TRIMBLE
HD-GNSS PROCESSING

WHITE PAPER

TRIMBLE SURVEY DIVISION

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ABSTRACT

GNSS carrier-phase processing has improved significantly since the development of the first algorithms for precision satellite surveying. In keeping with these ongoing advancements, Trimble’s new HD-GNSS processing engine provides markedly reduced convergence times as well as high position and precision reliability when compared to earlier processing engines, especially in poor GNSS environments. As an added benefit, the Trimble HD-GNSS processing engine requires far less data filtering and fewer user controls for post-processing. This paper describes the advantages of Trimble's HD-GNSS processing engine. It also describes the practical applications for real-time surveying in the field and post-processed surveying in the office.

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INTRODUCTION

Global Navigation Satellite System (GNSS) surveying is highly productive for many applications. Unlike classical surveying methods, a GNSS rover is not limited by line-of-sight to an optical sensor. With the expansion of permanent GNSS control networks, it is becoming increasingly rare that a surveyor needs to establish a field reference station at all. However, the use of GNSS for precise positioning has previously been limited to areas of good sky visibility. Using GNSS near trees or in dense urban areas was very difficult and sometimes not possible at all. This caused surveyors to revert to optical methods in environments where line-of-sight is especially restricted.

The technology for tracking and processing GNSS signals has significantly improved in recent years. In addition, the number of available satellites and signals has grown, and continues to grow, with the introduction of new and modernized satellite constellations. Currently, there are three GNSS constellations that are fully operational (GPS, GLONASS, and QZSS) and two that are being actively deployed (COMPASS and Galileo). As a result, it is now possible for surveyors to expand the reach of their GNSS rovers into areas that were previously too obscured. This paper focuses on improvements to the GNSS processing engine, a software component that calculates the precise position of a GNSS rover based on carrier phase observations.

Trimble’s Real-time Kinematic (RTK) and post-processed systems now use the latest and most advanced processing engine: Trimble HD-GNSS. Compared to older processing engines, Trimble HD-GNSS:

- Produces more reliable positions in poor GNSS areas
- Reduces the time required to converge on a solution
- Improves the consistency of precision reporting

For real-time applications, users experience reduced GNSS survey startup times and improved reliability of displayed RTK precisions. For post-processed applications, users experience faster processing with a simplified workflow that typically does not require raw GNSS data filtering before processing.

GNSS PROCESSING THEORY

Positioning a GNSS receiver with centimeter-level precision using signals broadcasted from satellites that are orbiting approximately 20,000 kilometers above the Earth at 14,000 kilometers per hour is quite a formidable task. But the basic theory can be easily understood. If we know where the satellites are, and we can measure how far the receiver is from each satellite, we can calculate the receiver’s location by trilateration (Figure 1).

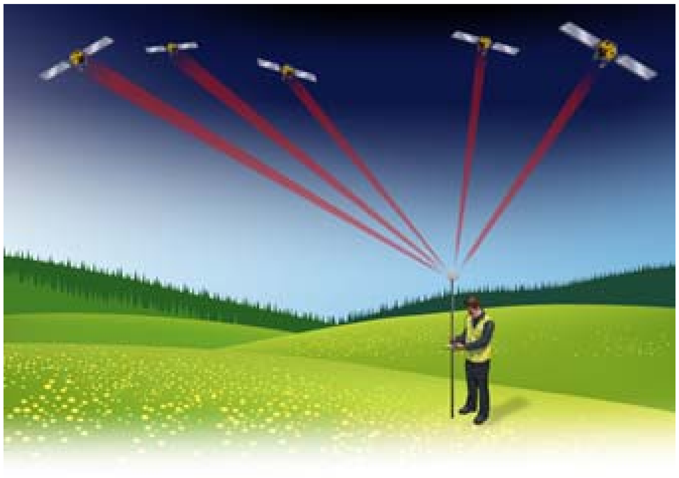


Figure 1. Trilateration of satellite ranges to estimate an autonomous receiver's position

