Digital Elevation Models for San Juan and Mayagüez, Puerto Rico: Procedures, Data Sources and Analysis

Prepared for the NOAA Pacific Marine Environmental Laboratory (PMEL), Center for Tsunami Inundation Mapping Efforts (TIME) by the NOAA National Geophysical Data Center (NGDC)
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1. INTRODUCTION

The National Geophysical Data Center (NGDC) has developed three bathymetric/topographic digital elevation grids of Puerto Rico for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Inundation Mapping Efforts (TIME). These nested elevation grids (grid boundaries shown in Fig. 1) will be used as input for the Method of Splitting Tsunami (MOST) Model (http://www.pmel.noaa.gov/pubs/PDF/tito1927/tito1927.pdf) developed by PMEL to simulate tsunami generation, propagation and inundation. An intermediate 9 arc-second bathymetric grid of the Caribbean previously developed by NGDC, will also be used as input to the MOST Model. This report provides a summary of the data sources and methodology used in developing a 3 arc-second grid covering the entire island of Puerto Rico and two 1/3 arc-second grids centered around Mayagüez and San Juan, Puerto Rico.

2. STUDY AREA

The study area covers the island of Puerto Rico, located in the Caribbean Sea, with special emphasis on the coastal communities of San Juan and Mayagüez. Puerto Rico covers 8,959 square kilometers with a population of almost 4 million people. The elevation grids that cover this region extend well offshore into deeper water for the purpose of tsunami modeling (Fig. 1a, b, c).

The island of Puerto Rico has three main physiographic regions: mountainous interior, coastal lowlands and a karst region. The mountainous interior covers 60% of the island with the highest peak, Cerro La Punta, reaching 1,338 meters. The coastal lowlands extend 13 to 19 km inward in the north and 3–13 km in the south. The karst region, is located in the north of the island.

The city of Mayagüez is located on the west-central coast of Puerto Rico, covering 197.6 sq km, with a population of 104,557 (2000 Census). The Rio Grande de Añasco river lies to the north and the Guanajibo River to the south of Mayagüez. Both rivers empty into the Caribbean Sea from the west coast of Puerto Rico.

San Juan, the capital of Puerto Rico, is located on the northeast coast and has one of the largest harbors in the Caribbean. San Juan covers 122 square kilometers with a population of 442,447 (2000 Census). The Bayamón River lies west of San Juan and empties into the Atlantic Ocean.

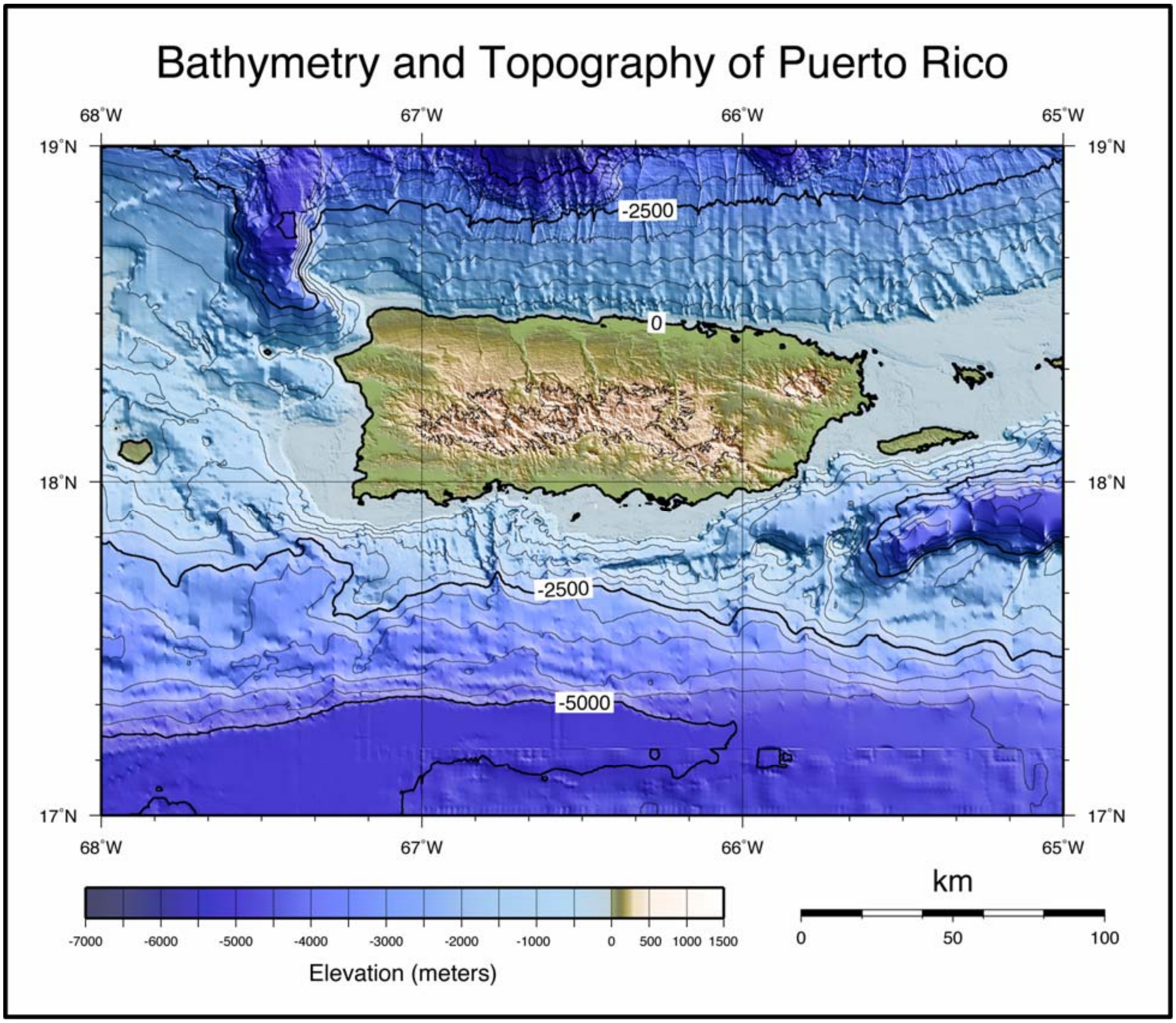

*Figure 1a. Shaded-relief image derived from the 3 arc-**second Puerto Rico elevation grid. Contour interval: 500 meters.***

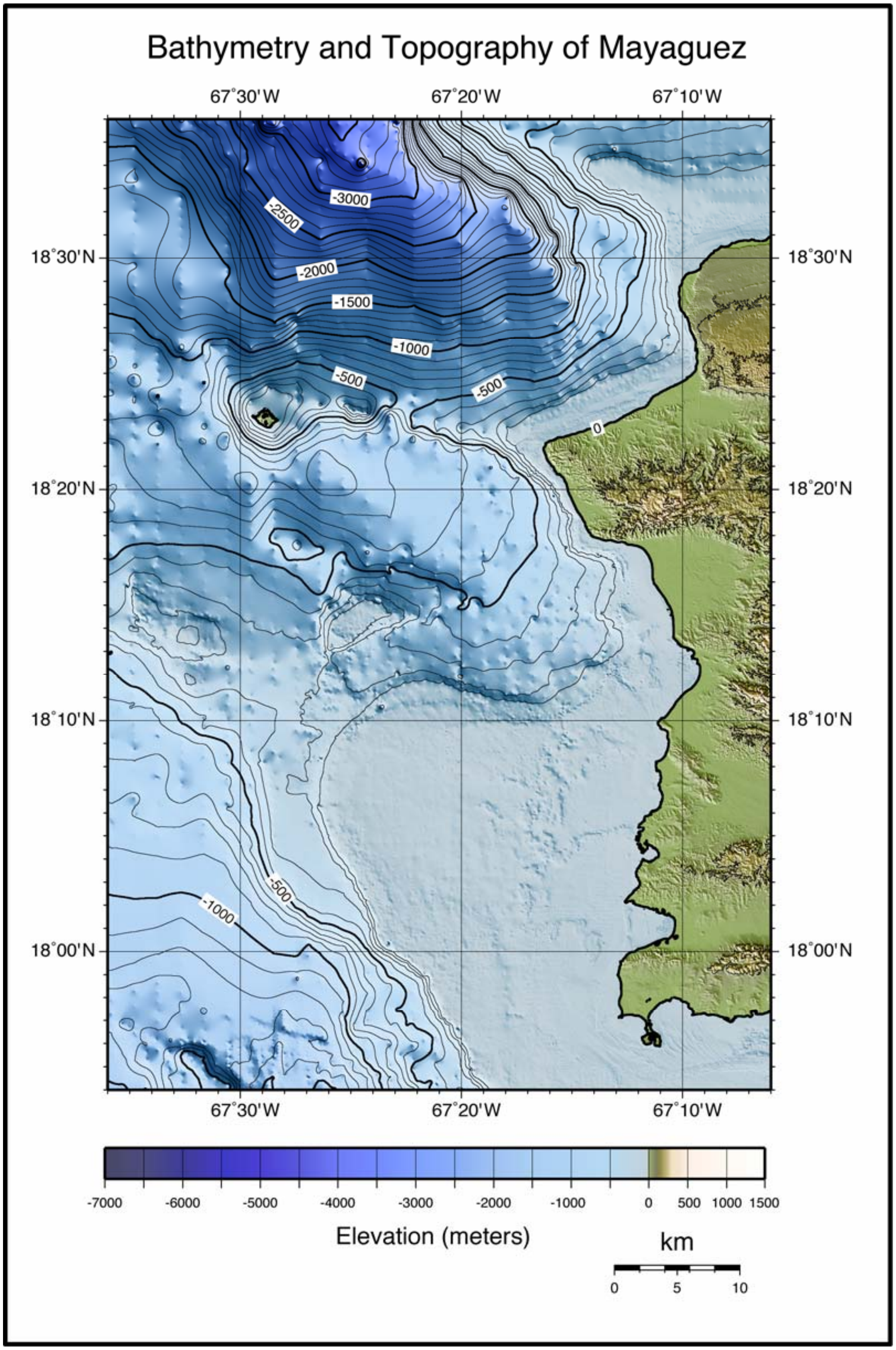

Figure 1b. Shaded-relief image derived from the 1/3 arc-second Mayagüez, Puerto Rico elevation grid. Contour interval: 100 meters.

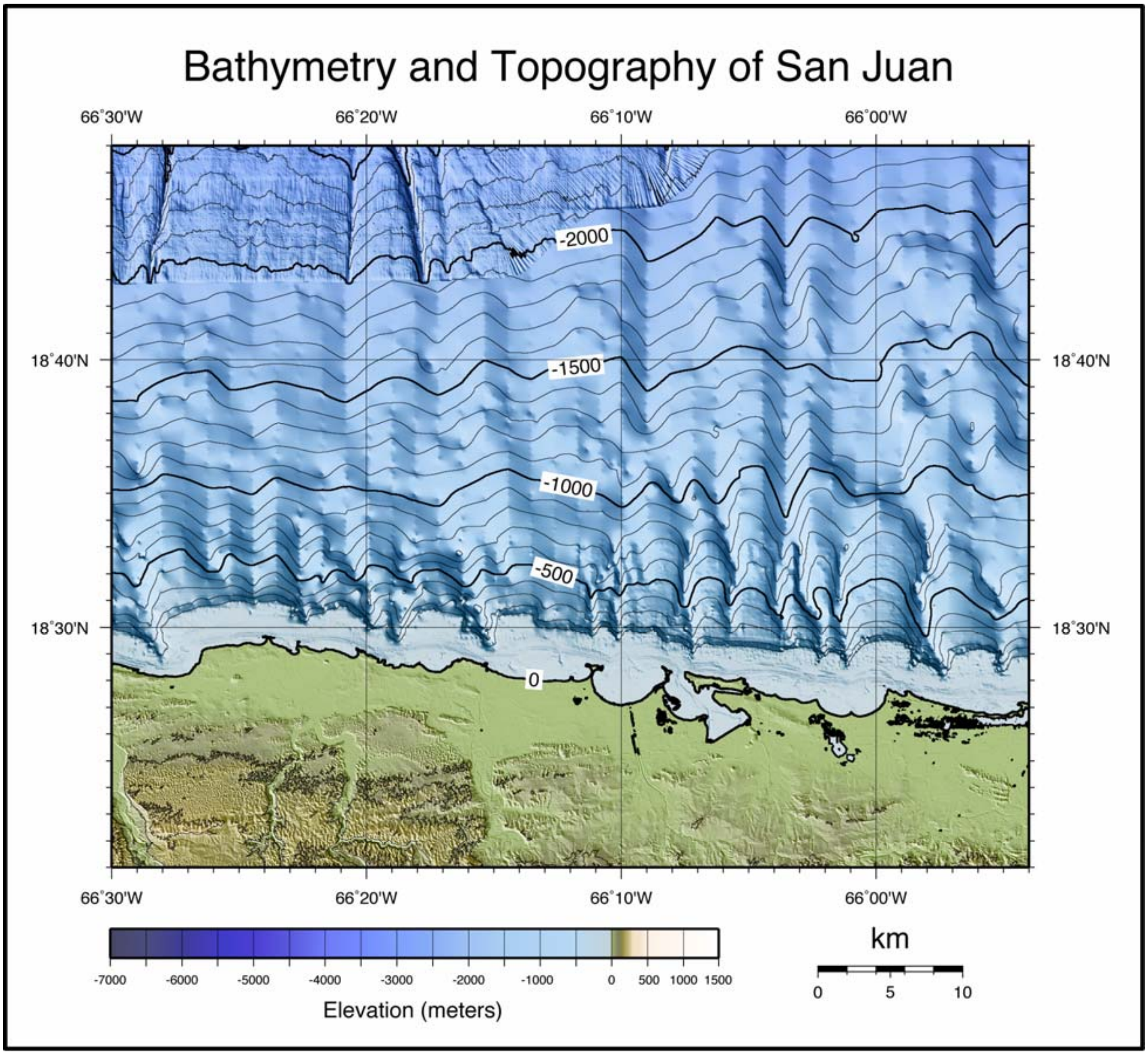

Figure 1c. Shaded-relief image derived from the 1/3 arc-second San Juan, Puerto Rico elevation grid. Contour interval: 100 meters.

