Development of Comprehensive Geodetic Vertical Datums for the United States Pacific Territories of American Samoa, Guam, and the Northern Marianas

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ABSTRACT: The importance of establishing accurate heights to support engineering, mapping, and scientific applications is very well recognized. A network of stable, easily accessible survey control points, referred to as bench marks (BMs), is crucial to a wide range of activities, including coastal zone management, floodplain mapping, stormwater and sewer utility management, large-scale engineering projects, hurricane evacuation and recovery planning, and topographic mapping. The official heights reported on a network of BMs are usually defined with respect to a regional, national, or international geodetic datum, such as the North American Vertical Datum of 1988 (NAVD 88). In the United States, the official vertical datums of each region are fundamental components of the National Spatial Reference System (NSRS), which is maintained by the National Geodetic Survey (NGS), an office of the National Ocean Service (NOS), National Oceanic and Atmospheric Administration (NOAA).

KEYWORDS: Geodesy, vertical datums, coastal zone management, floodplain mapping, topographic mapping, NSRS, NGS, American Samoa, Guam, Northern Marianas

Vertical Control Networks

Vertical control networks are most often realized by a network of monumented survey marks called bench marks (BMs). These marks usually take the form of a brass, bronze, or aluminum disk, typically 8-11 cm in diameter, set in bedrock, a concrete post (Figure 1), or other stable structure, such as bridge abutments and headwalls. Bench marks may also be monumented by stainless steel rods driven to refusal (Figure 2). The need for a high degree of monument stability (including mark stability within its setting, as well as setting stability relative to the surrounding crust) cannot be overstated.

Networks of BMs are normally set at 1- to 3-km intervals (with an average spacing of about 1.6 km), usually along primary and secondary roadways or along railroad lines. These networks are observed by differential leveling which can achieve extremely high degrees of precision (Figures 3 and 4).

Unfortunately, geodetic leveling is a very time-consuming and expensive process, with the rate of progress determined by the training and motivation of the observing team, congestion of traffic along roads, weather conditions, and the slope of the terrain. Elevation accuracies of geodetic networks in the United States are defined in the 1984 Federal Geodetic Control Committee *Standards and Specifications for Geodetic Control Network* (FGCC 1984). Relative accuracies

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Figure 1. Mark set in concrete post.

Figure 2. Stainless steel rod mark.

Figure 3. Differential leveling, Guam.

Figure 4. Differential leveling, Commonwealth of the Northern Mariana Islands.

between vertical control points are described as a constant times the square root of the length in km (k) of the distance of the leveling operation.

Improving Geodetic Vertical Control in United States Pacific Territories

The U.S. Geological Survey (USGS) performed geodetic leveling in the United States Pacific Island Territories of American Samoa (AS) in 1962 and the Commonwealth of the Northern Marianas (CNMI) in 1969, in support of the national topographic mapping program commonly referred to as "7.5 minute topo quads." The U.S. Coast & Geodetic Survey (USC&GS), the predecessor of NGS, conducted leveling on the island of Guam during 1963. The USGS surveys were performed to Third-Order accuracy, and the USC&GS leveling was observed to First-Order Class I standards (Table 1). All of the vertical datums on these islands were defined through measurements of local mean sea level (LMSL) at tide gages unique to each island.

First-Order, Class I	=	0.5 mm × $\sqrt{k}$
First-Order, Class II	=	0.7 mm × $\sqrt{k}$
Second-Order, Class I	=	1.0 mm × $\sqrt{k}$
Second-Order, Class II	=	1.3 mm × $\sqrt{k}$
Third-Order	=	2.0 mm × $\sqrt{k}$

Table 1. Elevation accuracy standards.

Data collected during USGS leveling surveys on these islands were never submitted to NGS for inclusion in the NSRS (National Spatial Reference System). Unfortunately, because the USGS data have not been automated, finding the control information for these data was not a simple process. Moreover, because there has never been a comprehensive network maintenance or recovery effort by any federal or territorial agency, so the exact status of the island networks was unknown until 2001. Natural events such as storms and erosion, as well as human activities including road and infrastructure improvements, land development, agriculture, and, unfortunately, vandalism have destroyed or disturbed many of these bench marks. After visiting Guam, American Samoa, and Commonwealth of the Northern Mariana Islands (CNMI), NGS determined that only 15-20 percent of the original bench marks still existed, and that the positions and elevations of those that did remain had not been validated in more than 40 years.

An additional reason to improve the vertical framework is the effect of tectonic motions. Guam and CNMI lie directly along the boundary of the Pacific and Philippine tectonic plates and are subject to significant motions generated by earthquakes. These naturally occurring events have also caused significant damage to the accuracy of previously established horizontal and vertical control points (see Figure 5).

To address the deterioration of these monumented bench mark networks, NGS, in collaboration with NOAA's Costal Services Center (CSC) and Pacific Services Center (PSC), proposed a comprehensive initiative for the development of new leveling activities for Guam, the American Samoa island of Tutuila, and the islands of Rota, Saipan, and Tinian in the Commonwealth of the Northern Mariana Islands.

