Vermont Real Time Kinematic Case Study

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Abstract

Real Time Kinematic (RTK) surveying has been in use now for over a decade. However, there is minimal documentation available related to suggested field procedures designed to produce positions of specific accuracies. Additionally, the methods for transmitting and receiving RTK corrections have expanded to include the use of cellular modems, thus overcoming the distance dependency of traditional UHF radio broadcasts, and most manufacturers support the collection and processing of Global Navigation Satellite Systems (GNSS), such as GLONASS. Text below describes a case study involving the use of single base RTK GNSS corrections being generated by the Vermont CORS Network and accessed with a cellular modem. The Vermont CORS Network is briefly described. Occupation time, baseline length, and field procedures are discussed and compared. The results of this case study indicate the guidelines listed for RT1, RT2, RT3, and RT4 will, in fact, produce the stated accuracies.

Introduction

In the fall of 2006, the Vermont Agency of Transportation began an ambitious effort to establish a state-wide network of Continuously Operating GNSS Reference Stations (CORS). This CORS infrastructure would be designed to provide both archived data for post-processing, as well as real-time corrections (single baseline) to support Real Time Kinematic (RTK) surveys. By spring 2007, the first eleven stations were in place and available for real-time applications. The Vermont CORS network is being designed to have a station spacing of approximately 40km to 50km. (See figure 1.)

The GNSS antenna's for the CORS were positioned relative to NAD83 CORS96 (Epoch 2002) by submitting numerous 12-hour datasets to NGS' Online User Positioning Service (OPUS). The OPUS solutions for each station were combined and then averaged to establish the position of the GNSS Antenna Reference Point (ARP).

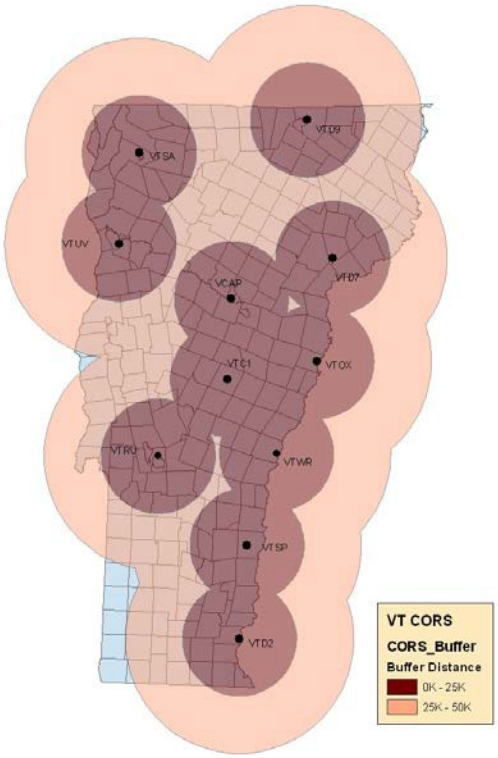

Figure 1 - Current configuration of VT CORS Network

Field Testing Procedure

Stations to be occupied

RTK observations were taken on existing control stations that are part of the National Spatial Reference System (NSRS). The published coordinates from the new national readjustment (NAD83 NSRS2007) would be used as truth. Whenever possible, stations that also had a published NAVD88 orthometric height would be used.

Baseline Lengths

Multiple baseline lengths would be tested to include the maximum expected distance from the nearest CORS once the network is complete. Proposed network design indicates this may be as much as 30km. For the purpose of this study, baseline lengths of more than double the expected network spacing were also tested.

In order to test at various baseline lengths, three test stations were selected in the central Vermont area. Observations were taken relative to three or more CORS at each station in order to gain samples at various distances. Table 1 shows the base/field station combinations used.

CORS	Field Station	Distance (m)
VCAP	**SKYL**	7888
VCAP	**SOBA**	11263
VTC1	**LLCZ**	17140
VCAP	**LLCZ**	19400
VTC1	**SOBA**	27097
VTC1	**SKYL**	30536
VTWR	**LLCZ**	52358
VTWR	**SOBA**	60397
VTUV	**SOBA**	63773
VTWR	SKYL	64112

Table 1 - Station Combinations for VT Procedure

Observation Scheme

When the draft guidelines became available for review, it was decided to implement these procedures in the field and collect data sets for analysis. Since it is Vermont's intent to base all of their RTK observations on their CORS stations, no "classical" RTK observations were taken. That is to say that, since the Vermont CORS provided the control, and the Vermont CORS stations are spaced at 40km – 50km, the ability to conduct observations from two bases at each station within specified distances was not possible for the RT1 and RT2 classifications. Regardless of the distance constraints, data was collected at each station using the observation time for all accuracy classes. Additionally, the draft guidelines call for maximum Positional Dilution of Precision (PDOP) and Root Mean Square (RMS) criteria for positions collected under each accuracy class. It was decided data would be collected regardless of the conditions at the time of observation and that the observation statistics would be extracted from the data after the fact for analysis.

On Site Collection Procedure

1. Setup bipod/antenna and start survey
2. Initialize to nearest CORS.
3. Collect observation using the criteria for RT1, RT2, RT3 and RT4 in rapid succession (regardless of actual field conditions.
4. End survey.
5. Start new survey.
6. Initialize to a different CORS.
7. Repeat steps 3 to 6 using a number of CORS stations.
8. End survey.
9. Move to different test locations and repeat steps 1 to 8.
10. Repeat procedure steps 1 to 9 four or more hours later.

Alternative On-site Collection Procedure (Unique Initializations):

1. Setup bipod/antenna and start survey
2. Initialize to nearest CORS.
3. Collect one observation at 30 epochs.
4. End survey/shut off receiver.
5. Restart receiver and start survey.
6. Repeat steps 2 to 5 a number of times.

Accuracy and Precision Analysis

The precision analysis will make a comparison of repeat observations relative to their difference from the mean. Accuracy analysis will be conducted by showing the difference in field derived values as compared to truth (published NSRS stations).

For this study, three separate individual field observers were used. Each observer worked independently in the field. All data was grouped by individual observer, and then later merged by accuracy class. Since a large amount of data was collected for this study, the analysis was first done based on the individual observer's data.

Data by Observer

Data was collected by Observers 1 and 2 2008 on Julian days 030 and 032 and on Julian days 025 and 026 by Observer 3. The data for each observer was organized by accuracy class and coordinate differences for each day were computed from the published station coordinates of each station he occupied. The average of the two observations was also computed. Figure 2 shows the comparison of the Day 1 and Day 2 and average observations differenced from the published values for the Northing, Easting and Ellipsoid height components respectively. The error bars on each data point show the RT1 precision constraint of +/- 1.5 cm horizontal and +/- 2.5 cm vertical. These graphs give both an indication of the accuracy of the observations, as well as the precision. The reader will certainly observe that one of the data points contains a significant error both in accuracy and precision.

