Life Cycle of Control Point Positions: A Case Study Using a Multi-State Control Point Database (MCPD)

Kazi Arifuzzaman and Keith T. Weber

Abstract

The life-cycle (usability) of a control point's position is tied closely to the control point's stability, its datum, and velocity changes across a region due to crustal movement. Analyses of the coordinates of numerous control points stored in the Idaho and Montana Multi-State Control Point Database (MCPD) showed no statistical differences due to a point's stability and its physical setting. However, analyses comparing various realizations of horizontal datum revealed some significant differences. Specifically, there is >1 m difference observed between coordinates using NAD 83(1986) relative to NAD 83(2011) and approximately 2 cm difference between NAD 83(CORS96) and NAD 83(2011) coordinates. A comparison of vertical coordinates derived from geoid models revealed a 30 cm mean difference between GEOID03 and GEOID12A, and >60 cm difference between GEOID99 and GEOID12A. The impact of velocity on these coordinates was apparent and varies strongly with local tectonics across the eastern Idaho study area. This study supports the NGS recommendation to use the most current realization of horizontal and vertical datum available.

Introduction

In 2011, Geodetic Working Groups in both Idaho and Montana created the multi-state control point database (MCPD) to share geodetic control point data. While frequently collected for only a single project, control point data has many uses for other projects and purposes (Pitzer, 2012). The control points (n = 13,000) currently contained in the MCPD were submitted by professional land surveyors in Idaho and Montana with over 8,000 control points found in Idaho alone with more being added each month.

The significance of MCPD control points is manifold. The MCPD acts as a repository of control points, and disseminates these data over the web *(http://ags.giscenter.isu.edu/flexviewers/mcpd/)*. These data are valuable as many existing passive markers (e.g., monuments and benchmarks) have been destroyed over time, or are scarce across the western US. Active markers (e.g., Continuously Operating Reference Stations (CORS)) are too few to provide adequate control for many local geospatial analyses. While the geospatial community may be aware of spatial data quality issues, they may not have at their disposal techniques and tools to determine quality (Li *et al.*, 2012). These concerns make the situation particularly acute for today's geographic information world and the MCPD provides a resource to resolve or address at least some of these issues for Idaho and Montana. For example, the use of passive, visible controls referenced through the MCPD would improve the quality of orthorectification of aerial imagery across Idaho's rough terrain.

Many control points in the MCPD are right-of-way corners or cadastral controls. Right-of-way corner controls define highway, road, and street alignments and are usually set by transportation departments (e.g., Idaho Transportation Department (ITD)). Cadastral controls define property boundaries set for the Public Lands Survey System (PLSS) by private surveyors. The monuments which represent a section corner were originally set by surveyors from the General Land Office (GLO) and, over time, either government or private surveyors have perpetuated many of these monuments. Examples of monument types are brass caps, brass plugs, marked stones, iron pipes, concrete posts, reinforcing bars with plastic or aluminum caps, and holes drilled in rocks. According to National Geodetic Survey (NGS) criteria, these kinds of monuments are considered stability category C or D. Stability is defined as the monument's ability to maintain a long-term, constant position relative to other local features. Stability category C indicates the position may hold well, but are commonly subject to movement, whereas stability D may show unknown reliability over time (Mark Stability, NGS).

The geodetic datums used to determine the horizontal and vertical coordinates of control points are stored in the MCPD database and are not consistent across the MCPD. While the North American Datum of 1927 (NAD 27) was not used, various realizations of North American Datum of 1983 (NAD 83) were used as a collection method of horizontal coordinates. The successive NAD 83 realizations are NAD 83(1986), NAD 83(HARN), NAD 83(CORS96), NAD 83(NSRS2007) and NAD 83(2011). The latest vertical datum is NAVD 88 for the conterminous US, and surveyors report vertical coordinates in NAVD 88. They also report the geoid model used to realize NAVD 88 vertical coordinates and these data are part of the MCPD. During Global Positioning System (GPS) surveys, a hybrid geoid model is used to convert NAD 83 ellipsoid heights into NAVD 88 heights.

The first realization of NAD 83(1986) employed the Geodetic Reference System of 1980 (GRS 80) as its reference ellipsoid to compute position coordinates of the monuments obtained by a triangulation network (Snay and Soler, 2000a). NAD 83 is a modern geocentric reference frame, commensurate with a Conventional Terrestrial Reference Frame (CTRF) such as the International Terrestrial Reference Frame (ITRF), World Geodetic System of 1984 (WGS 84) and International GNSS Service (IGS) frame, and GRS 80 entirely different from its predecessor, Clarke 1866 (a local geometric ellipsoid which was oriented based on celestial observations, and used for position determination in the triangulation network in NAD 27). With the advancement of GPS, positioning accuracy became higher than the 1st order accuracy obtained by older triangulation

GIS Training and Research Center, Idaho State University, 921 S. 8th Ave., Stop 8104, Pocatello ID 83209-8104 (arifkazi@isu.edu)

Photogrammetric Engineering & Remote Sensing
Vol. 84, No. 4, April 2018, pp. 215–225.
0099-1112/17/215–225

doi: 10.14358/PERS.84.4.215

method and, as a result, a national adjustment, NAD 83(HARN) was developed based on a state-by-state high accuracy reference network (HARN) GPS campaign. Simultaneously, another realization NAD 83(CORS96) was obtained based on the network of Continuously Operating Reference Stations (CORS) (Snay and Soler, 2008). Due to discrepancies between NAD 83(HARN) and NAD 83(CORS96), another readjustment combining all HARN and CORS observations evolved as NAD 83(NSRS2007) (Pursell and Potterfield, 2008). The latest realization NAD 83(2011) was adjusted from multiyear CORS data from 1994 to 2010 (Weston *et al*, 2012).

GPS positioning is computed in the frame of satellite orbits such as the World Geodetic System of 1984 (WGS 84) which employs WGS 84 as its reference ellipsoid. The geocenter for WGS 84 is known to be offset by roughly two meters from the NAD 83 geocenter (NIMA, 2000; Soler and Snay, 2004). WGS 84 maintains its orientation and scale consistent with the International Terrestrial Reference System (ITRS) and its realizations of the International Terrestrial Reference Frame (ITRF). Consequently, GPS-derived coordinates are converted from ITRS to NAD 83 coordinates. ITRF accounts for the motion of tectonic plates using the no net rotation (NNR) model which assumes the angular momentum caused by the motion of any tectonic plate is compensated for by the combined angular momentum of the rest of the tectonic plates (Snay and Soler, 2000b). In NAD 83, the North American Plate is held fixed where positions do not move. Time-varying parameters computed in ITRF are incorporated in NAD 83 using a 14-parameter transformation (7 parameters include 3 translations, 3 rotations and 1 scale parameter in an Earth-centered, Earth-fixed (ECEF) cartesian coordinate system, and time-varying components of these parameters result in the reported 14-parameters) so as to cancel time-varying motion in NAD 83 thus effectively holding the North American Plate fixed. However, it is evident that even after cancelling global tectonic velocity at NAD 83, there are residual motions, particularly due to the active pacific plate, Juan de Fuca Plate, and Glacial Isostatic Adjustment (GIA) across the Western US (Calais *et al.*, 2006; Sella *et al.*, 2007).

Since ITRS addresses global tectonic velocity, any updates of this and other technological improvements result in newer realizations of ITRF. Accordingly, NAD 83 realizations are made consistent with respective ITRF realizations. For example, NAD 83(2011), 2010.0 is consistent with ITRF2008, 2005.0. The decimal year represents an epoch which refers to a moment at which positions and velocity are conceptualized to exist (Meyer, 2010). NAD 83 will be replaced in 2022 with the new North American Terrestrial Reference Frame of 2022 (NATRF2022) which will have no geocentric offset compared to ITRF, WGS 84, or IGS frame (NGS 62, 2017).

The North American Vertical Datum of 1988 (NAVD 88) was the result of the adjustment of levelling networks in the US, Canada, and Mexico with a single control of tidal benchmark located at Father Point, Rimouski, Quebec (Zilkoski, 1992). Hybrid geoid models were used with GPS-based techniques to convert NAD 83 ellipsoid heights into levelled NAVD 88 orthometric heights (NGS 58, 1997; NGS 59, 2008). The equation that relates NAD 83 ellipsoid heights (h) and NAVD 88 heights (H) is, $H = h - N$; where N is the geoid height derived from geoid models. The gravimetric geoid (e.g., Earth Gravitational Model 1996 (EGM96) or Earth Gravitational Model 2008 (EGM2008)) is adjusted with NAVD 88 heights at benchmarks to create a hybrid geoid model (Arifuzzaman and Hintz, 2016). The newer hybrid geoid models result in improved spatial resolutions compared to the older models and are based upon more gravity data along with improved computational techniques (Roman, 2004 and 2009). The successive hybrid geoid models are GEOID96, GEOID99, GEOID03, GEOID09, GEOID12A, and GEOID12B. GEOID12A and GEOID12B are identical everywhere across the conterminous US except Puerto Rico and the US Virgin Islands region (Technical Details for GEOID12/GEOID12A/GEOID12B, NGS). The geoid models that have finer spatial resolution match closely with NAVD 88 heights. There will be one additional hybrid geoid model (GEOID19) which will convert ellipsoid heights to NAVD 88 heights (Brian Shaw, NGS, personal communication). Following this, NAVD 88 will be replaced in 2022 with a completely gravity-based vertical datum, North American-Pacific Geopotential Datum of 2022 (NAPGD2022), where ellipsoid heights and GEOID2022 will be used to derive orthometric heights (NGS 64, 2017).