3. METHODOLOGY

The three elevation grids were developed to meet PMEL required specifications (Table 1), based on input requirements for the MOST inundation model. The best available data were obtained by NGDC and used to produce the grids. Data processing, grid assembly, and quality assessment are described in the following subsections.

Table 1a: Specifications for the Puerto Rico grid.

Grid Area	Puerto Rico
Coverage Area	65° to 68° W; 17° to 19º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System (WGS84)
Vertical Datum	Mean High Water
Vertical Units	Meters
Grid Spacing	3 arc-seconds
Grid Format	ASCII raster grid

Table 1b: Specifications for the Mayagüez, Puerto Rico grid.

Grid Area	Mayagüez, Puerto Rico
Coverage Area	67.1º to 67.6º W; 17.9º to 18.6º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System (WGS84)
Vertical Datum	Mean High Water
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ASCII raster grid

Table 1c: Specifications for the San Juan, Puerto Rico grid.

Grid Area	San Juan, Puerto Rico
Coverage Area	65.9° to 66.5º W; 18.35º to 18.8º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System (WGS84)
Vertical Datum	Mean High Water
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ASCII raster grid

3.1 Data Sources and Processing

Shoreline, bathymetric, topographic, and orthophotographic data (Fig. 2) were obtained from numerous federal and state government agencies, universities and private companies, including the U.S. Department of Agriculture, the U.S. Geological Survey (USGS), the NOAA National Ocean Service (NOS), and the NOAA National Centers for Coastal Ocean Science (NCOOS). Datasets were converted into ESRI shape files and transformed to Mean High Water (MHW) vertical datum and WGS84 geographic coordinates. As no V-Datum (http://chartmaker.ncd.noaa.gov/csdl/vdatum.htm) model was available for Puerto Rico, vertical datum transformations were applied based on tidal model information supplied by PMEL (see Appendix A for details).

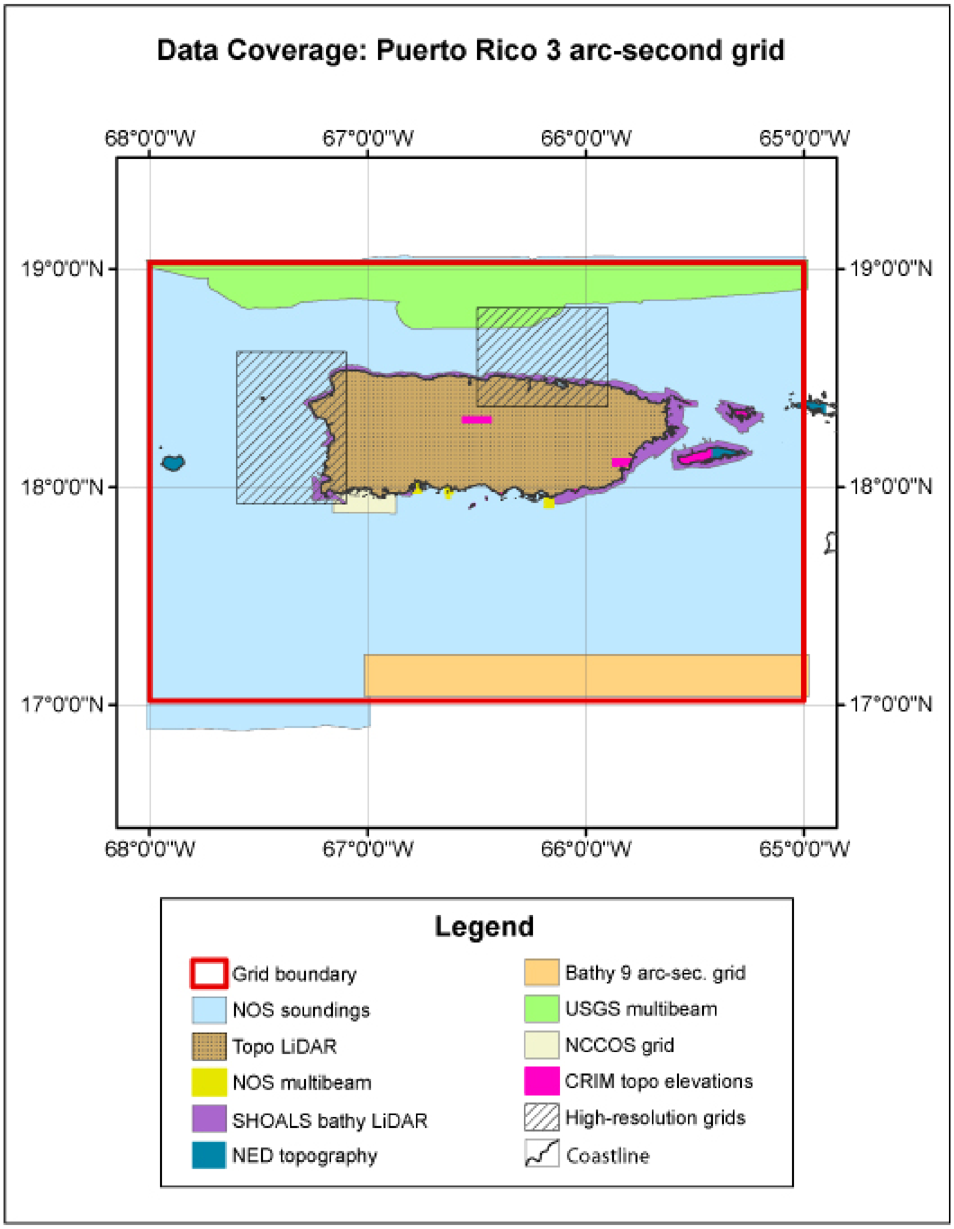

Figure 2a. Data sources used to compile the 3arc-second Puerto Rico grid. Areas covered by the high-resolution (1/3 arc-second) grids are identified by hachures.

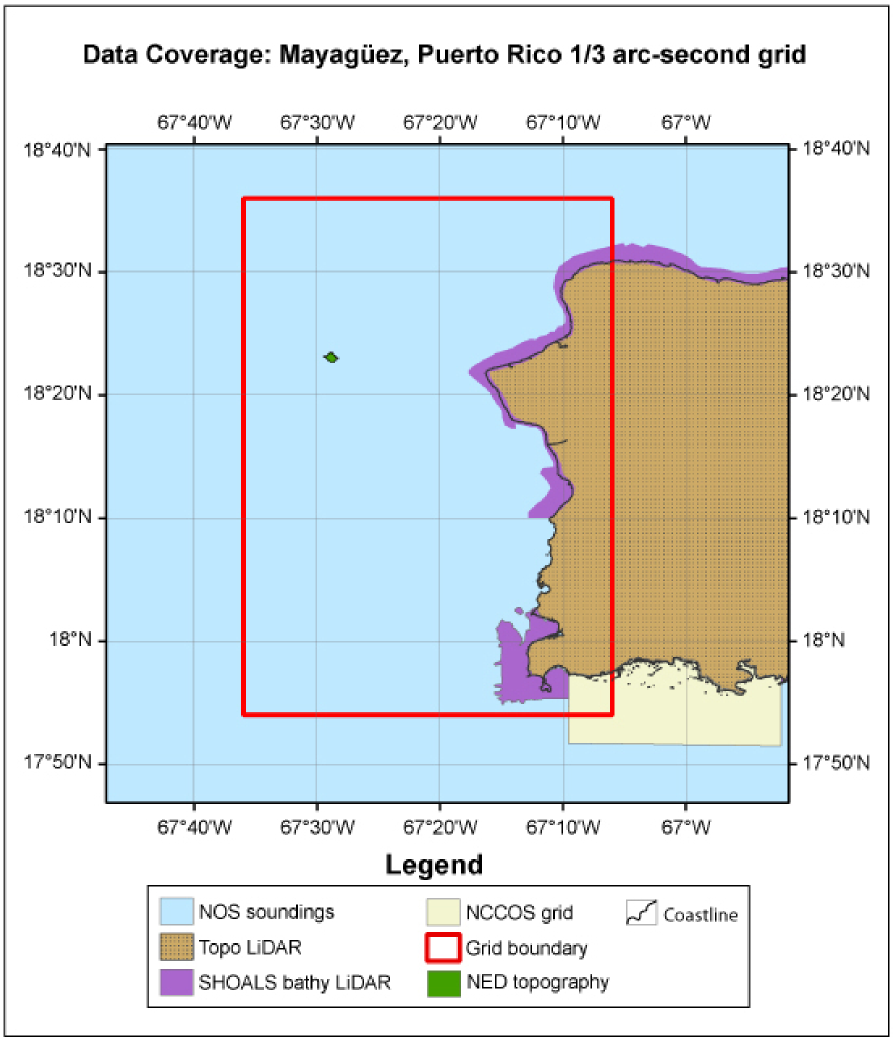

Figure 2b. Data sources used to compile the 1/3 arc-second Mayagüez, Puerto Rico grid.

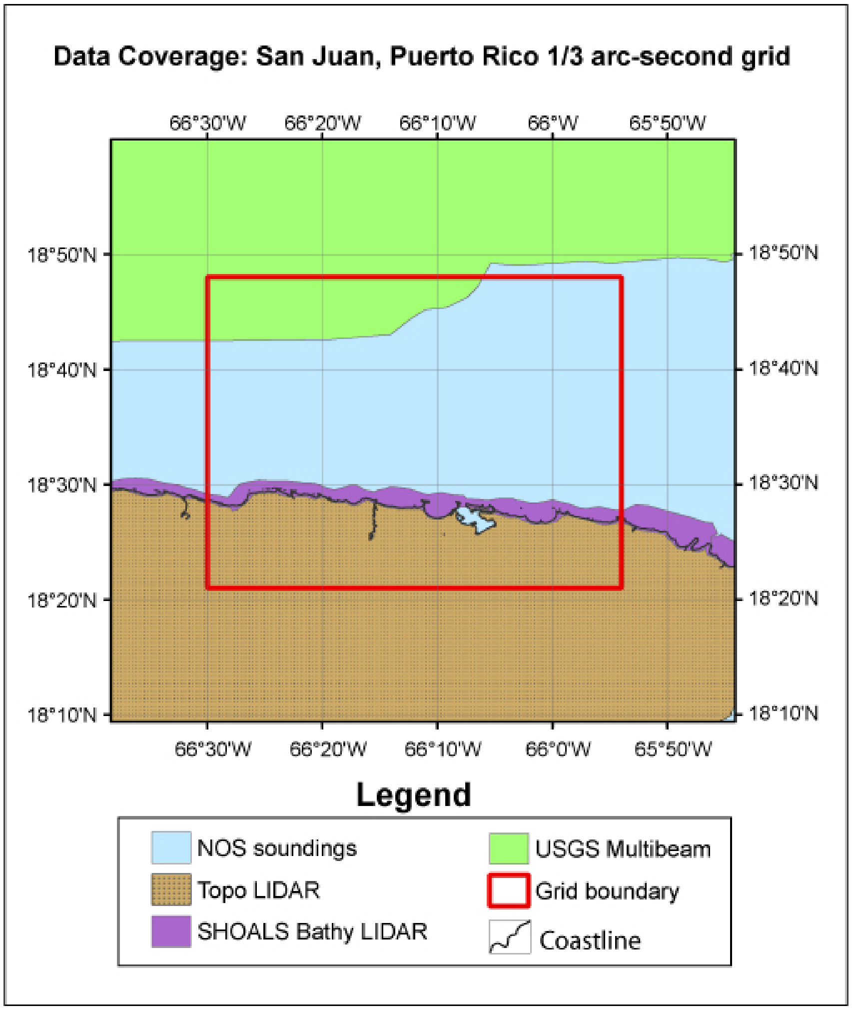

Figure 2c. Data sources used to compile the 1/3 arc-second San Juan, Puerto Rico grid.

3.1.1 Shoreline

Digital shorelines were obtained from the National Hydrographic Database, the National Geospatial-Intelligence Agency, the Puerto Rico Planning Board, the National Oceanic and Atmospheric Administration and Dr. Aurelio Mercado at the University of Puerto Rico. The differences between the coastlines are largely qualitative and are due mainly to mangrove swamps portrayed as either landward or seaward of the coastline. As areas of dense mangrove coverage are known to strongly dissipate tsunami energy, it is important to make the distinction as to where the coastline lies relative to these areas.

1) Digitized coastline of the main island of Puerto Rico obtained from the Puerto Rico Planning Board by Dewberry and Davis, Inc.

