Technologies for Optimized Pass-to-Pass Positioning Performance

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BIOGRAPHIES

Janet Brown Neumann is a NovAtel Fellow, working in the Positioning Algorithms Group. She holds an MS and a BS in Electrical Engineering from Iowa State University and the University of Kansas, respectively, and has been involved in the design and implementation of GNSS algorithms for the past 33 years.

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Anastasia Salycheva is a Geomatics designer at NovAtel. She received her M.Sc. degree in Geomatics Engineering from the University of Calgary in 2004. Anastasia has been involved in the development of various GNSS algorithms at NovAtel for over 11 years. Her current focus is on the PDP and GLIDE positioning engines.

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ABSTRACT

High quality continuous carrier phase can be used to estimate vehicle motion at the centimeter level over short periods of time even when the absolute position accuracy is at the meter level. Over longer periods of time, the knowledge of the motion is affected by the absolute position accuracy and the availability and quality of corrections for slowly changing errors. The change in the position error level over that period of time is determined by the accuracy with which the accumulated motion over the interval is known. This paper will describe the high level structure of the different positioning engines in NovAtel receivers and how accurate carrier phase is used to maintain a consistent position error over time, with results shown for different situations and absolute position error levels. Types of measures which can be used to evaluate error consistency will be covered and results from GLIDE, Steadyline and RTK ASSIST algorithms will be presented. Different Steadyline configurations will be described along with examples and a discussion of the handling of position types with a convergence phase.

This paper will also describe the major sources of error and the challenges in obtaining good pass to pass performance. It will discuss difficulties in maintaining position error levels in blockage conditions and in conditions with high position biases, such as those caused by large ionospheric error in a single frequency receiver. Results from a bias reduction algorithm which runs with GLIDE will be presented.

INTRODUCTION

Typically, it is assumed that a GNSS position solution optimized for absolute accuracy will be the "best" solution. However, for many positioning applications, particularly in agriculture, it is highly desirable to maintain a consistent error over time. This is commonly known as having good "pass to pass" performance. In very precise positioning systems such as short baseline RTK, this comes automatically with the precision and accuracy of the position. In other cases, such as Single Point (Autonomous) single or multiple frequency pseudorange positioning, there can be significant drift in the error with time due to pseudorange inaccuracy and lack of accurate error corrections. There can also be instantaneous changes in error, depending on the position estimation method. Even when using high accuracy positioning modes, significant position error changes can occur when changing positioning types such as when RTK corrections are temporarily lost.

To meet the objective of providing excellent pass to pass performance and discontinuity control for our various positioning options, NovAtel has developed positioning algorithms optimized to maintain very consistent error over time. This paper will present algorithmic concepts and results from the NovAtel GLIDE, Steadyline and RTK ASSIST algorithms which demonstrate their pass to pass accuracy and discontinuity control.

PASS TO PASS ACCURACY

Pass to pass accuracy reflects the consistency of position error over some given time window. Short time windows (a few seconds) reflect general smoothness. Longer time windows, for example, 900 seconds, can be very useful for certain applications such as agriculture. As an agricultural example, in many cases it is more important to maintain accurate between-row spacing than to have excellent absolute position accuracy.

There are several different methods which can be used to quantify pass to pass accuracy. NovAtel uses the following commonly used measure which is straightforward to compute and understand:

$$\text{Latitude } pp(\tau) = RMS\{\varepsilon_{lat}(t) - \varepsilon_{lat}(t-\tau)\} \quad (1)$$
$$\text{Longitude } pp(\tau) = RMS\{\varepsilon_{lon}(t) - \varepsilon_{lon}(t-\tau)\} \quad (2)$$

where $\varepsilon_{lat}(t)$ and $\varepsilon_{lon}(t)$ are the errors in latitude and longitude at time t, and τ is the time window applicable to the statistic. When analyzing data, we also keep track of any large discontinuities in the error. Error discontinuities are an example of poor pass to pass performance, but in long data sets, the effect of a few discontinuities may not show up clearly when combined with the rest of the data. Even a small number of discontinuities can, however, cause serious problems for users.

Figures 1-3 contain several one dimensional error plots which were artificially generated to illustrate the pass to pass accuracy concept and its relationship to absolute accuracy.

Figure 1 shows a plot of error with good short term pass to pass performance but poor 900 second pass to pass performance. Figure 2 shows an error which has a higher RMS absolute error than that in Figure 1, but much better 900 second pass to pass performance. This is because much of the RMS absolute error is due to a bias. Figure 3 shows an error plot with the same RMS absolute error as Figure 2, slightly better 900 second pass to pass performance when compared to Figure 2, but degraded short term pass to pass performance.