The NGS recommends using the most current realizations of the national datum and geoid model. However, since there are a plethora of NAD 83 realizations, and hybrid geoid models, surveyors, and mapping GIS professionals may not be consistent in their use of the most current datum realization and geoid model. Indeed, the MCPD contains control points derived from various realizations of horizontal datums as well as geoid models.

The question arises then, how long (across time) do positions assigned to control points hold true? Although the basic problem of the use of various datum realizations needs to be understood in the context of their developments, three important factors that can be analyzed to assess coordinate quality of the control points are the (a) stability of the physical setting of each control point, (b) effect of changes in the realization of the National Datum, and (c) displacement of positions due to residual velocity caused by the regional tectonic setting. Any position specified to a control point will be affected due to changes in any or all of these factors. This study examines each of these factors using the MCPD as its source data. The analysis of these aspects of control point positions is relevant in the context of the quality of the MCPD database and can be considered a life-cycle analysis of control point coordinates in general.

Methods

Survey control points are often subject to ground motion due to traffic/construction activities nearby, or the soil and/or geologic conditions of the site. The vertical component of control points tend to be affected more than the horizontal component because more often than not ground motion is in the vertical direction aside from tectonic activity (Fisher and Conway, 2009). One way to determine if there was a disturbance of the physical setting of any control point is to analyze changes in its position over time. Control points in the MCPD contain what are considered data overlaps where the same control point was surveyed by more than one surveyor over time. Analyzing these data overlaps across time provides insight describing a control point's change in position. For this study, control points were selected based on collection technique and datum realization and only those control points acquired using the same realization and collection technique over different times were used for analysis.

There are also control points that have been surveyed using two different realizations of a given horizontal datum and, in some cases, several realizations have been used. These data overlaps are an ideal source to determine the discrepancy of coordinates derived from different realizations. Various datum realizations were able to be compared using the MCPD; NAD 83(1986) versus NAD 83(2011), NAD 83(1986) versus NAD 83(NSRS2007), and NAD 83(CORS96) versus NAD 83(2011). To compare vertical coordinates, available combinations of geoid models in MCPD were similarly selected and analyzed; GEOID99 versus GEOID12A, and GEOID03 versus GEOID12A. Control points were reported with a stated accuracy convention such as local accuracy or network accuracy for both horizontal and vertical coordinates in MCPD. Control points described as network accuracy were chosen for this study as network accuracy represents uncertainty of control points with respect to the geodetic datum. Depending on the method used for data collection such as static GPS or Real-Time Kinematic (RTK) GPS, the accuracy (1σ) varies from ±0.002 m to ±0.05 m in both horizontal and vertical data.

Studies relating to regional velocities provides good evidence of whether the position of a control point should remain constant or show a pattern of movement coincident with overall regional velocity changes. For example, the average difference between NAD 83(2011) epoch 2010.0 and NAD 83(CORS96) epoch 2002.0 for easting was 0.05 cm ±5.25 cm, for northing 2.12 cm ±6.08 cm with vertical differences of -0.66 cm ± 2.24 cm, whereas the average difference of those two adjustments at the same epoch 2002.0 for easting was –0.14 cm ±1.04 cm, for northing 0.19 cm ±0.94 cm with vertical differences of 0.80 cm ±1.89 cm (CORS Myear FAQ 6, NGS). It is apparent the difference between two adjustments at the same epoch is very small, but the difference is larger between epochs of 2010.0 and 2002.0 because of the impact of velocity over time. Analyzing velocity of both the horizontal and vertical components of existing CORS sites allows for the subsequent analysis of MCPD control points in close proximity to a CORS site to determine if these control points exhibit the same positional behavior over time.

To accomplish this analysis, data in the MCPD were parsed by surveyor. Next, data overlaps (spatially coincident control points) between surveyors were identified using the intersect tool in ArcMap®. These data overlaps were further analyzed based on the township, range, direction, and section to verify they were indeed representing the same control point. The datasets used for all further analyses are described in Table 1.

Analysis involved the exploration of data derived from differences in northing, easting, and orthometric height. The objective of data exploration was to statistically analyze differences between two datasets describing the same control point. Data distribution patterns were analyzed using a histogram and box-plot. Normal probability plots were drawn to check the normality of the data and t-tests performed between the datasets. Both parametric and non-parametric t-tests were used depending on resulting normality. Parametric t-tests were performed under the null hypothesis, that

$H_0{:}\mu_{Difference} = 0$, against the alternate hypothesis, $H_1{:}\mu_{Difference} \neq 0$

Thus, the test of observed t-test statistic was $t = \frac{\mu_{Difference} - 0}{S/\sqrt{n}}$; where, $\mu_{Difference}$ is the mean value of the difference, S denotes the standard deviation of the differences, and n indicates the number of observed control points in the analysis. The observed t-statistic was compared with the

Table 1. Summary of control points statistical analyses completed in this study.

		Sample Size	Survey Periods	Mean (m)	Standard Deviation (m)	t-statistic
Differences between horizontal coordinates (2013 and 2015)						
Easting		82	Mar, 2013 vs Aug, 2015	0.000	0.023	0.18[1]
Northing				0.000	0.042	-
Horizontal				0.008	0.039	0.08[1]
Differences between vertical coordinates (2013 minus 2015)						
Using GEOID03		52	Mar, 2013 vs Aug, 2015	0.072	0.052	-
Differences between NAD 83(1986) and NAD 83(2011)						
Easting		85	Jun, 1997 vs Oct, 2015	-0.980	0.021	428.65[1]
Northing				0.680	0.011	551.55[1]
Horizontal				1.200	0.018	598.26[1]
Differences between NAD 83(1986) and NAD 83(NSRS2007)						
Easting		21	Aug, 2015 vs Dec, 2015	0.038	0.027	6.43[2]
Northing				-0.037	0.030	5.74[2]
Horizontal				0.062	0.025	10.94[2]
Differences between NAD 83(CORS96) and NAD 83(2011)						
Easting		16	Dec, 2012 vs Oct, 2015	0.009	0.011	1.90[3]
Northing				0.014	0.021	4.16[3]
Horizontal				0.022	0.017	4.84[3]
Vertical coordinate differences using geoid models						
GEOID99 vs GEOID12A		12	Dec, 2012 vs Sep, 2016	0.616	0.029	54.73[4]
GEOID03 vs GEOID12A		8	Oct, 2012 vs Jul, 2014	-0.304	0.237	3.63[5]
Differences in position due to velocity						
NAD 83(2011) 2010.0 vs NAD 83(CORS96) 2002.0	Easting	12	Sep, 2016 vs Dec, 2012	0.972	0.017	-
	Northing			-0.693	0.019	
	Easting	9	Oct, 2015 vs Dec, 2012	0.977	0.020	-
	Northing			-0.703	0.057	
	Easting	16	Oct, 2015 vs Dec, 2012	0.008	0.018	-
	Northing			0.014	0.013	

1. t-critical (0.05) value = 1.99
2. t-critical (0.05) value = 2.09
3. t-critical (0.05) value = 2.13
4. t-critical (0.05) value = 2.20
5. t-critical (0.05) value = 2.37

critical t-value at the 0.05 significance level for statistical inference.

Similarly, if the normal distribution assumption for the observed data was not justified, a nonparametric sign test was performed to determine whether any significant difference in the observations exists. If p is the probability that the difference between the two datasets is positive, and if the difference is insignificant, p will take the value 0.5 (i.e., the difference is the same about 50 percent of the time). Thus, the hypothesis was to test: H_0:p=0.5 against H_1:p≠0.5

For large samples,

under H_0, $Z = \frac{\sqrt{n}(\hat{p}-0.5)}{\sqrt{0.5(1-0.5)}} \sim N(0,1)$;

where n is the number of samples and $\hat{p}$ is the proportion of positive observations (Sheskin, 2003). The computed Z-value is compared with the critical Z-value at 0.05 significance level for a statistical result.

