using *FME* for assessing the data.

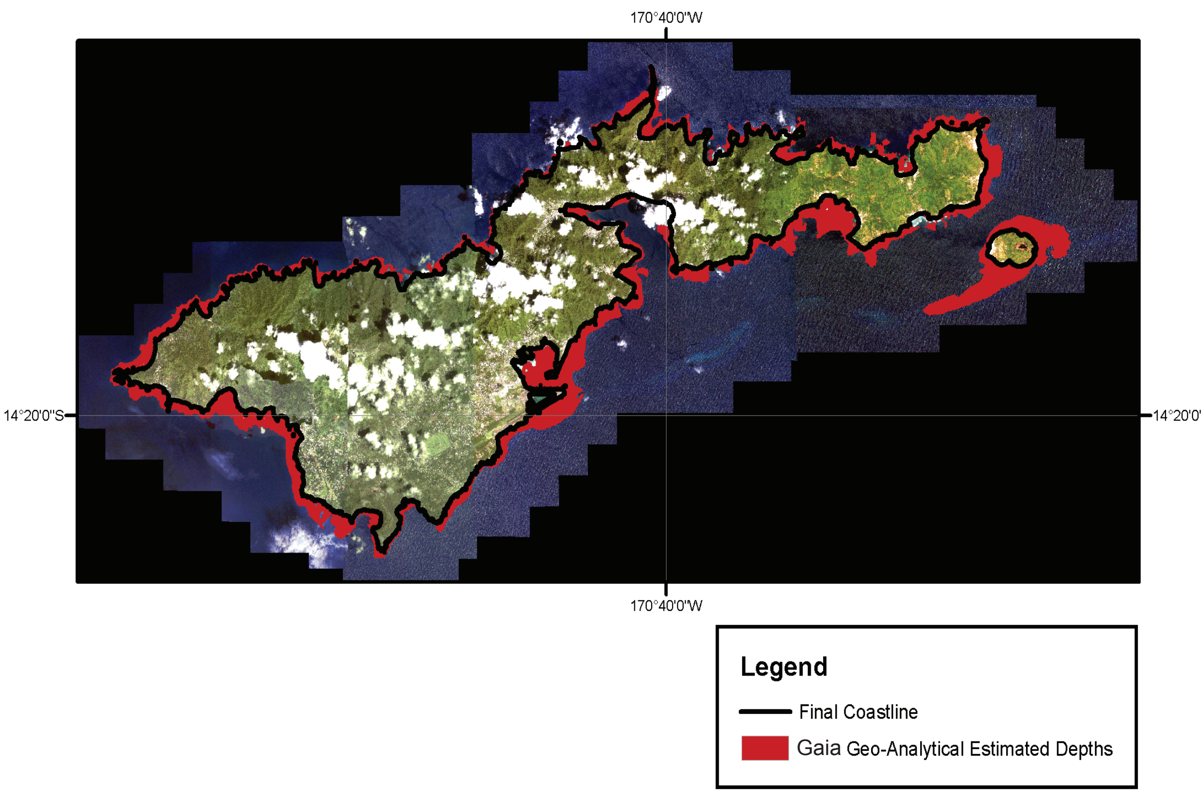

Figure 10. *Spatial coverage of estimated depths from Gaia Geo-Analytical draped over IKONOS satellite imagery.*

4) NGDC-digitized depths

NGDC digitized bathymetric values at Pago Pago International Airport using IKONOS satellite imagery to represent bodies of water not present in other datasets. Elevations of -1 meter were assigned to these points (Fig. 11).

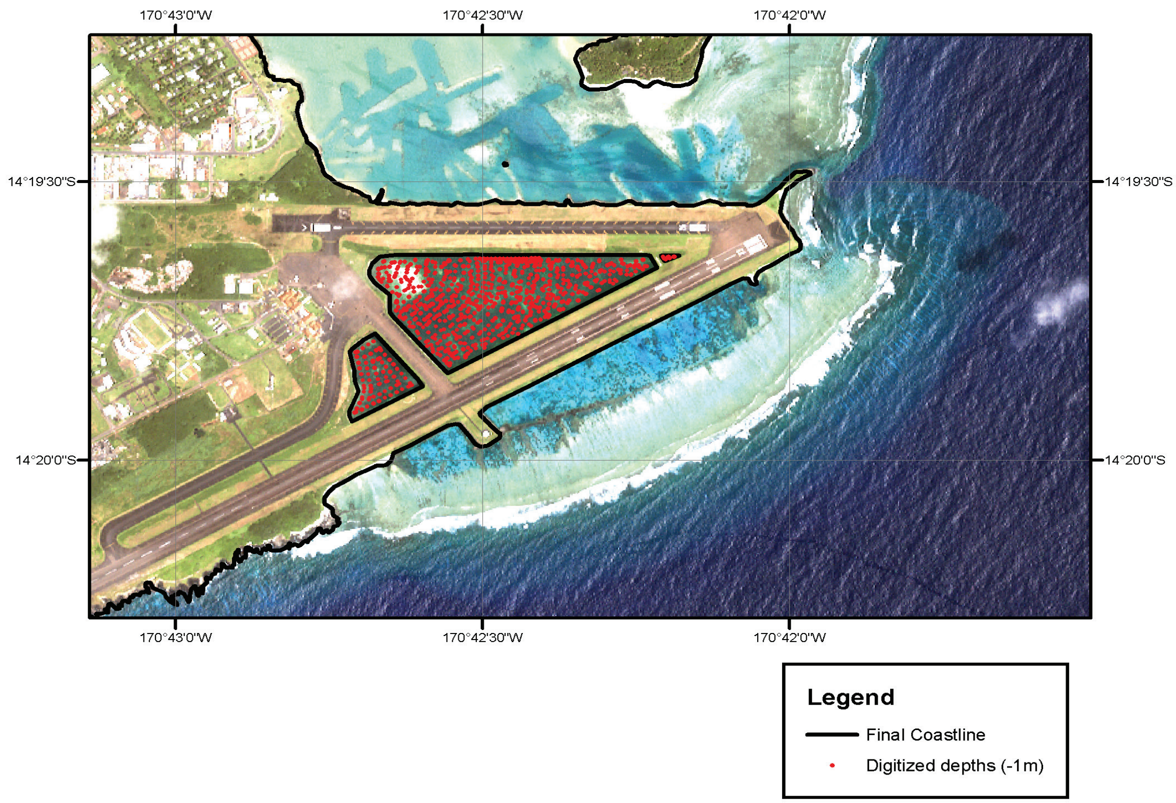

Figure 11. *NGDC-digitzed depths at Pago Pago International Airport. IKONOS satellite imagery in background.*

NOAA nautical chart #83484 was available for the Samoa Islands as a georeferenced Raster Nautical Chart (RNC; Table 6). The chart was downloaded from NOAA's Office of Coast Survey web site (http://nauticalcharts.noaa.gov). RNC #83484 was used to assess the quality of bathymetric datasets in the region.

