NOAA Technical Memorandum NESDIS NGDC-55

DIGITAL ELEVATION MODELS OF THE U.S. VIRGIN ISLANDS: PROCEDURES, DATA SOURCES AND ANALYSIS

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Marine Geology and Geophysics Division
Boulder, Colorado
August 2012

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Digital Elevation Models of the U.S. Virgin Islands: Procedures, Data Sources and Analysis

1. Introduction

In October 2010, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed three bathymetric–topographic digital elevation models (DEMs) of the U.S. Virgin Islands (Figs. 1 - 3) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). Two 1/3 arc-second[1] DEMs, one of St Thomas and St. John (Fig. 1) and one of St. Croix (Fig. 2), and a 1 arc-second DEM of the U.S. Virgin Islands region (Fig. 3), referenced to mean high water (MHW) will be used as input for the Method of Splitting Tsunami (MOST) model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEMs were generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 5). They will be used for tsunami forecasting, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Virgin Islands DEMs.

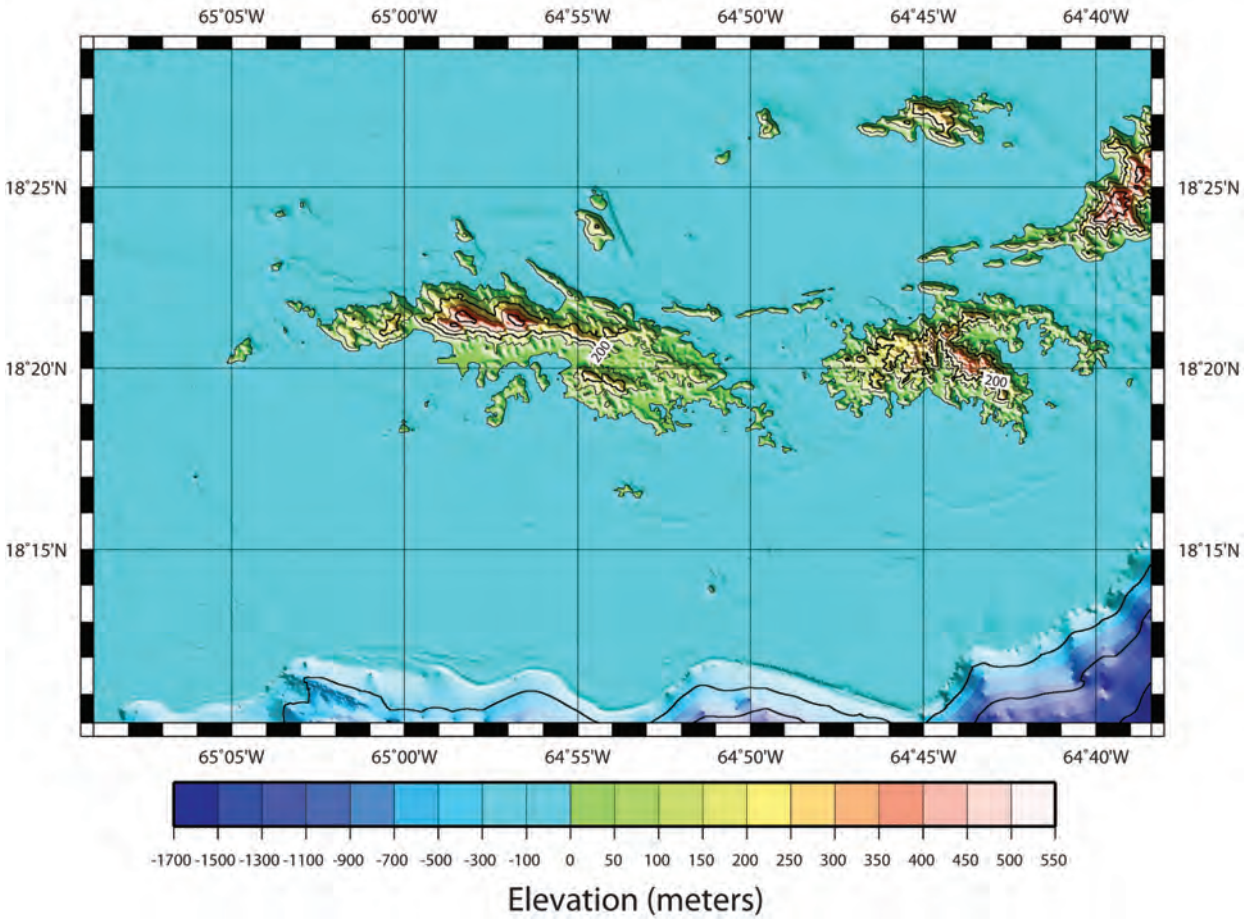

Figure 1. Shaded-relief image of St. Thomas and St. John, U.S. Virgin Islands MHW 1/3 arc-second DEM. Contour interval is 200 meters for the bathymetry and 50 meters for the topography. Image is in Mercator projection.

1. The Virgin Islands 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 St. Thomas and St. John, (18°19'48"N, -64°57'0"W) 1/3 arc-second of latitude is equivalent to 10.25 meters; 1/3 arc-second of longitude equals 9.79 meters; 1 arc-second of latitude is equivalent to 30.75 meters; 1 arc-second of longitude equals 29.36 meters. At the latitude of St. Croix, (17°42'0"N, -64°45'36"W) 1/3 arc-second of latitude is equivalent to 10.25 meters; 1/3 arc-second of longitude equals 9.8 meters; 1 arc-second of latitude is equivalent to 30.74 meters; 1 arc-second of longitude equals 29.46.

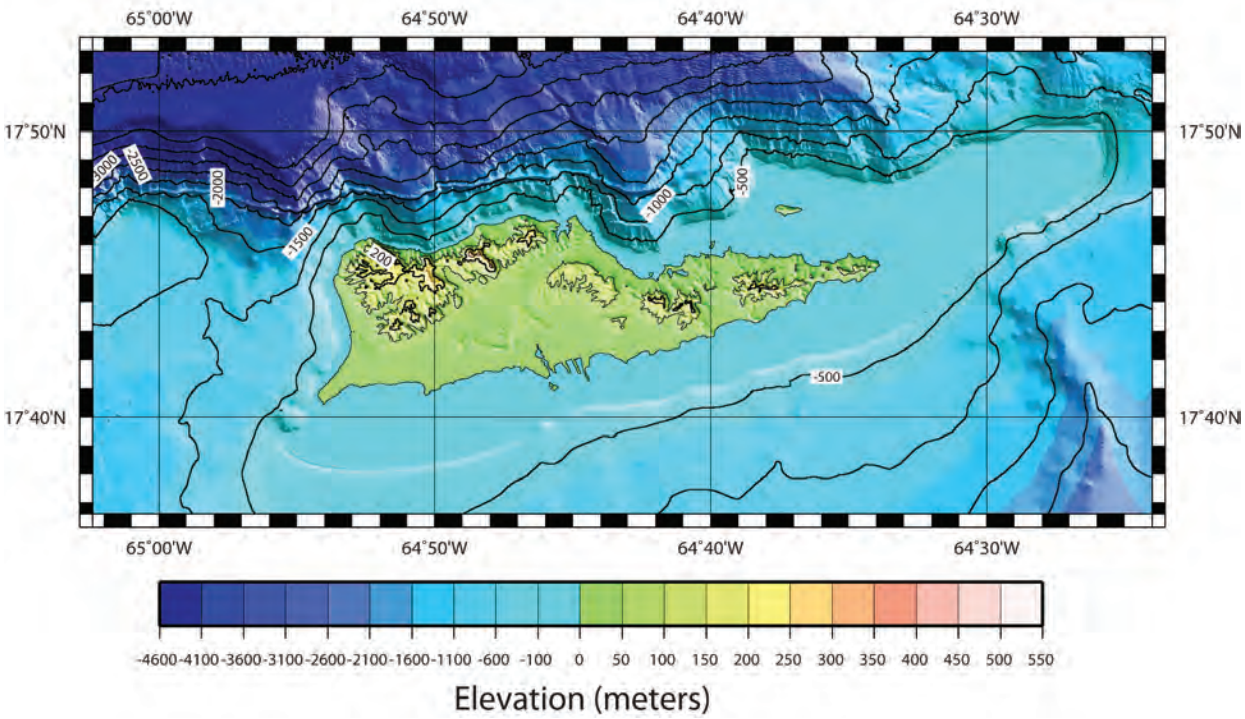

Figure 2. Shaded-relief image of St. Croix, U.S. Virgin Islands MHW 1/3 arc-second DEM. Contour interval is 500 meters for the bathymetry and 50 meters for the topography. Image is in Mercator projection.

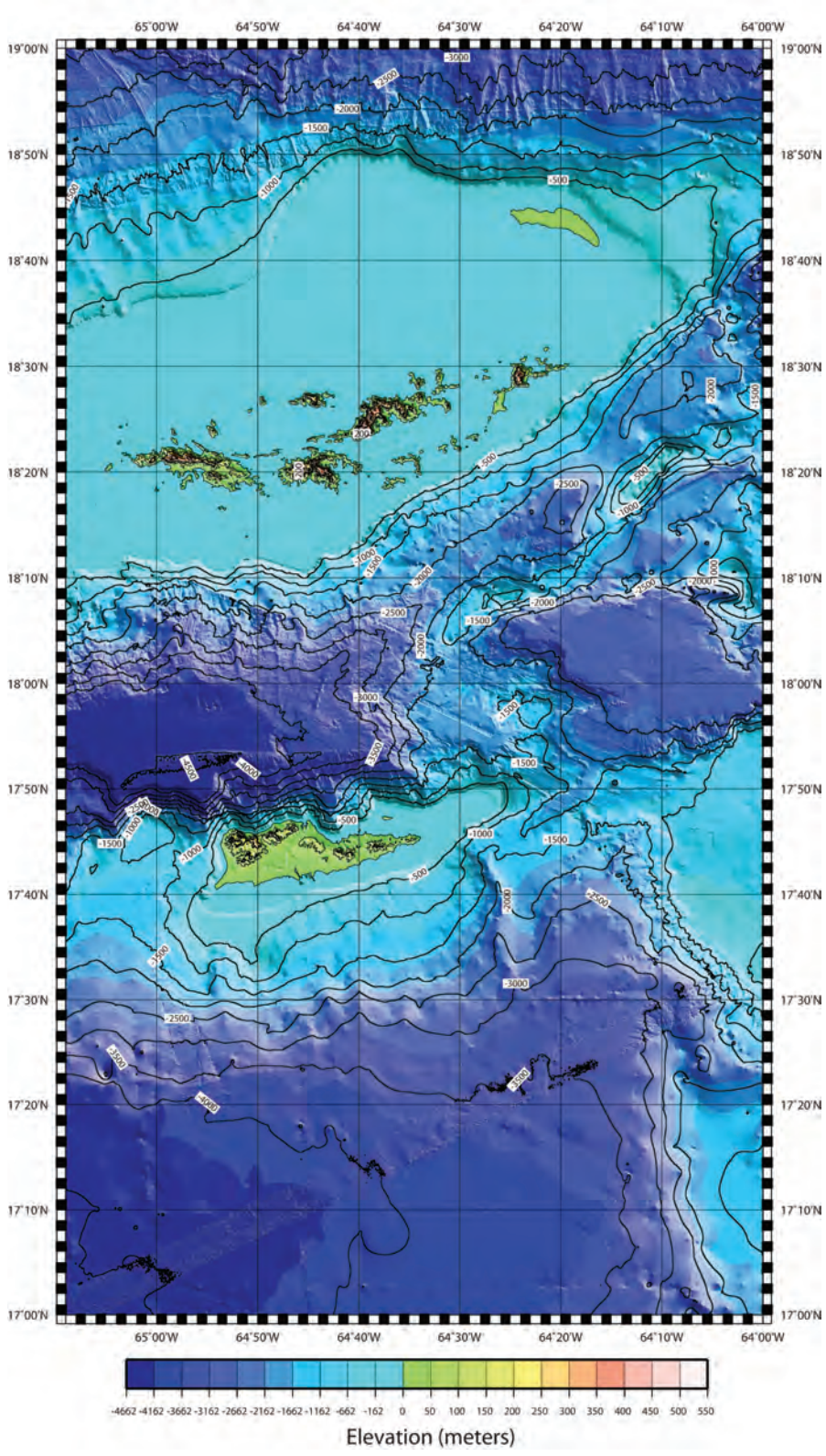

Figure 3. Shaded-relief image of the U.S. Virgin Islands MHW 1 arc-second DEM. Contour interval is 500 meters for the bathymetry and 50 meters for topography. Image is in Mercator projection.

2. Study Area

The Virgin Islands are a group of islands in the Caribbean, located in the Leeward Islands of the Lesser Antilles (Fig. 4). The Virgin Island archipelago is made up of United States and British territories. The U.S. Virgin Islands consist of the main islands of St. Thomas, St. John, and St. Croix and many smaller surrounding islands. The British Virgin Islands consists of Tortola, Virgin Gorda, and Anegada Islands along with many other smaller islands and cays.

The Virgin Islands are not known for having damaging tsunamis, but they have occurred. The region is at risk for tsunamis by several different mechanisms: teletsunamis, or tsunamis that originate from earthquakes across the Atlantic and other far away regions; local earthquakes along the Puerto Rico trench; and local landslides. There are only two recorded tsunamis that hit this region from far-field sources, one in 1755 and another in 1761, both from earthquakes near Lisbon, Portugal. There have also been two significant tsunamis from local earthquakes, one in 1867 and the other in 1918. Both caused considerable damage and run-up heights (~7 meters at St. Croix) for the U.S. and the British Virgin Islands.

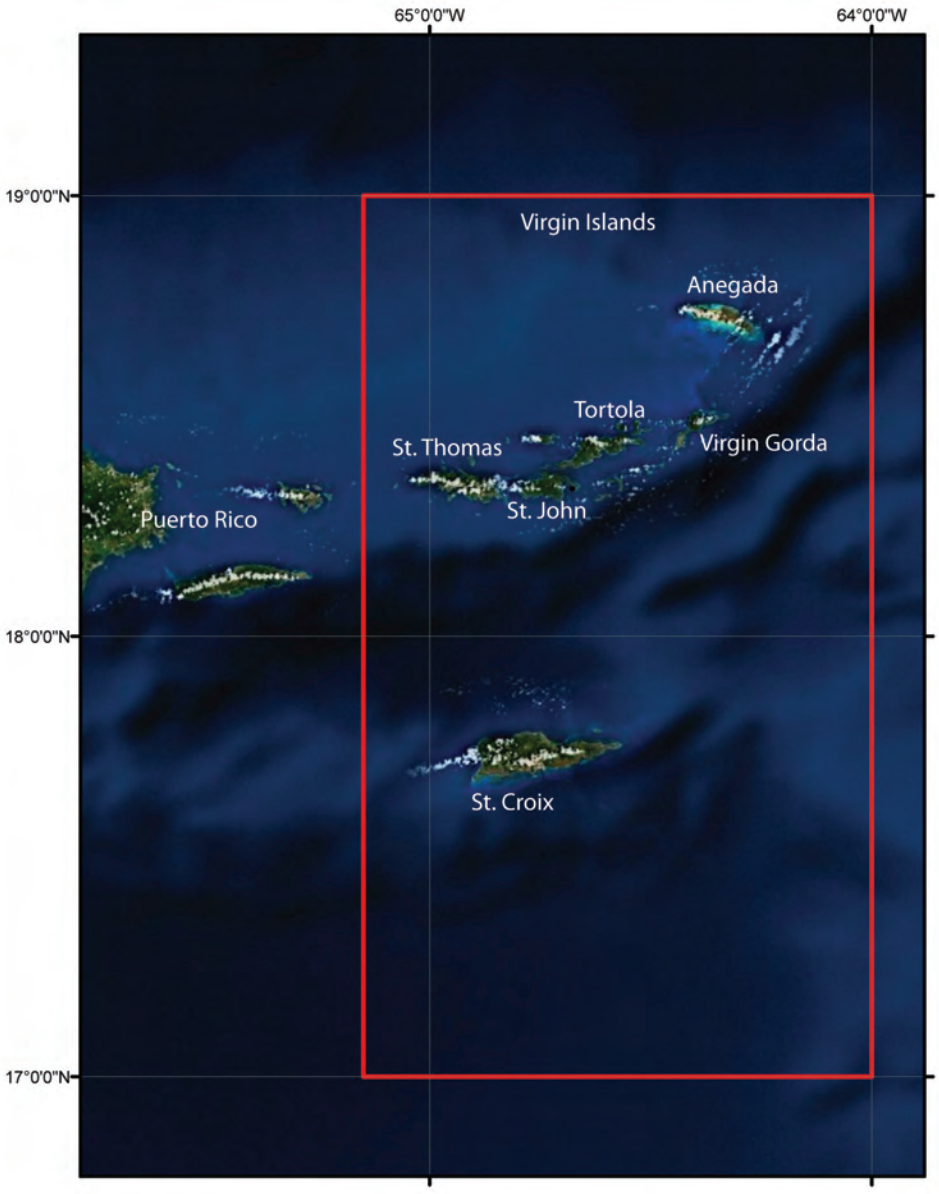

Figure 4. Map of the U.S. Virgin Islands region. Red box denotes the 1 arc-second DEM boundary. Image in background taken from ESRI's online World 2D imagery.

3. METHODOLOGY

The U.S. Virgin Islands DEMs were constructed to meet PMEL specifications (Table 1a - 1c), 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 bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: World Geodetic System of 1984 (WGS 84) and MHW for maximum flooding. Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. PMEL specifications for the U.S. Virgin Islands DEMs.

Grid Area	U.S. Virgin Islands	St. Thomas and St. John, U.S. Virgin Islands	St. Croix, U.S. Virgin Islands
Coverage Area	64º to 65.15º W; 17.00º to 19.00º N	64.64º to 65.15º W; 18.17º to 18.48º N	64.40º to 65.04º W; 17.61º to 17.88º N
Coordinate System	Geographic decimal degrees		
Horizontal Datum	World Geodetic System of 1984 (WGS 84)		
Vertical Datum	Mean High Water (MHW)		
Vertical Units	Meters		
Cell Size	1 arc-second	1/3 arc-second	1/3 arc-second
Grid Format	ESRI Arc ASCII raster grid		

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 5) were obtained from several U.S. federal and local agencies including: NGDC; NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), and Center for Coastal Monitoring and Assessment (CCMA); the U.S. Geological Survey (USGS); the National Aeronautics and Space Administration (NASA); and the University of Virgin Islands (UVI). Safe Software's *Feature Manipulation Engine (FME)*[2] data translation tool package and ESRI's *ArcGIS* were used to shift datasets to WGS 84 geographic horizontal datum. *FME*, *GDAL*[3], and *OGR*[4] were used to convert datasets into ESRI *ArcGIS* shapefiles and xyz format. The shapefiles and xyz files were then displayed with *ArcGIS* and Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*) to assess data quality and manually edit datasets. The methodology used for vertical datum transformations to in described in Section 3.2.1). ESRI's online *World 2D* imagery and NOAA's Raster Nautical Charts (RNCs) were used to analyze and modify data. *QT Modeler* software was used to evaluate processing and gridding techniques.

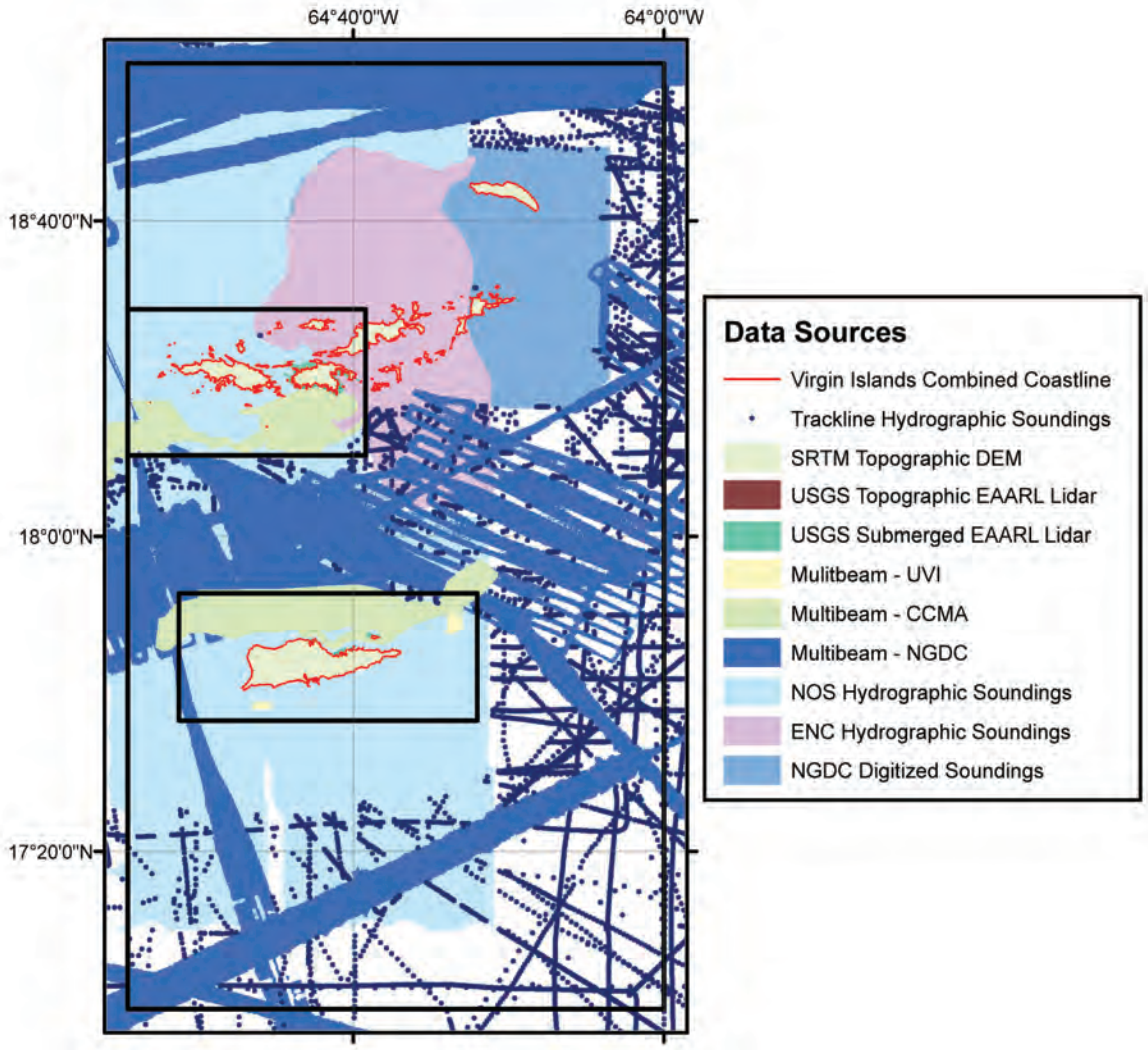

Figure 5. Source and coverage of datasets used in compiling the U.S. Virgin Islands DEMs. Black boxes denote the DEM boundaries.

