

# **Digital Elevation Models for Midway Atoll: Procedures, Data Sources and Analysis**

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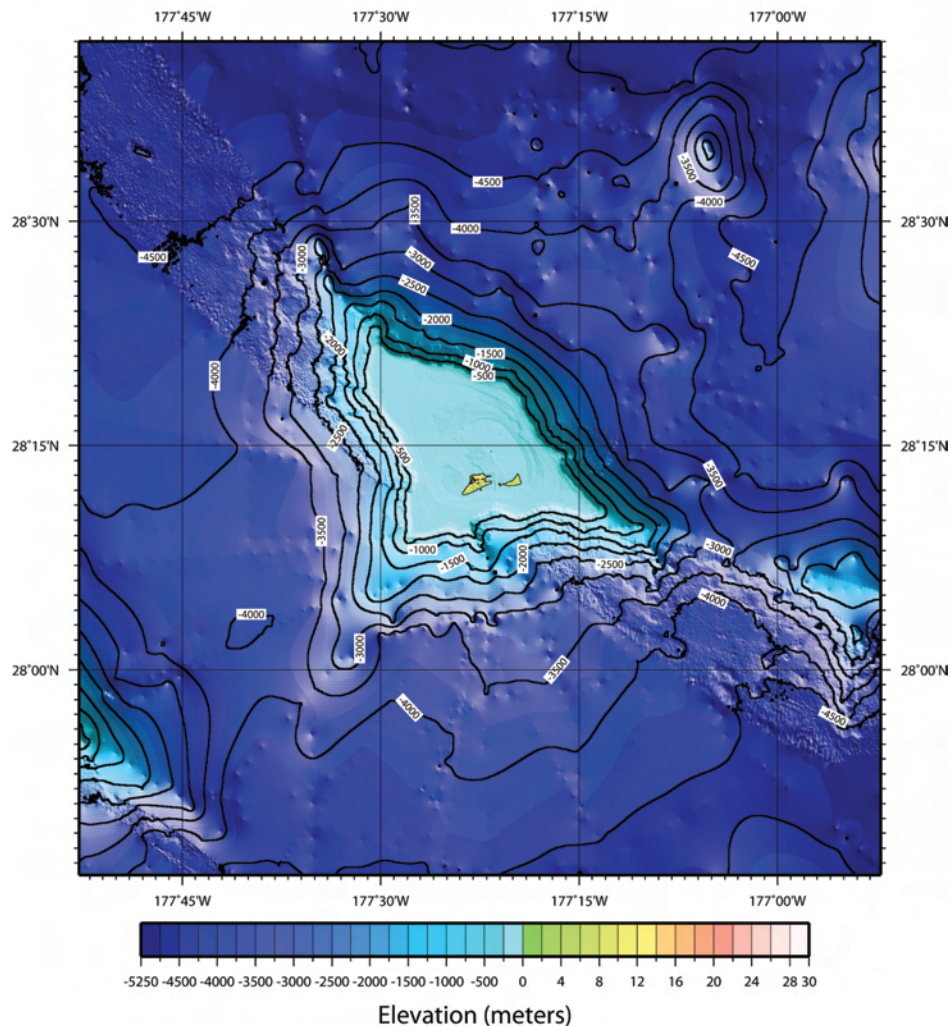
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# Digital Elevation Models of Midway Atoll: Procedures, Data Sources and Analysis

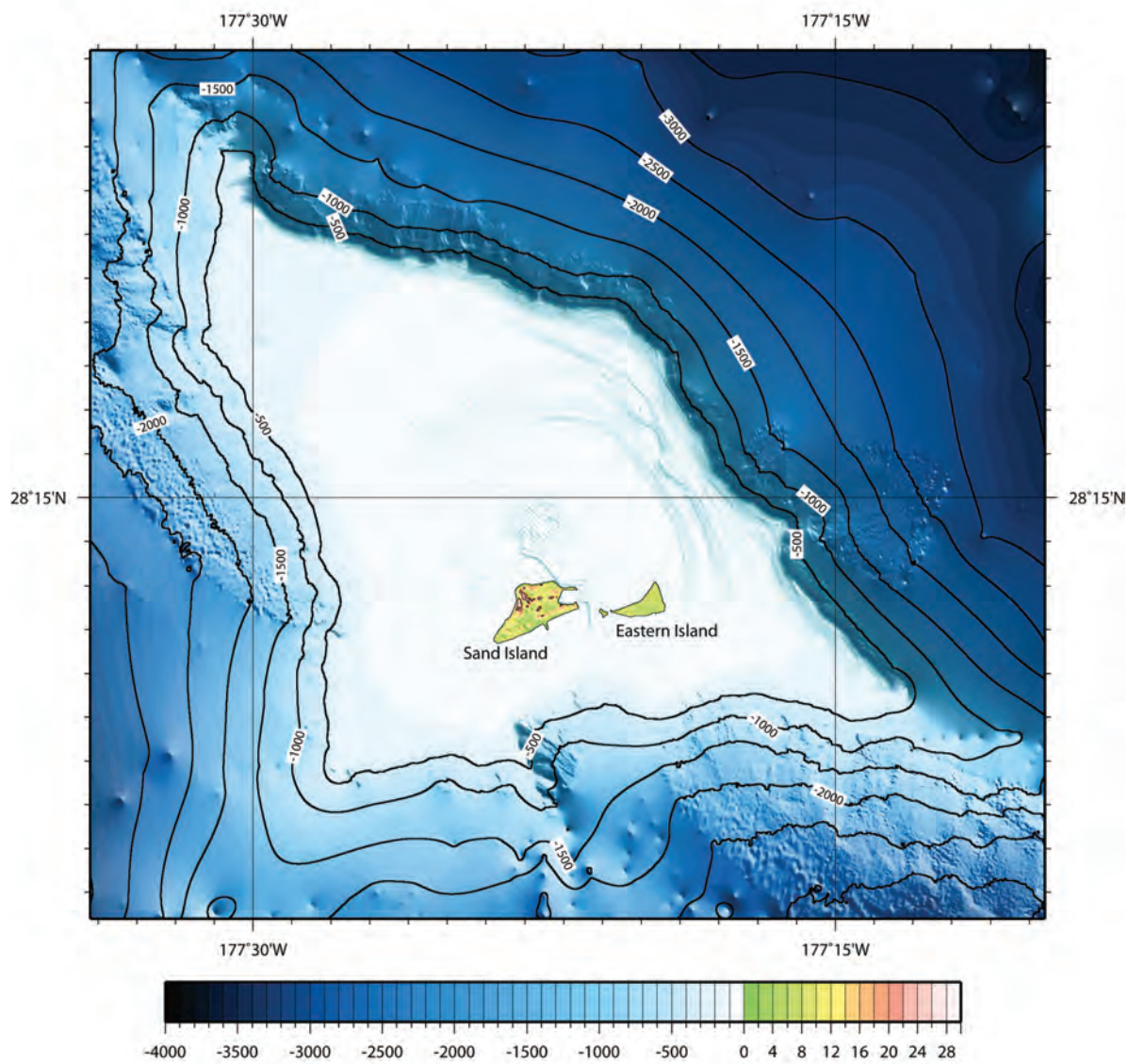
## 1. INTRODUCTION

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) centered on Midway Atoll 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<sup>1</sup> (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 SIFT (Short-term Inundation Forecasting for Tsunamis) 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 Midway Atoll, where high-resolution bathymetry multibeam data were available. This report provides a summary of the data sources and methodology used in developing the Midway Atoll DEMs.



**Figure 1.** Shaded-relief image of the 3 arc-second Midway Atoll DEM. Contour interval is 500 meters for bathymetry and 20 meters for topography.

1. The Midway Atoll 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 Midway Atoll (28°13'N, -177°21'W) 1/3 arc-second of latitude is equivalent to 10.26 meters; 1/3 arc-second longitude equals 9.09 meters. Three arc-seconds of latitude is equivalent to 92.35 meters; 3 arc-seconds of longitude is equivalent to 81.80 meters.



**Figure 2.** Shaded-relief image of the 1/3 arc-second Midway Atoll DEM. Contour interval is 500 meters for the bathymetry and 20 meters for the topography.



## 2. STUDY AREA

Midway Atoll is a circular atoll that consists of two islands, Sand Island and Eastern Island, collectively called Midway Island. The atoll is located in the Hawaiian archipelago approximately 1,150 miles west-northwest of Hawaii (Fig. 3). In 1940, an air and submarine base were built on the island. The island gained notoriety in 1942 after the Battle of Midway proved to be the turning point of WWII. In 2006, Midway Island was designated as a national monument with the other Northwestern Hawaiian Islands, and is managed by the U.S. Fish and Wildlife Service and NOAA.

Midway Atoll formed from a shield volcano that developed around 28 million years ago from the same hotspot that is located under Hawaii today. Pacific plate motion has moved the volcano northwest from the hotspot, where it has slowly subsided. A coral reef has grown around the rim of the atoll, which is currently 160 meters thick and is comprised of post-Miocene limestones and upper-Miocene sediments overlying basalt.