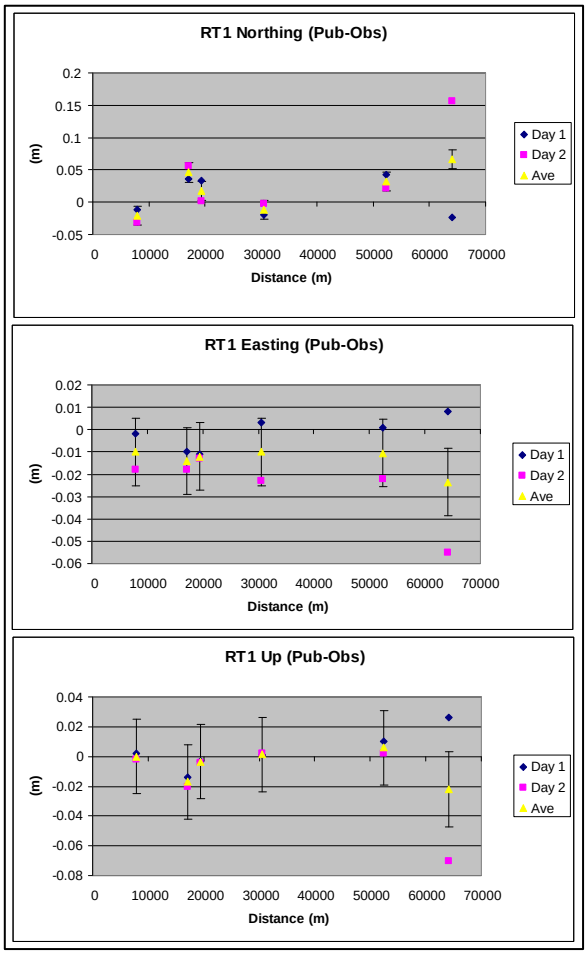

Figure 2 – Comparison of Day1, Day2 and average N, E, and U (published-observed) vs. baseline length using RT1 field procedures. Y-error bar scale is 1.5cm horizontal and 2.5cm vertical.

On inspection of the data, it was determined this is a classic example of a bad initialization. Although it does not happen often, it does happen. It was determined that the Day 2 observation contained the bad initialization, as this error carried through to all observations taken under this initialization. This was further verified in that other observations taken at this particular station from the same base provided acceptable results. The observations associated with the bad

initialization were rejected from the test data and will not be shown in any further graphs in order to better depict the accuracy/ precision of the remaining data sets.

As can be seen from each dataset's deviation from the mean, the Day 1 and Day 2 observations agree well within the specified RT1 precision tolerances, even at distances of over 50km. The accuracy of the observations relative to the published values generally tends to agree within +/- 2cm, with the exception of the northing average at 17km and 52km. Both of these distances represent observations taken at LLCZ and could therefore represent an error in the published value of LLCZ. Further discussion on accuracy will follow later.

Figures 3, 4, and 5 show the comparison of the Day 1 and Day 2 and average observations for the RT2, RT3, and RT4 observations taken by observer 1 differenced from the published values for the Northing, Easting and Ellipsoid height components respectively. The error bars on each data point show the RT1 precision constraint of +/- 1.5 cm horizontal and +/- 2.5 cm vertical. The RT1 error constraints are shown for the purpose of scale. It is important to remember these observations were not necessarily collected at the lower limit of the all allowable constraints of the error classes. For instance, the minimum number of satellites observed for an RT4 observation is 5, however the observations taken may have included as many as 13 satellites; in other words, the only observation criterion used in the field was duration of the observation.

When reviewing the plots for Observer 1, it can be inferred that there does not appear to be any degradation of precision or accuracy relative to the duration of observation. There does, however, appear to be a linear trend relative to the average accuracy of the ellipsoid height vs. baseline distance. This was an interesting feature and somewhat expected, as it is commonly accepted that GNSS RTK errors are correlated to distance. Evidence of this is seen in manufacturer specifications, i.e., RMS errors of 1cm+1ppm horizontal and 2cm+1ppm vertical. However, after looking at similar plots for Observer 2 and Observer 3 (Figures 4 and 5), it is clear this feature is non-existent in these observations. Additionally, there does not appear to be any notable difference in the magnitude of the vertical errors relative to the horizontal errors. This is further illustrated later when data from all observations are combined.

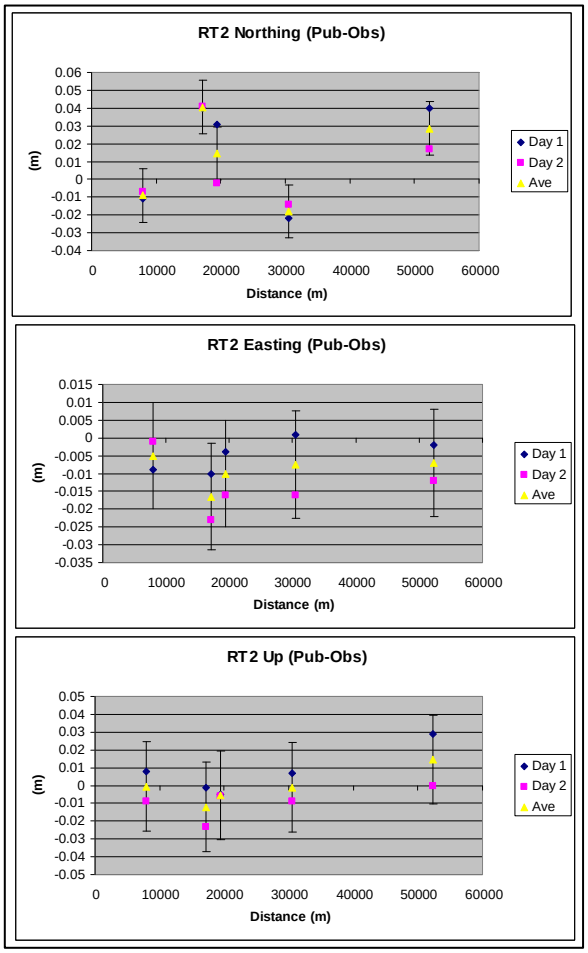

Figure 3 – Comparison of Day1, Day2 and average N, E, and U (published-observed) vs. baseline length using RT2 field procedures. Y-error bar scale is 1.5cm horizontal and 2.5cm vertical.

