OPUS-Database: Supplemental Data for Better Datum Conversion Models

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SUMMARY

NOAA’s National Geodetic Survey (NGS) is responsible for maintaining the National Spatial Reference System. This includes the national geometric and geopotential datums, which are the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88), respectively. For NAVD 88, Helmert orthometric heights were defined in a block adjustment of over 500,000 geopotential differences at bench marks. As an alternative to leveling from established bench marks, NGS provides geoid height models such as GEOID09 (Roman et al. 2011) that transform between NAD 83 and NAVD 88. This provides the ease of calculating your position with GPS but yields more practical orthometric heights. To develop such models requires that both the GPS-derived ellipsoidal and leveling-derived orthometric heights on Bench Marks (GPSBM's) be known. Because of the requirement for both heights on a bench mark, the pool of control points is much smaller (only about 18,000) and not very equitably distributed (with potential dm-level interpolation errors). This paucity of points is driven by the rigorous processes ("Bluebooking") required to enter data into the NGS Integrated Database (NGSIDB). To mitigate this, the Online Positioning User Service Database (OPUS-DB) was explored as a source for supplemental data. This nascent database is rapidly being accepted by the broader surveying community and can even be used to target significantly deficient areas. A pull of OPUS-DB in November 2010 yielded 422 points. While this number is small in comparison to the overall NGSIDB data, the potential for growth is significant. These points fell into three categories: (1) 80 that were common to both databases and were used in making GEOID09, (2) 57 that were common to both but not used in making GEOID09, and (3) 285 with new geometric observations for points not previously observed with GPS (i.e., new control points). Residual values were formed by removing the same geoid and orthometric heights from ellipsoid heights obtained from NGSIDB and OPUS-IDB. Smaller values imply a better fit and less noise. For the first group, OPUS-DB was noisier (SD 0.031 m (one sigma)) than NGSIDB (SD 0.015 m (one sigma)). For the second group, OPUS-DB was less noisy (0.037 m (one sigma)) than the NGSIDB (0.043 m (one sigma)). For the last group, only OPUS-DB data were available and they were a little worse (0.047 m (one sigma)) than before. This is consistent with the level of agreement seen when forming residuals between ellipsoidal heights from NGSIDB and OPUS-DB in groups 1 and 2 (SD of 0.028 m and 0.044 m (one sigma), respectively). Overall, OPUS-DB demonstrated very good agreement with more rigorously determined NGSIDB data, provided expanded coverage into regions with poor coverage, and demonstrated a significant potential for use in future geoid modeling.

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1. INTRODUCTION

The National Geodetic Survey (NGS) is a program office within the National Ocean Service of the National Oceanic and Atmospheric Administration. NGS is responsible for defining, maintaining, and providing public access to the National Spatial Reference System (NSRS)**,** a consistent national coordinate system that provides the foundation for mapping and charting; transportation, communication, and land records systems; and numerous scientific and engineering applications. The NSRS consists of two primary areas for the purposes of surveying including the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88). NAD 83 serves as the geometric datum based on a GRS-80 ellipsoidal shell, while NAVD 88 is the geopotential or orthometric datum developed from an adjustment of leveling across the United States. NAD 83 has been extended to other regions, such as the Marianas Islands, and has been modified somewhat to account for local reference frame movements. NAVD 88 exists in Alaska and the Conterminous United States (CONUS) and is tied to the tidal and leveling bench mark at Father Point/Rimouski in Canada. Other island states and territories of the United States have adopted local tide stations as the datum point for determining geopotential heights in their regions, but these follow similar collection and adjustment procedures to get consistent results. In this paper, the focus will be on NAVD 88 and NAD 83 to exemplify how the existing height data are used and how that process might be improved.

Surveyors desire to have a model that permits them to use GPS to determine ellipsoidal coordinates and transform into the desired local geopotential datum. This is accomplished by re-working the simple relationship between ellipsoidal (h), orthometric (H), and geoid (N) heights shown in Figure 1. The orthometric height may be estimated by subtracting the geoid height from the ellipsoid height (H = h – N).