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

3. *GDAL* is a translator library for raster geospatial data formats that is released under an X/MIT style Open Source license by the Open Source Geospatial Foundation. As a library, it presents a single abstract data model to the calling application for all supported formats. It also comes with a variety of useful commandline utilities for data translation and processing.

4. The *OGR* Simple Features Library is a C++ open source library and commandline tools providing read and write access to a variety of vector file formats, including ESRI shapefiles. *OGR* is a part of the *GDAL* library.

3.1.1 Shoreline

Coastline datasets of the Virgin Islands region were obtained from NOAA's OCS as Electronic Navigational Charts (ENCs)[5] (Table 2; Fig. 6). Datasets from six ENCs were used to develop a "combined coastline" of the Virgin Islands region.

Table 2. Shoreline datasets used in developing the U.S. Virgin Islands DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
OCS	2003-2008	ENC® Coastline	1:10,000 - 1:100,000	WGS 84 geographic	Mean High Water	http://www.nauticalcharts.noaa.gov/mcd/enc/

Six ENCs are available for the U.S. Virgin Islands region (Table 3; Fig. 6). They were downloaded from NOAA's OCS web site in S-57 format and included coastline data files referenced to MHW. The coastline shapefiles were extract using *FME* and compared to large-scale georeferenced Raster Nautical Charts (RNCs). The coastlines from the highest resolution ENCs were merged together into a "combined coastline". The combined coastline was edited as needed and modified to include large offshore rocks using ESRI'S online *World 2D imagery.* Small piers and docks were removed from the coastline.

Table 3. Shoreline datasets used in developing the Virgin Islands DEMs.

Chart	*Title*	*Edition*	*Edition date*	*Format*	*Scale*
25640	Puerto Rico and Virgin Islands	43	2008	RNC/ENC	1:326,856
25641	Virgin Gorda to St. Thomas and St. Croix and Krause Lagoon Channel	27	2004	RNC/ENC	1:100,000 and 1:20,000
25644	Frederiksted Road and Frederiksted Pier	13	2003	RNC/ENC	1:20,000 and 1:2,500
25645	Christiansted Harbor	18	2006	RNC/ENC	1:10,000
25647	Pillsbury Sound	11	2006	RNC/ENC	1:15,000
25649	St. Thomas Harbor	19	2003	RNC/ENC	1:10,000
25650	Virgin Passage and Sonda De Vieques	34	2004	RNC	1:100,000

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

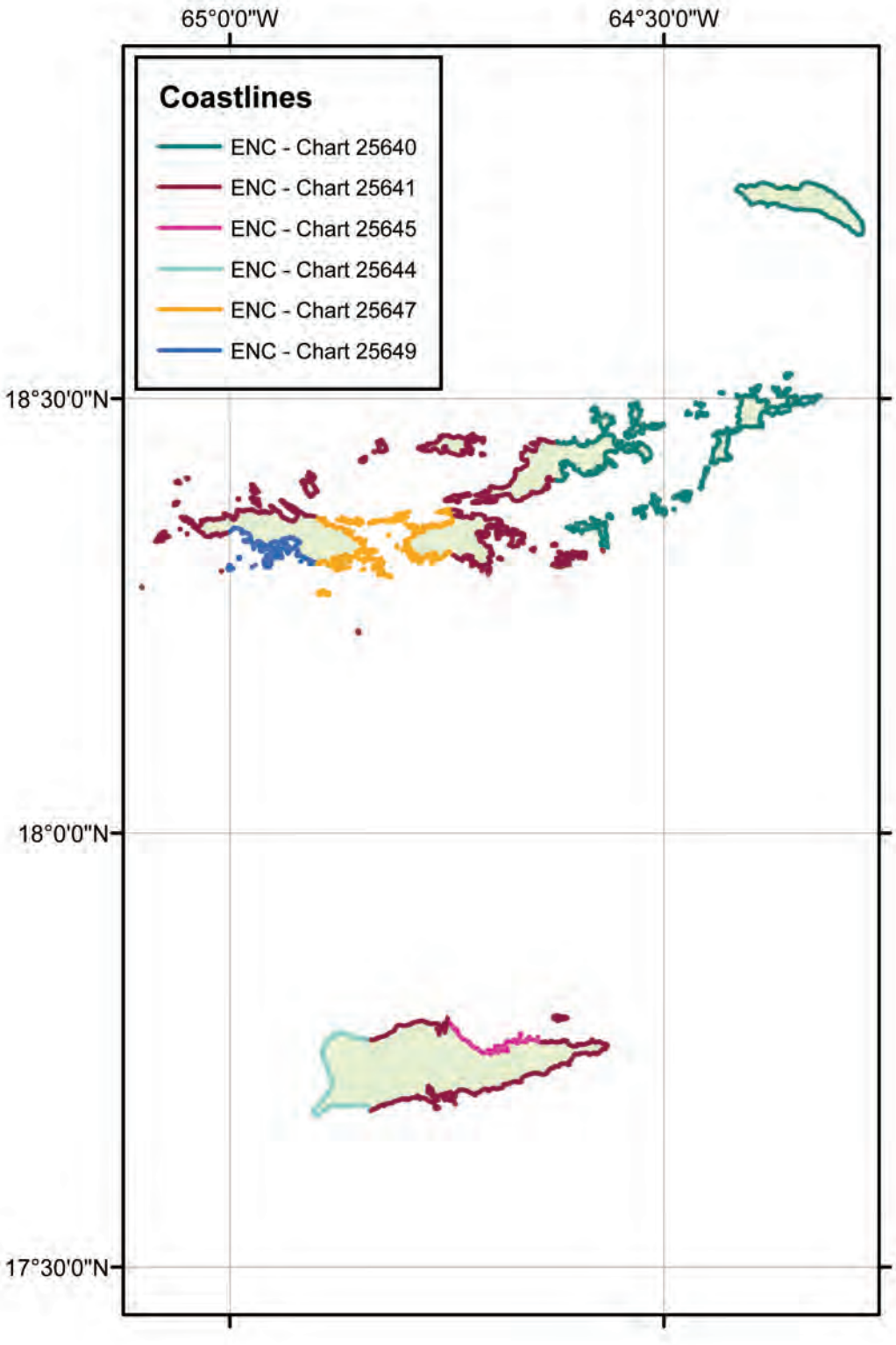

Figure 6. Digital coastline datasets used in a "combined coastline" of the Virgin Islands region.

3.1.2 Bathymetry

Bathymetric datasets available in the Virgin Islands region include 53 NOS hydrographic surveys; 13 multibeam surveys retrieved from the NGDC multibeam database; nine multibeam surveys from NOAA's CCMA; two multibeam surveys from UVI; bathymetric lidar from USGS; hydrographic soundings from ENCs; trackline soundings; and NGDC digitized soundings from nautical charts. (Table 4; Fig. 7).

Table 4. Bathymetric datasets used in compiling the U.S. Virgin Islands DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
CCMA	2004 to 2009	Multibeam DEM	1 - 10 meters	NAD 83 UTM Zone 20 N	MLLW	http://ccma.nos.noaa.gov/products/biogeography/usvi_nps/data.html
NGDC	1909 to 2003	NOS hydrographic survey soundings	Ranges from 5 meters to 1.2 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	Early Puerto Rico Island Datum, Puerto Rico Datum, NAD 27, NAD 83	MLLW and MLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1985 to 2005	Multibeam swath sonar surveys	Raw sonar files gridded to 3 arc-second	WGS 84 geographic	Assumed MSL (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NGDC	1962 to 2000	Trackline soundings	100's of meters along profiles	WGS 84 geographic	Assumed MSL (meters)	http://www.ngdc.noaa.gov/mgg/geodas/trackline.html
NGDC	2010	Digitized chart soundings	1:80,000, 1:30,000 and 1:12,473	WGS 84 geographic	MHW	N/A
OCS	2004 and 2008	Hydrographic soundings	1:326,856 and 1:100,000	WGS 84 geographic	MLLW	http://www.nauticalcharts.noaa.gov/mcd/enc/
USGS	2003	EAARL submerged topography lidar	1 meter	WGS 84 UTM zone 20 N	WGS 84 Ellipsoid referenced to ITRF	http://pubs.usgs.gov/ds/395/
USGS	2009	Multibeam DEM	5 meters	NAD 83 UTM Zone 20 N	MLLW	N/A
UVI	2009	Multibeam DEM	1 meter	NAD 83 UTM Zone 20 N	MLLW	N/A

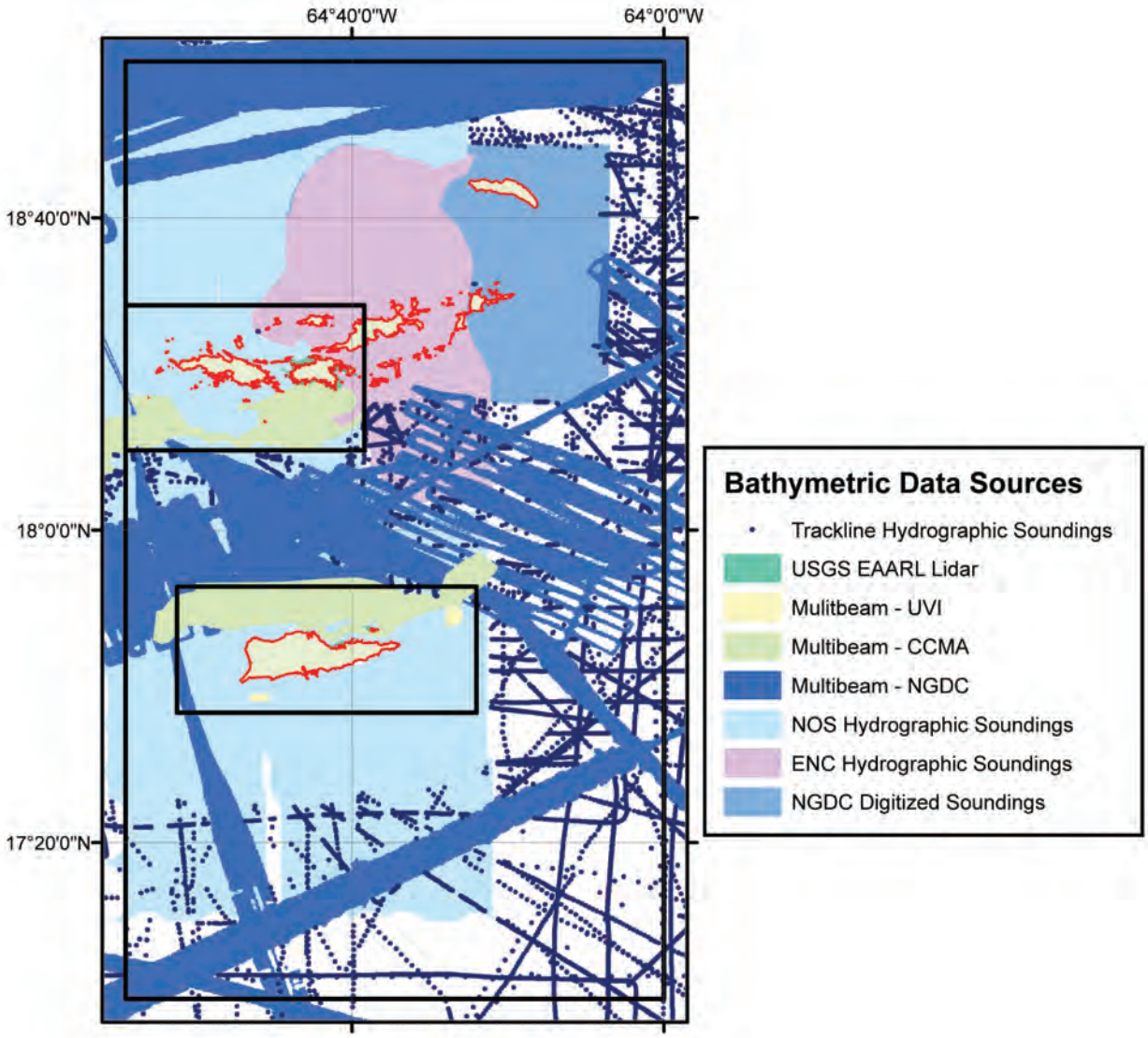

Figure 7. Source and coverage of bathymetric datasets used in compiling the U.S. Virgin Islands DEMs. Coastline in red. Regions of no data shown in white. Black boxes denote the DEM boundaries.

1) Center for Coastal Monitoring and Assessment

NGDC downloaded a unified ten meter bathymetric DEM surface from the CCMA web site that contained all their available multibeam data collected in 2009. CCMA also provided NGDC via ftp with three surveys collected by the USGS and one survey collect by Geophysics GPR International, Inc for the Caribbean Fisheries Management Council (Table 5; Fig. 8). This data ranged from one meter, five meter, 8 meters, and 50 meter resolution. The data were provided in GeoTIFF format, with a horizontal datum of NAD 83 UTM Zone 20 N, and vertical datum of mean lower low water (MLLW).

Table 5. CCMA multibeam surveys used in compiling the U.S. Virgin Islands DEMs.

Survey	*Year of Survey*	*Survey Scale*	*Source*
buck_island_01m	2009	1 meter	CCMA
EviequesTiki09_5m	2009	5 meters	USGS
NStxRon Brown06_50m	2006	50 meters	USGS
RedHindMCD_01m	2009	1 meter	Caribbean Fisheries Management Council
StJohnShelf_01m	2009	1 meter	CCMA
StJohnShelf_08m	2009	8 meter	CCMA
unified_bathy _10m	2009	10 meters	CCMA
StTSailRockTiki09_5m	2009	5 meters	USGS
VirginPass_01m	2009	1 meter	CCMA

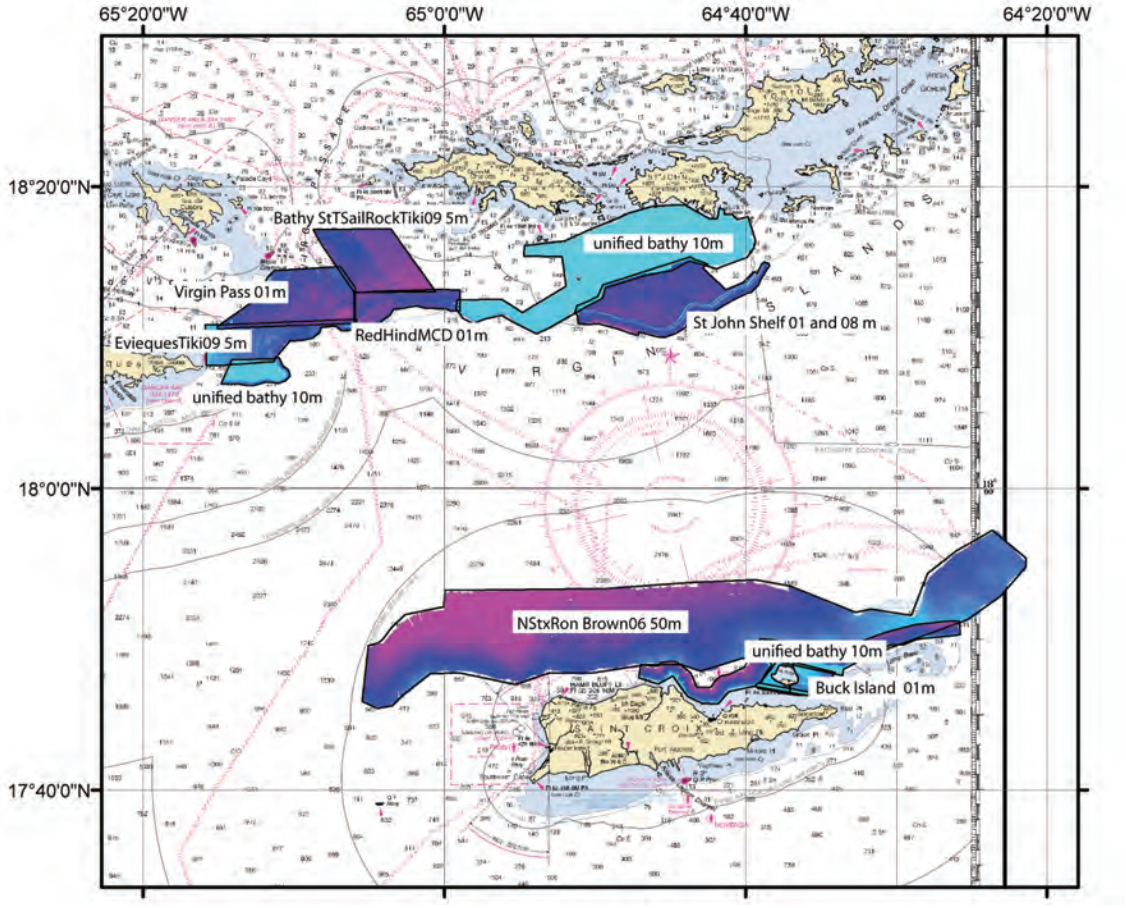

Figure 8. Spatial coverage of the CCMA-provided multibeam surveys. Light blue represents shallow depths; dark pink represents deep depths. Nautical chart #25640 in background.

2) National Ocean Service hydrographic survey data

Fifty-three hydrographic surveys conducted between 1909 and 2003 were available for use in the development of the Virgin Islands DEMs. Surveys were extracted as xyz files using *GEODAS* from NGDC's online NOS Hydrographic database with a buffer 0.05 degrees (~5%) larger than the 1 arc-second Virgin Islands DEM extent to support data interpolation along grid edges. The downloaded hydrographic survey data were vertically referenced to MLLW or mean low water (MLW) and horizontally reference to Early Puerto Rico Datum, Puerto Rico Datum, North America Datum of 1927 (NAD 27), and North America Datum of 1983 (NAD 83) (Table 6; Fig 9).

Data point spacing for the NOS surveys varied by scale. In general, small scale surveys had greater point spacing than larger scale surveys. The data were converted to WGS 84 and transformed to shapefiles using *FME* software. They were then displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to other bathymetric datasets, the combined coastline, and NOS RNCs. Older surveys were clipped to remove soundings that have been superseded by more recent NOS surveys and multibeam data.