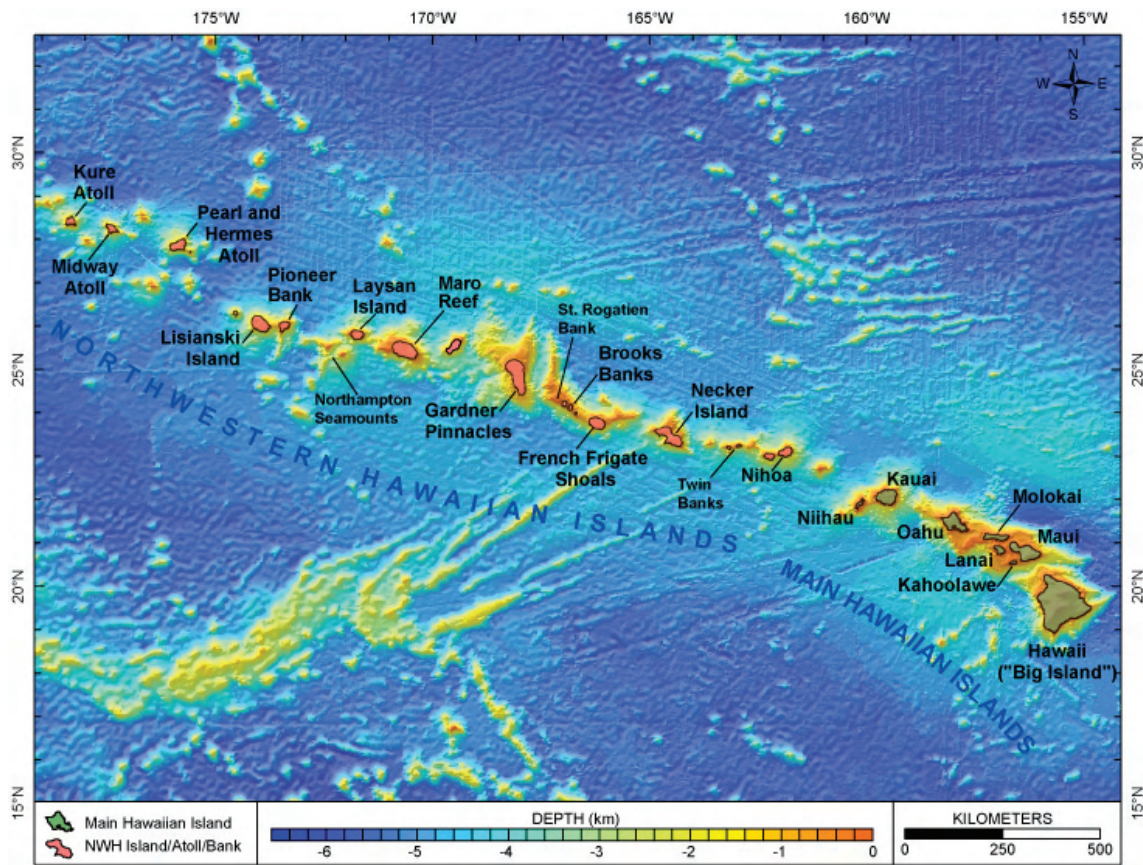


Figure 3: Location of Midway Atoll in the Northwestern Hawaiian Island Chain.  
([http://www.soest.hawaii.edu/pibhmc/pibhmc\\_nwhi.htm](http://www.soest.hawaii.edu/pibhmc/pibhmc_nwhi.htm))

### 3. METHODOLOGY

The Midway Atoll DEMs were constructed to meet PMEL specifications (Table 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: World Geodetic System 1984 (WGS 84) and Mean High Water (MHW), respectively, for modeling of maximum flooding. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

**Table 1a: PMEL specifications for the 3 arc-second Midway Atoll DEM.**

|                          |  |
|--------------------------|--|
| <b>Grid Area</b>         | Midway Atoll                             |
| <b>Coverage Area</b>     | 177.88° to 176.87° W; 27.77° to 28.70° N |
| <b>Coordinate System</b> | Geographic decimal degrees               |
| <b>Horizontal Datum</b>  | World Geodetic System 1984 (WGS 84)      |
| <b>Vertical Datum</b>    | Mean High Water (MHW)                    |
| <b>Vertical Units</b>    | Meters                                   |
| <b>Cell Size</b>         | 3 arc-second                             |
| <b>Grid Format</b>       | ESRI Arc ASCII grid                      |

**Table 1b: PMEL specifications for the 1/3 arc-second Midway Atoll DEM.**

|                          |  |
|--------------------------|--|
| <b>Grid Area</b>         | Midway Atoll                             |
| <b>Coverage Area</b>     | 177.62° to 177.11° W; 28.04° to 28.47° N |
| <b>Coordinate System</b> | Geographic decimal degrees               |
| <b>Horizontal Datum</b>  | World Geodetic System 1984 (WGS 84)      |
| <b>Vertical Datum</b>    | Mean High Water (MHW)                    |
| <b>Vertical Units</b>    | Meters                                   |
| <b>Cell Size</b>         | 1/3 arc-second                           |
| <b>Grid Format</b>       | 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 including: NOAA's National Geophysical Data Center (NGDC), Office of Coast Survey (OCS), and the Center of Coastal Monitoring and Assessment (CCMA); the U.S. Geological Survey (USGS); and the Naval Postgraduate School. Safe Software's (<http://www.safe.com/>) *FME* data translation tool package was used to shift datasets to WGS 84 horizontal datum and to convert them into ESRI (<http://www.esri.com/>) *ArcGIS* shape files. The shape files 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 #1619910 Sand Island, Midway Island. Applied Imagery's *Quick Terrain Modeler* software (<http://www.appliedimagery.com/>) was used for evaluating datasets before the final gridding process.

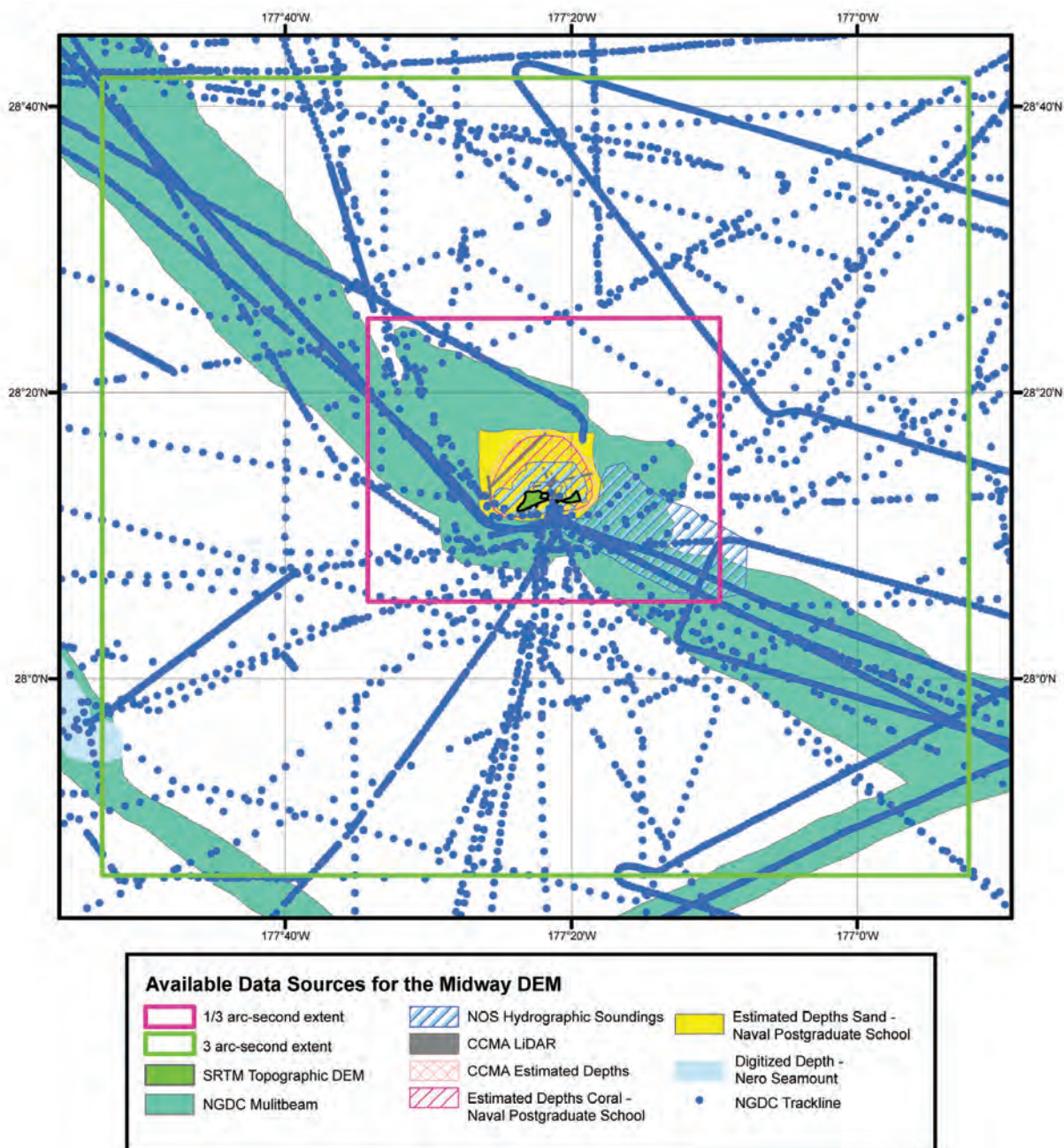


Figure 4. Source and coverage of datasets available in the Midway Atoll region. Areas of no data are white. NOS and CCMA surveys were not used in DEM development.