Table 6: NOAA nautical chart in the Pago Pago region.

Chart	*Title*	*Edition*	*Edition Date*	*Format*	*Scale*
83484	Samoa Islands	11th	2006	RNC	1:10,000 to 1:80,000

3.1.3 *Topography*

The USGS 1 arc-second National Elevation Dataset (NED) DEM provided full coverage of the islands and was used to build the Pago Pago DEMs (Table 7; Fig. 12). The NED data was supplemented with NGDC-digitized elevations.

Table 7: Topographic datasets used in compiling the Pago Pago DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
USGS	1999-2006	NED DEM	1 arc-second	WGS 84 geographic[a]	MSL[a]	http://ned.usgs.gov
NGDC	2009	Digitized points	n/a	WGS 84 geographic	n/a	

a) The metadata for the USGS NED topographic data indicates that the horizontal and vertical datums are NAD 83 geographic and NAVD88, respectively. The actual datums as denoted on the USGS topographic quadrangles for theregion indicate that the horizontal datum is WGS 84 geographic and vertical datum is mean sea level.

1) USGS NED topographic DEM

The U.S. Geological Survey (USGS) National Elevation Dataset (NED) provides complete 1 arc-second coverage of the Samoa Islands[3]. Data are documented in the metadata as being in NAD 83 geographic coordinates and NAVD 88 vertical datum (meters), and are available for download as raster DEMs. The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys; it has been revised using data collected in 1999 and 2006.

NGDC visually compared georeferenced IKONOS satellite imagery, USGS topographic quadrangles, a NOAA RNC, National Geodetic Survey (NGS) monuments, lidar data, multibeam data, and estimated depths in the Pago Pago region with the NED dataset. Although all of these datasets align, the NED topographic DEM was offset to the southeast by ~705 meters (Fig. 12). The NED topographic dataset was rectified to align with the IKONOS satellite imagery.

NGDC also visually compared georeferenced images (TIFFs) of USGS topographic quadrangles in the Samoa Islands with the NED dataset before and after its conversion to MHW. The 40-foot contours on the quadrangles are referenced to a vertical datum of MSL; the coastlines approximate the location of the MHW line. NGDC has concluded that the NED DEM in the Samoa Islands are actually in a mixed vertical datum (e.g., see NED documentation in *Lim et al., 2009*), with values above 40 feet relative to MSL, and the coastal "zero" value relative to MHW. The original NED DEM also included "zero" elevation values over the open ocean, which were removed from the dataset by clipping to the combined coastline. Values between zero (MHW) and 40 feet (MSL) are not consistent with either datum. Note that in the Samoa Islands, the MHW coastline is at approximately the 1-foot (0.38 meter) MSL contour (see Table 9).

In an effort to overcome this mixing of vertical datums, the NED DEM was converted from MSL to MHW by subtracting a constant value of 0.382 meters. After the conversion, some areas along the coast had elevations less than zero. To prevent inappropriate coastal flooding, elevations in the converted data that were greater than or equal to 0.5 meters were extracted directly from the grids. Elevations that were less than 0.5 meters were assigned a value of 0.5 meters above MHW. To smooth the data for use in building the 1/3 arc-second Pago Pago DEM, the NED DEM was sampled to 1/3 arc-second.

3. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the U.S. territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD 83 geographic, except for AK (NAD 27 geographic) and the Pacific Islands (WGS 84). The vertical datum is NAVD88, except for AK (NGVD29) and the Pacific Islands (MSL). NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 meter) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site and adapted based on inspection of NED data]

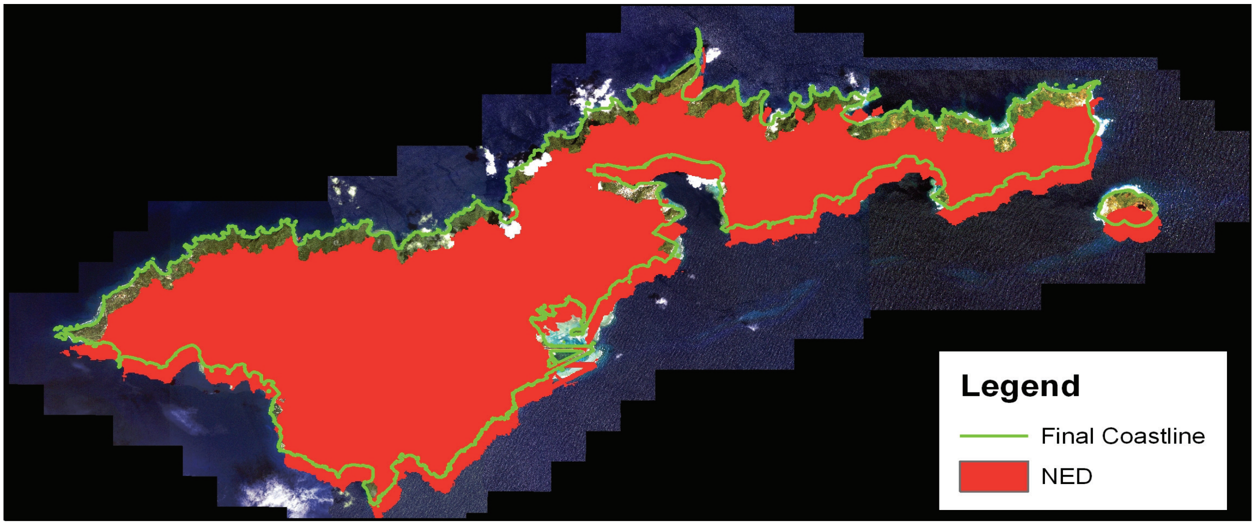

Figure 12. *1 arc-second NED topographic DEM offset 705 meters to the southeast relative to underlying IKONOS satellite imagery.*

2) NGDC-digitized elevations

NGDC digitized elevation points to supplement the NED at Pago Pago International Airport and where breakwaters are present within the 1/3 arc-second Pago Pago DEM (e.g., Fig. 13).

