Analysis of the TXDOT RTN and *OPUS-RS* from the Geoid Slope Validation Survey of 2011: Case Study for Texas

D. Smith[1]; K. Choi[2]; D. Prouty[3]; K. Jordan[4]; and W. Henning[5]

Abstract: As part of the Geoid Slope Validation Survey of 2011 (GSVS11), the global positioning system (GPS) was used in a variety of ways to determine the geodetic coordinates of nearly 400 passive geodetic control marks. The Texas DOT (TXDOT) real-time network (RTN) was one of the GPS positioning tools used. Both 6- and 180-s occupations were performed with the TXDOT RTN, as well as static 20-min occupations [processed using the National Geodetic Survey (NGS) *Online Positioning User Service, Rapid-Static* (*OPUS-RS*) tool], and 48+ h occupations were adjusted as a network (using the NGS *OPUS-Projects* tool). Although the original 20-min occupations processed by *OPUS-RS* had an unforeseen systematic error (invalidating their use in this comparison), a direct comparison between *OPUS-RS* and the other techniques was still possible by subdividing the *OPUS-Projects* 48+ h receiver independent exchange format (RINEX) files on 218 points into more than 30,000 individual 20-min segments. A comparison between all techniques, after accounting for various systematics such as antenna calibrations, different reference frames, and epochs, showed that the RTN had small biases, but, overall, its accuracy (1σ) was subcentimeter in longitude, less than 2 cm in latitude, and less than 3 cm in ellipsoid height. An investigation into outliers indicated that the RTN could occasionally have unexplained outliers as large as 10 cm, possibly, but not definitely dependent, on time of day or local environment. The analysis also showed that, for this in-the-field environment, the accuracy of *OPUS-RS* was somewhat better than expected (biases at the 0.1-cm level; SDs at 0.6 cm in latitude and longitude and 3.1 to 3.4 cm in height) but outliers ($>5\sigma$) did occur in approximately 1.5% of all runs, the largest of which was approximately 1.5 m off in latitude and height, and 0.4 m in longitude. Part, but not all, of this could be explained by being near the coastline. Finally, a significant cautionary result came from this study—users of the NGS *OPUS-RS* software should make certain that their receivers are generating P2 data (pseudoranges on L2, but not those from L2C). Without that data, *OPUS-RS* will not function at its highest accuracy. Although this has always been a requirement of *OPUS-RS* and was historically not an issue, the authors discovered that some GPS receivers inadvertently turn P2 off when L2C is turned on. **DOI:** 10.1061/(ASCE)SU.1943-5428.0000136. © *2014 American Society of Civil Engineers.*

Author keywords: Real-time network (RTN); *OPUS-RS*; *OPUS*; Geoid Slope Validation Survey of 2011 (GSVS11); Texas DOT (TXDOT); Ellipsoid height; Continuously Operating Reference Station (CORS).

Introduction

In 2011, the National Geodetic Survey (NGS) designed and executed a complex terrestrial survey, the Geoid Slope Validation Survey of 2011 (GSVS11). During GSVS11, surveys using geodetic leveling, the global positioning system (GPS), real-time GPS networks (RTN), gravity, light detection and ranging (LIDAR), imagery, and deflections of the vertical (DOV) were all performed over a 4-month period (Smith 2011b). The primary goal was to demonstrate that differential gravimetric geoid undulations, accurate to 1 cm, could be modeled at NGS, in preparation for the replacement of the North American Vertical Datum of 1988 (NAVD 88) (Zilkoski et al. 1992) in 2022 (National Geodetic Survey 2008). While this primary goal was achieved (Smith et al. 2013), the variety of survey techniques used in GSVS11 allowed for numerous secondary analyses to be performed. One such analysis compared the coordinates obtained from static GPS (both short and long sessions) and those obtained from the RTN run by the Texas DOT (TXDOT).

Data Collected

The GSVS11 survey took place specifically at 218 official marks, which were all passive geodetic control marks, and 80% of which were brass disks in concrete posts (Fig. 1). These points were all surveyed with long-session GPS campaign occupations (48+ h). The Digital Astronomical Deflection Measuring System (DIADEM, Diadem Business Technologies, York, Pennsylvania) camera (Müller et al. 2004) was used to measure the DOV. However, 167 of the 218 points were set in terrain that the DIADEM could not occupy (Smith 2011b). A second, temporary mark, called an eccentric camera mark, was established near these 167 locations so the DIADEM camera could be used, often being just a Parker-Kalon (PK) nail or chiseled cross (Fig. 2). In all situations, the eccentric camera mark was less than 125 m from the official mark, with an average distance of 27 m (Figs. 3 and 4). Having a short vector between the official mark and eccentric camera mark, measured by GPS, allowed for the mathematical transfer of the DOV to the official mark during postprocessing.

[1]Chief Geodesist, National Oceanic and Atmospheric Administration (NOAA), National Geodetic Survey, 1325 East West Highway, Silver Spring, MD 20910 (corresponding author). E-mail: dru.smith@noaa.gov

[2]Geodesist, National Oceanic and Atmospheric Administration (NOAA), National Geodetic Survey, 1325 East West Highway, Silver Spring, MD 20910.

[3]Geodesist, National Oceanic and Atmospheric Administration (NOAA), National Geodetic Survey, 1325 East West Highway, Silver Spring, MD 20910.

[4]Geodesist, National Oceanic and Atmospheric Administration (NOAA), National Geodetic Survey, 1325 East West Highway, Silver Spring, MD 20910.

[5]Retired Geodesist, National Oceanic and Atmospheric Administration (NOAA), National Geodetic Survey, 1325 East West Highway, Silver Spring, MD 20910.

Note. This manuscript was submitted on March 12, 2013; approved on March 24, 2014; published online on June 4, 2014. Discussion period open until November 4, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Surveying Engineering***,

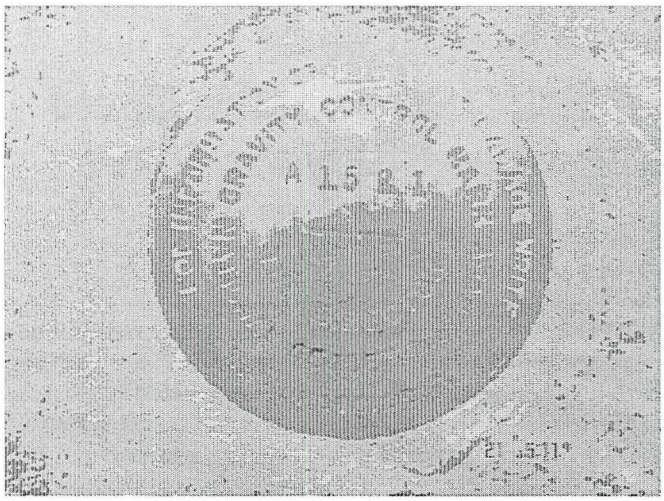

Fig. 1. Official mark A 1521 with SSN of 1116 (image by author)

Fig. 2. Eccentric camera mark A 1521 ECC with SSN of 5116; this point is 2.656 m from official mark A 1521 (image by author)

Originally, the TXDOT RTN (see section "TXDOT RTN") was planned as the preferred tool for determining the vector between official marks and eccentric camera marks. However, a scheduling conflict with equipment necessitated a change of this plan, and instead it was decided to perform 20-min static occupations at the eccentric camera marks, processed through *Online Positioning User Service, Rapid-Static* (*OPUS-RS 1.37 RS93.prl 1.89*), and to use these coordinates with the coordinates from the long-session GPS on the official marks, to compute the coordinate differences between points. However, after the 20-min campaign was over, the RTN equipment was available again; therefore, for the purposes of scientific analysis and redundancy, it was decided to use it to occupy both eccentric camera marks and official marks.

To summarize, the following GPS-based surveys were performed during GSVS11.

1. On the 218 GSVS11 official marks:
   a. Long-session (48+ h) data in campaign mode, leapfrog fashion (Fig. 5) adjusted in *OPUS-Projects page5 1209.04 master51.pl 082112*;
   b. RTN (6-s duration); and
   c. RTN (180-s duration).
2. On the 167 GSVS11 eccentric camera marks:
   a. Short-session (20 min) data in single-occupation mode run through *OPUS-RS* (however, see note in the following); and
   b. RTN (6-s duration).

It was the original intent of this study to compare *OPUS-RS* to the TXDOT RTN 6-s occupations at the 167 eccentric camera marks. However, postprocessing of the *OPUS-RS* results revealed a significant systematic problem with this approach; specifically, the receiver used in the 20-min occupations was not collecting P2 data, which is critical for accurate *OPUS-RS* results. As such, with the intent to still quantify *OPUS-RS* accuracy in this area, a different approach was taken, by subdividing the 48+ h files down to 20 min and running them through *OPUS-RS*. This issue with P2 and the results of the new analysis will be discussed in more detail later.

TXDOT RTN

The TXDOT RTN is used to support TXDOT projects within the state and was made available to the NGS for GSVS11. Some of the following information comes from a 2012 Civil GPS Service Interface Committee (CGSIC) presentation (Fuegner 2012).