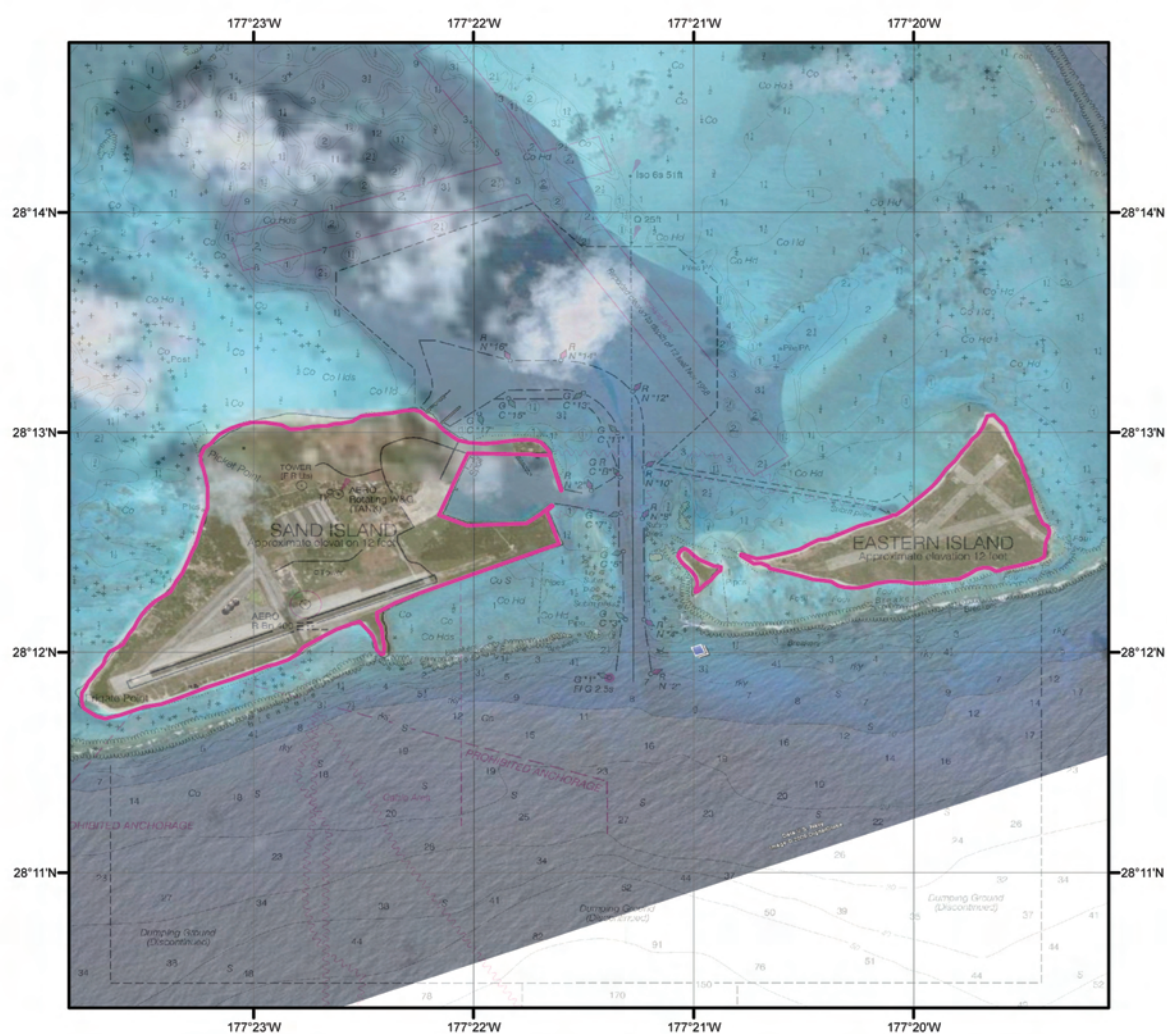


### 3.1.1 Shoreline

There were no NOAA Electronic Nautical Charts (ENCs) or high-resolution coastline datasets available for Midway Island, therefore, NGDC digitized the coastline based on NOAA Raster Nautical Chart (RNC) #19481 (Table 2).

**Table 2: Shoreline dataset used in the Midway Atoll DEMs.**

| Source          | Year | Data Type | Spatial Resolution | Original Horizontal Datum/Coordinate System | Original Vertical Coordinate System | URL   |
|-----------------|------|-----------|--------------------|---|-------------------------------------|---|
| NOAA RNC #19481 | 2009 | vector    | 1:32,500           | WGS 84 geographic                           | Mean High Water                     | <a href="http://www.nauticalcharts.noaa.gov/mcd/Raster/index.htm">http://www.nauticalcharts.noaa.gov/mcd/Raster/index.htm</a> |



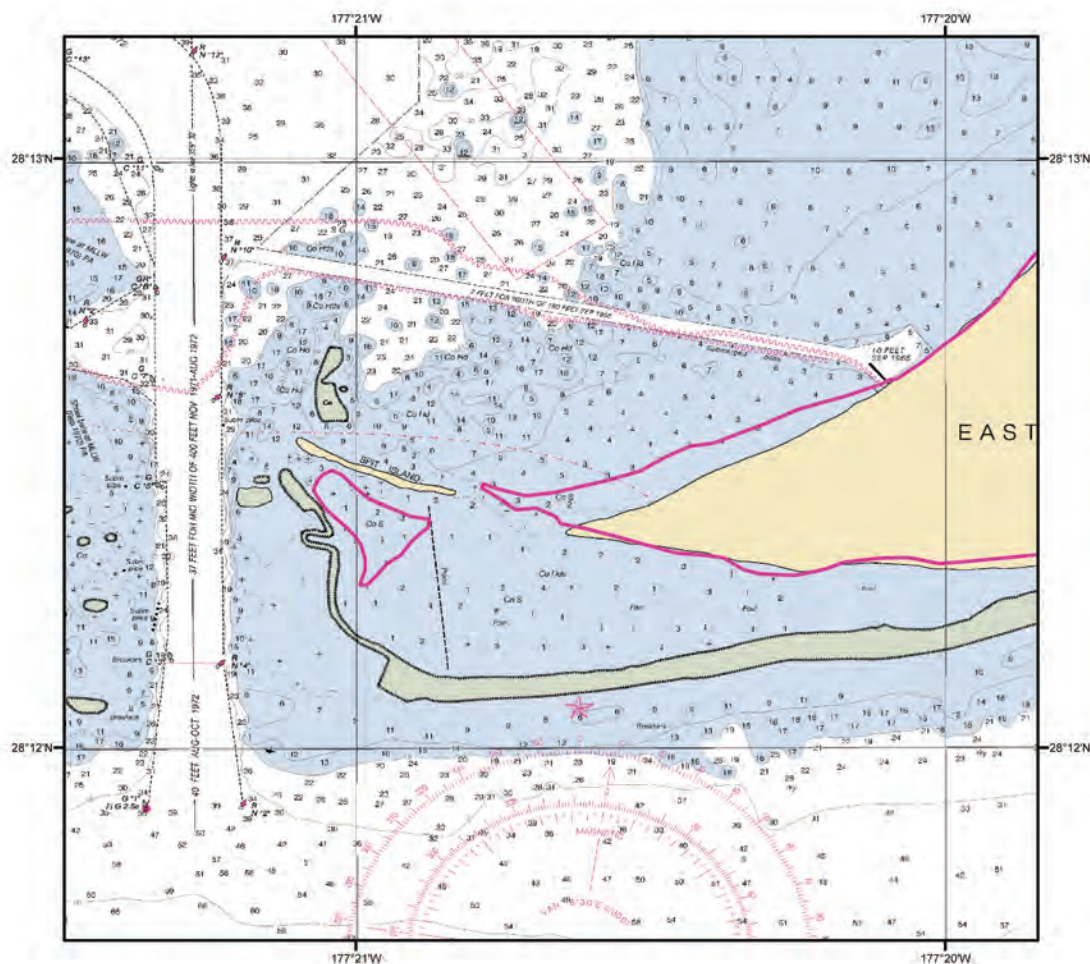
**Figure 5.** Satellite image (2007) of Midway Island, extracted from Google Earth. Final coastline in pink.

### 1) NGDC Digitized Coastline

NGDC digitized the Midway Island coastline from NOAA RNC #19481 (Table 3), which has a resolution of 1:32,500. NOAA RNC #19482 has higher resolution but was not used in digitizing the final coastline because significant coastal morphologic changes have occurred since 2000 (Fig. 6). *Google Earth* satellite imagery (2007) and the shallow-water Naval Postgraduate School's estimated depths (2006) were used to adjust the final coastline to match present morphology.

**Table 3: NOAA nautical charts available for Midway Atoll.**

| <i>Chart</i> | <i>Title</i>               | <i>Edition</i> | <i>Edition Date</i> | <i>Format</i> | <i>Scale</i> |
|--------------|----------------------------|----------------|---------------------|---------------|--------------|
| 19480        | Gambia Shoal to Kure Atoll | 9th            | 2007                | RNC           | 1:180,00     |
| 19481        | Midway Islands             | 11th           | 2005                | RNC           | 1:32,500     |
| 19482        | Midway Islands             | 9th            | 2000                | RNC           | 1:10,000     |



**Figure 6.** Example of coastal morphological change since 2000. NOAA RNC #19482 (2000) in background shows major differences in the sand spit from the final coastline (in pink), which was derived from NOAA RNC #19481 (2005) and *Google Earth* Satellite imagery (2007).