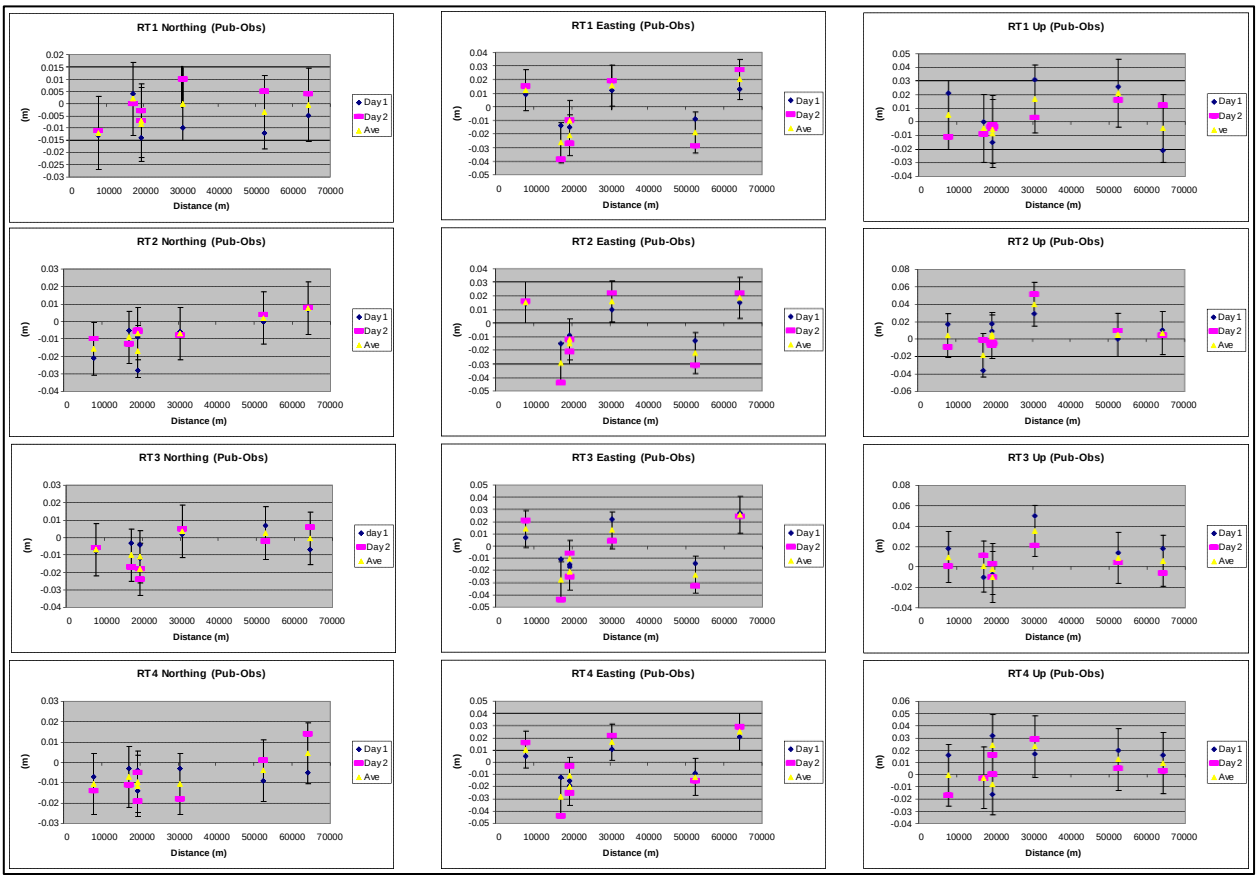

Figure 4 – Observer 2 Day1, Day2 and Average N, E, and U (published-observed) vs. baseline length using RT1 – RT4 field procedures. Y-error bar scale is 1.5cm horizontal and 2.5cm vertical.

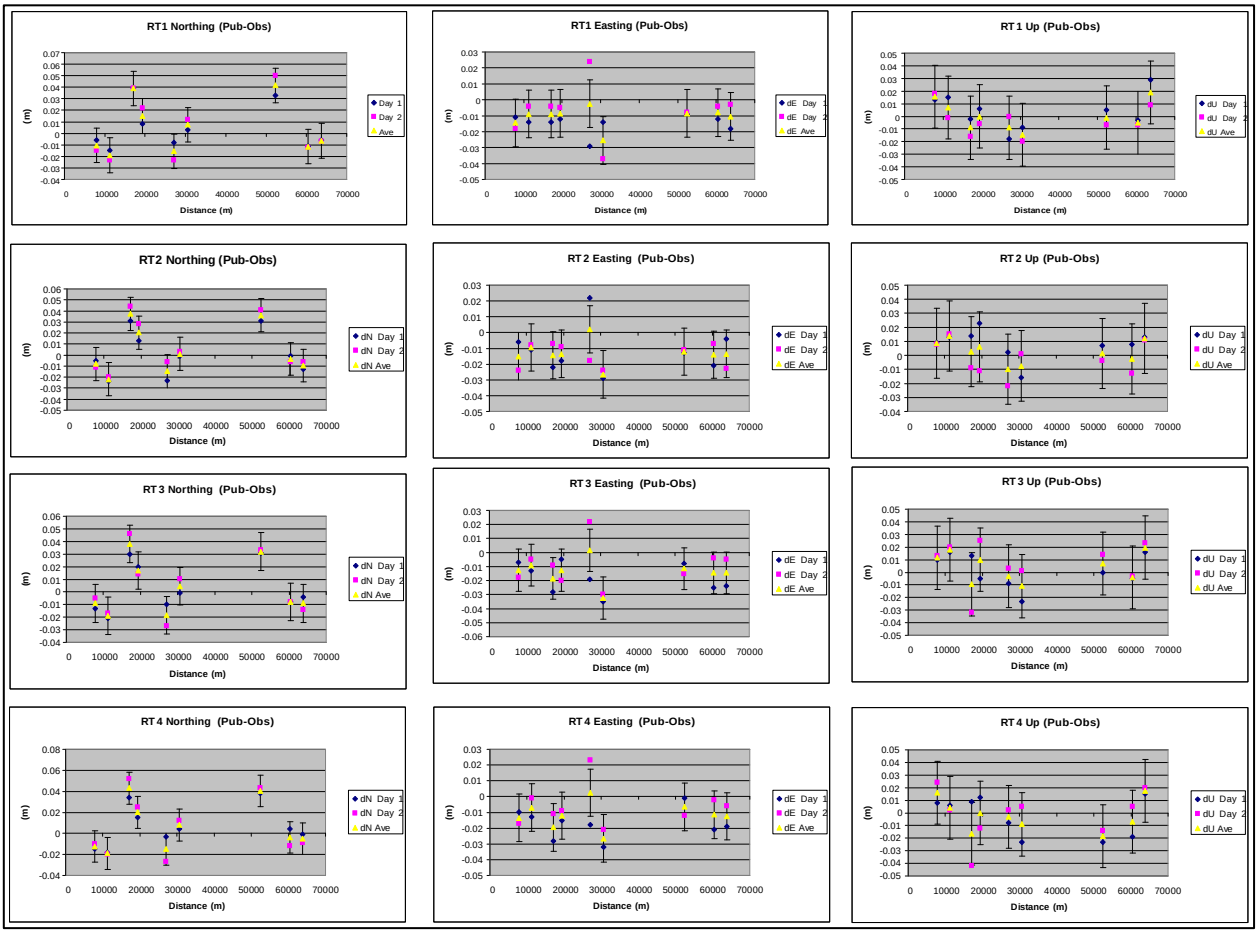

Figure 5 – Observer 3 Day1, Day2 and Average N, E, and U (published-observed) vs. baseline length using RT1 – RT4 field procedures. Y-error bar scale is 1.5cm horizontal and 2.5cm vertical.