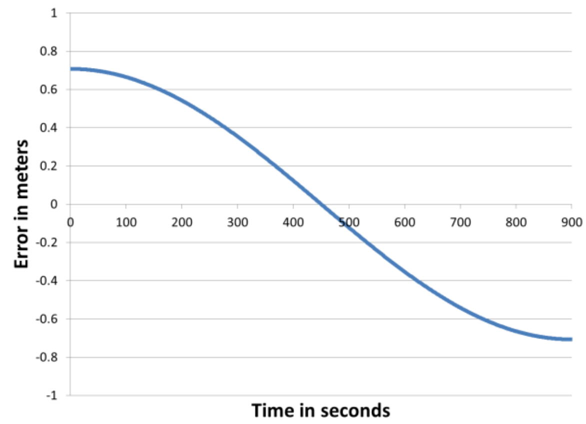

Figure 1: Pass to Pass Error Example 1
RMS=50cm, pp(5s)=0.9cm, pp(900s)=100cm

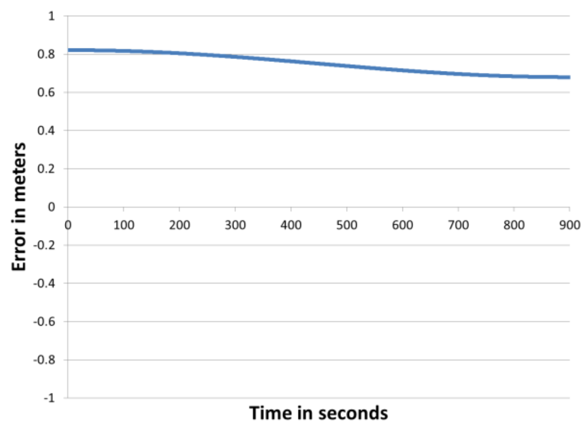

Figure 2: Pass to Pass Error Example 2
RMS=75.2cm, pp(5s)=0.1cm, pp(900s)=10cm

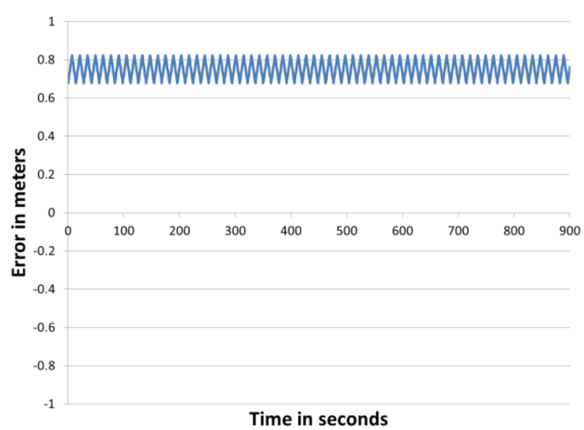

Figure 3: Pass to Pass Error Example 3
RMS=75.2cm, pp(5s)=7.6cm, pp(900s)=6.7cm

Some common sources of error variation with time in real world situations are:

- Natural error variation in lower accuracy (pseudorange-based) positioning.
- Offsets between different positioning types when a type switch is needed.
- Degradation of high accuracy modes when corrections are lost.
- Convergence periods for some positioning types.

NOVATEL PDP AND GLIDE: PSEUDORANGE POSITIONING OPTIMIZED FOR PASS TO PASS ACCURACY

The NovAtel PDP (pseudorange/delta-phase) filter was described in [1] in 2003. Its primary purpose is to provide short term smoothing to the pseudorange solution. GLIDE is based on a similar concept, but is optimized for pass to pass accuracy at longer time intervals such as 900 seconds.

Continuous carrier phase observations differenced over time (delta phase) provide an accurate measure of the change in the pseudorange to the satellite being tracked. The delta phase observation does not have an ambiguity and can be used to compute change in position over short time intervals in the same way that pseudorange observations are used to compute position. The change in position computed this way over a second or two is typically good to approximately a centimeter. By estimating change in position with delta phase, smoothing can be done without reliance on a specific dynamic model. This greatly reduces the problems of overshoot, filter-induced latency, and mis-modeling effects when estimating kinematic trajectories. Modeled dynamics are only used when insufficient continuous carrier phase observations are available. There is also no need to carrier-smooth individual pseudoranges over significant periods of time. This avoids problems with carrier-smoothed pseudorange positions such as constellation change jumps, degradation of smoothing when cycle slips occur and ionospheric divergence effects with single frequency observations.

Figures 4-6 show latitude and longitude errors vs. time taken from post-processed results using data from a 2 hour van test with L1L2, WAAS, GPS and GLONASS. The post-processor runs the same algorithms used in real-time and generates results consistent with real-time results. The advantage of post-processing is that exactly the same measurement data can be processed through different algorithms and compared. Figure 4 compares latitude error from an instantaneous pseudorange solution to the PDP (short term smoothed) solution error for a 1000 second segment of the test. It can be seen that the PDP error follows that of the instantaneous solution, but with much smoother short term fluctuations. Figures 5 and 6 show the latitude and longitude error for the full test and compare the PDP solution error to the GLIDE solution error. These figures show that the GLIDE error is much more consistent than the PDP error, especially when considered over 900 second time segments (the vertical gridlines are at 900 seconds). A possible disadvantage of GLIDE over PDP is that because it is intended to hold the error it starts with as tightly as possible, it can have a biased solution for significant periods of time. There is some general position smoothing as GLIDE starts, in order to be sure that the error held isn't based on a wild outlier point. Nevertheless, there may be some significant time segments where the PDP solution would have better RMS absolute position accuracy than the GLIDE solution.