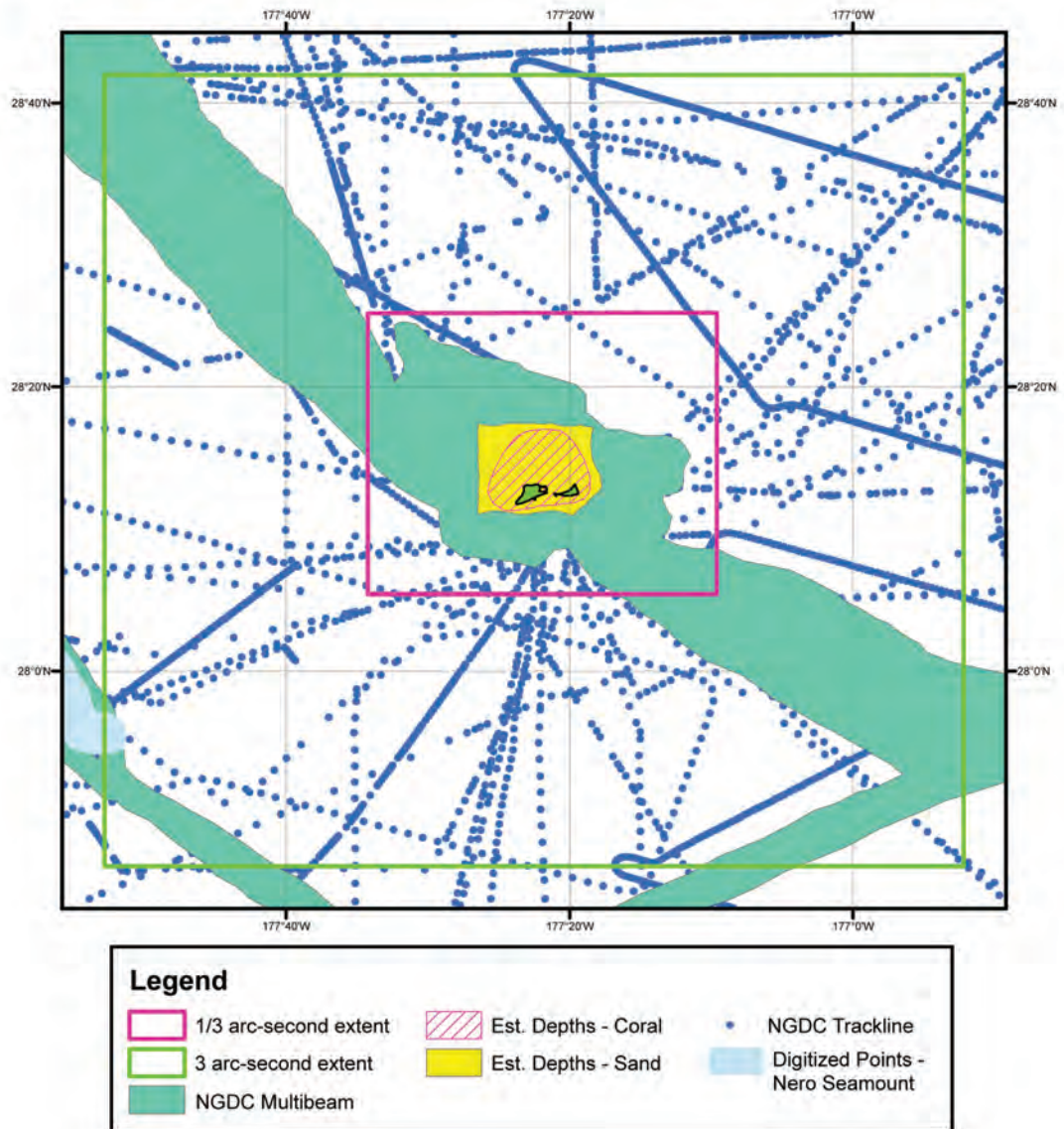
### 3.1.2 Bathymetry

Bathymetric datasets available for the compilation of the Midway Atoll DEMs include five multibeam swath sonar surveys from the NGDC multibeam sonar database, three NOS hydrographic surveys, 28 trackline geophysics surveys, CCMA bathymetric LiDAR surveys and estimated depths extracted from satellite imagery, and the Naval Postgraduate School's (NPS) estimated depths extracted from satellite imagery (Table 4; see Figs. 4, 7;). The NOS hydrographic soundings (1941) and CCMA's estimated depths from satellite imagery (2002) and bathymetric LiDAR data (2001) were not used in DEM development because they have been superseded by more recent, higher-resolution data.

**Table 4: Bathymetric datasets used in compiling the Midway Atoll DEMs.**

| <i>Source</i>             | <i>Year</i>  | <i>Data Type</i>                        | <i>Spatial Resolution</i>  | <i>Original Horizontal Datum/<br/>Coordinate System</i> | <i>Original Vertical Datum</i> | <i>URL</i>  |
|---------------------------|--------------|---|--|---|--------------------------------|---|
| NGDC                      | 1992 to 2005 | Multibeam sonar swath files             | raw MB files gridded to 1/3 arc-second                                       | WGS 84 geographic                                       | assumed MSL                    | <a href="http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html">http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html</a>   |
| NGDC                      | 1961 to 1991 | Trackline (single beam echo-sounder)    | soundings up to 100's of meters along profile with profiles spaced kms apart | WGS 84 geographic                                       | assumed MSL                    | <a href="http://www.ngdc.noaa.gov/mgg/geodas/trackline.html">http://www.ngdc.noaa.gov/mgg/geodas/trackline.html</a>           |
| Naval Postgraduate School | 2006         | Estimated Depths from Satellite Imagery | 3 to 5 meters  | WGS 84 geographic                                       | assumed MSL                    |   |
| NOAA RNC 19480            | 2009         | Digitized Points                        | 1:180,000  | WGS 84 geographic                                       | MHW                            | <a href="http://www.nauticalcharts.noaa.gov/mcd/Raster/index.htm">http://www.nauticalcharts.noaa.gov/mcd/Raster/index.htm</a> |





*Figure 7. Spatial coverage of bathymetric datasets used to compile the Midway Atoll DEMs. Areas of no data are white. Final coastline is illustrated in black.*



### 1) Multibeam swath sonar surveys

Five multibeam swath sonar surveys were available from the NGDC multibeam bathymetry database (<http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html>) for use in the Midway Atoll DEMs (Table 5, Fig. 8). This database is comprised of the original swath sonar surveys conducted mostly by the U.S. academic fleet. The data were gridded to 1/3 arc-second resolution using *MB-System*. *MB-System* is an NSF-funded free software application specifically designed to manipulate multibeam swath sonar data (<http://www.ldeo.columbia.edu/res/pi/MB-System/>). After assessing individual survey quality, the gridded data were transformed to MHW (see section 3.2.1) and shape files for editing in *ArcMap*. NGDC edited out noise along the swath edges and then converted to xyz format using *FME* for gridding of the preliminary bathymetric surface and final grid.

Surveys HI-05-03 and AHI-03-06 provide high-resolution coverage surrounding Midway Atoll but do not include the shallower region inside the atoll. The other three surveys are transits rather than dedicated sea-floor surveys. All have a horizontal datum of WGS 84 geographic and undefined vertical datum, which was assumed to be essentially mean sea level (MSL).

**Table 5: Multibeam swath sonar surveys used in compiling the Midway Atoll DEMs.**

| <i>Cruise ID</i> | <i>Ship</i>         | <i>Year</i> | <i>Original Vertical Datum</i> | <i>Original Horizontal Datum</i> | <i>Institution</i>   |
|------------------|---------------------|-------------|--------------------------------|----------------------------------|--|
| AVON-06MV        | Melville            | 1999        | Assumed MSL                    | WGS 84 geographic                | University of California, Scripps Institution of Oceanography (UC/SIO) |
| AHI-03-06        | Ahi                 | 2003        | Assumed MSL                    | WGS 84 geographic                | NOAA National Marine Fisheries Service (NMFS)                          |
| HI-05-03         | Hi'ialakai          | 2005        | Assumed MSL                    | WGS 84 geographic                | NOAA National Marine Fisheries Service (NMFS)                          |
| TUNE09WT         | Thomas Washington   | 1992        | Assumed MSL                    | WGS 84 geographic                | University of California, Scripps Institution of Oceanography (UC/SIO) |
| KOK0319          | Ka'imikai-O-Kanaloa | 2003        | Assumed MSL                    | WGS 84 geographic                | NOAA National Marine Fisheries Service (NMFS)                          |