The network was established in 2003, and by 2012 had 182 base stations (called regional reference points), 133 of which are in the NGS Continuously Operating Reference Station (CORS) network. The stations run at a 5-s rate with a 5° elevation mask. Formal accuracy estimates of RTN-determined positional coordinates do not seem to be publicly available. Fig. 6 shows a map of the network, overlain on the location of the GSVS11 survey.

Data-Collection Methodologies

Long-Session GPS Data on Official Marks

The general method of long-session GPS data collection on the 218 official marks was to set up 20 units at a time over 20 sequential points along the line, where each unit contained a fixed height tripod, one of three types of receivers (Trimble NetRS, Trimble R7, and Trimble 5700, Trimble, Sunnyvale, California), and all with the same antenna (Trimble Zephyr Geodetic; TRM41249.0 with no radome). These units ran consecutively for 24 h, after which time the rear 10 units were dismantled and moved to become the front 10 units. Then 24 h of new data were taken. This leapfrog pattern continued until the entire line had been surveyed (Fig. 5). Data outages and other problems eventually led to a few reoccupations, but in general, this method was followed.

Short-Session GPS on Eccentric Camera Marks

Although the results from this occupation were not actually used to quantify *OPUS-RS* accuracy, the survey is outlined briefly as follows for elucidation. The short-session GPS observations were conducted using a single Trimble R8 integrated GNSS Receiver/Antenna and one of two collapsible, calibrated 2-m, fixed-height tripods. The receiver collected data on a 5-s interval with a 10° elevation mask. The receiver had the option of L2C (civil signal on the L2 frequency) on or L2C off. At the time, not seeing any disadvantage to this approach, the entire set of 20-min occupations was conducted with L2C on. It was later recognized that this had turned P2 off, which significantly degraded the quality of results received from *OPUS-RS*. No further analysis of these data is presented in this paper. However, an entirely separate analysis of *OPUS-RS* was performed, using subdivided versions of the long-session GPS data (as previously described).

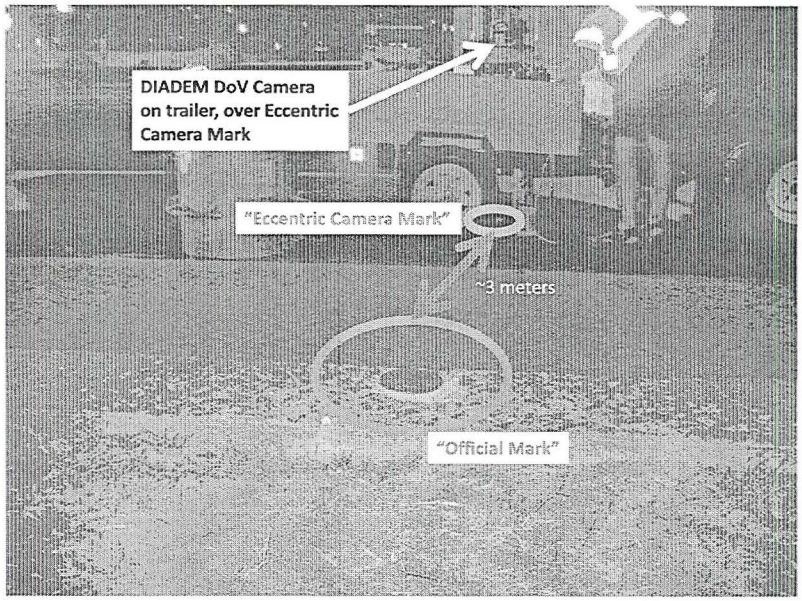

Fig. 3. Typical situation showing an official mark that cannot be driven over, necessitating the use of an eccentric camera mark (image by author)

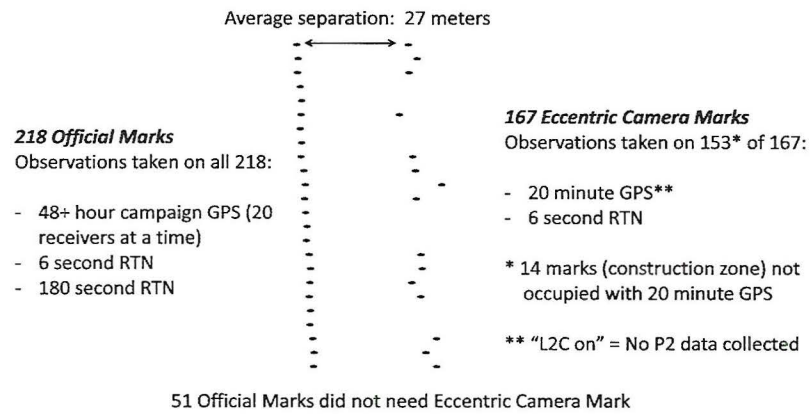

Fig. 4. Overall methodology of official marks and eccentric camera marks and their respective GPS observations

RTN on All Marks

The RTN coordinates were determined at both the eccentric camera marks and the official marks using varying occupation durations. The three types of occupations originally planned were

1. 6-s occupation on all 167 eccentric camera marks,
2. 6-s occupation on all 218 official marks, and
3. 180-s occupation on all 218 official marks.

Two GPS receivers were used for the RTN portion of GSVS11, a Trimble R8 with a TSC2 data collector, and an Altus APS-3 (Altus Positioning Systems, Torrance, California) with a Carlson Surveyor Plus data collector (Carlson, Maysville, Kentucky). The use of two different GPS receivers was required because of equipment availability. Both receivers had internal data modems and were attached to a variable height pole with a bipod (height was checked before and after each measurement).

After navigating to an official mark, the GPS receiver was set up over the mark using a variable height pole with a bipod. Six seconds of data were gathered, and the coordinates of the point were stored. The receiver was inverted (to cause reinitialization), then 180 s of data were gathered, and a second set of coordinates stored. If there was an eccentric camera mark associated with the official mark, then a 6-s occupation of that mark was also done, storing those coordinates, but no 180-s occupation occurred.

Reference Frames

Because the CORS network and all of the *OPUS* tools by NGS operate in the latest reference frame of the International GNSS Service (IGS) (in this case, the IGS08 reference frame), the intent was for all GPS-derived coordinates in this paper to be processed and compared in that frame. In *OPUS-RS* and *OPUS-Projects*, this was relatively straightforward. In the RTN, some transformation software was necessary, as explained in the following.

Coordinates from the TSC2 Data Collector (Trimble R8 receiver) were downloaded from the data collector in North American Datum (NAD) 83 (Schwarz 1989) [CORS 96 (Snay and Soler 2000)] latitude, longitude, and ellipsoid height. Coordinates from the Carlson Surveyor Plus data collector (Altus APS-3 receiver) were downloaded in state plane coordinates [NAD 83 (CORS 96), Texas South Central, Federal Information Processing Standards (FIPS) 4204] with NAVD 88

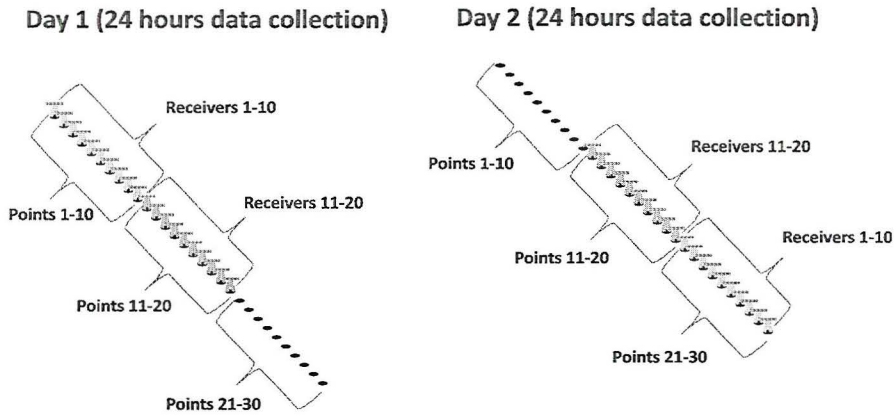

Fig. 5. Example of the leapfrog deployment of GPS receivers over 48 h, wherein 10 rear receivers are moved to become the forward receivers each 24 h

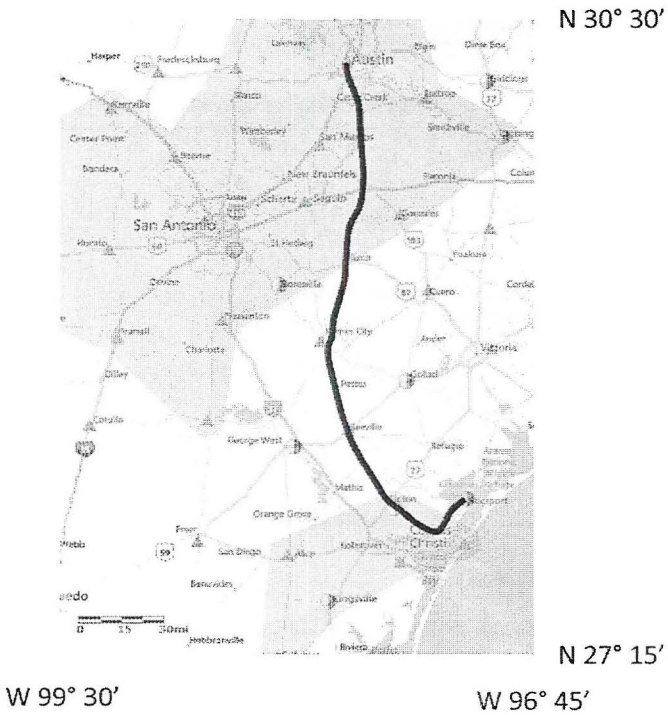

Fig. 6. TXDOT RTN overlaying the GSVS11 survey (solid line); triangles are stations that have been incorporated into the NGS CORS network (data from TXDOT 2011, with permission)

elevations, both in meters. *CORPSCON 5.11.08* was used to transform to NAD 83 (CORS96) latitude, longitude, and ellipsoid height. It seems likely (but not definitive) that the Altus APS-3 receiver transformed coordinates into state plane coordinates (SPC) using internal routines identical to *CORPSCON*. As such, no additional error budget was estimated for effectively undoing this transformation.