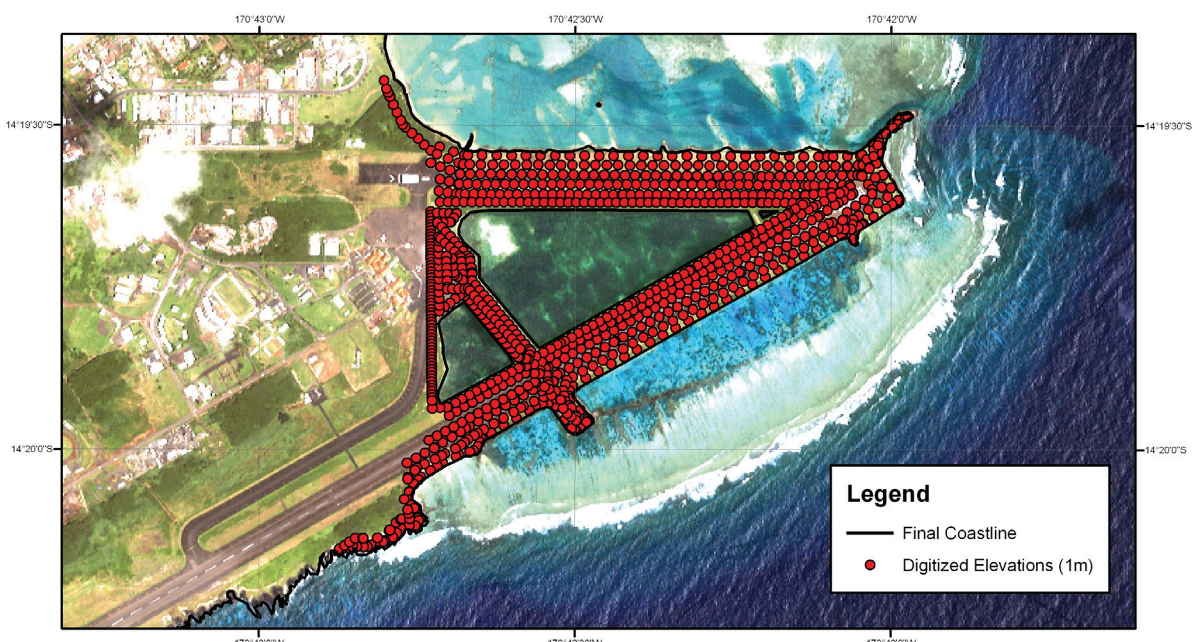

Figure 13. *NGDC-digitzed elevations at Pago Pago International Airport. IKONOS satellite imagery in background.*

3.1.4 *Bathymetry-topography*

Bathymetric-topographic lidar data obtained from the Naval Oceanographic Office (NAVOCEANO) provides coverage of the coasts of Pago Pago Harbor (Table 8; Fig. 14). The survey is from May 2006 and has a spatial resolution of 5 meters. Its horizontal and vertical datums are WGS 84 geographic and MSL, respectively. The lidar data were not processed to bare-earth so, because of the lush vegetation in the area, topographic values were not used in DEM development. Bathymetric values were converted from MSL to MHW by subtracting a constant value of 0.382 meters (see Table 9).

Table 8: Bathymetric-topographic dataset used in compiling the Pago Pago DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NAVOCEANO	2006	Bathymetric-topographic lidar	5 meters	WGS 84 Geographic	MSL	https://oceanography.navy.mil/legacy/web/

