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The Virgin Islands Vertical Datum of 2009

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ABSTRACT: The mission of the National Geodetic Survey (NGS) is to "define, maintain and provide access to the National Spatial Reference System to meet our nation's economic, social, and environmental needs." One component of that mission is to provide accurate geodetic control, including a vertical datum, for all territories of the United States. The U.S. Virgin Islands (U.S.VI) has had a mixed, patchwork series of geodetic control over the last century. This has included the lack of a comprehensive vertical datum for the entire U.S.VI. In accordance with its mission, NGS underwent an effort beginning in 2003, which has culminated in the Virgin Islands Vertical Datum of 2009. This paper defines that datum and describes the work leading up to its definition.

KEYWORDS: Vertical datum, Virgin Islands, leveling

History

The U.S. Virgin Islands are an insular area of the United States, comprised of the three major islands of St. Croix, St. John, and St. Thomas (Figure 1), and numerous minor islands. Located in the leeward area of the Caribbean Sea, the islands were purchased by the United States from Denmark in 1917. The territory has a total land area of approximately 134 square miles and a population of slightly less than 110,000 (2010 Census).

The U.S. Geological Survey (USGS) (1954) performed Third-Order geodetic leveling (Table 1) on St. Thomas in 1954 and St. Croix in 1957, in support of their topographic mapping operations. No records could be located which indicate that leveling has ever been performed on St. John. The heights on St. Croix and St. Thomas were determined as independent networks related to short-term tide gauges that had been previously established by the Coast and Geodetic Survey (C&GS), now the Center for Operational Oceanographic Products and Services (CO-OPS), which, like the National Geodetic Survey (NGS), is part of the National Oceanic and Atmospheric Administration, National Ocean Service (NOS). The network on St. Croix consisted of 14 permanent bench mark disks and 27 chiseled square reference points which were referenced to Mean Tide Level at the gauge in Frederiksted (CO-OPS station 9751584) that had operated for just five days, February 1-5, 1926. The network on St Thomas consisted of 20 permanent bench mark disks and seven chiseled square reference points referenced to Mean Low Water at the gauge at Creques Wharf in Charlotte Amalie (CO-OPS station 9751648), which operated during 1924-1925. This leveling also made a connection to the C&GS tide gauge at Magens Bay (CO-OPS station 9751635), but the heights do not refer to this tide gauge.

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Separate from the USGS efforts, C&GS performed astronomic latitude and longitude surveys in 1900 on St. Thomas (4 points) and St. Croix (1 point), with densification triangulation surveys performed in 1918 (on St. John and St. Thomas) and 1919 (on St. Croix). None of these stations were included in the USGS leveling so that there were no overlapping points between the 1900/1918/1919 horizontal surveys and the 1954/1957 vertical surveys. The C&GS triangulation data were integrated into the Puerto Rico Datum and later readjusted as part of the North American Datum of 1983 (NAD 83).

Additional geodetic work in the U.S. Virgin Islands includes the establishment, by the C&GS, of tide gauges on all three islands to support nautical charting, though these were never used to establish a vertical datum. Most of these gauges operated for less than six months.

During 1993, NGS established a small High Accuracy Reference Network (HARN) of GPS-surveyed passive control monuments to support the Federal Aviation Administration. Three HARN stations were established (one each at the St. Croix and St. Thomas airports and one at the Continuously Operating Reference Station (CORS)) collocated with the National Radio Astronomy