Once NAD 83 (CORS 96) coordinates were available, they were then input into the NGS *HTDP 3.1.2* software for final transforming from NAD 83 (CORS 96) (epoch = 2002.000) to IGS08/GRS80 (epoch 2011.852, which was the midpoint of the RTN surveys; November 7, 2011). It is possible that this attempt to retrieve the RTN coordinates in IGS08 introduced some level of error from the transformation, but for purposes of comparison, a single reference frame needed to be chosen. Fig. 7 shows how each GPS data collection arrived at the IGS08 coordinates.

The variety of data collection methods means that a number of comparisons can be made, each of which is discussed in the following.

RTN (6 s) versus RTN (180 s) (on 218 Official Marks)

Before comparing the TXDOT RTN coordinates against other independently determined coordinates, the different occupation durations within the TXDOT RTN system were compared. This was (generally) performed on the 218 official marks of GSVS11. As mentioned previously, the operator first collected 6 s of data, broke the setup through inversion, and then reoccupied the same point for 180 s. For various reasons, only 191 of the 218 points were actually occupied in this way, but this was still a viable sample size from which to draw useful conclusions. The coordinates may be found online at http://www.ngs.noaa.gov/GEOID/GSVS11/data. The statistical comparison of 6- to 180-s coordinates is found in Table 1.

The values in Table 1 demonstrate the overall self-consistency of the TXDOT system, while also illuminating some weaknesses. Although two different types of receivers were used in the RTN portion of the survey, each pair of 6- and 180-s occupations at any given point had the same receiver and were transformed to IGS08/GRS80 using the same software, thus eliminating any receiver/software discrepancies in Table 1. Because these values reflect agreement within the TXDOT system, they are merely representative of occupation-duration–dependent errors only, and should not reflect any biases (systematic errors) of the coordinates relative to the IGS08 reference frame itself.

Overall, the 6- and 180-s occupations have a total [three-dimensional (3D)] RMS disagreement between them of 1.1 cm, which is encouraging, but which must not be confused with absolute accuracy of the coordinates. Longitude shows the best stability with only 1-mm RMS disagreements. Latitude is four times worse than longitude. Ellipsoid heights show (as expected) the worst stability of coordinates with 1 cm of RMS between occupation types, effectively dominating the self-consistency error budget.

In the extreme cases, it can be seen that occupation duration alone can yield errors in latitude in excess of 1 cm and ellipsoid height in excess of 3 cm. These errors will be useful to keep in mind in future sections as the entire error budget of the TXDOT system becomes clearer.

RTN versus *OPUS-Projects* (on 218 Official Marks)

The most accurate IGS08/GRS-80 coordinates achieved in GSVS11 were during the long-session GPS campaign. In that 8-week-long

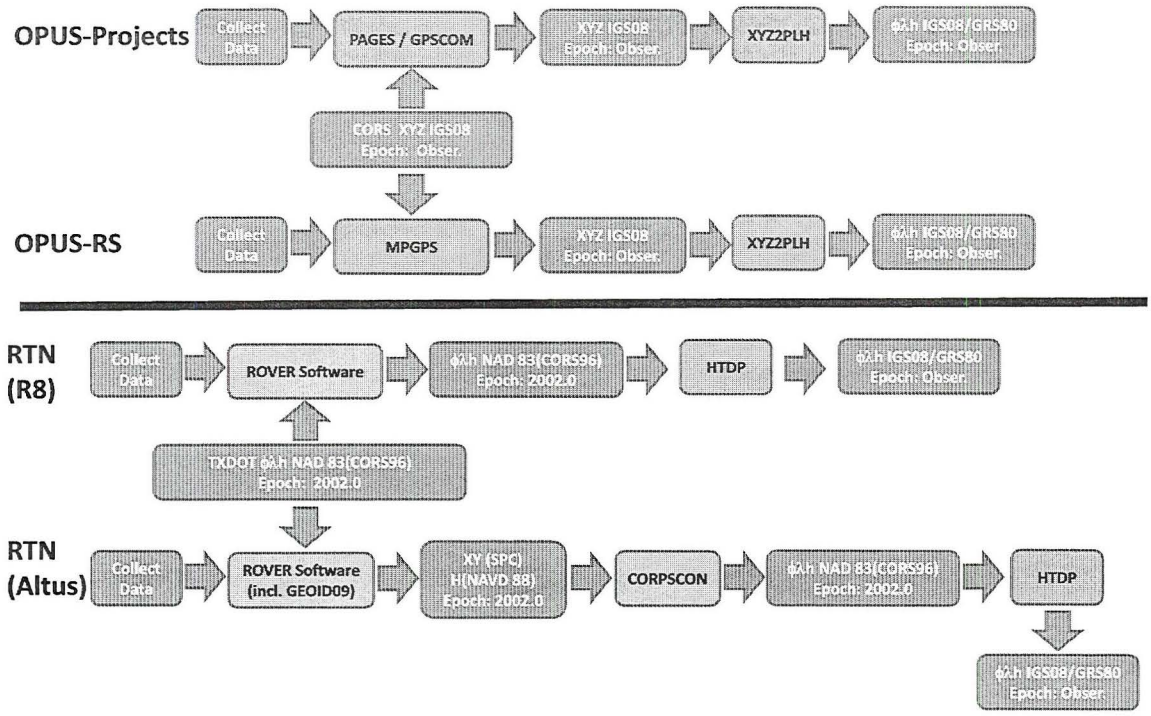

Fig. 7. Flowchart of how IGS08/GRS80 coordinates were achieved from all four methods of GPS data collection and processing

Table 1. Difference in Coordinates and 3D Distance between 6- and 180-s Occupations Using TXDOT RTN at Official Marks of GSVS11

Parameter	Latitude	Longitude	Ellipsoid height	3D distance
Number of values (of 218 points)	191	191	191	191
Average (cm)	−0.1	0.0	−0.1	0.9
SD (cm)	0.4	0.1	1.0	0.6
Minimum (cm)	−1.6	−0.2	−3.5	0.1
Maximum (cm)	1.2	0.4	2.6	3.5
RMS (cm)	0.4	0.1	1.0	1.1

Note: All comparisons done in IGS08/GRS-80.

campaign, 20 geodetic quality GPS receivers (with identical antennas) were deployed sequentially at official marks in leapfrog fashion, as previously outlined (Fig. 5). In this way, in general, every point logged at least 48 h of data, the first 24 h of which overlapped with 10 aft points, the last 24 of which overlapped with 10 fore points, and the whole of 48 h was coincident with nine neighboring sequential points. Each occupation was solved independently through *OPUS-RS*, but then was adjusted as an entire campaign in *OPUS-Projects* (Weston et al. 2007; Silver 2013) using the *GPSCOM 1210.24* software and CORS data available in the area. Equipment issues, different interpretations of the survey instructions, data loss, and other common field issues prevented a perfect execution of this leapfrog style survey, but complete coverage of the line did occur, with some stations collecting well in excess of 48 h of data.

The formal accuracy estimates of the *OPUS-Projects* IGS08/GRS-80 latitudes and longitudes, to the nearest millimeter, average 0.0 cm in both latitude and longitude and do not exceed 0.1 cm (1σ) for any point in the survey. The formal accuracy estimates (1σ) of ellipsoid heights average 0.3 cm with a SD of 0.1 cm, with a maximum value of 0.6 cm (Smith et al. 2013). With these values bounding *OPUS-Projects*, and serving as the closest estimate to truth, a comparison is made against the TXDOT RTN in both 6-s and 180-s occupation modes.

Table 2 shows the comparison with 6-s occupations, whereas Table 3 shows the comparison against the 180-s occupations. For various reasons, only 190 occupations were made at 6 s, and only 197 occupations made at 180 s of the 218 total official marks in GSVS11.

These data show many interesting things. First, confirming what is discussed in the previous section, the TXDOT RTN-derived longitudes as a whole are four to five times better determined than latitudes, whereas ellipsoid heights (h) are the worst determined values, dominating the error budget.