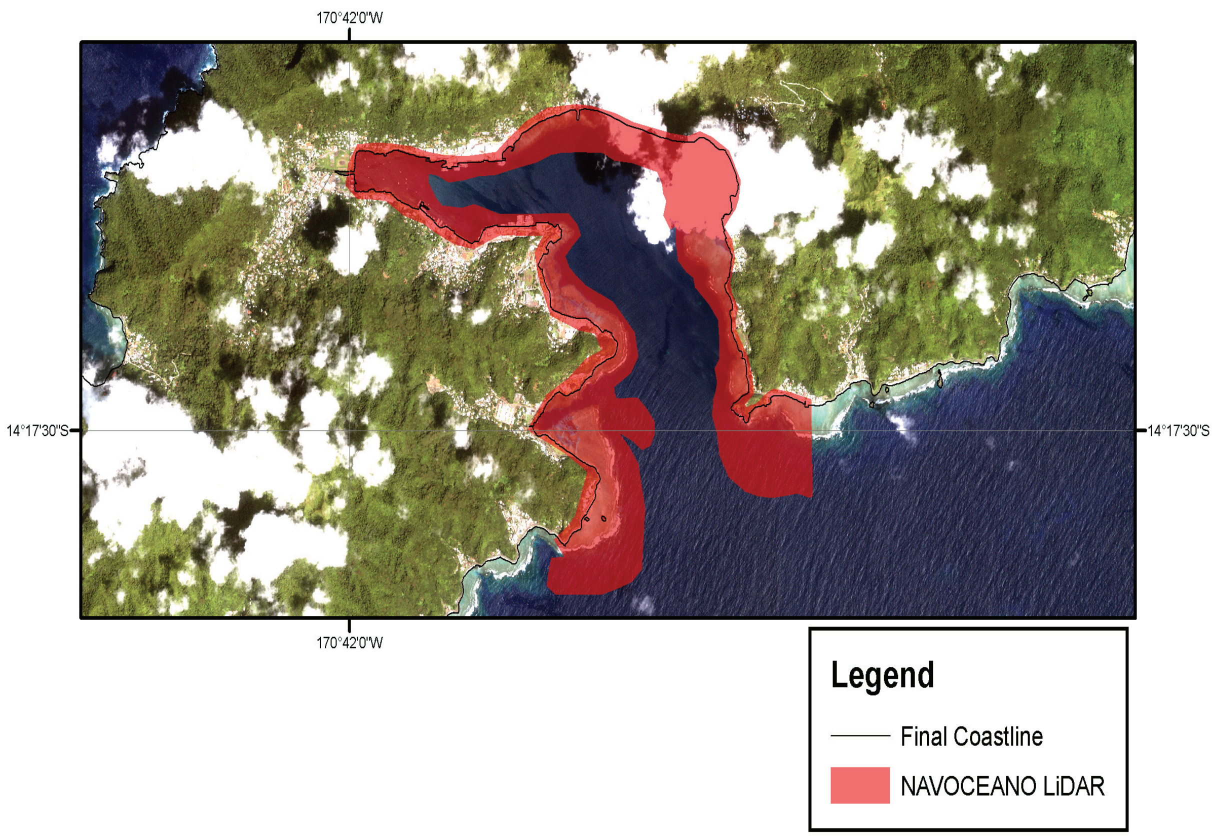

Figure 14. *Spatial coverage of the NAVOCEANO bathymetric-topographic lidar. IKONOS satellite imagery in background.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Pago Pago DEMs were originally referenced to a vertical datum of MSL. All datasets were transformed to MHW.

1) **Bathymetric data**

   The multibeam, trackline surveys, and estimated depths were transformed from MSL to MHW using *FME* software, by subtracting a constant offset of 0.382 meters, as measured at the Pago Pago NOAA tide station #1770000 (Table 9; http://tidesandcurrents.noaa.gov).

2) **Topographic data**

   The NED topographic DEM was determined to be in MSL vertical datum. Conversion to MHW was accomplished by subtracting a constant value of 0.382 meters (Table 9).

Table 9: Relationships between MHW and MSL in the Pago Pago region.

Vertical Datums	*Difference to MHW*
MSL	0.382 meters

Note: Datum relationship was determined using NOAA tidal station #1770000 at Pago Pago.

3.2.2 Horizontal datum transformations

All datasets used to compile the Pago Pago DEMs were originally referenced to WGS 84 geographic and no horizontal datum conversions were necessary.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

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

- Multibeam swath sonar survey data contained many erroneous values along the edges of swaths.
- Outside of Pago Pago Harbor, estimated depths were the only recent data available for the shallow water.
- NED topographic DEM was shifted south relative to the georeferenced IKONOS satellite imagery, USGS topographic quadrangles, a NOAA RNC, NGS monuments, lidar data, multibeam data, and estimated depths.
- Incomplete high-resolution multibeam bathymetry in the deep ocean.
- Many anomalous estimated depths (20-25 meters) at the coast.

3.3.2 Smoothing of bathymetric data

Two “pre-surface” bathymetric grids were generated for the Pago Pago DEMs due to the varying resolution of data coverage in the deep ocean. The NGDC multibeam swath sonar surveys are high resolution with beam spacing approximately 10 meters apart in shallow water, a marked contrast with the trackline surveys spaced 1 to 15 kilometers apart. The grids were generated using *GMT*[4]. The bathymetric point data were median-averaged using the *GMT* tool “blockmedian” to create 1 and 3 arc-second grids 0.05 degrees (~5%) larger than the 1/3 and 3 arc-second Pago Pago DEM gridding extents, respectively. The *GMT* tool “surface” was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by “surface” was converted into an ESRI Arc ASCII grid file, and clipped to the final coastline (to eliminate data interpolation into land areas). The resulting surface was compared with bathymetric source data to ensure grid accuracy (e.g., Fig. 15) and exported as an xyz file for use in the final gridding process (see Table 10). The statistical analysis of the differences between the 1 arc-second bathymetric surface and bathymetric values extracted from the NAVOCEANO lidar show that the majority of the lidar depths are in agreement with the bathymetric surface (Fig. 15). The largest differences result from averaging of multiple, closely-spaced lidar depths in regions of steep bathymetry.

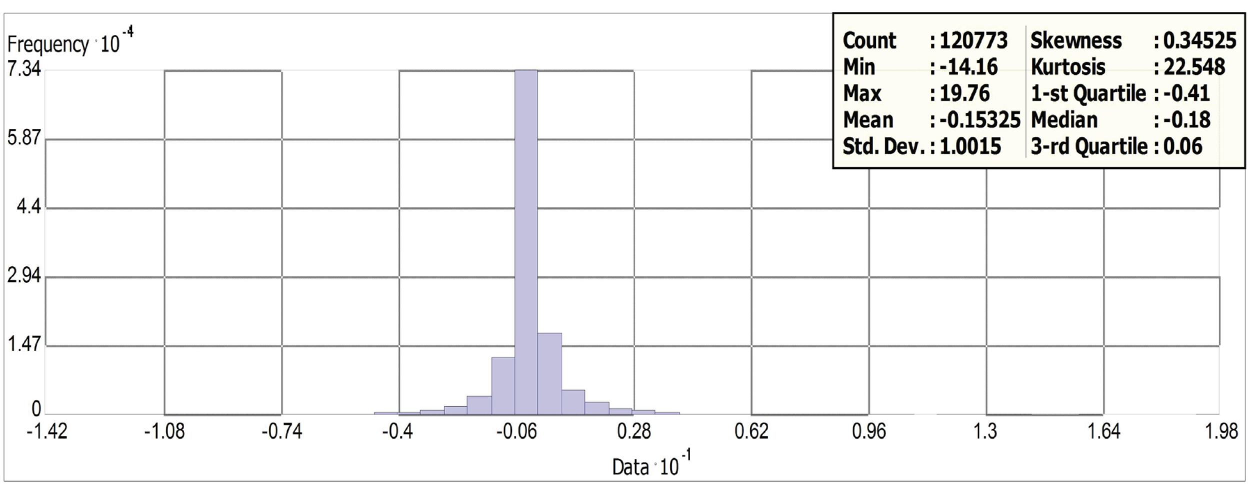

Figure 15. *Histogram of the differences between NAVOCEANO lidar and the 1 arc-second bathymetric grid.*

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

3.3.3 Gridding the data with MB-System

MB-System was used to create the Pago Pago DEMs. The *MB-System* tool "mbgrid" was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the "mbgrid" gridding algorithm, as relative gridding weights, is listed in Table 10. Greatest weight was given to the digitized features, lidar, and NED topography. Least weight was given to the coastline, trackline surveys, and the pre-surfaced bathymetric grid.