This coastline was digitized from 1995 aerial photos as part of the "Centro de Recaudación de Ingresos Municipales (CRIM), Land Information System Project" between 1996 and 1998. It was degraded from a scale of 1:2,000 to 1:5,000. Dewberry and Davis, Inc. received the coastline in multiple pieces by USGS quadrangle which were merged together and checked against orthometric photographs for accuracy.

2) Vectorized shoreline of Puerto Rico and the U.S. Virgin Islands derived from NOAA-NOS coastal survey maps and aerial photos developed from 1901 - 1995 source data.

This shoreline dataset represents a vector conversion of NOS shoreline (T-sheets) maps and CAD-based Standard Digital Data Exchange Format (SDDEF) data. It was created by the National Ocean Service, National Geodetic Survey as part of its ongoing mission to map the coastline of the United States. The NOAA NOS, Coastal Services Center developed the procedures used in this project and was responsible for project oversight.

3) NOAA, NOS, OCS extracted vector shoreline.

This coastline was extracted from nautical charts using software developed by the NOAA OCS Coast Survey Development Laboratory, Cartographic & Geospatial Technology Program. It is referenced to mean high water, NAD83 in non-projected geographic coordinates and based on charts with 1:10,000 to 1:80,000 scales.

Table 2: Coastline data sources used in gridding.

Source	Area	Description	URL
Puerto Rico Planning Board, Centro de Recaudación de Ingresos Municipales (CRIM), Land Information System Project	Main island	Digitized from aerial photos	http://www.crimpr.net/
NOAA, NOS Digitized coastline	Islands	Digitized NOAA, NOS shoreline maps	http://www.csc.noaa.gov/shoreline/data.html
NOAA, NOS, OCS Extracted Vector Shoreline	Mona Island	Extracted from NOAA nautical charts	http://nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm

After analysis of the available coastlines, the vector shoreline generated from orthometric photos by the Puerto Rico Planning Board obtained from Dewberry and Davis, Inc, was chosen for the main island. Surrounding islands were added from the NOAA, NOS, OCS Extracted Vector Shoreline and the NOAA, NOS Digitized Coastline using ESRI ArcEdit. This compiled coastline (Fig. 3) defines the mangrove-sea interface, encompassing mangrove areas around the island, except for the La Parguera area between 66.98º and 67.13º west (Fig.4).

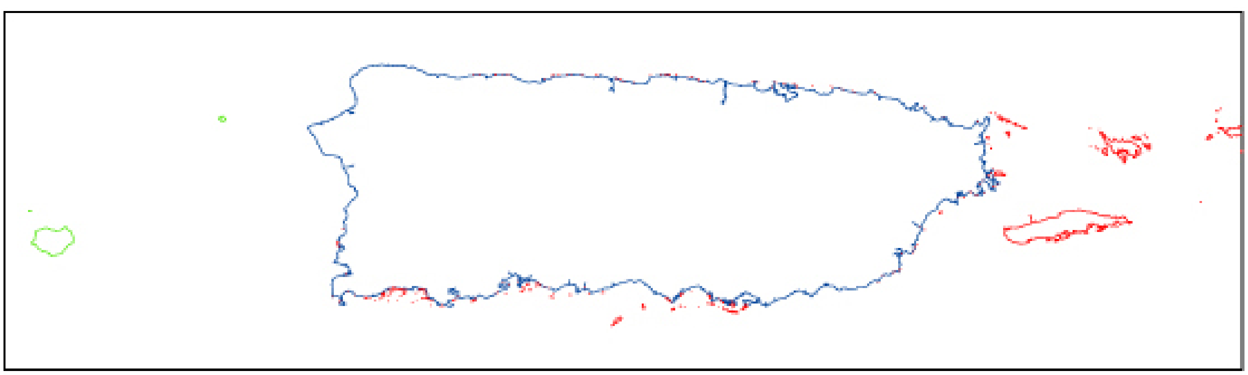

Figure 3: Coastline sources used in gridding, compiled from: 1) PRPB coastline (blue), 2) NOS Digitized coastline (red) and 3) NOAA, NOS, (OCS) Extracted Vector Shoreline (green).

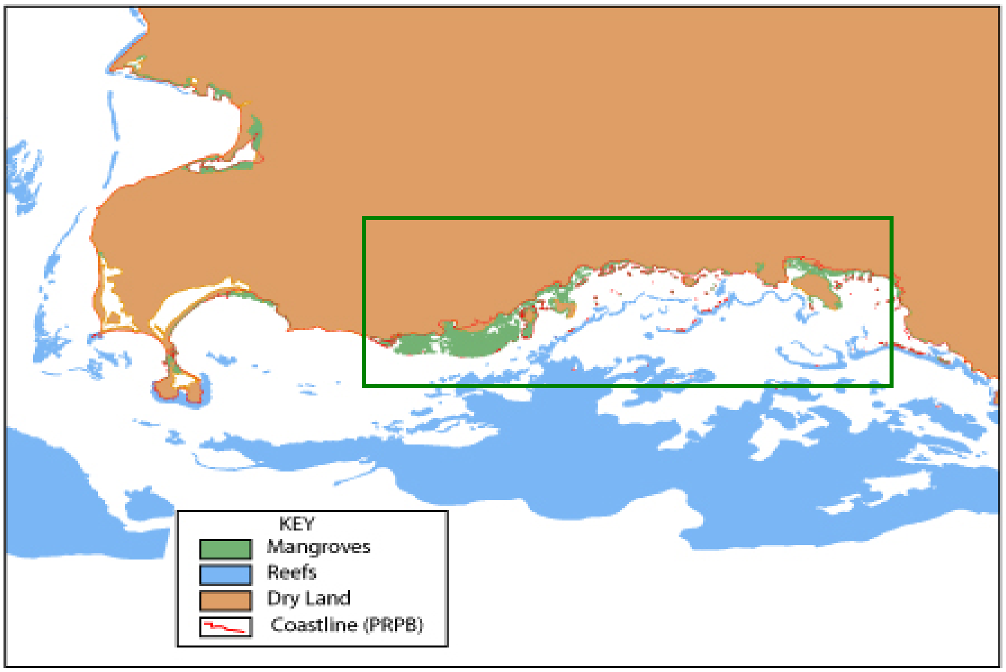

Figure 4: Mangrove and reef coverage around the south west shore of Puerto Rico. The green box represents the Parguera mangrove area which is not encompassed by the PRPB coastline. This area is characterized by an extensive development of coral reefs, seagrass beds, and mangrove forests. (Graphic created from ESRI shape files contained on NOAA, NOS, NCCOS, Science Biogeography Program CD-ROM: Benthic Habitats of Puerto Rico and the U.S. Virgin Islands. Silver Spring, MD: National Oceanic and Atmospheric Administration, 2001.)

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the grids included 96 NOS hydrographic surveys, 3 NOS multibeam surveys, US Army Corps of Engineers (USACE) SHOALS LiDAR data, a 5 meter resolution bathymetric grid derived from NOS hydrographic survey data and scuba depths off the southwest coast of the island of Puerto Rico, deep water multibeam data collected by the USGS north of the island and a 9 arc-second grid compiled from Smith and Sandwell predicted-topography data and General Bathymetric Chart of the Oceans (GEBCO) bathymetric contours for the southeast portion of the 3 arc-second grid (Fig. 2a).

1) NOS hydrographic survey data

A total of 96 NOS hydrographic surveys were used in the grid compilations. The survey data were originally vertically referenced to either mean lower low water or mean low water and horizontally referenced to Old Puerto Rico datum, Puerto Rico datum and NAD27. Data point spacing for the surveys ranges from about 10 meters up to 3 kilometers in deep water.

Table 3a. NOS hydrographic survey data included in the compilation of the 3 arc-second Puerto Rico grid.

NOS Survey ID	Year of Survey	Survey Scale	Original Vertical Datum	Original Horizontal Datum
H02468	1904	5,000	MLW	Early PR Island Datums
H02469	1900	10,000	MLW	Early PR Island Datums
H02472	1900	5,000	MLW	Early PR Island Datums
H02490	1909	40,000	MLW	Early PR Island Datums
H02491	1909	10,000	MLW	Early PR Island Datums
H02492	1905	10,000	MLW	Early PR Island Datums
H02536	1901	20,000	MLW	Early PR Island Datums
H02537	1901	20,000	MLW	Early PR Island Datums

H02555	1902	10,000	MLW	Early PR Island Datums
H02582	1905	20,000	MLW	Early PR Island Datums
H02584	1902	20,000	MLW	Early PR Island Datums
H02585	1902	10,000	MLW	Early PR Island Datums
H02633	1903	20,000	MLW	Early PR Island Datums
H02634	1903	20,000	MLW	Early PR Island Datums
H02640	1903	40,000	MLW	Early PR Island Datums
H02672	1904	40,000	MLW	Early PR Island Datums
H02673	1904	20,000	MLW	Early PR Island Datums
H02674	1904	20,000	MLW	Early PR Island Datums
H02676	1909	60,000	MLW	Early PR Island Datums
H02677	1904	20,000	MLW	Early PR Island Datums
H02678	1904	20,000	MLW	Early PR Island Datums
H02686	1904	10,000	MLW	Early PR Island Datums
H02690	1904	10,000	MLW	Early PR Island Datums
H02803	1906	40,000	MLW	Early PR Island Datums
H02804	1906	20,000	MLW	Early PR Island Datums
H02871	1907	20,000	MLW	Early PR Island Datums
H02876	1909	20,000	MLW	Early PR Island Datums
H02877	1909	20,000	MLW	Early PR Island Datums
H02883	1907	20,000	MLW	Early PR Island Datums
H02934	1908	20,000	MLW	Early PR Island Datums
H02935	1908	20,000	MLW	Early PR Island Datums
H02936	1908	20,000	MLW	Early PR Island Datums
H02937	1908	20,000	MLW	Early PR Island Datums
H02938	1908	20,000	MLW	Early PR Island Datums
H03004	1909	20,000	MLW	Early PR Island Datums
H04205	1921	20,000	MLW	Early PR Island Datums
H04725	1927	10,000	MLW	Early PR Island Datums
H04742	1927	10,000	MLW	Early PR Island Datums
H06556	1940	10,000	MLW	Early PR Island Datums
H08637	1962	10,000	MLW	Puerto Rico Datum
H08638	1962	10,000	MLW	Puerto Rico Datum
H08639	1969	5,000	MLW	Early PR Island Datums
H08780	1967	20,000	MLW	Early PR Island Datums
H08811	1964	10,000	MLW	Puerto Rico Datum
H08812	1967	20,000	MLW	Puerto Rico Datum
H08813	1964	5,000	MLW	Puerto Rico Datum
H08814	1964/65	10,000	MLW	Early PR Island Datums
H08848	1965	5,000	MLW	Puerto Rico Datum
H08849	1965	5,000	MLW	Puerto Rico Datum
H08862	1965	5,000	MLW	Early PR Island Datums
H08880	1966	20,000	MLW	Early PR Island Datums
H08985	1968/69	10,000	MLW	Early PR Island Datums
H08988	1968	10,000	MLW	Puerto Rico Datum
H09031	1969	5,000	MLW	Puerto Rico Datum
H09032	1969	5,000	MLW	Early PR Island Datums
H09034	1969	20,000	MLW	Early PR Island Datums
H09110	1970	5,000	MLW	Early PR Island Datums
H09135	1970/71	10,000	MLW	Early PR Island Datums
H09186	1971	10,000	MLW	Early PR Island Datums
H09190	1971	10,000	MLW	Early PR Island Datums
H09264	1972	10,000	MLW	Early PR Island Datums
H09265	1972	10,000	MLW	Early PR Island Datums
H09266	1972	20,000	MLW	Early PR Island Datums
H09267	1972/75	10,000	MLW	Early PR Island Datums
H09270	1967	40,000	MLW	NAD27
H09278	1972	100,000	MLW	Early PR Island Datums
H09463	1975	125,000	MLW	Early PR Island Datums
H09485	1975	10,000	MLW	Early PR Island Datums
H09486	1975	20,000	MLW	Early PR Island Datums
H09490	1975	5,000	MLW	Early PR Island Datums
H09491	1975	5,000	MLW	Early PR Island Datums
H09517	1975	20,000	MLW	Early PR Island Datums

H09587	1976	125,000	MLW	Early PR Island Datums
H09595	1976	100,000	MLW	Early PR Island Datums
H09596	1976	10,000	MLW	Early PR Island Datums
H09597	1976	10,000	MLW	Early PR Island Datums
H09601	1976	10,000	MLW	Early PR Island Datums
H09602	1976	10,000	MLW	Early PR Island Datums
H09603	1976	10,000	MLW	Early PR Island Datums
H09604	1976	20,000	MLW	Early PR Island Datums
H09605	1976	20,000	MLW	Early PR Island Datums
H09607	1976	10,000	MLW	Early PR Island Datums
H09608	1976	10,000	MLW	Early PR Island Datums
H09609	1976	5,000	MLW	Early PR Island Datums
H09610	1976	20,000	MLW	Early PR Island Datums
H09616	1976	10,000	MLW	Early PR Island Datums
H09617	1976	10,000	MLW	Early PR Island Datums
H09618	1976	20,000	MLW	Early PR Island Datums
H09992	1982	80,000	MLW	Early PR Island Datums
H09993	1982	80,000	MLW	Early PR Island Datums
H10073	1983	10,000	MLLW	Puerto Rico Datum
H10074	1983	80,000	MLLW	Puerto Rico Datum
H10076	1983	80,000	MLLW	Puerto Rico Datum
H10077	1983	10,000	MLLW	Puerto Rico Datum
H10078	1983	20,000	MLLW	NAD27
H10083	1983	80,000	MLLW	Puerto Rico Datum

Table 3b. NOS hydrographic survey data included in the compilation of the 1/3 arc-second Mayagüez, Puerto Rico grid.