The proposal included recovery and reconnaissance of the previously established USGS and USC&GS bench marks, establishing new monuments at approximately 0.9-1.5 km apart along public access roads in order to improve the stability and integrity of the vertical network, and establishing differential leveling between

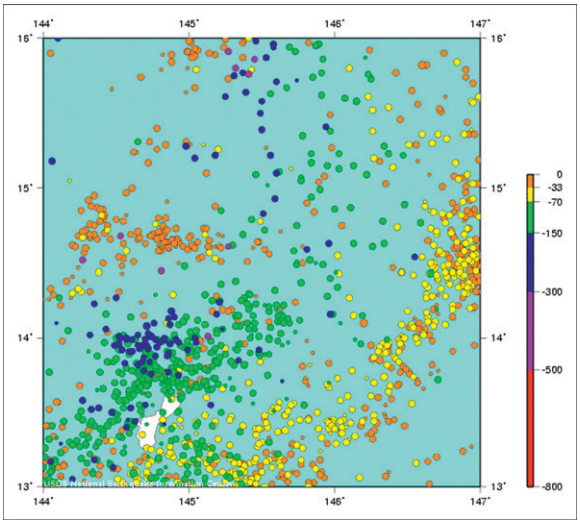

Figure 5. Earthquakes of magnitude 1.0 or larger in the area of Guam and the Commonwealth of the Northern Mariana Islands (Source: USGS National Earthquake Information Center).

these points to First-Order, Class II standards. The datum origin bench mark for each island was to be defined by the National Water Level Observation Network (NWLON) operated by the NOS Center for Operational Oceanographic Products and Services (CO-OPS). A significant part of this effort would be training and workshops on the proper use of geodetic control and capacity building given jointly with the surveying professionals of these communities.

The proposal also provided for the integration of the horizontal and vertical positional improvements gained from using Global Positioning System (GPS) specifications consistent with the NGS Height Modernization Initiative (NGS 1998). NGS oversight would ensure an integrated survey program to provide positional accuracies of not more than 1 cm in the horizontal and 2 cm in the ellipsoid height components (NOAA 1997) relative to the North American Datum of 1983 (NAD 83).

The goals of this effort were as follows:

- Increase the GPS geodetic control station densification by implementing a Federal Base Network (FBN) and Cooperative Base Network (CBN) network on all the primary islands of American Samoa, Commonwealth of the Northern Mariana Islands, and Guam.
- Observe a geodetic leveling network on each island, to at least First-Order, Class II standards with connections between the CO-OPS tidal bench marks, FBN/CBN stations, and Continuously Operating Reference Stations (CORS).
- Train island personnel in high-accuracy GPS and geodetic leveling techniques.
- Ensure the integration of the data collected into the NGS database and publication as part of NSRS.

The surveys were conducted by a team of NGS geodetic surveyors working with local surveying and mapping personnel from each island or island group. In addition to being an integral part of the survey team, the local surveyors benefited from advanced GPS training and gained familiarity with vertical concepts, applications, datum transformations, and surveying processes.

American Samoa

American Samoa is made up of seven islands in the western Pacific Ocean. The largest of these islands is Tutuila, neighbored closely by Aunu'u. The islands of Ofu, Olosega, and Ta'u (jointly called the Manu'a Islands) sit to the east of Tutuila, while Swains Atoll and Rose Atoll round out the list (Figure 6).

USGS performed geodetic Third-Order leveling in American Samoa in 1962 with sections up to two miles in length. This network consisted of 79 monumented bench marks (72 on Tutuila Island and seven on Ta'u Island). No leveling was performed on the islands of Aunu'u, Ofu, or Olesega, nor on the Swains or Rose atolls.[1]

Figure 6. Islands and atolls comprising American Samoa.

[1] However, USGS had established triangulation stations on the islands of Tutuila, Ofu, Olosega, and Ta'u at the same time as the leveling campaign. Of the 72 bench marks on Tutuila, 16 were also triangulation stations. Of the seven bench marks on Ta'u, four were also triangulation stations.

Heights on Tutuila were defined in 1962 by USGS as mean sea level (MSL) and were referenced to the USC&GS tide gage located at Pago Pago (177 0000) based on ten years of tidal records spanning 1949-1955 and 1957-1959. The primary bench mark for this tide gage had the designation "NO 2 1948" (no PID as it is not a point in the NGS Integrated Database), and its adopted height was 7.67 ft.

Heights on Ta'u were referenced to Mean Tide Level or MTL (though called "Half Tide Level" at the time of their creation) and were connected to a temporary tide gage established by USGS at Matavai Point for the duration of the leveling operations of May 19 to June 8, 1962. The primary bench mark had designation "TIDE GAGE" (no PID), and its adopted height was 5.425 ft. No effort was made to correlate this gage with the USC&GS gage at Pago Pago.

In 2002, NGS embarked on a project with the goal of establishing new geodetic control, including a new vertical datum, for American Samoa. This goal was met, as described below, and the vertical datum was named the American Samoa Vertical Datum of 2002 (ASVD02).

2002 Efforts

Participation

All work done in American Samoa was performed in partnership with American Samoa's Department of Commerce (DOC), Department of Public Works (DPW), and Power Authority (ASPA). NGS, The National Park Service (NPS), and the private firm of L.P. French and Associates were part of the team. All work was performed between March and September 2002.