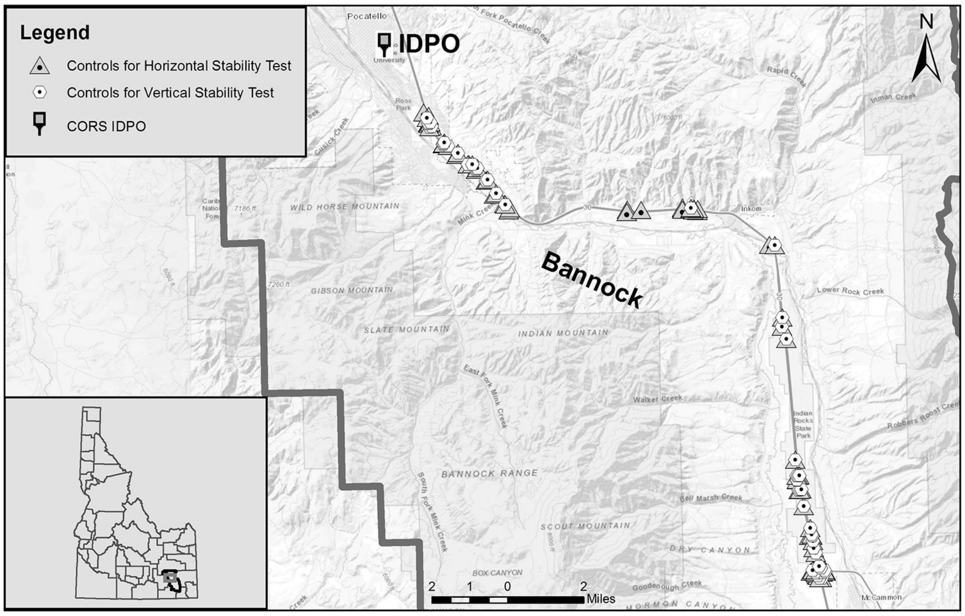

Figure 1. Control points used for horizontal and vertical stability analysis located in Bannock County, Idaho.

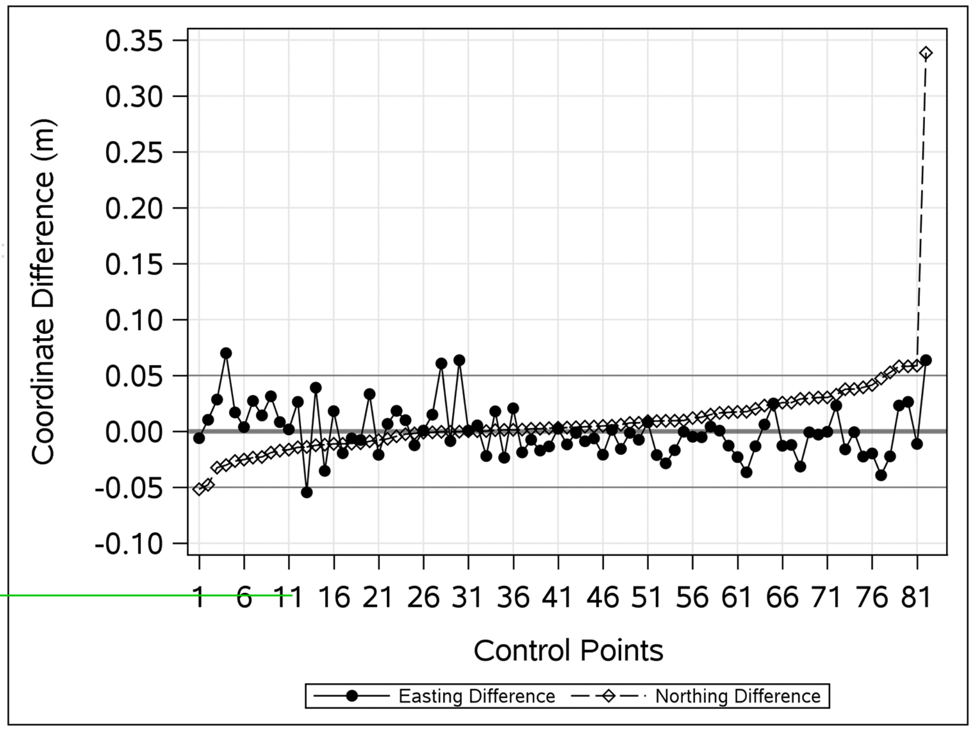

Figure 2. Differences in northing and easting between 2013 and 2015 control point observations using NAD 83(1986).

Results

Analysis of the Stability of Control Point Settings

A dataset consisting of 82 control points was used for stability analysis. This particular dataset was located in Bannock County, Idaho (Figure 1).

Analysis of Horizontal Coordinates

Horizontal components were collected in NAD 83(1986). Data were collected first in 2013 and then again in 2015 by two different surveyors and the Real-Time Kinematic (RTK) GPS technique was used for both collection methods.

The difference in horizontal components (i.e., the difference in easting and the difference in northing observed between 2013 and 2015) were analyzed to determine correlation (Figure 2). This figure was sorted by northing difference, so the abscissa indicates the control point's placement in the sorting order and the ordinate is the difference (in meters) between observations from 2013 relative to 2015. The difference is confined to be within for most control points tested. The 1σ reported for observations in both 2013 and 2015 was 3 cm. Most differences are well within ± the 2σ standard deviation. Only one extreme difference in northing is visible in the plot. Upon inspection, this control point showed an easting difference of 6.3 cm (very near 2σ) suggesting a data entry error for the northing value.

Histograms of differences are shown in Figure 3a. The population is zero centered in both easting and northing differences. To identify the possibility of outliers, boxplots were produced (Figure 3b). The box spans from the 0.25 quantile to the 0.75 quantile surrounding the median with whiskers that extend to span the dataset excluding outliers. The box-whisker plots indicate three probable outliers in easting and four probable outliers in northing.

The normal distribution assumption was justified for easting differences, and a t-test was performed to determine if the difference between the eastings measured in 2013 and 2015 were significant (Table 1). The observed t-statistic was 0.18, which was less than the critical t-value of 1.99 ($t_{0.025,81}$) at 5 percent significance level: p = 0.85 for a two-tailed comparison. Hence the null hypothesis is not rejected, and it was

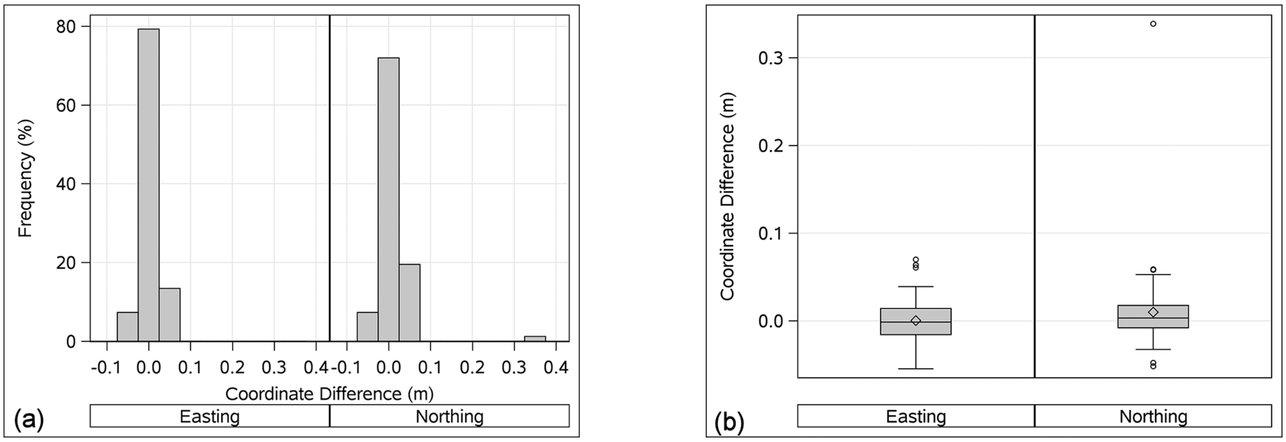

Figure 3. (a) Histograms, and (b) boxplots of the differences in easting and northing (in meters) between 2013 and 2015 control point observations using NAD 83(1986).