Each GNSS satellite broadcasts its location to a receiver in the form of ephemerides that describe the orbit and atomic clock offset for the satellite. Ranges from the receiver to various satellites can be measured using broadcast Pseudorandom Noise (PRN) code signals. However, because of the atmospheric effects on signal propagation and the low accuracy of broadcast satellite ephemerides, the position of a single autonomous receiver can be estimated only to roughly 1 to 5 meters. To overcome these fundamental error sources and achieve centimeter-level positioning, an autonomous GNSS receiver would need to connect to an additional source to receive very precise satellite positions and clock offsets, as well as accurate models for all atmospheric effects. When using broadcast ephemerides, a surveyor achieves precise positioning using a combination of a rover receiver and a reference GNSS station or Virtual Reference Station (VRS) network.

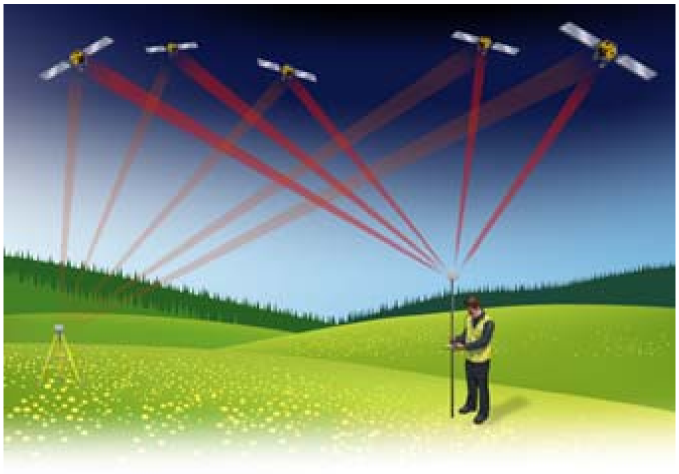


Figure 2. Precise rover positioning with a reference station

A differential GNSS processing engine uses the combined data from a rover and reference receiver to reduce the effects of orbit and atmospheric errors, as these errors are nearly identical at both receivers (Figure 2). The processing engine uses the carrier phase of each satellite signal to measure the range from the rover to the satellite with millimeter precision. This is possible because the carrier phase has a much smaller wavelength than the PRN code signal. The PRN signal has an effective wavelength given by the code bit length. For the Global Positioning System (GPS) coarse acquisition (C/A) code, this is 300 meters. The carrier wavelength on the GPS L1 frequency is just 19 centimeters. So like a measuring tape with a finer graduation, carrier phase can be used more precisely to measure the range to a satellite.

For this discussion, the carrier phase signal can be considered as a simple sine wave as shown in Figure 3. The carrier phase measurement is the difference in the phase of the received signal and the phase of an equivalent signal generated from the receiver's oscillator or clock. The phase of the receiver's clock, which starts at zero when powered-up, is arbitrary relative to the satellite's clock. For the first measurement after acquiring the satellite signal, only the fractional part of the phase can be measured. The actual range between the satellite and rover antenna is the sum of this fraction and an unknown number of whole wavelengths. The unknown number of wavelengths is called the "integer ambiguity." To precisely measure range, the processing engine must resolve this ambiguity.

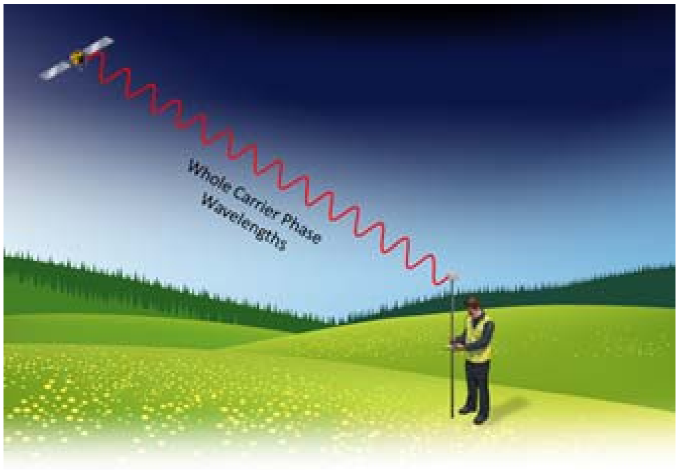


Figure 3. Integer ambiguity is the unknown number of whole carrier phase wavelengths between the rover and each satellite