Reconnaissance

Reconnaissance was performed to support new leveling (as well as GPS surveys) on the island of Tutuila only. No reconnaissance was done on the islands of Aunu'u, Ofu, Olosega, Swains Atoll, Rose Atoll, or Ta'u as no surveys were planned for them.

Of the 72 original (1962) bench marks on Tutuila, eight bench marks were recovered and deemed acceptable for inclusion in the new leveling survey. These eight BMs did not include any tidal bench marks from 1962. In addition 104 additional bench marks were available on Tutuila. Of these, 11 tidal bench marks from CO-OPS were installed after 1962, 43 bench marks were established between 1962 and 2002, and 50 bench marks were newly installed for the 2002 effort, bringing the total number of usable bench marks on Tutuila that were suitable for leveling to 112 (Figure 7). Included was a CO-OPS tidal bench mark designated 177 0000 S TIDAL (PID DE8786), which was used as the datum origin point for ASVD02 on the island of Tutuila (see datum definition section).

Of the 112 bench marks leveled in the 2002 effort, 20 (four from 1962, p. 16 post 1962) had a clear enough view of the sky to be surveyed with GPS as well. Additionally, a GPS survey was performed on one other point which was not part of the 2002 leveling network. That point was a newly installed FBN point. All 21 GPS-surveyed points on Tutuila are identified in Figure 7 even though they did not play a direct role in the definition of ASVD02.

Leveling

Leveling was performed only on the island of Tutuila, to connect the 112 bench marks. The leveling crew used a Zeiss Jena Ni002 level with calibrated Invar rods to perform levels to First-Order, Class II specifications.[2]

GPS Surveys

Although they did not play a role in the definition of ASVD02, GPS observations were performed at 21 points in American Samoa to provide additional geodetic control for this region. GPS

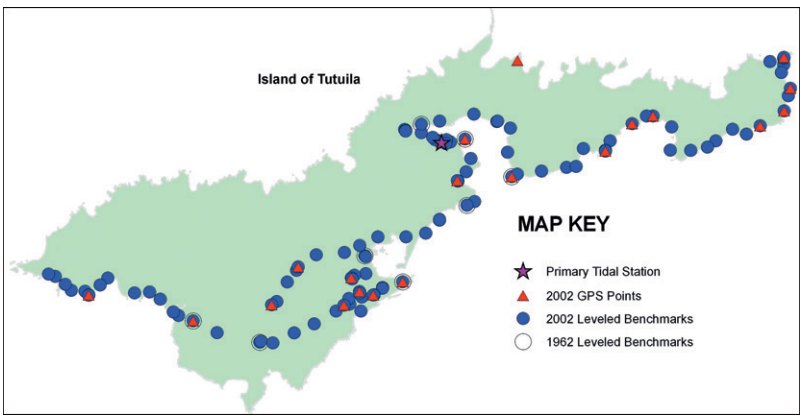

Figure 7. Geodetic control points used in American Samoa during the 2002 campaign.

[2] See Figure 2 for locations of the 112 bench marks leveled in the 2002 survey.

PID	Station	ASVD 02 (m)	USGS 62 (m)	Height Difference (m)
DE8779	2 RNG	4.257	4.258	−0.001
DE8758	4 RNG	3.220	3.229	−0.009
DE7243	13 RNG	32.382	32.388	−0.006
DE8751	11 RNG RM	91.620	91.619	0.001
AA3708	BREAKERS POINT RESET ET	51.885	51.884	0.001
AI9467	FOSTER	1.425	1.491	−0.066
AA3712	NO 1	2.901	2.952	−0.051
AA3719	TAFUNA 1A RESET ET	1.746	1.797	−0.051
			Average	−0.023
			Std. Dev.	0.035

Table 2. Height difference for island of Tutuila, American Samoa. USGS 62 heights published in U.S. Geological Survey, 1969.

static observations were performed on the island of Tutuila with Trimble 4000 SSE receivers with TRM 22,020.00 + GP antennas and Ashtech Z-Extreme receivers with ASH701975.01A antennas. The sessions varied in lengths, which was in conformance with the specifications outlined in NOAA Technical Memorandum NOS NGS 58. All control points were observed for three 5.5-hr sessions ver three days. See Figure 7 for locations of the 21 points that were observed with GPS in 2002.

American Samoa Vertical Datum 2002 (ASVD02) Definition

The bench mark designated 177 0000 S TIDAL (PID DE8786 in the NGS Integrated Database), and defined by CO-OPS as the primary BM of the Pago Pago NWLON station (177 0000), was adopted as the datum origin bench mark for the American Samoa Vertical Datum 2002 (ASVD02). The MSL value of 1.364 m—relative to the 1983-2001 National Tidal Datum Epoch (NTDE)—was adopted at this bench mark as the fixed height from which all other ASVD02 heights are referenced. ASVD02 is only defined and accessible on the island of Tutuila.

Comparison with Previously Published Heights

A comparison of the heights published in 1962 by the USGS and the new heights in ASV D02 (at the eight bench marks common to both surveys on Tutuila) showed very close agreement.