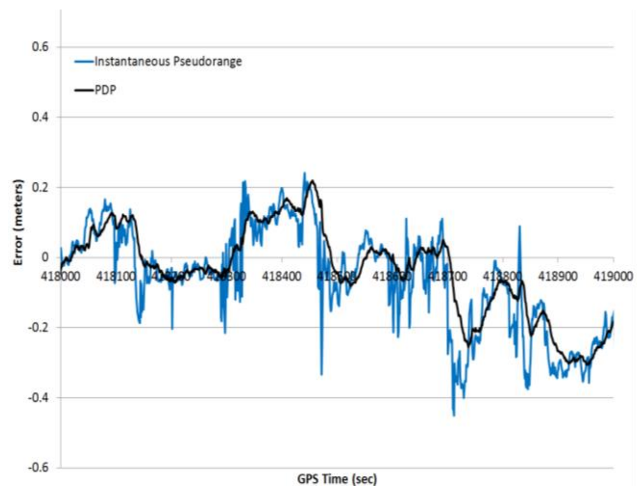

Figure 4: L1L2 WAAS Van Test Instantaneous Pseudorange and PDP Latitude Error Comparison

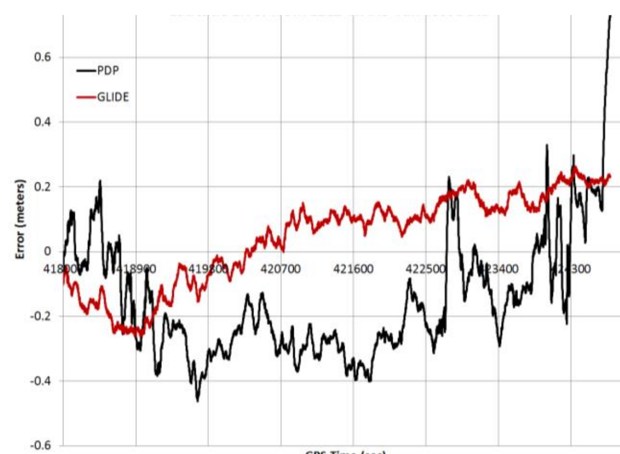

Figure 5: L1L2 WAAS Van Test PDP and GLIDE Latitude Error Comparison

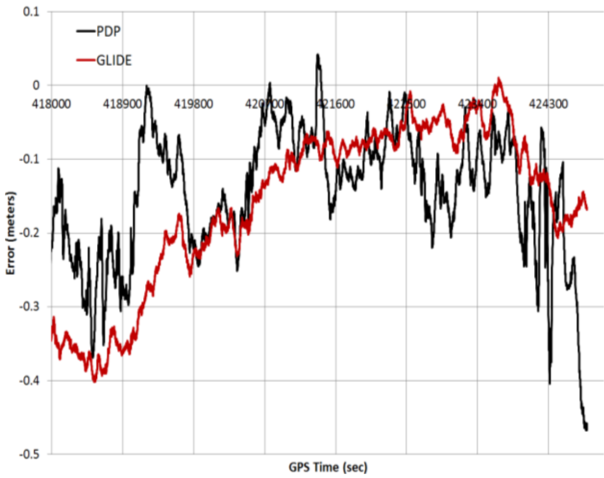

Figure 6: L1L2 WAAS Van Test PDP and GLIDE Longitude Error Comparison

GLIDE PASS TO PASS ACCURACY RESULTS

GLIDE pass to pass accuracy depends on:

- Absolute position accuracy.
- Ability to correct for changes in ionospheric and tropospheric error.
- Ability to correct for changes in satellite position and clock error.
- Multipath environment.
- Continuity of phase observations.

In open sky conditions, typical GLIDE 900 second pass to pass accuracy can range from about 15 cm or better for SBAS with L1 and L2 to about 25 cm for Single Point L1-only. Figure 7 shows a chart with the pass to pass values expected for GLIDE L1L2 SBAS when testing in relatively good conditions. The horizontal axis is the time window, τ, and the vertical axis represents the expected pass to pass value for that time window.

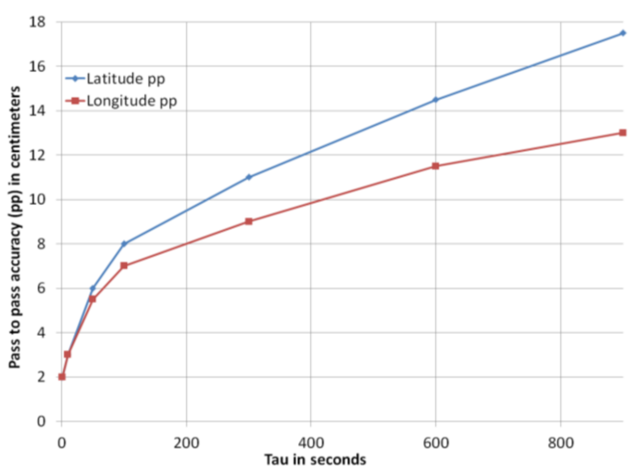

Figure 7: Expected GLIDE Pass to Pass Values (SBAS L1L2)

Figures 8 and 9 show latitude and longitude pass to pass results computed from the post-processed van test data used to obtain the results shown in Figures 4-6. Pass to pass results for the instantaneous pseudorange and PDP solutions are shown as well as those for the GLIDE solution in order to demonstrate the improvement provided by GLIDE. The pass to pass improvement for the PDP solution over the instantaneous pseudorange solution can also be seen. The GLIDE pass to pass results shown in Figures 8 and 9 are noticeably better than those in Figure 7 (the "expected" results). The expected results are set to be fairly conservative to allow for the variation that occurs from test to test due to different atmospheric conditions, test conditions, etc.