Second, extreme values of disagreement are 10 cm, which are much different than the 3 cm of self-consistency seen in Table 1. This raises the possibility that absolute height errors in the RTN itself as high as 7 cm may occur. This seems to be shored up by the increase from 1.0 cm of self-consistent h error to 2.7 cm compared with *OPUS-Projects*. That is, statistically, if the SD changes from 1.0 to 2.6 cm, then a rise of extreme values from 3.0 to 10.0 cm seems reasonable.

Finally, the increase of occupation duration from 6 to 180 s always improves the agreement with *OPUS-Projects*. This is logical under the dual assumptions that (1) longer RTN occupations improve absolute accuracy, and (2) *OPUS-Projects*, with 48 h of data adjusted together, is the closest approximation of truth available. Under these assumptions, and knowing that the *OPUS-Projects* data have a 3D RMS of approximately 0.3 cm (almost entirely in the ellipsoid heights), it can be concluded that with 180 s of data, the TXDOT RTN has a 3D coordinate error budget of 2.9-cm RMS. (That is, in a RMS sense, using 180-s occupations and beginning with 3.1 cm of RMS agreement with *OPUS-Projects*, taking away the 1.0 cm of internal precision and the 0.3 cm of *OPUS-Projects* uncertainty would leave an RMS of 2.9-cm RMS in absolute 3D coordinates.) A similar analysis implies that, in a RMS sense, using 6-s occupations will yield 3.0 cm (3D).

Table 2. Difference in Coordinates and 3D Distance between 6-s TXDOT RTN Occupations and 48-h Campaign-Adjusted Occupations

Parameter	Latitude	Longitude	Ellipsoid height	3D distance
Number of values (of 218 points)	190	190	190	190
Average (cm)	0.0	0.2	1.0	2.6
SD (cm)	1.6	0.2	2.6	1.9
Minimum (cm)	−9.3	−0.8	−8.1	0.2
Maximum (cm)	3.4	0.8	10.1	10.7
RMS (cm)	1.5	0.3	2.8	3.2

Note: All comparisons done in IGS08/GRS-80.

Table 3. Difference in Coordinates and 3D Distance between 180-s TXDOT RTN Occupations and 48-h Campaign-Adjusted Occupations

Parameter	Latitude	Longitude	Ellipsoid height	3D distance
Number of values (of 218 points)	197	197	197	197
Average (cm)	−0.1	0.2	0.9	2.5
SD (cm)	1.5	0.2	2.6	1.8
Minimum (cm)	−8.4	−0.9	−9.0	0.2
Maximum (cm)	3.5	0.6	9.8	10.9
RMS (cm)	1.5	0.3	2.7	3.1

Note: All comparisons done in IGS08/GRS-80.

In other terms, even if the internal occupation-duration–dependent errors (e.g., precision) of the RTN were driven to zero, it is reasonable to expect no better than 2.9 cm of 3D accuracy (1σ) from 180-s occupations using the TXDOT RTN (with outliers as large as a decimeter). Using the same logic, these can be broken into horizontal and vertical accuracies, showing that the TXDOT RTN has an empirically determined accuracy (1σ) of 1.5 cm in horizontal and 2.7 cm in ellipsoid height, using 180-s occupation durations.

The overall improvements in going from 6- to 180-s occupations (comparing Table 2 with Table 3) are quite small but measurable, which raises the question of cost and/or benefit. In going to a 180-s occupation, a 1-mm total improvement in 3D RMS values is gained, which does not reduce the possibility of 10-cm outliers. Readers are left to answer for themselves if 174 extra seconds in the field are worth a millimeter of improvement without reducing the possibility of 10-cm outliers. A more productive use of that time might be to perform repeated 6-s observations on each point, thereby adding redundancy and reducing blunders.

OPUS-RS L2C/P2 Issues (on 153 Eccentric Camera Marks)

This section will be somewhat different than the others, in that the *OPUS-RS* results from 20-min occupations on 153 eccentric camera marks were discovered to have been degraded by the lack of P2 data. Numerical results are therefore not included in this section.

The L2C on option in the Trimble R8 GNSS receiver used during the 20-min occupations on eccentric camera marks meant that no P2 data were collected for those satellites that were broadcasting L2C. This meant that, on average, most of the *OPUS-RS* solutions used only seven of 9–10 visible satellites. In the best case, occasionally a 20-min occupation saw only non-L2C satellites, but on the worst end of the spectrum, only three of seven visible satellites were usable because four of the visible satellites were broadcasting L2C. Counting up the actual observations (each occupation multiplied by each satellite multiplied by each 5-s epoch collected), the broadcasting of L2C (and subsequent failure to collect P2) meant that 25% of all satellite and/or epoch combinations were dropped by *OPUS-RS* for these 20-min occupations on the eccentric camera marks. This number was as high as 58% dropped for the worst occupation, but improved to 0% dropped in a few cases as well.

It is a testament to *OPUS-RS* that this was still enough data to yield results accurate enough not to cause any immediate concern. Only upon deeper inspection did the below-average performance of *OPUS-RS*, caused by missing P2 data, come to light. It would be unfair to present or discuss the comparison of abnormally poor *OPUS-RS* results against the RTN at the eccentric camera results. However, because *OPUS-RS* accuracy was a topic the authors intended to study, a method for analyzing *OPUS-RS* accuracy was developed using subdivided versions of the 48+ h files from the long-session GPS on the official marks. That analysis is presented in the next section.

This section closes only with the following brief conclusions:

1. Failure to collect P2 data will degrade *OPUS-RS* results, but will not necessarily make them unusable.
2. Hypothetically, L2C might be used in place of P2 in future versions of *OPUS-RS*. NGS briefly conducted some ad hoc experiments, using L2C in place of P2 for those observations where P2 was missing. Overall, *OPUS-RS* operated well during such tests, but further study is warranted before such a fix would become part of an operational *OPUS-RS* version. Further discussion of these experiments will be reserved for a more formal future study and publication.
3. The lack of P2 data was not restricted entirely to the Trimble R8. As discussed in the next section, the 48-h files from the Trimble NetRS, Trimble R7, and Trimble 5700 all had some limited instances where only L2C data were received without any P2 data. Further discussion is found in the next section.

OPUS-RS versus *OPUS-Projects* (on 218 Eccentric Camera Marks)

Because an evaluation of *OPUS-RS* behavior in field conditions was desired for this survey, but the original 20-min occupations on 153 eccentric camera marks were not usable, a separate evaluation was developed and performed. The long-session (48+ h) GPS files on the 218 official marks were subdivided at even 20-min intervals, and each one was individually run through *OPUS-RS*. Before any evaluation, this yielded 38,221 individual receiver independent exchange format (RINEX) files. However, as mentioned in the previous section, a small number of these files lacked P2 data, whereas some of them were of only 1–19 min in duration (because of the start or stop times of the 48+ h files that were not on even 20-min intervals). Finally, approximately 1,000 files simply caused *OPUS-RS* to fail to yield a successful result for one of a variety of reasons (large RMS values, poor CORS geometry, etc.). After removal of all types of invalid files, there were still 33,244 RINEX files of exactly 20-min duration, with P2 data, that were successfully run through *OPUS-RS* without warnings, aborts, or errors. The results of those runs were then compared with the official *OPUS-Projects* coordinates. An outlier rejection criterion of 5σ was applied, the overall statistics were computed, and are presented in Table 4. Without accounting for geography, time of day, or other factors, the comparison shows an overall good agreement between *OPUS-RS* and *OPUS-Projects*.

OPUS-Projects in this area operated with a formal accuracy of 0.0 cm in latitude, 0.0 cm in longitude, and 0.3 cm in ellipsoid height. This means that the 0.6 cm in latitude and longitude in Table 4 are effectively all from *OPUS-RS*. However, to state the ellipsoid height

Table 4. Difference in Coordinates between *OPUS-RS* and *OPUS-Projects* at 218 Official Marks

Parameter	East	North	Up
Number of comparisons	33,244	33,244	33,244
Average (cm)	0.1	0.1	−0.1
SD (cm)	0.6	0.6	3.1
Observations that were outliers (5-σ criteria)	1.6%	1.3%	1.0%
Worst outlier, minimum (cm)	−148.0	−39.7	−144.7
Worst outlier, maximum (cm)	+135.2	+25.9	+138.0

Note: All comparisons done in IGS08/GRS-80.

accuracy from *OPUS-RS*, it is important to pull out the contribution of *OPUS-Projects* from the 3.1-cm value. To do so, *OPUS-RS* runs are performed on data that also went into *OPUS-Projects*, so there is a likely (but unknown) positive correlation between the coordinates from *OPUS-RS* and *OPUS-Projects*. Presuming, therefore, a correlation coefficient (ρ) somewhere between 0 and +1 between ellipsoid heights from *OPUS-RS* and ellipsoid heights from *OPUS-Projects*, the expected accuracy of ellipsoid heights of *OPUS-RS* are bounded between 3.085 cm, which is rounded up to 3.1 cm (if $\rho = 0$) and 3.4 cm (if $\rho = +1$). For further details on bounding equations with unknown correlation coefficients, see Eqs. (7) and (8) in Smith (2011a).