The average height difference ($H_{\mathrm{ASVD02}} - H_{\mathrm{MSL1962}}$) at the eight common bench marks was just −23 mm (Table 2). Although only eight samples were available, the height difference indicates a high degree of integrity between the 1962 and 2002 datum definitions, and they do seem to show that the overall integrity of the 1962 leveling data is quite good. Considering that different tidal epochs (ca. 1954 for the 1962 heights and ca. 1992 for the 2002 heights) and different primary bench marks were used to define the datum origin in 1962 and 2002, the relatively small difference between the two should be noted.

CO-OPS tidal data between 1948 and 1999 at tidal station 177 0000 (used in both 1962 and 2002) indicate a systematic trend in relative sea level rise of 1.5 mm per year (±0.6 mm/yr; Figure 8). Applying this to the 38 years between the midpoints of the MSL1962 and ASVD02 epochs would imply that the height of the primary bench mark of this tide gage should have gone down by 57 mm. This 57-mm change should thus be reflected in the difference between the

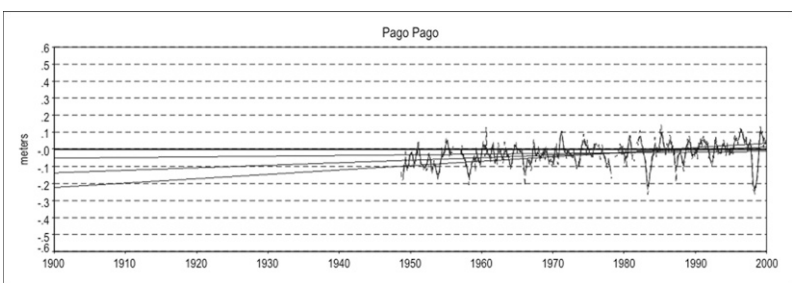

Figure 8. Mean sea level trend at tidal station #1770000 Pago Pago, American Samoa.

1962 and 2002 heights but, obviously, with an average difference of only –23-mm, it is not. Additional analysis of these data will be required to resolve this apparent discrepancy.

The Commonwealth of the Northern Mariana Islands

The Commonwealth of the Northern Marianas Islands is made up of 15 islands in the western Pacific Ocean. The three largest (all in the southern end of the island chain) are Rota, Saipan, and Tinian (Figure 9). USGS performed geodetic leveling on these islands in 1969, in support of their topographic mapping operations.

Each island's heights were determined as an independent network related to a temporary local tide gage operated by USGS.[3] On Rota, the tide gage was at the East Harbor which operated for 29 days (February 11 to March 11, 1969), and the primary tidal bench mark had designation "TIDAL 1 1969" (no PID, as it is not a point in the NGS Integrated Database) whose height was defined as 1.644 m. From this bench mark, leveling was performed to 21 other bench marks around the island with heights in a datum referred to as "mean sea level."

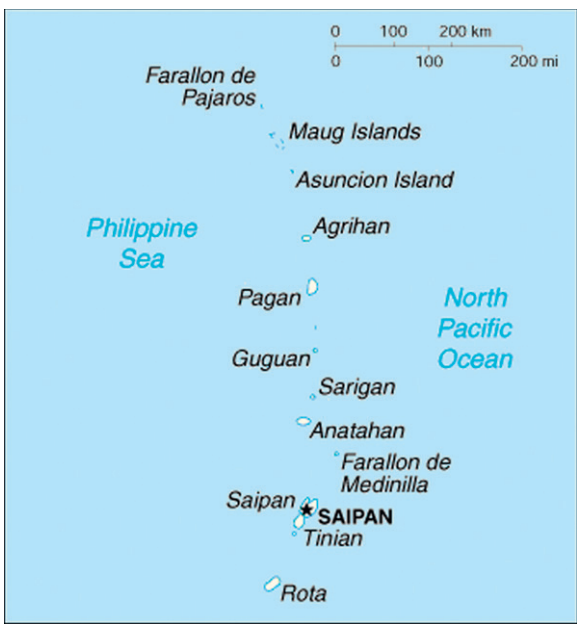

Figure 9. The Commonwealth of the Northern Mariana Islands.

On Saipan, the tide gage was at Tanapag Harbor, operated for 29 days (December 20, 1968 to January 20, 1969), and the primary tidal bench mark had designation "TIDAL 1, 1968" (no PID) whose height was defined as 1.772 m. From this bench mark, leveling was performed to 33 bench marks around the island with heights in a datum again referred to as "mean sea level".

On Tinian, the tide gage was at Tinian Harbor, operated for 56 days (February 7 to April 3, 1969), and the primary tidal bench mark had designation "TIDAL 1 1969" (no PID as it is not a point in the NGS Integrated Database) whose height was defined as 2.387 m. From this bench mark, leveling was performed to 29 bench marks around the island with heights in a MSL datum. Because none of the tide gages was a long-term gage, there was no attempt to remove long-term periodic signals in these short tidal records.

In 2003, the National Geodetic Survey embarked on a project with the goal of establishing new geodetic control, including a new vertical datum, for the Commonwealth of Northern Mariana Islands. This goal was met (see the section "2003 Efforts), and the vertical datum was named the Northern Marianas Vertical Datum of 2003 (NMVD03).