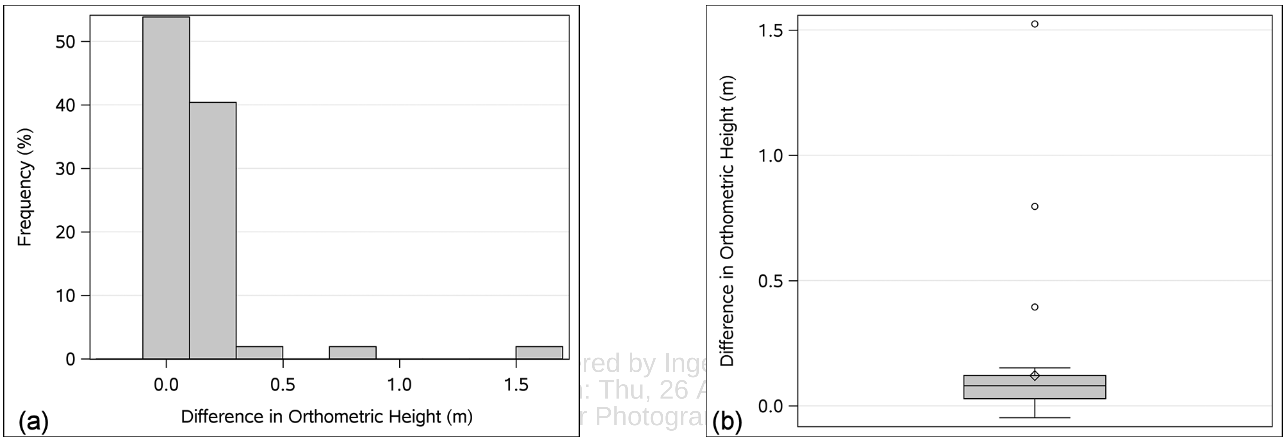

Figure 4: (a) Histogram, and (b) box plot for the difference in elevation (in meters) (2013 minus 2015) derived from GEOID03.

confirmed there was no significant difference between eastings measured in 2013 and 2015.

Northing data did not follow a normal distribution so a nonparametric sign test was performed to determine whether there exists any significant difference in northings derived in 2013 and 2015 observations. The computed $Z = 2.30$, was greater than 1.96 (the critical Z-value at 0.05 significance level). Hence the null hypothesis is rejected. However, if the confidence level were increased to 99 percent, the critical Z-value becomes 2.57 which is just slightly greater than the computed Z-value (2.30), and in this case one would conclude no significant difference at 0.01 significance level.

Total horizontal Cartesian differences were computed using the Pythagorean Formula $\sqrt{(\text{Diff\_Northing})^2 + (\text{Diff\_Easting})^2}$. A t-test was performed on the total Cartesian horizontal difference, and the t-statistic was found lower than t-critical value ($p = 0.93$ for a two-sided comparison). It is confirmed there is no statistical difference in horizontal coordinates between 2013 and 2015 observations. Therefore, the authors conclude there was no change in the physical environment of these monuments. However, the outlier point noted earlier with an extreme northing difference remains to be verified in the field, and possible elimination of erroneous data from the database.

Analysis of Vertical Coordinates

Using the same dataset described above, vertical coordinates of 52 control points were measured using the GEOID03 model in 2013 and again in 2015 (by different surveyors). The statistical significance of differences in measured data between 2013 and 2015 were analyzed. The histogram plot (Figure 4a) shows approximately 53 percent of measured heights have zero difference whereas about 40 percent data exhibit approximately 20 cm differences (mean was 12 cm). Three probable outliers are revealed in the boxplot analysis (Figure 4b).

A nonparametric sign test was performed to determine any significant difference in elevation derived between 2013 and 2015 observations. The computed Z-value was 5.57 which is greater than the critical Z-value of 1.96 at 0.05 significance level. Hence, it can be concluded elevations measured in 2013 and 2015 are not same.

Monument stability may be a factor causing the variation in elevation, so the observed differences were plotted by monument type (Figure 5), where C, I, N, R, and S denote monuments made of cement, iron, nail, rebar, and stone respectively. Monuments made of cement post lie close to the zero mean difference, whereas monuments made of stone are the farthest from zero mean difference. Three stone control points indicate extreme differences in elevation and may indicate possible subsidence of those monuments.

The 2σ measurement errors in elevation for both 2013 and 2015 observations were 9 cm. However, the mean difference between 2013 and 2015 observations was 12 cm which is approximately a 3σ error. After removing the values of the three possible outliers, the mean value of elevation differences was reduced to 7 cm which is likely a more representative result. Since vertical error in observations is always higher than horizontal error, and is dependent upon the type of GPS technique used, it can be safely concluded from the low estimate of mean differences between 2013 and 2015, that there is no indication of disturbance in the physical setting for the observed control points. However, the three outliers warrant physical inspection and possible resetting of the survey marks.

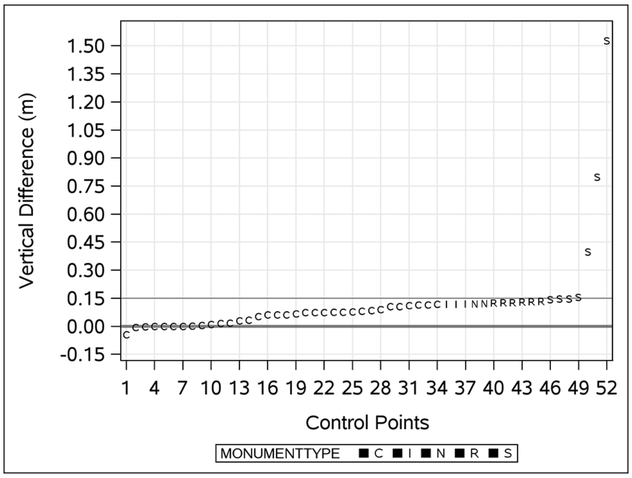

Figure 5. Vertical difference (2013 minus 2015) derived from GEOID03 plotted by the types of monument setting, cement (c), iron (i), nail (n), rebar (r), and stone (s).

Analysis of the Changes with Datum Realizations

Three datasets were selected for this analysis. These datasets contained control point coordinates observed in different realizations of NAD 83 for the same control point. Datasets were also chosen to study changes due to differing geoid models used to derive the vertical coordinates for the same control point. The three combinations of horizontal datum realizations and two combinations of geoid models found in the MCPD database (Figures 6 and 7) were statistically analyzed (Table 1).

NAD 83(1986) versus NAD 83(2011)

The test for this comparison used 85 control points located in Madison County, Idaho (Figure 6a). These control points were acquired by two different surveyors in 1997 and again in 2015 using NAD 83(1986) and NAD 83(2011), respectively. Frequency histograms are shown in Figure 8. Neither easting nor northing differences were zero-centered: for easting and northing, the means were –0.98 m and 0.68 m with standard deviations of 0.021 m and 0.011 m, respectively. Values of *t*-tests for the differences (428.65 for easting and 551.55 for northing) were far greater than the critical *t*-value (1.99) indicating a significant difference between easting and northing values obtained in NAD 83(1986) versus NAD 83(2011). The total horizontal Cartesian differences were computed and resulting ranges varied from 1.14 m to 1.25 m, with 99 percent of values found between 1.20 m to 1.25 m (p<0.0001). The mean value of the total horizontal difference was 1.20 m (Figure 8). It is

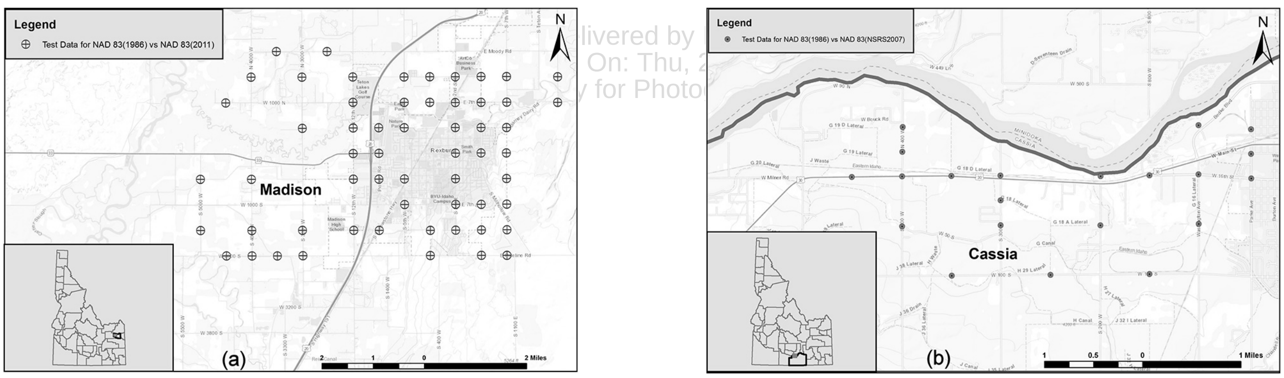

Figure 6. Datasets for: (a) NAD 83(1986) versus NAD 83(2011) in Madison County, and (b) NAD 83(1986) versus NAD 83(NSRS2007) in Cassia County, Idaho.

