Precise Positioning with NovAtel CORRECT Including Performance Analysis

NovAtel White Paper—April 2015

Overview

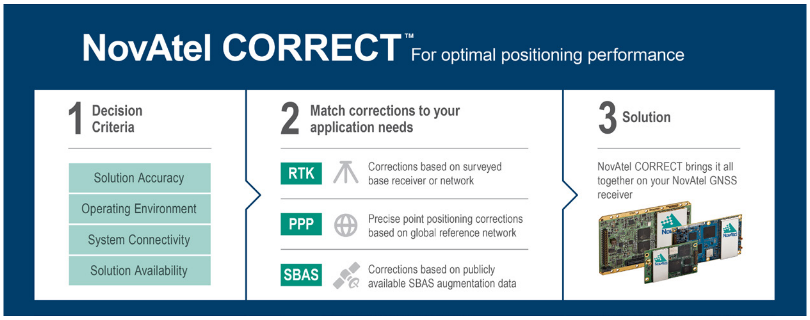
This article provides an overview of the challenges and techniques of precise GNSS positioning. It provides a description of Precise Point Positioning (PPP), as implemented in NovAtel CORRECT and compares PPP to the Real Time Kinematic (RTK) method that has been used for precise positioning for over 20 years. The relative advantages of RTK and PPP methods are summarized in terms of the implementation logistics and performance. Finally, sample performance data is presented to illustrate the typical results obtained using NovAtel CORRECT with the TerraStar service.

About NovAtel CORRECT

Choosing the best solution for your precise positioning application depends on many factors including performance, cost and implementation or setup requirements. NovAtel CORRECT is the state-of-the-art positioning algorithm on NovAtel's high precision GNSS receivers that handles corrections from a variety of sources, including RTK, PPP, Spaced Based Augmentation Systems (SBAS) and Differential Global Positioning Systems (DGPS). With NovAtel CORRECT, you can choose the corrections method that best meets the requirements and performance objectives of your application.

See more at:
www.novatel.com/solutions/novatel-correct-positioning

- **NovAtel CORRECT with RTK**: Real Time Kinematic positioning for the most precise measurements (cm level), relative to a local surveyed base station network.
- **NovAtel CORRECT with PPP**: Precise Point Positioning using data from the TerraStar correction service to deliver a globally available and reliable solution with precision approaching that of RTK (sub-dm level).
- **NovAtel CORRECT with SBAS**: Positioning utilizing publicly available SBAS augmentation data to provide sub-metre solutions.



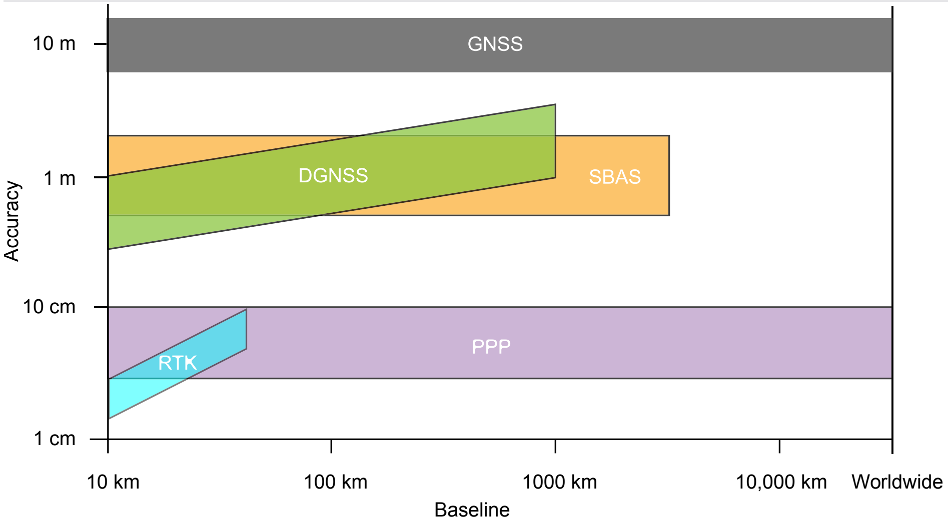
Achieving high-precision GNSS measurements

Standard civil GNSS provides a simple and ubiquitous solution for global positioning when metre-level accuracy is sufficient. Even though this is sufficient for a large number of applications, the need for high-precision positioning for certain applications has led to innovations in the way we use GNSS, and methods that provide centimetre, rather than metre-level accuracy.

The two most important examples of precise GNSS methods are RTK and PPP. As shown in Figure 1, these two methods provide significantly better accuracies compared to Differential GNSS (DGNSS) or single-point positioning when employing corrections provided by GNSS augmentation systems such asSBAS. Figure 1 also illustrates the difference in baseline limitations of each system, which constrain their use to within a certain range of base receivers or reference networks. PPP does not have any such limitations and it can be used anywhere on the Earth.

Two hurdles – precision and uncertainty

Figure 1 Comparison of GNSS Augmentation Techniques



Standalone GNSS is limited both in terms of the precision with which measurements can be made and the errors or uncertainty introduced by various physical effects. To understand these limitations, consider the challenges of making precise distance measurements using the links in a long piece of chain.

One problem is the links – they serve the purpose well as long as the precision needed is not much finer than the length of the link, otherwise the very shape and consistency of the links becomes a limitation. In the case of standalone pseudorange-based GNSS measurements, the links in the chain are the discrete steps in the chipping code that modulates the RF carrier signal. Precision is limited to about 0.2% of the chip length in the code. For L1 C/A , for example, this amounts to 2 nanoseconds, or 0.6 metres at the speed of light.

The second problem with high-precision measurements is the uncertainty in the measurement. In our chain analogy, we would have physical issues with sag in the chain, thermal expansion and other factors that would prevent us from trusting the measurement within certain limits. Similarly, GNSS signals suffer effects such as propagation delays and clock precision that lead to range measurement errors. These are described in more detail later.

Solving the precision hurdle – carrier phase measurements

The GNSS signal information is transmitted by modulating an RF carrier wave in the Gigahertz frequency range. While pseudorange measurements are based on the timing of the modulation and the information contained in it, both RTK and PPP methods measure the phase of the carrier wave itself to obtain more precise measurements. In the case of the L1 C/A signal, the carrier frequency is 1575 MHz, so one carrier cycle has a wavelength of approximately 19 cm. Modern geodetic quality GNSS receivers such as the NovAtel OEM628 can measure carrier phase with better than 1 mm accuracy. See *GNSS Measurements – Code and Carrier Phase Precision* on page 10 for more information.