NOS Survey ID	Year of Survey	Survey Scale	Original Vertical Datum	Original Horizontal Datum
H02536	1901	20,000	MLW	Early PR Island Datums
H02537	1901	20,000	MLW	Early PR Island Datums
H02555	1902	10,000	MLW	Early PR Island Datums
H02633	1903	20,000	MLW	Early PR Island Datums
H02640	1903	40,000	MLW	Early PR Island Datums
H02676	1909	60,000	MLW	Early PR Island Datums
H02678	1904	20,000	MLW	Early PR Island Datums
H02686	1904	10,000	MLW	Early PR Island Datums
H02690	1904	10,000	MLW	Early PR Island Datums
H02937	1908	20,000	MLW	Early PR Island Datums
H02938	1908	20,000	MLW	Early PR Island Datums
H08985	1968/69	10,000	MLW	Early PR Island Datums
H08988	1968	10,000	MLW	Puerto Rico Datum
H09463	1975	125,000	MLW	Early PR Island Datums

Table 3c. NOS hydrographic survey data included in the compilation of the 1/3 arc-second San Juan, Puerto Rico grid.

NOS Survey ID	Year of Survey	Survey Scale	Original Vertical Datum	Original Horizontal Datum
H02677	1904	20,000	MLW	Early PR Island Datums
H02876	1909	20,000	MLW	Early PR Island Datums
H02883	1907	20,000	MLW	Early PR Island Datums
H02934	1908	20,000	MLW	Early PR Island Datums
H02935	1908	20,000	MLW	Early PR Island Datums
H04205	1921	20,000	MLW	Early PR Island Datums
H06556	1940	10,000	MLW	Early PR Island Datums
H08848	1965	5,000	MLW	Puerto Rico Datum
H08849	1965	5,000	MLW	Puerto Rico Datum
H10073	1983	10,000	MLLW	Puerto Rico Datum
H10076	1983	80,000	MLLW	Puerto Rico Datum
H10077	1983	10,000	MLLW	Puerto Rico Datum
H10078	1983	20,000	MLLW	NAD27
H10083	1983	80,000	MLLW	Puerto Rico Datum

2) NOS shallow water multibeam

Three shallow-water multibeam surveys along the southern coast of the island of Puerto Rico were conducted by NOS in 2001, and were included in the 3 arc-second Puerto Rico grid. The multibeam data were originally vertically referenced to mean lower low water and horizontally referenced to NAD83.

Table 4. NOS shallow water multibeam data included in the compilation of the 3 arc-second Puerto Rico grid.

NOS Survey ID	Year of Survey	Survey Scale	Original Vertical Datum	Original Horizontal Datum
H11033	2001	5,000	MLLW	NAD83
H11034	2001	5,000	MLLW	NAD83
H11036	2001	5,000	MLLW	NAD83

3) NOAA NOS National Centers for Coastal Ocean Science (NCCOS) gridded data

NOAA’s National Ocean Service (NOS), National Centers for Coastal Ocean Science (NCCOS), Center for Coastal Ocean Science (CCOS), Biogeography Team provided a 5 meter bathymetric grid generated from NOS hydrographic survey data and depths collected by Biogeography Team SCUBA divers. SCUBA depths were used to fill gaps inshore of the NOS survey data. The grid was generated using a triangulated interpolated network (TIN) with ESRI ArcView® 3D Analyst software. All reef crests were given a depth of 0.3 meters. Model validation using an independent set of bathymetric data revealed an average error of less than 0.3 meters. TIN models were then converted into raster maps (spatial resolution = 5 x 5 m). After conversion of this grid to MHW and WGS84, depth values were compared to NOS hydrographic survey and SHOALS LiDAR data in the same area and were within ~ 0.5 meters in most areas.

Table 5. NOS hydrographic survey data included in the compilation of the NCCOS bathymetric grid.

NOS Survey ID	Year of Survey	Survey Scale	Original Vertical Datum	Original Horizontal Datum
H02676	1909	60,000	MLW	Early PR Island Datums
H08984	1968	10,000	MLW	Early PR Island Datums
H08985	1968/69	10,000	MLW	Early PR Island Datums
H08986	1968	10,000	MLW	Early PR Island Datums
H08987	1968	10,000	MLW	Early PR Island Datums
H08988	1968	10,000	MLW	Puerto Rico Datum
H08989	1968	20,000	MLW	Early PR Island Datums
H09029	1969	100,000	MLW	Early PR Island Datums
H09033	1969	20,000	MLW	Early PR Island Datums
H09119	1970	10,000	MLW	Early PR Island Datums
H09120	1970	5,000	MLW	Early PR Island Datums
H09183	1971	10,000	MLW	Early PR Island Datums

4) SHOALS LiDAR data

Bathymetric SHOALS LiDAR data were obtained from Dr. Aurelio Mercado-Irizarry at the University of Puerto Rico. The data were originally collected by the USACE from the shoreline to 1 km offshore at 5 meter spacing. The data were positioned using post-processed kinematic GPS and National Geodetic Survey monumentation.

5) **USGS multibeam data**

A 2002 USGS multibeam survey conducted by the NOAA ship Ron Brown over the Puerto Rico Trench was available from the NGDC multibeam Arc IMS interactive map (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html). The data were collected with a SeaBeam 2112 hull-mounted multibeam sonar system and incorporated into the 3 arc-second Puerto Rico and 1/3 arc-second San Juan grids.

6) **Intermediate 9 arc-second grid**

No detailed datasets were available for the southeast corner of the 3 arc-second Puerto Rico grid. Thus, depth values were extracted from the intermediate 9 arc-second grid, which was compiled from Smith and Sandwell predicted topography and GEBCO contours.

Table 6. Bathymetric data sources used in gridding.

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum	Original Vertical Datum	URL
NOS	1900 to 1983	Hydrographic survey data	Ranges from 10 meters to 3 kilometers (Varies with scale of survey, depth, traffic and probability of obstructions)	Early Puerto Rico Island Datum, Puerto Rico Datum, NAD27	MLW, MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NOS	2001	Shallow-water multibeam	100%	NAD83	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NCCOS (Ada Otter)	2004	Grid of NOS hydrographic surveys and scuba depths	10 meter	WGS84	MLLW	http://coastalscience.noaa.gov/
University of Puerto Rico (Dr. Aurelio Mercado)		USACE SHOALS bathymetric LiDAR data	5 meter posting	NAD83 US Virgin Islands, Puerto Rico State Plane	MLLW	http://shoals.sam.usace.army.mil/
USGS (Uri ten Brink)	2002, 2003	Deep-water multibeam survey data	100%	UTM, Zone 19	Ellipsoid	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NGDC	2005	Grid of Smith and Sandwell Predicted Topography combined with GEBCO contours.	9 arc-second	WGS84	MSL	http://topex.ucsd.edu/marine_topo/ and http://www.bodc.ac.uk/projects/international/gebco/gebco_digital_atlas/gda_development/

3.1.3 Topography

Topographic datasets used in the elevation grids consist of LiDAR collected at 15 meter postings by the USACE obtained from the USDA, National Resources Conservation Service for the main island, USGS National Elevation Dataset (NED) 1 arc-second gridded data for Mona, Desecheo and the eastern half of Vieques Islands and 10 meter gridded topography compiled from photometrically derived elevations by the Puerto Rico Office of Management and Budget for small coastal areas of the islands plus Culebra and the western half of Vieques.

1) USACE topographic LiDAR data.

These topographic LiDAR data were collected by 3001, Inc. for the USACE in 2004 as part of an effort to develop digital orthophoto imagery for administration of the US Department of Agriculture GIS Orthophotography update program. These data cover nearly the entire island of Puerto Rico at 15 meter postings. It was processed to bare earth and referenced to the ellipsoid, with a vertical accuracy of 30 cm RMSE.

2) USGS National Elevation Dataset (NED)

The USGS National Elevation Dataset (NED) 1 second DEM data were used for the islands of Desecheo, Mona, St. Thomas, and the east half of Vieques. The bare-earth elevations obtained were referenced to NAD83 and NAVD88 and have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov/). The dataset was derived from USGS quad maps and aerial photos based on surveys conducted in the 1970s and 1980s.

3) Puerto Rico Office of Management and Budget photometrically-derived elevations

A Digital Elevation Model (DEM) representation of altitudes over USGS Quadrangles in Puerto Rico, with a fixed spatial cell size of 10 by 10 meters, was obtained from the Puerto Rico Office of Mangement and Budget (PROMB). The Centro de Recaudación de Ingresos Municipales (CRIM) Basemap Project provided the original linework, elevation points and breaklines to the PROMB. The PROMB derived the DEMs from TINs previously generated from elevation mass points and 3-D features such as hydrography, and breaklines at a scale of 1:2,000. This dataset was used for Culebra Island, the western half of Vieques, and to fill gaps within the USACE LiDAR data on the island of Puerto Rico and small, near-coastal islands. The CRIM data meet National Mapping Standards for scales 1:2,000.

Table 7. Topographic data sources used in gridding.

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum	Original Vertical Datum	URL for more info
USDA/USACE	2003	Topographic LiDAR	15 meter posting	UTM, Zone 19	Ellipsoid	http://www.nrcs.usda.gov/programs/
USGS	various	National Elevation Dataset (NED)	1 arc-second	WGS84	NAVD88 (MSL)	http://seamless.usgs.gov/
Puerto Rico Office of Management and Budget, Centro de Recaudación de Ingresos Municipales (CRIM) Basemap Project	1996-1998	Photometrically derived elevations	10 meter gird	NAD83 HARN US Virgin Islands, Puerto Rico State Plane	NAVD88 (MSL)	http://www.crimpr.net/

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Generating a consistent solid-earth surface model is the ultimate goal of this project. Acquired input data to the model were originally referenced to a number of different vertical datums. As the three grids developed for Puerto Rico are primarily designed for tsunami inundation modeling, a common Mean High Water (MHW) vertical reference frame was chosen. Transformation of the various datasets to this reference frame required careful determination of the offsets between the original vertical datums and the MHW datum for Puerto Rico. See Appendix A for full details on establishing the relationships and transformational equations between these datums.

3.2.2 Horizontal datum transformations.

Datasets used to compile the grids were originally horizontally referenced to NAD83, NAD27, Puerto Rico and Virgin Islands State Plane, Early Puerto Rico Island Datum, Puerto Rico Datum, UTM Zone 19 and WGS84. NOS survey data was converted to WGS84 using GEODAS (NADCON); the relationships and transformational equations between these horizontal datums are well established. All other data, except that referenced to NAD83—the difference between NAD83 and WGS84 is negligible—were converted to a horizontal datum of WGS84 using FME software (http://www.safe.com). FME is an integrated collection of spatial extract, transform, and load tools for data transformation and data translation.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets.

After horizontal and vertical transformations were applied, ESRI shape files were generated for each data file, and value consistency between datasets was checked in ESRI ArcMap. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. Problems included:

- National Elevation Data (NED) obtained for the islands of Mona, Monito and Desecheo were offset horizontally (up to 100 meters) relative to the digital coastline and surrounding NOS survey data. The NED data were manually shifted to fit the digital coastline.
- Vertical units for the ArcGIS raster grid of NOS survey data/NCCOS dive soundings were determined to be feet instead of meters. The grid was converted to meters.
- A few bad soundings were discovered in the NOS survey data (positive values rather than the proper negative ones) and were corrected.
- Several bad sonar pings were identified in the USGS multibeam data north of the island of Puerto Rico. These pings were excised from the data prior to gridding, using the MB-System tool 'mbedit'.
- Rectangular gaps within the USACE LiDAR data were identified at 18º17′ N, 66º30′ W and 18º05′ N, 65º50′ W. CRIM photometric data were used to fill these gaps.
- The margins of each CRIM photometric data tile were filled with "zero" values that had to removed.
- All of the topographic datasets (LiDAR, NED and CRIM photometric) contained anomalous values over water. In each case, these datasets were clipped to the combined digital coastline so as to preserve negative elevation values in the coastal interior areas.
- A 2005 multibeam survey of the Muertos Trough south of the island of Puerto Rico was conducted jointly between the USGS and various Spanish, Puerto Rican, Dominican Republic and British Virgin Islands universities and institutions aboard the Spanish research vessel Hespérides (Carbo, et al., 2005). This data was originally referenced to the Ellipsoid and UTM Zone 19. After adjusting the values to the geoid and then to MHW (see Appendix A), the resulting depths were between 10 and 40 meters shallower than multibeam depths from the 2004 USGS Puerto Rico Trench multibeam data. Because of this depth value discrepancy, the data were not used in the compilation of the grids. The NOAA ship Ron Brown is currently conducting multibeam surveys in the same area, which will result in an independent check of depth values in areas where the surveys overlap. After the vertical reference issue is resolved, this Muertos Trough multibeam data could be added to the 3 arc-second Puerto Rico and 1/3 arc-second Mayagüez grids.