Traditional GNSS processing engines used the combination of reference and rover data to attempt to "fix" the number of whole wavelengths between the rover and satellites. The process normally occurred in two distinct steps in the processing engine:

1. A "float" solution was generated using both the PRN code and carrier phase observables.
2. A search was performed to resolve the integer ambiguities.

A successful search process yielded a solution that was “fixed”.

The precisions for float solutions were primarily influenced by the PRN code noise, so the solutions were quite poor. Typical float precisions were several decimeters and were of limited value for most survey applications. The float solution was often maintained for a considerable amount of time when working in a difficult environment or with a long baseline, and was followed by an instantaneous switch to a fixed solution. Hence, the convergence from float to fixed was highly polarized.

There were a number of disadvantages to the float/fixed approach for integer ambiguity resolution. For one thing, the user was unable to extract usable positions until the receiver had converged on a fixed solution. Also, there was the possibility of an incorrect solution where the processing engine selected the wrong set of integer ambiguities. In this event, the correct integer set was discarded and could not be selected until the search was repeated. For RTK, this resulted in a position outlier being reported with unrealistically good precisions for many seconds until detected by an automated integrity check.

These various conditions are depicted in Figure 4, where the precisions are given by the magnitude of the ellipses.

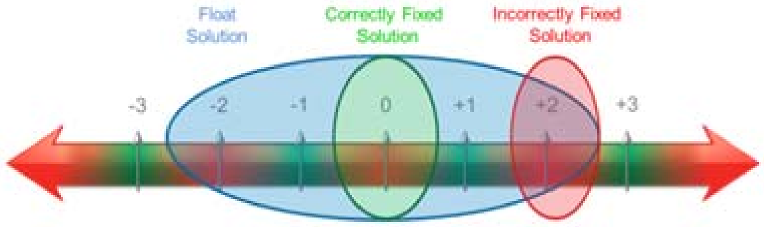


Figure 4. In poor GNSS environments, a legacy GNSS processor was susceptible to imprecise float solutions and incorrectly fixed solutions for integer ambiguity

Trimble HD-GNSS provides a breakthrough in ambiguity resolution technology that is made possible by a number of factors:

- There have been numerous improvements in GNSS receiver hardware since these first processing algorithms were developed. Most notably, the receivers have evolved along with the increase in satellite and signal availability. The original survey-grade GPS receivers could only track two carrier signals: GPS L1 and L2. Trimble’s latest R10 receiver, with its 440-channel capacity, is capable of tracking the 16 GNSS carriers listed in Table 1.

Table 1. Trimble R10 tracking capabilities

GNSS System	Carrier Signal	Frequency (MHz)
GPS	L1	1575.42
	L2	1227.60
	L5	1176.45
GLONASS	L1	1602 + 0.5625*N
	L2	1246 + 0.4375*N
Galileo	E1	1575.42
	E5	1191.795
	E5a	1176.45
	E5b	1207.14
QZSS	L1	1575.42
	L2	1227.60
	L5	1176.45
	LEX	1278.75
Compass	B1	1561.098
	B2	1207.14
	B3	1268.52

- Modern GNSS antennas and receivers are far better at mitigating multi-path signals. Once digitally sampled, the multipath errors are further reduced via proprietary software processing techniques.
- The availability of enhanced computing power has facilitated the use of more sophisticated GNSS signal tracking algorithms and RTK processing techniques. The R10 GNSS receiver is based around the state-of-the-art Trimble Maxwell-6 custom integrated circuit technology for GNSS signal processing. RTK calculations are performed in the R10, with a micro-processor that is orders of magnitude more powerful and energy efficient than its predecessors. For GNSS data post-processing, the average desktop computer typically includes a high-powered multi-core micro-processor.