The carrier phase measurements come with a catch however. The measurement does not indicate the full range to the satellite, only the length of the last fractional wave arriving at the receiver antenna. Carrier phase measurements on their own are like fine graduations on a tape measure which has no labels. We can track relative changes in range, caused by movements of the satellite and the receiver, with great precision, but determining the absolute range is a complex puzzle. The unknown part of the carrier range measurement is referred to as the carrier phase ambiguity. By analyzing multiple carrier phase measurements from multiple satellites, it is possible to determine the value for the carrier phase ambiguity that fits best with the observed measurements. The methods of determining the phase ambiguity differ in that RTK exploits the data available from two receivers to simplify the puzzle, while PPP requires a much greater number of measurements from the single receiver to gradually converge on a solution. Once the phase ambiguity is estimated with sufficient accuracy or the integer nature of it is solved, both RTK and PPP methods can estimate the position with high accuracy using carrier-phase measurements.

This leaves the limitation of uncertainty in the measurement and the need to mitigate the sources of measurement errors.

Reducing measurement uncertainty – mitigation of errors

A level of precision is only useful to the extent that the measurement can be trusted to the same level. The sources of errors in GNSS measurements include satellite position, signal propagation delays and timing accuracy in both the satellite and receiver. Typical levels of uncertainty are shown in Table 1 in metres. The errors must be mitigated to enable centimetre-level positioning using PPP or RTK.

Table 1: Source of GNSS Errors

Error Source	Error Range
Satellite clock error	±2 m
Satellite orbit error	±2.5 m
Ionospheric delays	±5 m
Tropospheric delays	±0.5 m
Receiver noise	±0.3 m
Multipath	±1 m

The mitigation of errors is different between RTK and PPP methods. This is partly due to the difference in the means of error mitigation and partly due to the difference in relative versus point positioning measurements. The following section discusses error mitigation for RTK and PPP in more detail.

Error mitigation – RTK versus PPP methods

RTK is a relative positioning method that provides the position of one receiver antenna (the "rover") relative to another receiver antenna (the "base"). If the location of the base receiver is known, an absolute position of the rover can be estimated. Most error sources are common to both the rover and base receivers, and therefore can be mitigated by differencing measurements across receivers. This reduces the magnitude of the errors significantly when the distance (baseline) between receivers is not long. The length of the baseline must typically be 40 km or less to enable RTK carrier-phase ambiguity resolution when ionospheric conditions are not extreme. Refer to Figure 2.

PPP is a point positioning method which provides an absolute position for the rover receiver based only on the GNSS measurements available at a single receiver and globally applicable correction products. Unlike RTK, using data from reference receivers and networks is not needed for PPP. Therefore, PPP can provide centimetre level positioning anywhere on the Earth. Refer to Figure 3.

When employing PPP, all significant error sources must be mitigated with the best possible accuracy using error models or error corrections products such as precise satellite orbit and clock corrections. The error sources to be mitigated when employing PPP or RTK are shown in Table 2.