The 3.1- to 3.4-cm ellipsoid height accuracy that Table 4 predicts for *OPUS-RS* agrees well with the expected accuracy (2–3 cm) predicted by Schwarz et al. (2009) for this region of the country. Furthermore, that same paper predicts 0.6–0.8 cm [one-dimensional (1D)] horizontal accuracy (using a vertical and/or horizontal accuracy factor of 3.6), which agrees perfectly with the 0.6 cm seen in both the east and north components of Table 4.

Another study of *OPUS-RS* accuracy was performed by Snay et al. (2011). In Fig. 1 in Snay et al. (2011), SDs of 4.9 cm were seen in ellipsoid heights with 15-min occupations of *OPUS-RS* in average conditions. Ellipsoid height accuracy is shown to improve dramatically (to 3 cm) with better conditions [smaller interpolative dilution of precision (IDOP) and smaller RMS distance (RMSD) to surrounding CORS], which is precisely the CORS coverage that this area of Texas exhibits [see Fig. 9 in Schwarz et al. (2009)]. Thus, the 3.1- to 3.4-cm ellipsoid height accuracy agrees well with the 3 cm predicted. Snay et al. (2011) used a vertical and/or horizontal factor of 3.7 to predict horizontal (1D) accuracies of 0.8 cm where the IDOP is small. The 0.6-cm values for latitude and longitude in Table 4 therefore show even better performance of *OPUS-RS* than expected.

Finally, NGS offers an online tool for estimating *OPUS-RS* expected accuracies (http://www.ngs.noaa.gov/OPUSI/Plots/Gmap/OPUSRS_sigmap.shtml). Using that tool, and bounding it at Austin and Rockport, Texas, the two endpoints of GSVS11, the range of expected accuracies (1σ) for a 15-min occupation was determined to be 0.7–1.0 cm (horizontal) and 2.8–3.6 cm (ellipsoid height), both of which are in strong agreement with the 0.6 and 3.1–3.4 cm from the 20-min occupations.

The overall performance of *OPUS-RS* in this part of the country shows good agreement with predicted accuracy from all three sources. The behavior of the 33,244 *OPUS-RS* runs by various categories is investigated in the following subsections.

Comparison by Hour of Day

To better understand the variables that affected the agreement between *OPUS-RS* and *OPUS-Projects*, the residuals were first broken down by which hour of the day they occurred. Looking first at the RMS agreement (Fig. 8), a distinct pattern of increased noise was seen during the hours of universal time coordinated (UTC) 18–24 (about local time noon through 6 p.m. for this survey). Surprisingly, though, there was also a somewhat unexplainable bump in noise at UTC 6 and 10–11 (midnight and 4–5 a.m., local time). To further expand on this information, the outliers were investigated in a similar fashion, and their maxima plotted in Fig. 9. In this way, the *OPUS-RS* degradation during midday hours (during a heat wave in excess of 38°C daily) can be seen more clearly, but there is also no question that some aberrant behavior also occurred in the middle of the night.

Comparison by Point

The GSVS11 survey was laid out in a more or less north-south linear fashion, with the southernmost points being at the coast, where CORS coverage becomes sparser. As such, the *OPUS-RS*/*OPUS-Projects* residuals are viewed by point number for all 218 official marks. These residuals are found in Fig. 10. If *OPUS-RS* was truly having difficulties with CORS coverage as movement takes place toward the coast, seeing steadily rising noise from left to right may be expected (north-south). However, no such monotonically rising signal is apparent. If one plots how many CORS were used in the *OPUS-RS* runs (Fig. 11), it is obvious that there is not a huge drop off in the southernmost points. The average number of CORS used remains well above eight for all points on the line. However, there is a subtle, yet discernable, dip in the average number of CORS around point 200 or so. This is about the same size as the dip around points 90–110. These also both line up with regular instances of some solutions having as few as five CORS in them. In addition, around point 200 and points 90–110 are where (Fig. 10) extra noise is seen, especially in the up component. The likely explanation for this is that *OPUS-RS* is noticeably sensitive to the number of CORS used in each solution, a finding originally seen in Schwarz et al. (2009). This is discussed in the next subsection.

Comparison by Number of CORS

The previous section pointed out that *OPUS-RS* accuracy is noticeably susceptible to the number of CORS used in each solution, as per Schwarz et al. (2009). This section attempts to validate that finding. Although *OPUS-RS* requires at least three CORS (and up to nine) to operate, there were no instances (in this study) of any runs where less than five CORS were used. Fig. 11 shows that the average number was well above eight for all stations with usable solutions. However, more than 6,000 of the 33,244 good solutions used only five to eight CORS. To see how this affects *OPUS-RS* behavior, the results were binned by number of CORS used. The results are shown in Fig. 12. There is no longer any subtlety about the relationship with the number of CORS. There is a clear degradation seen in all three directional components as *OPUS-RS* drops from nine CORS down to five. The longitude (east) component (which has the strongest GPS orbital geometry of all three components) degrades faster than the latitude component (north) as CORS dwindle. Discussions with Tom Soler of NGS (personal communication, 2013) indicate that this result is somewhat expected because of errors in Earth rotational parameters and their effect on short occupations, such as 20 min. What is not clear from Fig. 12 is whether any specific CORS contributes to the noise in *OPUS-RS*. This investigation is covered in the next subsection.

Comparison by Which CORS Stations Were Chosen

Building on the previous subsection, an investigation was performed to determine whether any particular CORS stations might contribute more noise to *OPUS-RS* than others.

In the 33,244 *OPUS-RS* runs in this study, a total of 47 individual CORS were autoselected by *OPUS-RS* to participate in solutions. The participation rate is shown in Fig. 13. Then, for each of the 47 different

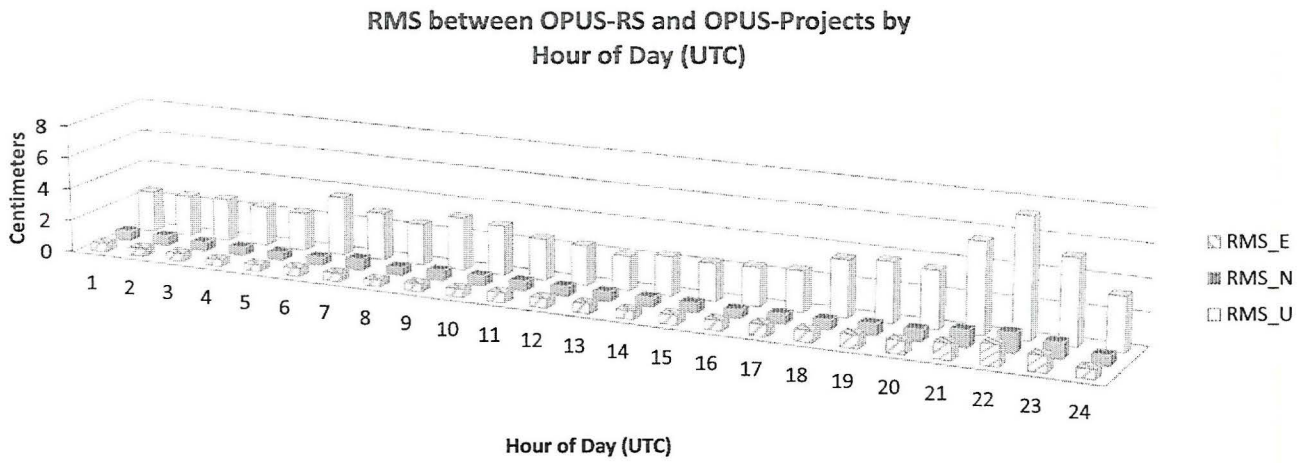

Fig. 8. RMS residuals between *OPUS-RS* and *OPUS-Projects* by hour of the day (UTC); E = east; N = north; U = up

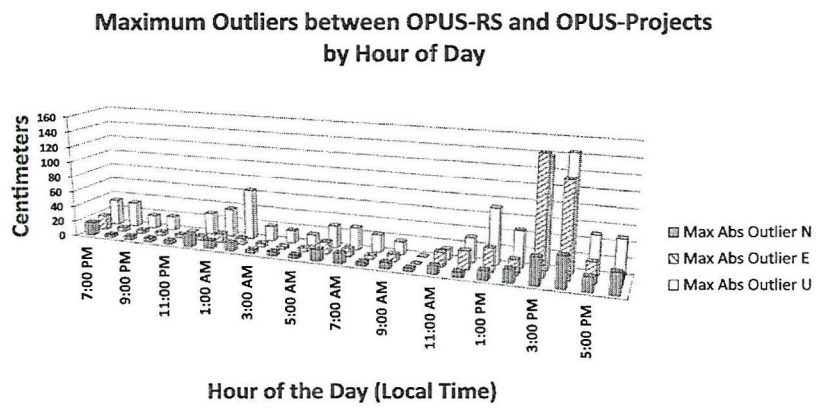

Fig. 9. Maximum outliers between *OPUS-RS* and *OPUS-Projects* by hour of the day (UTC); E = east; N = north; U = up