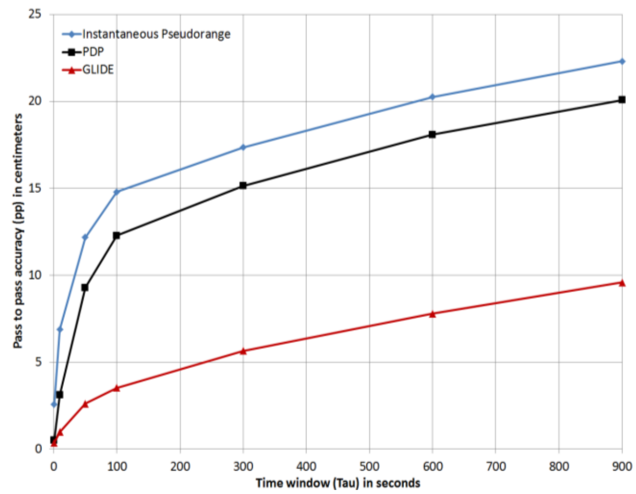

Figure 8: L1L2 WAAS Van Test Latitude Pass to Pass Results

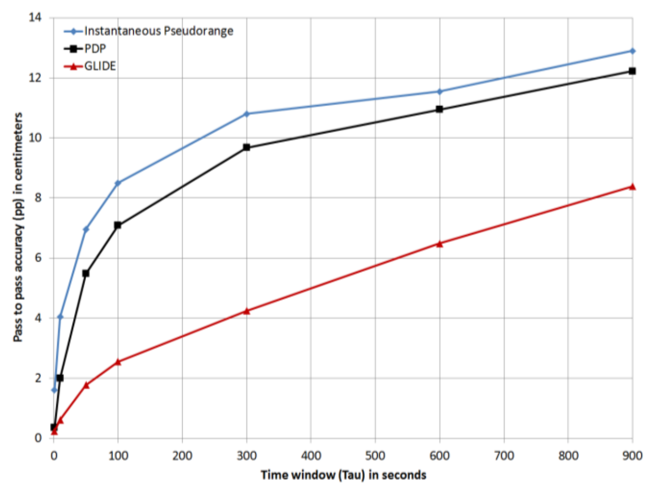

Figure 9: L1L2 WAAS Van Test Longitude Pass to Pass Results

ABSOLUTE ACCURACY EFFECTS ON GLIDE

The accuracy of the delta position estimate is affected by the absolute position accuracy. This effect is very small over a second or two, but since it is highly time correlated, it can accumulate into a significant pass to pass error after hundreds of seconds, and is a particular problem when the absolute error is unusually large. This can be a major issue for GLIDE in high ionospheric conditions when there are no good ionospheric corrections. This becomes difficult to deal with because ionospheric errors change slowly and it is therefore hard to remove them by simply averaging.

Figure 10 shows the latitude error for a set of static L1 only, high ionosphere, Single Point data post-processed through the GLIDE algorithm with 3 different methods:

1) The first post-processing method simply runs the standard GLIDE algorithm with the assumption that the receiver is moving. Therefore, even though the data is static, the results reflect what they would be if the receiver were moving.
2) The second method was the same as the first, except that the first 10 minutes assume the position is stationary allowing for absolute accuracy improvement with averaging.
3) The third method is the same as the second, except a bias reduction algorithm is used both during the static and kinematic portions. This bias reduction algorithm runs automatically within GLIDE when only single frequency data is available in Single Point and SBAS modes. The bias is removed as quickly as possible during an initial stationary period, but is removed very gradually once the user has been in motion in order to maintain good pass to pass performance.

It can be seen from the results of method 1 that if nothing is done, there is a very large error on the position, and this in turn causes very poor pass to pass behavior. The averaging done in method 2 provides only a small improvement because there isn't enough variation in the ionospheric error over 10 minutes to gain much accuracy from averaging. The results from method 3 are much better. The pass to pass accuracy is not as good as it would be with ionospheric correction or lower ionospheric activity, but there is a marked improvement over the method 1 and 2 results.