Figure 2 RTK System Illustration

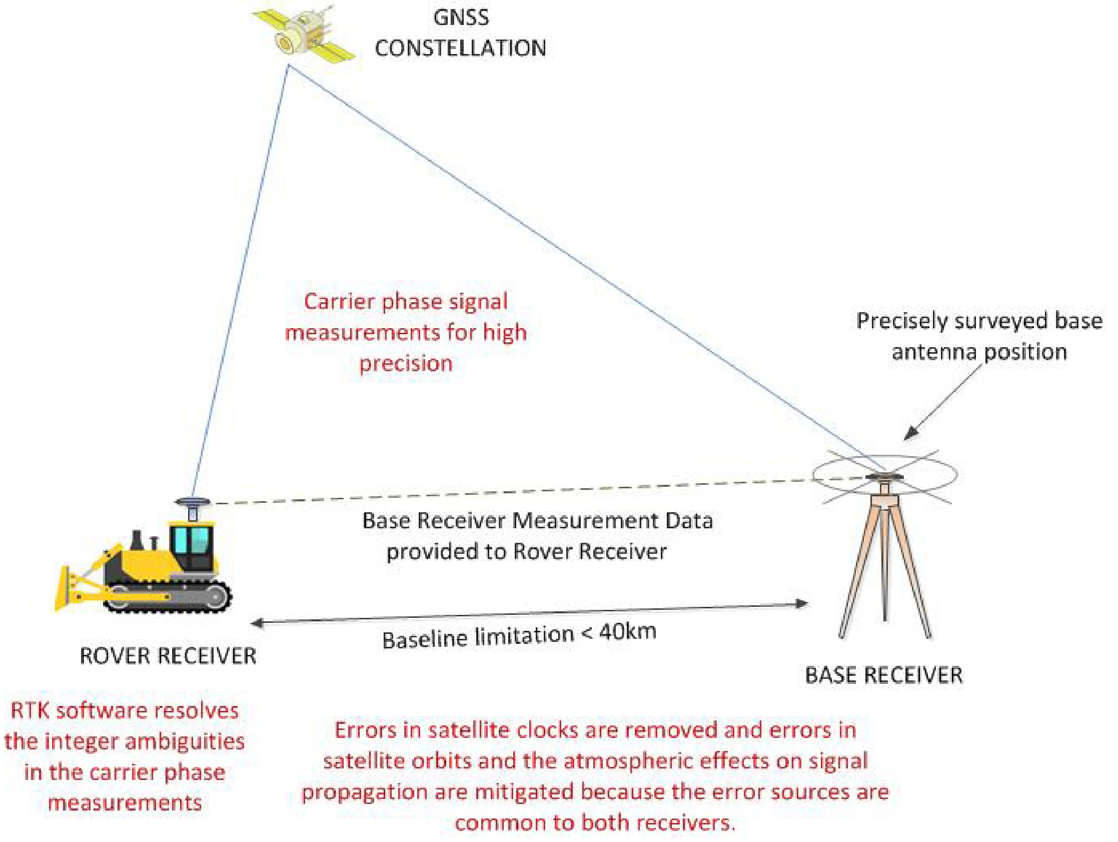


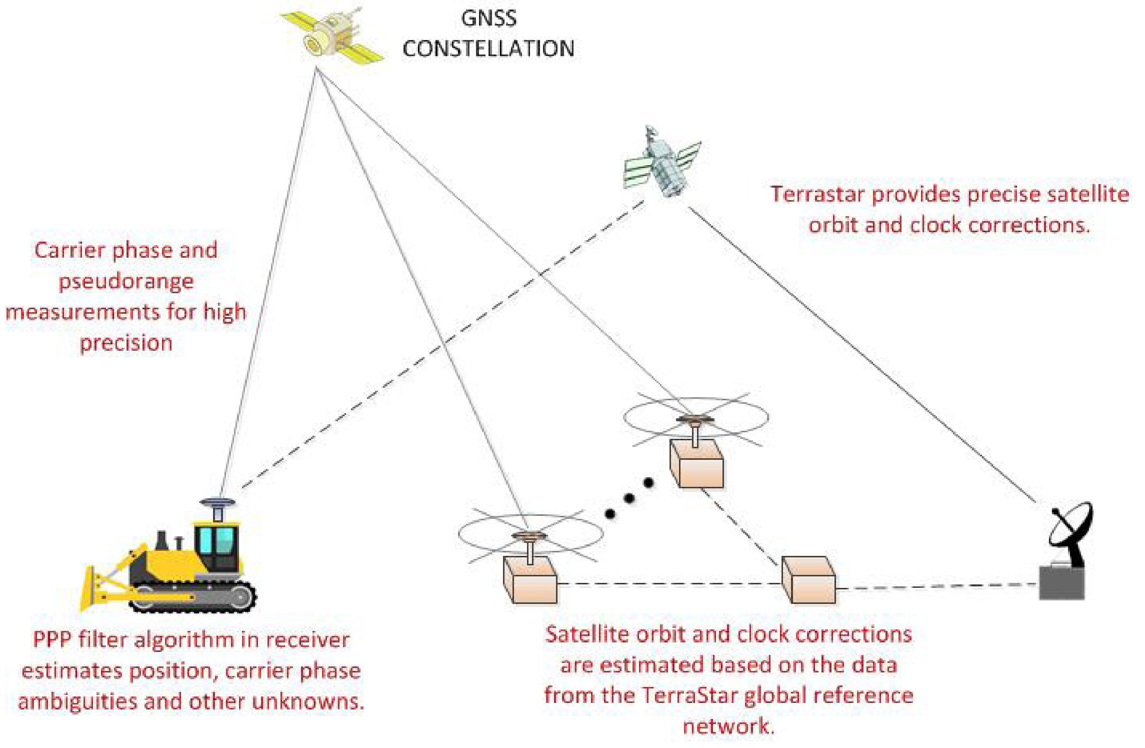
Table 2: Error Corrections and Models Required for PPP vs RTK

Correction Type	PPP	RTK
Satellite Orbit and Clock		
Precise satellite clock corrections	Required	Not required
Precise satellite orbits	Required	Not required for short baselines
Group delay differential	Required if using L1 only	Not required
Relativity term	Required	Not required
Satellite antenna phase wind-up error	Required	Not required
Receiver Specific Errors		
Receiver antenna phase wind-up	Required	Not required
Geophysical Models		
Solid earth tide displacements	Required	Not required
Atmospheric Modeling		
Tropospheric delay	Required	Not required
Ionospheric delay	Required (dual-frequency ionosphere-free measurement combination)	Required (dual-frequency measurement combinations)

The main error sources for PPP are mitigated in the following ways:

1. **Dual-frequency operation**. The first order ionospheric delay is proportional to the carrier wave frequency. Therefore, the first-order Ionospheric delay can totally be eliminated by using the combinations of dual-frequency GNSS measurements.
2. **External error correction data**. This includes satellite orbit and clock corrections. In the case of NovAtel CORRECT with PPP, the corrections generated by TerraStar are broadcast for end-users by Inmarsat telecommunication satellites.
3. **Modeling**. The tropospheric delay is corrected using the UNB model developed by the University of New Brunswick. However, the wet part of tropospheric delay is highly varying and it cannot be modeled with sufficient accuracy. Thus, residual tropospheric delay is estimated when estimating position and other unknowns. Modeling is also used in the PPP receiver to correct the solid earth tides effect (see next section "Global Versus Local Datum").
4. **PPP filter algorithms**. An Extended Kalman Filter (EKF) is used for the PPP estimation. Position, receiver clock error, tropospheric delay and carrier-phase ambiguities are estimated EKF states. EKF minimizes noise in the system and enables estimating position with centimetre-level accuracy. The estimates for the EKF states are improved with successive GNSS measurements until they converge to stable and accurate values. The typical convergence time of PPP to under 10 cm horizontal error is between 20 and 40 minutes, but it depends on the number of satellites available, satellite geometry, quality of the correction products, receiver multipath environment and atmospheric conditions.

Figure 3 PPP System Illustration



Global Versus Local Datum

Another difference between the RTK and PPP methods is the reference frame/datum of the position solution. The surface of the Earth is constantly moving because of site-displacement effects such as plate tectonics and solid earth tides. RTK provides a position relative to the coordinates of the base station, which are typically fixed to a local datum such as North American Datum of 1983 (NAD83). On the other hand, PPP provides a position relative to the global reference frame (IGS08) that is rotating with the Earth, but independent of other geophysical movements (a global datum). To provide positions consistent with the IGS08 frame, site displacement effects must be taken into account when estimating PPP position. These effects are included with the error corrections shown in Table 2.

Comparison of RTK and PPP Performance

As described in the previous sections, RTK and PPP are two GNSS positioning methods which provide centimetre-level accuracy. The primary difference between the methods is that RTK provides relative positioning with respect to a reference station and PPP provides world wide positioning using globally applicable correction data. When using RTK, the data from a reference receiver to the rover can be provided, for example, using Ultra High Frequency (UHF) radio or over NTRIP. When using PPP, satellite orbit and clock corrections can be provided to the rover receivers using telecommunication satellites (in case of TerraStar) or over NTRIP.

The table below compares RTK and PPP methods in terms of a number of performance parameters.