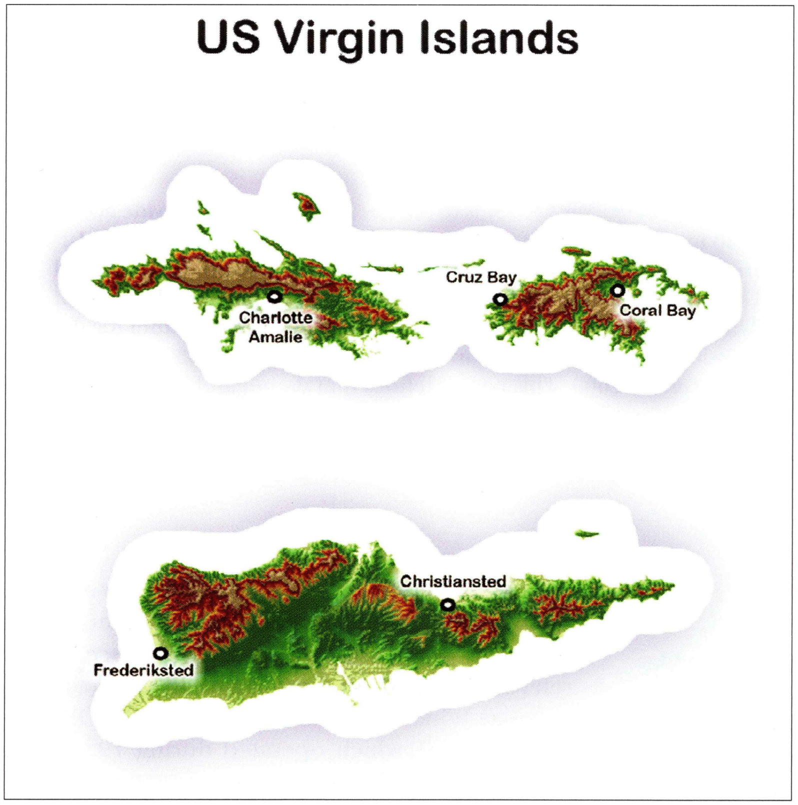

Figure 1. St. Thomas, St. John, and St. Croix islands.

Observatory, Very Long Baseline Array site on St. Croix. No HARN points were established on St. John. In addition to these HARN points, Primary and Secondary Airport Control Stations were established at the airports on St. Croix and St. Thomas. On St. John, no systematic leveling was performed prior to 2008, and no vertical datum has ever been established on the island.

In 2003, NGS, in collaboration with the Office of the Lieutenant Governor and the University of the Virgin Islands, initiated a program to improve the geodetic spatial framework for the territory. In addition to the installation of CORS at the University of the Virgin Islands campuses on St. Croix and St. Thomas, this effort included the implementation of a new vertical datum based on geodetic leveling campaigns on each island. The program's goal was met, as described below, and the vertical datum was named the Virgin Islands Vertical Datum of 2009 (VIVD09).

First-Order Class I	3 mm × √k
First-Order Class II	4 mm × √k
Second-Order Class I	6 mm × √k
Second-Order Class II	8 mm × √k
Third-Order	12 mm × √k

k = length of the line in kilometers.

Table 1. Geodetic leveling loop misclosures.

Reconnaissance and Mark Setting

During March 2004, a team from NGS performed reconnaissance and new mark site selection setting to support new leveling as well as GPS surveys on St. Croix and St. Thomas. Part of this reconnaissance was an effort to recover and document the condition of the bench marks previously set by USGS. With no existing leveling work on St. John, no recovery effort was necessary there. No field work was planned for the other islands, so neither reconnaissance nor mark setting was performed. The island-by-island details of the reconnaissance and mark setting are listed below. Installation of new marks was conducted just prior to the leveling observations on St. Croix and St. Thomas in 2007, and St. John in 2008.

Due to the expense of shipping equipment and supplies, no stainless steel rod marks were set as part of this project. All new marks consist of a standard NGS vertical control disk embedded in a concrete post, in an existing stable structure (e.g., bridge headwall, sea wall, etc.), or in bedrock.

St. Croix

Of the 14 original (1957) USGS marks on St. Croix, four were recovered. The locations of these marks were such that they were not close to the planned leveling routes and were not included in the new leveling. They should be considered for any possible future network densification efforts.