The quality-assessed ESRI shape files were subsequently converted to xyz files in preparation for gridding.

3.3.2 Smoothing of sparse deep-water NOS soundings.

In deep water, the NOS survey data had point spacings of up to ~3 kilometers. In order to reduce the effect of artifacts in the form of lines of "pimples" in the grid due to this low resolution dataset, a surface was generated from these data using ESRI ArcGIS. The surface was then sub-sampled to 10 arc-seconds and exported as an xyz file. The original soundings were checked against the processed values to ensure sounding value accuracy. NOS hydrographic survey data in each high-resolution grid were surfaced to 1 arc-second.

3.3.3 Gridding the data with MB-System.

All processed xyz files were gridded using MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/). MB-System is an NSF-funded share-ware software application specifically designed to manipulate submarine multibeam sonar data, though it can utilize a wide variety of diverse datasets, including generic xyz data. The MB-System tool 'mbgrid' was used to create each grid—a modeled surface draping the point data—of weighted sounding and elevation point data. The data hierarchy used in the 'mbgrid' gridding algorithm as relative gridding weights is listed in Table 8. Greatest weight was given to the Puerto Rico coastline dataset to preserve the submarine–subaerial transition zone. Least weight was given to values extracted from the Intermediate 9 arc-second grid, which was used in the 3 arc-second Puerto Rico grid where no other data existed.

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

Dataset	Relative Gridding Weight
Digitized coastline	500
USDA/USACE topographic LiDAR	50
PROMB (CRIM) photometrically-derived topography	10
SHOALS bathymetric LiDAR	10
Multibeam bathymetry	10
USGS NED topography	1
NOS hydrographic survey data	1
NCCOS bathymetric grid	1
Intermediate 9 arc-second grid values	0.1

3.4 Quality Assessment of the Grids.

The 3 arc-second Puerto Rico and 1/3 arc-second San Juan grids were compared with the San Juan Bench Mark (Appendix A) to check for accuracy. Values extracted from each of these grids at the location of the benchmark were 0.76 and 0.13 meters, respectively: actual value of the benchmark is 1.169 meters above MHW. The various techniques that can be used to create a representative surface over the individual elevation points result in grid elevations for the benchmark site below that of its actual elevation. This is due to predominance of submarine values immediately offshore the benchmark; the benchmark lies at the southernmost spit of land jutting southward into the San Juan harbor (Fig. 5c).

3.4.1. Horizontal accuracy

The elevation grids have an estimated horizontal accuracy 5 meters for topographic features. Bathymetric features are resolved only to within a few hundred meters in most deep water areas; shallow, near-coastal regions have an accuracy approaching the subaerial topographic features. Positional accuracy is limited by transformation of multiple datasets from various datums, and by potentially large positional accuracy of pre-satellite navigated (GPS) hydrographic surveys.

3.4.2 Vertical accuracy

The grids have an estimated vertical accuracy of 0.1 to 1 meters for topographic areas and 0.1 meters to 5% of water depth for bathymetric areas. Topographic values are largely derived from USACE LiDAR surveys, which have an estimated vertical accuracy of 0.1 to 0.15 meters. The one arc-second NED data have a vertical accuracy of ~1 meter. Bathymetric values were derived from the wide range of input data sounding measurements from the early 20^{th} century to recent, GPS-navigated multibeam sonar surveys and SHOALS LiDAR near-shore surveys. Gridding interpolation to determine values between sparse, poorly-located NOS soundings degrades the vertical accuracy of elevations in deep-water.

3.4.3 Slope maps

A slope map was generated from each ArcGIS grid to inspect for artificial slopes along boundaries between datasets (Fig 5a, b, c). The grids were transformed to UTM Zone 19 coordinates (horizontal units in meters) in ArcGIS before derivation of the slope grids. Flat-lying slopes appear as white; dark shading denotes steep slopes. The shelf break is clearly identified in the slope maps at ~100 meters water depth. Analysis of the slope maps revealed suspect data points, which were corrected before re-gridding the data. Known limitations in the grids are also apparent from these maps. The boundary between 9 arc-second gridded data and NOS hydrographic survey data in the south east area of the 3 arc-second grid (Figure 5a) shows artifact slopes due to differences in data spacings and grid resolution. Large ship-track spacing in the generally north-south, east-west NOS hydrographic survey data is shown as anomalous striations along tracks in all three grids.

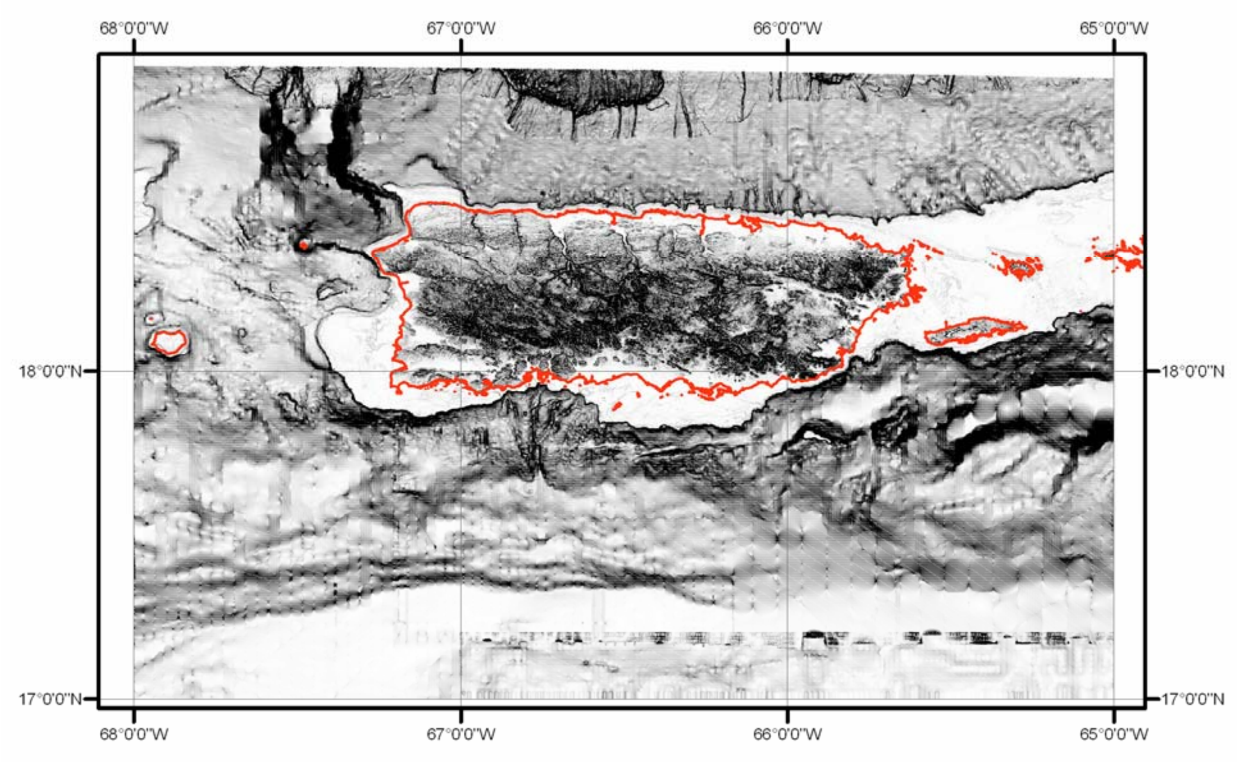

Figure5a. Slope map of the 3 arc-second Puerto Rico grid with coastline in red. Flat-lying slopes are white; dark shading denotes steep slopes.

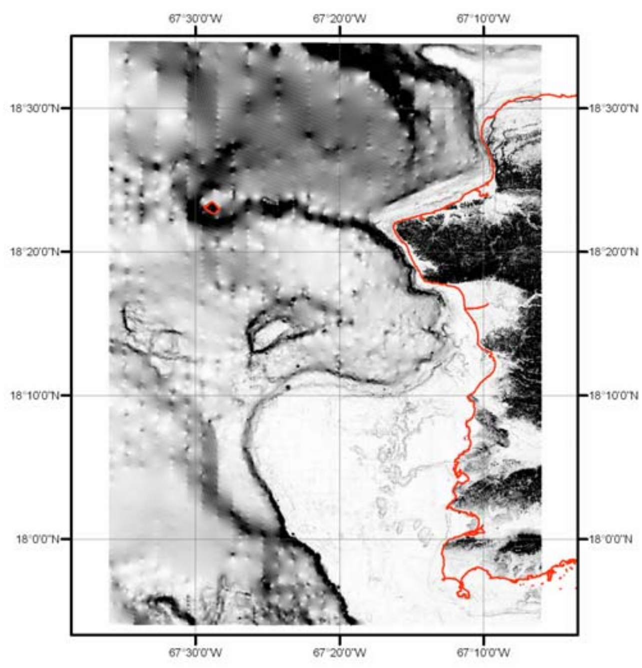

Figure 5b. Slope map of the 1/3 arc-second Mayagüez, Puerto Rico grid with coastline in red. Flat-lying slopes are white; dark shading denotes steep slopes.

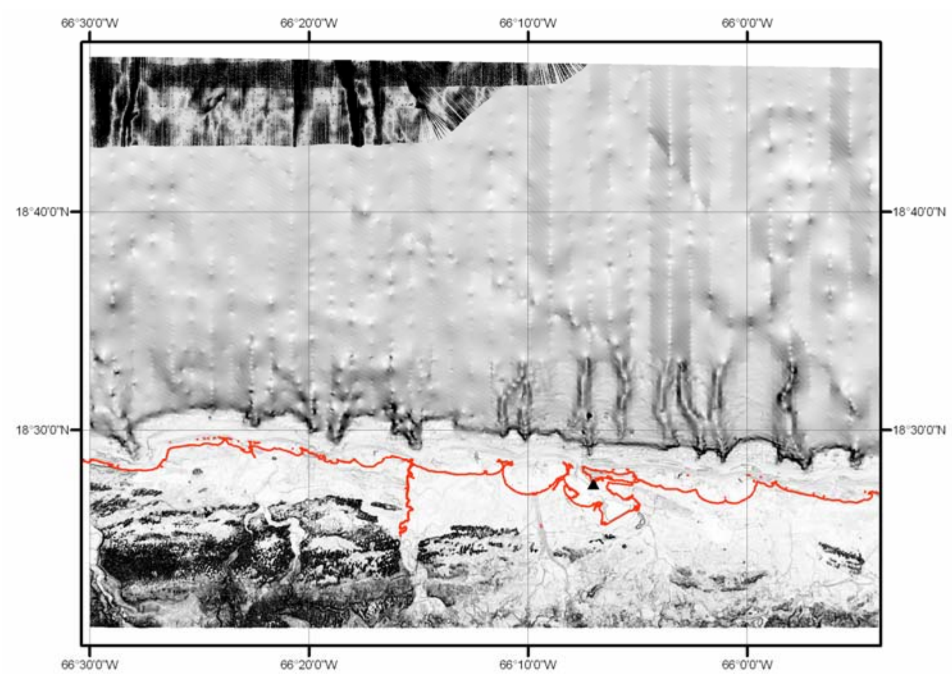

Figure 5c. Slope map of the 1/3 arc-second San Juan, Puerto Rico grid with coastline in red. Flat-lying slopes are white; dark shading denotes steep slopes. Triangle locates San Juan benchmark.

4. Summary and Conclusions

Three topographic/bathymetric digital elevation grids were built for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Inundation Mapping Efforts (TIME), a 3 arc-second grid covering the whole island of Puerto Rico and two 1/3 arc-second grids centered around Mayagüez and San Juan, Puerto Rico. The best available data from US federal and state agencies and the University of Puerto Rico were obtained for grid compilation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT and MB-System software.

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

- New bathymetric LiDAR data being collected along the west and southwest shores of Puerto Rico in 2006 by the NOAA Office of Coast Survey should be added to the DEMs when available.

- New multibeam data being collected by the NOAA ship, Nancy Foster along the west and southwest shores of Puerto Rico at time of writing for the NOAA Center for Coastal Monitoring and Assessment, Biogeography Program should be added to the DEMs when available.

- Include 2005 multibeam survey of Muertos Trough (Carbó et al, 2005) after vertical reference issue is resolved (See Section 3.3.1).

5. Acknowledgments

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http://138.23.217.17/jwilbur/student_files/Spatial%20Reference%20Seminar/dzilkoski.ppt

APPENDIX A. VERTICAL DATUM TRANSFORMATION DESCRIPTION

Tidal datums are defined by ocean coastal water levels at particular stages of the tidal cycle. Given that ocean water levels are strongly influenced by gravity, tidal datums relate closely to gravitationally defined geoidal datums. Tidal datums are also the most traditional of vertical datums, with elevations most frequently referenced to Mean Sea Level (MSL) and hydrographic depths referenced to Mean Lower Low Water (MLLW). Referencing depths to MLLW provides a minimum value estimate of depth to accommodate a given ship draft, thereby maximizing navigational safety. Similarly, air gap, the clearance between the water surface and an overlying structure such as a bridge is measured with respect to Mean High Water (MHW), to give a conservative, minimum estimate of that clearance. The important characteristics of tidal datums are:

1) They are a spatially variable surface, defined by the characteristics of the tide at any given location,
2) They are defined by averages over a 19-year period in order to include the entire 18.6 year astronomical cycle that accounts for all significant variations in the moon and sun that cause slowly varying changes in the range of tide, and
3) They vary over time, from 19-year epoch to 19-year epoch.