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

Dataset	*Relative Gridding Weight*
NGDC-digitized features	1,000
NAVOCEANO lidar	1,000
NED Topographic DEM	1,000
NGDC Multibeam surveys	100
Gaia Geo-Analytical Satellite Imagery Estimated Depths	100
Pre-surfaced bathymetric grid	1
NGDC Trackline	1
NOAA/CSC coastline	1

3.4 Quality Assessment of the DEMs

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Pago Pago DEMs are dependent upon cell location and the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of ~30 meters (NED). Bathymetric features are resolved only to within a few kilometers in deep-water areas. Shallow, near-coast regions have an accuracy approaching 25 meters for the Gaia estimated bathymetry and 10 meters for the NAVOCEANO lidar.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Pago Pago DEMs are also highly dependent upon the source datasets contributing to DEM cell values. The NED topographic DEM has an estimated vertical accuracy of up to 7 meters. NAVOCEANO lidar has an estimated accuracy of 1 to 2 meters. Bathymetric values have an estimated accuracy between 1 meter and 5% of water depth. The deep water values in the 3 arc-second DEM have an estimated accuracy of a few hundred meters due to gridding interpolation between sparse trackline soundings.

3.4.3 Slope maps and 3-D perspectives

ESRI *ArcCatalog* was used to generate slope grids from the Pago Pago DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Figs. 16 and 18). The DEMs were transformed to UTM Zone 2 South coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEMs. Three-dimensional viewing of the UTM-transformed DEMs was accomplished using ESRI *ArcScene* and *QT Modeler*. Figures 17 and 19 show perspective views of the 1/3 and 3 arc-second Pago Pago DEMs in their final versions, created by *Persistence of Vision™ Raytracer (POV-Ray)*.

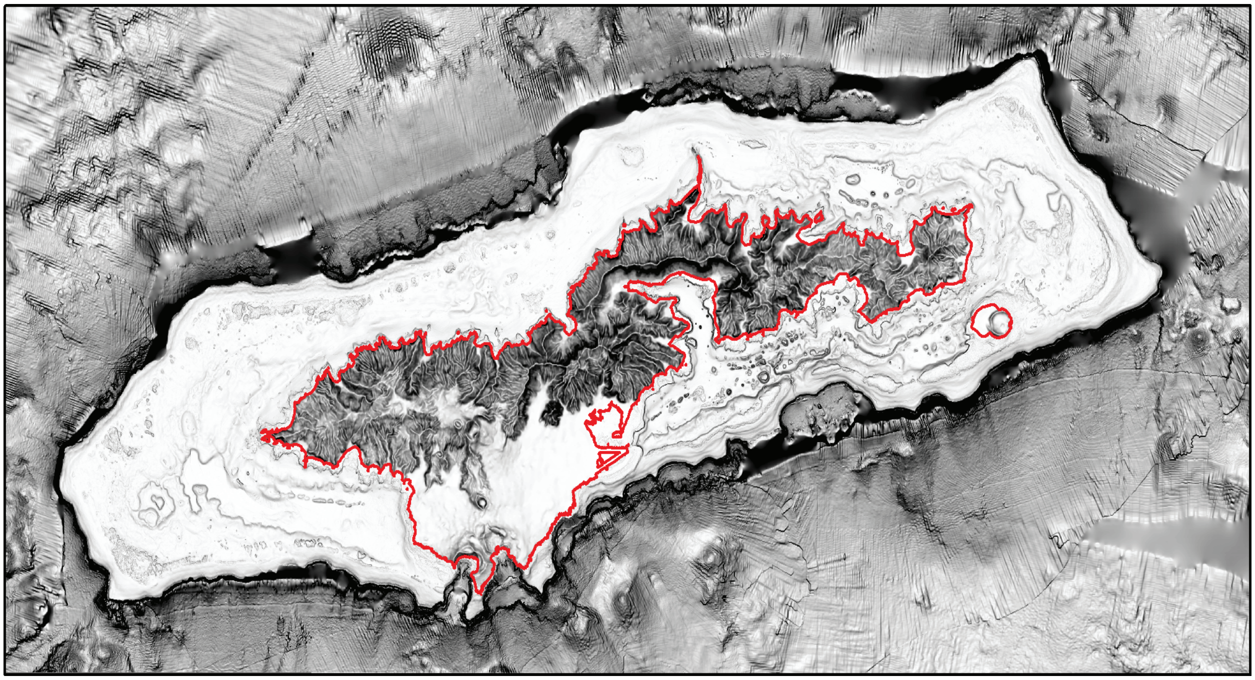

Figure 16. *Slope map of the 1/3 arc-second Pago Pago DEM. Flat-lying slopes are white; dark shading denotes steep slopes; coastline in red.*