All of these improvements have led to the development of a much more robust GNSS processing methodology.

To take full advantage of today’s many GNSS constellations and Trimble’s Maxwell technology, both the Trimble R10 receiver and Trimble Business Center (TBC) office software now incorporate Trimble’s HD-GNSS processing engine. Trimble HD-GNSS technology provides a new approach to resolving integer ambiguities that differs from traditional fixed/float solutions.

Ambiguity resolution now occurs as a rapid convergence to a precise solution with more realistic precisions being reported. The discontinuity that occurred from the float/fix transition is gone. Therefore users no longer need to concern themselves with “fixed” and “float” solutions, but can focus instead on the desired solution precision. The convergence of the position solution is very rapid under normal tracking conditions. It is apparent only on longer baselines or in difficult environments, such as near a tree canopy. But even in these challenging environments, good solutions are typically available during convergence, unlike traditional float solutions. Trimble HD-GNSS is also much less susceptible to unpredictable behavior in the presence of measurement biases such as multipath, which will now simply degrade precisions as expected.

With multi-frequency data from at least five common satellites at the reference and rover, the Trimble HD-GNSS processing engine can solve for integer ambiguities. Subsequent RTK point occupations allow storage with centimeter-level precisions with only two epochs of data. To account for new satellites and temporary losses of signal tracking, the processing engine resolves integer ambiguity as a continuous process. In difficult GNSS environments, traditional processing engines would invariably drop to a float solution and produce unacceptable positions. In comparison, Trimble HD-GNSS continuously provides the best possible positions with reliable precision estimates that are commensurate with the environment and satellite visibility. This significantly increases the availability of useable positions in challenging environments.

Figure 5 displays position error over time for Trimble HD-GNSS solutions as compared to traditional float and fixed solutions. In legacy processing, the switch from float to fixed occurred after a period of float convergence but while the float solution errors were still large. The Trimble HD-GNSS solution converges very quickly, and will typically reach fixed-level precisions several seconds before the legacy engine. The figure also shows that the legacy method was susceptible to producing incorrectly fixed solutions with high position error. When this occurred, acceptable precisions were falsely reported to the user. By contrast, the Trimble HD-GNSS processing engine reports more reliable precision values throughout the convergence process.

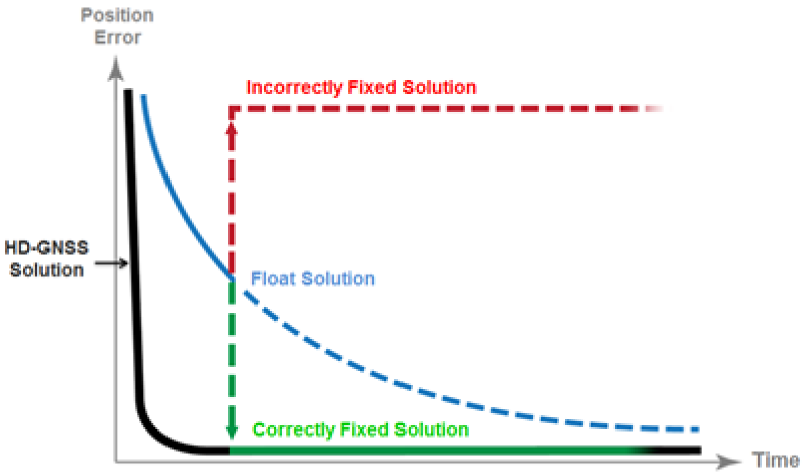


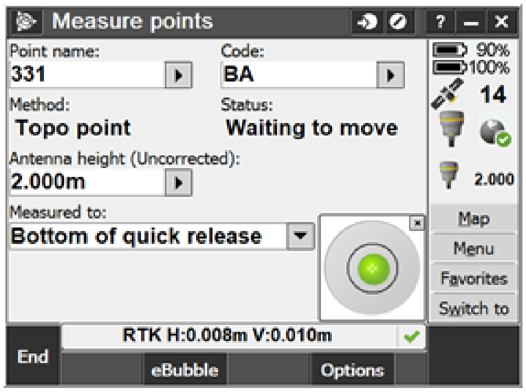
Figure 5. The Trimble HD-GNSS processing engine rapidly resolves integer ambiguities to produce fixed-level precisions