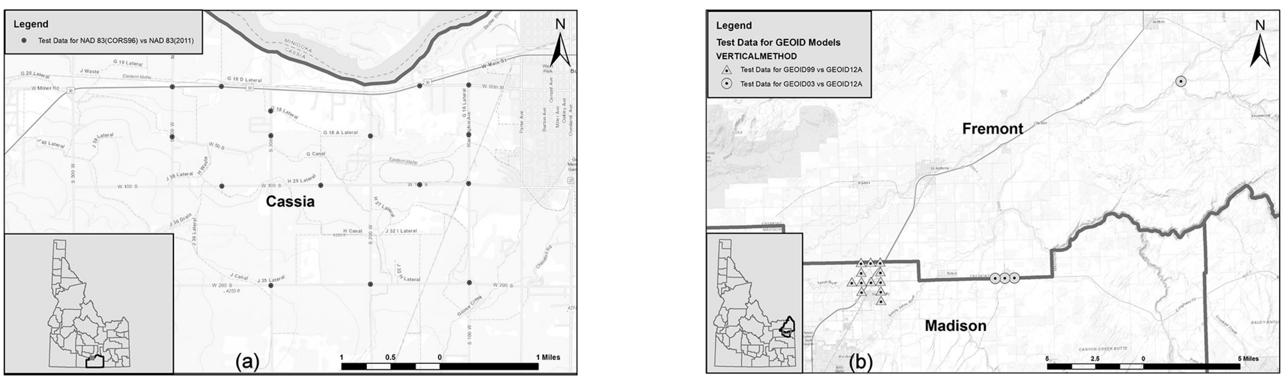

Figure 7. Datasets for: (a) NAD 83(CORS96) versus NAD 83(2011) in Cassia County, and (b) GEOID99 versus GEOID12A in Madison County and GEOID03 versus GEOID12A in Fremont County, Idaho.

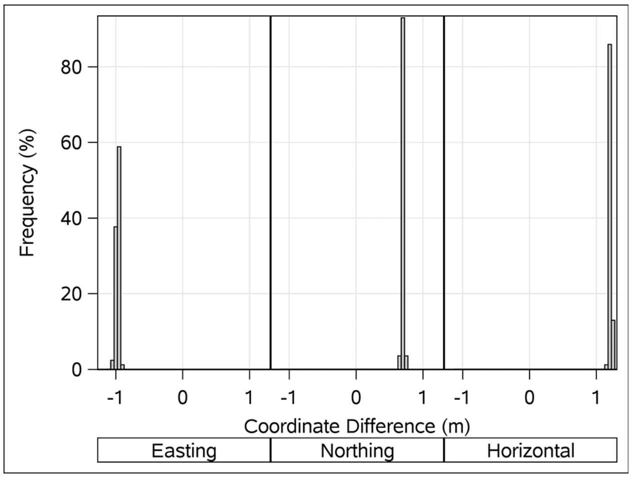

Figure 8. Histogram plots for the difference (m) in easting, northing, and total horizontal Cartesian differences between NAD 83(1986) and NAD 83(2011).

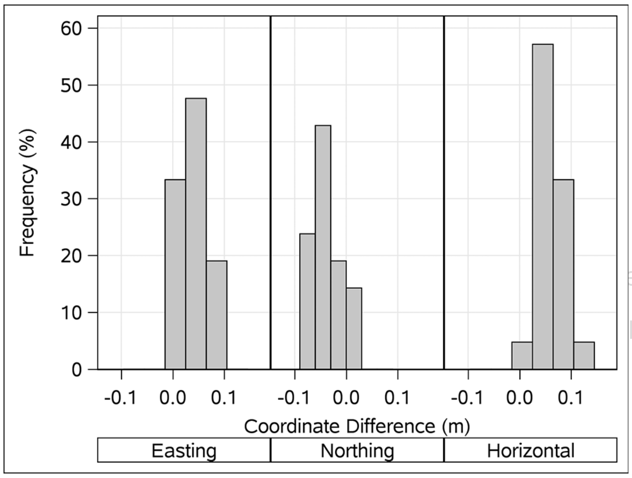

Figure 9. Histogram plots for the differences (m) in easting, northing, and total horizontal Cartesian differences between NAD 83(1986) and NAD 83(NSRS2007).

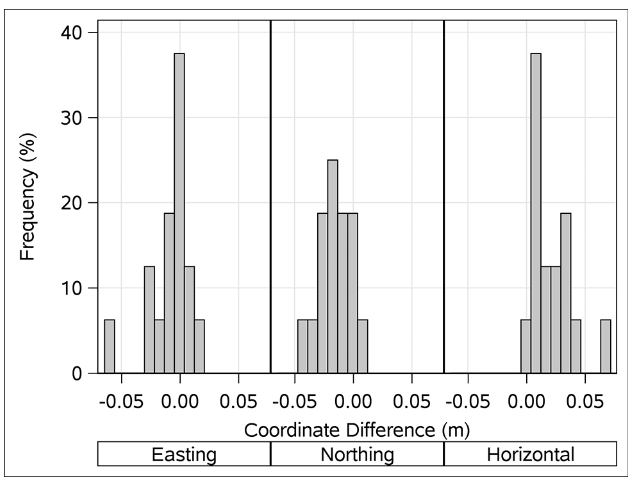

Figure 10. Histogram plots for differences (in meters) in northing and easting, and total horizontal Cartesian distance between NAD 83(CORS96) and NAD 83(2011).

apparent that NAD 83(1986) and NAD 83(2011) vary greatly in coordinate values.

NAD 83(1986) versus NAD 83(NSRS2007)

A dataset with 21 control points was used to compare NAD 83(1986) and NAD 83(NSRS2007) coordinate values (Figure 6b). These control points were observed by two different surveyors in 2015 using two different realizations (NAD 83(1986) and NAD 83(NSRS2007)). The difference in easting and northing values in both observations were statistically analyzed with minimum differences found to be -0.01 m and -0.09 m, respectively. The maximum observed differences in easting and in northing were 0.09 m and 0.02 m, respectively.

A *t*-test for each easting and northing difference was performed and in both tests, the observed *t*-values (6.43 and 5.74) were greater than the critical *t*-values (2.09) indicating both easting and northing values were different when obtained in NAD 83(1986) versus NAD 83(NSRS2007). Mean values for the difference in easting and northing were 0.04 m and –0.04 m, and the standard deviations were 0.027 m and 0.030 m in easting and northing, respectively. The mean value in total horizontal Cartesian difference was 0.06 m ($p < 0.001$) and the maximum value was 0.11 m (Figure 9).

NAD 83(CORS96) versus NAD 83(2011)

This dataset contained 16 control points located in Cassia County, Idaho (Figure 7a). Two surveyors observed the same control points using NAD 83(CORS96) in 2012 and NAD 83(2011) in 2015. To understand differences in easting, northing, and total horizontal Cartesian distance between these two realizations, these data were explored and statistically analyzed as described above. Frequency histograms are shown in Figure 10. The means for easting and northing differences were 0.009 m and 0.014 m with standard deviations of 0.011 m and 0.021 m, respectively. Only 18 percent of values were zero-centered for northing differences, whereas 37 percent of values were zero-centered for easting differences. The results of *t*-test show northings were different at the 0.05 significance level while eastings were different at the 0.10 significance level.

The mean difference in northing values (0.014 m) exceeded that found for easting values (0.09 m). The maximum horizontal Cartesian difference was 0.071 m and the resulting *t*-test indicated the two dataset were significantly different ($p < 0.001$). Hence there is a difference in horizontal values obtained in NAD 83(CORS96) relative to the values obtained in NAD 83(2011).

GEOID99 versus GEOID12A and GEOID03 versus GEOID12A

A small testable dataset containing only 12 control points was found in Madison County, Idaho. Vertical coordinates (orthometric height) for these control points were observed using two different geoid models, GEOID99 and GEOID12A. Another small dataset of 8 control points was found in Fremont County, Idaho with vertical coordinates observed using GEOID03 and GEOID12A (Figure 7b). Heights derived from both GEOID99 and GEOID03 were subtracted from heights derived from GEOID12A. Frequency histograms are given in Figure 11. The mean difference was 0.62 m in the case of GEOID99 versus GEOID12A, whereas the mean difference was –0.30 m in the case of GEOID03 versus GEOID12A. The visible contrast (some were positive and some showed negative differences) in the differences between GEOID03 versus GEOID12A (Figure 11) indicates higher values tend to be acquired from GEOID12A at some control points relative to GEOID03. Upon further investigation, it was observed that control points with higher values (from GEOID12A) were located further northeast than the other control points (Figure 7b), and a possible upliftment of that area may be a factor explaining this observation. An NGS-derived velocity map explains this further (Figure 12b).