Also of notable interest is the fact that all observations meet the RT1 precision horizontal cutoff of 1.5cm and 2.5cm horizontal and vertical based on the individual component differences. This is not a true indicator, as the guidelines are based on a horizontal (resultant) and vertical repeatability at 95 percent. However, it allows us to view individual component differences looking for trends or biases.

It was noted before that the northing difference (published-observed) at LLCZ might indicate an error in the published value for this station. Comparing the average northing differences for this station from each observer shows that both Observer 1 and Observer 3 show a difference from the published northing of LLCZ of about +4cm, while Observer 2 shows a difference of approximately -1cm. This would generally indicate there could, in fact, be an issue with the published northing for LLCZ. As a check, two hours of static data was collected at LLCZ and submitted both to the NGS Online Positioning User Service (OPUS) and OPUS Rapid-Static (OPUS-RS). The OPUS and OPUS-RS derived coordinates verified that northing of LLCZ appeared to be about 2cm out. The OPUS-derived position for LLCZ was input as the published value and the data replotted. Figures 6 and 7 show the RT1 northing plots for Observer 2 and Observer 3 using the OPUS-derived coordinate.

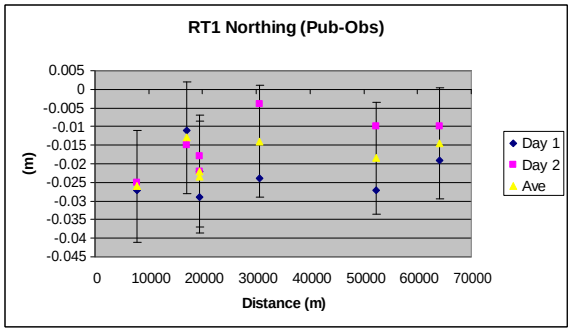

Figure 6 – Observer 2 (OPUS as published)

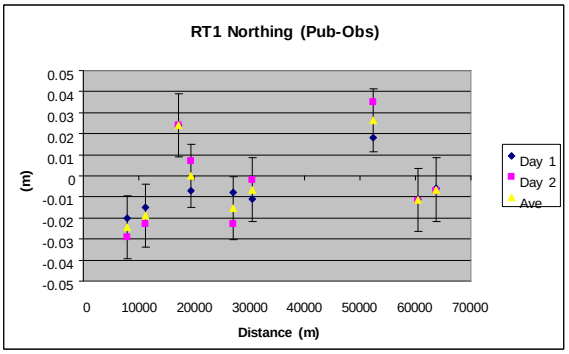

Figure 7 – Observer 3 (OPUS as published)

LLCZ can be seen at the two data points at 17km and 52km. The observations between Observers 2 and 3 are now within a couple of cm of truth, however there is still a significant disagreement between the two. The site at which LLCZ is set would tend to dictate that observers orient their bipods approximately the same way each time it was observed. There is a dirt road to the north of the station and thick grasses to the west, south, and east. It was confirmed that each observer did indeed set their bipods with the bubbles to the north when observations were taken. Since observer one and three used the same equipment, this might indicate the bubble on one of the two bipods was out of adjustment and that an equipment bias was introduced.

Data by Accuracy Class

Further analysis was conducted by combining all observers' data by Accuracy Class in order to better determine if differences in perceived accuracy were evident. See Figure 8.

Examination of Figure 8 would again seem to indicate there was a loss of accuracy based on duration of observation. With the exception of the northing component at 17km and 52km (LLCZ), the component residuals generally fall within +/- 2cm of the published values. It is also noted that there appear to be clusters of points representing different accuracy classes. On further

examination of the data, it can be seen these clusters represent data points collected under the same initialization. The field collection procedure dictated that the observers initialize to a CORS and collect RT1-RT4 observations under the same initialization. This would indicate the observation time is generally independent of the accuracy and that the determining factor is the initialization itself.

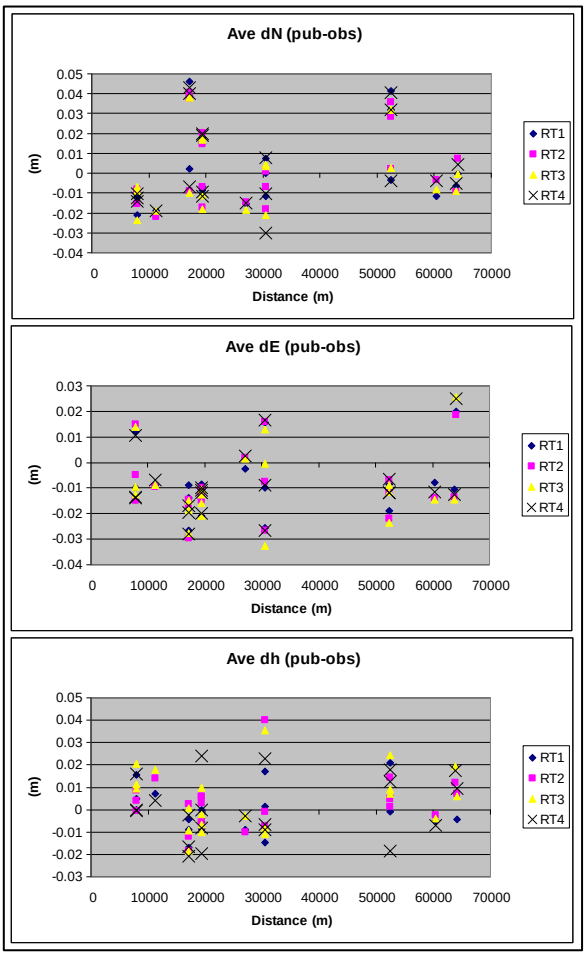

Figure 8 – Combined data (average day1-day2) from all observers separated into accuracy classes.

A visual inspection of Figure 8 does infer, however, that there appears to be more random scatter in vertical plot, especially in the RT4 observations. To quantify the differences, Table 2 shows the standard deviation of the component differences for each accuracy class.