**Figure 8.** Ship tracks of multibeam swath sonar surveys used in compiling the Midway Atoll DEMs.

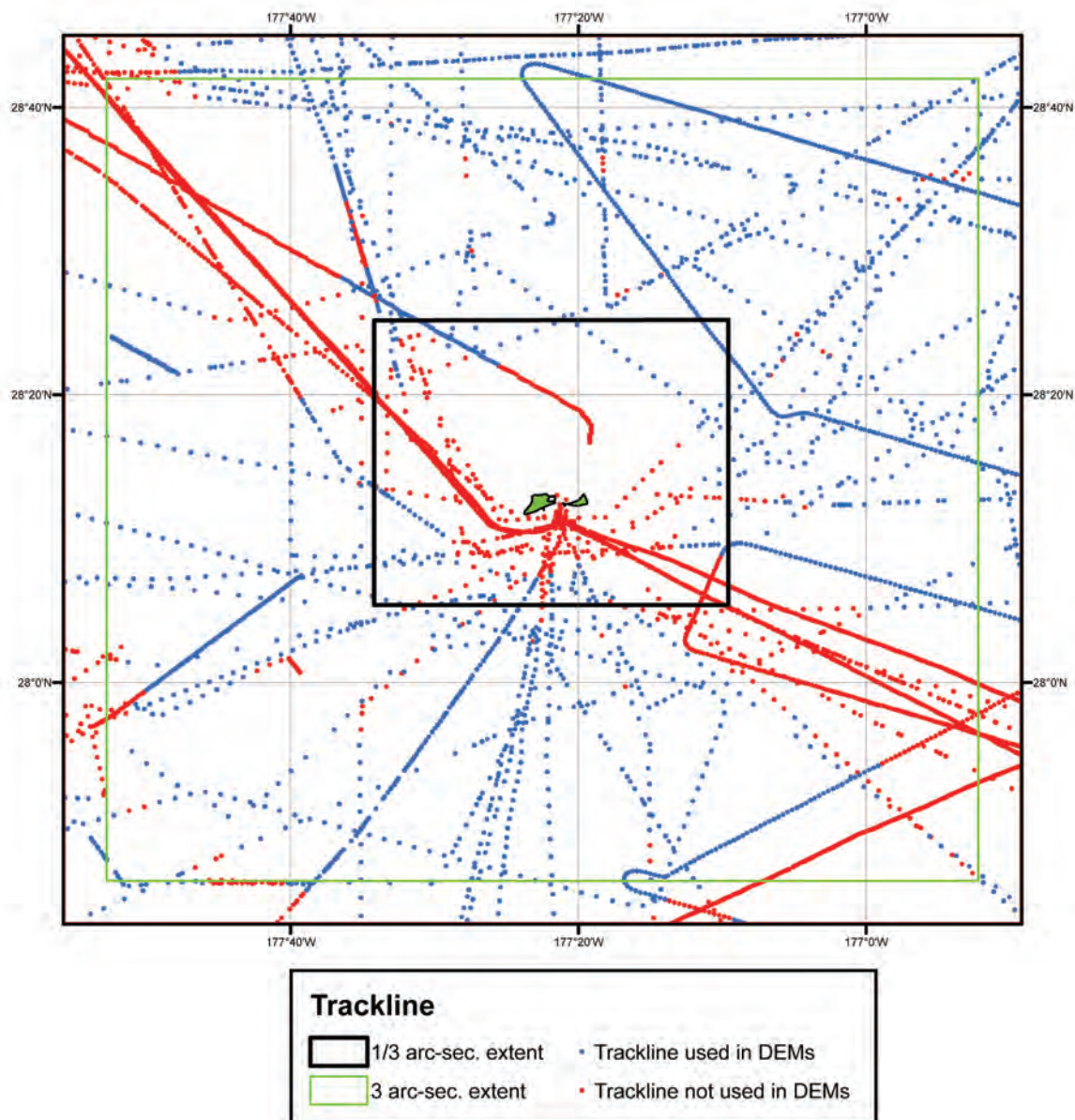
## 2) Trackline surveys

Twenty-eight single-beam echo-sounder surveys were available from the NGDC marine geophysical trackline database (<http://www.ngdc.noaa.gov/mgg/geodas/trackline.html>) for use in the Midway Atoll DEMs (Table 6, Fig. 9). This database is comprised of bathymetry, magnetics, gravity, and seismic navigation data collected along ship track during marine cruises from 1953 to present. The data were downloaded as xyz files in WGS 84 and converted to MHW using *FME*.

The tracklines are spaced 10's of kilometers apart and were only used where no high-resolution multibeam bathymetric data exist.

**Table 6: Trackline surveys available in the Midway Atoll region.**

| <i>Cruise ID</i> | <i>Ship</i>       | <i>Year</i> | <i>Original Vertical Datum</i> | <i>Original Horizontal Datum</i> | <i>Institution</i>                            |
|------------------|-------------------|-------------|--------------------------------|----------------------------------|---|
| 73102500         | Kana Keoki        | 1973        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| 75072600         | Kana Keoki        | 1975        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| 76080601         | Kana Keoki        | 1976        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| 76080602         | Kana Keoki        | 1976        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| 77031705         | Kana Keoki        | 1977        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| 77031706*        | Kana Keoki        | 1977        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| 80041401         | Kana Keoki        | 1980        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| 80041402         | Kana Keoki        | 1980        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| 84042805         | Kana Keoki        | 1984        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| KK720702         | Kana Keoki        | 1972        | assumed MSL                    | WGS 84 geographic                | University of Hawaii, HIG                     |
| KH7402           | Hakuho Maru       | 1974        | assumed MSL                    | WGS 84 geographic                | Ocean Research Institute, University of Tokyo |
| V2005            | Vema              | 1964        | assumed MSL                    | WGS 84 geographic                | Lamont-Doherty Geological Observatory         |
| V2006            | Vema              | 1964        | assumed MSL                    | WGS 84 geographic                | Lamont-Doherty Geological Observatory         |
| V2404            | Vema              | 1967        | assumed MSL                    | WGS 84 geographic                | Lamont-Doherty Geological Observatory         |
| V2405            | Vema              | 1967        | assumed MSL                    | WGS 84 geographic                | Lamont-Doherty Geological Observatory         |
| POL7201          | Oceanographer     | 1972        | assumed MSL                    | WGS 84 geographic                | NOAA  |
| CMAPPI7E         | Pioneer           | 1961        | assumed MSL                    | WGS 84 geographic                | NOAA Nation Ocean Service                     |
| CMAPSU7E         | Surveyor          | 1963        | assumed MSL                    | WGS 84 geographic                | NOAA Nation Ocean Service                     |
| POL7004          | Oceanographer     | 1970        | assumed MSL                    | WGS 84 geographic                | NOAA POL                                      |
| POL6829          | Surveyor          | 1968        | assumed MSL                    | WGS 84 geographic                | NOAA POL                                      |
| STYX07AZ         | Agassiz           | 1968        | assumed MSL                    | WGS 84 geographic                | Scripps Institution of Oceanography           |
| NOVA01AR         | Argo              | 1967        | assumed MSL                    | WGS 84 geographic                | Scripps Institution of Oceanography           |
| TSDY03WT         | Thomas Washington | 1973        | assumed MSL                    | WGS 84 geographic                | Scripps Institution of Oceanography           |
| FARN0691         | Farnella          | 1991        | assumed MSL                    | WGS 84 geographic                | Natural Environment Research Council          |
| FARN1091         | Farnella          | 1991        | assumed MSL                    | WGS 84 geographic                | Natural Environment Research Council          |
| SI932003         | Silas Bent        | 1971        | assumed MSL                    | WGS 84 geographic                | US Navy Naval Oceanographic Office            |
| SI932009         | Silas Bent        | 1972        | assumed MSL                    | WGS 84 geographic                | US Navy Naval Oceanographic Office            |
| L876NP           | Samuel P. Lee     | 1976        | assumed MSL                    | WGS 84 geographic                | USGS Branch of Pacific Marine Geology         |



**Figure 9.** Spatial coverage of trackline surveys in the Midway Atoll region. Trackline data shown in red were not used in the final DEM gridding, as there were high-resolution multibeam coverage or newer, more accurate trackline surveys available. Trackline data shown in blue were used for gridding of the final DEM.

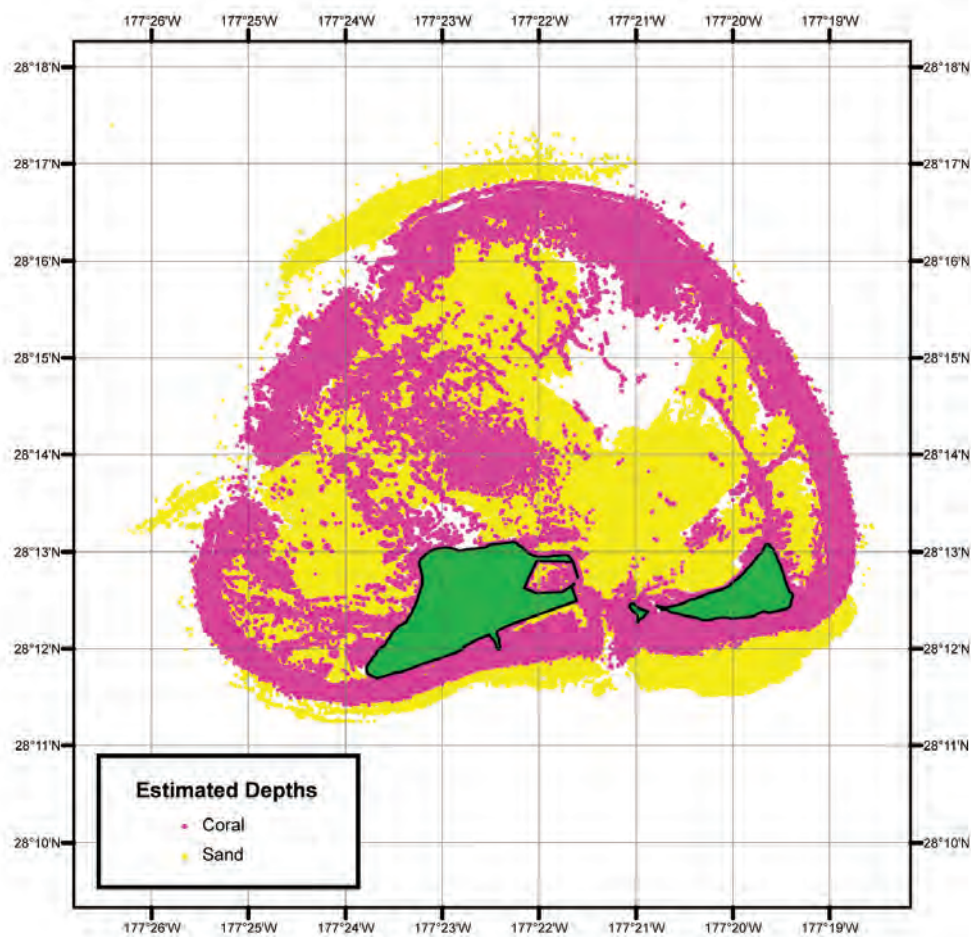
### 3) Naval Postgraduate School Estimated Depths

Graduate student Mark A. Camacho of the Naval Postgraduate School (NPS), completed his masters thesis on a depth analysis of Midway Atoll using high-resolution satellite imaging. Mr. Camacho's co-advisor, Dr. Richard Olsen, graciously provided NGDC with the resulting data.

Comancho used a high-resolution multispectral image taken from the QuickBird satellite in October 2004. Environment for Visualizing Images 4.2 was used to analyze and process the image. Corrections were made for atmospheric absorption and scattering, the water column, and reflection from waves due to wind. Two separate bathymetric images were produced from two different algorithms for the main benthic classes: sand and coral.

Data were provided to NGDC as two xyz files, coral bottom and sand bottom. No vertical datum was documented, so NGDC assumed the data were essentially MSL. The xyz files were transformed to shape files and MHW using *FME* for assessing the data (Fig. 10). The data have a correlation of 86.5% between predicted depth and actual depths based on NOAA nautical chart values.

NPS estimated depth data are the most recent, high-resolution data, so were used instead of the CCMA bathymetric LiDAR (2001) and estimated depths (2002), or the 1941 NOS surveys.