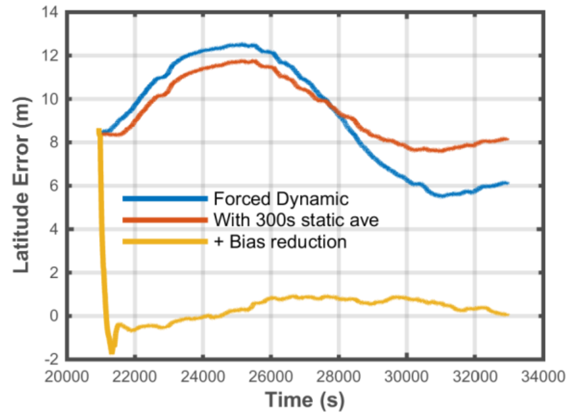

Figure 10: GLIDE Latitude Errors, L1 only during High Ionospheric Activity

GLIDE DISCONTINUITY HANDLING

Position Type Switches

GLIDE can generate Single Point, DGPS or SBAS position types using single or dual frequencies. In its startup phase, it can go through one or more position type transitions as it gains corrections allowing a position type with a higher level of accuracy. During this improvement phase, it will immediately jump to the higher accuracy type, causing error discontinuities. Once it has reached the target position type, it will no longer jump when type changes are needed due to loss or reacquisition of corrections. Figure 11 shows an example of GLIDE latitude error during a WAAS rooftop test using kinematic mode assumptions. Corrections are periodically removed for about 20 minutes. It can be seen that there are no noticeable error discontinuities when the WAAS corrections are removed or returned. There are also no obvious error discontinuities when particular satellites come in or out of the solution.

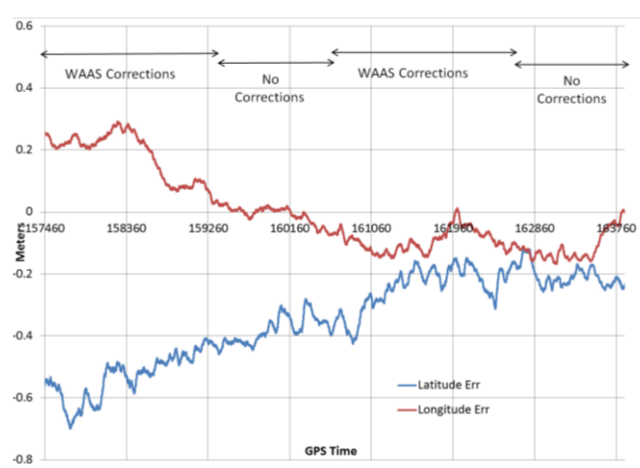

Figure 11: Glide Position Error with Intermittent WAAS Corrections

Signal Outages

Signal outages can pose a major challenge to producing discontinuity-free GLIDE positions with good pass to pass performance. If any epochs do not have sufficient continuous delta phase observations to produce a good delta-position estimate, continuity is lost. For short baseline RTK and cases where RTK or PPP have been running long enough to have good model convergence, the inherent position accuracy leads to good pass to pass and discontinuity performance once a position is again available. PDP and GLIDE, however, do not have the inherent position accuracy to create automatic good position error continuity after a signal outage. Good reinitialization after an outage is particularly important for GLIDE since it will hold tightly to the error it starts with.

There are a number of options for reinitializing GLIDE after a signal outage. A few of these are:

- Reinitialize with a pseudorange position.
- Use other sensor input such as from an INS system.
- Use the integer nature of the delta phase ambiguities to reinitialize.

Using pseudoranges to reinitialize is simple and robust, but will obviously degrade the pass to pass accuracy. It also has the disadvantage that the obstructions causing the signal outage may still be degrading the pseudorange observations when the reinitialization occurs. The current GLIDE algorithm uses pseudorange measurements along with some dynamics information to reinitialize after a signal outage.

The use of other sensors requires availability of those sensors, and can be complicated to implement, especially if various types of possible sensors must be handled. It also contains some challenges since GNSS inputs are frequently used to estimate sensor biases, potentially causing a dangerous inter-relationship when an INS output is used to initialize the GNSS solution.

After an outage, the delta phase observation will have lost continuity, but the discontinuity will contain an integer number of cycles (cycle slips). This characteristic can be used and the integer discontinuity or cycle slip values can be estimated with an integer ambiguity resolution algorithm. A good explanation of this technique applied to PPP positioning can be found in [2]. The application to GLIDE is very similar. Integer ambiguity estimation is fairly complex to implement, but we have experimented with this type of initialization and found it worked quite well for short "clean" outages. Figure 12 shows post-processed GLIDE results using data from a kinematic van test with 4 short (approximately 10 seconds) and clean outages. The latitude error shown in orange is produced by integer wide-lane reinitialization and the error shown in blue represents results from the current reinitialization using pseudoranges. It can be seen in this latitude error plot that the discontinuities are nearly completely removed with the integer reinitialization, which is typical for tests of this type. Longer, more ragged outages, such as are found under treelines at the edges of agricultural fields are more challenging. Figure 13 shows longitude (cross-track) errors for a GLIDE test done on a tractor driving back and forth in a field and driving well under large trees at the north end of the field. This is a very challenging environment for error continuity maintenance. The outages are between 20-40 seconds and don't have clear start and stop points since signals are continually coming in and out under the trees, and have high degradation when they are received. The blue line in the graph shows the error using the existing pseudorange based reinitialization and the orange line shows the error using wide-lane integer ambiguity based reinitialization. Even in this challenging environment, the integer ambiguity method improves the reinitialization performance. Figure 14 shows the size of the 15 longitude discontinuities at each turn under the trees. It can be seen that 6 have similar performance for the two reinitialization methods, indicating that either integer ambiguity estimation was not possible, or that it provided similar results to the existing method. In 8 cases, the re-initialization is noticeably improved, and in one case it is worse, probably due to an incorrect wide-lane ambiguity estimate. Use of the integer ambiguity method reduced the RMS of the discontinuities from 0.439 meters to 0.189 meters. This GLIDE reinitialization method would need further testing and fine tuning to ensure a robust and reliable solution, but our results to this point show good promise.