REAL-TIME APPLICATION

Trimble HD-GNSS processing is available for real-time GNSS surveying with the Trimble R10 receiver (Figure 6) and Trimble Access™ field software. Users will first notice that RTK surveys initialize very quickly. Legacy RTK systems used the term “initialization” to describe the transition from float to fixed in the traditional sense. “Initialization” is now defined more generally as the process of starting an RTK survey by connecting to the reference data stream or VRS server, followed by the rapid convergence to a centimeter-level precision solution.

Figure 6. Trimble R10 receiver with the Trimble HD-GNSS processing engine

With the adoption of the new Trimble HD-GNSS processing engine in the receiver, the display in Trimble Access field software no longer shows the terms “fixed” or “float” when surveying with a Trimble R10. As shown in Figure 7, the more generic term “RTK” is displayed at the start of the rapid convergence process as soon as reliable precisions are available. In a benign environment, centimeter-level precisions often occur in a matter of seconds after starting a GNSS survey, meeting the typical thresholds set for survey point measurement.



Point name: 331
Code: BA
Method: Topo point
Status: Waiting to move
Antenna height (Uncorrected): 2.000m
Measured to: Bottom of quick release
RTK H:0.008m V:0.010m

Figure 7. Trimble Access displays “RTK” when the Trimble R10 is initialized (Note the Trimble Access eBubble, which shows the instrument is plumb.)

Once the Trimble R10 is initialized, it is capable of capturing on-demand measurements with the displayed level of precision. This makes it possible to operate the system in a poor GNSS environment, such as a dense urban area where many satellites are obscured. While the most precise results are achieved in open areas, the user can continue measuring with confidence in obscured areas so long as the precisions displayed are acceptable for the given application. As shown in Figure 7, Trimble Access displays a green checkmark to indicate that precisions are meeting the user-defined requirement.

The Trimble HD-GNSS processing engine enables users to measure stop-and-go topographic points with an initialized Trimble R10 in just two measurement epochs. Combined with the use of the eBubble in Trimble Access to capture point measurements automatically when the rover is held static and plumb (see Figure 7), the reduced stop-and-go occupation time results in greatly improved productivity.

RTK precision values will still reflect fundamental concepts such as satellite visibility, satellite geometry (PDOP), and baseline length. Users can optimize precision by limiting distance from a single RTK base-station or by using a VRS network. Good survey practices are still recommended, especially in hostile GNSS environments where users should exercise their preferred integrity checks, such as revisiting points and checking in to known points.

For establishing survey control points, Trimble still recommends that the user occupy each point for 3 minutes, and then again for another 3 minutes at least 2 hours later with a significantly different satellite constellation. The increased occupation time increases confidence in the individual measurement. Multiple occupations provide independent checks on the internal and external accuracy of the control network. For very accurate control work, many users will prefer to collect and post-process raw GNSS data.

POST-PROCESSING APPLICATION

Post-processed GNSS surveying remains one of the most precise and flexible techniques available for establishing survey control. After all, this original form of GNSS surveying freed the surveyor from the line-of-sight requirement of optical techniques. Even for topographic surveying, post-processing is occasionally preferred over RTK because it enables the user to operate without a data radio or mobile Internet connection.

Figure 8 shows that when establishing survey control, post-processing allows the user to create an interconnected network of control stations that are highly accurate, both relative to one-another and to a global datum. A highly accurate control network can greatly improve survey efficiency for follow-on operations. For example, a survey crew can confidently check into these control stations while performing a stake-out survey without "chasing error" around a project.