Table 3 - RTK and PPP Performance Criteria

Performance Parameter	RTK	PPP	Notes
Accuracy	cm	cm ~ dm	RTK baseline length can impact accuracy. Both RTK and PPP can be affected by the GNSS constellation state and local observing conditions like multipath and buildings or trees blocking visibility to satellites.
Continuity	Relies on the continuity of the reference station and communication link	Relies on the continuity of the PPP correction generation service and telecommunication satellite link	PPP depends on the continuity of the PPP correction generation service, which is generally assured by the service provider (TerraStar). RTK continuity depends on the reference station availability and the communication link reliability, which vary depending on the setup or service used.
Integrity	Receiver side integrity monitoring and common errors between the rover and reference receivers may cancel out	Receiver side integrity monitoring. In addition, use of a global network of monitoring stations adds integrity	The global monitoring network used for PPP increases the integrity compared to stand-alone GNSS. When employing RTK, the impact of integrity issues common to the rover and reference receivers can often be mitigated.
Reliability	Determined by the reliability of the rover receiver, base receiver and communication link	Determined by the reliability of the user receiver and correction service	PPP is not vulnerable to the problems caused by the reference receiver or telecommunication link between receivers.
Initialization Period	Determined by setup time	Determined by convergence time	PPP may have shorter setup times because it does not require a connection with a reference receiver. However, PPP has a convergence period of approximately 30 minutes each time the system is started. RTK initializes almost immediately and also recovers from system outages much faster.
Solution Availability	Performance is dependant on the distance from the base receiver to the rover receiver (baseline). A long baseline impacts accuracy and initialization.	Same performance achieved anywhere on Earth.	Both PPP and RTK can be affected by local observing conditions.

The Right Solution for the Application

The choice between PPP and RTK is a trade-off between the operational simplicity and global availability of PPP and the accuracy and fast initialization of RTK.

Accuracy

When the application requires the best possible accuracy and the setup requirements can be met, RTK remains the best choice. The accuracy of PPP is continuing to improve and the accuracy difference between PPP and RTK is narrowing. Therefore, more applications that were once only addressable by RTK are becoming candidates for PPP.

Initialization Time

The initial convergence time of PPP refers to the time required to obtain accuracy that is sufficient for the application. Depending on the number of available satellites, satellite geometry, atmospheric conditions, receiver multipath environment and quality of the PPP correction products, it takes typically between 20 and 40 minutes to obtain smaller than 10 cm horizontal error. By comparison, RTK initialization and recovery from signal outages is almost instantaneous.

The initialization time difference between PPP and RTK may or may not have a large impact, depending on the application and work flow.

Availability of Base Receiver

RTK relies on the availability of a base receiver within a 40 km range in typical atmospheric conditions. Local observing conditions may cause more sensitivity to baseline length. This limits the availability in cases where a base receiver is not available or it is difficult to access, or where the rover receiver needs to cover large distances. Offshore work, remote environments and aerial mapping are examples where this is typically a problem. RTK baselines can extend to 100 km, but in this case both accuracy and initialization time will be compromised.

Operational Complexity

Even when the use of a reference receiver is practical, handling the communication between the reference and rover receivers and possible outages and security of the reference receiver complicates using RTK from the user perceptive. On the other hand, when employing PPP using TerraStar corrections, a user needs only an L-Band capable GNSS receiver and antenna, which makes things simpler and more reliable compared to employing RTK. In addition, subscribing and setting up TerraStar service is easy from the end user perspective.

The following section provides some characterization and comparisons of NovAtel CORRECT with PPP with emphasis on convergence time and final accuracy.

NovAtel CORRECT with PPP Performance

NovAtel has partnered with TerraStar to offer NovAtel CORRECT with PPP, a complete solution that includes a NovAtel OEM6® receiver and TerraStar correction data services.

This section provides a variety of test results that characterize NovAtel CORRECT performance using the TerraStar-C service. All the tests, even static ones, are processed in the PPP dynamic mode, where large position process noise is assumed. The test results presented in the following pages deal with the following aspects of performance:

A) Typical convergence time for NovAtel CORRECT with PPP, in static conditions

B) Typical re-convergence time for NovAtel CORRECT with PPP, in static conditions

C) Comparison of single constellation (GPS) versus dual constellation (GPS+GLONASS) performance

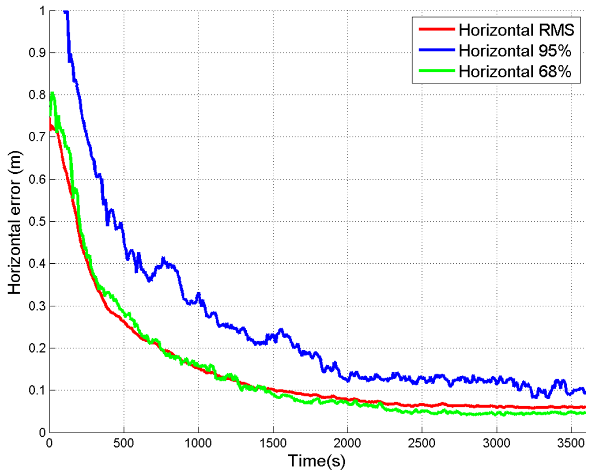
D) Performance variability with geographic region

E) Comparison with OmniStar in static and dynamic conditions

A - Convergence Time in Static Conditions

This plot shows typical convergence time for NovAtel CORRECT with PPP, under static (stationary antenna) conditions. As shown, the solution typically converges to within 20 cm Root Mean Square (RMS) error within 12 minutes and 10 cm RMS error within 25 minutes. The RMS error result is plotted as well as the 68th percentile and 95th percentile results to provide an indication of variability in the performance. Variability in the convergence time in this case is primarily due to the changing GNSS constellations.

Figure 4 NovAtel CORRECT with PPP, GPS+GLONASS

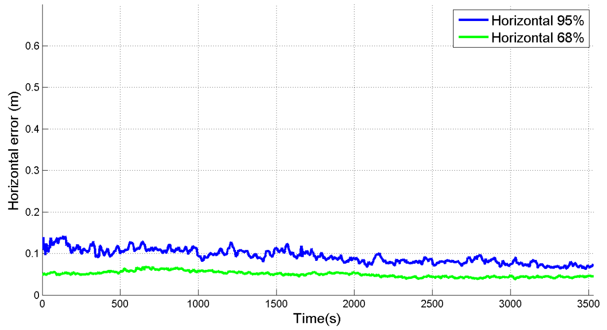


Location: Hyderabad, India (medium Ionospheric activity region)
Data collection: 3 day duration, with solution reset every hour

B – Re-Convergence Time in Static Conditions

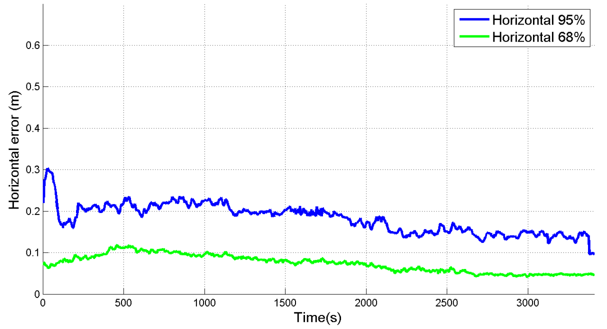
These results show the typical re-convergence time of NovAtel CORRECT with PPP. Data recorded at exactly the same time as in Section A is used to test the re-convergence performance in the case of 60 and 180 second signal outages. Signal outages occurred every hour in these tests and data was accumulated for 3 days.