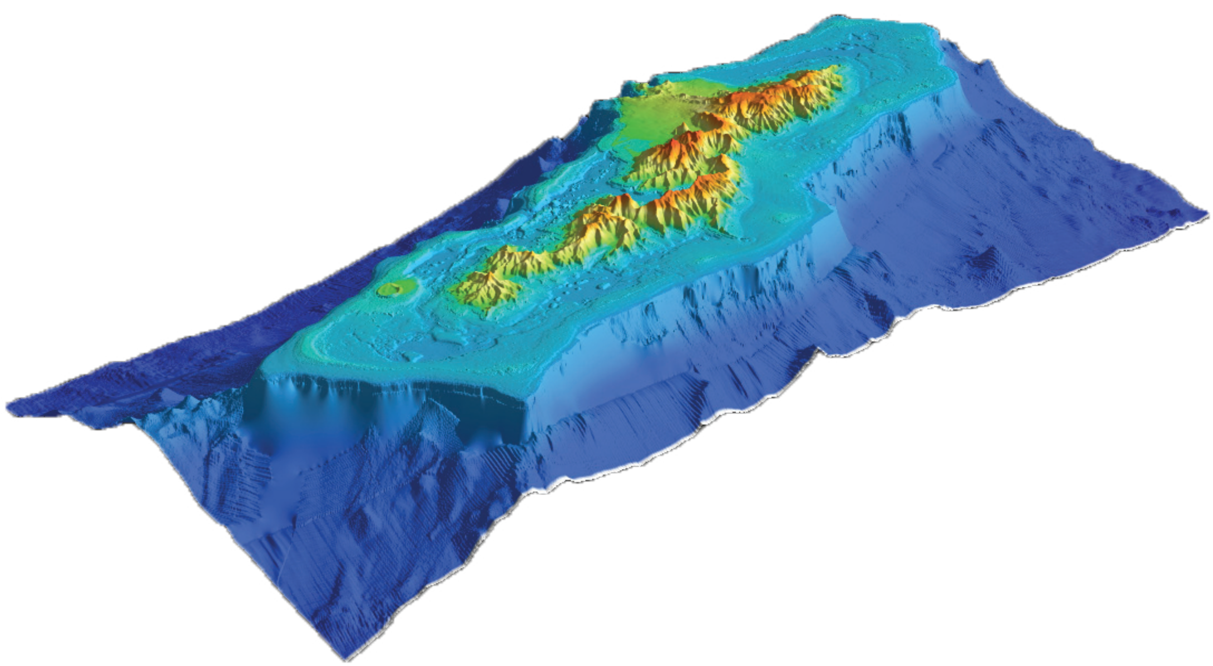

Figure 17. *Perspective view from the northeast of the 1/3 arc-second Pago Pago DEM.*

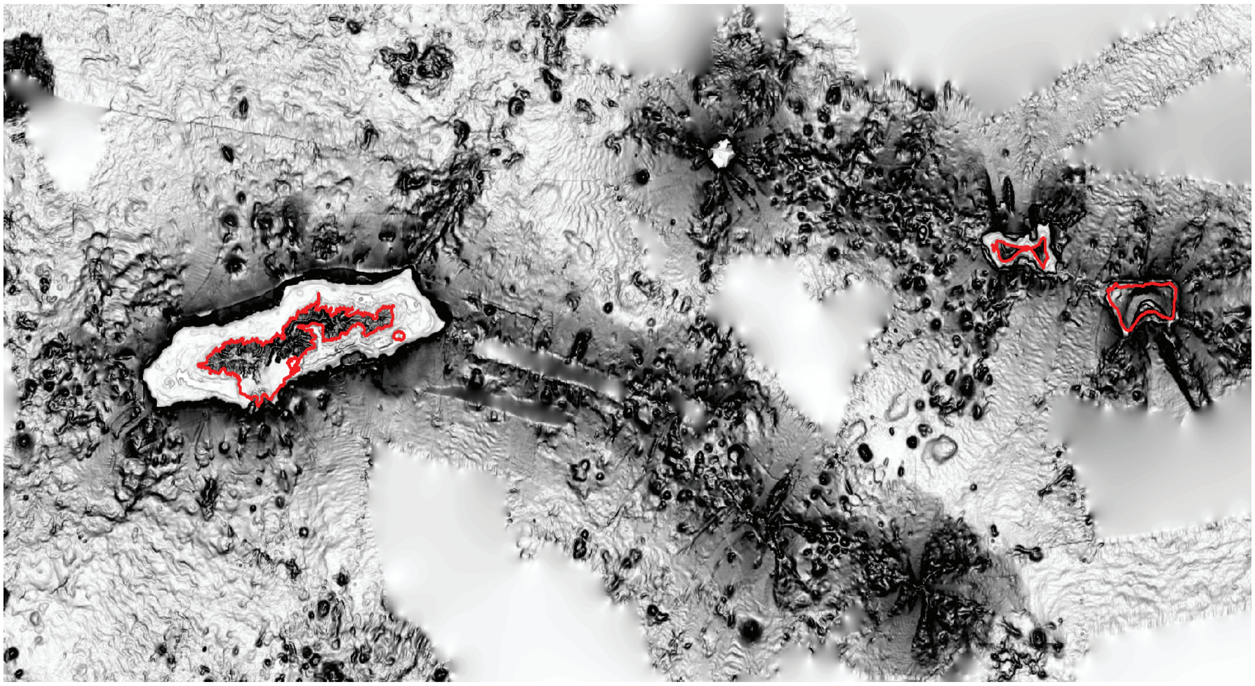

Figure 18. *Slope map of the 3 arc-second Pago Pago DEM. Flat-lying slopes are white; dark shading denotes steep slopes; coastline in red.*

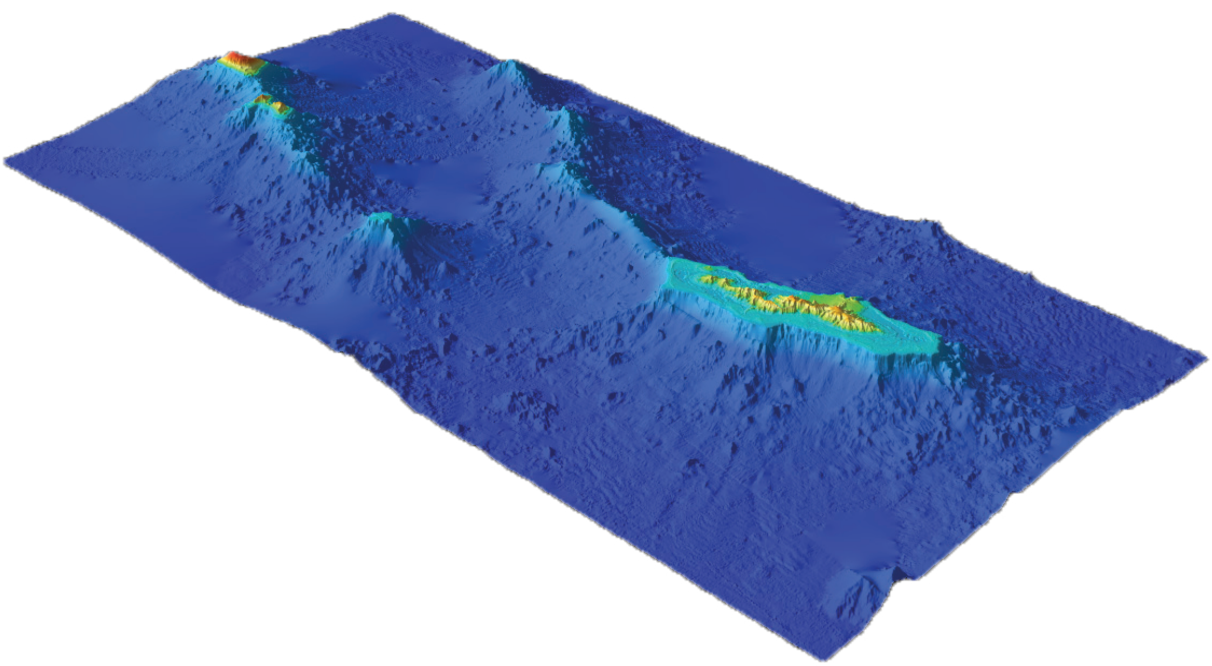

Figure 19. *Perspective view from the northwest of the 3 arc-second Pago Pago DEM*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Pago Pago DEMs were compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the differences between a multibeam survey and the 3 arc-second Pago Pago DEM is shown in Figure 20. The greatest differences occurred due to averaging of overlapping surveys in deep-water swaths where the data are noisiest.