2003 Efforts

Participation

All work done in CNMI was performed in partnership with the Commonwealth's Department of Lands and Natural Resources, Coastal Resources Management Office, and Ports Authority. All work was performed between April and August 2003.

Reconnaissance

Reconnaissance in the CNMI was performed to support new leveling as well as GPS surveys on the islands of Rota, Saipan, and Tinian. No field work was planned for the remaining 12 islands, so no reconnaissance was performed. The island-by-island details of the reconnaissance are given below.

Rota: Of the 21 original (1969) bench marks on Rota, six were recovered and deemed acceptable for inclusion in the new leveling survey. These included one tidal bench mark from 1969 (TIDAL 3 1969), although this bench mark was not the defining mark used in the 1969 height definitions. In addition to these six marks from 1969, additional 30 bench marks (27 established between 1969 and 2003 and three newly installed for the

[3] In addition, USGS established triangulation points during this time. There is some overlap between the 1969 bench marks and triangulation points.

2003 effort) were available on Rota, bringing the total number of usable bench marks suitable for leveling to 36. These included a CO-OPS tidal bench mark designated "TIDAL 3" (PID DG4014) which was used as the datum origin point for NMVD03 on the island of Rota (see datum definition section, later).

Of the 36 bench marks leveled in the 2003 effort, nine (five from 1969, four post 1969) had a clear enough view of the sky to be surveyed with GPS as well. GPS surveys were performed on two other points that were not part of the 2003 leveling network. None of the 11 GPS-surveyed points on Rota played any direct role in the definition of NMVD03 (see Figure 10 for the Rota points).

Saipan: Of the 33 original (1969) bench marks on Saipan, 10 were recovered and deemed acceptable for inclusion in the new leveling survey, even though only two were in locations suitable for a GPS survey. None of the three tidal bench marks from 1969 were among the 10 original bench marks. Sixty-four additional bench marks were available on Saipan—seven CO-OPS tidal and six geodetic bench marks established between 1969 and 2003, plus 51 marks installed for the 2003 effort—bringing the total number of bench marks usable for leveling to 74. These included a CO-OPS tidal bench mark designated "163 3227 TIDAL UH-2C (PID DG3988)" which was used as the datum origin point for NMVD03 on the island of Saipan (see datum definition section, below).

Of the 74 bench marks leveled in the 2003 effort, 10 (two from 1969 eight post 1969) had a clear enough view of the sky to be surveyed with GPS as well. GPS surveys were performed on one other point which was not part of the 2003 leveling network.[4] Although all 11 GPS-surveyed points on Saipan are identified in Figure 10, they did not play a direct role in the definition of NMVD03.

Tinian: Of the 29 original (1969) bench marks on Tinian, six were recovered and deemed acceptable for inclusion in the new leveling survey. These six included two tidal bench marks (TIDAL 1 1969; TIDAL 3 1969) from 1969. In addition there were 40 more bench marks available on Tinian (three established between 1969 and 2003 and 37 installed for the 2003 effort), bringing the total number of usable bench marks for leveling to 46. These included a CO-OPS tidal bench mark designated "TIDAL 1 (PID AA4407)" which was used as the datum origin point for NMVD03 on the island of Tinian (see datum definition section, below).

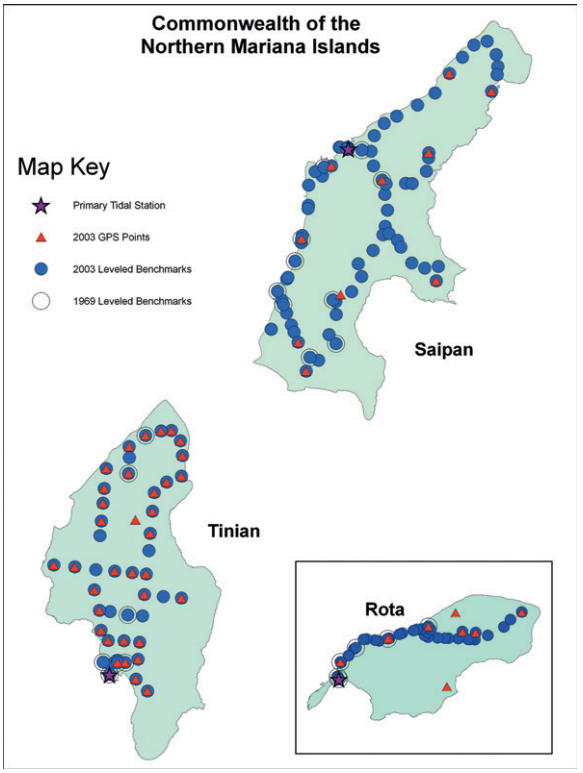

Figure 10. Geodetic control points used in the Commonwealth of the Northern Mariana Islands during the 2003 campaign.

Of the 46 bench marks leveled in the 2003 effort, 36 (seven from 1969, 29 post 1969) had a clear enough view of the sky to be surveyed with GPS as well.[5] None of the 36 GPS-surveyed points on Tinian (identified in Figure 10) played a direct role in the definition of NMVD03.

Leveling

On all three islands, the leveling crew used a Zeiss Jena Ni002 level and calibrated Invar rods to observe to First-Order, Class II specifications. See Figure 10 for locations of the bench marks.