Table 6. Digital NOS hydrographic surveys used in compiling the U.S. Virgin Island DEMs.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
D00002	1977	50,000	Early Puerto Rico Island Datums	MLW
F00277	1985	2,500	Puerto Rico Datum	MLLW
F00279	1985	5,000	Puerto Rico Datum	MLLW
H02491	1909	10,000	Early Puerto Rico Island Datums	MLW
H04652B	1924	20,000	Early Puerto Rico Island Datums	MLW
H04653D	1924	10,000	Early Puerto Rico Island Datums	MLW
H04743B1	1923	20,000	Unknown	MLW
H08877	1966	5,000	Early Puerto Rico Island Datums	MLW
H09270	1967	40,000	North American Datum 1927	MLW
H09271	1972	10,000	Early Puerto Rico Island Datums	MLW
H09272	1972	10,000	Early Puerto Rico Island Datums	MLW
H09273	1972	20,000	Early Puerto Rico Island Datums	MLW
H09352	1973	20,000	Early Puerto Rico Island Datums	MLW
H09353	1973	10,000	Early Puerto Rico Island Datums	MLW
H09365	1973	10,000	Early Puerto Rico Island Datums	MLW
H09507	1975	10,000	Early Puerto Rico Island Datums	MLW
H09514	1975	10,000	Early Puerto Rico Island Datums	MLW
H09515	1975	10,000	Early Puerto Rico Island Datums	MLW
H09516	1975	20,000	Early Puerto Rico Island Datums	MLW
H09517	1975	20,000	Early Puerto Rico Island Datums	MLW
H09601	1976	10,000	Early Puerto Rico Island Datums	MLW
H09602	1976	10,000	Early Puerto Rico Island Datums	MLW

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
H09603	1976	10,000	Early Puerto Rico Island Datums	MLW
H09604	1976	20,000	Early Puerto Rico Island Datums	MLW
H09605	1976	20,000	Early Puerto Rico Island Datums	MLW
H09616	1976	10,000	Early Puerto Rico Island Datums	MLW
H09617	1976	10,000	Early Puerto Rico Island Datums	MLW
H09618	1976	20,000	Early Puerto Rico Island Datums	MLW
H09929	1981	5,000	Early Puerto Rico Island Datums	MLW
H09930	1981	5,000	Early Puerto Rico Island Datums	MLW
H09934	1981	2,500	Puerto Rico Datum	MLLW
H09935	1981	10,000	Early Puerto Rico Island Datums	MLW
H09936	1981	10,000	Puerto Rico Datum	MLLW
H09937	1981	10,000	Early Puerto Rico Island Datums	MLW
H09938	1981	10,000	Early Puerto Rico Island Datums	MLW
H09992	1982	80,000	Early Puerto Rico Island Datums	MLW
H09993	1982	80,000	Early Puerto Rico Island Datums	MLW
H09997	1982	10,000	Puerto Rico Datum	MLLW
H09998	1982	80,000	Early Puerto Rico Island Datums	MLW
H09999	1982	5,000	Early Puerto Rico Island Datums	MLW
H10002	1981	10,000	Early Puerto Rico Island Datums	MLW
H10003	1982	10,000	Early Puerto Rico Island Datums	MLW
H10004	1982	80,000	Early Puerto Rico Island Datums	MLW
H10006	1982	10,000	Early Puerto Rico Island Datums	MLW
H10007	1982	10,000	Puerto Rico Datum	MLLW
H10008	1982	10,000	North American Datum 1927	MLLW
H10009	1982	10,000	Puerto Rico Datum	MLLW
H10074	1982	80,000	Puerto Rico Datum	MLLW
H10505	1993	5,000	North American Datum 1983	MLLW
H10506	1993	5,000	North American Datum 1983	MLLW
H10211	1985	10,000	Puerto Rico Datum	MLLW
H11146	2002	5,000	North American Datum 1983	MLLW
W00004	2003	500,000	North American Datum 1983	MLLW

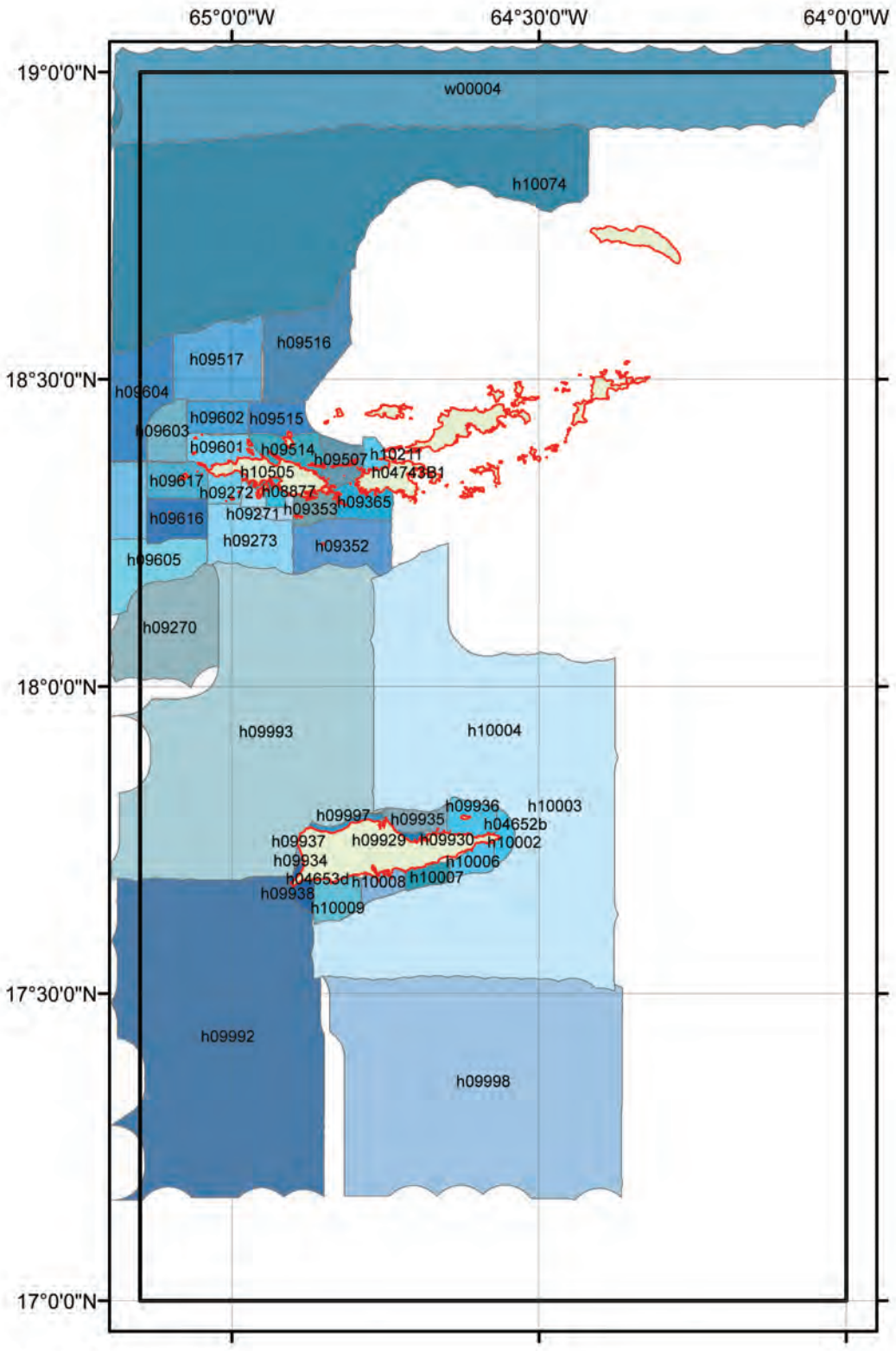

Figure 9. Digital NOS hydrographic survey coverage in the Virgin Islands region. Coastline in red.

3) NGDC multibeam swath sonar surveys

Thirteen multibeam swath sonar surveys were available from the NGDC multibeam bathymetry database for use in the development of the U.S. Virgin Islands DEMs (Table 7; Figure 10). The data were horizontally referenced to WGS 84 geographic datum and were assumed to be vertically referenced to mean sea level (MSL) datum. The data were gridded to extents with a buffer of 0.05 degrees (5%) larger than the DEM extents using *MB-System*[6] (http://www.ldeo.columbia.edu/res/pi/MB-System/) at 3 arc-seconds and viewed in *QT Modeler* for quality analysis. Editing was performed using *QT Modeler* to eliminate errors and where survey data overlapped. The grid was then converted to xyz format and the elevations were transformed from MSL to MHW.

Table 7. Multibeam swath sonar surveys used in compiling the U.S. Virgin Islands, DEMs.

Survey ID	*Date*	*Institution*	*Ship*
AT04L04	2004	Woods Hole Oceanographic Institution (WHOI)	Atlantis
EW0309*	2003	Columbia University, Lamont-Doherty Earth Observatory (CU/LDEO)	Maurice Ewing
EW0404	2004	CU/LDEO	Maurice Ewing
EW9605	1996	CU/LDEO	Maurice Ewing
EW9606	1996	CU/LDEO	Maurice Ewing
EW9706	1997	CU/LDEO	Maurice Ewing
HLY05TH	2005	Rolling Deck to Repository (R2R) Program	USCGC Healy
KN151L4	1997	WHOI	Knorr
KN173L02*	2003	WHOI	Knorr
NF0406*	2004	NOAA	Nancy Foster
NF0505*	2005	NOAA	Nancy Foster
RB0303	2003	US Geological Survey (USGS)	Uri ten Brink
RC2605*	1985	CU/LDEO	Robert Conrad

*indicates data were not used due to poor quality or overlapped by more recent survey

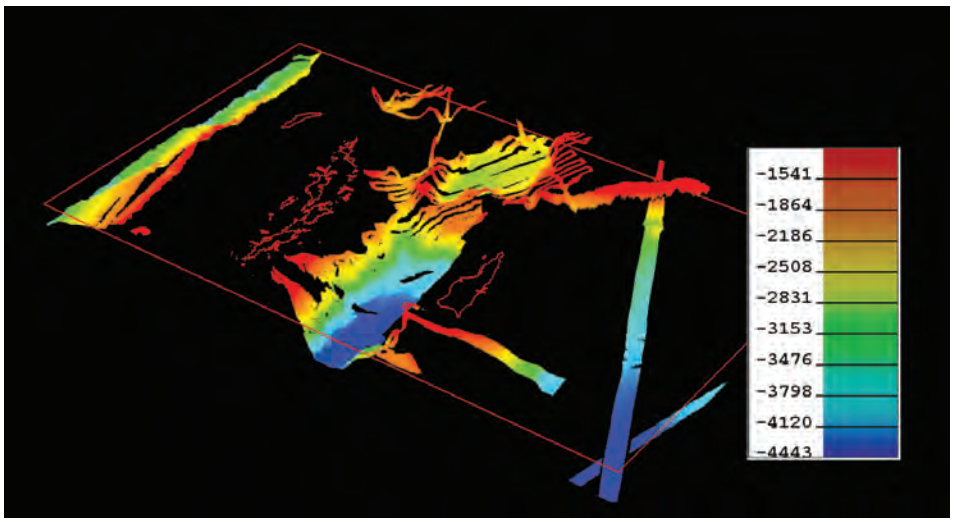

Figure 10. Multibeam data coverage in the Virgin Islands region. Vertical exaggeration 5 times.

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

4) NGDC trackline surveys

Sixty-three single-beam trackline surveys were available from the NGDC Marine Geophysical Trackline Database for use in the development of the U.S. Virgin Islands DEMs (Table 8; Fig 11). This database is comprised of bathymetry, magnetics, gravity, and seismic navigation data collected during marine cruises from 1953 to present. The data were downloaded as xyz files horizontally referenced to the WGS 84 geographic and vertically referenced to assumed MSL.

Table 8. Trackline surveys available in the Virgin Islands region.

Cruise ID	*Ship*	*Year*	*Institution*
4873	Gibbs	1970	Defense Mapping Agency (DMA) Hydro/Topo Centre
13976	Gibbs	1970	DMA Hydro/Topo Centre
20276	San Pablo	1967	DMA Hydro/Topo Centre
45783	Vessel TRB-4	1972	DMA Hydro/Topo Centre
19930013	HMY Britannia	1985	United Kingdom Hydrographic Office (UKHO)
20000140	HMS Manchester	2000	UKHO
87004711	Jean Charcot	1987	France - IFREMER
87004712	Jean Charcot	1987	France - IFREMER
A2054L03	Atlantis II	1969	USGS Woods Hole (WHOI)
AKU05	Kurchatov	1969	Russia - IFZ AN SSSR
B82161	Hayes	1982	US Naval Research Laboratory (US NRL)
BA67001	Baffin	1967	Canadian Hydrographic Service (CHS)
BA70002	Baffin	1970	CHS
CH034L01	Chain	1962	WHOI
CH075L01	Chain	1967	WHOI
DI109L1	Discovery	1980	Institute of Oceanographic Sciences, UK
DSDP45GC	Glomar Challenger	1976	Scripps Institution of Oceanography (SIO)
DSDP46GC	Glomar Challenger	1976	SIO
DSDP51GC	Glomar Challenger	1977	SIO
DSDP78AC	Glomar Challenger	1981	SIO
DSDP78BC	Glomar Challenger	1981	SIO
EW9207	Maurice Ewing	1992	CU/LDEO
FARN0682	Farnella	1982	Natural Environment Research Council (NERC)
FRNL85-4	Farnella	1985	WHOI
H0506A	HNLMS Luymes	1972	Netherlands Hydrographic Office
HU70002	Hudson	1970	CHS
IG1505	Ida Green	1975	University of Texas Institute for Geophysics (UTIG)
INMD12MV	Melville	1978	SIO
KA344602	Kane	1976	US Naval Oceanographic Office (US NAVO)
KA68J	Kane	1968	US Navy NORDA
KN054L04	Knorr	1976	WHOI
KN151L4	Knorr	1997	WHOI
LY70B	Lynch	1970	US Navy NORDA
LY70F	Lynch	1970	US Navy NORDA
ODP171BJ	JOIDES Resolution	1997	Ocean Drilling Program/ Texas A and M (ODP/TAMU)
P1085VI	Powell	1985	USGS Branch of Pacific Marine Geology

Cruise ID	*Ship*	*Year*	*Institution*
P1185VI	Powell	1985	USGS Branch of Pacific Marine Geology
P286CB	Powell	1986	USGS Branch of Pacific Marine Geology
P385CB	Powell	1985	USGS Branch of Pacific Marine Geology
P386CB	Powell	1986	USGS Branch of Pacific Marine Geology
P486CB	Powell	1986	USGS Branch of Pacific Marine Geology
RC0707	Robert Conrad	1963	CU/LDEO
RC0708	Robert Conrad	1963	CU/LDEO
RC0801	Robert Conrad	1963	CU/LDEO
RC0809	Robert Conrad	1964	CU/LDEO
RC0812	Robert Conrad	1964	CU/LDEO
RC1612	Robert Conrad	1973	CU/LDEO
RC1613	Robert Conrad	1973	CU/LDEO
RC1904	Robert Conrad	1975	CU/LDEO
RC1907	Robert Conrad	1976	CU/LDEO
RC2116	Robert Conrad	1978	CU/LDEO
RC2212	Robert Conrad	1979	CU/LDEO
RC2215	Robert Conrad	1979	CU/LDEO
RC2605	Robert Conrad	1985	CU/LDEO
RC2907	Robert Conrad	1988	CU/LDEO
S386CB	Starella	1986	USGS Branch of Pacific Marine Geology
TYDE88_5	Tydeman	1988	Netherlands Hydrographic Office
U371CB	United Geo I	1971	USGS Branch of Pacific Marine Geology
U771PR	United Geo I	1971	USGS Branch of Pacific Marine Geology
V1803	Vema	1962	CU/LDEO
V2001	Vema	1964	CU/LDEO
V2002	Vema	1964	CU/LDEO
V2202	Vema	1966	CU/LDEO
V2607	Vema	1969	CU/LDEO
V3003	Vema	1973	CU/LDEO
WI932010	Wilkes	1972	US NAVO

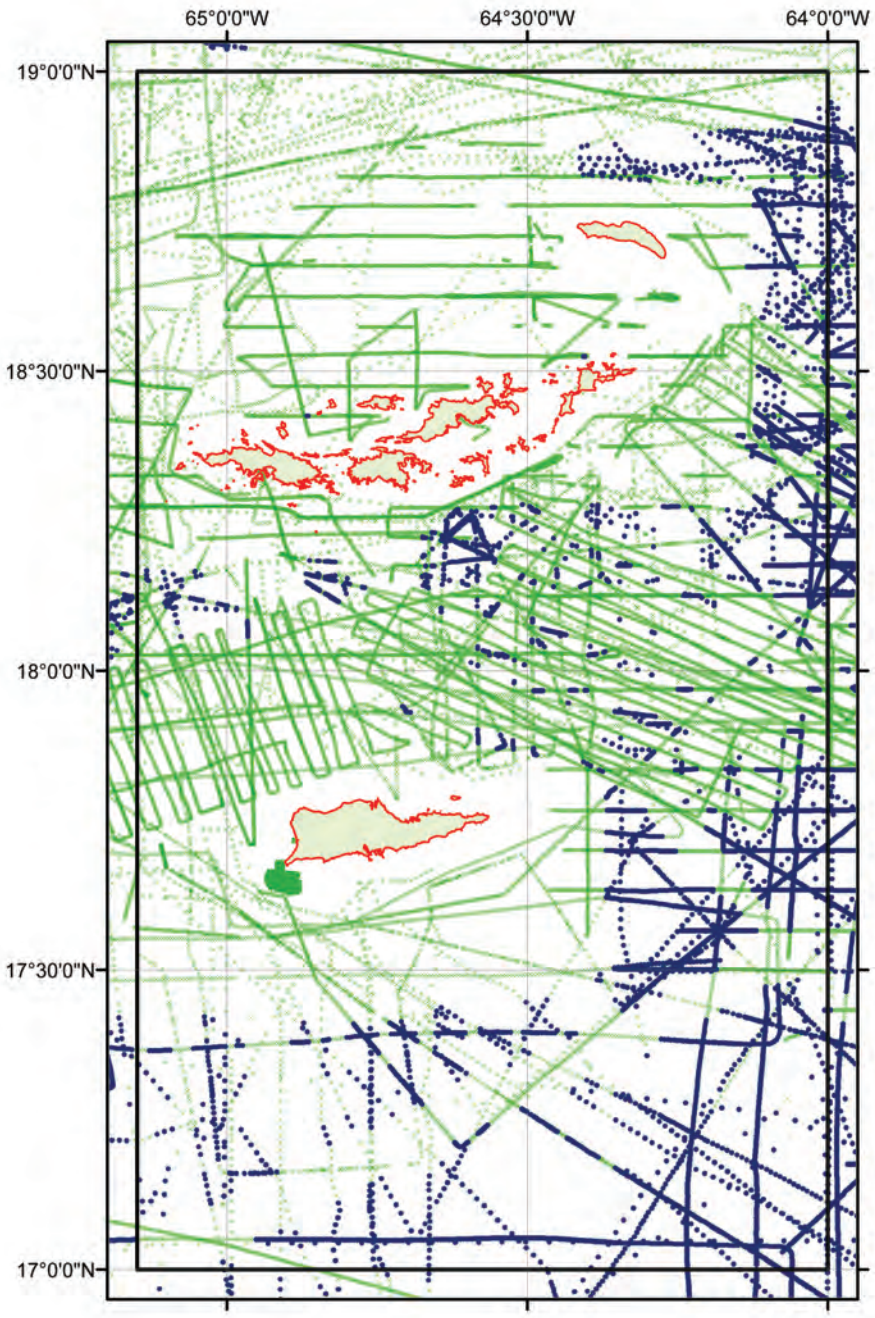

Figure 11. Trackline data coverage in the Virgin Islands region. Soundings in blue represent the data used in building the DEMs. Soundings in green were removed before building the DEM as newer and higher-resolution data were available for those areas.

5) NGDC digitized hydrographic sounds

Digital data were sparse near the British Virgin Islands. NGDC scanned and georeferenced three paper U.S. nautical charts from the Defense Mapping Agency in *ArcMap* and digitized the soundings for use in building the DEMs (Table 9; Fig 12). Nautical charts were obtained from the University of Colorado's Map Library. The charts contained soundings in meters or fathoms and had a vertical datum of MLLW or MLW. Soundings on the charts were only digitized in areas where no other data were available or only sparse NOAA ENC data were available.

Table 9. Nautical charts of the British Virgin Islands region used for digitizing hydrographic soundings.

Chart	*Title*	*Edition*	*Edition Date*	*Scale*	*Horizontal Datum*	*Vertical Datum*
25609	West Indies Virgin Islands St. Thomas to Anegada	5th	1996	1:80,000	WGS 84 geographic	MLW (meters)
25610	West Indies British Virgin Islands Approaches to Gorda Straight	8th	1996	1:12,473	WGS 84 geographic	MLLW (fathoms)
25609	West Indies Virgin Islands Approach to Road Harbour	22nd	1995	1:30,000	WGS 84 geographic	MLW (meters)

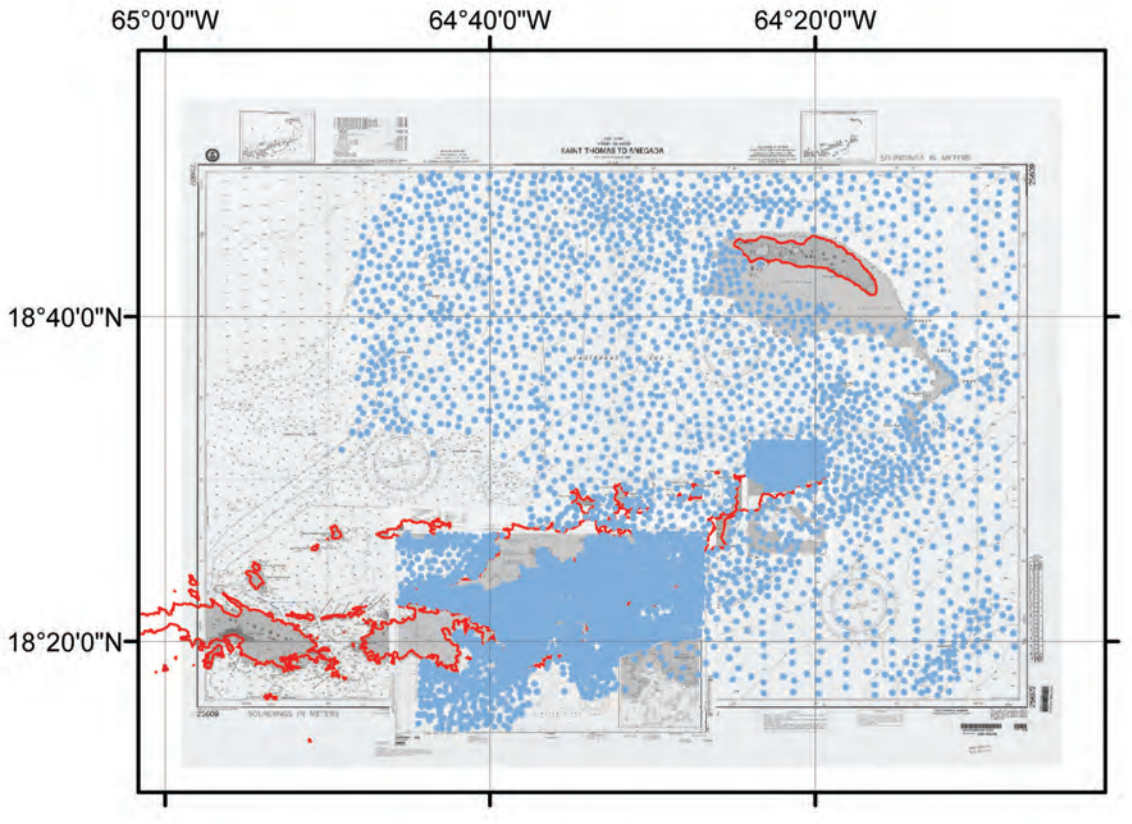

Figure 12. Coverage of digitized hydrographic soundings from georeferenced U.S. nautical charts. Scanned georeferenced nautical charts in background.