NGS installed 18 new bench marks along proposed leveling routes. Additionally, a total of 12 existing CO-OPS tidal bench marks (at 2 tide gauges) were part of the new leveling network. Finally, three existing airport marks were chosen, bringing the total number of marks in the VIVD09 leveling network on St. Croix to 33.

St. Thomas

Of the 20 original (1954) USGS marks on St. Thomas, three were recovered. The locations of these marks were such that they were not close to the planned leveling routes and were not included in the new leveling. They should be considered for inclusion in any future network densification efforts.

NGS installed eight new bench marks along the proposed leveling route. Additionally, a total of seven existing CO-OPS tidal bench marks (at 1 tide gauge) were part of the new leveling network. In addition, four existing airport marks were chosen, bringing the total number of marks in the VIVD09 leveling network on St. Thomas to 19.

St. John

Due to the lack of existing geodetic control of any kind at St. John, mark recovery was restricted to locating tidal bench marks near tide gauges. NGS installed 34 new bench marks along the proposed leveling route. Additionally, a total of 10 existing CO-OPS tidal bench marks (at 2 tide gauges) were part of the new leveling network, bringing the total number of marks in the VIVD09 leveling network on St. John to 44.

Leveling

On all three islands, the leveling crew performed double-run First-Order Class II leveling (Table 1) with a Leica DNA03[1] digital bar-code level and calibrated Invar rods (Figure 2). All work done in the U.S. Virgin Islands was performed by employees of NGS. An island-by-island breakdown of the leveling can be found below.

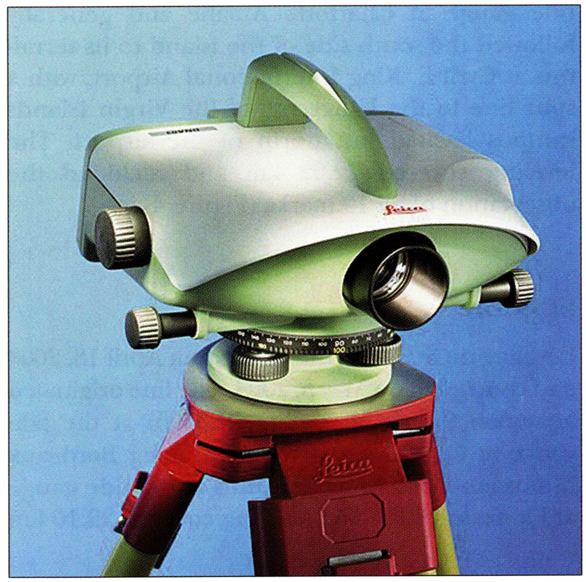

Figure 2. Leica DNA03 digital bar-code level.

St. Croix

Leveling on St. Croix commenced on August 13, 2007, at the primary bench mark, 975 1364 A (PID DK7162) at the gauge at Christiansted (#9751364), and concluded on August 24, 2007 at station 975 1401 M (PID DK7165), the primary bench mark at the tide gauge at Lime Tree Bay. From Christiansted, the leveling follows Highway 6 to Lime Tree Bay with 3.4 km spur line to Henry E. Rohlsen (formerly Alexander Hamilton) International Airport. The leveling covered 54.73 km and included the observation of all 33 marks (Figure 3).

St. Thomas

Leveling on St. Thomas commenced on August 13, 2007 and concluded on August 22, 2007. The line originated at the primary bench mark at the