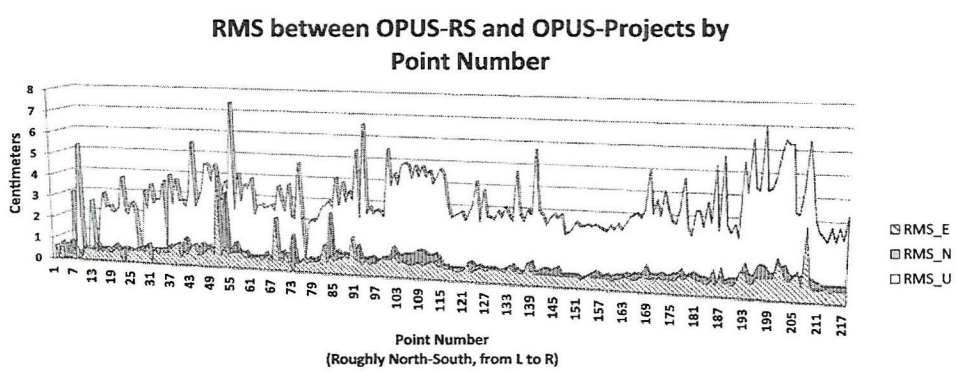

Fig. 10. RMS residuals between *OPUS-RS* and *OPUS-Projects* by point number [roughly north/south from left to right (L to R)]; E = east; N = north; U = up

CORS stations, all of the *OPUS-RS* runs in which that station participated were compared with *OPUS-Projects* and their statistics generated. The results are shown in Fig. 14. Note that the *X*-axis is laid out identically to that of Fig. 13, so that the most-used stations are to the right and least-used stations are to the left. With this in mind, it is easy to explain the large residuals that begin to become evident around station DWI1 and all of the other stations left of that. What is interesting is the incredibly similar behavior of all residuals for all CORS stations that were used in at least 100 of the 33,244 *OPUS-RS* runs (station TXCT and all those to the right of it). This indicates a few things. First, the algorithm in *OPUS-RS* that selects the best nine CORS sites appears to be working very well. For example, sites ARP7 and ARP8, despite being geographically close to the southernmost end of GSVS11 were only selected seven times and one time, respectively, whereas nearby station TXPO was used 9,891 times. Also, the quality of the CORS coordinates is equivalent throughout this part of Texas. This is clearly the result of the most recent IGS and CORS reprocessing effort (Griffiths et al. 2010).

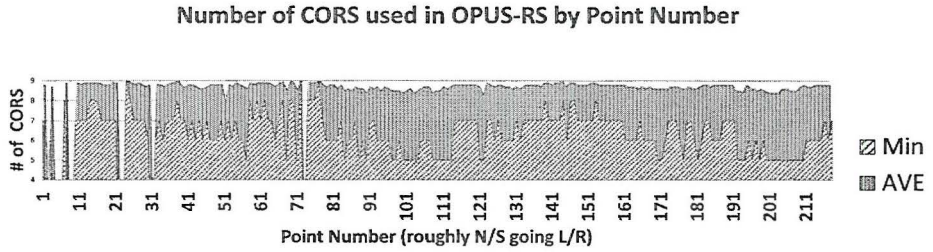

Fig. 11. Average and minimum CORS used in all successful 20-min *OPUS-RS* runs, by point number [roughly north/south (N/S) from left to right (L/R)]

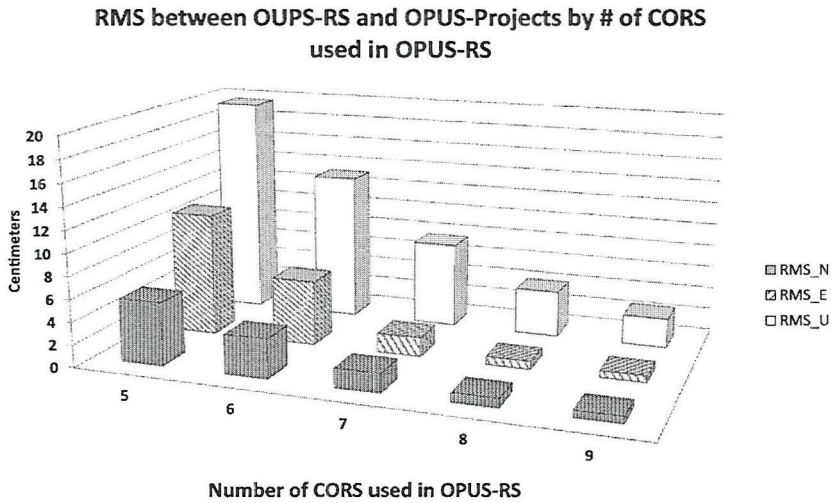

Fig. 12. RMS residuals between *OPUS-RS* and *OPUS-Projects* by number of CORS used in *OPUS-RS*; E = east; N = north; U = up

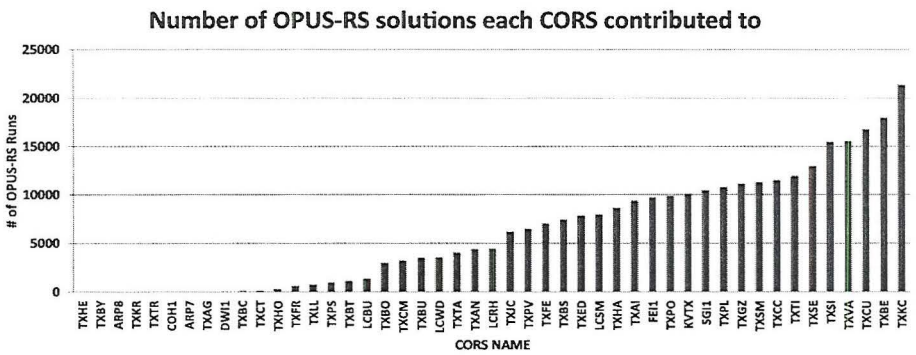

Fig. 13. Number of *OPUS-RS* runs by CORS name

The evidence from Fig. 14 is that while some CORS do contribute to noisy residuals, *OPUS-RS* generally is not selecting those stations. That is, all of the CORS in this region of Texas listed in Fig. 13, from TXBC and to the right, appear to have consistently good contributions to *OPUS-RS*, and *OPUS-RS* is correctly choosing them automatically.

Comparison of Modeled Accuracy versus Actual Performance

As part of the output of *OPUS-RS*, each run lists formal accuracy estimates of the computed coordinates. As a final way of investigating the performance of *OPUS-RS*, the actual residuals between *OPUS-RS* and *OPUS-Projects* are viewed with both the formal accuracies received from *OPUS-RS* and the modeled accuracies of Schwarz et al. (2009), which were based entirely on the geometry of the surrounding CORS. On a point-by-point basis, the RMS values of the *OPUS-RS* residuals, the formal *OPUS-RS* accuracy estimates, and the modeled accuracy estimates were gathered. These are presented in Figs. 15–17, in which some interesting results are found.

First, it is apparent that the modeled horizontal accuracies can be called generally correct, although they are far too optimistic at points with large residuals. This is entirely expected, because the modeled accuracies do not take the data into account, only the network geometry. In contrast, the formal accuracies show more variety but only occasionally (approximately 50% of the time) do they actually spike where true residuals occur. For instance, of the six most difficult east points (actual residuals more than 1 cm) seen

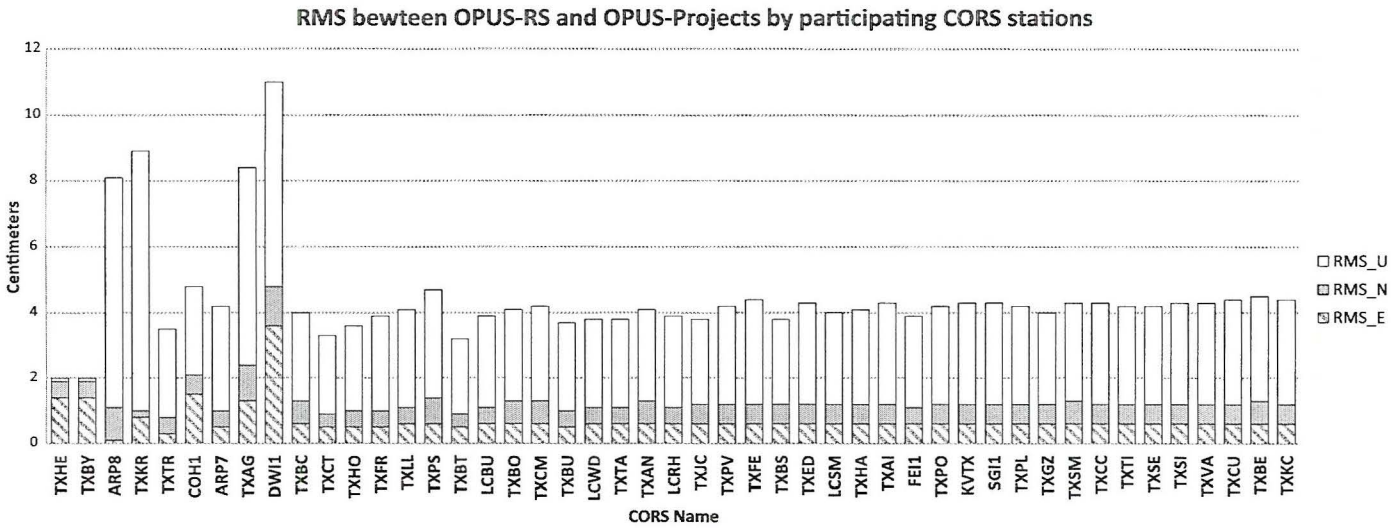

Fig. 14. RMS residuals between *OPUS-RS* and *OPUS-Projects* by CORS station used in *OPUS-RS*; E = east; N = north; U = up