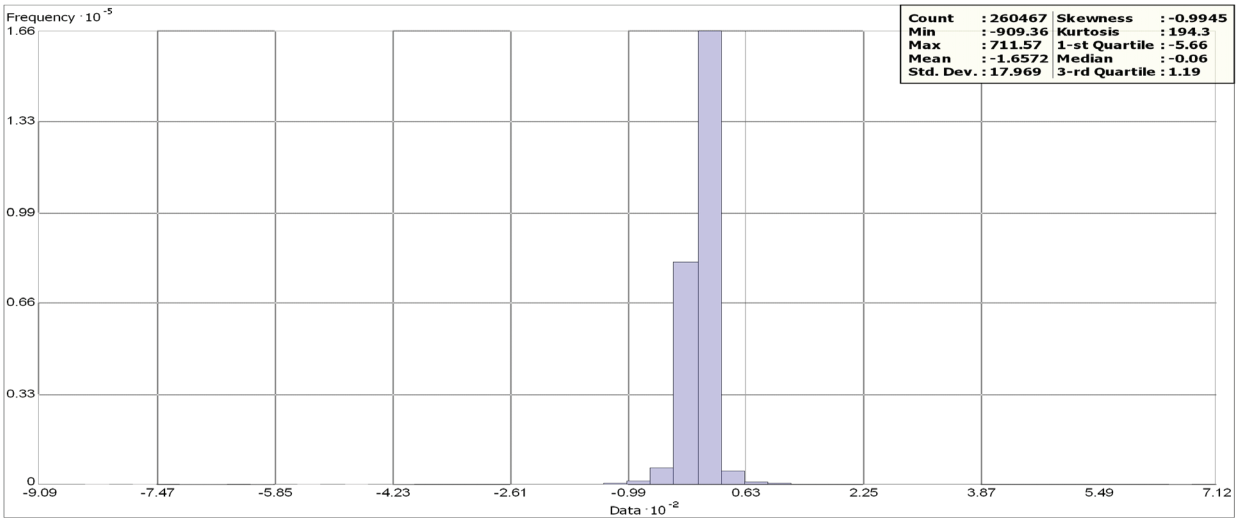

Figure 20. *Histogram of the differences between the Kilo Moana multibeam swath sonar survey, KMO506 and the 3 arc-second Pago Pago DEM.*

A histogram of the differences between the 1 arc-second NED topographic DEM and the 3 arc-second Pago Pago DEM is shown in Figure 21. Differences range from -131 meters to +125 meters. The greatest differences occur in areas of steep and rugged topography where multiple NED values contribute to each cell in the 3 arc-second DEM.

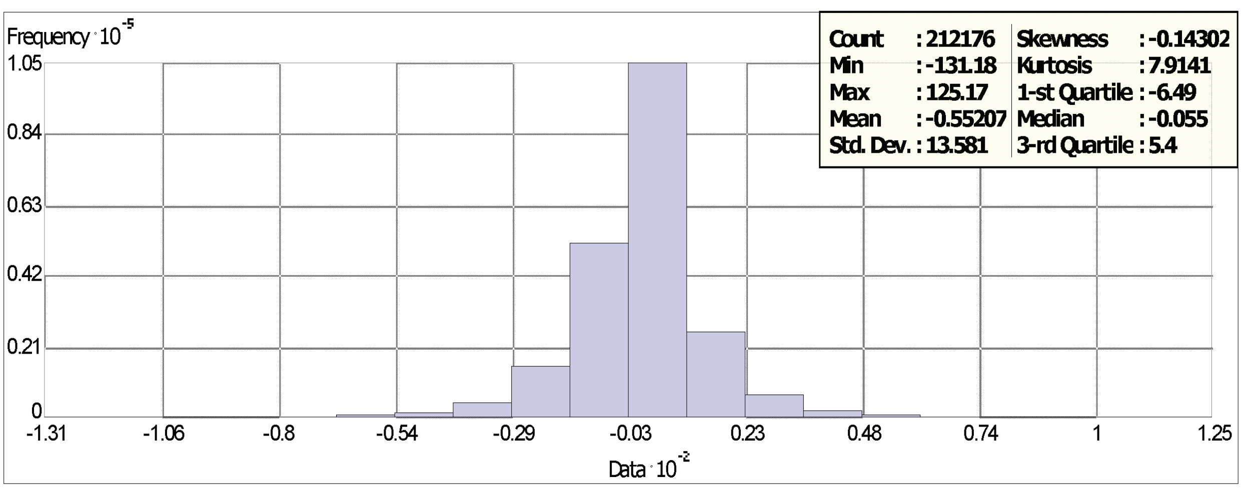

Figure 21. *Histogram of the differences between NED data and the 3 arc-second Pago Pago DEM.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 232 NOAA's National Geodetic Survey (NGS) geodetic monuments (Fig. 22) were extracted from online shapefiles of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 geographic[5] and elevations in American Samoa Vertical Datum of 2002 (ASVD 02). The basis for all ASVD 02 heights is MSL, for the epoch 1983-2001 (*Zilkoski, 2009*). Elevations were shifted from MSL/ASVD 02 to MHW vertical datum (see Table 9) for comparison with the 3 arc-second Pago Pago DEM. Differences between the 3 arc-second Pago Pago DEM and the NGS geodetic monument elevations range from -130 to +68 meters (Fig. 23). The outliers are from horizontal inaccuracy (~ 20-30 meters) of topographic features derived from NED, due to the 705 meter offset rectified and described in Section 3.1.3.