A *t*-test for each dataset showed the observed *t*-statistics were greater (54.73 and 3.63) than the critical *t*-values (2.20 and 2.37) at 0.05 significance for both GEOID99 versus GEOID12A, and GEOID03 versus GEOID12A, respectively. The difference between GEOID03 and GEOID12A was smaller than GEOID99 and GEOID12A. The maximum and minimum differences were 0.72 m and 0.58 m between GEOID99 and GEOID12A, and –0.45 m and 0.08 m between GEOID03 and GEOID12A.

Analysis of Change in Coordinates due to Velocity

NAD 83(2011) epoch 2010.0 incorporates regional velocity, and coordinate analyses in NAD 83(2011) epoch 2010.0 versus NAD 83(CORS96) epoch 2002.0 indicate scale of changes over eight years from epoch 2002.0 to epoch 2010.0. A velocity map for Idaho produced by NGS shows the velocities and direction of these movements of the CORS (Figure 12).

It is apparent when examining the magnitude as indicated by the arrows in Figure 12 that east Idaho experiences a higher magnitude of velocity relative to southwest Idaho. Correspondingly, the arrow at CORS site IDBY in east Idaho suggests a total horizontal displacement of about 30 mm (comparing the given magnitude of 10 mm scale) over eight years in a southeast direction (Figure 12a). Three datasets close to the IDBY CORS in Madison County, Idaho (Figure 13) were analyzed to determine if velocity differences were consistent between CORS sites and nearby control points. Circle-shaped points indicate dataset 'A' (located between 7 to 9 km north of IDBY), square-shaped points indicate dataset 'B' (located between 2 to 4 km west of IDBY), and cross-shaped points indicate dataset 'C' (located between 6 to 9 km south of IDBY). Datasets were observed in NAD 83(2011) and NAD 83(CORS96), with survey periods for dataset 'A' in September 2016 and December 2012, dataset 'B' in October 2015 and December 2012, and dataset 'C' in October 2015 and December 2012, respectively. RTK was used as a data collection technique for all these datasets. Dataset 'A' consisted of 12 control points, 'B' consisted of 9, while 'C' consisted of 16 control points. These control points were chosen to analyze coordinate change with respect to changes in crustal velocity.

Boxplots of easting and northing differences for all three datasets obtained from NAD 83(2011) epoch 2010.0 minus NAD 83(CORS96) epoch 2002.0 are shown in Figure 14(a) and 14(b). Both datasets 'A' and 'B' represent positive easting and negative northing differences which indicate these two datasets have moved in southeast direction. It is imperative to note that datasets 'A' and 'B' mimic the movement of IDBY in a southeast direction, however their rates of changes over eight

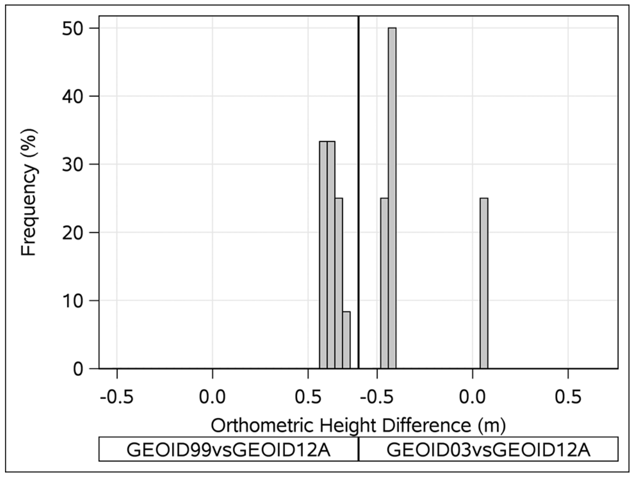

Figure 11. Histogram plots for the differences in orthometric heights (in meters) for GEOID99 versus GEOID12A and GEOID03 versus GEOID12A.

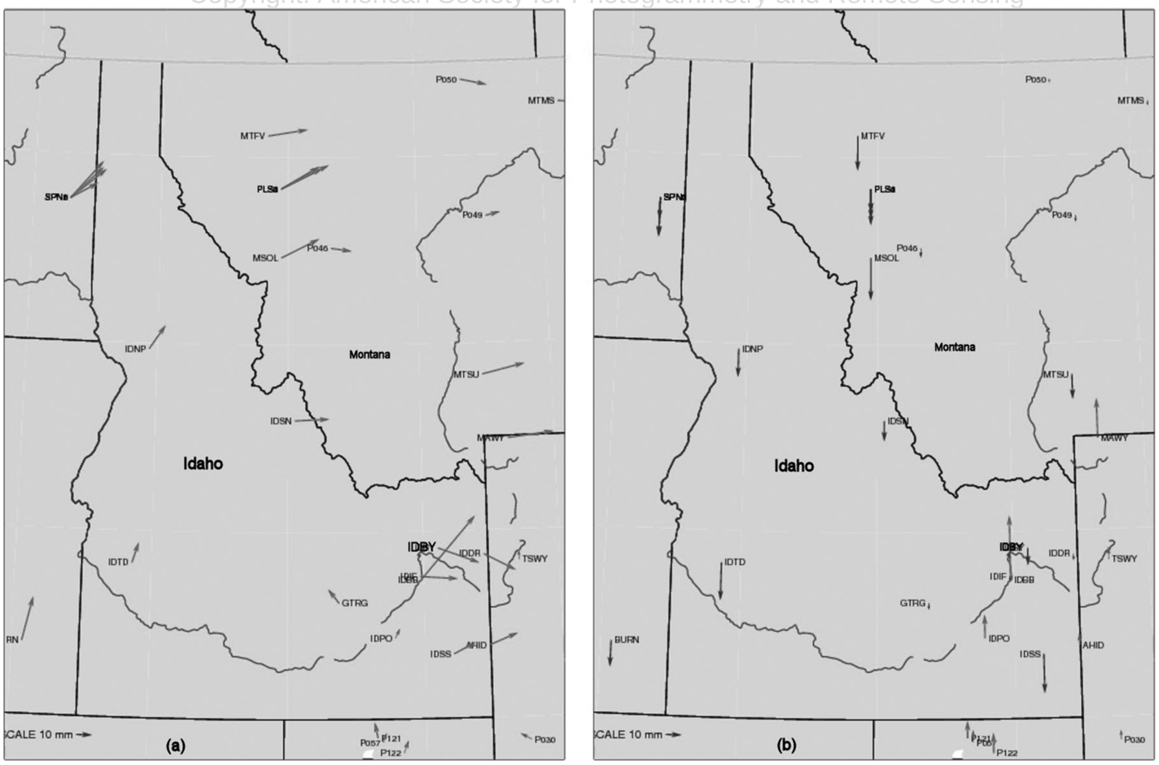

Figure 12. Velocity vectors of CORS in Idaho: (a) horizontal vectors are shown as red arrows, (b) upward vertical as red and downward vertical as blue arrows (and river marked blue); derived from NAD 83(2011) epoch 2010.0 minus NAD 83(CORS96) epoch 2002.0 (Source: CORS Myear, NGS).

years are about 80 cm which is larger than the NGS predicted coordinate change at IDBY of 30 mm over eight years (Figure 12a). Dataset ‘C’ shows a smaller change of about 2 cm over eight years in a northeast direction. This suggests data collections are strongly influenced by local tectonic factors that may not be captured by a single CORS. In addition, all three datasets (A, B, and C) were collected between 2012 and 2016, and the multiyear NGS velocity map (Figure 12) was based on data up to 2010. This indicates this area might be experiencing further movement since 2010. We examined the long term time series plot found at NGS CORS website for IDBY (CORS IDBY, NGS), but the plot has data only from 2007 to 2011. No information could be extracted that could have been used to correlate with the collection time of the three datasets used in this study. Since the change in dataset C was small, IDBY and dataset C might represent movement of the same geologic setting, and datasets A and B may represent movement of another local geologic setting. Existence of numerous active faults (Figure 13) in the area supports this idea. Geologically, this area is located near the Intermountain Seismic Belt, a prominent NS-trending zone of seismicity and a region of moderate-to-high seismic hazard (Sbar *et al.*, 1972; USGS, Earthquake Hazards Program).

The analysis of vertical velocity changes compared orthometric heights derived from GEOID99 and GEOID12A (ellipsoid heights obtained from NAD 83(2011) were used in the construction of GEOID12A and ellipsoid heights from NAD 83(CORS96) used GEOID99). The comparison of vertical data indicates higher values in GEOID12A (Figure 14c) corresponding with an upward velocity in the area (Figure 12b).