**Figure 10.** Spatial coverage of estimated depths from the Naval Postgraduate School. Yellow represents a sandy bottom; pink represents coral cover.



#### 4) NGDC Digitized Depths

NGDC digitized Nero Seamount from the NOAA RNC #19840 in the southwestern area of the 3 arc-second DEM (Figure 11). Multibeam swath sonar survey KOK0319 covered the area, but had bad returns that did not accurately reflect the seamount, so was not used.

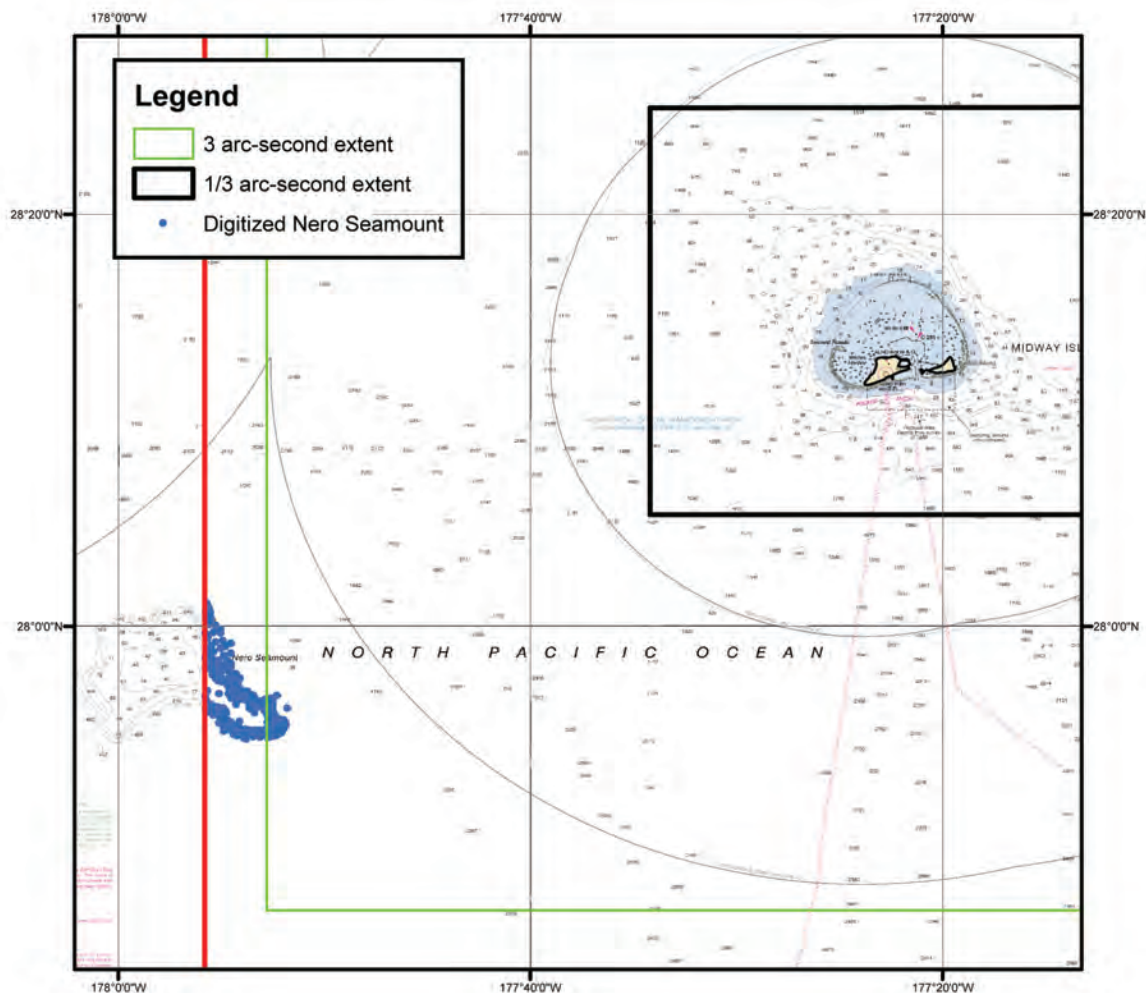


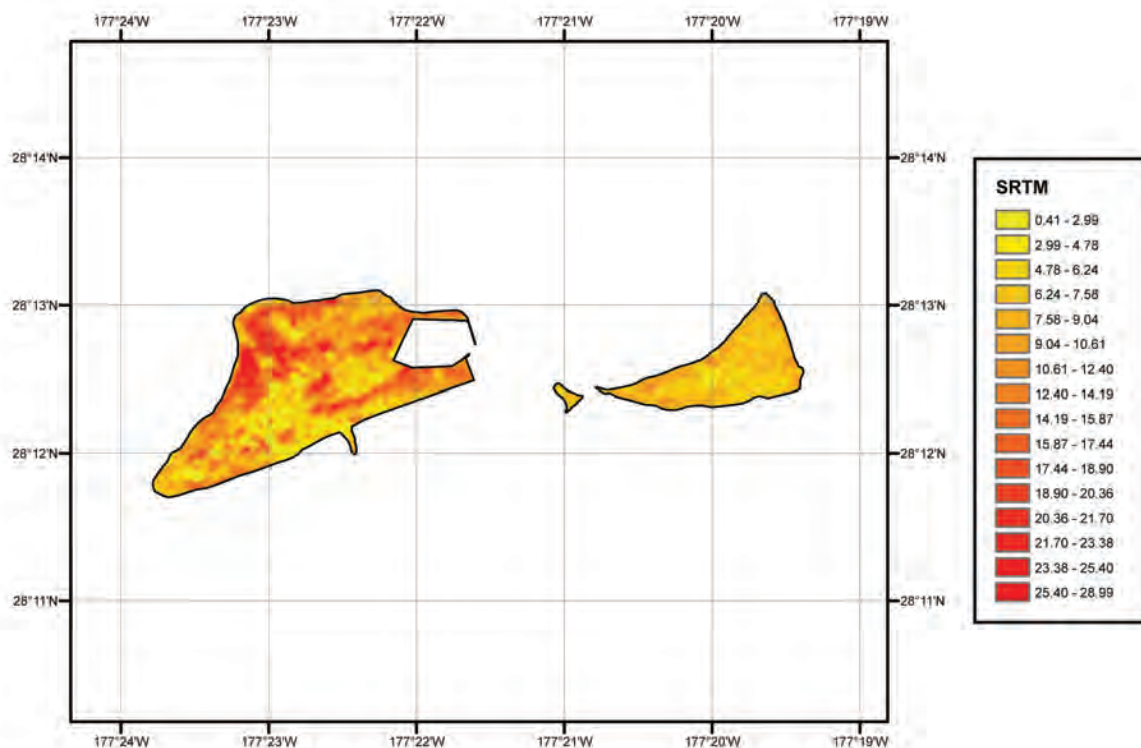
Figure 11. Soundings on Nero Seamount digitized from NOAA RNC #19840.

### 3.1.3 Topography

The NASA Space Shuttle Radar Topography (SRTM) 1 arc-second DEM provided full coverage of the islands and was used to build the Midway Atoll DEMs (Table 7; Fig. 12).

**Table 7: Topographic dataset used in compiling the Midway Atoll DEMs.**

| <i>Source</i> | <i>Year</i> | <i>Data Type</i> | <i>Spatial Resolution</i> | <i>Original Horizontal Datum/<br/>Coordinate System</i> | <i>Original Vertical Datum</i> | <i>URL</i>  |
|---------------|-------------|------------------|---------------------------|---|--------------------------------|---|
| NASA          | 2000        | Topographic DEM  | 1 arc-second              | WGS 84 Geographic                                       | WGS 84/EGM 96 Geoid            | <a href="http://srtm.usgs.gov/">http://srtm.usgs.gov/</a> |
| NGDC          | 2009        | Digitized Points |                           | WGS 84 Geographic                                       | MHW                            |   |



**Figure 12.** SRTM data coverage for Midway Island. Coastline in black.

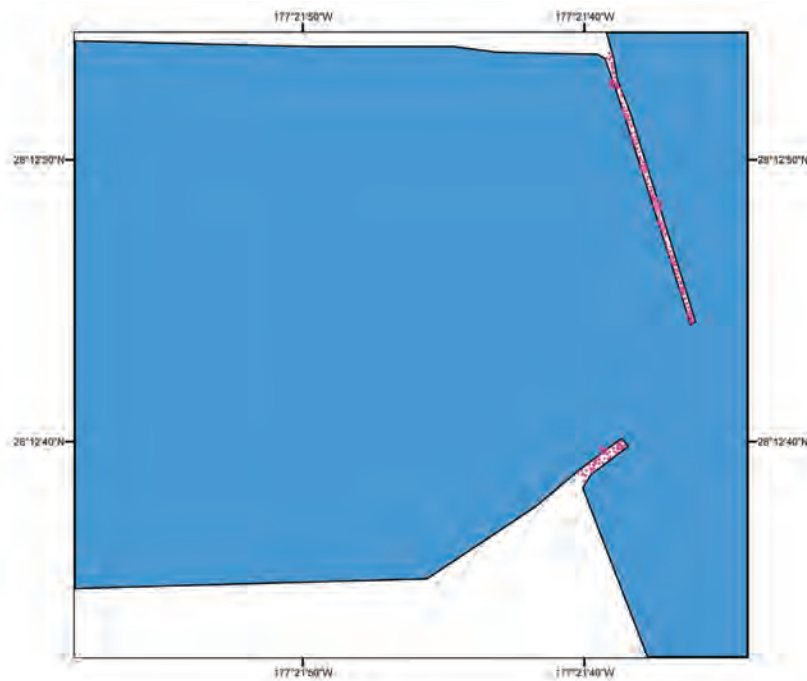
### 1) NASA space shuttle radar topography

The NASA Shuttle Radar Topography Mission (SRTM) obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth<sup>2</sup>. 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 x 1 degree tiles that have been 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, and have absolute horizontal and vertical accuracies of 20 and 16 meters, respectively.