GPS surveys

While they did not play a role in the definition of NMVD03, the GPS observations performed at 58 points (11 on Rota, 11 on Saipan, and 36 on Tinian) provided additional geodetic control for this region. GPS static observations were performed with Trimble 4000 SSE receivers with TRM 22,020.00 + GP antennas and Ashtech Z-Extreme

[4] This point happened to be a 1969 USGS triangulation station.

[5] There were no points surveyed with GPS in 2003 that were not part of the 2003 leveled bench mark set.

Figure 11. Tide gage (NWLON site #1633227) at Tanapag Harbor, Saipan, CNMI.

receivers with ASH701975.01A antennas. Sessions varied in lengths, in conformance with the specifications outlined in NOAA Technical Memorandum NOS NGS 58. All control points were observed for three 5.5-hr sessions over three days. See Figure 10 for locations of all 70 points that were observed with GPS on Rota, Saipan, and Tinian in 2003.

CNMI Vertical Datum 2003 (NMVD03) Definition

The bench mark designated "163 3227 TIDAL UH-2C" (PID DG3988 in the NGS Integrated Database), and defined by CO-OPS as the primary bench mark of the Tanapag Harbor, Saipan NWLON site (#1633227; see Figure 11), was adopted as the datum origin bench mark for the Northern Marianas Vertical Datum 2003 (NMVD03). The MSL value of 1.657 m, relative to the 1983-2001 NTDE, was adopted at this bench mark as the fixed height from which all other NMVD03 heights on Saipan are referenced.

For the purpose of establishing NMVD03 on Rota and Tinian, a sea-level adjustment of 0.026 m (approximately 0.1 ft), computed by CO-OPS, was applied to the designated primary tidal bench mark elevations determined by USGS in 1969. As such, TIDAL 3 (PID DG4014) on Rota with a value of 1.482 m and TIDAL 1 (PID AA4407) on Tinian with a value of 2.361 m were adopted as the fixed heights on these datum origin bench marks from which all other NMVD03 heights are referenced on the two islands. NMVD03 does not exist on any other islands in the CNMI.

Comparison with Previously Published Heights

A comparison of the published heights from USGS with those from the new leveling indicates considerable variations (Tables 3-5).The average differences on the three islands show no real cohesiveness, and the standard deviation about the mean is quite high on Saipan. While Tinian and Rota show smaller standard deviations, these are still too large to allow for a comparison between the two geodetically leveled networks. Unfortunately, no long-term sea-level trend data are available for these islands, hence, differences in local mean sea level cannot be factored into the height differences. The differences between the new and old networks reflect a combination of factors including the lower order of accuracy of the USGS leveling data, local tectonic activity, the very short length of the original LMSL observations performed by USGS, and the fact that no attempt was made to connect the three islands' MSL values in 1969, while a local sea-level correction was applied to the 2003 data to make NMVD03 interconnected across the three islands.

Guam

The Territory of Guam lies in the western Pacific Ocean and comprises the island of Guam plus surrounding reefs and smaller islands, such as Cocos. The island of Guam is the largest and southernmost of the Mariana Islands, although the Territory of Guam is not part of the Commonwealth of the Northern Marian Islands (Figure 12).

In contrast to American Samoa and the CNMI, geodetic leveling was performed in 1963 on Guam by the USC&GS (not USGS) to First-Order (but not Third-Order) specifications. This network consisted of a total of 138 monumented First-Order bench marks.[6]

Heights on Guam were defined in 1963 by the USC&GS as mean sea level and were referenced to the USC&GS tide gage located at Apra Harbor (163 0000) based on 13 years and 10 months of tidal records spanning January 1949 to October

[6] Additionally, triangulation stations were established on the islands of Cocos and Guam during the leveling campaign. Of the 138 bench marks on Guam, 40 were both triangulation and levelling stations.

PID	Station	NMVD 03 (m)	USGS 69 (m)	Height Difference (m)
DG3973	TAM 1	1.714	1.999	−0.285
DG3969	TAM 4	3.516	3.821	−0.305
DG3968	TAM 5	3.580	3.640	−0.060
DG3965	TAM 6	2.801	3.092	−0.291
DG3960	TAM 11	30.020	30.305	−0.285
DG3958	TAM 14	53.865	54.153	−0.288
DG3956	TAM 16	49.247	49.633	−0.386
DG3932	TAM 25	9.022	9.360	−0.338
DE7018	KANOA	2.364	2.669	−0.305
DE7041	SAIPAN AZ MK	204.920	205.204	−0.284
			Average	−0.283
			Std. Dev.	0.085

Table 3. Height differences for the island of Saipan, CNMI.

PID	Station	NMVD 03 (m)	USGS 69 (m)	Height Difference (m)
DE7887	ET TINI 1	1.287	1.251	0.036
DG4136	TAM 10	21.894	21.873	0.021
DE6132	TAM 19	23.599	23.563	0.036
DE6120	TAM 8	10.576	10.557	0.019
AA4407	TIDAL 1	2.361	2.387	−0.026
DE6136	TIDAL 3	19.335	19.306	0.029
			Average	0.019
			Std. Dev.	0.023

* DE6133 was rejected from this analysis due to its large magnitude. One possible explanation is some computational error being made when the mark was reset, but this has not been verified.