6) Office of Coast Survey Electronic Navigation Chart soundings

Soundings from ENCs #25640 and #25641 around the British Virgin Islands were used in building the U.S. Virgin Islands DEMs (see Table 3; Fig. 13). The extracted soundings were transformed from MLLW to MHW.

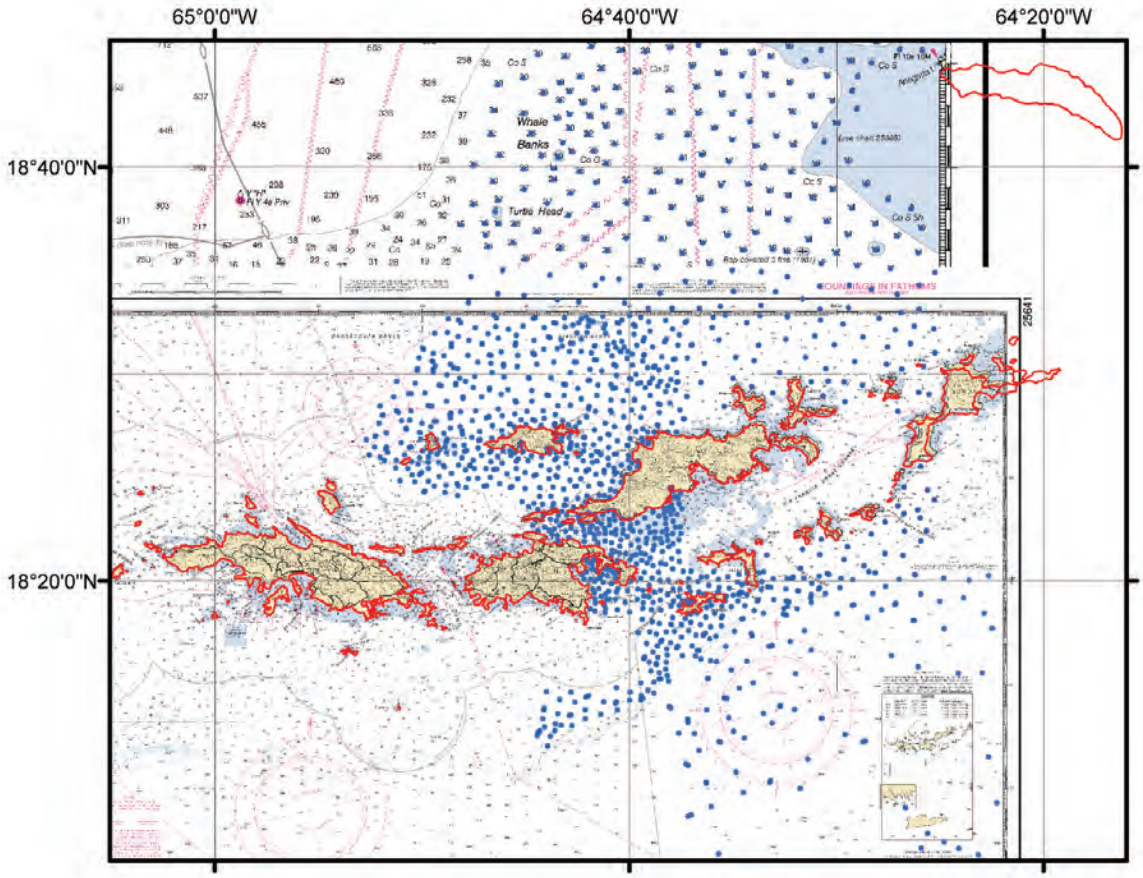

Figure 13. Coverage of NOAA ENC soundings used in compiling the U.S. Virgin Islands DEMs. RNC chart #25640 and #25641 in background. Coastline in red.

7) USGS EAARL submerged topographic lidar

A submerged topographic DEM was produced for a portion of the U.S. Virgin Islands cooperatively by USGS, NASA, and the National Park Service (NPS). The DEM was produced from remotely sensed, geographically referenced elevation measurements[7]. The data required several processing steps to convert to MHW (see Sec. 3.2.1) which potentially added several centimeters of error to the accuracy of the data.

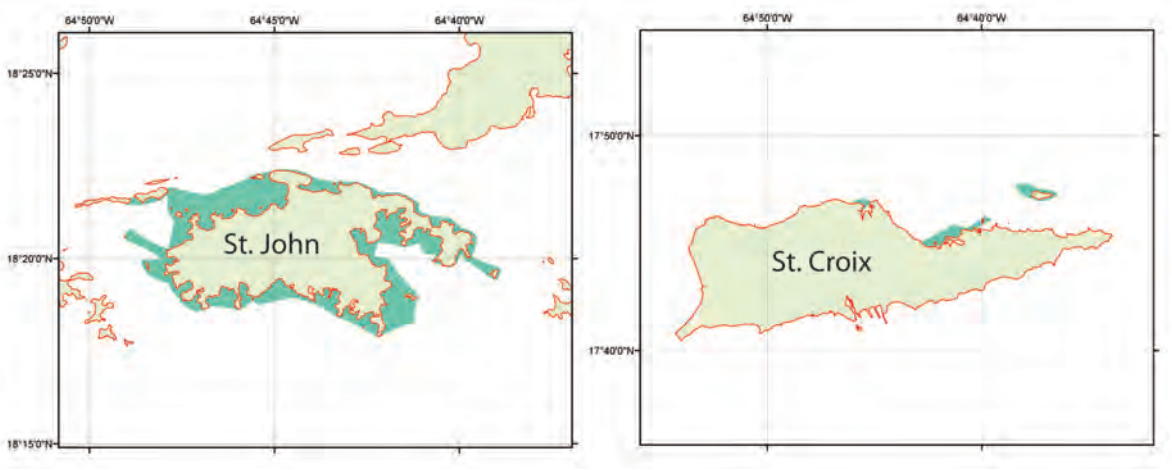

Figure 14. Coverage of the USGS EAARL submerged topographic lidar.

8) UVI gridded multibeam bathymetry

UVI provided NGDC with two multibeam bathymetry grids (Table 10; Fig. 15) that fall in the 1/3 arc-second DEM of St. Croix. The data were provided as one meter bathymetric grids in NAD 83 UTM Zone 20 N at MLLW.

Table 10. Multibeam surveys from UVI used in compiling the U.S. Virgin Islands DEMs.

Survey Name	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
lang_1m	2009	1 meter	NAD 83 UTM Zone 20 N	MLLW
mutton_1m	2009	1 meter	NAD 83 UTM Zone 20 N	MLLW

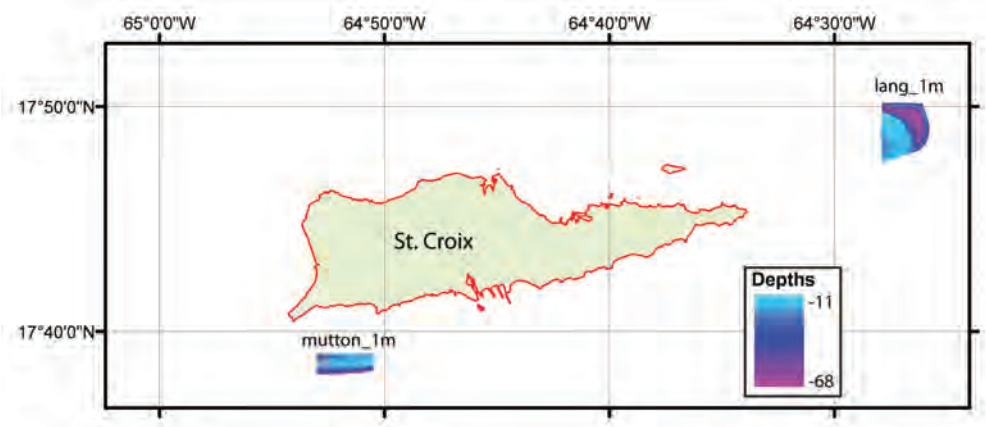

Figure 15. Coverage of gridded multibeam provided by UVI.

7. The lidar data were collected using the NASA Experiment Advanced Airborne Research lidar (EAARL) and have a vertical accuracy of 15 cm and horizontal accuracy within one meter. The data were horizontally referenced in WGS 84 UTM Zone 20 N and vertically referenced in the WGS 84 coordinate system, with an ITRF reference [USGS metadata].

3.1.3 Topography

Three topographic datasets—1 and 3 arc-second Shuttle Radar Topography Mission (SRTM) DEM, USGS topographic lidar, and NGDC digitized elevations—were used in building the U.S. Virgin Islands DEMs (Table 11; Fig 16). The 1 arc-second National Elevation Dataset (NED) topographic DEM from USGS was evaluated but not used in the building of the DEM. In addition, NGDC digitized elevation points of offshore rocks that were not resolved completely in the other topographic datasets.

Table 11. Topographic datasets used in compiling the U.S. Virgin Islands MHW DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	2002	Digitized elevations	10 meters	WGS 84 geographic	MHW	NA
NASA	2000	Topographic DEM	3 arc-second and 1 arc-second	WGS 84 geographic	Assumed MSL	http://edcsns17.cr.usgs.gov/EarthExplorer/
USGS	2003	Topographic lidar	1 meter	WGS 84 UTM Zone 20 N	WGS 84 Ellipsoid referenced to ITRF	http://pubs.usgs.gov/ds/406/index.html

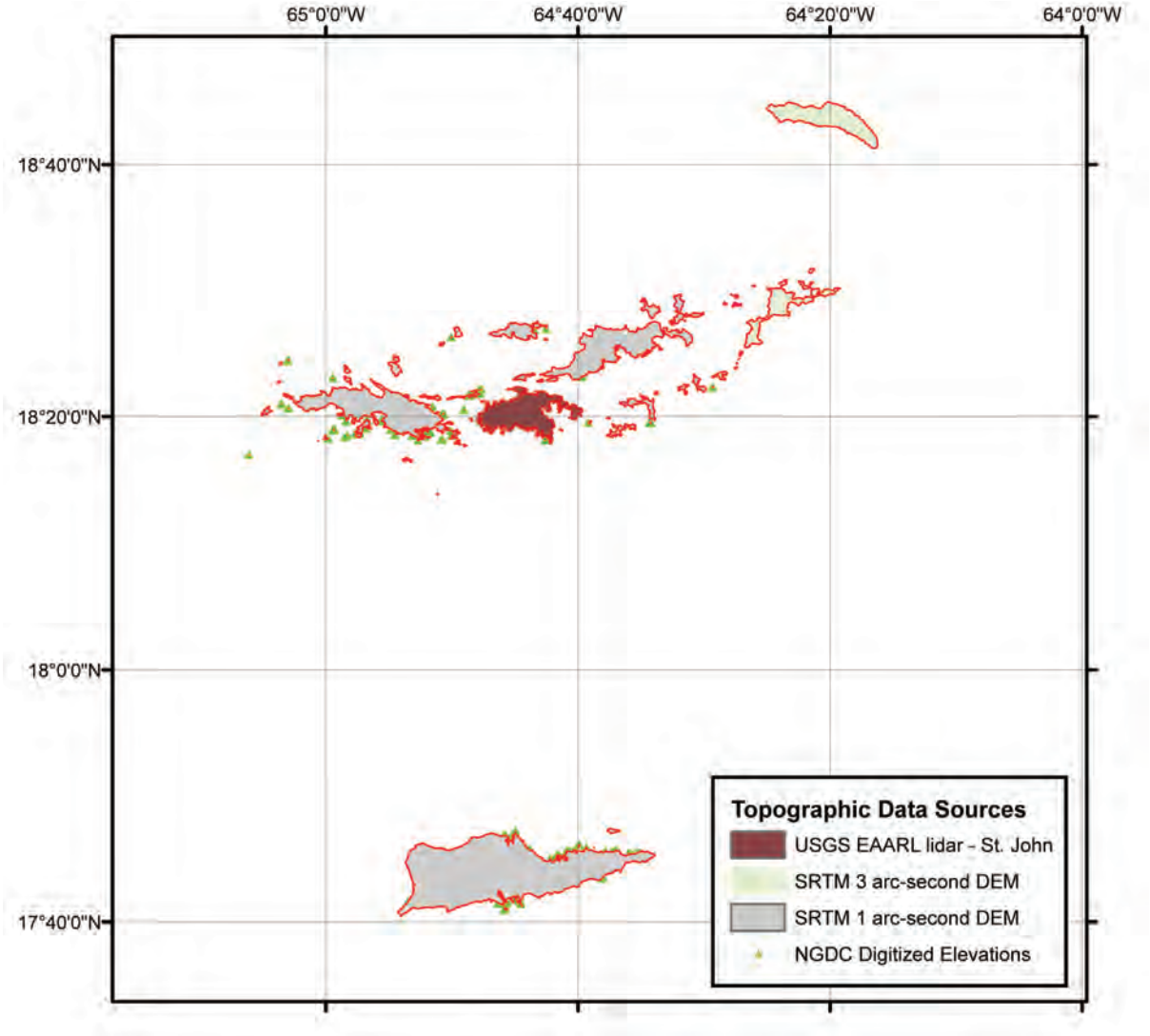

Figure 16. Source and coverage of topographic datasets used in compiling the U.S. Virgin Islands DEMs.

1) NGDC digitized elevations

Many offshore rocks were not represented in the available digital elevation datasets. NGDC digitized offshore rocks using elevation values marked on NOAA RNCs. RNC charts reference elevations in MHW, therefore no vertical datum transformation was needed.

2) NASA SRTM 1 and 3 arc-second topographic DEMs

The NASA Shuttle Radar Topography Mission obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth[8]. The SRTM consisted of a specially modified radar system that flew on board the Space Shuttle Endeavour during an 11-day mission in February 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 Earth Explorer web site as raster DEMs. The data have not been processed to bare earth, but meet the absolute horizontal and vertical accuracies of 20 and 16 meters, respectively.

For the outermost British Virgin Islands, the data have 3 arc-seconds spacing while the remainder of the most populated U.S. and British Virgin Islands have 1 arc-second spacing (see Fig. 16). The data are referenced to the EGM 96 Geoid. The SRTM data contained elevation values over the open ocean, which were deleted by clipping to the combined coastline.

3) USGS EAARL topographic lidar

A first surface elevation grid of St. John was produced cooperatively by USGS, NASA, and NPS (Fig. 17). Elevation data were remotely collected using the NASA Experimental Advanced Airborne Research Lidar (EAARL) to measure ground elevation, tree canopy, and coastal topography. The data are horizontally referenced to WGS 84 UTM Zone 20 N and vertically referenced to the WGS 84 ellipsoid, with reference to ITRF. They have a vertical accuracy of 15 cm and a horizontal accuracy of 1 meter.

The dataset represented multiple problems in using it for building the U.S. Virgin Islands DEMs. First, the data are not bare earth and due to the thick tree canopy represented in the unfiltered lidar data, NGDC was unable to accurately represent the bare-earth surface in the final DEMs. Second, the data are in WGS 84 Ellipsoid, which required several processing steps to transform to MHW (see sect. 3.2.1), which potentially decreased vertical accuracy.

8. 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]

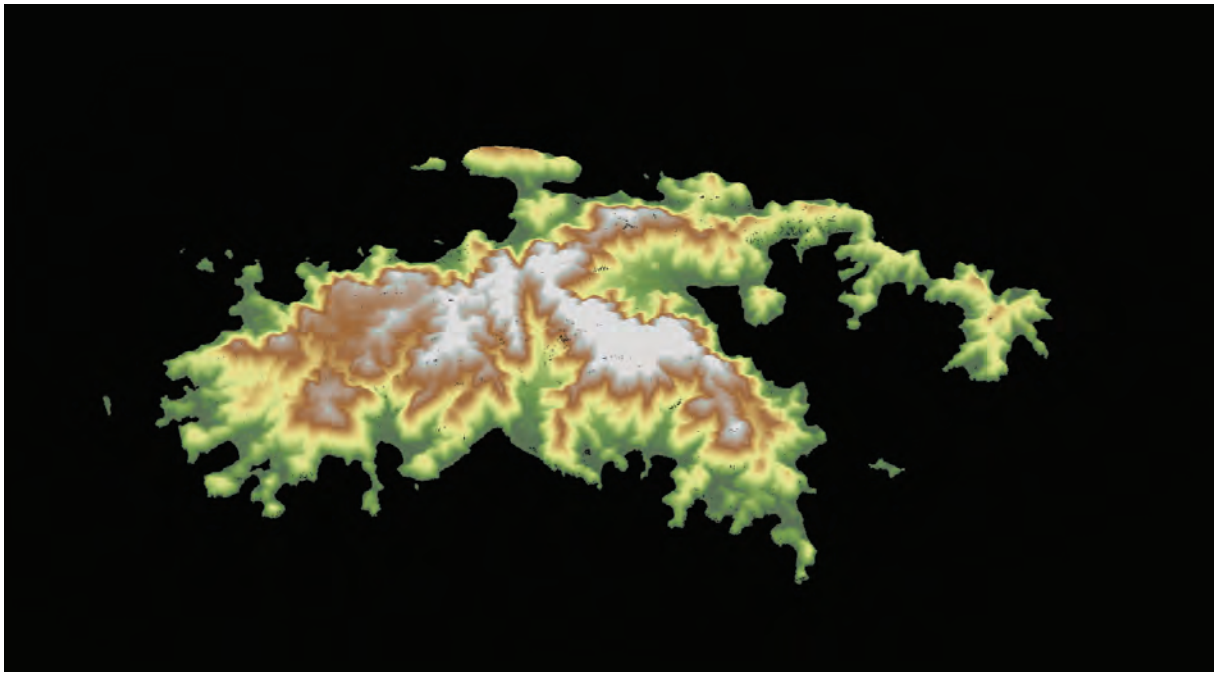

Figure 17. USGS topographic lidar DEM of St. John.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the U.S. Virgin Islands DEMs were originally referenced to a number of vertical datums including MLLW, MLW, MSL, EGM 96 Geoid, and the WGS 84 Ellipsoid referenced to the ITRF. All datasets were transformed to MHW for modeling of maximum flooding. Vertical datum transformations to MHW were accomplished using *GDAL*, based upon data from NOAA tide stations in the region (Table 12; Fig. 18). See Appendix A for NGDC's conversion grid methodology.

Table 12. Tide stations near the Virgin Islands and the relationships between MHW and other vertical datums.

Station Name	*Station Number*	*Latitude*	*Longitude*	*MLLW to MHW Difference (meters)*	*MLW to MHW Difference (meters)*	*MSL TO MHW Difference (meters)*
Charlotte Amalie	9751639	18.335	-64.92	0.227	0.213	0.113
Christiansted Harbor, St. Croix	9751364	17.75	-64.705	0.215	0.207	0.103
Culebra	9752235	18.30000	-65.30167	0.285	0.238	0.121
Esperanza, Vieques Island	9752695	18.09333	-65.47000	0.216	0.209	0.104
Lameshur Bay, St. Johns	9751381	18.31667	-64.72333	0.238	0.222	0.12
Lime Tree Bay, VI	9751401	17.68333	-64.75333	0.214	0.21	0.102

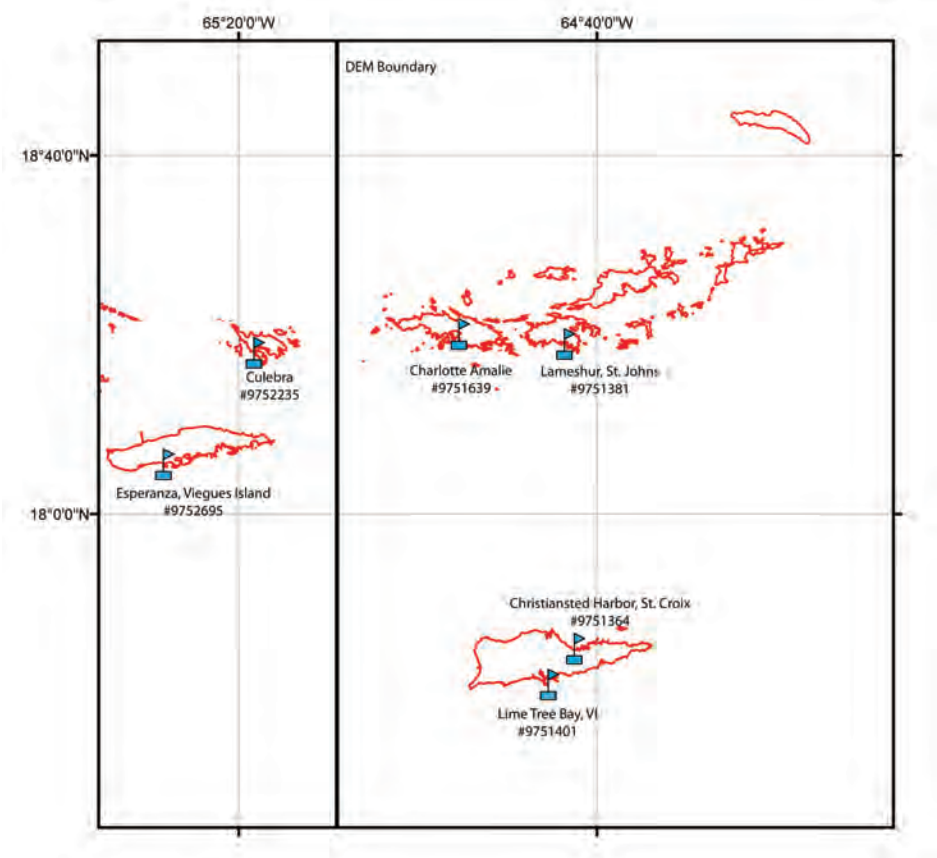

Figure 18. Location of NOAA tide station in the Virgin Islands region used for datum transformations to MHW.