A topographic surface was created with GMT to resample the SRMT from 1 arc-second to 1/3 arc-second. This created a smoother fit along the coastline when the SRTM DEM was clipped to the coast to delete values over the open ocean. The clipped data were converted into an xyz format for the final gridding process.

### 2) NGDC Digitized Breakwater

NGDC digitized elevation points at 0.5 meters along the breakwater to the harbor (Figure 13). The width of the breakwater is ~5-6 meters, less than the width of one cell size for a 1/3 arc-second grid. A few points were digitized to create a continuous wall above MHW in the DEM, to avoid “channels” of water between cells representing the breakwater.



**Figure 13.** Digitized points (in pink) on the breakwaters around the boat harbor. Coastline in black.

2. 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]

## 3.2 Establishing Common Datums

### 3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Midway Atoll DEMs were originally referenced to vertical datums of mean lower low water (MLLW), mean sea level (MSL), and WGS 84/EGM 96 Geoid. All datasets were transformed to MHW to provide the maximum flooding scenario for inundation modeling.

#### 1) Bathymetric data

The multibeam, trackline surveys, and estimated depths were transformed from MSL to MHW using *FME* software, by adding a constant offset of -0.132 meters measured at the Midway Island NOAA tidal station #1619910 (Table 8; <http://tidesandcurrents.noaa.gov/>).

#### 2) Topographic data

The SRTM topographic DEM was originally in WGS 84/EGM 96 Geoid vertical datum. There are no survey markers near Midway Island that relate this datum to the local tidal datum. Thus, we assumed the datum to be essentially equivalent to MSL in this area (Table 8). Conversion to MHW was accomplished by adding a constant value of -0.132 meters.

**Table 8: Relationship between mean high water and other vertical datums in the Midway Atoll region.\***

| <i>Vertical Datums</i> | <i>Difference to MHW</i> |
|------------------------|--------------------------|
| MSL                    | 0.132 meters             |
| MLLW                   | 0.328 meters             |

\*Datum relationships determined by NOAA tidal station 1619910 at Midway Island

### 3.2.2 Horizontal datum transformations

Datasets used to compile the Midway Atoll DEMs were originally referenced to WGS 84. No conversion was needed for the datasets in WGS 84. Datasets that were available but were not used for the final gridding process were referenced to UTM Zone 2 (CCMA) and undetermined horizontal datum (NOS). The relationship and transformational equations between WGS 84 and UTM Zone 2 are well established. These data were converted to WGS 84 using *FME* software. There was no defined relationship between the undetermined and WGS 84 datums, so smoothsheets of the NOS surveys were georeferenced in *ArcMap* and the data were manually shifted to visually match the smoothsheets.



### 3.3 Digital Elevation Model Development

#### 3.3.1 Verifying consistency between datasets

After vertical transformations were applied, the resulting ESRI shape files 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 shape files were then converted to xyz files in preparation for gridding. Problems included:

- Old NOS surveys in the shallow water with an undetermined horizontal datum
- Estimated depths were the only recent data available for the shallow water region
- Recent morphological changes due to the jetties at the boat harbor on Sand Island, constructed after surveys were conducted in the area.
- Limited high-resolution bathymetric measurements in the deep ocean surrounding the atoll
- Lack of metadata for the LiDAR surveys and estimated depths from the Naval Postgraduate school, leading us to assume MSL vertical datum

#### 3.3.2 Smoothing of bathymetric data

Two ‘pre-surface’ bathymetric grids were generated for the Midway Atoll 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, a marked contrast with the trackline surveys spaced 1 to 15 kilometers apart. NGDC created a 1 arc-second cell size bathymetric grid slightly larger than the 1/3 arc-second DEM extent, and a 3 arc-second cell size bathymetric grid slightly larger than the 3 arc-second DEM extent. The grids were generated using *GMT*, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (<http://gmt.soest.hawaii.edu/>).

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 final Midway Atoll DEM gridding extents. 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 original soundings to ensure grid accuracy (Fig. 14) and exported as an xyz file for use in the final gridding process (see Table 9). The statistical analysis of the differences between the 1 arc-second bathymetric surface and the estimated depths from the coral layer show that the majority of the soundings are in agreement with the bathymetric surface. Depths with the greatest difference (-10 and +10 meters) are due to averaging of multiple, closely spaced depths.

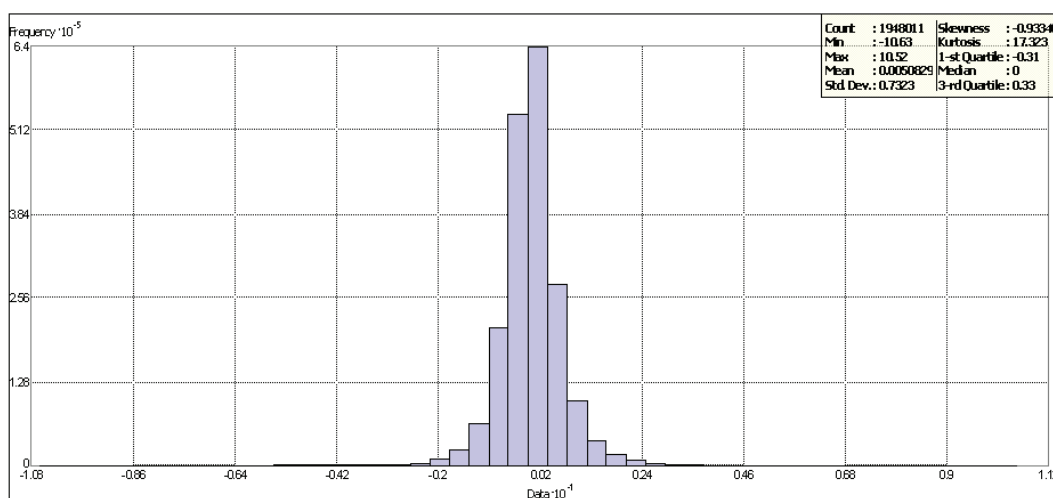


Figure 14. Histogram of the differences between Naval Postgraduate School estimated depths from the coral layer and the 1 arc-second bathymetric grid.

### 3.3.3 Gridding the data with MB-System

*MB-System* (<http://www.ldeo.columbia.edu/res/pi/MB-System/>) was used to create the Midway Atoll 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 9. Greatest weight was given to the digitized features. Least weight was given to the coastline, trackline surveys, and the pre-surfaced bathymetric grid.

Table 9. Data hierarchy used to assign gridding weight in MB-System.

| <i>Dataset</i>                             | <i>Relative Gridding Weight</i> |
|--|---------------------------------|
| NGDC digitized features                    | 1,000                           |
| NGDC Multibeam surveys                     | 100                             |
| NPS Satellite Imagery Depths               | 100                             |
| SRTM Topographic DEM                       | 10                              |
| 1 arc-second Pre-surfaced bathymetric grid | 1                               |
| NGDC Trackline                             | 1                               |
| Midway Island coastline                    | 1                               |

## 3.4 Quality Assessment of the DEMs

### 3.4.1 Horizontal accuracy

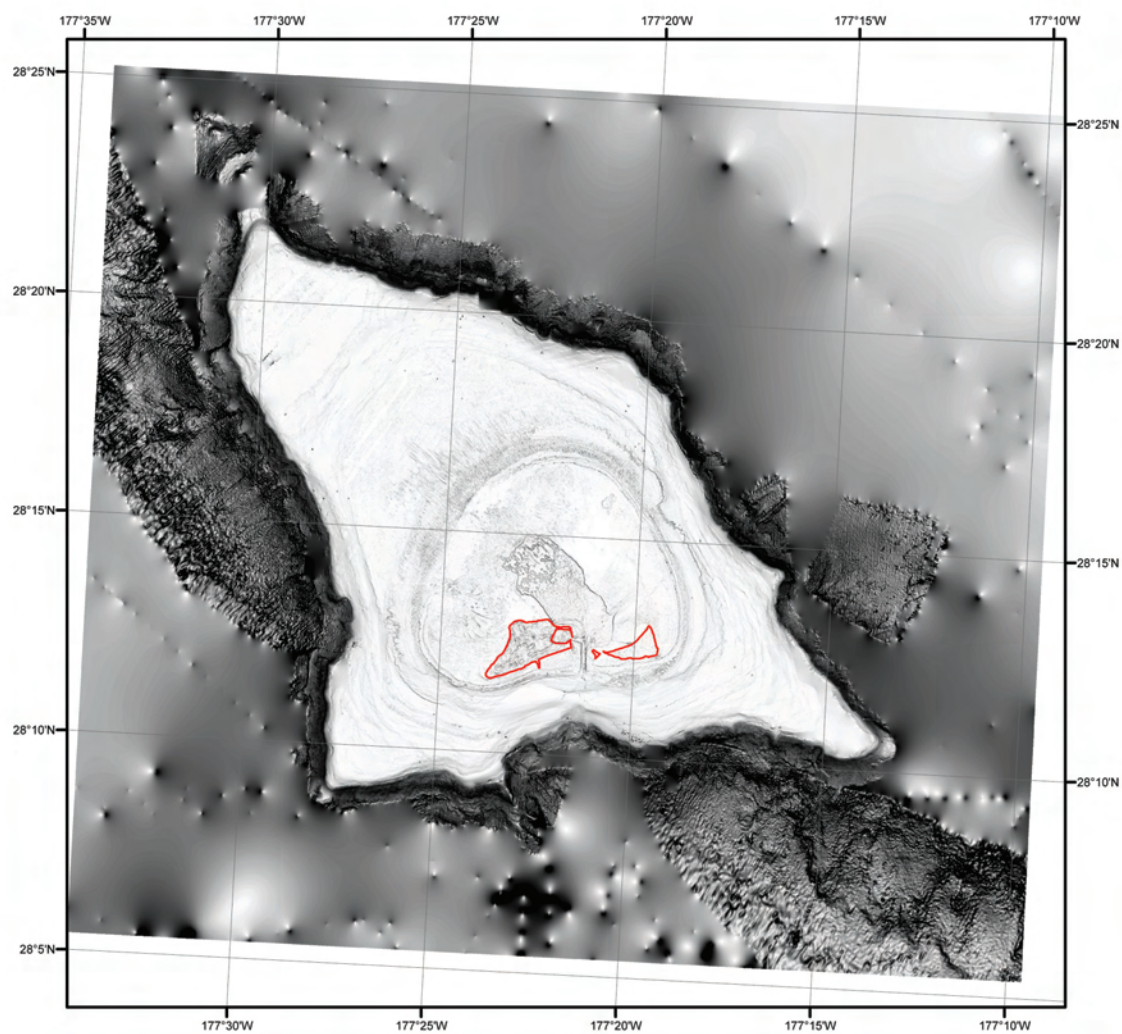
The horizontal accuracy of topographic and bathymetric features in the Midway Atoll DEMs are dependent upon cell location and the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of no better than 30 meters (SRMT). Bathymetric features are resolved only to within a few kilometers in deep-water areas. Shallow, near-coastal regions have an accuracy approaching 10 meters (NPS). Positional accuracy is limited by: the paucity of deep-water soundings and by recent morphologic change.