Discussion

The stability analysis of monument settings on a large set of data consisting of 82 control points presents a new approach to recognizing differences in the coordinates of control points. Although it might be intuitive to check physical sites in person, the approach taken in this paper is a convenient way

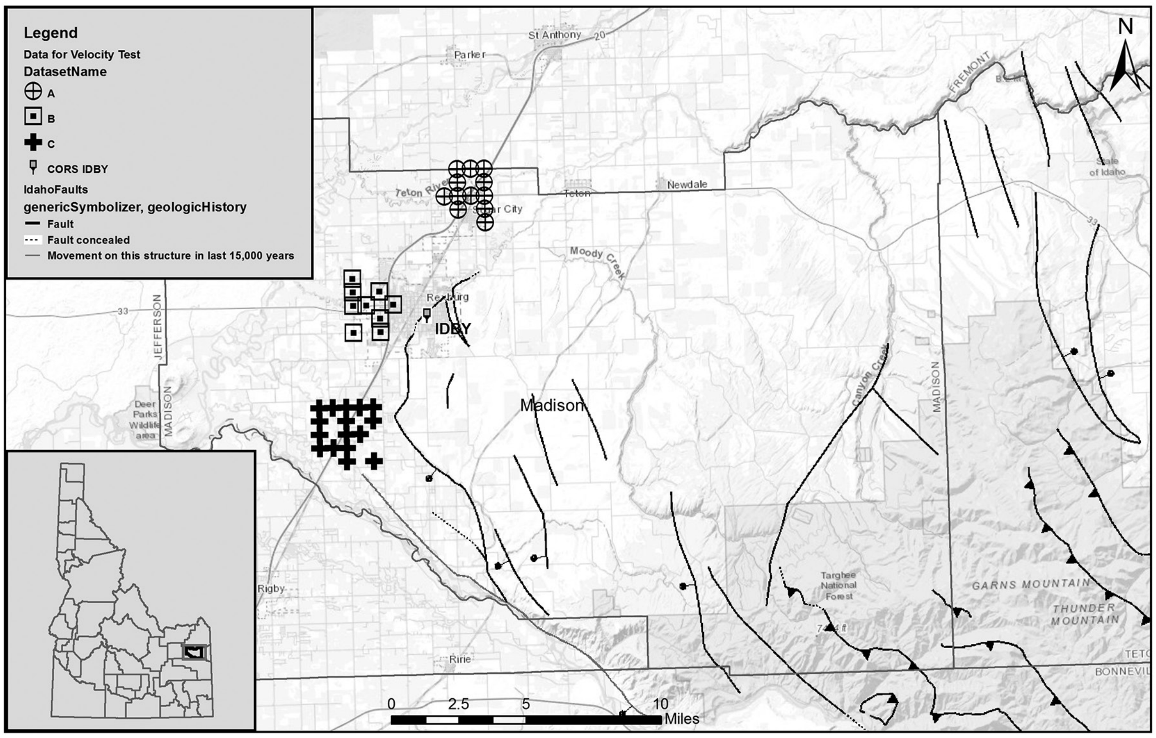

Figure 13. Datasets (‘A’ circle, ‘B’ square, and ‘C’ cross) for velocity comparisons near IDBY CORS site. Faults (triangles indicate thrust fault; solid circles indicate downthrown block) are shown in solid black lines, and recent movement along red line (Source of Faults: Inside Idaho).

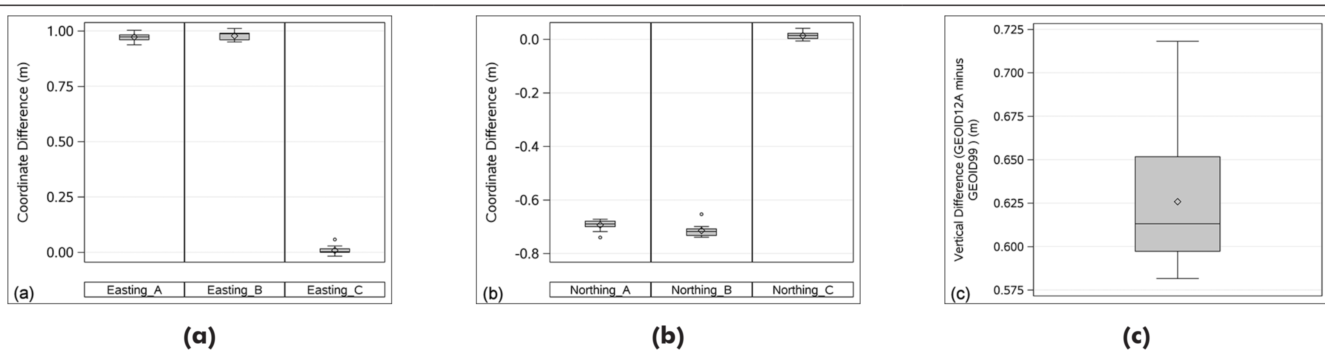

Figure 14. Boxplots of, (a) easting, and (b) northing differences (in meters) in NAD 83(2011) minus NAD 83(CORS96) for datasets ‘A’, ‘B’, and ‘C’; and (c) vertical difference (in meters) for GEOID12A minus GEOID99.

Table 2. Results of horizontal datum comparison.

	NAD 83(1986) vs NAD 83(2011)	NAD 83(1986) vs NAD 83(NSRS2007)	NAD 83(CORS96) vs NAD 83(2011)
Statistically different in easting, northing and Cartesian horizontal	Yes	Yes	Yes
Mean difference (easting)	98 cm	4 cm	0.9 cm
Mean difference (northing)	68 cm	4 cm	1.4 cm
Mean difference (Cartesian Horizontal)	120 cm	6.2 cm	2.2 cm

Table 3. Results of geoid model comparison.

	GEOID03 vs GEOID12A	GEOID99 vs GEOID12A
Statistically different in GPS-derived vertical coordinates	Yes	Yes
Mean difference	30 cm	63 cm

to deal with the stability of monument settings. Four control points were found to be outliers, while one was obviously far from the mean, and this control point was removed from analysis requiring physical inspection. While there were no differences in easting, the observed difference in northing (at 0.05 significance) diminished when the confidence level was increased to 99 percent. This slight discrepancy does not in any way indicate a problem with the stability of the monuments as the *t*-test performed on the total horizontal difference indicated the two datasets were not different in terms of their horizontal components. After removing three outliers, the mean difference of vertical coordinates was 7 cm (within 2ğ measurement errors) and is not considered excessive relative to the GPS techniques used and the short term of observations to acquire these data. Monument stability analysis revealed that monuments made of cement post provided comparably better long-term accuracy than monuments made of stone.

While the geocenter and length of the axes of the coordinate frame in the first realization of NAD 83(1986) were computed based on Doppler data, subsequent realizations (e.g., NAD 83(HARN)) included improved knowledge of axis lengths and orientations based on advancements of GPS and other technologies. Although the geocenter remained unchanged, a new scale factor was introduced in order to be consistent with ITRF89 (Snay and Soler, 2000a). These changes made the newer realizations different from the first realization of NAD 83(1986). It is expected that NAD 83(HARN) coordinates may differ by nearly 1 m from corresponding NAD 83(1986) coordinates (Snay and Soler, 2000a). NAD 83(NSRS2007) is a refinement of NAD 83(HARN) or NAD 83(CORS96) as it included better ellipsoid heights and implemented better computational techniques. The difference in coordinates between NAD 83(HARN) versus NAD 83(CORS 96) realizations were expected to be <10 cm (Snay and Soler, 2000a). However, because of insufficient samples within the MCPD database, we could not make this comparison. In our analysis, comparisons between NAD 83(1986) and NAD 83(NSRS2007) resulted in only +/-6 cm difference; however, we believe a larger difference would likely follow with a more representative dataset. The changes in coordinates between NAD 83(2011) epoch 2010.0 and NAD 83(CORS96) epoch 2002.0 were expected to be approximately 2 cm (Sickle, 2013) if no velocity factors were involved.

A summary of horizontal datum comparisons (Table 2) indicates the largest changes or differences in coordinates exist between NAD 83(1986) versus NAD 83(2011) realizations.

Since successive geoid models have better resolutions and improved gravimetric models, GPS-derived orthometric heights using the latest geoid model provides better results (Table 3). The development of GEOID03 was better than that of GEOID99, partly because there were more satellites available in the GPS constellation, additional airborne based gravimetric data existed, better global gravity models had been developed, far more GPS baselines were available, and better ellipsoid heights, and better computational techniques were available. As a result, there are larger difference in elevation reported between GEOID99 and GEOID12A, relative to the differences reported between GEOID03 and GEOID12A.

The velocity map for Idaho published by NGS is an indication of probable changes in coordinates due to the velocity of crustal motion across a region. The datasets analyzed near the IDBY CORS clearly indicate changes in horizontal coordinates and generally conform to changes in position due to velocity suggested by NGS. The variable horizontal differences around IDBY suggest east Idaho is subject to substantial crustal motion.