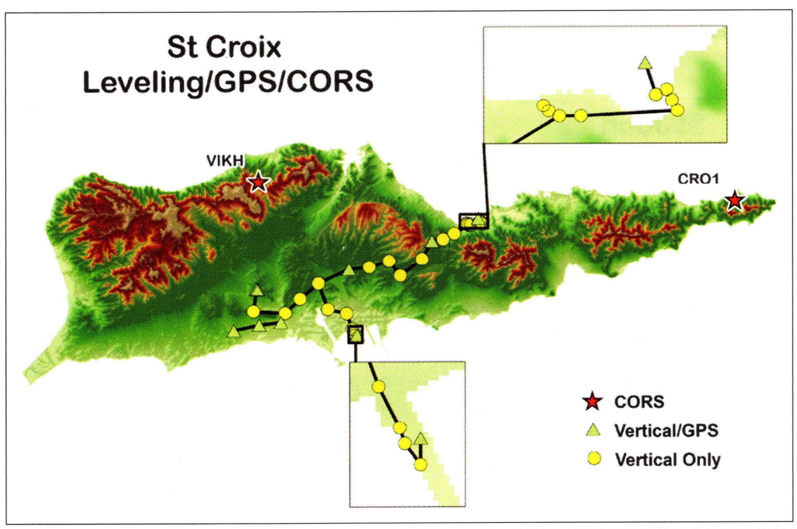

Figure 3. Leveling and GPS control on St. Croix.

[1] Reference to a commercial product does not constitute an endorsement of the product or manufacturer by the National Geodetic Survey.

tide gauge at Charlotte Amalie and generally followed the south side of the island to its terminus at Cyril E. King International Airport, with a spur line to the University of the Virgin Islands campus located just north of the airport. The leveling covered 22.02 km and included the observation of all 19 marks (Figure 4).

St. John

Leveling on St. John commenced on April 18, 2008 and concluded on May 3, 2008. The line originated at station 975 1472 5 (PID DL3596) at the tide gauge at Cruz Bay and followed along Bordeaux Mountain Road to its terminus at the tide gauge at Lameshur Bay. The leveling covered 29.10 km and included the observation of all 44 marks (Figure 5).

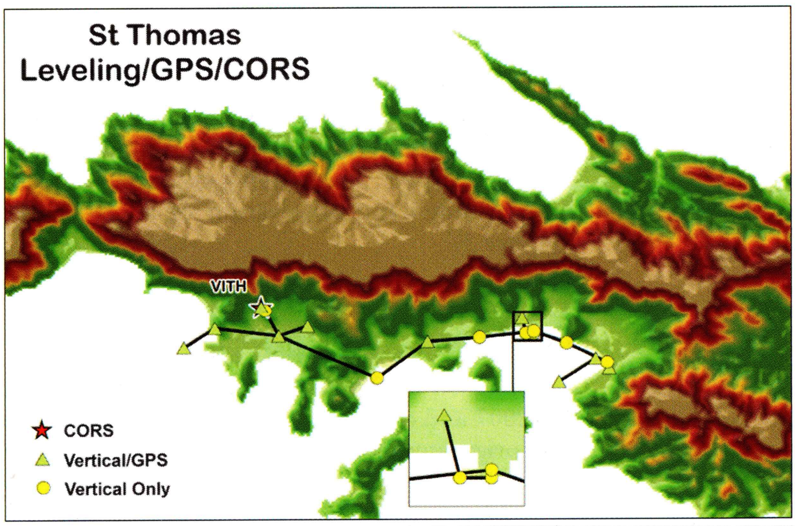

Figure 4. Leveling and GPS control on St. Thomas.

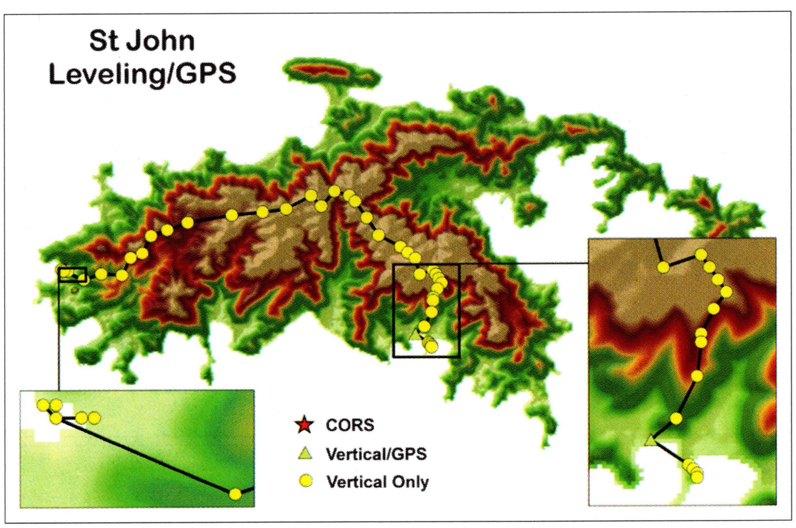

Figure 5. Leveling and GPS control on St. John.