### 3.4.2 Vertical accuracy

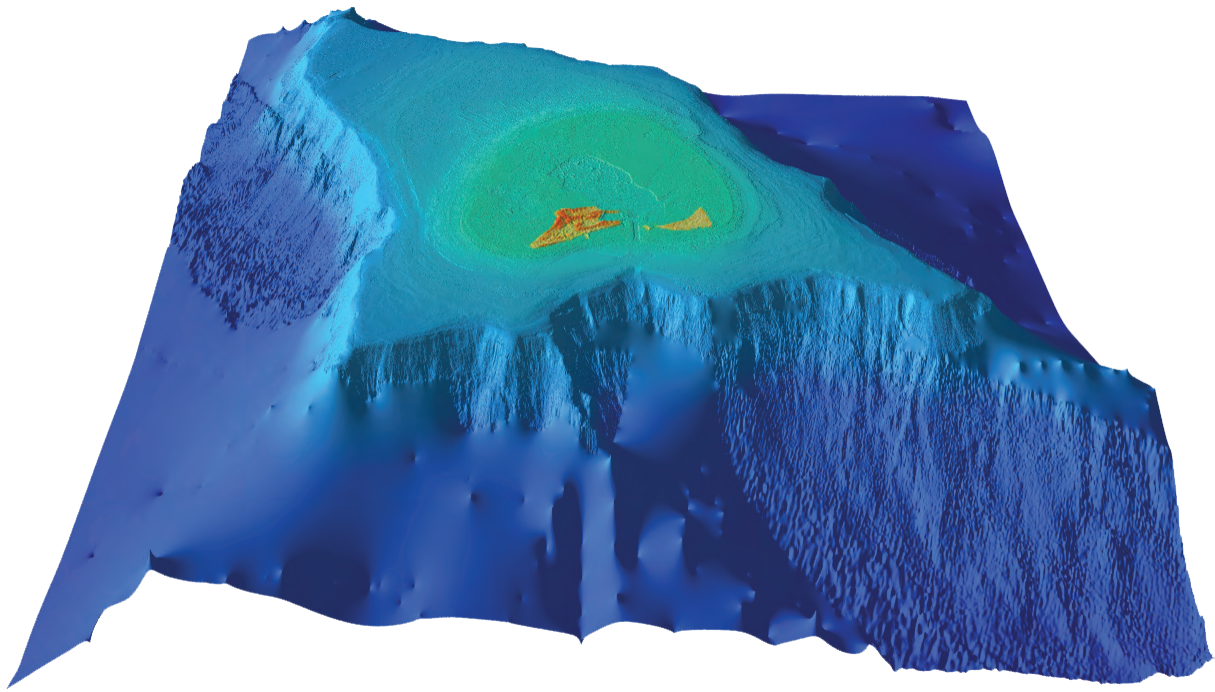
Vertical accuracy of elevation values for the Midway Atoll DEMs are also highly dependent upon the source datasets contributing to DEM cell values. The SRTM topographic DEM has an estimated vertical accuracy between 10 and 16 meters. Bathymetric areas have an estimated accuracy of between 0.1 meters and 1% of water depth for the 1/3 arc-second DEM. The deep water values in the 3 arc-second DEM have an estimated accuracy of hundreds of meters due to gridding interpolation between sparse soundings.

### 3.4.3 Slope maps and 3-D perspectives

ESRI *ArcCatalog* was used to generate slope grids from the Midway Atoll DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 15). The DEMs were transformed to UTM Zone 2 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*. Figure 16 shows a perspective view of the 1/3 arc-second Midway Atoll DEM in its final version, created by *Persistence of Vision™ Raytracer (POV-Ray)*.



*Figure 15. Slope map of the 1/3 arc-second Midway Atoll DEM. Flat-lying slopes are white; dark shading denotes steep slopes; Midway Island coastline in red.*

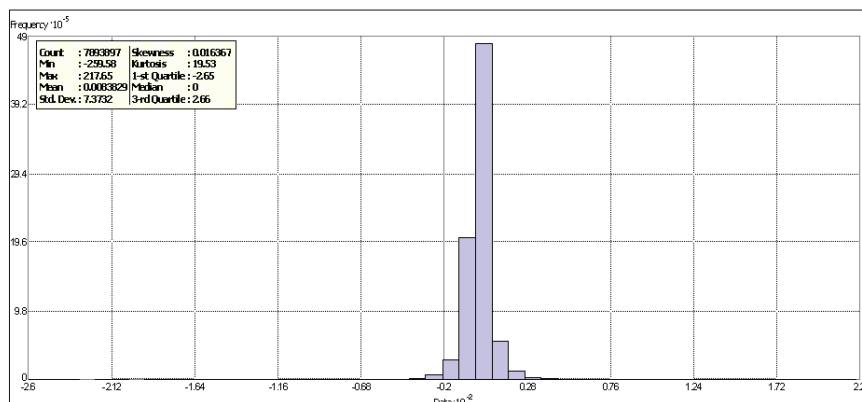


*Figure 16. Perspective view from the south of the 1/3 arc-second Midway Atoll DEM.  
1.5x vertical exaggeration.*



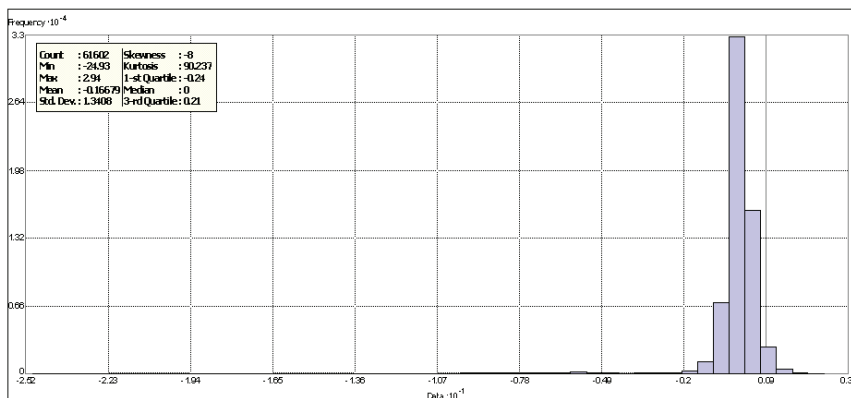
### 3.4.4 Comparison with source data files

To ensure grid accuracy, the Midway Atoll 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 multibeam surveys and the 3 arc-second Midway Atoll DEM is shown in Figure 17. The greatest differences occurred along the edges of the deep-water swaths where the data are noisiest.



**Figure 17.** Histogram of the differences between the NOAA National Marine Fisheries Service multibeam swath sonar surveys and the 3 arc-second Midway Atoll DEM.

A histogram of the differences between the SRTM topographic DEM gridded to 1/3 arc-second and the 1/3 arc-second Midway DEM is shown in Figure 18. Differences range from -25 meters to 3 meters, where negative values indicate that elevations of the SRTM data are higher than the DEM elevations. The greatest differences occurred along the harbor coastline where the SRTM data (2000) were clipped to the present coastline.



**Figure 18.** Histogram of the differences between SRTM data and the 1/3 arc-second Midway Atoll DEM.

#### 4. SUMMARY AND CONCLUSIONS

Two integrated bathymetric–topographic digital elevation models of Midway Atoll, with cell spacing of 3 arc-seconds and 1/3 arc-seconds, were developed for the Pacific Marine Environmental Laboratory (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*, *MB-System*, and *Quick Terrain Modeler* software.

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

- Conduct hydrographic surveys in shallow-water areas inside the atoll.
- Conduct bathymetric–topographic LiDAR surveys of the entire atoll.
- Conduct multibeam swath sonar surveys of the deep ocean surrounding the atoll.
- Digitize NOAA Raster Nautical Charts as Electronic Nautical Charts (ENCs).

#### 5. ACKNOWLEDGMENTS

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- Nautical Chart #19480 (RNC), 9th Edition, 2007. Gambia Shoal to Kure Atoll. Scale 1: 180,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #19481 (RNC), 11th Edition, 2005. Midway Islands. Scale 1: 32,500. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.
- Nautical Chart #19482 (RNC), 9th Edition, 2000. Midway Islands. Scale 1: 10,000. 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, Oregon, <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, 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/>