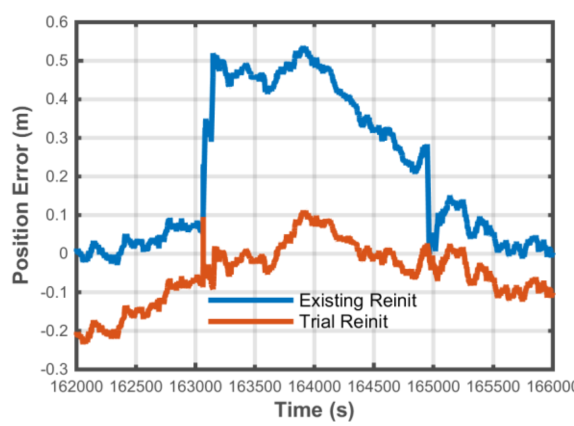

Figure 12: GLIDE Latitude Error Comparing Reinitialization Methods after Short, Clean Outages

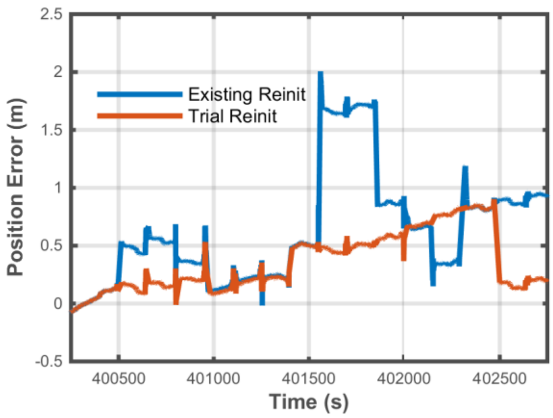

Figure 13: GLIDE Longitude Error Comparing Reinitialization Methods after 20-40s Outages under Trees

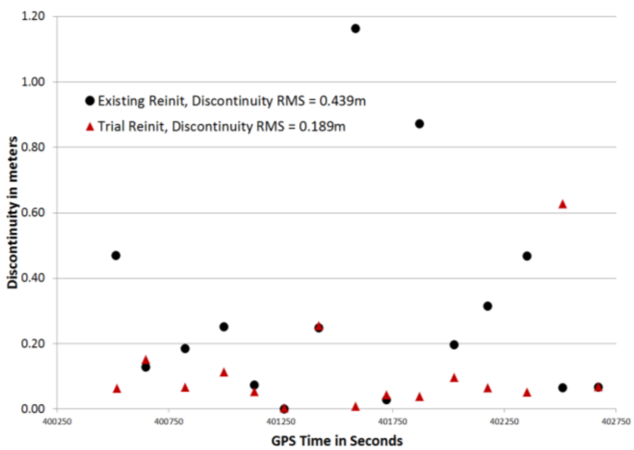

Figure 14: GLIDE Longitude Discontinuity Magnitudes Comparing Reinitialization Methods after 20-40s Outages under Trees

NOVATEL STEADYLINE: PROVIDING SMOOTH TRANSITIONS BETWEEN RTK, PPP AND PSEUDORANGE BASED POSITION TYPES

Figure 15 shows a block diagram of the high level structure of the computation of the NovAtel jump-free “best position”. The position type chosen for output is based on the standard deviations of the various choices.

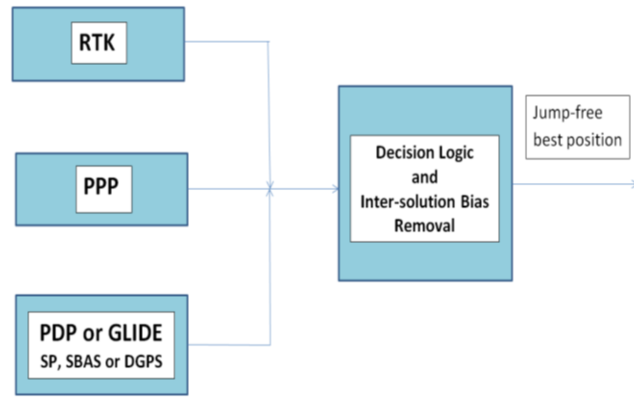

Figure 15: NovAtel Jump-free Position Generation

Sometimes it is necessary to switch between different position types, such as when RTK or PPP corrections are lost. When this switching happens, error discontinuities can occur due to offsets between the different position types. The NovAtel Steadyline algorithm can be enabled to prevent discontinuities when switching between RTK, PPP and pseudorange based positioning types. It can also be used to avoid discontinuities between sub-modes of those types such as RTK float to fixed, between solutions using different RTK base stations, or between the initial PDP accuracy improvement jumps. Steadyline holds the desired error level after a position type change as best it can. Offsets between the modes are continuously monitored and used to prevent discontinuities and to hold the proper error level. Delta phase positioning can maintain the original position type accuracy for a significant period of time, depending on the accuracy of the original and new position types. Several user-configurable Steadyline mode options are available to control the specific behavior of the transitions.