Ellipsoidal datums are referenced to an ellipsoid of revolution, about its minor axis, making them axially symmetric, as would be expected from a rotating body, such as the earth. The ellipsoid is calculated to best fit to an equipotential surface of the earth's gravity field, the geoid, which is defined by multiple observations including direct gravity measurements, satellite altimetry, vertical deflections, *etc*. The ellipsoid is a very simple mathematical surface, defined by two parameters: the semi-major axis, ‘a’, the distance from the center to the surface at the equator, and the semi-minor axis, 'b,' the distance from the center to the surface at the pole. This simplicity makes ellipsoids an attractive reference frame.

Geoidal datums are referenced to a geoid, an equipotential gravity surface for the earth (Fig. A-1). An equipotential surface is a surface of equal gravitational energy and can be thought of as a surface of equal gravity, recognizing that gravity grows weaker with distance from the earth. Geoidal surfaces are spatially variant, rising in areas of increased gravity and dropping in areas of decreased gravity. The area in the vicinity of Puerto Rico is one of decreased gravity because of the effect of the Puerto Rico Trench, just to the north of the island. The decrease in gravity corresponds to the decrease in mass since the trench is filled with water, which is of lower density than that of the surrounding seafloor rocks.

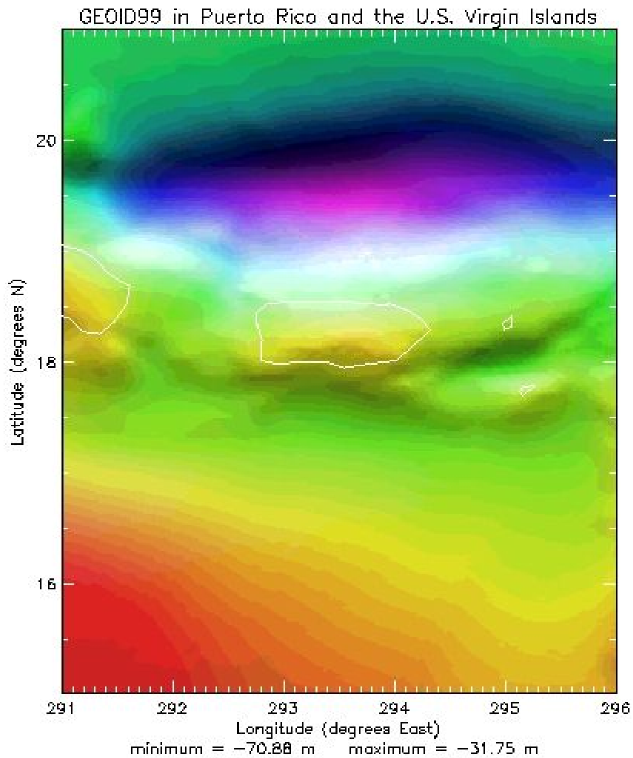

Figure A-1. Geoid surface near Puerto Rico. Geoid heights range from -70.8m (magenta) to -34.4m (red). Note the extreme low north of the island, due to the Puerto Rico Trench and the gradient adjacent to the trench.

Terminology

A clear understanding of the following terms is essential to making the proper vertical adjustments and transformations, as well as understanding the limitation of available data and the uncertainties those limitation impose on the final data sets.

***Ellipsoid Height*:** The signed height (positive up, away from the earth), perpendicular to the ellipsoid, from the ellipsoid to the point being measured. For the San Juan benchmark, 1.334 meters above MSL, the ellipsoid height is -41.66 meters or 41.66 meters earthward (below) the WGS84 Ellipsoid.

***Geoid Height*:** The signed height (positive up, away from the earth), perpendicular to the ellipsoid, from the ellipsoid to the geoid at a given geographic location. For the San Juan benchmark, the geoid height is -45.26 meters. This is consistent with the fact that the geoid is close to MSL.

***Orthometric Height*:** The height (positive up, away from the earth), along a plumb line, from the geoid to the point being measured. A plumb line is defined by the path, which is continually perpendicular to the gravitational equipotential surface. It corresponds to the direction defined by a falling object, which is gravitationally "down." The illustration below demonstrates the relationship between these three heights:

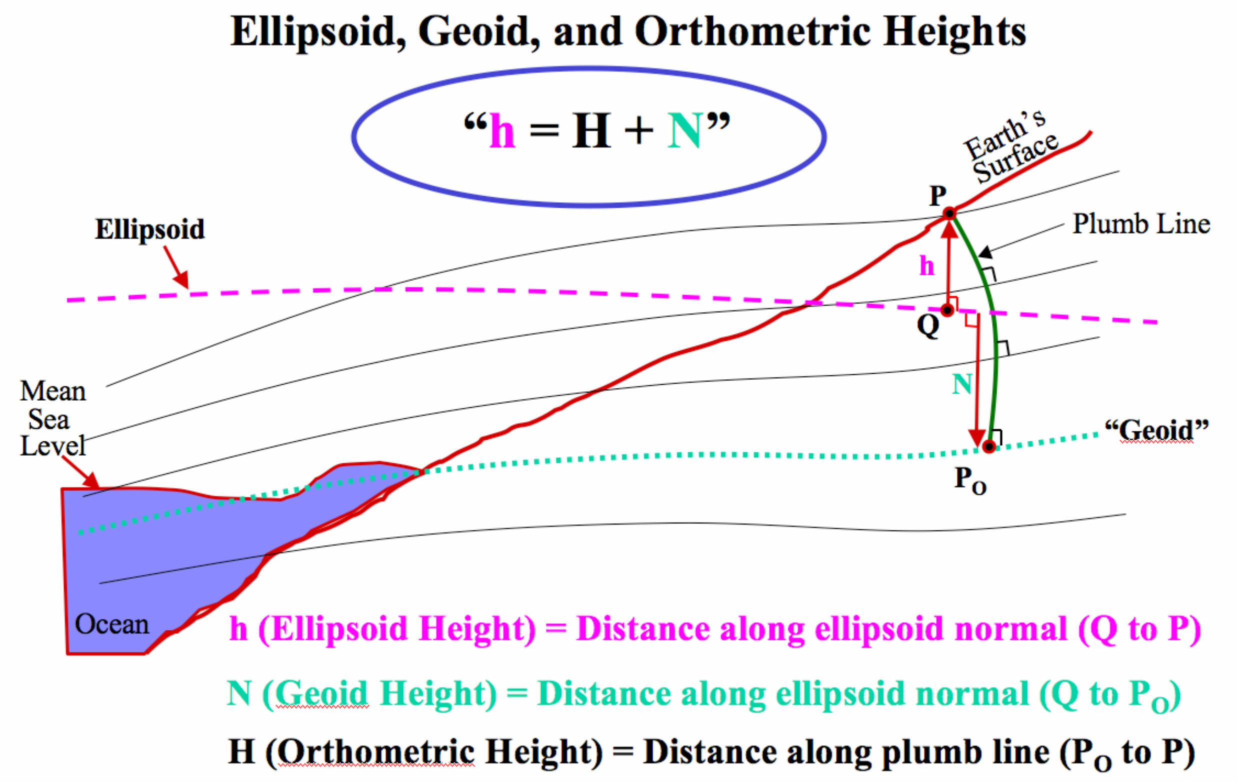

Figure A-2: Definitions of heights with respect to the Ellipsoid and Geoid from Zilkoski (2004).

***Elevation*:** A loosely defined term, nominally the height, along a plumb line, from MSL or the geoid, where MSL is not available, to the point being measured. The elevation of the San Juan benchmark is 1.334 meters, referenced to the Puerto Rico Vertical Datum of 2002 (PRVD02), *i.e.* MSL.

***Mean Lower Low Water (MLLW)*:** The tidal datum defined by the average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch. The National Tidal Datum Epoch is a specific 19-year period over which tide observations are taken to determine Mean Sea Level and other tidal datums such as Mean Lower Low Water and Mean High Water. The latest update defines the 19-year period as 1983-2001. The MLLW tidal datum is used for soundings (depths) on nautical charts to provide a conservative, minimum estimate of depth for safe passage of vessels.

***Mean Sea Level (MSL)*:** The average elevation of the sea surface, averaged over the 18.6 year astronomical cycle of tide generating forces. Another definition refers to the still water level, where the winds, waves, and tides are averaged out over a long observation period. The difficulty with both definitions is that sea level, and in fact all tidal datums, is rising at the measurable rate of about 3 mm per year, resulting in a 60 mm sea level rise over an 18.6 year averaging period. Furthermore, sea level is frequently measured with respect to a benchmark on land, giving a relative measurement of movement of the sea with respect to the land. In some places, clearly identifiable land motions, such as uplift due to glacial rebound (Maine), subsidence due to fluid withdrawal (Long Beach, CA), or changes due to earthquake (Anchorage, AK), produce significant changes in sea level, not totally attributable to the sea.

***Mean Tide Level (MTL)*:** The tidal datum defined by the arithmetic mean of mean high water and mean low water. This is an average of averages and does not necessarily equal Mean Sea Level (MSL).

***Mean High Water (MHW)*:** The tidal datum defined by the average of all the high water heights observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch. This datum is used to define the shoreline, the land surface intersection with MHW. MHW is the datum from which air gap, or bridge clearance, is measured, to provide a conservative, minimum estimate of that clearance for safe passage of vessels.

Algebra, Vectors, and Signs.
In discussions of various elevations and conversions from one datum to another, virtually everything is relative, and care must be taken to compare entities, which are both relative to the same datum or reference. In the definitions above, both the sign of the direction, nominally positive "up," away from the center of the Earth, and the reference direction, from one surface, to another were specified. Vectors are useful for specifying such entities, having both a magnitude and a direction. In Figure A-2 above, both Ellipsoid Height and Geoid Height are vector quantities, having magnitude and a single direction. Note that Orthometric Height has magnitude, but lies along a curved path with more than a single direction. Thus the equation in Figure A-2 is only approximate.

In converting from Ellipsoid to Mean High Water (MHW), changes in magnitude and signs between datums must be carefully taken into account. In general, given two measurements relative to the same datum, A and B, (e.g. MSL and MHW, both relative to MLLW), subtracting one (the subtrahend) from the other (the minuend) results in the measurement (the difference) of the latter, the minuend, relative to the former, the subtrahend.
Thus: A - B = D,

or

MSL-MHW=Distance, and direction, from MHW to MSL,
(MSL relative to MHW).

This is a negative number, representing distance, in a downward direction, *from* MHW *to* MSL.

Tidal and Geodetic Data and Data Sources.

Puerto Rico has a limited number of tide and geodetic stations. For all such stations, we obtained a "Data Sheet," which fully describes the station, including its location as well as position, and heights with respect to various datums. For our final analysis, we identified four useful stations: a tidal station at Mayagüez, a tidal and geodetic station at San Juan, and four CORS (Continually Operating Receiving Station – Global Positioning System) Stations.

Tidal Stations

An average of the values from the two available tidal stations, Mayagüez and San Juan, on the Island of Puerto Rico were calculated (MSL = 0.221 meters above MLLW and MHW = 0.386 meters above MLLW). The San Juan station has both geodetic and tidal data, thus serves to establish the tie between the geoid and tidal datums.

Table A-1. Tidal Datum Values for Puerto Rico, n/a: not available, n/c: not computed

Tidal Bench Mark				Tidal Datums				
	PID	***Name***	***MLLW***	***MLW***	***MSL***	***MTL***	***MHW***	***MHHW***
975 5371	**TV1513**	**San Juan**	0.000	n/a	0.234	n/a	0.400	n/a
975 9394	*[None]*	**Mayagüez**	0.000	0.050	0.208	0.211	0.372	0.427
		Average:	0.000	n/c	**0.221**	n/c	**0.386**	n/c

Geodetic Stations

We were able to locate Data Sheets for 114 geodetic stations on Puerto Rico, six of which were clustered on La Puntilla, Old San Juan, thus were geographically redundant. They provide a measure of the precision of Geoid Height determination.

Table A-2: Ellipsoid, Geoid, and Elevation Heights for San Juan, Puerto Rico

		Position		Heights		
PID	**Name**	**Latitude**	**Longitude**	**Ellips**	**Geoid**	**PRVD02**
AA7648	San Juan	18°27'33.0"N	66°06'59.0"W		-45.27	1.447
TV1513	San Juan	18°27'32.2"N	66°06'59.5"W	-41.66	-45.26	1.334
AA7649	San Juan	18°27'35.0"N	66°06'57.0"W		-45.28	1.421
AA7650	San Juan	18°27'39.0"N	66°06'58.0"W		-45.30	1.998
AA7651	San Juan	18°27'37.0"N	66°07'01.0"W		-45.29	1.557
AA7652a	San Juan	18°27'37.0"N	66°07'03.0"W		-45.29	1.515

The San Juan stations, all at 18°28'N, 66°07'W provide the estimate of certainty in Geoid Height, with an average of -45.28 meters and a standard deviation of 0.0147 meters. The implication of the standard deviation is that the geoid height is known only to a precision of two standard deviations, 0.0294 meters, roughly 3 cm, with 67% confidence. The San Juan station, TV1513, serves is the single tie point between the Tidal Datums and the Geodetic Datums.