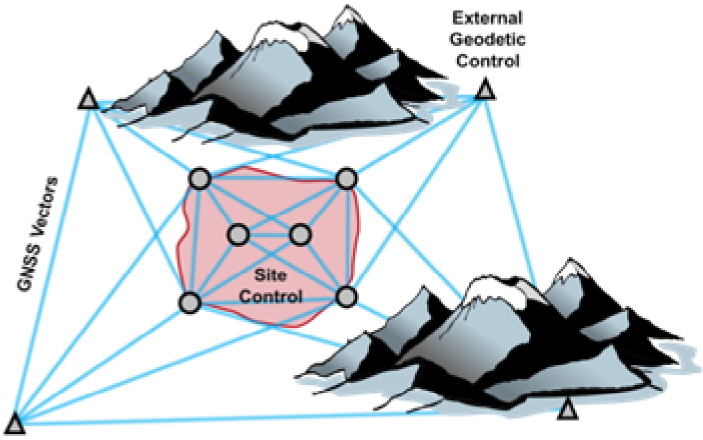
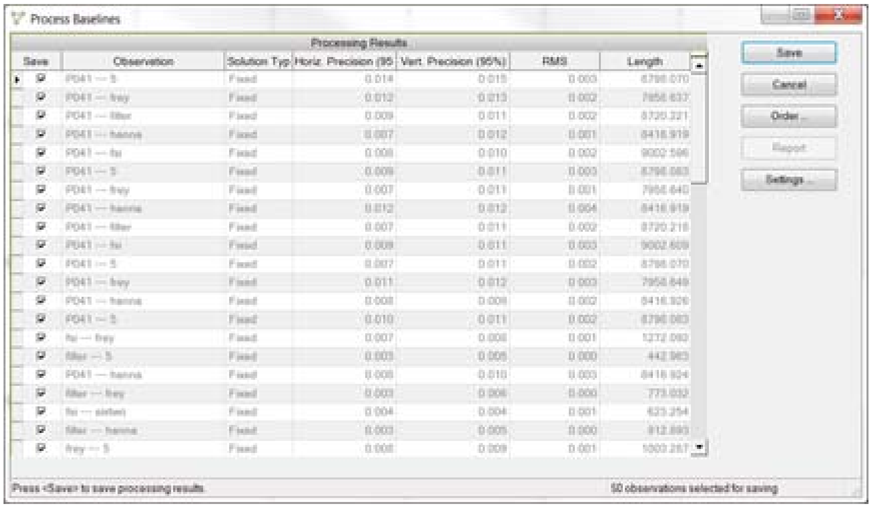


Figure 8. Post-processed GNSS surveying is used to establish an interconnected GNSS control network with obscured line-of-sight

Unfortunately, many surveyors avoid post-processed GNSS surveys because they think they are complicated and prone to blunders. Trimble's GNSS post-processing application, Trimble Business Center (TBC), utilizes the Trimble HD-GNSS processing engine to improve post-processing performance and reduce complexity. In TBC, a user can achieve excellent results without hand editing the raw GNSS data or changing the default processor settings.

The HD-GNSS-based TBC post-processing engine uses the same breakthrough data processing techniques as the Trimble R10 for data editing, filtering, carrier phase ambiguity resolution, and precision estimation. The reported horizontal and vertical precisions are reliable and consistent for all environments and should be used as the primary evaluation criteria for processing results.

Figure 9 shows typical baseline processing results in TBC. The software continues to report “Fixed” and “Float” for baseline solutions, but these terms no longer indicate that the integer ambiguities have been resolved in the traditional sense. The terms are now intended to classify the precisions of baseline solutions relative to legacy fixed or float solutions. Many surveyors require this classification to meet requirements for project reporting.