Table 4. Height difference for the island of Tinian, CNMI.

PID	Station	NMVD 03 (m)	USGS 69 (m)	Height Difference (m)
DG4003	TAM 1	15.606	15.632	−0.026
DG3994	TAM 3	10.648	11.446	−0.798*
DG4023	TAM 5	5.196	5.288	−0.092
DG4014	TIDAL 3	1.482	1.508	−0.026
AA4404	TATGUA 2	59.503	59.538	−0.035
DE7086	VIL	1.810	1.840	−0.030
			Average	−0.042
			Std. Dev.	0.028

* DG3994 was rejected from this analysis. The mark was found in a road and it is believed that it was moved from its original position, thus resulting in the large discrepancy observed. The original USGS description does not mention the mark being in a road, which strengthens the idea of a possible move.

Table 5. Height differences for the island of Rota, CNMI.

1962. The primary bench mark for this tide gage had designation "NO 5 1949" (PID TW0042), and its adopted height was 0.599 m (U.S. Coast and Geodetic Survey 1964).

In 2004, NGS developed a project with the goal of establishing new geodetic control, including a new vertical datum, for Guam. This goal was met, as described below, and the vertical datum was named the Guam Vertical Datum of 2004 (GUVD04).

2004 Efforts

Participation

All work done in Guam was performed in partnership with the Guam Department of Land Management, Guam Power Authority, and Duenas and Associates. All work was performed between June and September 2004.

Reconnaissance

Reconnaissance was performed to support new leveling (as well as GPS surveys) on the island of Guam. No field work was planned for the island of Cocos, hence, no reconnaissance was performed.

Figure 12. Map of Guam.

Of the 138 original (1963) bench marks on Guam, 29 were recovered and deemed acceptable for inclusion in the new leveling survey. These included two tidal bench marks (NO 4 1949 and NO 6 1949) from 1963. In addition, 135 bench marks were available on the island (five CO-OPS tidal and 115 geodetic bench marks established between 1963 and 2004, plus 15 installed for the 2004 effort), bringing the total number of bench marks usable for leveling to 164 (Figure 13). The bench marks included a CO-OPS tidal bench mark designated "163 0000 TIDAL 4 (PID TW0041)" which was used as the datum origin point for GUVD04 on the island of Guam (see datum definition section, below).

Of the 164 bench marks leveled in the 2004 effort, 16 (six from 1963, 10 post 1963) had a clear enough view of the sky to be surveyed with GPS as well. GPS surveys were also performed on nine other points that were not part of the 2004 leveling network. These included four newly installed FBN points and five existing triangulation-only stations from 1963. Although all 25 GPS-surveyed points on Guam are identified in Figure 13, they did not play a direct role in the definition of GUVD04.

Leveling

Leveling was performed in order to connect the 164 bench marks on Guam. The leveling crew used a Leica digital bar-code levels NA 3003 and DNA03 and calibrated Invar rods to perform levels to First-Order, Class II specifications. See Figure 13 for locations of the 164 bench marks leveled in the 2004 survey.

GPS Surveys

GPS observations were performed at 25 points in order to provide additional geodetic control for Guam and surrounding region. Static observations

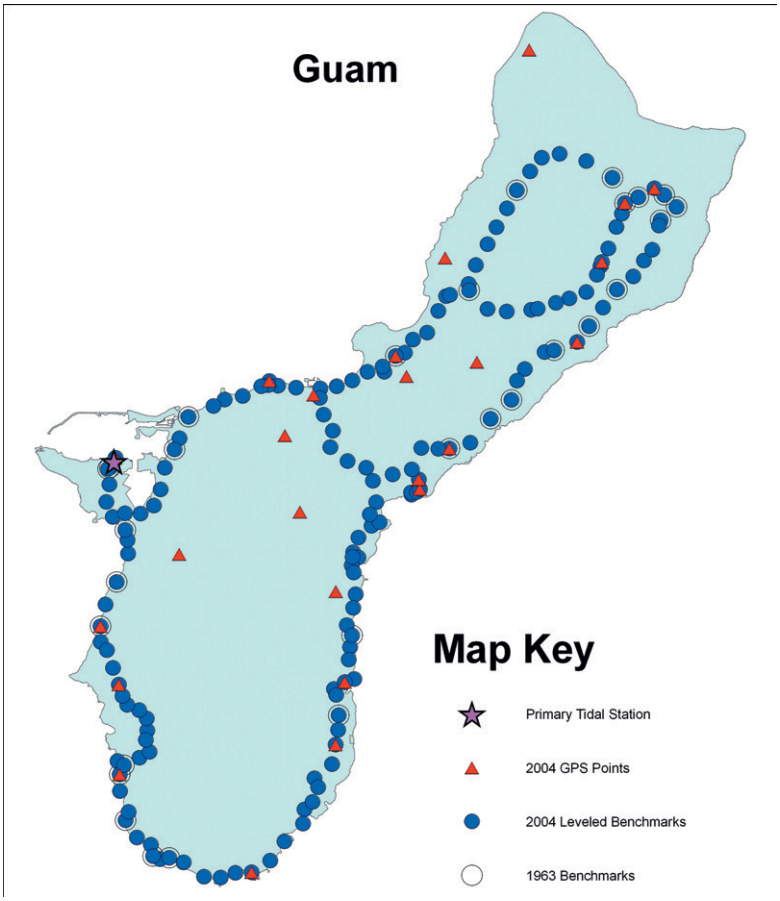

Figure 13. Geodetic control points used in Guam during the 2004 campaign.