With the addition of these CORS data, enough points are available to make a reasonable comparison between the observed geoid height and that predicted by a geoid model. We used the GEOID99 model from the NOAA National Geodetic Service (NGS) as an estimator of the MHW datum, offset by a constant. We then used the model and a calculated offset constant to adjust Ellipsoidal Heights to elevations or depths with respect to MHW. The specifics of this process involved downloading the GEOID99 and using it to estimate the geoid height at all elevation points, measured with respect to the ellipsoid.

Corrections and Adjustments

The heights and depths in our final output are to be referenced to a tidal datum, MHW. Source data of depths and elevations come from a number of sources, referenced to a number of datums:

1. Ellipsoid for USDA/USACE topographic LiDAR data, which were collected with GPS navigation,
2. MLLW and MLW for NOS hydrographic sounding data,
3. Geoid for some data sets that have been partially adjusted.

Applying corrections to each of these types of referenced data requires knowledge of Geoid Height and Tidal datum differences as well as the Tidal Datum Height referenced to the Geoid.

Beginning with a ***coastal*** Ellipsoidal height measurement, referencing Figure A-3, and abiding by the sign conventions described above,

1. The ***Ellipsoidal Height*** would be a negative number, because its elevation is below (earthward from) the Ellipsoid.
2. The ***Geoid Height***, a negative number extracted from the Geiod99 interpolated grid, is subtracted from the Ellipsoid Height. This is subtracting a negative number, algebraically equivalent to adding the absolute value of the Geoid Height. Since we have subtracted 1) the Geoid Height (height of the Geoid with respect to the Ellipsoid) *from* 2) the Ellipsoid Height (height of the measurement with respect to the Ellipsoid), the result is 3) the height of the measurement with respect to the Geoid.

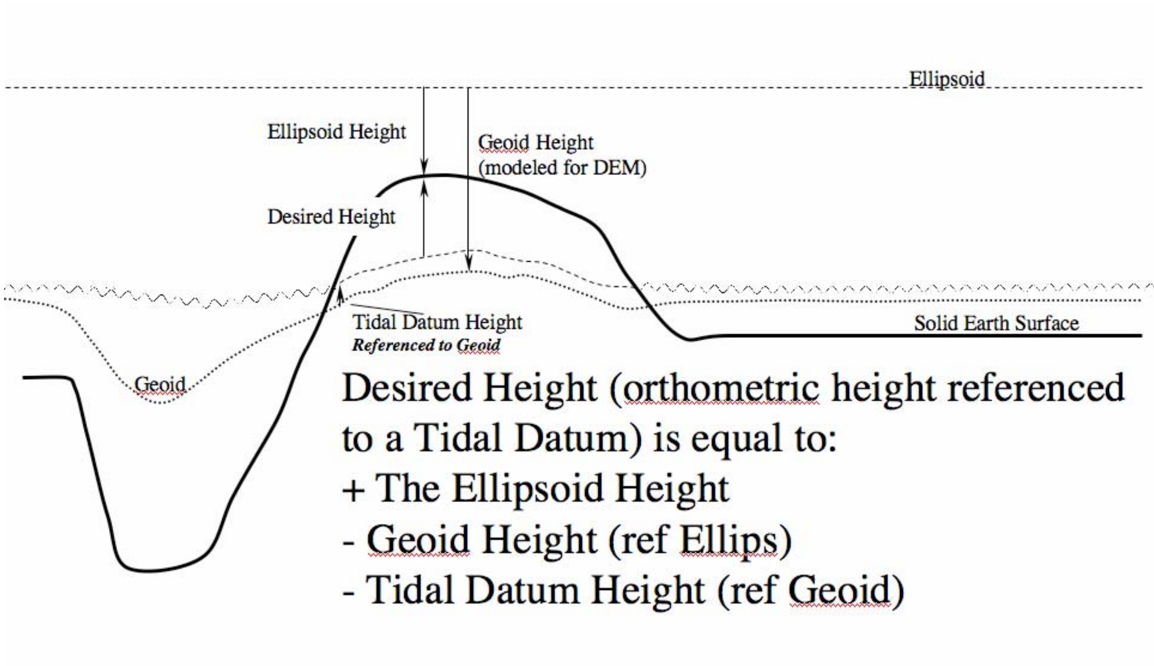

Figure A-3. Height-datum relationships.

3. Finally, the difference between the Geoid and the ***Tidal Datum (MHW)*** must be included. This entails subtracting the height of MHW with respect to the Geoid from the result in Step 2, which is the measured elevation with respect to the Geoid. Again, subtracting 1) the height of MHW with respect to the Geoid *from* 2) the measured elevation with respect to the Geoid results in 3) the value of the measured elevation with respect to MHW.

Using numbers from the available values for the San Juan Benchmark, TV1513 (Table A-1):

1. The ***Ellipsoidal Height*** of the Benchmark is -41.66 meters.
2. The ***Geoid Height*** at the Benchmark, is -45.26 meters.
3. The elevation of the Benchmark with respect to PRVD02, Mean Sea Level, is 1.334 meters, which, when combined with other data, will yield the ***MHW*** elevation with respect to the Geoid.

From Table A-1:

4. The Puerto Rican difference from average MLLW to MHW is +0.386 meters.
5. The Puerto Rican difference from average MLLW to MSL is +0.221 meters.
6. The Puerto Rican difference between average MHW and MSL is (0.386 – 0.221) = +0.165 meters, the height of MHW with respect to MSL.

The difference between the ***Tidal Datum*** and the Geoid must be calculated at the tie point of Benchmark TV1513 (the only location on Puerto Rico where we have all the necessary components to make this calculation).

7. The Benchmark is -41.66 meters (below) the ellipsoid, the Geoid, at the same point is -45.26 meters (below) the ellipsoid, and the Benchmark is 1.334 meters above MSL.
8. The Geoid Height, -45.26 meters, is equal to the sum of: a) the Benchmark Ellipsoid Height, -41.66 meters, b) the negative of the Benchmark Height relative to MSL, -1.334 meters, c) the Height of MLLW with respect to MSL, -0.221 meters, and d) a difference term, which relates the tidal datums to the Geoid.
9. That difference is +2.045 meters from the Geoid to MLLW.

10. Adding the average MHW with respect to MLLW (0.386 meters), yields an adjustment of **+2.431** meters from ***Geoid to MHW***.

To complete the calculation

- The ***Ellipsoidal Height*** is -41.66 meters.
- Subtract the ***Geoid Height*** of -45.26 meters (minus a minus) to get +3.6 meters, the elevation of the benchmark above the Geoid.
- Subtract the height of MHW, the ***Tidal Datum***, above the Geoid, 2.431 meters, to get +1.169 meters, the height of the benchmark above MHW.
- **Check and confirm** in this case, average MSL with respect to MHW is -0.165 meters (value 6, above), which, when subtracted from 1.169, equals 1.334, the given elevation on the data sheet, with respect to PRVD02.

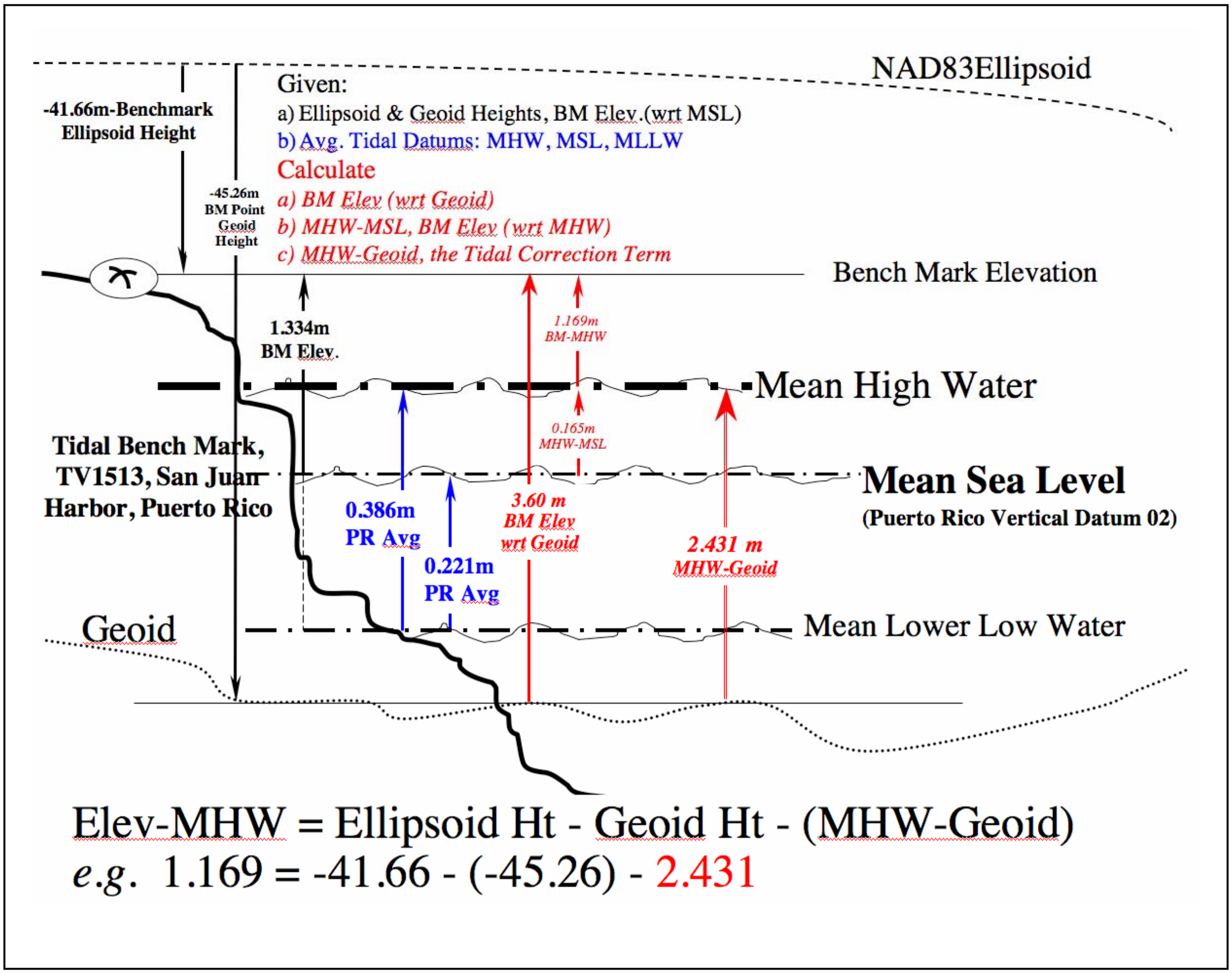

Figure A-4. Final Adjustment Values for Puerto Rico, Black are given values, blue are averages, and red are calculated values.

Values Used for Puerto Rico Datum Conversion

1) *Tidal Datum Information*

Average MHW – MLLW: +**0.386 meters**
Average MSL – MLLW: **+0.221 meters**

2) Geoidal Height:
Described by a Grid based on GEOID99

3) Geoid to MHW Adjustment Term
MHW – Geoid: **+2.431 meters**

NAVD88 to MHW Correction:

MHW is, on average, 0.165 meters above mean sea level, based on two stations in Puerto Rico, San Juan and Mayagüez. The National Elevation Dataset (NED) data and the photometrically derived elevations from the Puerto Rico Office of Planning and Budget were adjusted by -0.165 meters to convert from a NAVD88 (MSL) datum to a Mean High Water datum.