GPS Surveys

Although GPS observations did not play a role in the definition of VIVD09, a number of marks did receive GPS observations for other geodetic purposes while NGS was in the area. All GPS static observations were performed with Ashtech Z-Xtreme[1] receivers with both ASH701975.01AGP and ASH701975.01BGP antennas. GPS sessions were of various lengths from 4 to 5.5 hr and in conformance with the specifications outlined in National Oceanic and Atmospheric Administration Technical Memorandum NOS NGS 58 (1997). All stations were occupied in at least two separate sessions offset by 4 hr. All stations were processed relative to the CORS network in the Virgin Islands, and final positions were computed in the NAD 83 (2007) realization. These stations will also participate in the upcoming NAD 83 (2011) national adjustment. An island-by-island breakdown of the GPS surveys is found below.

St. Croix

New GPS observations were taken on 9 of the 33 bench marks that make up VIVD09 on St. Croix. Of these, six were stations that had never been previously observed with GPS, while three were stations that had existing GPS-derived coordinates, but whose quality was somewhat suspect, leading to somewhat large network accuracies (see later). The GPS-surveyed points on St. Croix are identified in Figure 3.

St. John

A single bench mark C 1001 (PID DL3633) on the island was observed with GPS. This point will provide the only reference for a corrector surface for any future geoid model computation (as noted later in this paper). This single point is identified in Figure 5.

St. Thomas

Of the 19 bench marks leveled in the 2007 effort, four had a sufficiently clear view of the sky to be surveyed with GPS for the first time, while seven others received new observations, replacing older GPS observations. All 11 GPS-surveyed points on St. Thomas are identified in Figure 4.

Definition of Virgin Islands 2009 Vertical Datum

A decision was made to define the realization of VIVD09 on each island by holding fixed the 1983-2001 National Tidal Datum Epoch Local Mean Sea Level (LMSL) value at the primary bench mark of the longest active CO-OPS tide gauge on each island. This method was chosen as it was considered superior to that used in the Commonwealth of the Northern Marianas Islands (also three islands with one datum) in defining Northern Marianas Vertical Datum of 2003 (Carlson et al 2009). In the case of the U.S. Virgin Islands, each island had its own long-term tide gage to serve as a datum origin, and did not rely on intraisland tide "correctors" being calculated. The datum origin points for each of the three islands are described below. VIVD09 does not exist on any other islands in U.S. Virgin Islands at this time.

St. Croix

The bench mark designated "975 1401 M 1983" (PID DK7165 in the NGS Integrated Database), and defined by CO-OPS as the primary bench mark of the Lime Tree Bay, St. Croix NWLON site (#9751401; see Figure 6), was selected as the datum origin bench mark for VIVD09 on St. Croix. The LMSL value of 3.111 m was adopted at this bench mark as the fixed height from which all other VIVD09 heights on St. Croix are referenced.

St. John

The bench mark designated "975 1381 TIDAL A" (PID DL3636 in the NGS Integrated Database), and defined by CO-OPS as the primary bench mark of the Lameshur Bay, St. Thomas NWLON site (#9751381; see Figure 7), was selected as the datum origin bench mark for VIVD09 on St. Thomas. The LMSL value of 1.077 m was adopted at this bench mark as the fixed height from which all other VIVD09 heights on St. John are referenced.

Figure 6. Tide gauge (NWLON site #9751401) Lime Tree Bay, St. Croix.