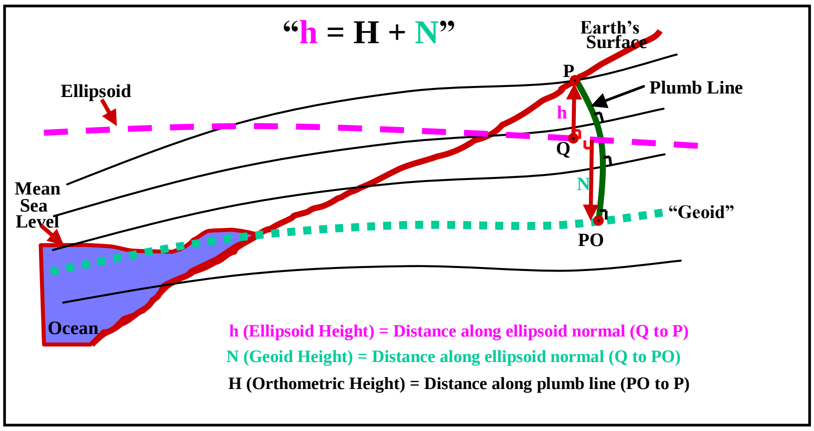

Figure 1 Relationship between ellipsoid (h), geoid (N) and orthometric (H) heights. This can be re-worked to subtract geoid heights from ellipsoid heights to determine orthometric heights (H = h – N).

This then takes advantage of the ease and efficiency of GPS while still yielding more desirable orthometric heights. To that end, NGS has provided geoid height models as a datum conversion tool for nearly twenty years. This is accomplished by first developing a geoid height model based entirely upon gravity observations and terrain data. This gravimetric geoid provides a realistic physical estimate of separation between the ellipsoid and the geopotential surface that closely approximates global mean sea level. USGG2009 (Wang et al. 2011) is the most recent. However, it is based on a GRS-80 ellipsoid with a geocenter in the ITRF00 reference frame. Additionally, the geopotential surface it defines is not the same as NAVD 88. Hence control data, where both the heights above NAD 83 and NAVD 88 are known, are used to warp the surface of the gravimetric geoid to fit to these datums. This is accomplished by extracting GPS-derived ellipsoidal heights that exist on leveled bench marks (GPSBM’s) that were rigorously collected, adjusted, and loaded into the NGS Integrated Database (NGSIDB) Least Squares Collocation is then used to fit a conversion surface through these points for making the transformation. This paradigm follows the techniques pioneered under Smith and Milbert (1999), continued in Smith and Roman (2001), and Roman et al. (2004); however, this is proving to no longer be sufficient.

Supplemental data, particularly those which can be targeted to regions of poor to very poor spatial coverage, will provide the best means for improving datum conversion tools in the future. Of the nearly 500,000 bench marks on NAVD 88, only about ten percent have actually been occupied to determine geometric coordinates. Less than half of these have been occupied using more appropriate GPS observation techniques. The insufficient quality and distribution of these points is a central tenant behind this paper. The need for supplemental data will become clear after a discussion of these existing GPSBM’s used to develop the GEOID09 model (GPSBM2009).

2. GPSBM2009 and GEOID09

The GPSBM2009 data (Figure 2) netted 18,398 points for CONUS. However, the inequitable distribution of the data can clearly be seen. Over half the data are in just the four states of Minnesota, Florida, North Carolina, and South Carolina. The remaining points are spread across the other 44 states in CONUS with many states having less than 100 points. This widely varying coverage adversely affects the modeling used to make GEOID09.

GEOID09 was developed by forming residuals in the same manner as discussed later in this paper. Least Squares Collocation (LSC) was used to form a mathematical model describing the correlated signal between the GPSBM's, which serve as control points for this modeling. Six positive definite matrices were used to model correlated features at various scales and then added to produce a single invertible matrix that produced the conversion surface needed to make GEOID09. Essentially, LSC extracted the correlated signal seen between these control points at various scales and built a model of this. Hence the spacing of the control data limits which filters apply for a given region. Correlation lengths (essentially equivalent to the half-wavelength) for these filters were 30, 60, 90, 120, 260, and 600 km. For further details on LSC modeling and the multi-matrix method see Roman et al. (2004, 2011).