were performed with Trimble 4000 SSE receivers with TRM 22,020.00 + GP antennas and Ashtech Z-Extreme receivers with ASH701975.01A antennas. The sessions varied in lengths, in conformance with the specifications outlined in NOAA Technical Memorandum NOS NGS 58. All primary control points were observed for three 5.5-hr sessions over three days. Figure 12 shows the locations of the 25 points that were observed with GPS in 2004.

Guam Vertical Datum 2004 (GUVD04) Definition

Bench mark 163 0000 TIDAL 4 (PID TW0041), defined by CO-OPS as the primary bench mark of the Apra Harbor NWLON site (#1630000) (Figure 14), was adopted as the datum origin bench mark for Guam Vertical Datum 2004 (GUVD04). The MSL height of 2.170 m, relative to the 1983-2001 NTDE, was adopted at this bench mark as the fixed value from which all other GUVD04 heights are referenced. GUVD04 only exists on the island of Guam.

Comparison with Previously Published Heights

A comparison of the 29 points common to both the 1963 USC&GS leveling and the new 2004 leveling shows considerable variation in leveled height differences. These differences have an average of −0.04 ± 0.066 m, ranging from +0.162 m to −0.243 m (Table 6). The long-term LMSL trend computed by CO-OPS (for 1948-1999 at tide gage 163 0000; Figure 15) is only 0.1 mm per year, which would only account for about 4 mm (10 percent) of the average difference between the 1963 and 2004 heights. However, the computed trend also has a very high standard error (±0.9 mm/yr), making it is difficult to draw strong conclusions from the data. As Guam experiences considerable tectonic activity, the computed differences could be the result of an uplift. Even after removing four points that exhibit changes larger than 0.1 m (and are large enough to

Figure 14. Tide station, Apra Harbor, Guam.

PID	Station	GUVD 04 (m)	GUVD 63 (m)	Height Difference (m)
TW0043	163 0000 TIDAL 6	1.537	1.531	0.006
TW0044	163 0000 TIDAL 7	2.264	2.263	0.001
TW0367	ASALONSA	73.973	74.063	−0.090
TW0095	AAFB 1	160.784	160.805	−0.021
TW0096	AAFB 21	160.322	160.354	−0.032
TW0097	AAFB 27	161.011	161.049	−0.038
TW0372	BEACH	1.858	1.897	−0.039
TW0373	BIXBY	3.539	3.608	−0.069
TW0374	CASTRO	184.693	184.710	−0.017
TW0376	CRUSHER	87.451	87.493	−0.042
TW0379	GAYINERO	166.784	166.816	−0.032
TW0133	H 2	3.072	3.089	−0.017
TW0382	HAWAIIAN	112.012	112.064	−0.052
TW0388	MANALISAY	0.898	0.966	−0.068
TW0389	NCS	133.167	133.172	−0.005
TW0135	NSD 5	9.211	9.221	−0.010
TW0393	SABANON	167.476	167.520	−0.044
TW0017	SALISBURY	187.872	187.710	0.162
TW0396	SASA	3.298	3.442	−0.144
TW0398	SOLEDAD	44.194	44.437	−0.243
TW0399	SPLIT	139.69	139.731	−0.041
TW0400	SPUR	122.851	122.895	−0.044
TW0401	SYLAR	177.853	177.878	−0.025
TW0402	TAMUNING	33.812	33.833	−0.021
TW0403	TART	7.993	8.065	−0.072
TW0406	UMATAC	5.585	5.575	0.010
TW0407	USO	3.480	3.621	−0.141
TW0122	V 1	3.747	3.794	−0.047
TW0408	WETTENGEL	90.176	90.195	−0.019
			Average	−0.041
			Std. Dev.	0.066

Table 6. Height differences for the island of Guam.

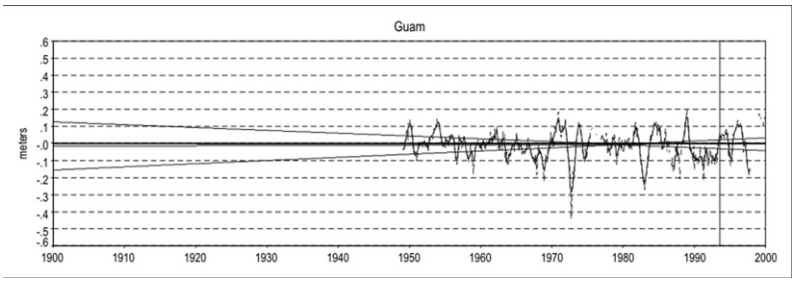

Figure 15. Mean sea level trend at tidal station #1630000 Guam.

be considered as outliers, possibly due to man-made disturbances), the residual average change of approximately 0.03 m in the local height system cannot be accounted for by the LMSL trend.

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