Figure 5 Re-convergence after 60 second signal outage



In the case of the 60 second outages, the solution recovers to a sub-decimetre accuracy almost instantly (68% line). Figure 6 shows that an outage of longer duration, in this case 3 minutes, impacts how quickly the solution can recover. Even in this case, the solution accuracy stays below 10 cm for almost the entire 3 day test.

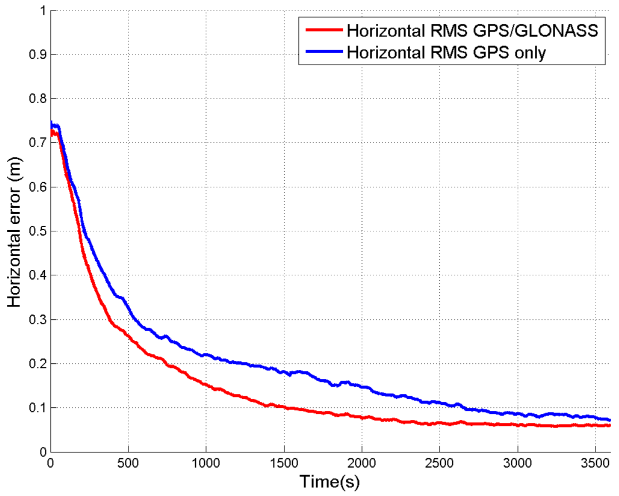
Figure 6 Re-convergence after 180 second signal outage



C – Advantage of Using Two Constellations

Convergence time is a function of the number of observables available to the PPP receiver, so for most applications the use of two constellations (GPS and GLONASS) is recommended. The greater number of simultaneously available satellites in a multi-constellation solution also makes for improved geometries and a more constrained position estimate. Dual constellation is the standard configuration for test results presented in this report. Figure 7 illustrates the degradation in convergence time for a GPS-only configuration compared to GPS+GLONASS.

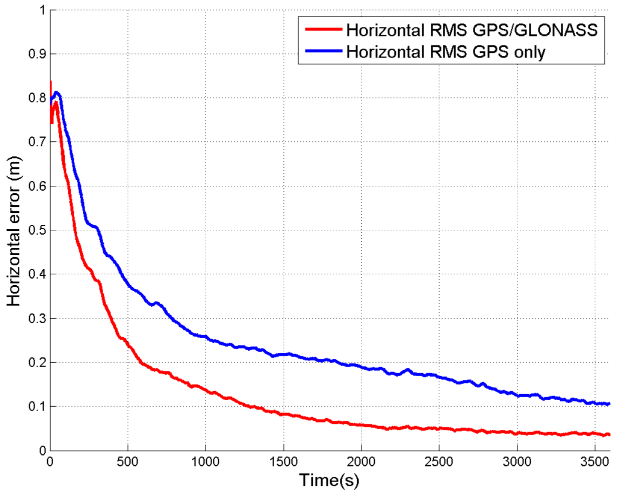
Figure 7 Convergence time (India) – GPS vs GPS+GLONASS



Data collection: 3 day duration, with solution reset every hour

The advantage of dual constellations is even greater in northern latitudes, as shown the following plot.

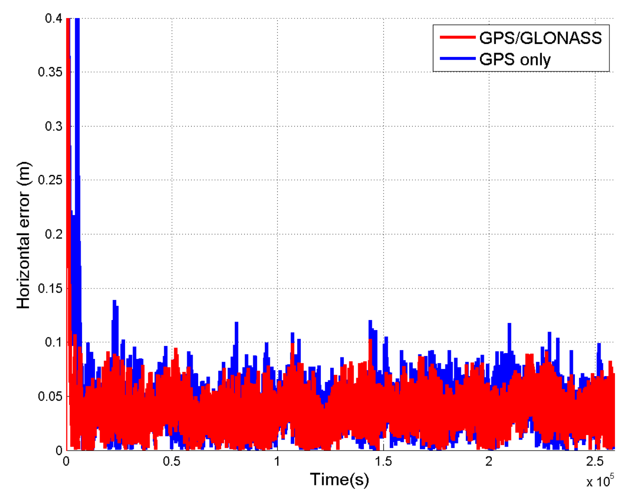
Figure 8 Convergence time (Canada) – GPS vs GPS+GLONASS



Location: Calgary, Canada (benign Ionospheric activity region)
Data collection: 3 day duration, with solution reset every hour

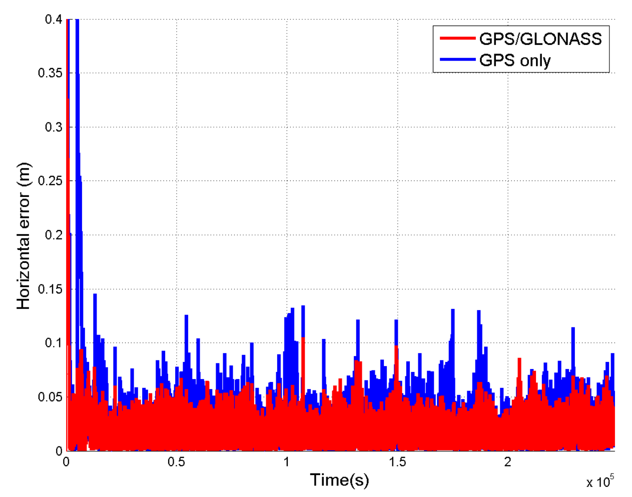
Accuracy is also higher for a dual constellation receiver compared to GPS-only. The following plots compare the long term accuracy of the GPS-only and GPS+GLONASS configurations for static conditions. Error statistics based on the same dataset are shown in Table 4 and Table 5.