	σ N (m)	σ E (m)	σ h (m)
RT1	0.021	0.012	0.011
RT2	0.020	0.013	0.012
RT3	0.020	0.014	0.014
RT4	0.021	0.013	0.014

Table 2 – Standard Deviation of the average of Day1-Day2 observations

Table 2 illustrates there is no significant difference in the precision of the horizontal components, relative to duration of observation. There is, however, a minor improvement with observation time in the vertical component. It should be noted that the standard deviation of the northing component includes the suspect observations at LLCZ. If those observations are removed, the standard deviation is into the 1cm to 1.5cm range and is very comparable to standard deviation shown for the easting component. Table 2 also shows that the vertical precision is equally as good as the horizontal precision.

Field Requirements (Quality Indicators)

There are a number of quality indicators available to the observer in the field. Though not a guarantee that the field measurements are precise or will yield an accurate position, these indicators are used to help insure quality data. Information that is readily available to the observer in the field consists of the number of the satellites being observed, the geometry of those satellites (Dilution of Precision), and the field-derived precision of the measurement being taken (RMS). This section will look at these indicators and determine their affect on precision and accuracy of the field derived positions.

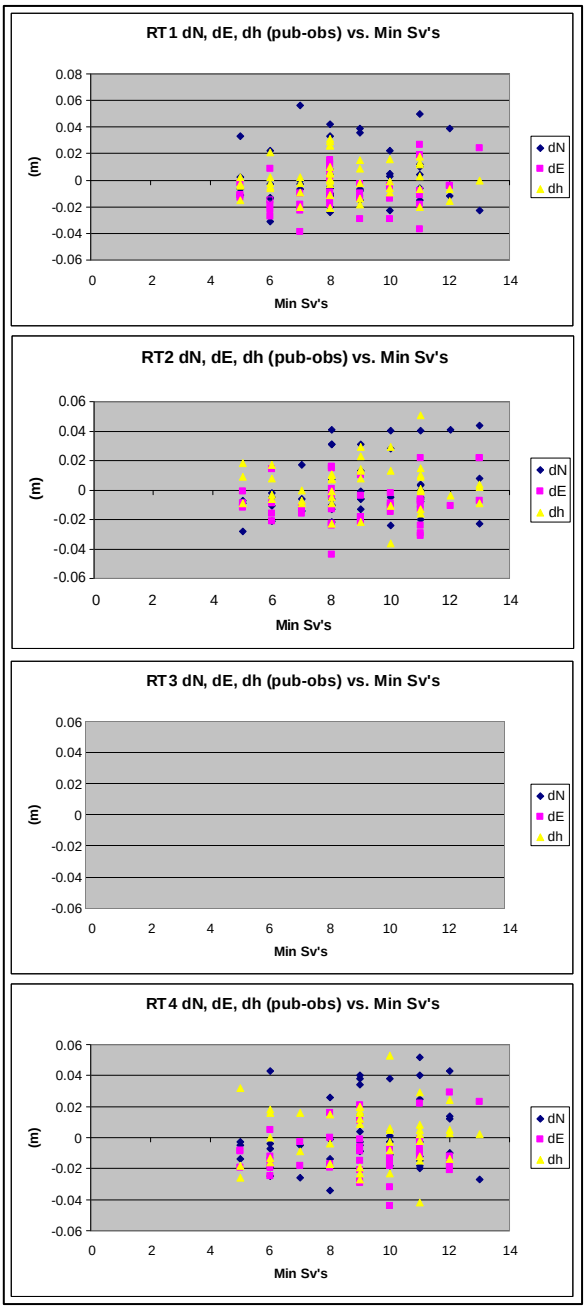

Figure 9 – Plots showing RT1-RT4 observations plotted vs. minimum number of satellites during occupation.

Number of Satellites

Component residuals from each of the RT classes (published-observed) were plotted relative to the number of satellites used in each solution. Figure 9 illustrates this comparison. Based on visual inspection of the plots, there appears to be little correlation, if any.

Field Derived RMS

The RMS observed in the field is a direct measurement of the precision of the derived position. That is to say, it is a measure of the scatter of all epochs that went into the final derivation of the position or vector. It should be noted also that measure is usually in the form of a two-dimensional horizontal RMS and a one-dimensional vertical RMS, as opposed to showing each component individually. The horizontal RMS is used as an indicator in the NGS guidelines.

In order make a direct comparison, it was necessary to compute a horizontal resultant of the northing and easting residuals (published-observed). This was simply done by using the equation:

$$\sqrt{(N_{pub} - N_{obs})^2 + (E_{pub} - E_{obs})^2}$$

This calculation was performed for each data point, so that a two-dimensional horizontal displacement could be determined. These numbers, being component resultants, will have a positive sign and will indicate only the distance on the ground from the published value. A direction could be computed, but for this exercise it is not relevant. Figure 10 show the component resultants plotted relative to field RMS. As with most of these plots, the magnitude of the data points are of little concern, as it is the precision or repeatability that is of importance. Specifically, in Figure 10 we are looking for any correlation between the component resultants and the field RMS. As with the plot relative to minimum number of satellites, there does not appear to be any correlation.

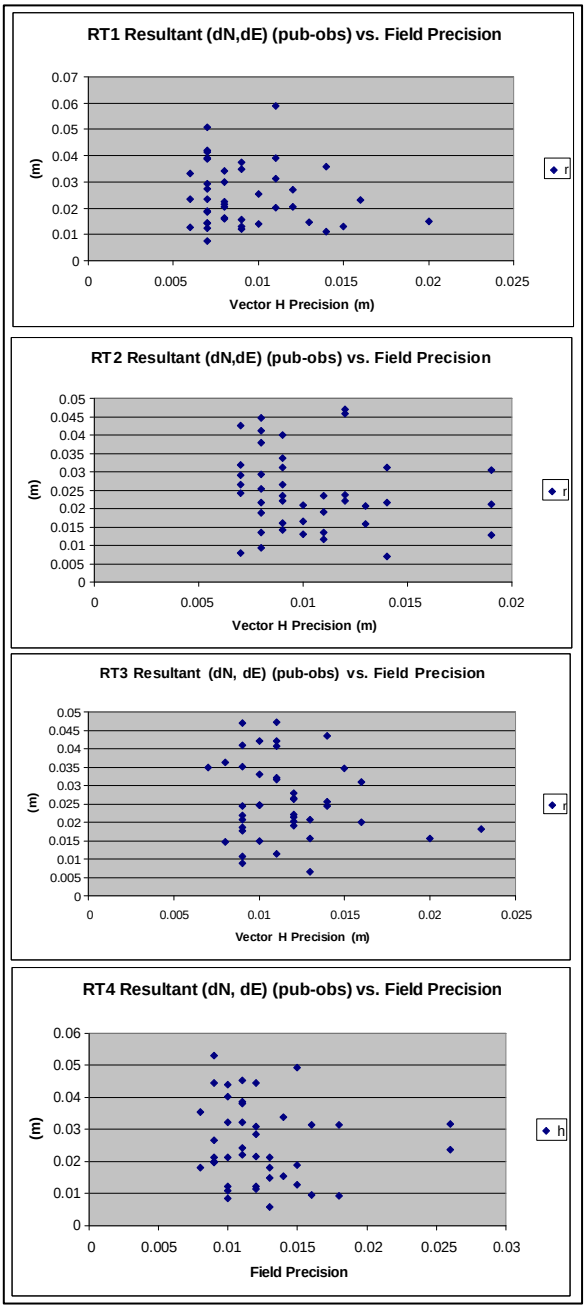

Figure 10 – Plots showing RT1-RT4 observations plotted vs. field precision (RMS) during occupation.