For the state of Minnesota, where over 4,000 points were available, the interpolation error is negligible as some regions approach a control point at about every 2 km. Such a data interval is more than sufficient to resolve the conversion from NAD 83 to NAVD 88. For the state of Utah, only 55 points were available to define the transformation across the entire state – a region which is actually just a little larger than the state of Minnesota (219,899 sq km). If these points were evenly distributed, they would be 63 km apart. However, gaps between points are clearly seen to reach 200-300 km. Hence, the modeling would be based on only the matrices with the two longest correlation lengths (260 km and 600 km), which will miss over 40% of the signal contained in the other four matrices. The power in the missing signal is about 0.038 m (one sigma) and can contribute to dm-level interpolation errors for such sparsely covered regions seen in most of the western states. Significant signal exists at smaller scales but it cannot be resolved in the modeling and is, therefore, treated as noise. This led to the development of multi-matrix LSC for GEOID03.

This wide variance in data distribution cannot be overcome by simply searching the NGSIDB more closely – the data simply aren't there. While there are over 500,000 bench marks on the NAVD 88, most have no GPS observations on them. Hence, the Online Positioning User System Database (OPUS-DB) was examined as an alternative source for obtaining GPS coordinates on as yet unvisited bench marks.

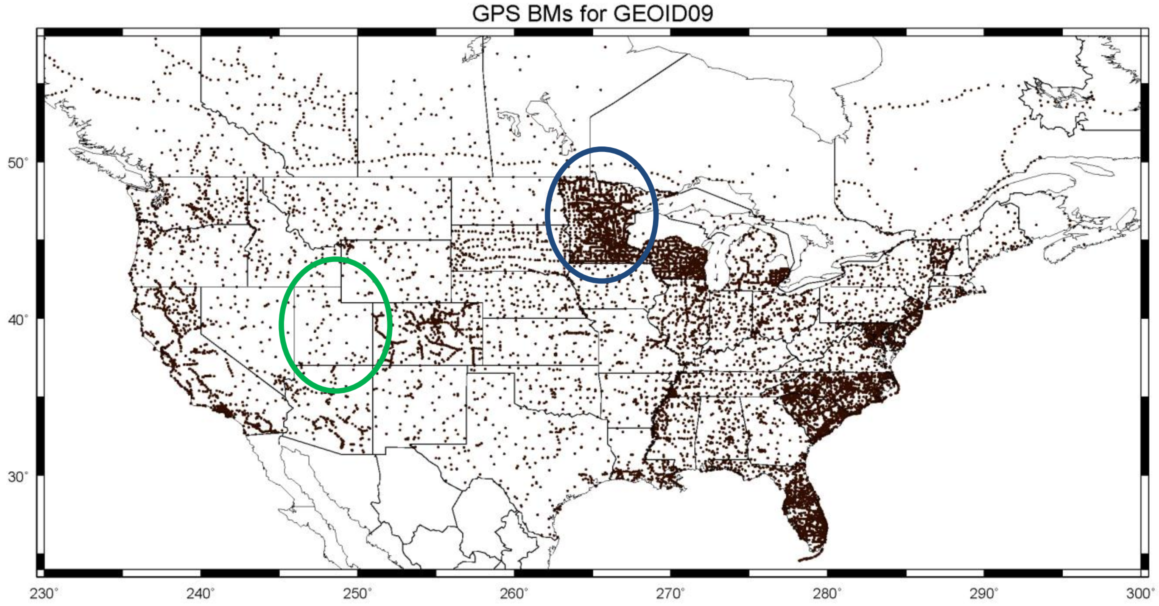

Figure 2. Distribution of GPSBM2009. There are 18,398 points in CONUS plus 579 in Canada. Note inequitable data distribution. The state of Minnesota is circled in blue and Utah is in green.