1) **Bathymetric data**

The NOS hydrographic surveys, NGDC multibeam swath sonar surveys, trackline surveys, ENCs, CCMA and UVI multibeam surveys, and digitized chart sounds were transformed from MLLW, MLW, and MSL to MHW using the conversion grids. The USGS EAARL submerged topographic lidar data were transformed to MHW by using the WGS 84 to the NAD 83 Ellipsoid conversion grid, the Hybrid model to VIVD 09 (assumed MSL) conversion grid, and then the MSL to MHW conversion grid.

2) **Topographic data**

The USGS EAARL topographic lidar data were transformed to MHW using the WGS 84 to the NAD 83 Ellipsoid conversion grid, the Hybrid model to VIVD 09 (assumed MSL) conversion grid, and then the MSL to MHW conversion grid.

The SRTM data were first transformed from the EGM 96 Geoid to the WGS 84 Ellipsoid using a geoid height transformation grid acquired from the National Geospatial Intelligence Agency (http://earthycinfo.nga.mil/GradnG/wgs84/gravitymod/egm96.html). The data were then transformed by using the WGS 84 to the NAD 83 Ellipsoid conversion grid, the Hybrid model to VIVD 09 (assumed MSL) conversion grid, and then the MSL to MHW conversion grid.

The multiple vertical datum transformations to MHW potentially introduced cm-scale vertical accuracy errors. The data were carefully evaluated after each step to ensure the conversion grid was applied correctly and that the final MHW data accurately portrayed the elevation values in the area.

3.2.2 Horizontal datum transformations

Datasets used to compile the U.S. Virgin Islands DEMs were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, NAD 83 UTM Zone 20 N, Early Puerto Rico Island Datum, and Puerto Rico Datum. The relationships and transformational equations between the geographic horizontal datums are well established. Transformations to WGS 84 geographic were accomplished using *FME* software and *GDAL's* transformation tool.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

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

- Inconsistent, overlapping datasets. Older and lower resolution datasets were clipped to newer and higher resolution datasets.
- Data values over the ocean in the SRTM DEMs and the USGS topographic lidar datasets. These datasets required automated clipping to the combined coastline to remove those values over the open ocean.
- SRTM and USGS lidar data not processed to bare earth. Data contains elevation values of dense tree canopy that could not be removed.
- Digital, measured bathymetric values from NOS surveys date back over 100 years. The older NOS survey data were excised where more recent bathymetric data exist.
- Offshore rocks were not included in the topographic data. Elevation values were digitized based on NOAA RNCs.
- Sparse digital data around the British Virgin Islands. Paper nautical charts were scanned, georeferenced, and digitized.
- No *VDatum* was available. Most datasets were transformed to MHW using a conversion grid from tide stations, but several data sources required multiple transformations to achieve a vertical datum of MHW.

3.3.2 Smoothing of bathymetric data

Older NOS hydrographic survey data, ENC soundings, and digitized chart soundings are generally sparse at the resolution of the U.S. Virgin Islands DEMs in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the form of lines or "pimples" in the DEM due to these low resolution datasets, and to provide effective interpolation into the coastal zone, a 3 arc-second-cell size 'pre-surface' bathymetric grid of the Virgin Islands 1 arc-second DEM, and two 1/3 arc-second-cell size 'pre-surface' bathymetric grids of St. Thomas and St. John, and St. Croix, were generated using *GMT*[9], an NSF-funded software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The older NOS hydrographic point data, ENC soundings, and trackline data were manually clipped to remove overlap with the newer NOS surveys, NGDC multibeam data, and the multibeam surveys provided by CCMA and UVI. All of the bathymetric data were then combined with points extracted from the adjusted MHW coastline—to provide a buffer along the entire coastline. The coastline elevation values were set to -1 meter to ensure a bathymetric surface approaching zero relative to MHW in areas where bathymetric data are sparse or non-existent.

The point data were then median-averaged using the *GMT* tool 'blockmedian' to create a 3 arc-second grid 0.05 degrees (~5%) larger than the 1 arc-second DEM gridding region, and a 1/3 arc-second grid 0.05 degrees larger than the 1/3 arc-second DEM gridding region St. Thomas and St. John, and St. Croix. The higher resolution grids required the bathymetric surface to be gridded at the same resolution as the DEM to prevent 'topographic creep', in other words, the topography creeping in the open water due to sparse data along the coast. 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 combined coastline to eliminate data interpolation into land areas.

The resulting surface was compared with original soundings to ensure grid accuracy. Figures 19 and 20 show histograms of the NGDC multibeam data and trackline data compared to the 3 arc-second pre-surface bathymetric grid. Figures 21-26 show histograms of the NOS, CCMA multibeam, and UVI multibeam surveys, and ENC and digitized chart soundings compared to both the 1/3 arc-second pre-surface bathymetric grids. Differences cluster around zero with the multibeam data have the largest differences of -200 to +170 meters when compared to the bathymetric

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

surface. Points with the largest differences are located along steep gradients of elevation (e.g., submarine canyons) where the high-resolution surveys may include over 100 points that are averaged to a single cell elevation value.

Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the NOS hydrographic surveys. In areas where more recent data were available, the older surveys were either edited or not used. The gridded bathymetric surface was then converted to an xyz file for use in building the MHW DEMs.

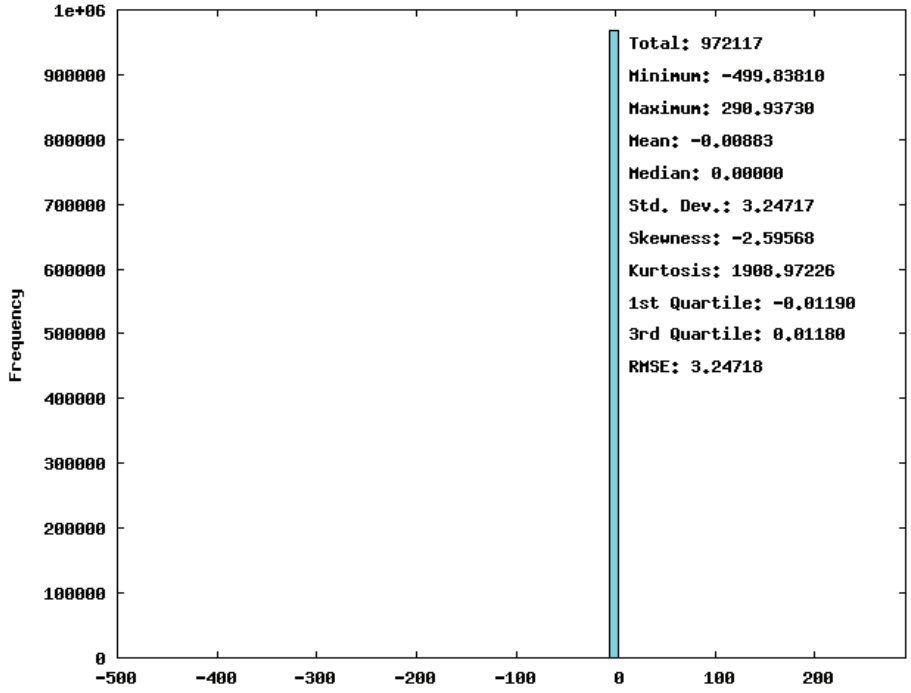

Figure 19. Histogram of the differences between all NGDC multibeam data and the 3 arc-second pre-surfaced bathymetric grid.

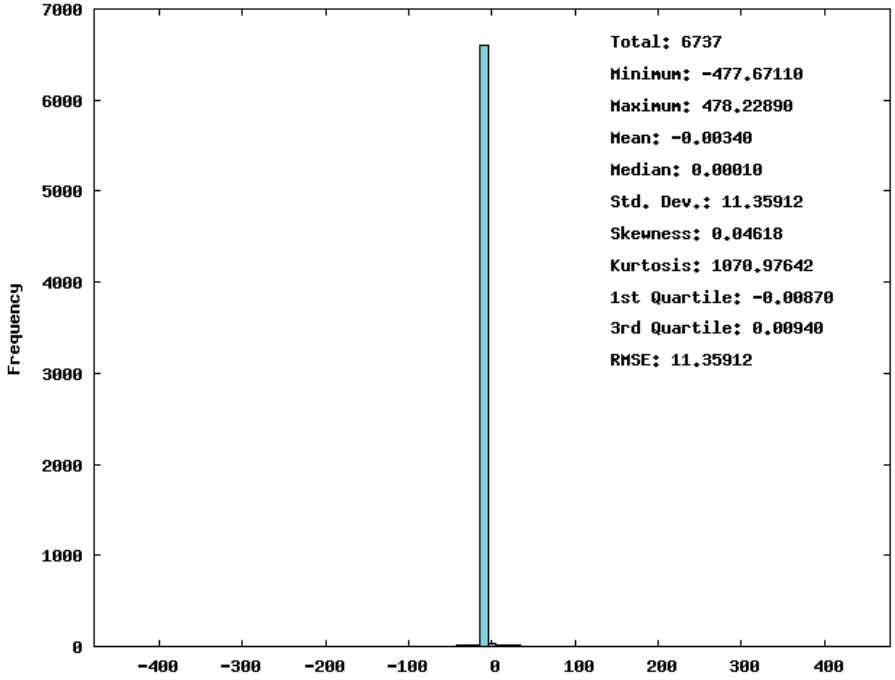

Figure 20. Histogram of the differences between all trackline surveys and the 3 arc-second pre-surfaced bathymetric grid.

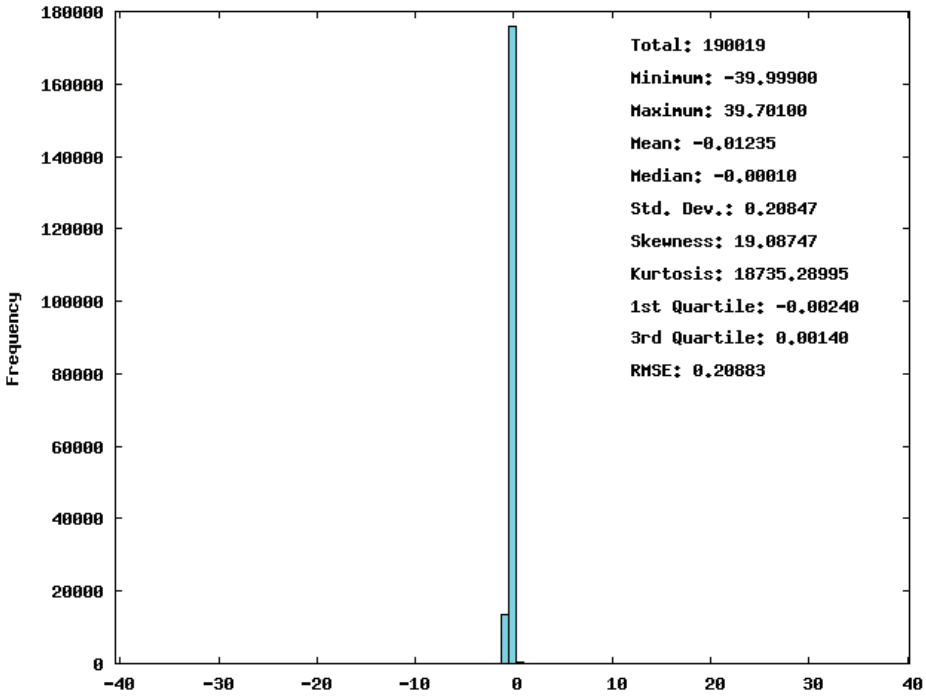

Figure 21. Histogram of the differences between all NOS survey data and the 1/3 arc-second pre-surfaced bathymetric grid of St. Thomas and St. John.

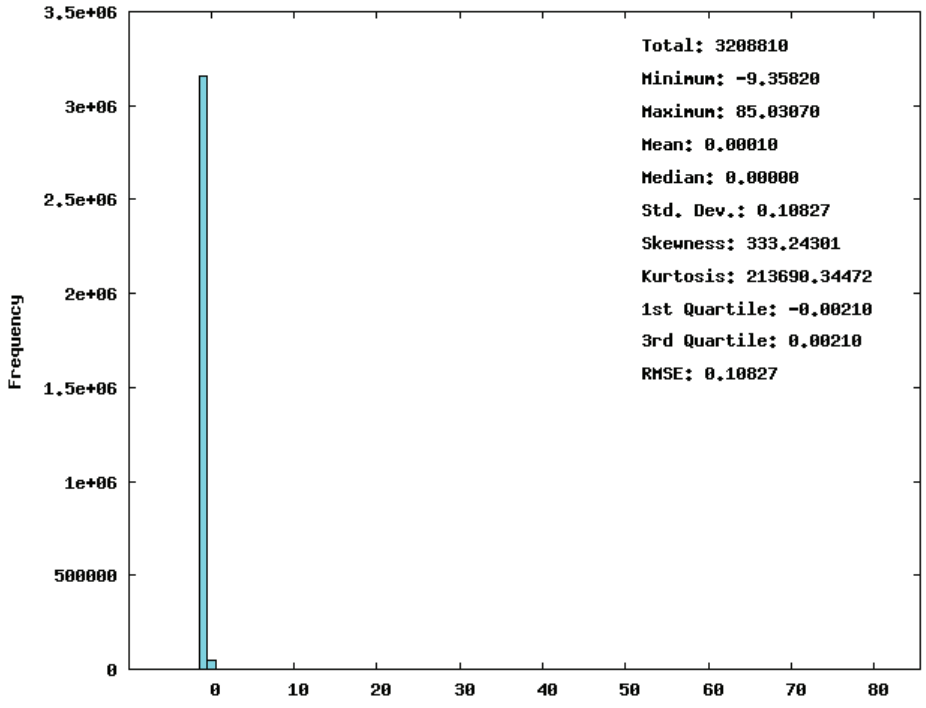

Figure 22. Histogram of the difference between all CCMA multibeam data and the 1/3 arc-second pre-surfaced bathymetric grid of St. Thomas and St. John.

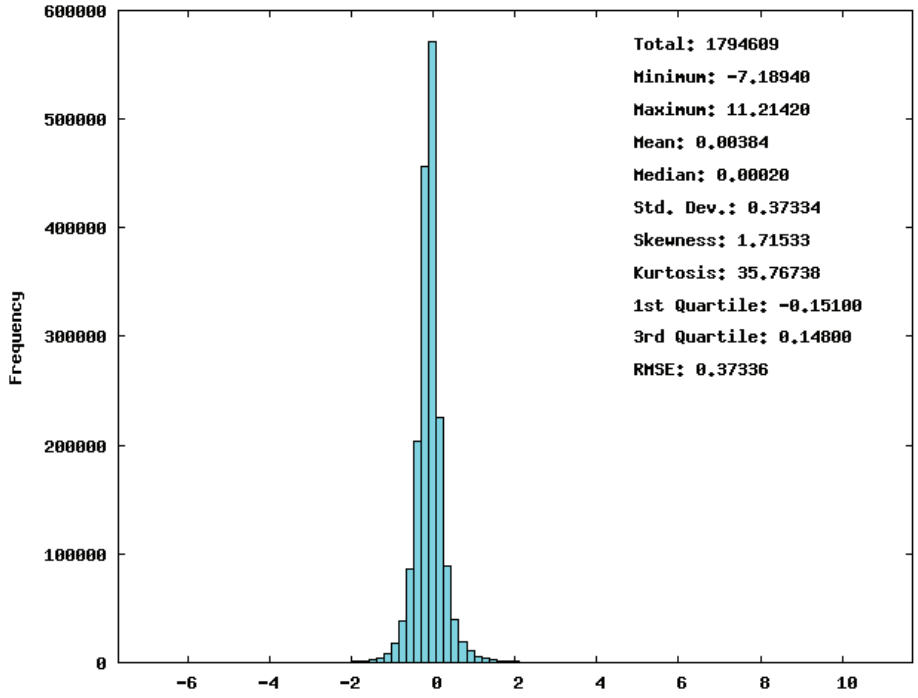

Figure 23. Histogram of the difference between on the USGS submerged bathymetric lidar data and the 1/3 arc-second pre-surface bathymetric grid of St. Thomas and St. John.

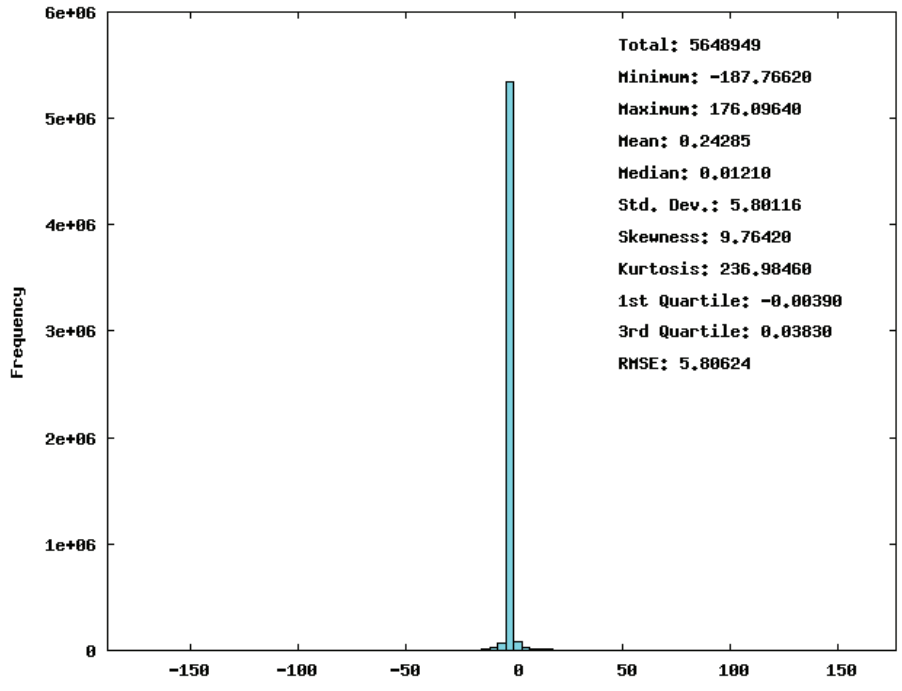

Figure 24. Histogram of the difference between the CCMA multibeam data and the 1/3 arc-second pre-surface bathymetric grid of St. Croix.

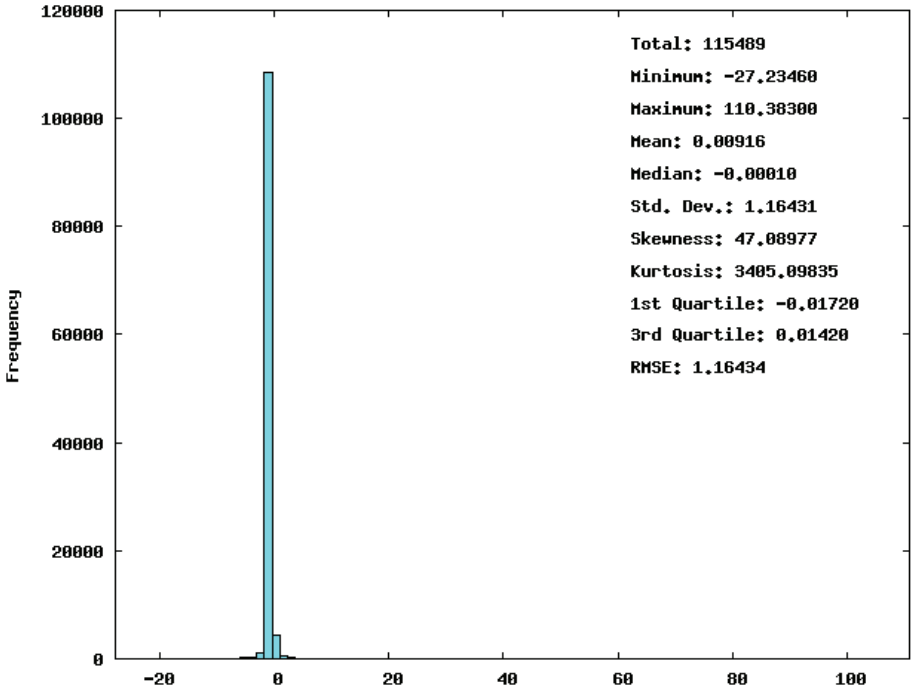

Figure 25. Histogram of the difference between the NOS survey data and the 1/3 arc-second pre-surface bathymetric grid of St. Croix.

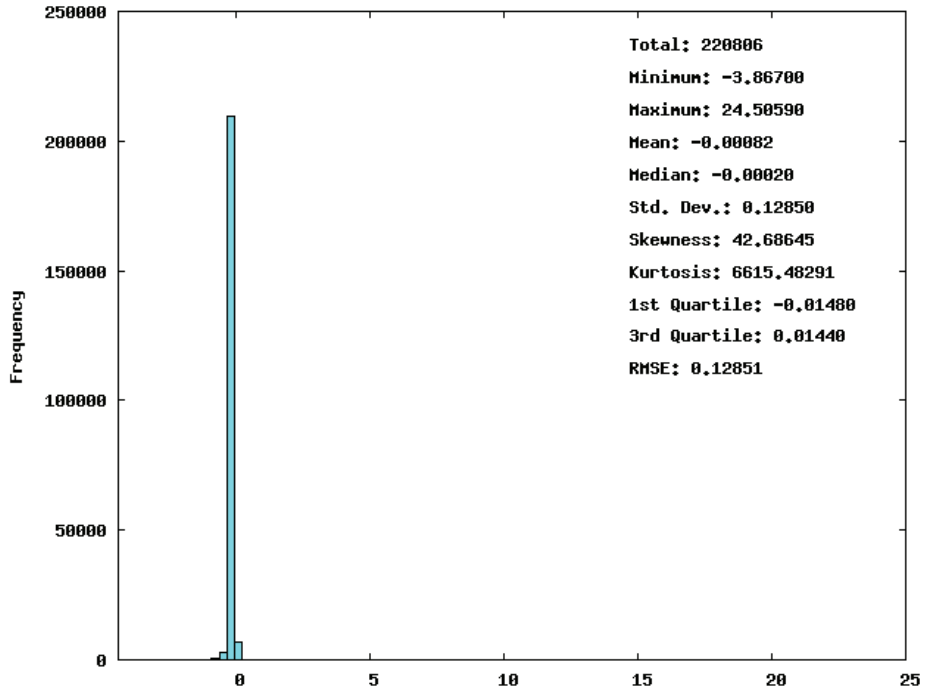

Figure 26. Histogram of the differences between the University of Virgin Islands multibeam data and the 1/3 arc-second pre-surface bathymetric grid of St. Croix.