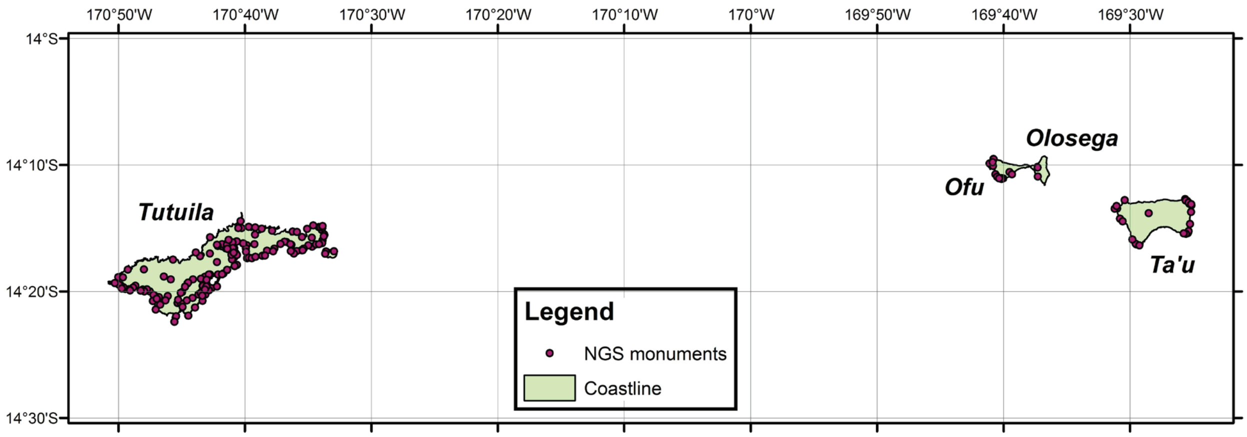

Figure 22. *Location of NGS geodetic monuments. NGS monuments were used to evaluate the 3 arc-second Pago Pago DEM.*

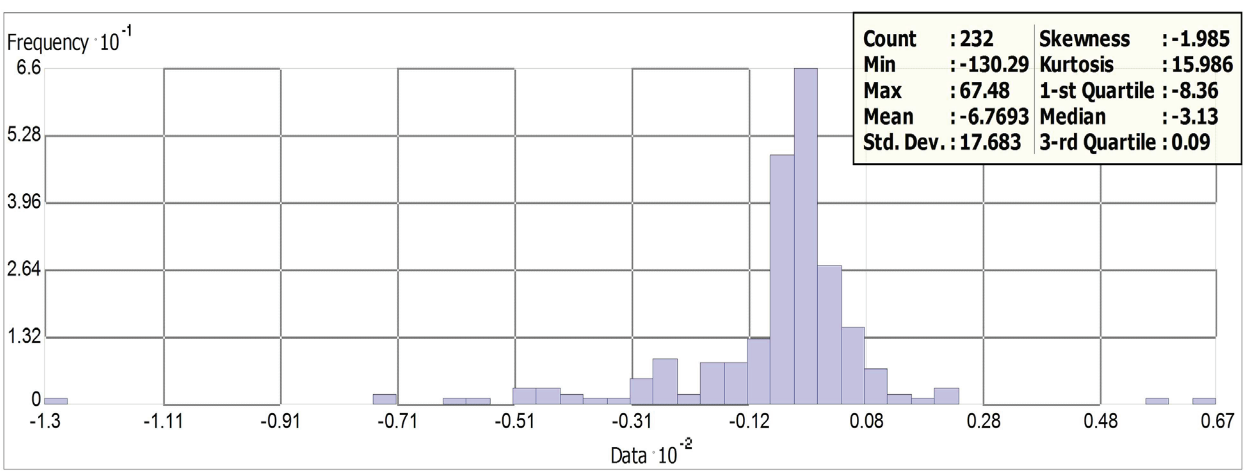

Figure 23. *Histogram of the differences between NGS geodetic monuments and the 3 arc-second Pago Pago DEM.*

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

4. Summary and Conclusions

Two integrated bathymetric–topographic digital elevation models of Pago Pago, American Samoa, with cell sizes of 3 arc-seconds and 1/3 arc-second, were developed for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research. The best available digital data 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, MB-System*, and *Quick Terrain Modeler* software.

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

- Conduct hydrographic surveys in shallow water areas.
- Conduct bathymetric–topographic lidar surveys along the coast of Tutuila.
- Complete multibeam swath sonar surveys of the deep ocean surrounding American Samoa.
- Correct NED topography offset.

5. Acknowledgments

The creation of the Pago Pago DEMs was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL). We would also like to thank Kyle Hogrefe and Dawn Wright (Gaia Geo-Analytical and Oregon State University) for providing us with estimated depths from Kyle Hogrefe's thesis research, and the Naval Oceanographic Office for providing the bathymetric-topographic lidar survey of Pago Pago Harbor.

6. References

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Lim, E., L.A. Taylor, B.W. Eakins, K.S. Carignan, R.R. Warnken, and P.R. Medley, 2009. Digital Elevation Model of Portland, Maine: Procedures, Data Sources, and Analysis, NOAA Technical Memorandum NESDIS NGDC-30, March 2009, 29 pp, http://www.ngdc.noaa.gov/mgg/inundation/tsunami/data/portland_me/portland_me.pdf.

Nautical Chart #83484 (RNC), 11th Edition, 2006. Samoa Islands Pago Pago Harbor. Scale 1: 15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Zilkoski, D., 2009. Affirmation of Vertical Datum for Surveying and Mapping Activities for the Island of Tutuila, American Samoa. Federal Register, Notices, Vol. 74, No. 13, p. 3991, Thursday, January 22, 2009, http://www.ngs.noaa.gov/PUBS_LIB/AffirmationOfVerticalDatumForSurveyingAndMappingGuamNMVD03_FRN.pdf.

7. Data Processing Software

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

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

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

GMT v. 4.1.4 – Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu.

MB-System v. 5.1.0, free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System.

Persistance of Vision Pty. Ltd,. (2004), Persistence of Vision™ Raytracer. Persistance of Vision Pty., Williamstown, Victoria, Australia, http://www.povray.org.

Quick Terrain Modeler v. 6.0.1, lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com.