3. OPUS-DB

OPUS as a tool has been under development for some time (Stone 2006). Many surveyors have taken advantage of this tool to rapidly reduce their observations in a manner consistent with the CORS network (Weston et al. 2007). GPS data are collected at a desired point and submitted online for processing in combination with observations at Continuously Operating Reference Stations (CORS). Data at the CORS sites are collected and stored continuously. When a processing request is made, the archived CORS observations are used to reduce the data submitted online by the surveyor. The primary limitation to this approach has been that each point is treated separately and that no network adjustment is made. Adjustments that follow the more rigorous standards of NGS' Bluebook yield better defined network errors for data stored in the NGSIDB. Because of the degree of uncertainty associated with the CORS positions, OPUS-DB determined positions have an additional level of uncertainty. To resolve this, a multi-year solution will be finalized later in 2011to refine the CORS coordinates.

One variant on OPUS has been the concept of archiving the results of the reductions in a database. While this is still a nascent operation, many points have already been loaded into the database. Since the only points of interest here are those where both ellipsoidal and orthometric heights are available, only those points in the OPUS-DB with a valid NGS Point ID (PID) were selected. This resulted in 422 points for consideration (Figure 3).

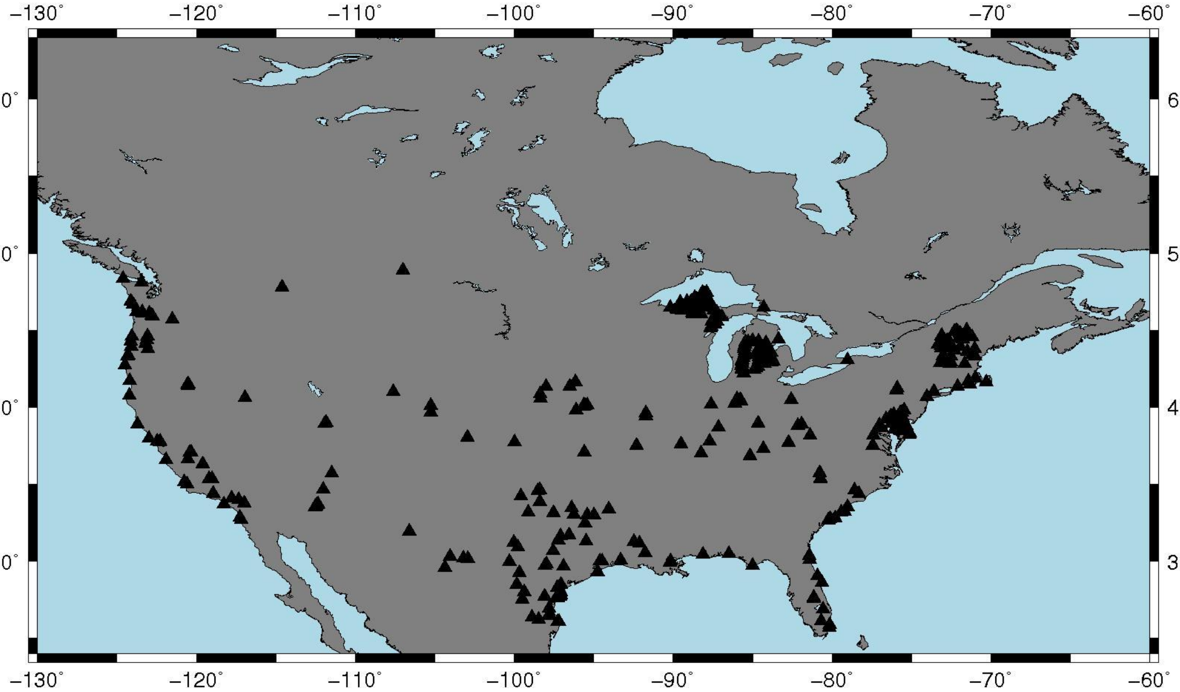

Figure 3. Coverage of the 422 points pulled from OPUS-DB to supplement NGSIDB for potential use in future geoid models. There are some concentration areas but generally a good spread across the country.

These 422 points can be broken into three groups. The first 80 are those points common to both the OPUS-DB and NGSIDB and used in making GEOID09 (i.e., in GPSBM2009). The next 57 are also common points but were not used in making GEOID09. These were points that had geometric coordinates determined from older techniques, which were not adjusted as a part of NGS' National Readjustment in 2007 (i.e., older data that are no longer supported). The third group are the remaining 285 points that represent first time GPS observations on established bench marks (new data). These groups are described further in Table 1.