Figure 9 Accuracy (India) – GPS vs GPS+GLONASS



Location: Hyderabad, India (medium Ionospheric activity region)
Data collection: 3 day duration with no solution resets

Figure 10 Accuracy (Canada) – GPS vs GPS+GLONASS



Location: Calgary, Canada (benign Ionospheric activity region)
Data collection: 3 day duration with no solution resets

Table 4: Error Statistics at the India Station

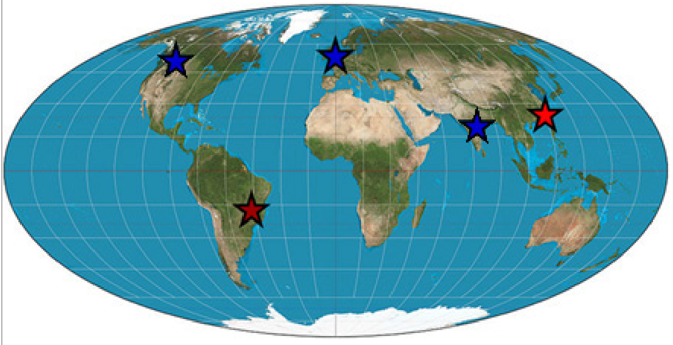
PPP Correction Source	Horizontal RMS Error (cm)	Vertical RMS Error (cm)
TerraStar-C (GPS/GLONASS)	5.3	7.6
TerraStar-C (GPS only)	6.4	9.7

Table 5: Error Statistics at the Canada Station

PPP Correction Source	Horizontal RMS Error (cm)	Vertical RMS Error (cm)
TerraStar-C (GPS/GLONASS)	3.3	4.9
TerraStar-C (GPS only)	4.4	6.5

D – Variability with geographic region

Figure 11 NovAtel Test Sites

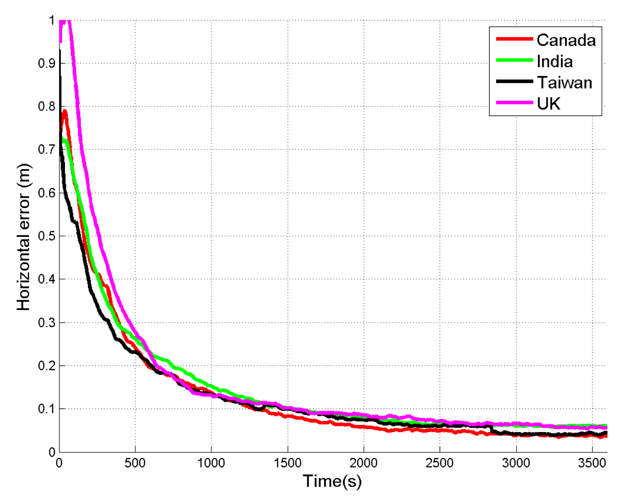


NovAtel test sites in:

- Calgary, Canada
- Brazil
- UK
- India
- Taiwan

Convergence times vary with geographic region due to different levels of ionospheric activity and other regional differences and local multipath conditions. The plot below shows average convergence times for four different global NovAtel test sites. This plot shows horizontal RMS convergence curves for a three-day collection period.

Figure 12 Convergence Time in Different Regions



NovAtel CORRECT with TerraStar-C
Data collection: 3 days duration, with solution reset every hour

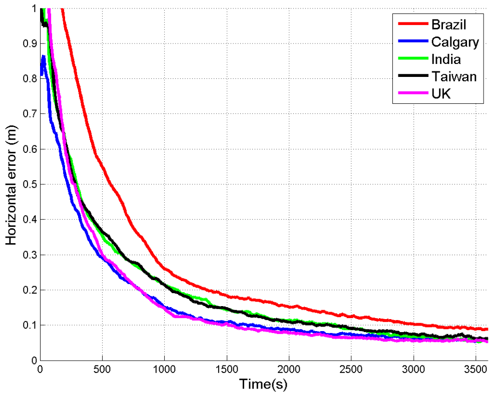
Table 6: Convergence Time by Geographical Region

Region	Convergence Time to 10 cm RMS Error
Calgary	22 minutes
India	25 minutes
Taiwan	24 minutes
UK	26 minutes

Areas with higher ionospheric activity level will show a high variability in accuracy and convergence time depending on the local state of the ionosphere.

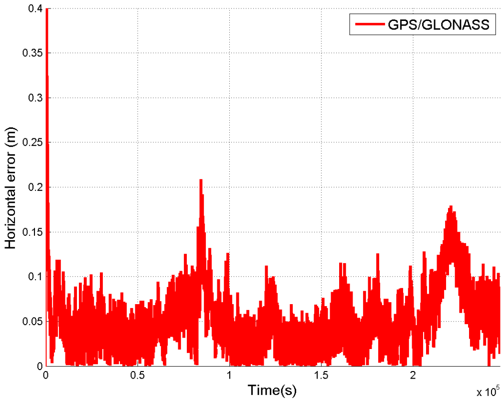
Data collected in tests from 2014 show how ionosphere activity affects convergence performance in Brazil. Ionospheric scintillation causes the receiver to lose tracking particularly of the P2 signal, resulting in a smaller number of available observations and longer convergence time. For example, when analyzing carrier-phase lock times at the Brazil station for a different test period, there are two problematic two hour time periods where the number of cycle-slips are large.

Figure 13 Convergence Time in Different Regions



When examining continuous data from the Brazil station at the same time as the convergence test, it can be seen that, while atmospheric scintillation does impact convergence times, the impact on maintaining a sub-decimetre solution is not significant. The continuous performance is shown in the figure below.

Figure 14 Scintillation Impact on Error in Brazil



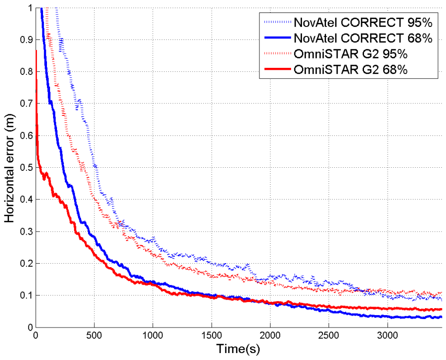
E – Comparison with OmniStar G2 performance

This section compares the performance of NovAtel CORRECT with PPP using TerraStar-C correction data to a similar NovAtel receiver operating with the OmniStar G2 correction service under various test conditions. Both TerraStar and OmniStar tests were performed on NovAtel OEM6 receivers. The OmniStar library version 6.29 was used for all tests. The tests in this section show that although the OmniStar solution initially converges faster, the NovAtel CORRECT solution actually performs much better in kinematic applications, averages to a better final accuracy and re-converges much faster and more consistently.