Conclusions

The techniques used in this research present a case study and approach to analyze the quality of a passive control database. This study deals with factors that contribute to changes in horizontal and vertical positioning over time and the three strategies applied were successful in delineating the essential information necessary to understand the effect of time on space. Stability analysis on control points in Bannock County provided a good picture of monument stability. Survey marks of cement post represent relatively consistent positional accuracy relative to other monument types.

The comparison of coordinates between NAD 83(1986) and NAD 83(2011) highlights the importance of using the latest realization of the horizontal datum. In essence, there is more than one meter difference between these datums across this case study. Comparisons between vertical coordinates derived from realizations of different geoid models revealed a substantial difference (63 cm) between GEOID99 and GEOID12A. As expected, this difference was greater than vertical differences between GEOID03 and GEOID12A.

As the phenomenon of regional tectonic velocity varies across the western US, the results from the comparison of coordinate displacement between NAD 83(2011) epoch 2010.0 and NAD 83(CORS96) epoch 2002.0 should also vary and be dependent on crustal velocity of the area. Since the impact of velocity on coordinates has been incorporated into the current realization of NAD 83(2011), it is considered best practice to use this datum for coordinate determination especially in Idaho due to its active tectonics. Since position coordinates are only relevant with the datum in which they were measured, the NGS recommends using the latest national datum.

The discrepancies and differences described in this study agree with this recommendation.

A geodetic database may contain coordinates from several thousand survey marks and a periodic assessment is required to ensure data quality. The lesson learned and described in this paper is that regional surveyors should be employed to collect redundant data and submit these observations to a geodetic database like the MCPD. These redundant data, ideally distributed across all counties and across the entire state, can be used to ensure improved positioning results and subsequently improve the positional accuracy of other GIS layers, thus improving the spatial data infrastructure overall. The life cycle of a position is subject to changes in the stability of monument settings, changes in coordinates due to varying horizontal and vertical datum usage, and changes in coordinates due to the velocity of crustal movements across an area. These factors were explored in this case study and the results presented herein describe a method to determine the life cycle or usability of control point positions.

References

Arifuzzaman, K. and R. Hintz, 2016. A Spatial Analysis of GEOID03 and GEOID09 in Connecticut, *Journal of Applied Geodesy*, 10(2):95–102.

Calais, E., J.Y. Han, C. DeMets, and J.M. Nocquet, 2006. Deformation of the North American plate interior from a decade of continuous GPS measurements, *Journal of Geophysical Research*, 111(B6):1–23.

CORS Coordinates Myear FAQ, National Geodetic Survey (NGS), FAQ 6: What has changed between NAD 83(2011,MA11,PA11) epoch 2010.00 and NAD 83(CORS96,MACP00,PACP00) epoch 2002.00?, URL: *https://www.ngs.noaa.gov/CORS/coord_info/myear_FAQ.shtml#CoordDiff*, Silver Spring, MD (last date accessed: 24 May 2017).

CORS – IDBY, National Geodetic Survey (NGS), Time-Series (Long Term), URL: *ftp://www.ngs.noaa.gov/cors/Plots/Longterm/idby_08.long.png*, Silver Spring, MD (last date accessed 26 February 2018).

Fisher, B., and B. Conway, B., 2009. Evaluation of Survey Control Stations Height Stability in Subsidence Zones, Presented to American Congress on Surveying and Mapping (ACSM), February 2009, Salt Lake City, Utah.

Inside Idaho, Idaho's Geospatial Data Clearinghouse, GeologicMapIdaho_faults (MapServer), URL: *http://cloud.insideidaho.org/arcgis/rest/services/IGS/GeologicMapIdaho_faults/MapServer* (last date accessed: 26 February, 2018).

Li, D., J. Zhang, and H. Wu, 2012. Spatial Data Quality and Beyond, *International Journal of Geographical Information Science*, 26(12):2277–2290.

Mark Stability, National Geodetic Survey (NGS), Help File for Mark Descriptions, URL: *https://www.ngs.noaa.gov/marks/descriptors.shtml*, Silver Spring, MD (last date accessed on 26 February 2018).

Meyer, T., 2010. *Introduction to Geometrical and Physical Geodesy Foundation of Geomatics*, ESRI Press, California, 246 p.

NGS 58, 1997. *Guidelines for Establishing GPS-Derived Ellipsoidal Heights (Standards: 2cm and 5cm)* - Version 4.3, NOAA Technical Memorandum NOS NGS-58, Silver Spring, Maryland.

NGS 59, 2008. *Guidelines for Establishing GPS-Derived Orthometric Heights*, NOAA Technical Memorandum NOS NGS-59, Silver Spring, Maryland.

NGS 62, 2017. *Blueprint for 2022, Part 1: Geometric Coordinates*, NOAA Technical Report NOS NGS 62, Silver Spring, Maryland.

NGS 64, 2017. *Blueprint for 2022, Part 2: Geopotential Coordinates*, NOAA Technical Report NOS NGS 64, Silver Spring, Maryland.

NIMA, 2000. World geodetic systems 1984, its definition and relationship with local geodetic systems. *US DMA Technical Report TR 8350.2*, U.S. Defense Mapping Agency, Denver, Colorado.

Pitzer, D., 2012. *The Idaho-Montana Geopositioning Cooperative*, abstract for presentation submitted to URISA/ NWGIS Conference, 30 September to 04 October, Portland, Oregon.

Pursell, D.G., and M. Potterfield, 2008. *NAD 83 (NSRS2007) National Readjustment final Report*, NOAA Technical Report NOS NGS 60, Silver Spring, Maryland.

Roman, D.R., Y.M. Wang, W. Henning, and J. Hamilton, 2004. Assessment of the New National Geoid Height Model, GEOID03, *Surveying and Land Information Science*, 64(3):153–162.

Roman, D.R., Wang, Y.M., Saleh, J., Li, X., 2009. National Geoid Height Models for the United States: USGG2009 and GEOID09. ACSM-MARLS-UCLS-WFPS Conference, 20-23 Feb, Salt Lake City, UT.

Sbar, L.M., M. Barazangi, J. Dorman, H.C. Scholz, and M.R. Smith, 1972. Tectonics of the Intermountain Seismic Belt, Western United States: Microearthquake Seismicity and Composite Fault Plane Solutions, *Geological Society of America Bulletin*, 83:13–28.

Sella, G.F., S. Stein, T.H. Dixon, M. Craymer, T.H. James, H. Mazzotti, and R.K. Dokka, 2007. Observation of glacial isostatic adjustment in "stable" North America with GPS, *Geophysical Research Letters,* 34(2):1–6.

Sheskin, J.D., 2003. *Handbook of Parametric and Nonparametric Statistical Procedures*, Chapman & Hall/CRC Press, Florida, 1193 p.

Sickle, V.J., 2013. Association of Petroleum Surveying and Geomatics (APSG), URL: *http://www.apsg.info/Resources/Chapters/US%20West/2013.01.18_USWest_Jan_Van_Sickle_NorthAmericanHorizontalDatums.pdf*; US West, (last date accessed: 26 February 2018).

Snay, R.A., and T. Soler, 2000a. Modern Terrestrial Reference Systems Part 2 - The evolution of NAD83, *Professional Surveyor*, 20(2):16–18.

Snay, R.A., and T. Soler T., 2000b. Modern Terrestrial Reference Systems Part 3 - WGS 84 and ITRS, *Professional Surveyor*, 20(3):24–28.

Snay, R.A., and T. Soler, 2008. Continuously operating reference station (CORS): History, applications, and future enhancements, *Journal of Surveying Engineering*, 134(4):95–104.

Soler, T., and R.A. Snay, 2004. Transforming positions and velocities between the International Terrestrial Reference Frame of 2000 and North American Datum of 1983, *Journal of Surveying Engineering*, 130(2):49–55.

Technical Details for GEOID12/12A/12B, National Geodetic Survey (NGS), URL: *https://www.ngs.noaa.gov/GEOID/GEOID12B/GEOID12B_TD.shtm*, Silver Spring, MD (last date accessed: 23 May 2017).

United States Geological Survey (USGS), Earthquake Hazards Program, Information by Regions-Idaho, 2014 Seismic Hazard Map, URL*: https://earthquake.usgs.gov/earthquakes/byregion/idaho-haz.php*, Golden, CO, (last date accessed: 26 February 2018.

Weston, N.D., R.A. Soler, and D. Roman, 2012. Recently Adopted Changes to the Terrestrial Reference Frames used in the United States, *Proceedings of FIG Working week 2012*, "Knowing to manage the territory, protect the environment, evaluate the cultural heritage", 06-10 May, Rome, Italy.

Zilkoski, D.B., J.H. Richards, and G.M. Young, 1992. Results of the General Adjustment of the North American Vertical Datum of 1988, *Surveying and Land Information Systems*, 52(3):133–149.