It can be seen though that the field RMS improves with time on station. That is to say, the longer one observes, the lower the RMS. This is evident when looking at the upper and lower limits and distribution of the RMS in the RT1 and RT4 plots. The question is whether this field RMS actually translates to accuracy. For instance, the one bad initialization shown earlier had a field RMS of less than 1cm.

PDOP (Position Dilution Of Precision) At the beginning of this study, it was thought the PDOP could be recovered from the field data after the fact. This was not the case. Though the PDOP was available to the observer in the field, it was not available for reporting once the data was downloaded. The indicator that was available was RDOP, or Relative Dilution Of Precision.

Unlike PDOP, which is a measure of satellite geometry at a single epoch relative to a single point being positioned, RDOP considers the changing satellite geometry over the length of an observation session at both stations that define a baseline. An investigation published by Yang and Brock (2000) indicate that "In contrast to the commonly used values of PDOP which indicate the effect of the instantaneous satellite geometry at a single epoch on point positioning, the values of RDOP give information about the effect of the continuously changing satellite geometry over a certain observation period on relative positioning. Similar to PDOP, the lower the value of RDOP the better the solution of a GPS baseline."

The RDOP quality indicator does not appear to be widely supported by most GNSS manufacturers, but since it is the only DOP we had available, it was used for this study.

According to Yang and Brock (2000) and Trimble (1991), RDOP values of less than three tend to indicate the duration of the observation session was long enough to allow for sufficient change in satellite geometry to produce accurate baselines. Trimble (1991) goes on to say that a baseline with a low RDOP that has poor ratio might indicate other factors such as ionosphere could be causing problems.

Figure 11 shows the coordinate residuals (published-observed) relative to session RDOP.

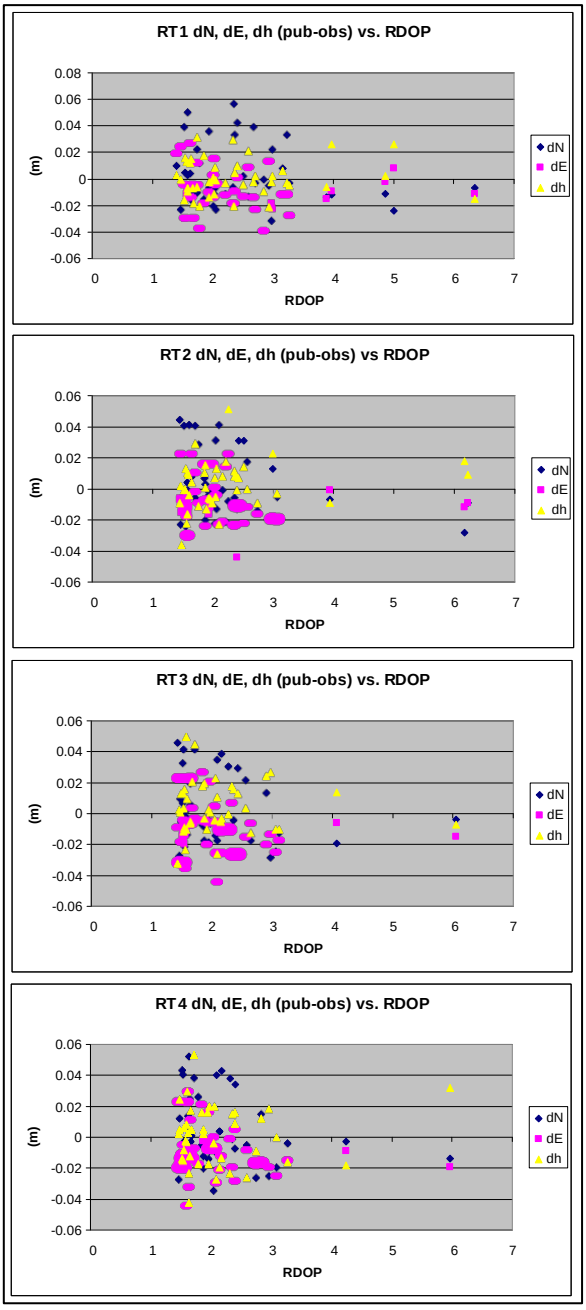

Figure 11 – Plots showing RT1-RT4 observations plotted vs. RDOP.

It should be pointed out that the suspect data for LLCZ is still included. This is easily seen when looking at the northing residuals. The northing residuals that plot at around 4 cm or higher can be attributed to this suspect data. The inclusion of these points tends to give the appearance of a negative correlation of precision to RDOP, however if the suspect residuals are visually ignored, the distribution of the data points appear to be much more random and suggest no correlation.

Final Tests relative to Accuracy Class

Finally, we will look at all data specific to their accuracy class and test them against precision cutoffs listed in the guidelines. We will also look at a measure of accuracy to determine if the same results are repeatable through independent observations conducted by other parties.

Precision Measures

The real time accuracy classes are defined by an observer's ability to take two measurements at a location under different conditions and obtain agreement of each of the observations within a certain separation from their mean. That is to say that in order to meet the requirement for the RT1 accuracy class, the two observations must agree horizontally with their mean to within 1.5 cm and vertically with their mean to within 2.5 cm. In order to test the horizontal precision, the following equation was derived:

$$H\ Resultant = \sqrt{\left(\frac{dN_{d1} - dN_{d2}}{2}\right)^2 + \left(\frac{dE_{d1} - dE_{d2}}{2}\right)^2}$$

Where *H Resultant* = the spatial difference from the mean of each set of redundant observations, *dN* and *dE* are the delta northing and easting (published-observed) and subscripts *d1* and *d2* denote day1 and day2 observations. The vertical precision was simply computed by the equation:

$$V = \frac{dh_{d1} - dh_{d2}}{2}$$

Where *V* is the vertical height difference (ellipsoidal) from the mean of each set of redundant observations, *dh* is the delta ellipsoid height (published-observed) and subscripts *d1* and *d2* denote day1 and day2 observations.

Figure 12 shows the results of this analysis and is a direct measure of precision relative to an observer's ability to repeat a measurement within a certain tolerance. The lines on the graph labeled as "H Env" and "V Env" are respectively the Horizontal and Vertical RT Class tolerance envelope. The RT4 tolerance envelope was not plotted, as all data points are well within that tolerance, and plotting the RT4 envelope would only serve to make the graph less readable.