Figures 16 and 17[3] illustrate the behavior of the Steadyline “Maintain” and “Transition” concepts. “Maintain” will always work to hold the error constant to that before the most recent position type switch. “Transition” will gradually move to the new error level at a user definable rate. “Maintain” and “Transition” can both be requested as Steadyline mode options. Figure 18[3] illustrates the “Prefer Accuracy” mode. In this mode, it will use “Maintain” when switching to a less accurate positioning type and “Transition” when switching to a more accurate type. Yet another mode option is “User Accuracy Levels” which allows even finer tuning of the switching behavior by the user. The user can request Steadyline to utilize any of these 4 mode options.

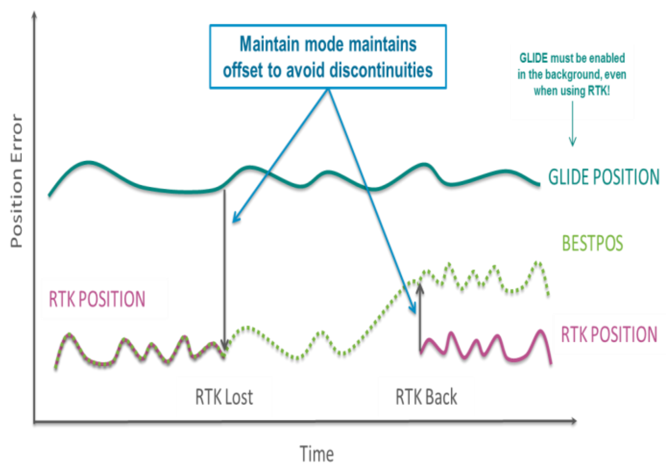

Figure 16: Steadyline Maintain Mode

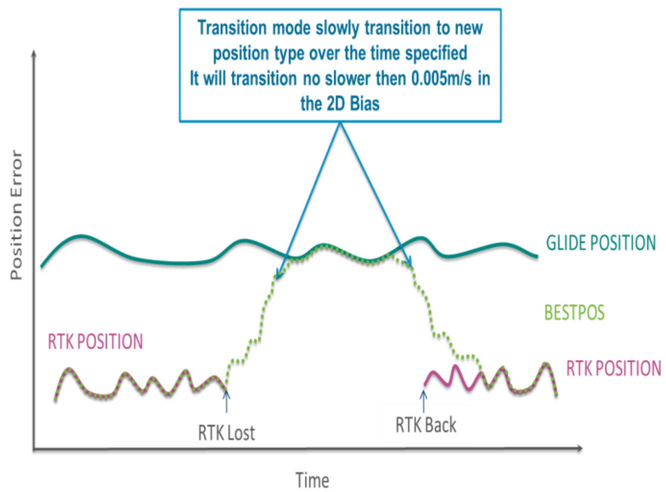

Figure 17: Steadyline Transition Mode

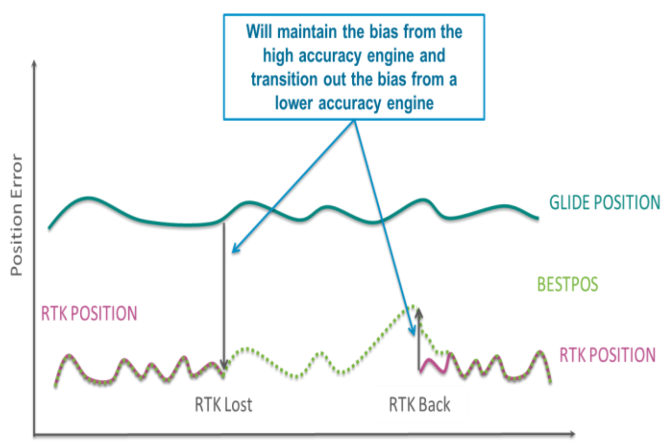

Figure 18: Steadyline Prefer Accuracy Mode

Figure 19 shows the latitude error from RTK kinematic van test data post-processed with 3 different Steadyline mode options. In all cases, the use of RTK corrections was toggled on and off every 1000 seconds (about 16-17 minutes) with a 60 second correction timeout phase whenever the corrections are removed. No other corrections are available to the receiver, so the next best position type is GLIDE L1L2 Single Point. The first post-processing method did not use Steadyline at all (Steadyline Disable). Jumps of 50-90cm occur when the RTK corrections come in and out, and the error drifts noticeably while the corrections are gone completely. The post-processing results using Steadyline in "Maintain" and "Prefer Accuracy" modes show that the instantaneous jumps are removed, and bias behavior is as described for those Steadyline modes. Note that when transitioning between the Single Point position type (less accurate) to the RTK position type (more accurate) in "Prefer Accuracy" mode, the transitions occur over 30 seconds. This transition time can be specified by the user when requesting the "Transition" or "Prefer Accuracy" Steadyline modes.