Initial Convergence

The following plot compares the initial convergence performance of NovAtel CORRECT with PPP to OmniStar. Though the OmniStar solution converges faster to 20 cm, both solutions take the same time to reach 10 cm and the TerraStar solution reaches a better final accuracy.

Figure 15 Convergence – NovAtel CORRECT vs OmniStar

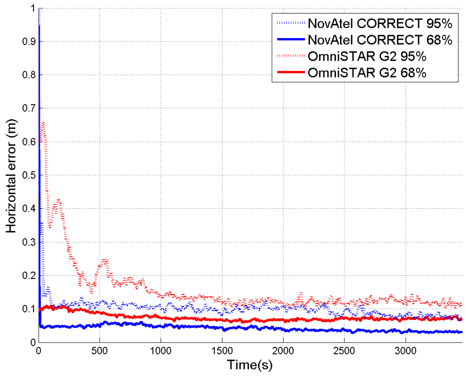


NovAtel CORRECT with TerraStar-C
OmniStar G2
Location: Calgary, Canada (benign Ionospheric conditions)
Data collection: 8 days duration, with solution reset every hour

Re-Convergence

The plot below compares the re-convergence performance of NovAtel CORRECT with PPP and OmniStar after a 30 second signal outage. This test is similar to Section B but with a 30 second outage and the addition of the OmniStar comparison. Looking at the 95% line, the TerraStar solution recovers much faster from the outage and recovers back to a better accuracy than the OmniStar G2 solution.

Figure 16 Re-Convergence – NovAtel CORRECT vs OmniStar



NovAtel CORRECT with TerraStar-C
OmniStar G2
Location: Calgary, Canada (Benign Ionospheric conditions)
Data collection: 3 days duration, with a 30 second outage every hour

Kinematic Performance - Calgary

The following plots compare the performance under dynamic conditions of NovAtel CORRECT with PPP and OmniStar when the ionospheric conditions are benign. Tests were conducted in both open sky conditions and more challenging observing conditions. The plots below show a test case that illustrates performance under dynamic conditions, including the initial convergence time. The top plot shows the vehicle velocity. The convergence time and accuracy achieved in the dynamic test is similar to the static results. Users can expect similar performance in dynamic and static environments, with the primary effect on performance being atmospheric, constellation and observing conditions.

Figure 17 Vehicle Velocity – Calgary

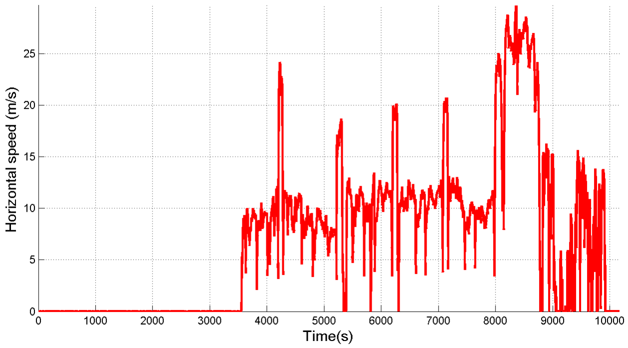


Figure 18 Horizontal Position Error – Calgary

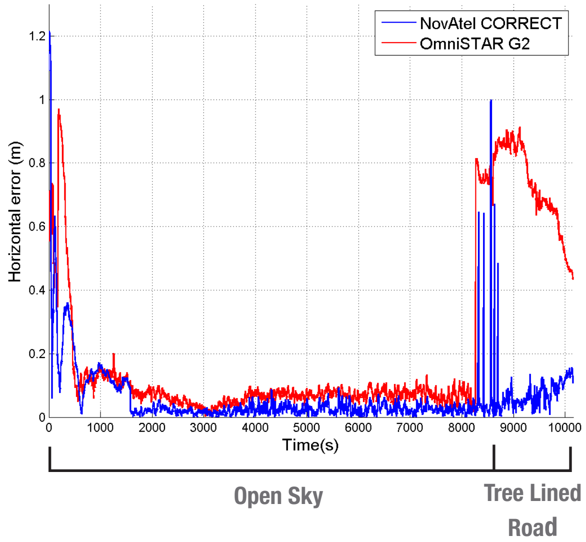


Figure 18 shows how consistently NovAtel CORRECT with TerraStar behaves in both open sky and the more difficult observing conditions of the tree lined road.

Kinematic Performance - Brazil

The following plots compare the performance under dynamic conditions of NovAtel CORRECT with PPP and OmniStar when the ionospheric conditions are high. Tests were conducted in both open sky conditions and more challenging observing conditions.

Note the route taken was primarily open sky with turns at the tree line, indicated by the corresponding spikes (refer to Figures 19 and 20 where the turns correspond to the vehicle velocity dropping to zero).

Figure 19 Vehicle Velocity – Brazil

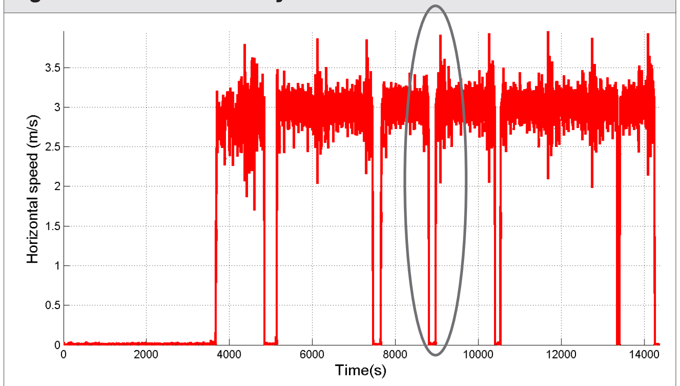


Figure 20 Horizontal Position Error – Brazil

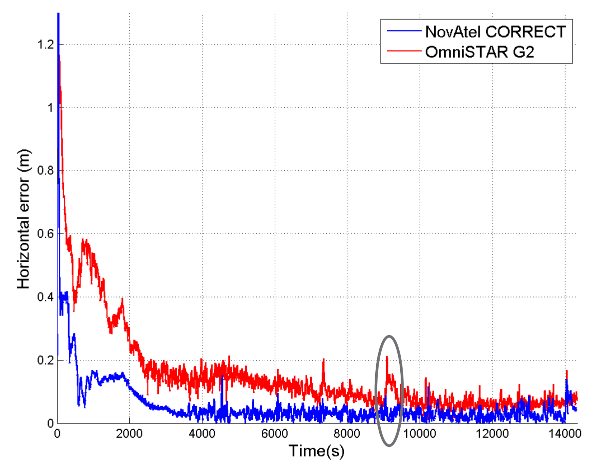


Figure 21 Making a Turn at the Tree Line

Convergence times, re-convergence and final accuracy are influenced by both the correction data from the service provider and the filter algorithm in the receiver. The best strategy for optimizing a PPP solution is to develop and test these constituent parts together. The NovAtel and TerraStar teams will continue to work together to deliver system improvements to both the correction data and receiver algorithms in order to optimize the combined solution.