The results in Figure 12 show all individual precisions are within the specified tolerances. Also shown on each plot are the combined horizontal and vertical precisions at 95 percent. As has already been seen, there is no significant difference in the horizontal precision between the different accuracy classes, but there is a definite noticeable improvement in the vertical relative to the length of observation based on the 95 percent precisions.

The 95 percent horizontal and vertical precisions were computed using the draft National Standard for Spatial Data Accuracy (FGDC 1997) where the 95 percent accuracy level for circular error is defined as 1σ * 2.4477. The final FGDC standard was published in 1998 and is based on Root Mean Square Error (RMSE), as opposed to standard deviation. The use of the draft standard was an oversight by the author; however, the difference in computational statistics is insignificant at this stage as we are primarily concerned with precisions, not accuracies.

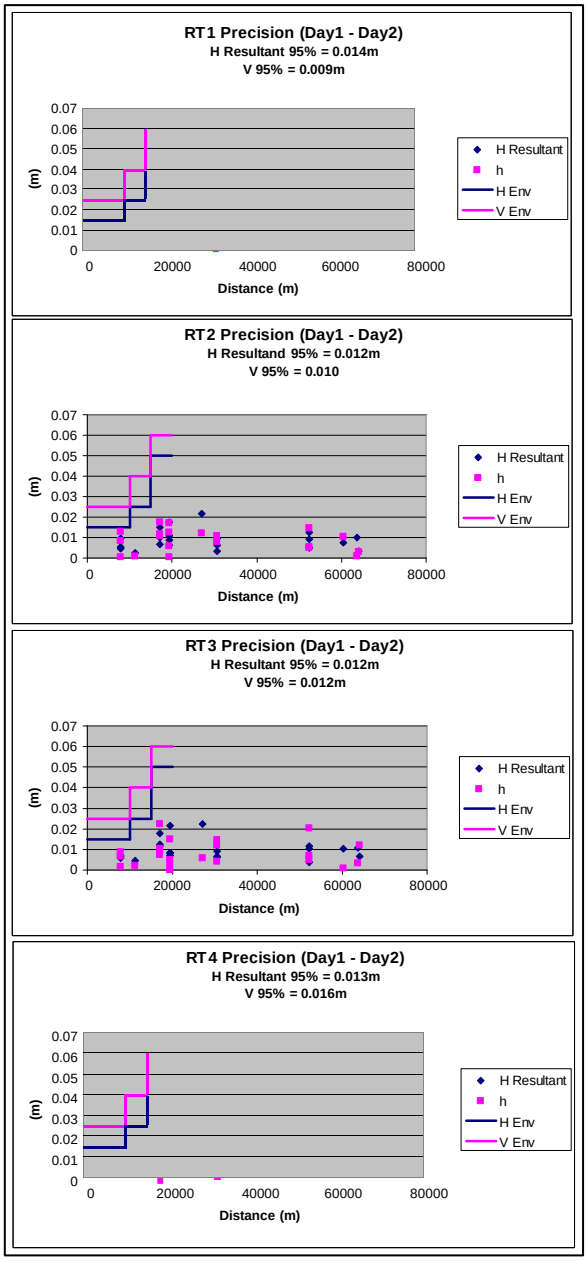

Figure 12 – Plots showing RT1-RT4 average horizontal and vertical observation differences from day1 and day2. "H env" and "V env" are respectively the horizontal and vertical RT1-RT3 class tolerance envelopes.

Transitioning Precision Measures to Accuracy Measures

The accuracy of a measurement is defined by how closely the measurement compares to truth. In this case study, measurements were taken at points with known coordinates, so accuracy can be tested by

comparing our measurements to these known values. More importantly, we can measure the scatter of the data for each accuracy class collected by different observers. By doing this, we can determine any observer's ability to be within some statistical horizontal radius and vertical separation from each other. In lieu of a known value, the average of all observers' measurements would best represent truth. Figure 13 shows the average radial error for each observation set (Day1, Day2). Figure 14 shows the corresponding average vertical error for each observation set.

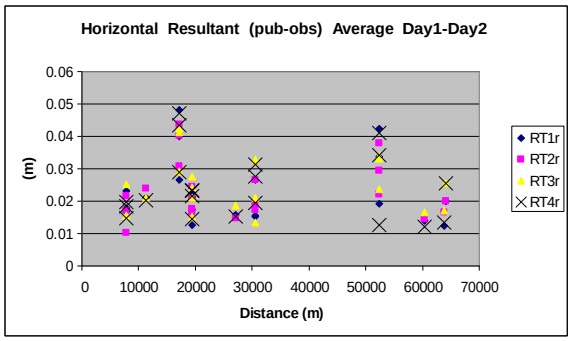

Figure 13 – Plot showing RT1-RT4 average radial error (Published – Average Day1, Day2).

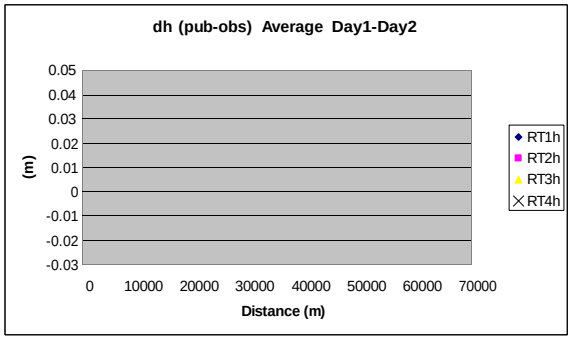

Figure 14 – Plot showing RT1-RT4 average vertical error (published – Average Day1, Day2).

As before, the larger residuals at LLCZ have been left in the analysis, but as previously indicated, these observations may contain an equipment bias. Table 3 shows the horizontal and vertical 2σ error estimates from the data contained in figures 13 and 14.

	2σ Horizontal (m)	2σ Vertical (m)
RT1	0.024663	0.020933
RT2	0.021754	0.023475
RT3	0.020684	0.027002
RT4	0.025223	0.027488

Table 3 – Horizontal and Vertical 2σ Error Estimates (Average of Day1-Day2 observations)

Table 4 shows the horizontal 2σ error estimates, if the large residuals at LLCZ are removed from the analysis.

	2σ Horizontal (m)
RT1	0.010786
RT2	0.011772
RT3	0.013639
RT4	0.014448

Table 4 – Horizontal 2σ Error Estimates (Average of Day1-Day2 observations) with Large LLCZ Residuals Removed

Tables 3 and 4 are showing the observers' ability to produce the same radial error. For instance, Table 4 indicates that observations taken under RT1 criterion will produce a radial error within 0.011 meters of similar observations 95 percent of the time. These numbers directly correspond to the expected accuracy of one observer's coordinate determination relative to another observer's coordinate determination.