Table 1. Statistics of residuals formed from ellipsoid (h), orthometric (H), and geoid (N) heights. Residuals (= h – H – N) were formed from ellipsoid heights for both NGSIDB (column A) and OPUS-DB (column B). Column C shows the statistics of the differences between the NGSIDB and OPUS-DB ellipsoid heights. There are 3 groups that correspond to (1) the Common Points to both OPUS-DB & NGSIDB used to make GEOID09, (2) Common Points to both but *not* used to make GEOID09, and (3) Points not previously observed with GPS (i.e., no ellipsoidal coordinates in the NGSIDB). Some points were rejected from the first and third groups with solutions provided both with (a) and without (b) them. Since no NGSIDB ellipsoid heights exist for the third group, columns A and C are not applicable. All values are in meters.

		A		**B**		**C**	
Groups of the 422 points pulled from OPUS-DB	**No. Pts**	**NGSIDB Res.**		**OPUS-DB Res.**		**OPUS-DB–NGSIDB**	
		Ave	**SD**	**Ave.**	**SD**	**Ave**	**SD**
(1.a) All Common Points that were used in GEOID09	80	-0.009	0.065	0.004	0.036	0.013	0.060
(1.b) Common Points less the 9 rejects	71	-0.004	0.015	0.003	0.031	0.006	0.028
(2) Common Points but *not* used to make GEOID09	57	0.001	0.043	0.007	0.037	0.006	0.044
(3.a) Points Not Previously Observed with GPS	285	n/a	n/a	-0.011	0.112	n/a	n/a
(3.b) Points Not Previously Observed less the 11 rejects	274	n/a	n/a	-0.008	0.047	n/a	n/a

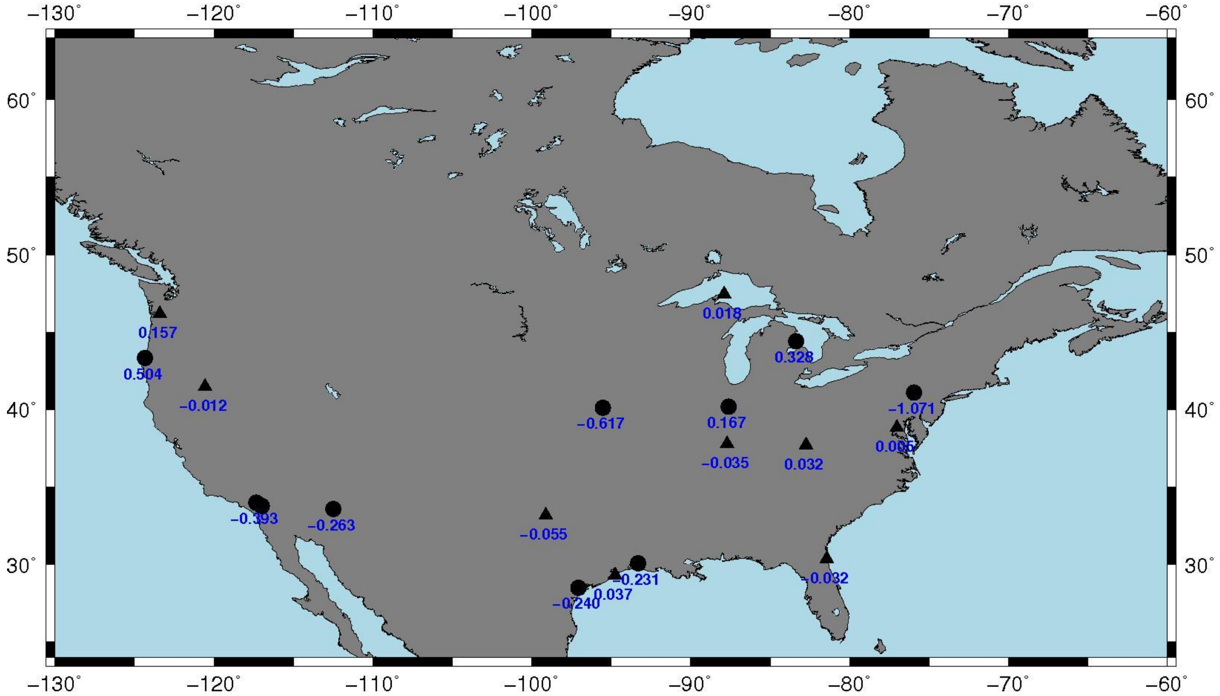

Figure 4 Locations of 20 rejected points given in Table 2. The 9 points rejected from the Common Points (rows 1.b in Table 1) are shown by triangles. The 11 rejected points from those not previously visited with GPS (row 3.b in Table 1) are shown by circles. Magnitude of residuals is in blue with units in meters.