Processing Results						
Save	Observation	Solution Typ	Horiz. Precision (95	Vert. Precision (95%)	RMS	Length
☑	PD41 — 5	Fixed	0.014	0.015	0.003	8798.070
☑	PD41 — frey	Fixed	0.012	0.013	0.002	7956.637
☑	PD41 — filler	Fixed	0.009	0.011	0.002	8720.221
☑	PD41 — hanna	Fixed	0.007	0.012	0.001	8416.919
☑	PD41 — fsi	Fixed	0.008	0.010	0.002	9002.596
☑	PD41 — 5	Fixed	0.009	0.011	0.003	8798.083
☑	PD41 — frey	Fixed	0.007	0.011	0.001	7956.640
☑	PD41 — hanna	Fixed	0.012	0.012	0.004	8416.919
☑	PD41 — filler	Fixed	0.007	0.011	0.002	8720.218
☑	PD41 — fsi	Fixed	0.009	0.011	0.003	9002.609
☑	PD41 — 5	Fixed	0.007	0.011	0.002	8798.070
☑	PD41 — frey	Fixed	0.011	0.012	0.003	7956.649
☑	PD41 — hanna	Fixed	0.008	0.009	0.002	8416.926
☑	PD41 — 5	Fixed	0.010	0.011	0.002	8798.083
☑	fsi — frey	Fixed	0.007	0.008	0.001	1272.092
☑	filler — 5	Fixed	0.003	0.005	0.000	442.983
☑	PD41 — hanna	Fixed	0.008	0.010	0.003	8416.924
☑	filler — frey	Fixed	0.003	0.006	0.000	773.032
☑	fsi — sieben	Fixed	0.004	0.004	0.001	423.254
☑	filler — hanna	Fixed	0.003	0.005	0.000	912.893
☑	frey — 5	Fixed	0.008	0.009	0.001	1003.267

Press <Save> to save processing results.

50 observations selected for saving

Figure 9. Processed GNSS baselines in Trimble Business Center

TBC automatically determines the best approach to deal with signal delays and advances due to transmission through the Earth’s atmosphere. For very short baselines, these delays are common to both the base and rover receivers and are therefore eliminated when processing carrier phase measurements. For longer baselines, the delays are not common and so they must be modeled or eliminated in a different way.

For dual- or triple-frequency carrier phase measurements, ionospheric biases can be minimized on long baselines simply by processing ionospheric-free carrier phase combinations. However, although this combination minimizes ionospheric influences, it is not optimal due to increased noise. Therefore, the Trimble HD-GNSS post-processing engine automatically determines the optimal carrier phase combination to use for any kinematic trajectory or static baseline. The combination is such that for very short baselines it tends to the narrow lane combination (lowest carrier phase noise); for very long baselines it tends to the ionospheric-free combination (highest carrier phase noise, but unbiased).

The post-processing engine applies an empirical tropospheric delay model to signal delays resulting from transmission through the troposphere. For all kinematic sessions and for static sessions lasting less than 1 hour, tropospheric delays are computed using the Hopfield model. For static sessions lasting longer than 1 hour on baselines longer than 2 kilometers, tropospheric delays are computed using the Hopfield model along with Niell mapping functions. In addition, TBC can optionally improve the tropospheric delay model by estimating corrections using carrier phase measurements. This combination of models and corrections consistently produces the best results and does not require input from the TBC user.

Solutions for baselines over 20 kilometers can be improved by processing with precise satellite ephemerides. In older applications, downloading and importing precise ephemeris files was time consuming and complicated. With TBC’s Internet Download function, the user can access these files using just a few simple clicks. Since it is so easy, users should consider using precise ephemerides for all processing. The Internet Download function can also be used to retrieve raw reference station data from GNSS networks all around the world.