As was seen previously, the precision of the vertical component decreases slightly as observations are shortened. Also, now that the suspect data at LLCZ has been removed (Table 4), a slight decrease in horizontal precision is also evident, as observation times were shortened. Figure 15 shows the relationship of horizontal and vertical 2σ precisions relative to the length of observation.

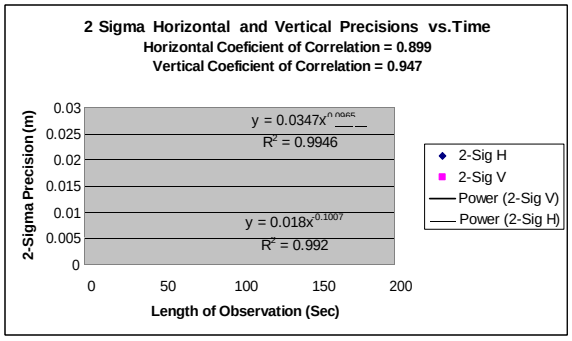

Figure 15 – Plot 2σ Horizontal and Vertical Precisions relative to Length of Observation.

Though the overall differences between the 10-second (RT4) and 180-second (RT1) observations are in the range of millimeters, it is clear a correlation exists, as is further illustrated by the horizontal and vertical correlation coefficients at the top of the plot.

Computing Horizontal and Vertical Accuracies

According to the Federal Geographic Data Committee (1998), horizontal error at point ***i*** is defined as:

$$\sqrt{(x_{data,i} - x_{check,i})^2 + (y_{data,i} - y_{check,i})^2}$$

where $x_{data,i}$ and $y_{data,i}$ are the x and y values from the field data and $x_{check,i}$ and $y_{check,i}$ are the published x and y values.

Horizontal accuracy is defined in terms of radial Root Mean Square Error ($RMSE_r$) and is determined with the equation:

$$\sqrt{\frac{\sum_{i=1}^{n}\left((x_{data,i} - x_{check,i})^2 + (y_{data,i} - y_{check,i})^2\right)}{n}}$$

where n is the number of check points tested. Horizontal accuracy at 95 percent is computed by the formula:

If the x and y errors are assumed to be equal, then $Accuracy_r = 1.7308*RMSE_r$

Vertical Accuracy at 95 percent = $Accuracy_z = 1.96*RMSE_z$

$$RMSE_z = \sqrt{\frac{\sum_{i=1}^{n}(z_{data,i} - z_{check,i})^2}{n}}$$

Table 5 lists the 95 percent horizontal and vertical accuracies, as defined by the FGDC National Standard for Spatial Data Accuracy (NSSDA).

	95%(RMSEr) (m)	95%(RMSEz) (m)
RT1	0.032967	0.018825
RT2	0.033251	0.0237233
RT3	0.036622	0.027924
RT4	0.036143	0.026851

Table 5 – NSSDA Horizontal and Vertical Accuracy (Average of Day1-Day2 observations) for RT1-RT4 observations with Large LLCZ Residuals Removed

Technically speaking, the accuracy test just performed is designed for spatial data, not survey data. The proper way to determine accuracies for survey data is through a properly weighted least squares adjustment. As this data has not been run through an adjustment, the only way to determine accuracies is through an analysis similar to the one performed here.

As was seen in the precision analysis (Table 4), the accuracy analysis indicates a correlation between accuracy and observation time. This is most noticeable in the horizontal accuracy results.
Another interesting feature that exists in Table 5 is that the apparent vertical accuracy is better than the horizontal accuracy. Since the horizontal precisions in Table 4 were very good and the accuracy test contains all errors, including those associated with the check coordinates, this would indicate the presence of a bias in either the published horizontal coordinates or the field derived

horizontal coordinates. A horizontal bias could also exist between the published coordinates for the CORS stations and those of the check stations. Without a high-order resurvey of the three check stations relative to CORS, there is no way to determine the exact cause of the larger horizontal accuracies.

Discussion

A number of the results shown in this study appear to be contrary to commonly accepted beliefs relative to GNSS Surveys. However, it must also be pointed out that this study is very limited in its scope, as it was conducted using only one type of equipment; in one part of the country which tends to have a dryer troposphere than other parts of the country, such as Florida or Southern Louisiana. This study was also conducted at a time when the ionosphere is quiet. In fact, we are currently at the lowest point on the curve of the 11-year solar cycle.

In this study:

- More satellites observed did not result in better precisions. However, it should be noted that field observations were not designed to test the worst case scenario of each accuracy class.
- Observations with lower DOP values were not determined to be better than those with higher DOP values. But, as with criterion for minimum number of satellites, the observations were not designed to test the worst case.
- The length of observed baseline had little to no affect on the relative precision of the baselines.
- Lower field RMS did not yield better horizontal or vertical precisions in the office.

Some common beliefs were also reinforced:

- The precision of each of the horizontal components appeared to be about equal the precision of the vertical component. However, once the data was cleansed of some high- residual outliers, it was seen that, in fact, the horizontal precisions were better than the vertical. Based on this study, the horizontal 2-dimensional position is better than the vertical 1-dimensional position by a factor of 1.9.
- The horizontal and vertical precision first appeared to be independent of length of occupation. However, once the data was cleansed of some high residual outliers, both the horizontal and vertical precisions showed a strong correlation to length of occupation.

Based on this discussion, it is clear more research is needed. Future research should:

- Include many different models of GNSS equipment to include those that are both GLONASS and non-GLONASS capable.
- Be conducted in other parts of the county to include areas with a wetter troposphere.
- Continue to be conducted or re-conducted periodically, as we climb up the curve toward solar-max, to measure the effect of active ionosphere.

Conclusions

As the use of RTK positioning continues to increase, so does the need for development of standards, specifications, and guidelines designed to meet specific levels of precision and accuracy. The results shown in this case study are very encouraging, relative to the ability to produce observations of high precision with “Single Base RTK.” In fact, the results far exceeded the author’s expectations, relative to the NGS Accuracy Classes. Further research may show some of the observation criterion listed, such as minimum number of satellites, PDOP, and RMS, may be relaxed or may be shown to

have little to no effect on one's ability to produce precise RTK measurements.

The case study reported here shows that Single Base RTK observations can be taken over significantly long distances up to 60 km and still produce results that meet or approach the precision levels of much shorter observations. It is also shown that the duration or length of observation is a definite factor in the precision of RTK measurements. Finally, it can be concluded that, if:

- Observations are designed with proper redundancy to remove systematic errors (tropo, iono) and detect bad initializations;
- The data is analyzed to detect and remove statistical outliers.

Single Base RTK observations meeting or exceeding the precision criterion of NGS Single Base Guidelines for RT1, RT2, RT3, and RT4 accuracy classes is achievable, carried out under normal field conditions similar to those experienced during this case study.

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