Additional distinction is made for the first and third groups to reject outliers. Of the 80 points in common to both the NGSIDB and OPUS-DB (row 1.a), there were 9 that had been rejected in the making of GEOID09. The solution without the rejected points is given on the next line (row 1.b). Of the 285 points not previously visited by GPS to determine geometric coordinates (row 3.a), there were 11 points dropped due to significant residual values. The solution without those rejected points is given on the last line (row 3.b). All 20 points are listed in Table 2 and shown in Figure 4. The criterion used in culling the GPSBM2009 data to make GEOID09 was anything with a residual value greater than 0.160 m absolute value. This was adopted here as well.

Table 2 Details about 20 rejected points given in Table 1. The nine (9) rejected points from Common group are in upper half (corresponding to the 9 rejected points listed in row 1.b of Table 1). The eleven (11) rejected points from those with no previous GPS observations (corresponding to row 3.b in Table 1) are in the bottom half. All values given in meters. Residuals were formed as given in Table 1. PID is the Point ID used to uniquely determine points listed in the NGSIDB. Reject code is explained in the text.

PID	Reject Code	NAVD88 ortho. ht.	GEOID09 height	NGSIDB ellips. ht.	NGSIDB Residual	OPUSDB Ellips. ht.	OPUSDB Residual
AW5707	S	0.709	-26.638	-25.916	0.013	-25.892	0.037
HA0997	h	118.247	-30.526	87.726	0.005	87.686	-0.035
DO0454	H	383.465	-28.982	353.943	-0.540	354.428	-0.055
GY1636	h	218.677	-32.382	186.330	0.035	186.327	0.032
HV9071	h	3.505	-32.143	-28.656	-0.018	-28.633	0.005
MW0121	h	1337.183	-22.185	1314.984	-0.014	1314.986	-0.012
SC0330	H	17.233	-21.296	-3.923	0.140	-3.906	0.157
SG0004	h	189.404	-35.290	154.085	-0.029	154.132	0.018
BC2486	H	1.247	-28.527	-27.343	-0.063	-27.312	-0.032
AN1829	not in IDB	21.222	-27.417	n/a	n/a	-6.438	-0.243
BK1521	not in IDB	1.319	-27.163	n/a	n/a	-26.075	-0.231
DV0102	not in IDB	404.859	-30.096	n/a	n/a	374.500	-0.263
DX5394	not in IDB	467.098	-32.369	n/a	n/a	434.548	-0.181
EV3460	not in IDB	284.083	-32.962	n/a	n/a	250.728	-0.393
OA0650	not in IDB	4.600	-26.362	n/a	n/a	-21.258	0.504
PK0048	not in IDB	184.093	-35.268	n/a	n/a	149.153	0.328
LB1860	not in IDB	201.307	-32.618	n/a	n/a	168.856	0.167
LF0630	not in IDB	336.765	-30.541	n/a	n/a	305.607	-0.617
LY1475	not in IDB	372.450	-32.186	n/a	n/a	339.193	-1.071
TT0450	not in IDB	11.425	8.766	n/a	n/a	21.028	0.837

Tables 1 and 2 provide a lot for discussion. Most of the following discussion will focus on Table 1 and draw from Table 2 to highlight where significant residuals occurred of potential significance. For the NGSIDB, dropping the 9 rejected points from Group 1 (the Common Points) significantly improved the comparisons by dropping the standard deviation (SD) from 0.065 m to 0.015 m (compare rows 1.a and 1.b in Column A). Of note, dropping the same points for the OPUS-DB ellipsoidal heights only dropped the SD from 0.036 m to 0.031 m (rows 1.a and 1.b in Column B). This is mainly because the bench mark with PID of DO0454 had a residual value of -0.540 m for the NGSIDB but only -0.055 m for OPUS-DB (see third entry of Table 2). Clearly, the OPUS-DB solution identified a bust in the solution for the ellipsoidal height listed in the NGSIDB.