3.3.3 Building the DEMs using MB-System

MB-System was used to create the U.S. Virgin Islands 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 13. Greatest weight was given to the multibeam surveys and the EAARL lidar surveys. Least weight was given to the pre-surfaced bathymetric grid.

Table 13. Data hierarchy used to assign gridding weight in *MB-System*

Dataset	*Relative Gridding Weight*
CCMA Multibeam	100
NGDC Multibeam	100
UVI Multibeam	100
NOS Surveys	100
USGS EAARL Submerged Lidar	100
USGS EAARL Topographic Lidar	100
NGDC Digitized Features	100
ENC Soundings	10
SRTM Topographic DEM	10
Trackline Soundings	1
NGDC Bathymetric Surface	0.1

3.4 Quality Assessment of the DEMs

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the U.S. Virgin Islands DEMs is dependent upon DEM cell size and source datasets. Topographic features have an estimated horizontal accuracy of 10-30 meters for the 1/3 arc-second DEMs and up to 90 meters for the 1 arc-second DEM: gridded USGS EAARL topographic lidar data have an accuracy of approximately 1 meter and 1 arc-second SRTM DEM data is accurate to approximately 30 meters and 3 arc-second SRTM data is accurate to approximately 90 meters. Bathymetric features are resolved only to within a few hundreds of meters in deep-water areas. Shallow, near-coastal regions have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings and potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values in the U.S. Virgin Islands DEMs is also dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy of 15 centimeter for the USGS EAARL topographic lidar data and 20 meters for the SRTM DEMs. Bathymetric values have an estimated accuracy between 0.1 meters and 5% of water depth. Those values were derived from the wide range of sounding measurements from the early 20th century to recent, GPS-navigated multibeam swath sonar survey. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Virgin Islands DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Figs. 27-29). The DEMs were transformed to WGS 84 UTM Zone 20 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids using *QT Modeler* revealed suspect data points, which were corrected before recompiling the DEM. Figures 31-33 show a perspective rendering of the final DEMs. Figure 30 shows a data contribution plot of the U.S. Virgin Islands DEMs.

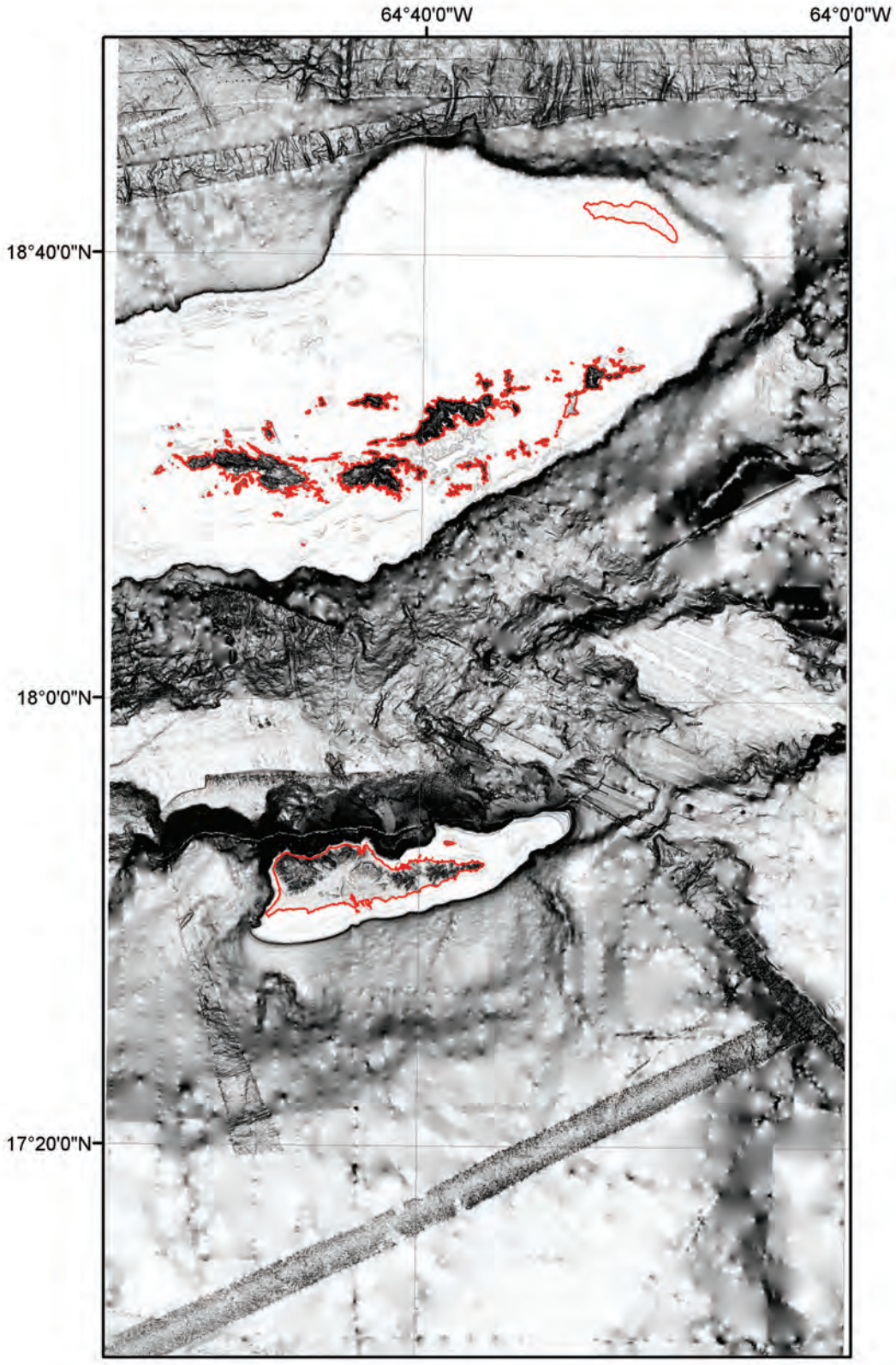

Figure 27. Slope map of the 1 arc-second U.S. Virgin Islands DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined coastline indicated in red.

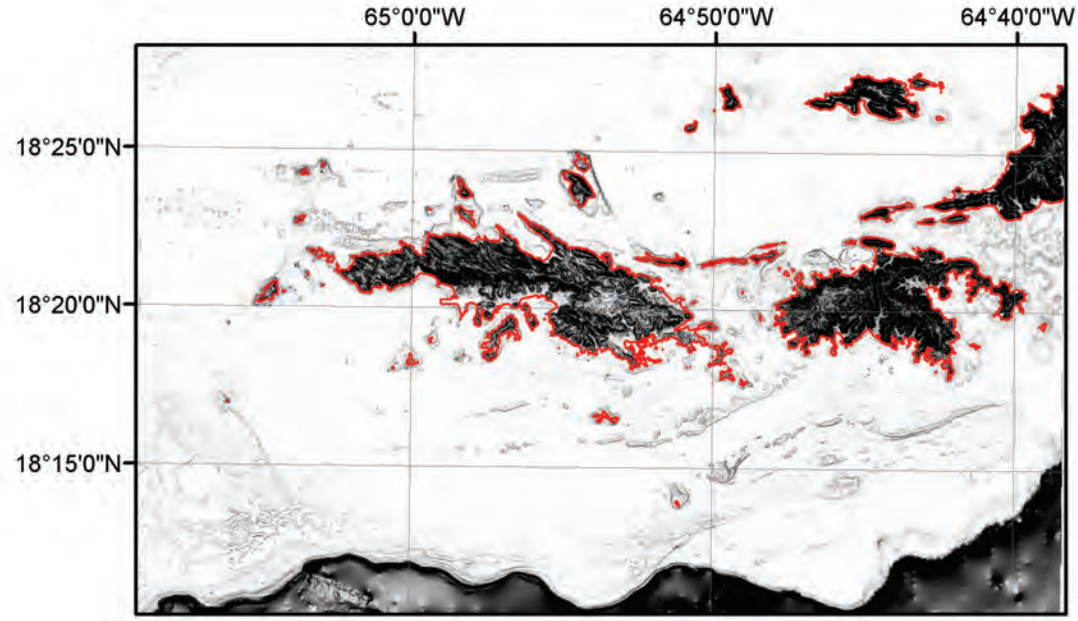

Figure 28. Slope map of the 1/3 arc-second St. Thomas and St. John, U.S. Virgin Islands DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined coastline indicated in red.

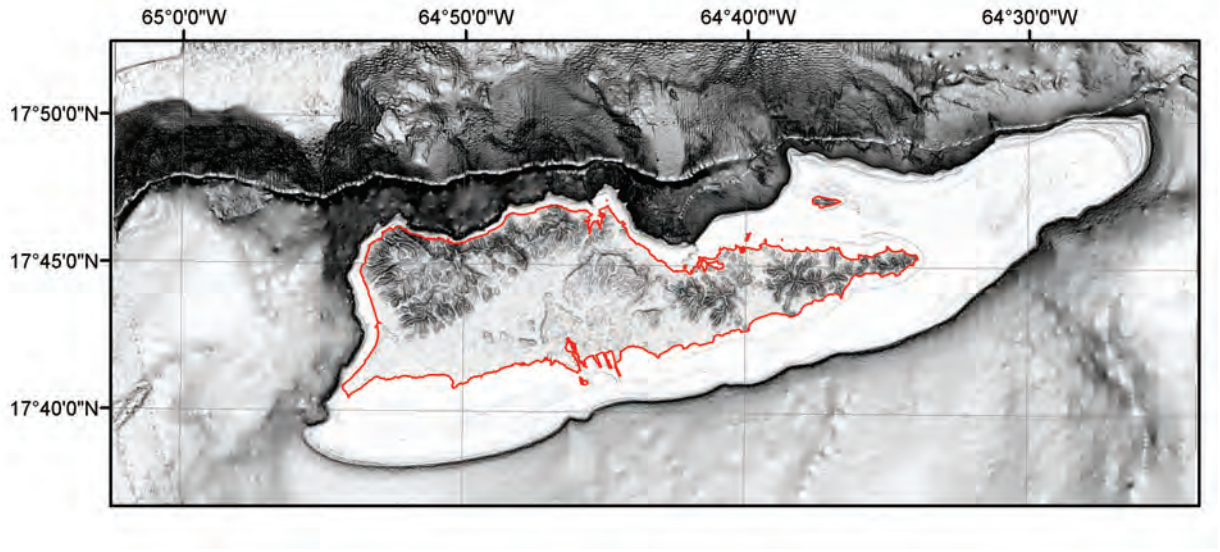

Figure 29. Slope map of the 1/3 arc-second St. Croix, U.S. Virgin Islands DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined coastline indicated in red.

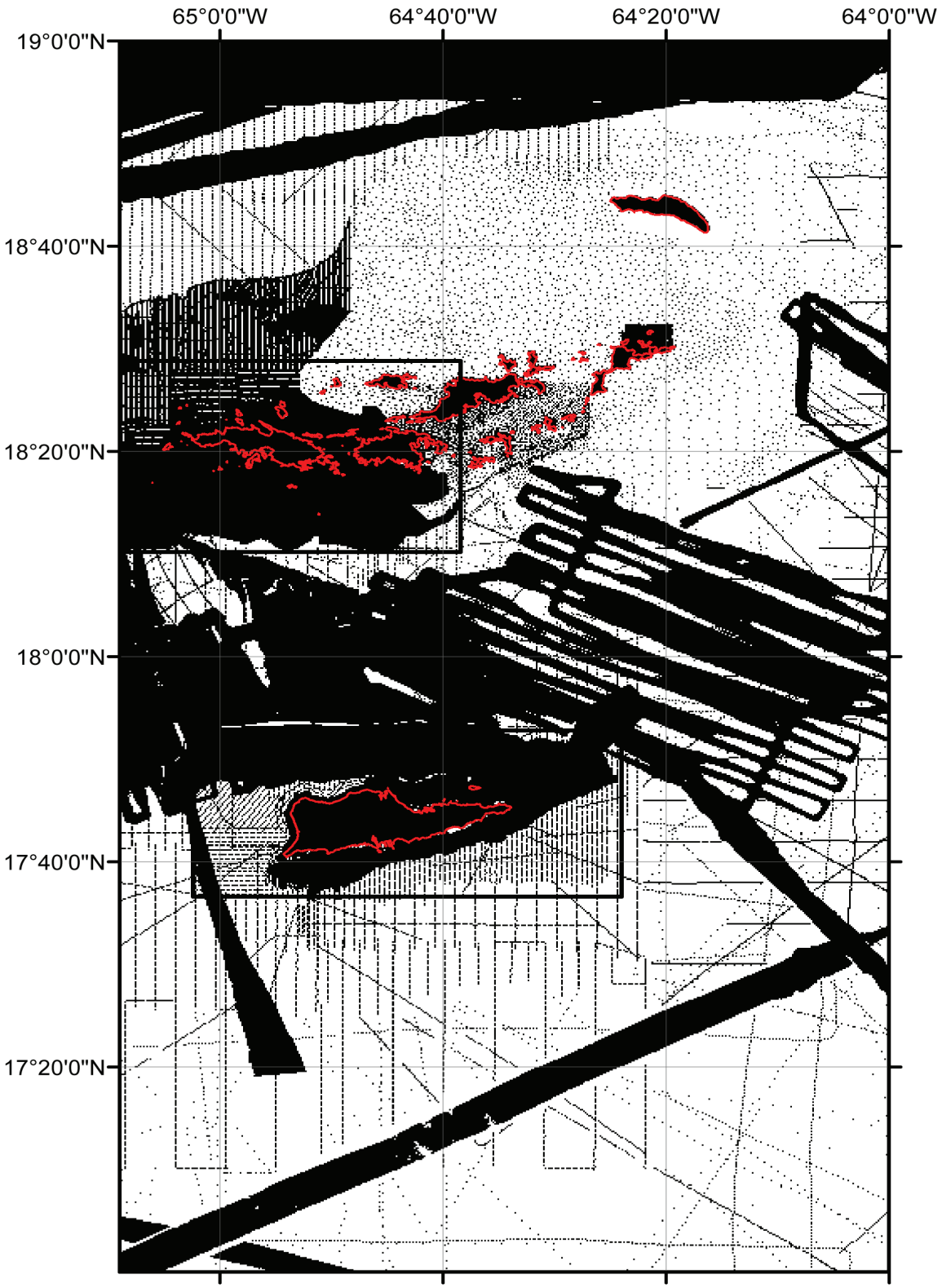

Figure 30. Data contribution plot of the U.S. Virgin Islands 1 arc-second DEM. Grey depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. Due to the scale of the image, sparse soundings may not be visible in the graphic. Coastline indicated in red.

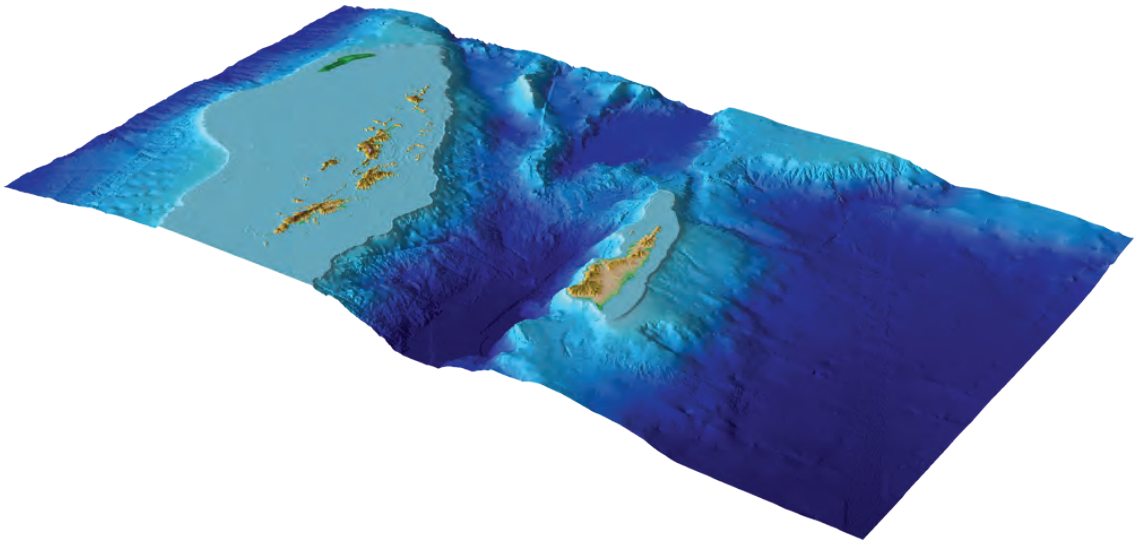

Figure 31. Perspective view from the southwest of the 1 arc-second U.S. Virgin Islands DEM. Vertical exaggeration - times 2.

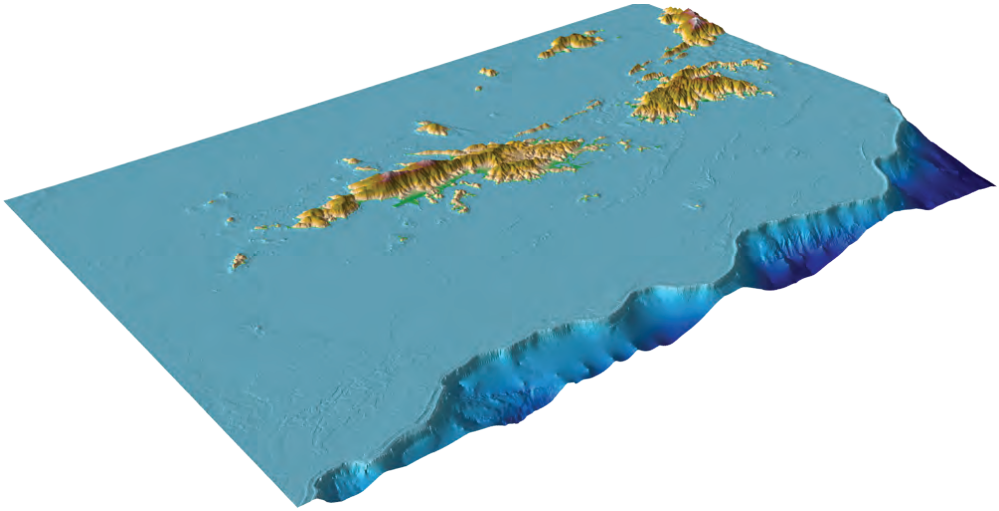

Figure 32. Perspective view from the southwest of the 1/3 arc-second St. Thomas and St. John, U.S. Virgin Islands DEM. Vertical exaggeration - times 2.

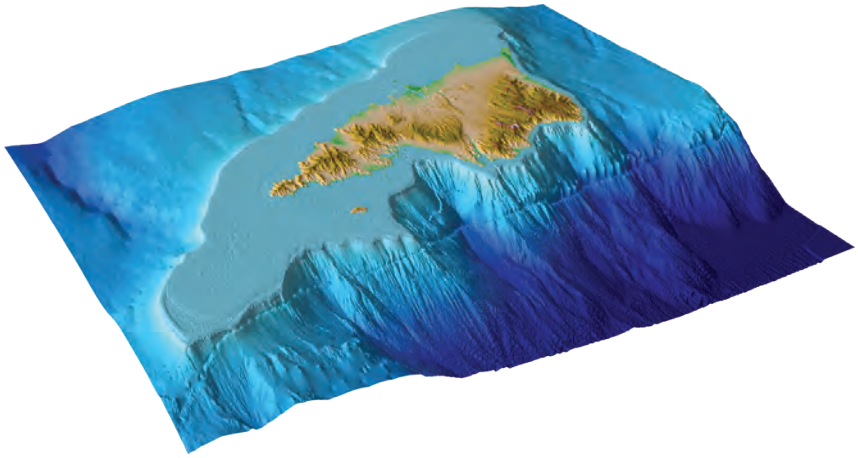

Figure 33. Perspective view from the northeast of the 1/3 arc-second St. Croix, U.S. Virgin Islands DEM. No vertical exaggeration.

3.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 335 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (Fig. 34). Only 122 monuments with conditions noted as 'GOOD' or 'MONUMENTED' were included in the analysis. Shapefile attributes give positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in local datum (in meters), which was assumed to be MSL. The elevations were converted to MHW and compared to the Virgin Islands MHW DEM (Fig. 35). Differences between the DEM and the monument elevations range from -73.28 to 79.44 meters. The mean distribution was ~ 3 meters. The overall large differences in elevations are mostly due to the topographic data not representing bare earth or lidar data on St. John averaged from 1 meter resolution to 30 meters resolution of the grid. The largest difference of +/- 70 meters occurred on offshore rocks where no topographic data existed. Rocks were digitized based on NOAA RNC charts.