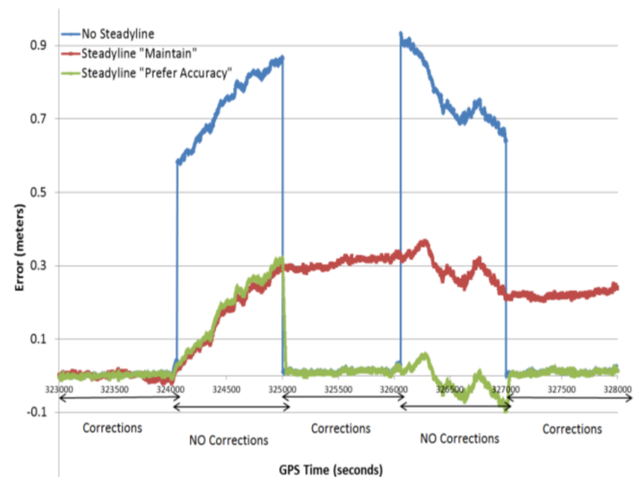

Figure 19: Steadyline Results, Latitude Error with 1000s RTK Correction Outages, no SBAS or PPP

Some positioning types, such as PPP and longer baseline RTK, have a period of convergence. The PDP performance improvement phase could also be considered to be a type of convergence. These convergence periods inherently have poor pass to pass performance, but ultimately lead to better absolute position accuracy, and hence improved pass to pass performance. Steadyline allows the user to customize the behavior in this situation:

- Transition mode will follow the convergence at the user requested rate.
- Maintain mode will hold the initial unconverged value, but will make use of the improved pass to pass performance of the underlying converged position.
- Other Steadyline modes will make use of the above transition and maintain mode behaviors.

- The user may also choose to wait until after the convergence period to enable Steadyline. In the data processing used for “Maintain” mode in Figure 15, Steadyline was not enabled until RTK had reached cm-level accuracy, so that is the error level it starts with.

NOVATEL RTK ASSIST: ACCURATE POSITIONING THROUGH RTK CORRECTION OUTAGES

SBAS, DGPS, RTK and PPP positioning modes sometimes encounter correction losses. All these corrections model slowly changing measurement errors, so when handled correctly, as in NovAtel PDP, GLIDE, RTK and PPP, position accuracy isn’t affected immediately. The use of delta phase observations allows accuracy to be maintained for a period of time. Eventually, however, the correction loss will cause a slow degradation in absolute and pass to pass position accuracy. The rate and level of the degradation will depend on the accuracy of the original position, and on the behavior of the effects being corrected.

An alternative correction source can help when the primary source is lost. NovAtel RTK ASSIST is a new feature that uses TerraStar corrections delivered via L-band to reduce the position accuracy degradation due to RTK correction outages. It allows RTK error level positions to be generated for up to 20 minutes with an RTK ASSIST subscription. RTK ASSIST will operate in either “Coast” or “Full Assist” mode, depending on where it is in its internal convergence process. “Full Assist” mode offers improved error drift performance and recoverability from complete GNSS signal outages.

Figure 20 shows a graph of typical RTK horizontal error during an RTK correction outage with and without the use of RTK ASSIST. The values are the RMS of the horizontal error divergence over 20 minutes from a test with 20 correction outage iterations. It can be seen that without RTK ASSIST, this typical error goes above 3 cm after about 3 minutes, and is over 20cm after 20 minutes. With RTK ASSIST in Full Assist mode, the error remains close to 3cm for the entire 20 minutes. The error in RTK ASSIST Coast mode grows faster than in Full Assist mode, but still provides a noticeable improvement over the uncorrected answer.

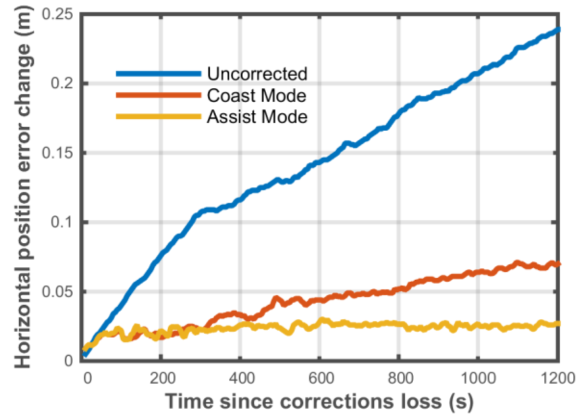

Figure 20: RTK ASSIST Performance During Correction Losses

CONCLUSION

For many end-users, low variation of position error with time can be more important than absolute RMS position error. Even when it’s not the primary performance metric, low position error variation typically has at least some importance. The NovAtel GLIDE, Steadyline and RTK ASSIST algorithms are designed to provide small error variation without discontinuities when using Single Point, DGPS, SBAS, RTK and PPP positioning modes. Results show that these algorithms can provide the user with the desired consistent and seamless position output. Challenges are posed by high absolute position error, signal and long correction outages, but much progress has been made on these challenges with work still continuing.

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[2] Banville, S., and Langley, R., “Improving Real-Time Kinematic PPP with Instantaneous Cycle-Slip Correction.” *Proceedings of the 22nd International Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2009)*, Savannah, GA, September 2009, pp 2470-2478.

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