Interestingly, the residual values for both NGSIDB and OPUS-DB for the point with PID SC0330 (see seventh entry of Table 2) show similar values of 0.140 m and 0.157 m. This seems to indicate an error with the NAVD 88 orthometric height that will require further investigation. Most of the remaining points show little residual values for the Group 1. The points were rejected based on the strict criteria used to develop GEOID09. The residual values in this group for both NGSIDB and OPUS-DB are both fairly small except for the above noted examples. The reject codes given in the second column of Table 2 indicate if there was uncertainty in the ellipsoidal height (h), orthometric height (H) or if the State Adviser (S) for a given state said not to use it.

In Table 1, OPUS-DB appears to have nearly double the amount of noise than NGSIDB (0.031 m versus 0.015 m). This is probably due to the more rigorous collection, adjustment and reduction procedures (e.g., Bluebook) required for geometric data to be entered into the NGSIDB. OPUS-DB solutions require less observation time than would be required for acceptance into the NGSIDB. Further examination will need to be made to determine if the noise is white or colored, but the expectation is that the OPUS-DB data are simply noisier due to less observation time and possible inconsistencies in the CORS positions.

Group 2 forms from the additional 57 points where an ellipsoidal coordinate was known from the NGSIDB but it wasn't used in the GEOID09 model (row 2 in Table 1). Usually this arises when a point was determined from older GPS. These points typically listed Horizontal coordinates as 'B' (e.g., the old HARN sites). Hence, these were not as reliable for LSC modeling for GEOID09. The statistics of the residuals in comparison to GEOID09 and NAVD 88 show that OPUS-DB did a little better here than the NGSIDB (SD of 0.037 m and 0.043 m (one sigma), respectively). This is most probably because the older coordinates aren't as good - even though they are in the NGSIDB. None of these points were rejected; hence, there is no discussion on that.

For both Groups (1) and (2), comparisons were also made between the OPUS-DB and NGSIDB ellipsoidal heights by simply subtracting the NGSIDB values from the OPUS-DB values to produce a set of residuals. The statistics of those residuals are given in Column C of Table 1. The statistics of the comparison between the Common points with rejected points removed (row 1.b) show that there is good agreement between them. A SD of 0.028 m is within the acceptable noise level for NGS observation standards (0.020-0.040 m is considered the norm when following NGS procedures). The comparison on the next line (row 2) shows a SD of 0.044 m, which is significantly higher. However, this is more likely an indication of the inferiority of the NGSIDB data. Recall that OPUS-DB had a smaller SD than NGSIDB for these points. There were sound reasons for not using such data in making the GEOID09 model. This is borne out by these comparisons.

Finally, there were 285 points in Group 3 which had never been visited with GPS before.

These points are some of the 450,000 bench marks never previously visited with a GPS receiver that can be used to supplement the existing coverage in the NGSIDB. There were some definite busts in this group with one residual being over a meter and three others being over half a meter (last group of eleven in Table 2). Removal of the 11 tagged for rejection, brought the SD down from 0.112 m to 0.047 m. This last number is somewhat noisier than would be desirable. Further study will be needed to ascertain how much of this, if any, is also colored noise.

The rejected data are spread around the country (see Figure 4) but seem to be located in regions where some type of extreme subsidence can occur. One in Anchorage, Alaska (not actually shown) was monumented in 1964. This was about the time of a significant earthquake where the ground shifted by a meter immediately, and this was followed by another meter of vertical change over the ensuing year. Hence, the monumented orthometric height given on the bench mark is suspect. Other rejected points occur in the valleys of central California where massive ground water withdrawal has lowered the ground by meters. Still other points were located in regions with either ground or oil withdrawal or in mining regions where mines have collapsed. The OPUS-DB datasheets actually include images of the locale around the marks, and the datasheet for one of the suspect points actually shows oil or water extraction wells in the background behind it.