Figure 7. Tide gauge (NWLON site #9751381) Lameshur Bay, St. John.

St. Thomas

The bench mark designated "975 1639 F" (PID DL3908 in the NGS Integrated Database), and defined by CO-OPS as the primary bench mark of the Charlotte Amalie, St. Thomas NWLON site (#9751639; see Figure 8), was selected as the datum origin bench mark for VIVD09 on St. Thomas. The LMSL value of 1.552 m was adopted at this bench mark as the fixed height from which all other VIVD09 heights on St. Thomas are referenced.

Integration with the Geoid Model

The current geoid model for the U.S.VI is GEOID03, which in this region is a purely

Figure 8. Tide gauge (NWLON site #9751639) Charlotte Amalie, St. Thomas.

gravimetric geoid (meaning that there are no GPS on bench mark observations integrated into the model as are found in the rest of the United States and its territories, with the exception of Puerto Rico and Hawaii). As with other Height Modernization survey programs, a significant part of this effort was to construct a vertical datum that when combined with GPS observations would provide a corrector surface to the gravimetric data to create a "hybrid" geoid, which will provide a direct transformation from GPS-derived ellipsoid heights in NAD 83 to orthometric heights in VIVD09.

Table 2 shows that on St. Croix, GEOID03 is biased relative to the newly determined VIVD09 heights by approximately 58 cm, with an uncertainty of approximately 11 cm (2 standard deviations) about that bias. Table 3 shows that on St. Thomas, GEOID03 is biased relative to the newly determined VIVD09 heights by approximately 28 cm, with an uncertainty of approximately 7 cm (2 standard deviations) about that bias.

As noted previously, a single bench mark was observed on St. John and the offset with respect to GEOID03 for this station is 0.42 m (Table 4). Considering the 11 cm and 7 cm 2-sigma values about the biases on St. Croix and St. Thomas, and without some additional GPS on bench mark observations, the use of GEOID03 in combination with GPS observations as the sole method to determine accurate VIVD09 heights on the island should be highly suspect, at least at the decimeter level.

It should be noted that the VIVD09 heights shown in Tables 2, 3, and 4 are unadjusted values and subject to minor changes. The GPS data will be included in the forthcoming national adjustment of the North American Datum of 1983 to be labeled NAD 83 (2011) and will contribute to a significant improvement in the prediction of local orthometric heights with the subsequent publication of an improved geoid model expected sometime in 2012. It is important to note that any improvements to the geoid model will be limited

PID	Designation	Observed VIVD09	h	N (GEOID03)	Predicted VIVD09 (H)	H - VIVD09
DK7140	VIKH B	31.997	−9.369	−41.934	32.565	−0.568
DK7141	VIKH A	29.683	−11.682	−41.932	30.250	−0.567
DK7148	B 1002	38.743	−2.611	−41.892	39.281	−0.538
DK7153	B 1012	69.964	28.654	−41.846	70.500	−0.536
DK7160	975 1364 C TIDAL	1.659	−39.670	−41.861	2.191	−0.532
DK7165	975 1401 M TIDAL	3.111	−38.120	−41.775	3.655	−0.544
TV1512	STX C	15.845	−25.379	−41.861	16.482	−0.637
TV1536	ST CROIX APT AP STA B	6.390	−34.783	−41.842	7.059	−0.669
TV1535	ST CROIX APT ARP STX	10.972	−30.233	−41.852	11.619	−0.647
					Average	−0.582
					2 SD	0.108

h = NAD 83 (2007) ellipsoid height.
All values are in meters.

Table 2. Comparison of VIVD09 with predicated heights from GEOID03 on St. Croix.