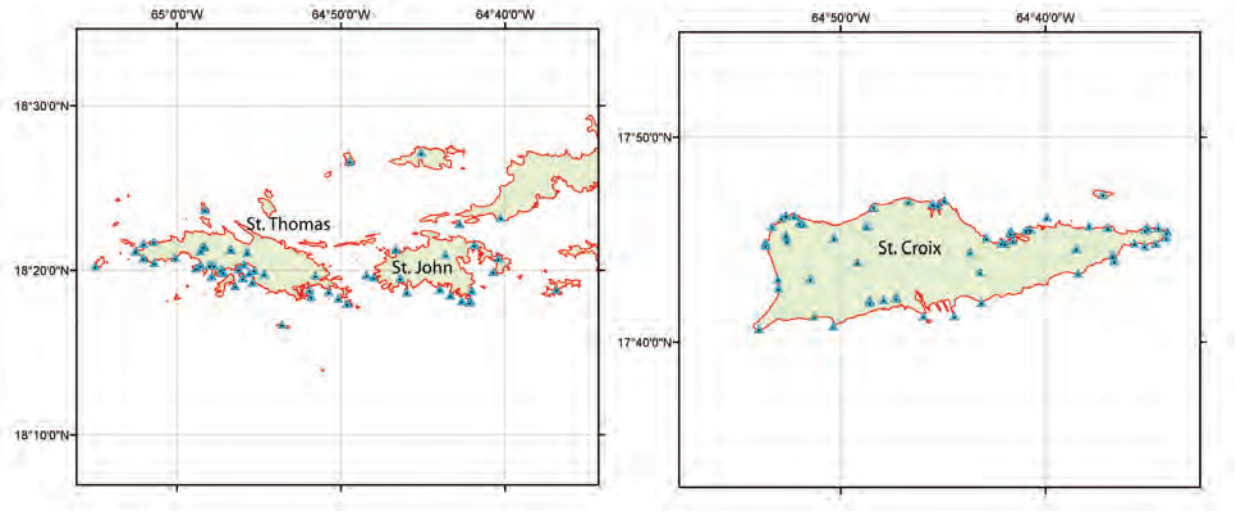

Figure 34. Location of NGS geodetic monuments in the Virgin Islands region.

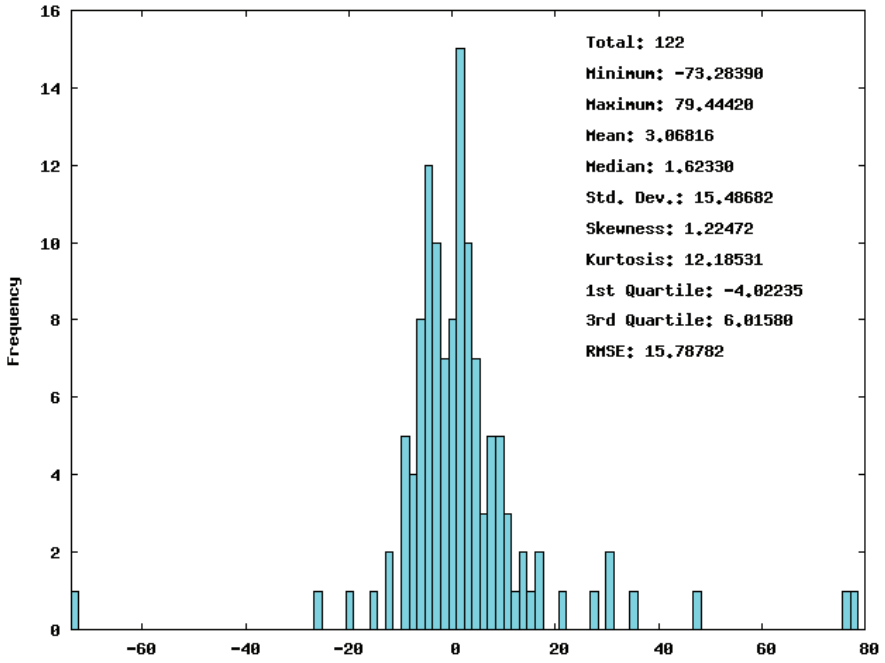

Figure 35. Histogram of the differences between NGS geodetic monument elevations and the U.S. Virgin Islands 1 arc-second DEM.

3.4.5 Virgin Islands DEMs comparison with source data files

To ensure grid accuracy, the U.S. Virgin Islands DEMs were compared to source data files. Select bathymetric data and topographic data files were compared to the 1 arc-second DEM of the U.S. Virgin Islands, and the 1/3 arc-second DEMs of St. Thomas and St. John, and St. Croix using *GDAL*.

A histogram of the differences between data points from NOS data, CCMA multibeam data, topographic lidar and the 1/3 arc-second St. Thomas and St. John DEM are shown in Figures 36 - 38. In Figure 36, the NOS data points agree well with the grid with a mean around 0. Difference of 20 meters or more occur on the steep shelf where multibeam data influence the cell value, and also along the edges of the land where topography data influence the cell value. In Figure 37, the USGS EAARL topographic data points also agree well with the grid with a mean around 0. Large differences are due to averaging the dense data points into a 10 meter cell that reflect both tree canopy and bare earth elevations. In Figure 38, CCMA multibeam data points agree well with the grid with a mean around 0. Differences of up to +/- 100 meters occur where dense data at the edge of the steeply dipping shelf are averaged into a 10 meter grid cell.

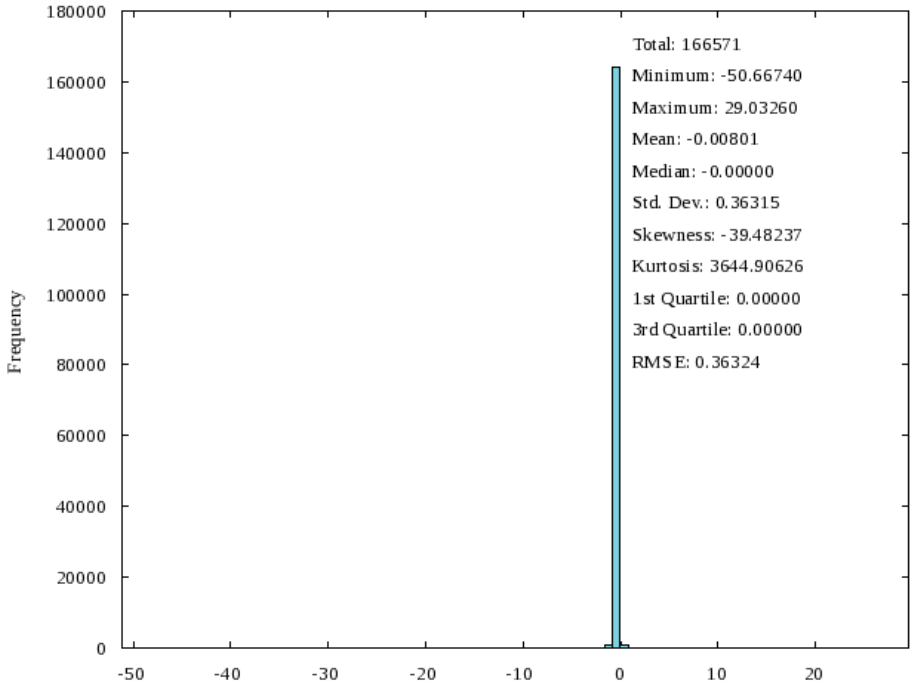

Figure 36. Histogram of the differences between NOS data points and the 1/3 arc-second St. Thomas and St. John DEM.

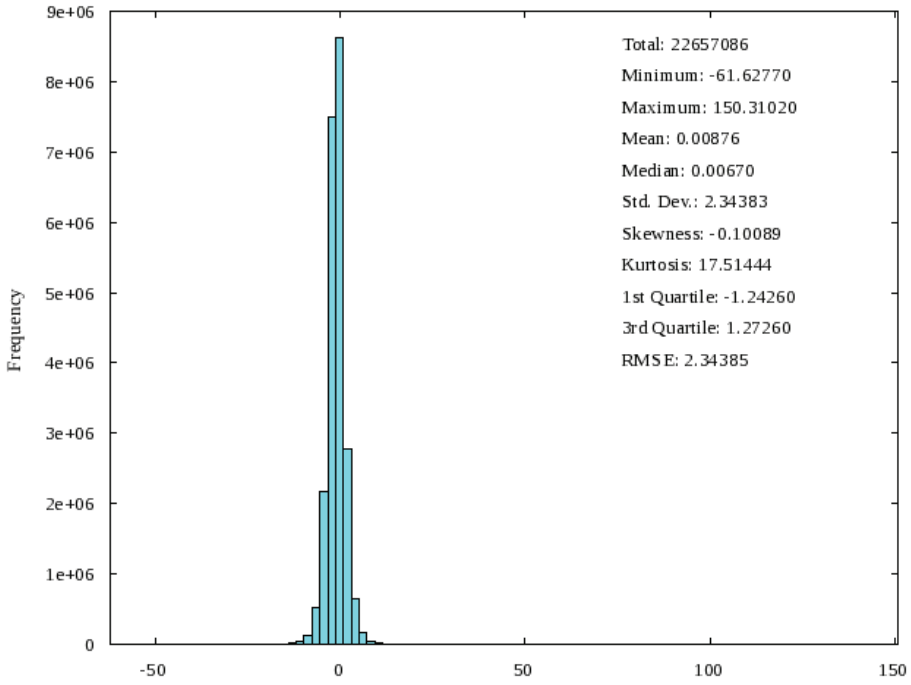

Figure 37. Histogram of the differences between USGS EAARL topographic lidar data points and the 1/3 arc-second St. Thomas and St. John DEM.

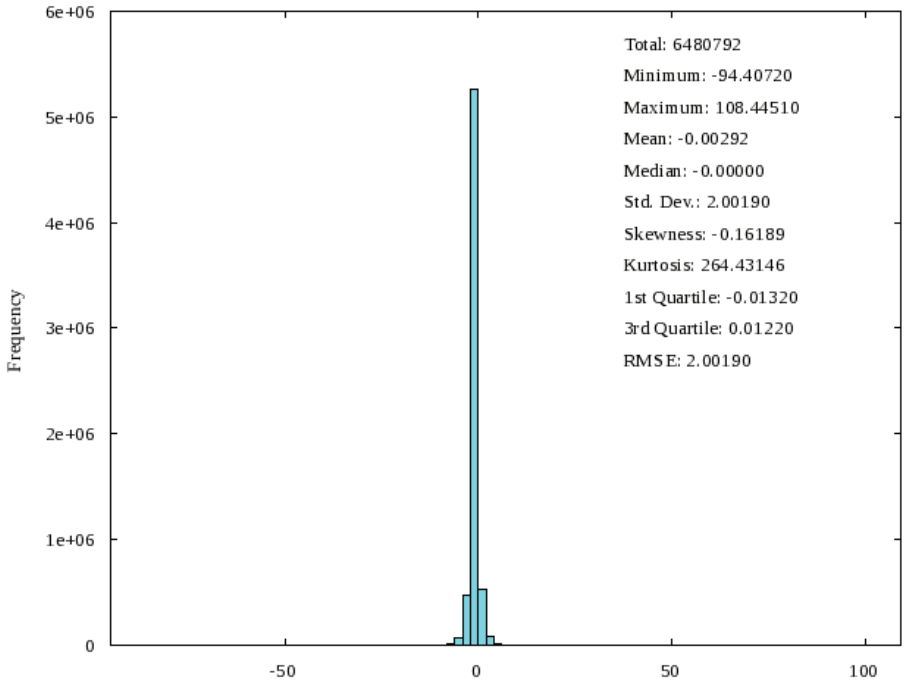

Figure 38. Histogram of the differences between CCMA multibeam data points and the 1/3 arc-second St. Thomas and St. John DEM.

A histogram of the differences between data points from NOS data, CCMA multibeam data, and SRTM DEM data and the 1/3 arc-second St. Croix DEM are shown in Figures 39 - 41. In Figure 39, the NOS data points agree well with the grid with a mean around of 0. Differences up 100 meters occur on the steep shelf where multibeam data influence the cell value, and also along the edges of the land where topography data influence the cell value. In Figure 40, CCMA multibeam data points also agree well with the grid with a mean around of 0.2. Differences of up to +/- 180 meters occur in the steep drop off from the shelf where multiple data points are averaged together. In figure 41, SRTM DEM data points agree quite well with the grid with a mean around 0. Minor differences up to 20 meters occur along the edge of the coast were bathymetry data falls in the same cell as the SRTM data.

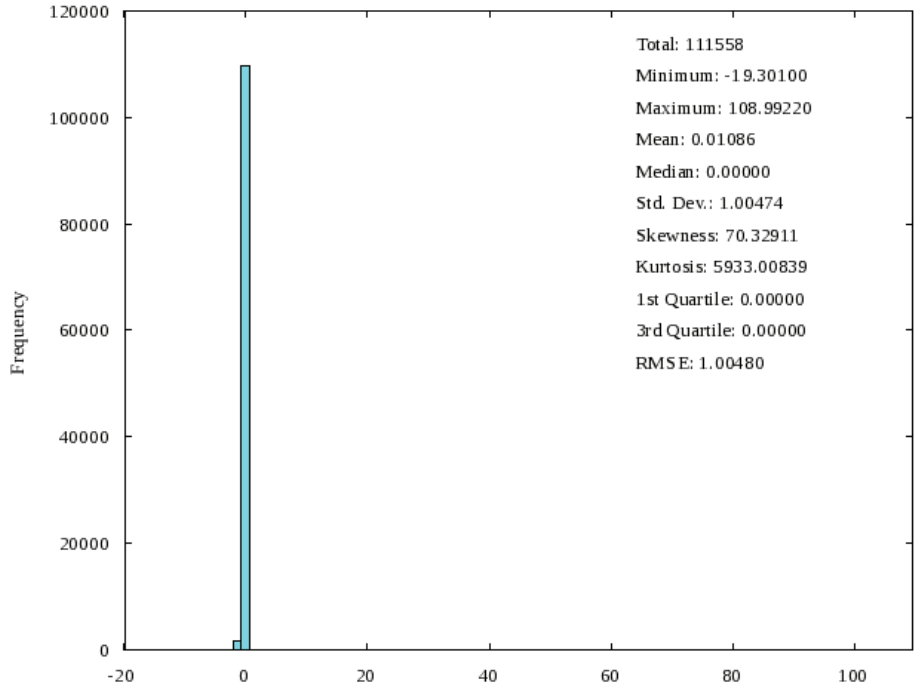

Figure 39. Histogram of the differences between NOS data points and the 1/3 arc-second St. Croix DEM.

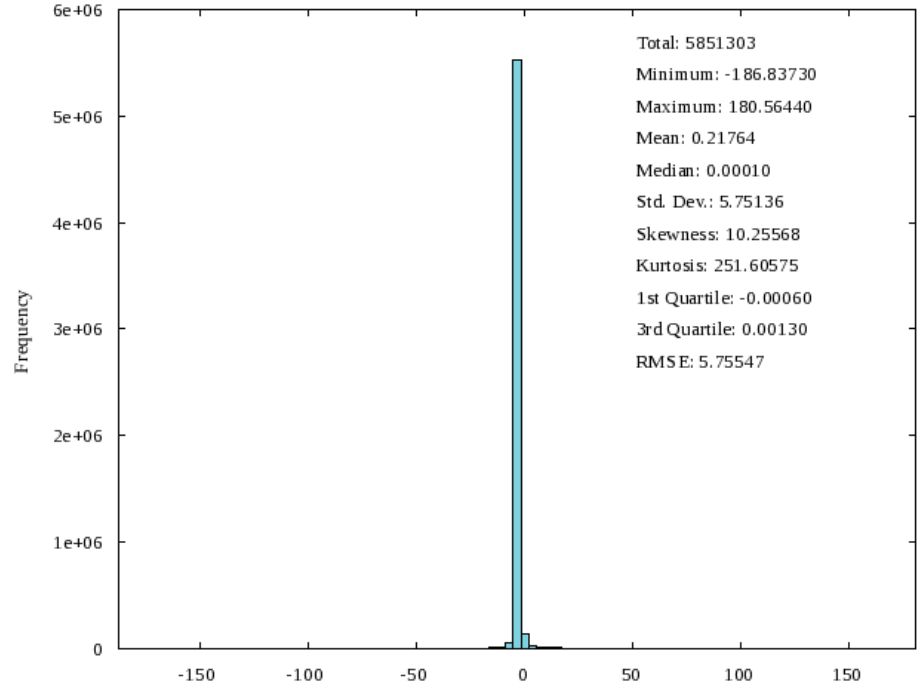

Figure 40. Histogram of the differences between CCMA multibeam data points and the 1/3 arc-second St. Croix DEM.

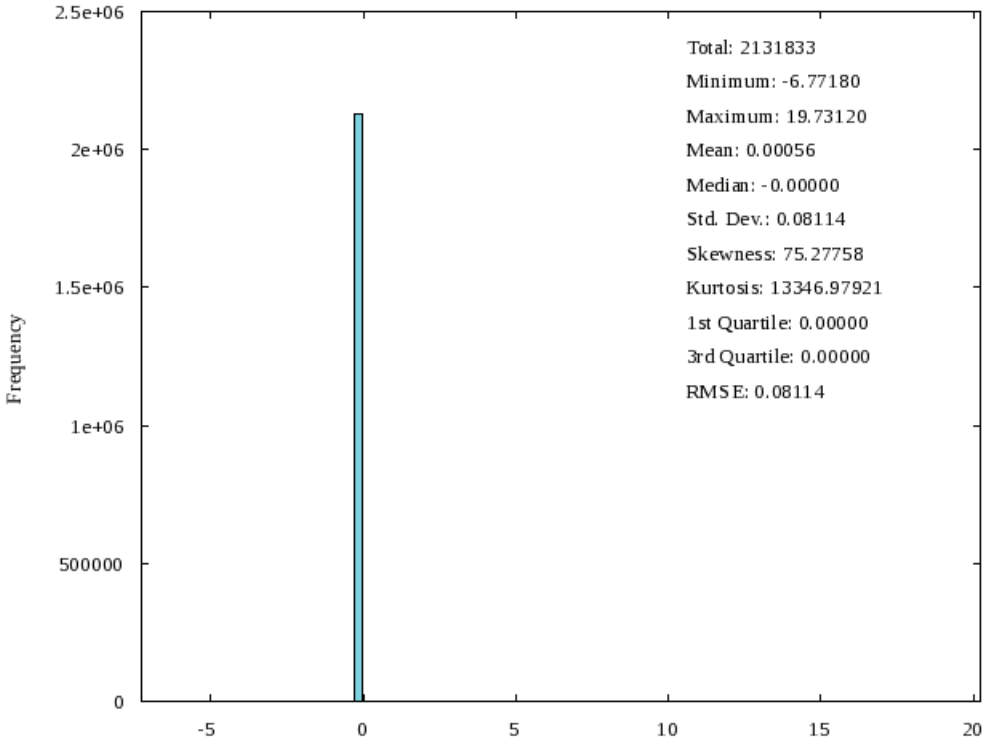

Figure 41. Histogram of the difference between SRTM DEM data points and the 1/3 arc-second St. Croix DEM.

A histogram of the differences between NGDC multibeam data points and the 1 arc-second U.S. Virgin Islands DEM are shown in Figure 42. The NGDC multibeam data points agree well with the grid with a mean value around 0. Few differences up 195 meters occur along the edges of the surveys where the data are influenced by surrounding surveys.

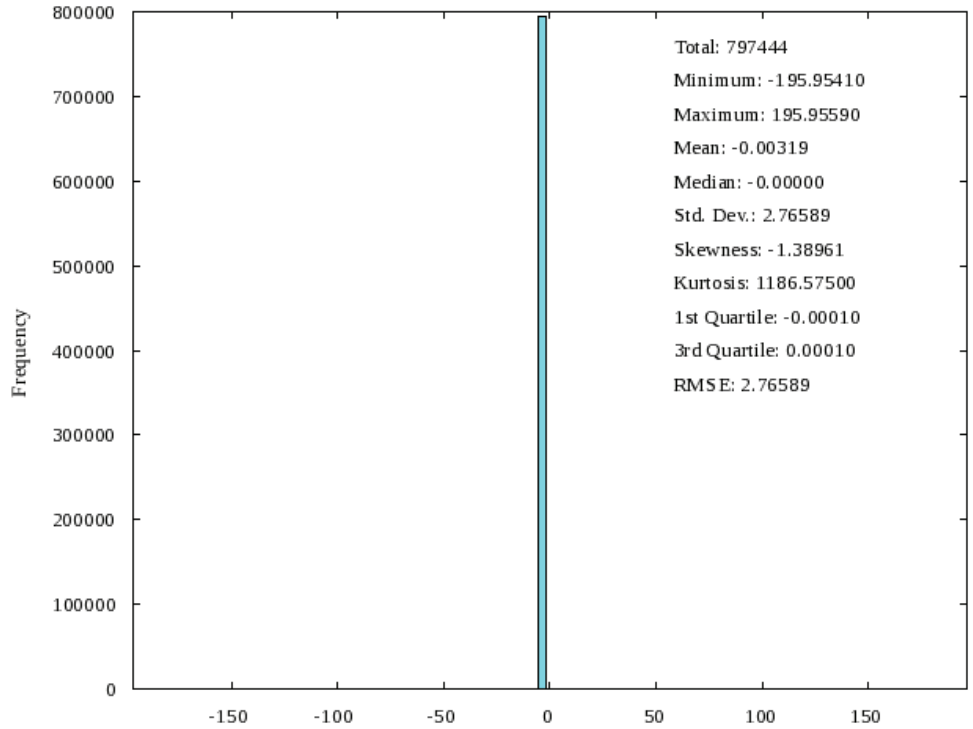

Figure 42. Histogram of the difference between the NGDC multibeam data points and the 1 arc-second U.S. Virgin Islands DEM.

4. Summary and Conclusions

Three integrated bathymetric–topographic digital elevation models of the U.S. Virgin Islands region, with cell sizes of 1 and 1/3 arc-second, were developed for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Research. The best available digital data from U.S. federal and academic 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 ESRI *ArcGIS*, ESRI *ArcGIS World Imagery 2D*, *FME*, *GMT*, *MB-System*, *QT Modeler*, *GDAL*, and *VDatum* software.