The outliers in these three groups are quite extreme with four being over 0.500 m. However twenty total points out of 422 represents less than 5% of the total, which is proportionate to the rejected numbers from GPSBM2009. In GPSBM2009, there were a little over 1,000 points rejected out of about 20,000 - again, about 5%. Hence, the reject rate from this small slice of data from OPUS-DB is consistent with that seen from data extracted from the NGSIDB.

4. CONCLUSIONS AND OUTLOOK

NGS is charged with defining, maintaining and providing access to the National Spatial Reference System. The existing datums in the NSRS are NAD 83 (geometric) and NAVD 88 (geopotential). Geoid height models are used to transform between these datums, but such models are dependent on the quality and distribution of the existing ellipsoidal and orthometric heights on bench marks in the NGS Integrated Database (NGSIDB). Supplementing this coverage would reduce the size of the gaps between control points and provide more information for correlating the signal between these points. This improved signal would better account for differences between the NAD 83 and NAVD 88 datums, which should reduce the magnitude of the errors in the interpolation of the geoid grid and provide a better transformation.

The Online Positioning User Service Database (OPUS-DB) provides such a supplemental source. A pull in November 2010 yielded 422 points that were broken into three groups: those that were common to the NGSIDB and OPUS-DB and used in modeling GEOID09 (80 total with 9 being rejected), those that were common but not used in GEOID09 modeling (57 total), and those that represented new geometric coordinates on existing leveled bench marks (285 total with 11 being rejected). Residual values were formed by removing the geoid and orthometric heights from the ellipsoidal heights obtained from the NGSIDB and OPUS-DB, respectively. The statistics of these comparisons showed that the OPUS-DB values were twice as noisy for the first group (SD of 0.031 m versus 0.015 m (one sigma)) and better for the second group (SD of 0.037 m and 0.043 m (one sigma)). The third group yielded a SD of 0.047 m (one sigma), which was consistent with the overall differences between ellipsoid heights in OPUS-DB and NGSIDB (0.044 m (one sigma)).

The take away is that the OPUS-DB data might be a little noisier - possibly due to shorter observation sets, solutions that do not involve a network adjustment of nearby neighbors (i.e., no network adjustment), and uncertainties in the absolute positions of the CORS sites. This doesn't provide a significantly poor finding, because least squares collocation (LSC) can effectively account for increased white noise (random errors) in the modeling. However, the noise must be examined to see if it is white or colored noise. Direct comparison of the solutions in the NGSIDB and OPUS-DB were made by subtracting the two sets of values where both existed (137 total points). This also pointed to similar levels of agreement between the two.

The real gain comes from the inclusion of 285 additional points located in voids that were interpolated across using LSC in GEOID09. By adding data into these voids, even noisier data, modeling will be improved and the effective interpolation errors reduced. Even more significant, is the idea that such efforts could be targeted.

Discussions with NGS State Advisers and other state and professional organizations indicates a willingness on the part of surveyors to target observations on bench marks in regions of sparse to poor coverage. Such a concerted effort to reduce the size of the gaps being interpolated will have the effect of improving the local performance of the geoid height model in transforming between the geometric and geopotential datums.

Once the quality and reliability of such data are validated, then a process for vetting and using OPUS-DB ellipsoid heights on leveled bench marks will be used to supplement the existing coverage. This supplemental data would then be utilized in the development of a future geoid height models. For now, the use of such data remains strictly exploratory but the potential for future use is great.

ACKNOWLEDGMENTS

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BIOGRAPHICAL NOTES

Daniel R. Roman, Ph.D., has been a Research Geodesist with the National Geodetic Survey since 1999. He is the team lead for Geoid Modeling and Research as well as the Principal Investigator for the Gravity for Redefinition of the American Vertical Datum (GRAV-D) Project. He developed GEOID99, GEOID03, GEOID06, GEOID09, and associated models.

Neil D. Weston, Ph.D. is the Chief of Spatial Reference System Division at the National Geodetic Survey and a principle behind the development of OPUS. He has also been involved in the development of OPUS-DB and OPUS Projects.

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