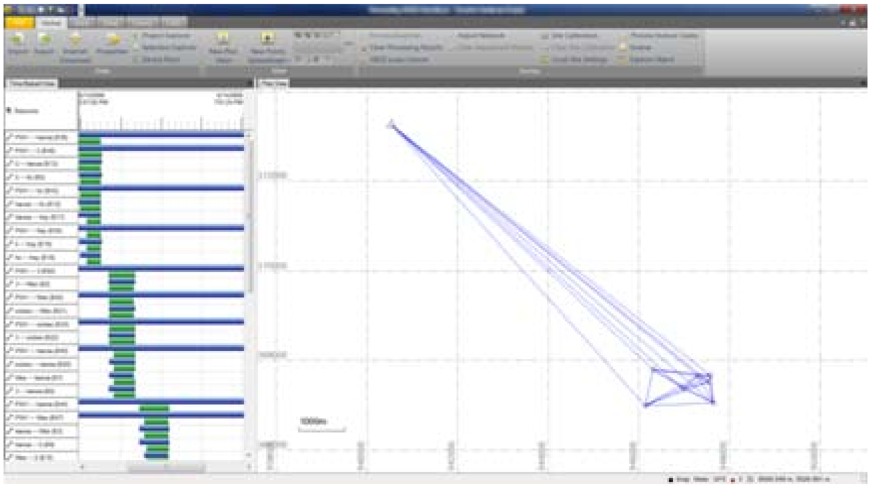
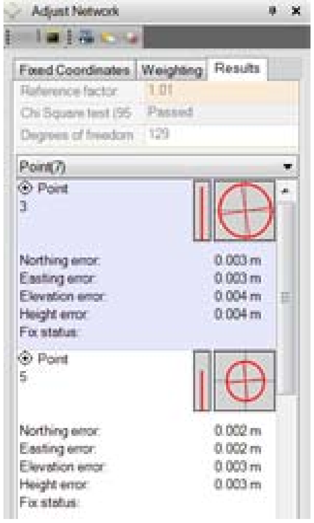


Figure 10. Completed GNSS control network in Trimble Business Center

Adjusting a network of vectors processed in TBC with the Trimble HD-GNSS engine is now more straight-forward than ever. Because of the improved precision estimates from the processing engine, the weights for each observation in the network are more realistic. When the user adjusts the network, the comparison between the error estimates and the amount of adjustment the vectors need during the unconstrained or minimally constrained adjustment will generally produce a network reference factor close to 1.00. This eliminates the additional step of scaling overly optimistic errors which were commonly produced by older processing engines.



Reference factor 1.01
Chi Square test (95 Passed
Degrees of freedom 129

Point
3

Northing error: 0.003 m
Easting error: 0.003 m
Elevation error: 0.004 m
Height error: 0.004 m
Fix status:

Point
5

Northing error: 0.002 m
Easting error: 0.002 m
Elevation error: 0.003 m
Height error: 0.003 m
Fix status:

Figure 11. A least-squares adjustment in Trimble Business Center generally yields a network reference factor near 1.00 for vectors processed with the Trimble HD-GNSS engine

CONCLUSION

Advancements in GNSS processing, the availability of additional satellites and signals, and improved signal tracking have combined to increase the reach of GNSS surveying into more difficult environments. The new technology has also reduced the complexity of applying GNSS for both real-time and post-processed techniques, making it possible for a surveyor to confidently and precisely position points in nearly any outdoor environment.

Successful GNSS surveying has traditionally required lengthy training on software with complicated interfaces that was prone to user mistakes. Now, with the Trimble HD-GNSS processing engine in the Trimble R10 receiver and Trimble Business Center desktop software, the user can bypass all of these complicated procedures and focus on the reported precisions.

In addition to the benefits users can realize today when employing the Trimble HD-GNSS processing engine, the shift to this new methodology makes it possible for Trimble to continue to improve performance as GNSS constellations develop. Trimble HD-GNSS has been designed to be fully scalable through firmware and software updates. Therefore, it is well positioned to take full advantage of additional GNSS satellites and signals to further improve surveying in increasingly demanding field conditions. The future of GNSS is clearly one of continuing technological expansion, from which Trimble users will benefit in terms of ever increasing survey accuracy and productivity.