PID	Designation	Observed VIVD09	h	N (GEOID03)	Predicted VIVD09 (H)	H - VIVD09
AI4809	STT F	4.183	−38.147	−42.666	4.519	−0.336
DL3907	975 1639 G	2.495	−39.874	−42.639	2.765	−0.270
DL3914	A 1000	4.812	−37.569	−42.656	5.087	−0.275
DL3917	VITH A	41.481	−0.918	−42.671	41.753	−0.272
DL3918	VITH B	40.579	−1.821	−42.671	40.850	−0.271
TV1532	AP STA B	2.986	−39.351	−42.681	3.330	−0.344
TV1533	STT C	3.659	−38.668	−42.670	4.002	−0.343
TV1534	STT D	4.940	−37.387	−42.687	5.300	−0.360
TV1537	BETSY	2.529	−39.781	−42.647	2.866	−0.337
TV1548	TIDAL BM 1639 M	2.500	−39.849	−42.641	2.792	−0.292
TV1549	WESTON	0.973	−41.384	−42.648	1.264	−0.291
					Average	−0.279
					2 SD	0.072

h = NAD 83 (2007) ellipsoid height.
All values are in meters.

Table 3. Comparison of VIVD09 with predicated heights from GEOID03 on St. Thomas.

PID	Designation	Observed VIVD09	h	N (GEOID03)	H Predicted VIVD09 (H)	H - VIVD09
DL3633	C 1001	7.472	−34.793	−42.688	7.895	−0.423

h = NAD 83 (2007) ellipsoid height.
All values are in meters.

Table 4. Comparison of VIVD09 with predicated heights from GEOID03 on St. John.

to the areas in the vicinity of the leveling and should be used with caution when attempting to predict VIVD09 in other parts of the islands. While the standard deviations at the 95 percent confidence level for the data sets for St. Croix and St. Thomas are both rather high, they are influenced by three stations on St. Croix that have NAD 83 (2007) ellipsoid heights with network accuracies of 4.9-5.6 cm and seven stations on St. Thomas with network accuracies of 7.4-8.3 cm. When these are removed from the comparisons the error estimates drop to 1.6 and 0.2 cm, respectively. The problem stations were all reobserved with GPS in this project and should produce significantly improved ellipsoid heights when adjusted as part of the NAD 83 (2011) solution.

Consistency with Flood Insurance Rate Maps

During 2007, the Federal Emergency Management Agency (FEMA) published new Flood Insurance Rate Maps for U.S.VI. These maps are in no way related to the vertical control published by NGS as part of VIVD09. The FEMA Flood Insurance Study of April 16, 2007 indicates that 13 "bench marks" were used to support this mapping effort. The Flood Insurance Study (780000V000A, Section 3.4, and Table 8) (FEMA 2007) indicates that these marks are related to NOS tidal datums and that the heights were computed by the U.S. Army Corps of Engineers, Jacksonville District. No further information detailing which tidal datum was used or the accuracy of the heights is provided in the report. A single station, BETSY (PID TV1537), on St. Thomas is the only station common to the VIVD09 and FEMA data sets. The height difference between the two systems at this mark is 1.5 cm (0.05 ft) as shown below. While this value may hint at some consistency between the two data sets, it must be considered "no check" and should not be used as the basis to perform any height transformations. This warning is especially true for work done on St. Croix and St. John where no overlapping points exist.

PID	DESIGNATION	VIVD09 (m)	FEMA (m)	HT DIFF (m)
TV1537	BETSY	2.529	2.514	0.015

Surveyors, engineers, and others conducting flood plain surveys and other studies related to the Flood Insurance Rate Maps should use extreme caution and validate the relationship between VIVD09 and the FEMA control stations.

Future Network Densification

The work completed by NGS represents the foundation from which the local government should pursue a program of height modernization and bench mark densification for the rest of the territory. This is especially true on the islands of St. Croix and St. Thomas where a significant portion of the population is still some distance from the leveling network. While the populated areas of St. John are relatively well supported with the leveling network, additional GPS observations on bench marks should be conducted to improve the ability of future geoid models to predict accurate VIVD09 values in this and other parts of the islands. NGS is not aware of any plans for such surveys at this time.

ACKNOWLEDGMENTS

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