Recommendations to improve the U.S. Virgin Islands DEM, based on NGDC's research and analysis, include:

- Conduct high-resolution bathymetric multibeam surveys to cover the remainder area of the two 1/3 arc-second grids.
- Conduct bare-earth topographic lidar surveys of St. Thomas, St. John, and St. Croix.
- Conduct high-resolution hydrographic surveys near the British Virgin Islands.
- Conduct deep-water multibeam surveys south of St. Croix.

5. Acknowledgments

The creation of the Virgin Islands DEMs was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL); Bryan Costa and Tim Battista (CCMA); Uri ten Brink (USGS); Jeremiah Blondeau (UVI); Amar Nayega (USGS); and Dan Roman (NGS).

6. References

Electronic Navigational Chart #25640, 43rd Edition, 2008. Puerto Rico and Virgin Islands. Scale 1:326,856. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #25641, 27th Edition, 2004. Virgin Gorda to St. Thomas and St. Croix and Krause Lagoon Channel. Scale 1:100,000 and 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #25644, 13th Edition, 2003. Frederiksted Road and Frederiksted Pier. Scale 1:20,000 and 1:2,500. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #25645, 18th Edition, 2006. Christiansted Harbor. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #25647, 11th Edition, 2006. Pillsbury Sound. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #25649, 19th Edition, 2003. St. Thomas Harbor. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Electronic Navigational Chart #25650, 34th Edition, 2004. Virgin Passage and Sonda De Vieques. Scale 1:100,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #25609, 5th Edition, 1996. West Indies Virgin Islands St. Thomas to Anegada. Scale 1:80,000. Defense Mapping Agency.

Nautical Chart #25610, 8th Edition, 1996. West Indies British Virgin Islands Approaches to Gorda Strait. Scale 1:12,473. Defense Mapping Agency. Nautical Chart #25610, 22nd Edition, 1995. West Indies Virgin Islands Approach to Road Harbour. Scale 1:30,000. Defense Mapping Agency.

7. Data Processing Software

ArcGIS v. 9.3.1 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/.

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

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

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

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

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

MB-System v. 5.1.0 – 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/

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.

Appendix A. Vertical Datum Conversion Grids

NGDC created three offset grids approximating the relationship between MHW and MLLW, MHW and MLW, and MHW and MSL for the Virgin Islands region (Figs. A1 - A3). The grids were built in *ArcGIS* using the 'Inverse Distance Weighting' tool and the differences, in meters, between the vertical datums as measured at 6 NOAA tide stations (http://tidesandcurrents.noaa.gov/) (see Table 12; see Fig. 18). The grids span from 63º W to 66º W and 16º N to 20º N with a grid cell size of 3 arc-seconds. All vertical transformations to MHW were performed using these offset grids developed by NGDC.

Creating the Virgin Islands DEM proved to be challenging for several data sources with vertical datums in Ellipsoid heights or in a different geoid than Geoid 09. As of September 2009, there is no official vertical datum of the Virgin Islands, but the National Geodetic Survey provided NGDC with a preliminary hybrid model (Geoid 09) that relates the NAD 83 Ellipsoid (NSRS 2007) to the Virgin Islands Vertical Datum 2009 (VIVD 09)[10]. VIVD 09 is assumed to be equivalent to MSL. The model was provided to NGDC as xyz format and NGDC used the *GMT* tool 'surface' to smoothly grid the data at 1 arc-minute, spanning from 61º W to 70º W and 15º N to 21º N (Fig. A5).

Before the model could be applied to the data, all data needed to be the NAD 83 Ellipsoid (NSRS 2007). Several data sources have a vertical datum in the WGS 84 Ellipsoid. A conversion grid was built in *ArcGIS* using the 'Inverse Distance Weighting' tool using the differences between the WGS 84 and NAD 83 Ellipsoid heights of 14 selected points in the 1 arc-second DEM (Table A4). The difference values were found using the NGS Horizontal Time Dependent Positioning web site (http://www.ngs.noaa.gov/cgi-bin/HTDP/htdp.prl?f1=4&f2=1).

Table A1. Difference values between the WGS 84 and NAD 83 Ellipsoids.

Latitude	Longitude	Difference
-64	19	1.863
-65	19	1.862
-64	17	1.904
-65	17	1.902
-64.25	18.25	1.879
-64.75	18.25	1.878
-64.25	17.75	1.889
-64.75	17.75	1.888
-64.5	19	1.863
-64.5	17	1.903
-64.5	18	1.883
-65.15	19	1.862
-65.15	17	1.902
-65.15	18	1.882
-64	18	1.884

10. This is a Hybrid model for Puerto Rico and Virgin Islands that relates NAD 83 (NSRS 2007) to the Puerto Rico Vertical Datum 2002 (PRVD 02) surface in Puerto Rico and VIVD 09 datum in the U.S. Virgin Islands. VIVD 09 was not officially released at the time this DEM was created, but any changes in the model are only expected to be on the mm-scale, which is miniscule compared to the overall vertical accuracy of the DEM.

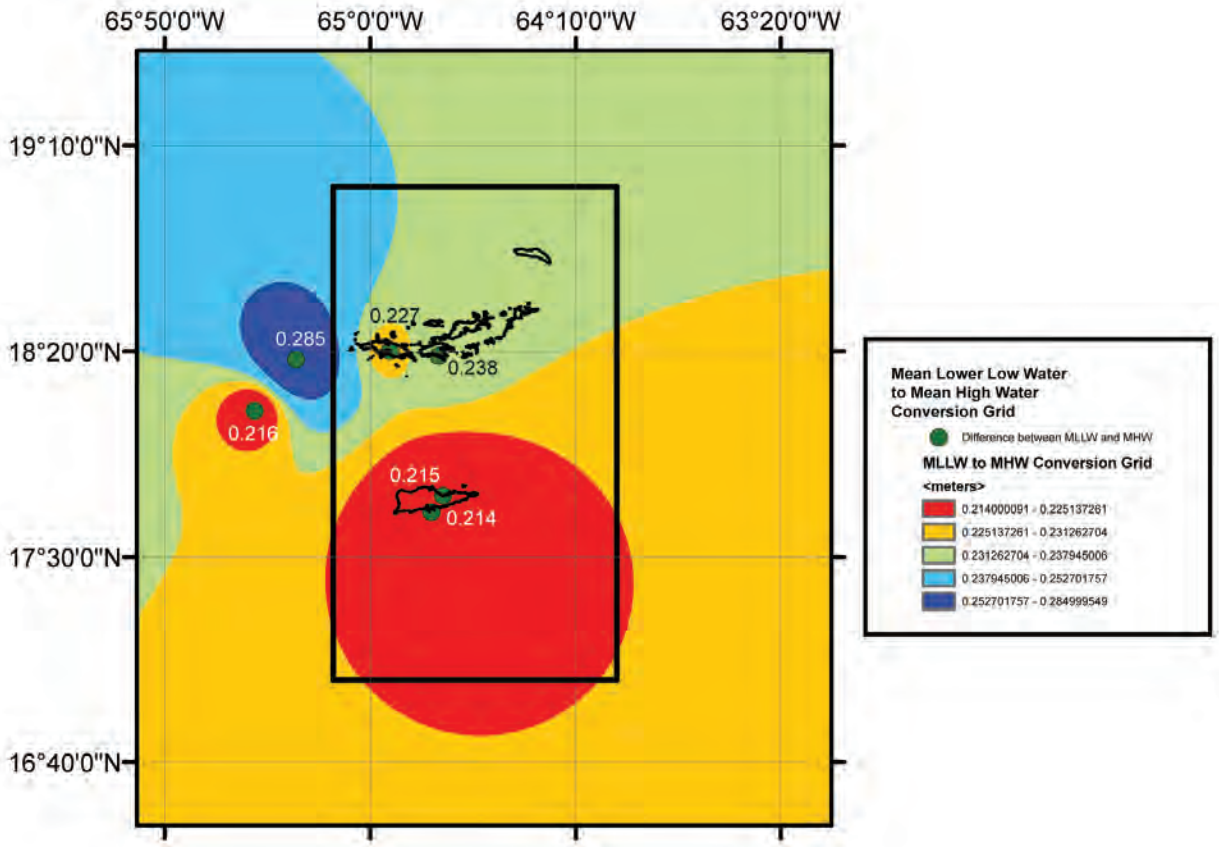

Figure A1. Color image of the conversion grid from MLLW to MHW using offsets from tide stations.

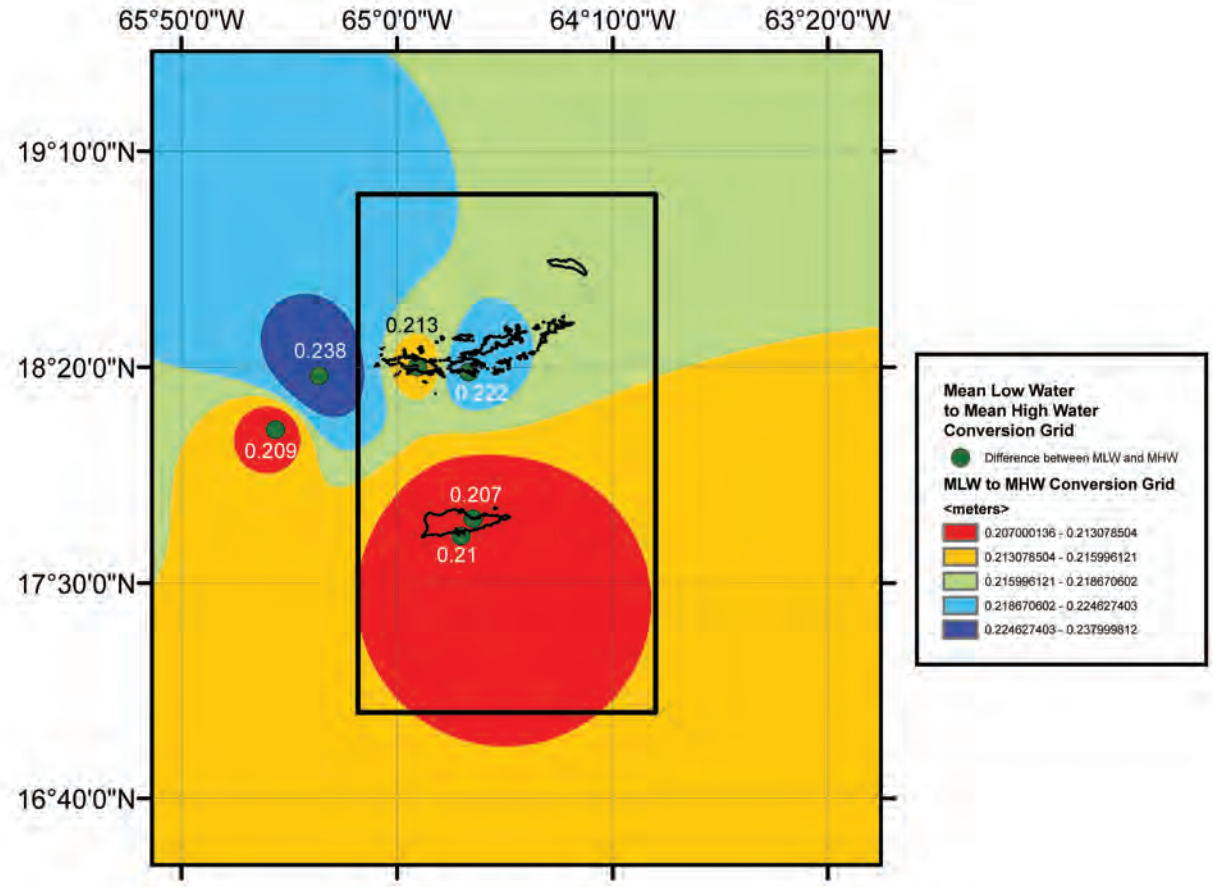

Figure A2. Color image of the conversion grid from MLW to MHW using offset from tide stations.

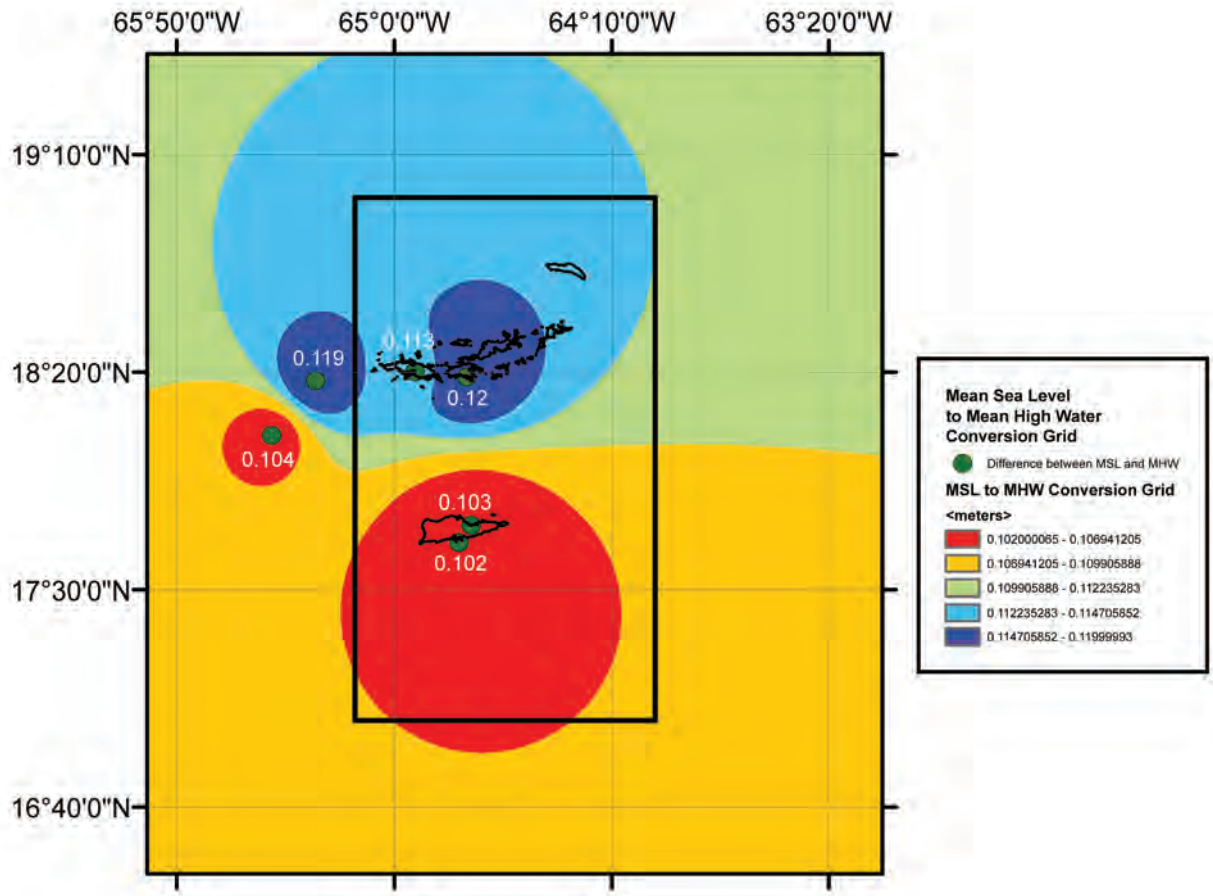

Figure A3. Color image of the conversion grid from MSL to MHW using offset from tide station

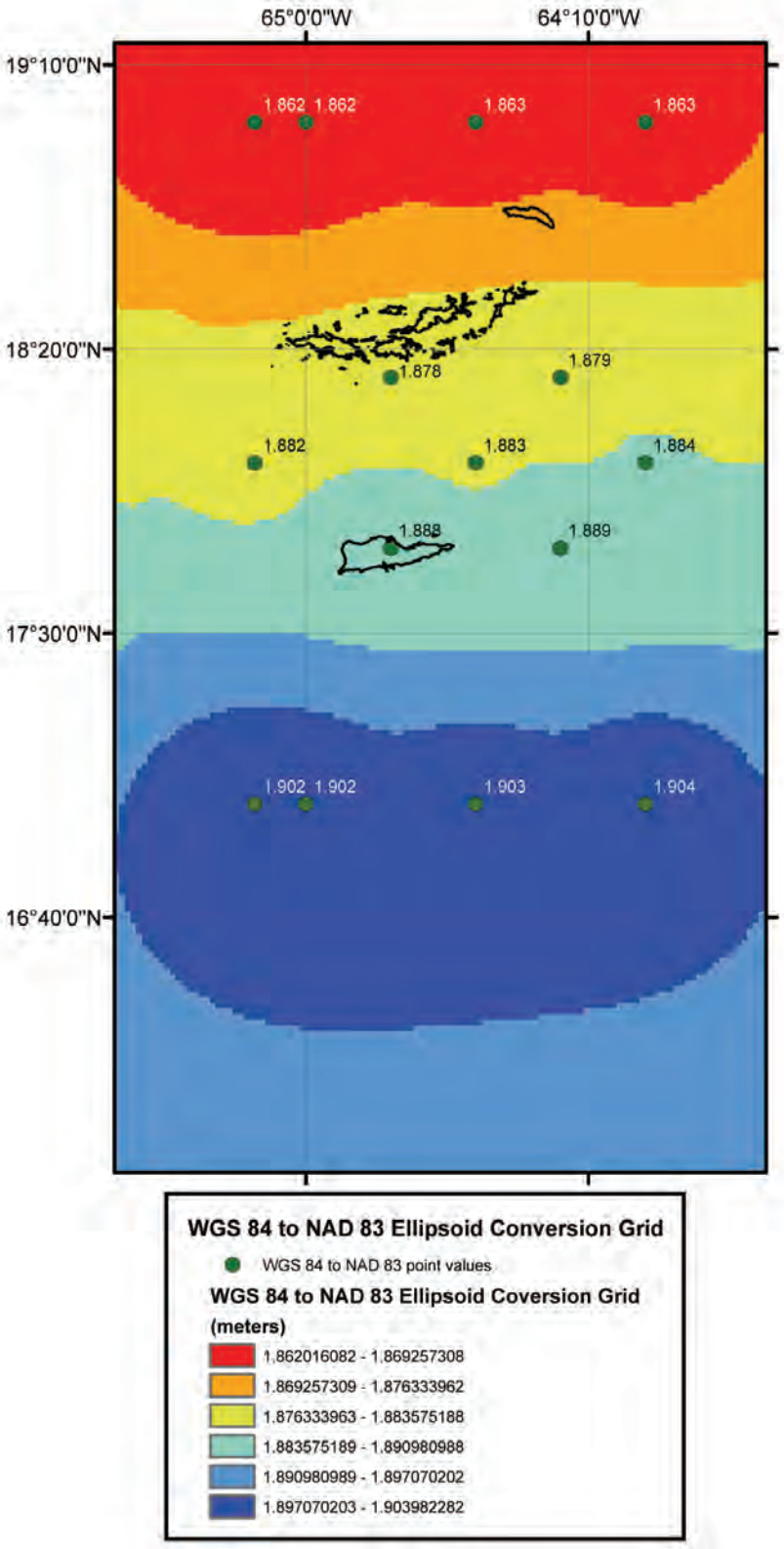

Figure A4. Color image of the conversion grid used to convert data from the WGS 84 ellipsoid to the NAD 83 ellipsoid.

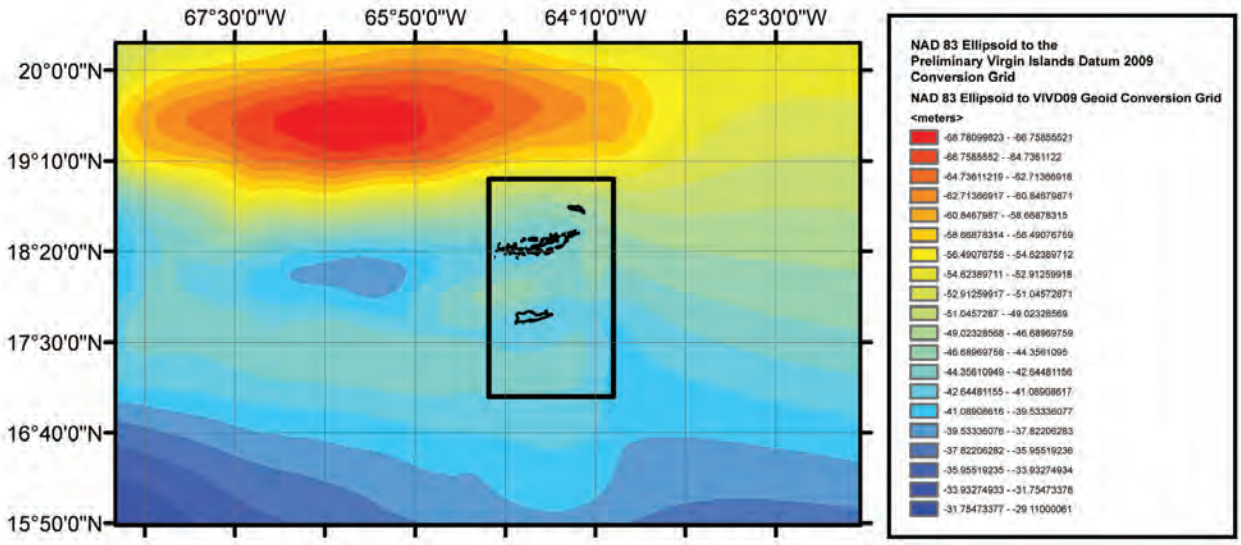

Figure A5. Color image of the conversion grid used to convert data from the NAD 83 ellipsoid to the preliminary VIVD 09 Geoid. VIVD 09 is assumed MSL.

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