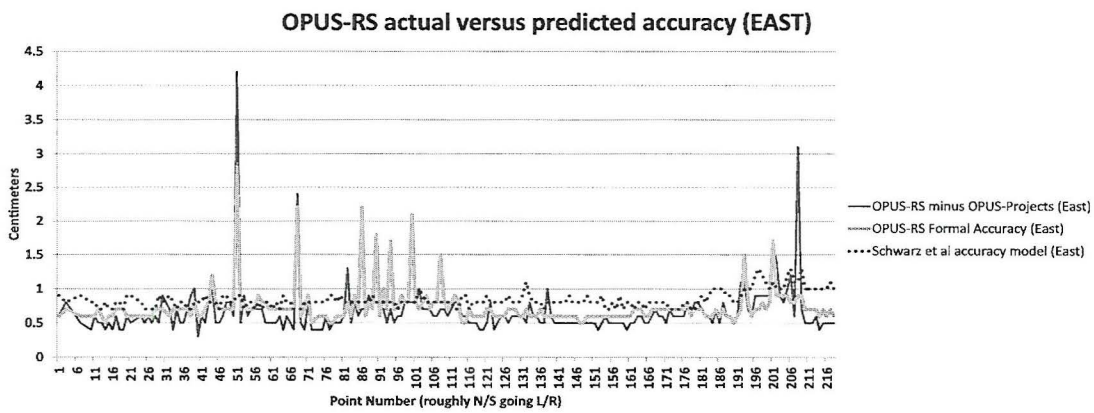

Fig. 15. Actual versus predicted behavior of *OPUS-RS* (east)

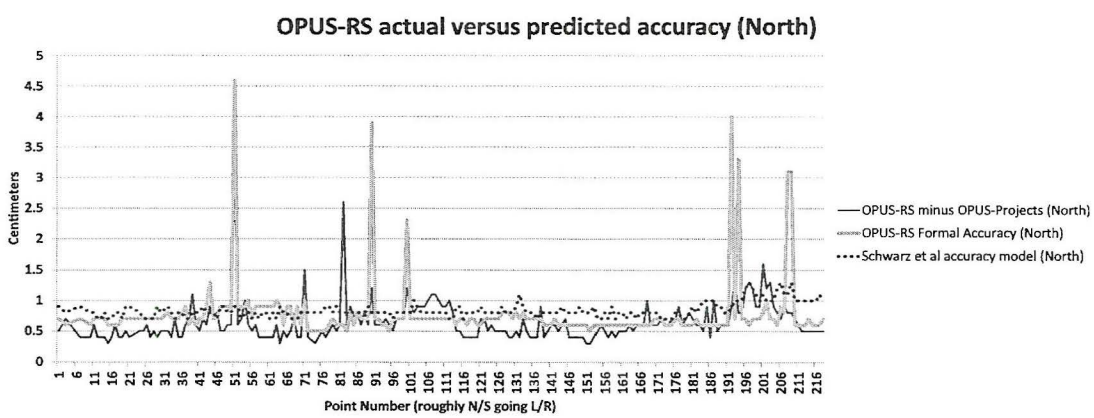

Fig. 16. Actual versus predicted behavior of *OPUS-RS* (north)

in Fig. 15, *OPUS-RS* comes up with a large formal accuracy estimate only four times. On top of that, it predicts four other points of high inaccuracy when the actual residuals do not shore this up. These are the outliers, however, and for the remainder of the line, the formal accuracy estimates of *OPUS-RS* overpredict the actual residuals by approximately 0.1 cm, but still are correct to within ±0.6 cm 95% of the time.

Similar results are seen in Fig. 16, with some true peaks missed and some peaks predicted where the data behaved well. However, overall, the *OPUS-RS* predicted accuracies in the north component are good,

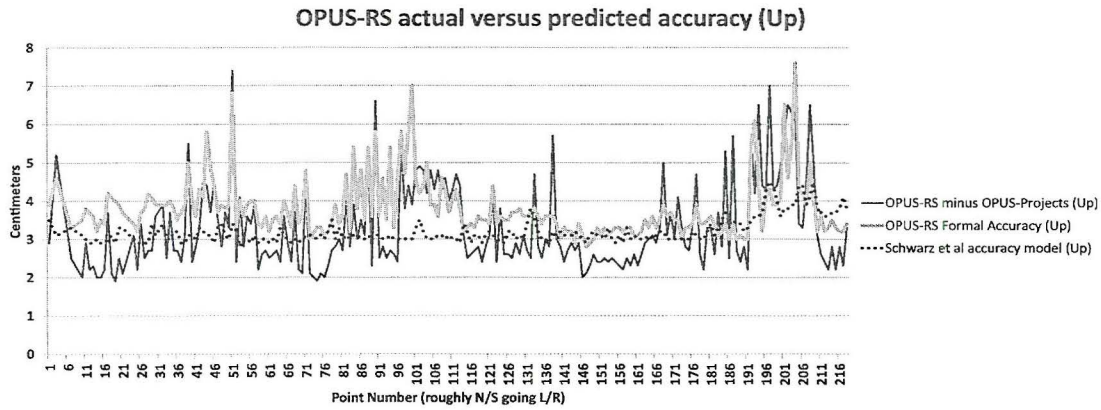

Fig. 17. Actual versus predicted behavior of *OPUS-RS* (up)

although again, on average overpredicting the true residuals by approximately 0.1 cm while being correct to ±1.0 cm 95% of the time.

The up component (Fig. 17) shows a similar, if noisier, result as the previous figures. Approximately half of the true peaks are missed, and approximately that same number of unsubstantiated peaks are predicted. In the up component *OPUS-RS* is again overpredicting on average, in this case by approximately 0.5 cm, but at that bias it remains a good predictor of actual accuracy at approximately the 1.6-cm level 95% of the time.

Investigating Specific Outliers

A brief examination of a few select outliers was performed to determine if systematic causes can be identified. Because of their differing potential error sources, this is broken down into the three main comparisons: RTN (6 s) versus RTN (180 s); RTN (180 s) versus *OPUS-Projects*; and *OPUS-RS* versus *OPUS-Projects*. In the following sections, each survey mark's station serial number (SSN), which is a unique numerical identifier for this mark in this particular survey, is used to clarify the exact point being used.

RTN (6 s) versus RTN (180 s)

Outlier #1A: Ellipsoid Height Difference of 2.6 cm at 877 4770 TIDAL 8 (SSN 2003; Point #218)

This is a multipath rich environment. Sailboats, cars, buildings, and trees are all within 2–100 m of this mark. Comparisons with *OPUS-Projects* show significant differences in ellipsoid height differences of −4.3 cm (6 s) or −1.7 cm (180 s). The likely cause is a multipath affecting the 6-s RTN coordinates, which is slightly alleviated by going to 180-s occupations.

Outlier #1B: Ellipsoid Height Difference of −3.5 cm at J 1522 (SSN 1164; Point #52)

There are some low buildings within 100 m of the mark that might act as multipath sources, but that is about all. Comparisons with *OPUS-Projects* show an improving ellipsoid height when going from 6 s (3.4 cm) to 180 s (−0.1 cm). There is no likely cause, just an unexplainable poor height from the 6-s occupation on the official mark.

OPUS-Projects versus RTN (180 s)

Outlier #2A: Latitude Difference of −8.4 cm at Q 1525 (SSN 3023; Point #136)

This point also happens to have the largest longitude difference of −0.9 cm between *OPUS-Projects* and the RTN. Furthermore, the 6-s RTN occupation has a noticeably large latitude disagreement (−9.3 cm). There is nothing in the environment out of the ordinary at this point that would make it better or worse than most other points along the survey line. However, this point shows other general issues of disagreement (ellipsoid heights off by 5.1 cm for 6-s occupations and 6.9 cm off for the 180-s occupation). This point is not particularly near the coast, and neighboring points do not show any of the levels of disagreement seen here. Considering that the 6- and 180-s occupations agree to within 0.9 cm (3D) of one another, it is possible that the *OPUS-Projects* solution for latitude in this area is off by 8 cm or so. However, *OPUS-Projects* had nearly 96 h of GPS data on Q 1525 and no noticeable problem in the adjustment, making *OPUS-Projects* a less likely culprit. Furthermore, the *OPUS-RS* comparisons with *OPUS-Projects* at this point show no significant outlier problems.

The likely cause is an undetermined phenomenon local in time and space, biasing the RTN on the specific day of occupation.