Summary Conclusions

Innovations in GNSS technology have led to several orders of magnitude improvement in measurement precision and accuracy. Carrier phase observations provide the precision needed to estimate position with centimetre-level accuracy. The RTK and PPP methods apply different techniques to determine the phase ambiguity term and mitigate errors to support similar accuracy levels.

Today, RTK and PPP offer complimentary solutions for users of precise GNSS positioning. RTK offers higher accuracy and quick initialization at the expense of more operational complexity and constraints and higher costs, while PPP offers a turnkey, global solution that is easier to implement, but with somewhat lower accuracy and longer initial convergence time.

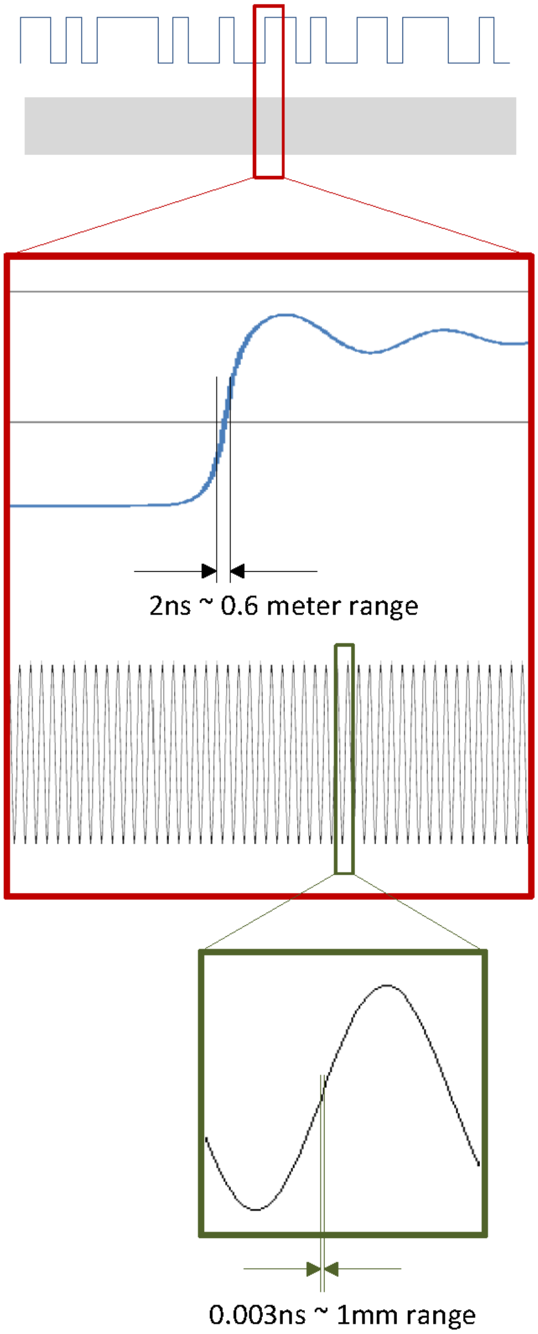
NovAtel CORRECT with RTK offers the most accurate relative positioning solution, with fast initialization time for applications suited to the use of a base/rover receiver pair.

NovAtel CORRECT with PPP provides a competitive answer for applications that are suited to the PPP approach and the benefits of a turnkey, global point positioning solution. NovAtel and TerraStar will continue to evolve the correction data service and receiver algorithms so that our customers can expect the best possible performance from their PPP-based applications.

For more information about NovAtel CORRECT with PPP, refer to the following sources:

- *Advanced GNSS Positioning Solutions with Precise Point Positioning (PPP)* (Velocity Magazine 2014) www.novatel.com/technology-in-action/velocity/velocity-2014/advanced-gnss-positioning-solutions-with-precise-point-positioning-ppp
- *Kinematic Performance of NovAtel CORRECT with TerraStar-D Precise Point Positioning (PPP) Service* (ION September 2014) http://www.novatel.com/assets/Documents/Papers/Kinematic-Performance-of-NovAtel-CORRECT-with-TerraStar-D-Precise-Point-Positioning-PPP-Service.pdf

GNSS Measurements – Code and Carrier Phase Precision

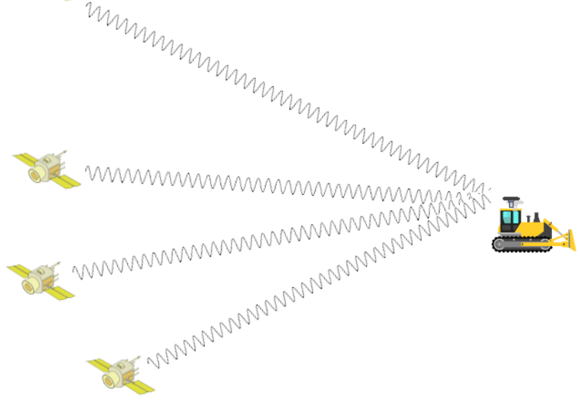


Phase modulation of carrier wave using Pseudorandom Noise (PRN) code is used to differentiate satellite signals and to provide signal timing information for range measurements.

Measurements based on the PRN modulation are unambiguous, but precision is limited to submetre.

The carrier wave for the GNSS signal is a sine wave with a period of less than one metre (19 cm for L1), allowing for more precise measurements.

Measurements of the phase of the carrier wave can be made to millimetre precision, but the measurement is ambiguous because the total number of cycles between satellite and receiver is unknown.



Resolving or estimating the carrier phase ambiguities is the key to achieving precise positioning with RTK or PPP. The two methods use different techniques to achieve this but both make use of:

- Pseudorange (code-based) position estimates.
- Mitigation of positioning errors, either by using relative positioning or correction data.
- Multiple satellite signal observations to find the ambiguity terms that fit best with the measurement data.