NGS Data Sheet TV1513

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DATABASE = Sybase ,PROGRAM = datasheet, VERSION = 7.30

1 National Geodetic Survey, Retrieval Date = FEBRUARY 1, 2006
TV1513
***********************************************************************
TV1513 TIDAL BM -This is a Tidal Bench Mark.
TV1513 DESIGNATION -975 5371 A TIDAL
TV1513 PID -TV1513
TV1513 STATE/COUNTY-PR/PUERTO RICO
TV1513 USGS QUAD -
TV1513
TV1513 *CURRENT SURVEY CONTROL
TV1513 ___________________________________________________________________
TV1513* NAD 83(2002)-18 27 32.23680(N) 066 06 59.20580(W) ADJUSTED
TV1513* PRVD02 -1.334 (meters) 4.38 (feet) ADJUSTED
TV1513 ___________________________________________________________________
TV1513 X -2,450,319.715 (meters) COMP
TV1513 Y --5,533,748.475 (meters) COMP
TV1513 Z -2,006,620.132 (meters) COMP
TV1513 LAPLACE CORR-0.30 (seconds) DEFLEC99
TV1513 ELLIP HEIGHT--41.66 (meters) (05/06/04) GPS OBS
TV1513 GEOID HEIGHT--45.26 (meters) GEOID99
TV1513 DYNAMIC HT -1.331 (meters) 4.37 (feet) COMP
TV1513 MODELED GRAV-978,668.5 (mgal) NAVD 88
TV1513
TV1513 HORZ ORDER -FIRST
TV1513 VERT ORDER -FIRST CLASS II
TV1513 ELLP ORDER -FOURTH CLASS I
TV1513
TV1513.The horizontal coordinates were established by GPS observations
TV1513.and adjusted by the National Geodetic Survey in May 2004.
TV1513.This is a SPECIAL STATUS position. See SPECIAL STATUS under the
TV1513.DATUM ITEM on the data sheet items page.
TV1513
TV1513.The orthometric height was determined by differential leveling
TV1513.and adjusted by the National Geodetic Survey in November 2002.
TV1513
TV1513.This Tidal Bench Mark is designated as VM 1386
TV1513.by the Center for Operational Oceanographic Products and Services.
TV1513
TV1513.Photographs are available for this station.
TV1513
TV1513.The X, Y, and Z were computed from the position and the ellipsoidal
ht.
TV1513
TV1513.The Laplace correction was computed from DEFLEC99 derived deflections.
TV1513
TV1513.The ellipsoidal height was determined by GPS observations
TV1513.and is referenced to NAD 83.
TV1513
TV1513.The geoid height was determined by GEOID99.
TV1513
```

```
TV1513.The dynamic height is computed by dividing the NAVD 88
TV1513.geopotential number by the normal gravity value computed on the
TV1513.Geodetic Reference System of 1980 (GRS 80) ellipsoid at 45
TV1513.degrees latitude (g = 980.6199 gals.).
TV1513
TV1513.The modeled gravity was interpolated from observed gravity values.
TV1513
TV1513; North East Units Scale Factor Converg.
TV1513;SPC PRVI -269,274.029 233,472.092 MT 1.00000165 +0 05 56.9
TV1513;UTM 19 - 2,043,391.781 804,564.644 MT 1.00074692 +0 54 49.4
TV1513
TV1513! -Elev Factor x Scale Factor = Combined Factor
TV1513!SPC PRVI -1.00000655 x 1.00000165 = 1.00000820
TV1513!UTM 19 -1.00000655 x 1.00074692 = 1.00075347
TV1513
TV1513 SUPERSEDED SURVEY CONTROL
TV1513
TV1513 NAD 83(1997)-18 27 32.23507(N) 066 06 59.20832(W) AD( ) 1
TV1513 ELLIP H (05/12/97) -41.56 (m) GP( ) 4 2
TV1513 ELLIP H (11/17/95) -41.61 (m) GP( ) 1 2
TV1513 NAD 83(1993)-18 27 32.23272(N) 066 06 59.21837(W) AD( ) 1
TV1513 ELLIP H (01/13/94) -41.46 (m) GP( ) 4 1
TV1513
TV1513.Superseded values are not recommended for survey control.
TV1513.NGS no longer adjusts projects to the PR datum.
TV1513.See file dsdata.txt to determine how the superseded data were derived.
TV1513
TV1513_U.S. NATIONAL GRID SPATIAL ADDRESS: 19QHA0456543392(NAD 83)
TV1513_MARKER: DJ = TIDAL STATION DISK
TV1513_SETTING: 32 = SET IN A RETAINING WALL OR CONCRETE LEDGE
TV1513_SP_SET: SEAWALL
TV1513_STAMPING: 5371 A 1977
TV1513_MARK LOGO: NOS
TV1513_MAGNETIC: N = NO MAGNETIC MATERIAL
TV1513_STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO
TV1513+STABILITY: SURFACE MOTION
TV1513_SATELLITE: THE SITE LOCATION WAS REPORTED AS SUITABLE FOR
TV1513+SATELLITE: SATELLITE OBSERVATIONS - May 24, 2004
TV1513
TV1513 HISTORY - Date Condition Report By
TV1513 HISTORY - 1977 MONUMENTED NOS
TV1513 HISTORY - 19950620 GOOD NGS
TV1513 HISTORY - 19950912 GOOD NGS
TV1513 HISTORY - 20020125 GOOD NGS
TV1513 HISTORY - 20020510 GOOD NGS
TV1513 HISTORY - 20030203 GOOD NGS
TV1513 HISTORY - 20040524 GOOD COMPA
TV1513
TV1513 STATION DESCRIPTION
TV1513
TV1513'DESCRIBED BY NATIONAL OCEAN SERVICE 1977
TV1513'THE STATION IS LOCATED AT THE SOUTH END OF THE COAST GUARD STATION IN
TV1513'OLD SAN JUAN. TO REACH SAY YA HOO AND DRIVE LIKE CRAZY.
TV1513'THE DISK IS SET FLUSH IN THE TOP OF THE CONCRETE SEA WALL. IT IS 20.4
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TV1513'M (66.9 FT) SOUTHEAST OF A STEEL FLAGPOLE, 6.1 M (20.0 FT) SOUTHWEST
TV1513'OF THE NORTH CORNER OF THE NOS TIDE HOUSE AND 0.9 M (3.0 FT) NORTH OF
TV1513'THE SOUTH FACE OF SEA WALL AND 0.2 M (0.7 FT) ABOVE THE GROUND.
TV1513
TV1513 STATION RECOVERY (1995)
TV1513
TV1513'RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 1995 (CSM)
TV1513'STATION IS LOCATED AT THE OLD SAN JUAN U.S. COAST GUARD BASE NEAR THE
TV1513'EXTREME SOUTHERN POINT OF THE BASE (LA PUNTILLA) NEAR THE EAST END OF
TV1513'A CONCRETE QUAY. THE STATION MAY BE REACHED FROM THE SAN JUAN LUIS
TV1513'MUNOZ MARIN INTERNATIONAL AIRPORT BY TAKING HIGHWAY 26 WEST TO THE
TV1513'JUNCTION WITH HWY 25 THEN PROCEED NORTH AND WEST ON HWY 25 ALONG THE
TV1513'NORTH SIDE OF OLD SAN JUAN TO A POINT JUST WEST OF FORT SAN CRISTOBAL.
TV1513'FROM THIS POINT MEANDER WEST AND SOUTH ON ONE WAY ROADS WHICH ARE NOT
TV1513'WELL MARKED TO A ROAD LEADING SSE JUST EAST OF THE CUSTOMS HOUSE, TAKE
TV1513'THE ROAD LEADING SSE TO ITS END AT THE GATE OF THE COAST GUARD BASE.
TV1513'FROM THE GATE PROCEED SOUTH AND EAST TO THE CONCRETE DOCKS THEN
TV1513'PROCEED SOUTH AND SOUTHEAST ALONG THE CONCRETE DOCK TO ITS END AT THE
TV1513'NOS TIDE HOUSE AND THE STATION TO THE RIGHT IN A SHORT SECTION OF
TV1513'SEAWALL JUTTING NORTHWEST FROM THE SOUTHERNMOST CORNER OF THE SEAWALL.
TV1513'THE MARK IS AN NOS TIDAL BENCH MARK DISK WITH A CENTER CROSS STAMPED.
TV1513'MARK IS REPORTEDLY THE PRIMARY BENCH MARK OF NOS TIDE STATION
TV1513'975-5371, SAN JUAN, LA PUNTILLA, SAN JUAN BAY. IT IS, 20.1 FT (6.1 M)
TV1513'NORTHWEST OF THE NORTH CORNER OF THE TIDEHOUSE, 3.1 FT (0.9 M)
TV1513'NORTHEAST OF THE SOUTHWEST FACE OF THE SEAWALL ABOUT 0.8 FT (24.4 CM)
TV1513'ABOVE GROUND LEVEL. DESCRIBED BY C.S. MIDDLETON JR.
TV1513
TV1513 STATION RECOVERY (1995)
TV1513
TV1513'RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 1995 (JHR)
TV1513'ADJUSTMENT ID=00000122 (DATUM=LT)
TV1513'
TV1513'COMPUTATION OF HEIGHT FOR CONSTRAINT FOLLOWS...
TV1513'
TV1513'DATA PUBLISHED 09/06/1989 FOR SAN JUAN, LA PUNTILLA, SAN JUAN BAY,
TV1513'TIDE STATION 975 5371 BASED ON THE FOLLOWING-
TV1513'
TV1513'LENGTH OF SERIES = 10 YEARS
TV1513'TIME PERIOD = 1978-1987
TV1513'TIDAL EPOCH = 1960-1978
TV1513'CONTROL TIDE STATION = KEY WEST (872 4580)
TV1513'
TV1513'BENCH MARK ELEVATION INFORMATION
TV1513' ELEVATION IN FEET ABOVE
TV1513' BENCH MARK STAMPING MLLW MHW
TV1513' 5371 A 1977 5.32 3.99
TV1513'
TV1513'ACCEPTED STATION DATUMS FOR 1960-1978 FOR TIDE STATION 975 5371,
TV1513'DATA RETRIEVED IN SEPTEMBER OF 1995-
TV1513'MHW - MSL = 1.381 - 1.213 = 0.168 METER = 0.55 FOOT
TV1513'
TV1513'1989 MHW + 1995 (MHW-MSL) = 3.99 + 0.55 = 4.54 FEET = 1.384 METERS
TV1513'
TV1513'
```

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TV1513'COMPUTATION OF GRAVITY PREDICTION FOLLOWS...
TV1513'
TV1513'LATITUDE LONGITUDE HEIGHT BOUG ANOM
TV1513'(DEC DEG) (DEC DEG) (M) (MGAL)
TV1513'18.46000 66.11667 1.384 978.6685
TV1513
TV1513 STATION RECOVERY (2002)
TV1513
TV1513'RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 2002 (JMW)
TV1513'4.8 KM (3.0 MI) NORTHERLY ALONG STATE HIGHWAY 25 FROM THE JUNCTION OF
TV1513'STATE HIGHWAY 2 IN SAN JUAN, THENCE 0.3 KM (0.2 MI) SOUTHERLY AND
TV1513'THEN WESTERLY ALONG ONE WAY STREETS TO A TRAFFIC CIRCLE NEAR A U.S.
TV1513'CUSTOMS BUILDING, THENCE 0.3 KM (0.2 MI) SOUTHWESTERLY ALONG A PAVED
TV1513'ROAD ON THE WEST SIDE OF THE BUILDING TO THE LA PUNTILLA U.S. COAST
TV1513'GUARD STATION SECURITY GATE, THENCE 0.2 KM (0.125 MI) SOUTHERLY ALONG
TV1513'A PAVED ROAD TO A SEAWALL, THENCE 0.05 KM (0.03 MI) SOUTHWESTERLY TO
TV1513'THE END OF THE SEAWALL, 8.4 M NORTHWEST OF THE SOUTH CORNER OF THE
TV1513'SEAWALL, 4.1 M NORTHWEST OF THE NORTHWEST CORNER OF A TIDE GAUGE
TV1513'BUILDING, 3.1 M NORTHWEST OF BENCH MARK SJH 44, 1.6 M SOUTHEAST OF A
TV1513'CHAIN-LINK FENCE, AND 1.0 M NORTHEAST OF THE SOUTHWEST FACE OF THE
TV1513'SEAWALL. NOTE--THE MARK IS ON PROPERTY OWNED BY THE U.S. GOVERNMENT
TV1513'AND THE U.S. COAST GUARD, CONTACT JORGE R. GAUDIER, 5 CALLE LA
TV1513'PUNTILLA, SAN JUAN, PR 00910, PHONE 787-729-4304.
TV1513
TV1513 STATION RECOVERY (2002)
TV1513
TV1513'RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 2002 (JMW)
TV1513'RECOVERED AS DESCRIBED.
TV1513
TV1513 STATION RECOVERY (2003)
TV1513
TV1513'RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 2003 (DRD)
TV1513'PUERTO RICO VERTICAL DATUM OF 2002 (PRVD02)
TV1513'
TV1513'COMPUTATION OF HEIGHT FOR CONSTRAINT FOLLOWS...
TV1513'
TV1513'USING DATA WITH A WORKING DATE OF 11/18/2002 FOR
TV1513'SAN JUAN, LA PUNTILLA, SAN JUAN BAY, PUERTO RICO,
TV1513'TIDE STATION 975 5371 BASED ON THE FOLLOWING-
TV1513'
TV1513'LENGTH OF SERIES = 17 YEARS
TV1513'TIME PERIOD = 1/1/1983 - 12/31/1987,
TV1513' 1/1/1990 - 12/31/2001
TV1513'TIDAL EPOCH = 1983-2001
TV1513'
TV1513'BENCH MARK ELEVATION INFORMATION IN METERS ABOVE
TV1513'
TV1513' STAMPING OR DESIGNATION MLLW MHW
TV1513'
TV1513' 5371 A 1977 1.568 1.168
TV1513'

TV1513'USING ELEVATIONS OF MEAN HIGH WATER (MHW) AND MEAN SEA LEVEL (MSL)
TV1513'TIDAL DATUMS REFERRED TO MEAN LOWER LOW WATER (MLLW), IN METERS
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TV1513'
TV1513'(MHW - MSL) = 0.400 - 0.234 = 0.166 METER
TV1513'
TV1513'(MHW - MSL) + MHW FOR 5371 A 1977 = 0.166 + 1.168 = 1.334 METERS
TV1513'
TV1513'
TV1513'THE ORTHOMETRIC HEIGHTS RESULTING FROM THE PRVD02 ADJUSTMENT DONE IN
TV1513'THE SPRING OF 2003 WERE COMPUTED BASED ON NORMAL GRAVITY (SEE USC+GS
TV1513'SPECIAL PUBLICATION 240).
TV1513'
TV1513'NOTE--'TRUE' ORTHOMETRIC HEIGHTS WILL BE RECOMPUTED LATER WHEN ACTUAL
TV1513'GRAVITY VALUES ARE AVAILABLE IN PUERTO RICO.
TV1513
TV1513 STATION RECOVERY (2004)
TV1513
TV1513'RECOVERY NOTE BY COMPASSCOM INC 2004 (IR)
TV1513'RECOVERED IN GOOD CONDITION.
```