Outlier #2B: Ellipsoid Height Difference of −9.0 cm at K 1528 (SSN 3094; Point #217)

This is the next-to-last point, in Rockport, Texas. Because it is a downtown street, it has plenty of multipath sources, as do many other points near this end of the line, which do not have a 9.0-cm height issue. The 6-s occupation also has a large (−8.1 cm) disagreement, but none of the latitudes and longitudes do. The 6- and 180-s RTN occupations agree in height to 0.9 cm. Like Outlier #2A, there is a chance this is an *OPUS-Projects* problem, but the *OPUS-RS* and *OPUS-Projects* runs agree without any sign of substantial outliers, making the RTN a more likely source of error here.

This likely cause is an undetermined phenomenon local in time and space, biasing the RTN on the specific day of occupation.

OPUS-Projects versus OPUS-RS

Outlier #3A: Longitude Difference of −148.0 cm at N 1527 (SSN 3073; Point #194)

Although near the coast, this point has no worse multipath or CORS coverage than other neighboring points, which tends to exonerate the local environment. However, a quick inspection of the *OPUS-RS* runs on this point both preceding and following this outlier is very telling. Approximately 2 h before, this run, which had been hovering around a few millimeters, suddenly jumped to decimeters. The *OPUS-RS* run immediately following this outlier was so large that it aborted the *OPUS-RS* run. The run after that showed an 11-cm residual, but this quickly settled back down to millimeters. The number of CORS used in each solution is also very telling; approximately 2 h before this run, the number of CORS drops from

nine to eight, then kept dropping until this outlier had only five CORS. Within 1 h after this run, that number rose back up to nine. What this seems to indicate is a localized disruption to the available good CORS data, either an outage or a genuine few hours of poor GPS data being received at all CORS in the region.

The likely cause is a temporary lack of reliable GPS data at surrounding CORS stations.

Outlier #3B: Ellipsoid Height Difference of +138.0 cm at G 1385 (SSN 2070; Point #177)

Like the preceding outlier, nothing particularly egregious about the field conditions is apparent here, but an examination of the *OPUS-RS* runs preceding and following this point tell an obvious story. In both the preceding and following runs, outliers begin to rise from millimeters to decimeters, the number of available good CORS drops, and multiple *OPUS-RS* aborted runs occur. Whether this is the result of no data or poor data of the surrounding CORS, the result is the same.

The likely cause is a temporary lack of reliable GPS data at surrounding CORS stations.

Conclusions

IGS08/GRS-80 geodetic coordinates were determined over 350 geodetic marks, using a variety of GPS-based positioning techniques as part of the GSVS11. A comparison of coordinate differences between survey methods yielded a variety of conclusions about both the TXDOT RTN and the NGS software *OPUS-RS*. The following are the primary findings:

1. The TXDOT RTN has an occupation-time–dependent (6 s versus 180 s) variability (1σ) of approximately 0.1 cm in longitude, 0.4 cm in latitude, and 1.0 cm in ellipsoid height, but no significant bias from occupation duration alone.
2. Independent of occupation duration, the TXDOT RTN exhibits small biases and SDs in latitude, longitude, and ellipsoid height of -0.1 ± 1.5 cm, 0.2 ± 0.2 cm, and 1.0 ± 2.6 cm, respectively. Increasing occupation duration of the TXDOT RTN from 6 to 180 s improves height accuracy (SD about the bias) by only 0.1 cm without significantly improving latitude or longitude accuracy and without reducing the likelihood of decimeter level outliers.
3. *OPUS-RS* exhibits an overall 0.6-cm horizontal accuracy (1D) and 3.1- to 3.4-cm vertical accuracy in this region. However, *OPUS-RS* did exhibit large (>100 cm) outliers in about 1.5% of runs in this region of Texas during the summer of 2011. The cause of some of these outliers seemed to be a temporary lack of reliable data at surrounding CORS.
4. Field GPS crews should ensure that their receivers are collecting P2 data if they intend to use *OPUS-RS*.

Many positive conclusions can be made from this study. First, the TXDOT is operating an RTN which, with just 6 s of data, is capable of subcentimeter longitude determination, latitude determination to better than 2 cm, and ellipsoid height determination to better than 3 cm with no RTN-based outliers observed in excess of 11 cm. This is a remarkable achievement and shores up claims on the reliability of the system for subdecimeter mapping purposes. Second, the results from the *OPUS-RS* comparisons show stable repeatable accuracies that agree well with previous predictions (Schwarz et al. 2009; Snay et al. 2011). As of 2011, the state of available accurate GPS surveying is strong in this region of Texas.

Acknowledgments

The authors thank all those who worked on the GSVS11 survey, but in particular the GPS crews who provided so much of this data. They especially acknowledge Dan Prouty, who performed the RTN survey, Kevin Jordan, who did the *OPUS-RS* occupations, and Cliff Middleton, who led the long-session GPS survey crews. They are also grateful to the NGS antenna calibration team (Andria Bilich, Charlie Geoghegan, and Clancy Lokken), who calibrated the individual Trimble R8 for this paper and provided insight into the problems of calibrating that particular antenna. Finally, the authors thank the Texas DOT for their cooperation in allowing NGS access to their private RTN during GSVS11.

References

CORPSCON 5.11.08 [Computer software]. U.S. Army COE, Army Geospatial Center, Alexandria, VA.

Fuegner, A. (2012). "TxDOT GPS applications." ⟨http://www.gps.gov/cgsic/states/2012/austin/fuegner.pdf⟩ (Feb. 7, 2013).

GPSCOM 1210.24 [Computer software]. Silver Spring, MD, National Geodetic Survey.

Griffiths, J., et al. (2010). "Reanalysis of GPS data for a large and dense regional network tied to a global frame." *Proc., Int. Association of Geodesy (IAG) Commission 1 Symp. 2010, Reference Frames for Applications in Geosciences (REFAG2010)*. ⟨http://geodesy.noaa.gov/web/science_edu/presentations_library/files/refag-f10-cors_repro.pdf⟩ (Feb. 7, 2013).

HTDP 3.1.2 [Computer software]. Silver Spring, MD, National Geodetic Survey.

Müller, A., Bürki, B., Kahle, H.-G., Hirt, Ch., and Marti, U. (2004). "First results from new high-precision measurements of deflections of the vertical in Switzerland." *Proc., Int. Association of Geodesy (IAG) Int. Symp. on Gravity, Geoid, and Space Missions 2004 (GGSM2004)*, C. Jekeli, L. M. C. Bastos, and J. Fernandes, eds., Vol. 129, Springer, Berlin, 143–148.

National Geodetic Survey (NGS). (2008). "The National Geodetic Survey ten-year plan: Mission, vision and strategy 2008–2018." ⟨http://www.ngs.noaa.gov/INFO/NGS10yearplan.pdf⟩ (Nov. 18, 2013).

OPUS-Projects page5 1209.04 master51.pl 082112 [Computer software]. Silver Spring, MD, National Geodetic Survey.

OPUS-RS 1.37 RS93.prl 1.89 [Computer software]. Silver Spring, MD, National Geodetic Survey.

Schwarz, C. R. (1989). "North American datum of 1983." NOAA Professional Paper NOS 2, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration (NOAA), Silver Spring, MD.

Schwarz, C. R., Snay, R. A., and Soler, T. (2009). "Accuracy assessment of the National Geodetic Survey's OPUS-RS utility." *GPS Solut.*, 13(2), 119–132.

Silver, M. (2013). "OPUS-Projects: The next revolution in GPS." *Amer. Surv.*, 10(11), 1–5.

Smith, D. A. (2011a). "A numerical method for computing lower and upper bounds on the values of unreported local accuracies in NAD 83 (NSRS2007)." *Surv. Land Inf. Sci.*, 71(2), 57–67.

Smith, D. A. (2011b). "True zero." *Point of Beg.*, 37(3), 20–25.

Smith, D. A., et al. (2013). "Confirming regional 1 cm differential geoid accuracy from airborne gravimetry: The Geoid Slope Validation Survey of 2011." *J. Geod.*, 87(10–12), 885–907.

Snay, R., Choi, K., Mader, G., Schwarz, C., Soler, T., and Weston, N. (2011). "How precise is OPUS, part 1: Experimental results." *Amer. Surv.*, 8(5), 1–4.

Snay, R. A., and Soler, T. (2000). "Reference systems: Part 2: The evolution of NAD 83." *Professional Surveyor Magazine*, 20(2).

Texas DOT (TXDOT). (2011). "TXDOT RTN map." ⟨http://ftp.dot.state.tx.us/pub/txdot-info/isd/gps/Documents⟩.

Weston, N., Mader, G., and Soler, T. (2007). "OPUS-Projects—A web-based application to administer and process multi-day GPS campaign data." *Proc., 30th FIG General Assembly and Working Week 2007*, Int. Federation of Surveyors (FIG), Copenhagen, Denmark, 1–10.

Zilkoski, D. B., Richards, J. H., and Young, G. M. (1992). "Results of the general adjustment of the North American Vertical Datum of 1988." *Surv. Land Inf. Syst.*, 52(3), 133–149.