GNSS POSITIONING TECHNIQUES FOR AGRICULTURE

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ABSTRACT

Broadacre, row crop and high value crops each have different positioning needs. Within these agricultural groups, individual practices such as mapping, guidance and machine control for tillage, application and harvest each have their own Global Navigation Satellite Systems (GNSS) needs for an optimal price/performance and value equation. New research and algorithm development by NovAtel has resulted in a significant simplification of positioning methodology with increased reliability and performance worldwide.

There are typically two fundamental measurements that are made from GNSS satellites: the pseudorange and the carrier phase. Many different kinds of algorithms have been developed to convert these measurements into positions that can then be used by agricultural applications. This presentation will illustrate how pseudorange and carrier phase measurements made from the same rover antenna can be processed with very different techniques to produce position solutions with radically different performance characteristics as well as price points.

This presentation will describe the various error sources that contribute to position errors, as well as techniques to mitigate or eliminate these errors. NovAtel CORRECT™ positioning technology was released in early 2014. NovAtel CORRECT optimally combines data from multiple GNSS satellite constellations with corrections from a variety of sources, to deliver the best position solution possible. NovAtel CORRECT provides systems integrators with the opportunity to choose pricing and subscription options that best match their OEM business objectives. With NovAtel in control of the entire positioning solution, future innovation including seamless integration with all positioning modes and correction types is assured.

Additionally, this presentation will compare and contrast several positioning approaches commonly used by agricultural application. Advantages and disadvantages of each approach will be discussed, as well as quantification of the accuracy and robustness of the computed position. The various positioning approaches will include NovAtel's GLIDE technique (with a comparison of single-frequency and dual-frequency approaches), Precise Point Positioning (PPP), as well as Real-Time Kinematic (RTK). These three approaches allow for positions ranging from sub-meter (GLIDE), decimeter (PPP) to centimeter (RTK).

Keywords: **GNSS, GPS, PPP, RTK, GLIDE**

INTRODUCTION

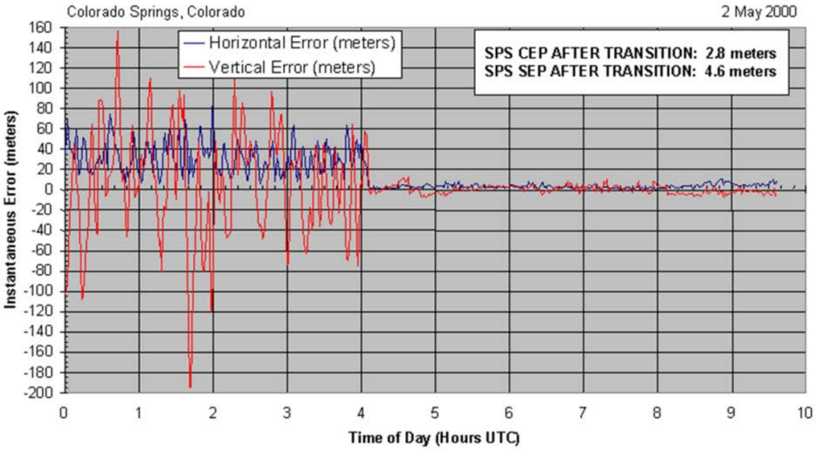
The Changing Face of GNSS

The nature of GNSS is about to change dramatically and irrevocably over the next eight to fifteen years. Gone will be the days of Global Positioning System (GPS) satellites as a primary system with GLONASS satellites as a secondary augmentation system, where the only real choices were single- or dual-constellation and single- or dual-frequency. Instead, users of GNSS will have a choice of four separate but somewhat interoperable global systems, with a widely varied mix of signals and frequencies. Sometime around 2020 four different constellations will be functional: GPS (US), GLONASS (Russia), Galileo (Europe) and BeiDou (China).

GPS and GPS Modernization

The GPS reached its Initial Operational Capability (IOC) in December 1993, and was declared to have reached Full Operational Capability (FOC) in mid-July 1995, with 24 fully functional satellites in orbit. The GPS has maintained a remarkably high level of serviceability, with only the occasional occurrence of satellite anomaly, usually associated with the failure of an on-board atomic clock. The GPS has never experienced a system-wide failure, which has resulted in increased confidence and dependence upon its information. In its original concept, GPS satellites transmitted on two carrier frequencies, L1 (1575.42 MHz, with a wavelength of 19.0cm and L2 (1227.60 MHz, with a wavelength of 24.4cm). The satellite clocks were intentionally degraded, or dithered, through a "feature" called Selective Availability (SA). With SA active, a stand-alone GPS receiver was capable of computing a horizontal position that varied by tens of meters. Various differential techniques were soon developed that would effectively eliminated the intentional dither, resulting in horizontal positions that were on the order of a meter or two. Advanced differential techniques were invented that would also rely on the precise (but ambiguous) carrier phase information for each satellite. These RTK techniques could rapidly and quite reliably produce centimeter-level GPS-derived positions.

A defining moment in GPS occurred on May 2, 2000. At the order of President Clinton, Selective Availability was turned off (OSTP 2000). In the matter of just a few seconds, the achievable accuracy for a stand-alone GPS receiver dropped from tens of meters to a couple meters. The United States government has declared that SA will never be enabled again (OPS 2007). In fact, the new Block III satellites do not even have the capability to enable SA.



Credit: http://www.gps.gov/systems/gps/modernization/sa/

Figure 1 - Plot showing the removal of Selective Availability on May 2, 2000

The push to modernize the GPS continued, with the development of a second civilian signal that will eventually replace the encrypted L2 signal. The L2C signal is supported on Block IIR-M and Block IIF satellites and the upcoming Block III satellites. A third civilian signal, termed L5 is also supported on Block IIF and Block III satellites. There are currently eleven satellites broadcasting on L2C and four broadcasting on L5 as of mid-April 2014. There was a successful launch of a Block IIF GPS satellite in February 2014, but this satellite has not yet completed its commissioning phase and is currently set as unhealthy. Two additional launches of Block IIF satellites are scheduled for later in 2014. Finally, the new Block III satellites will support a fourth civilian signal, termed L1C. This new signal is designed specifically for interoperability with the upcoming European Galileo constellation. The L1C signal format is also being adopted by China's BeiDou system, and regional systems such as Japan's Quasi-Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS). By the end of 2020 almost all GPS satellites will have L2C, two-thirds will have L5, and one-third will have L1C. The number of satellites (actual and planned) as well as signal availability from 1997-2020 for both GPS and GLONASS is shown at Figure 2.

GLONASS and GLONASS Modernization

In December 1995 the GLONASS constellation consisted of 24 satellites in orbit, and the constellation was declared to be at FOC. Unfortunately, severe economic conditions in Russia resulted in no GLONASS launches for four years, and the constellation rapidly degraded. By 2001 there were only 6 operational GLONASS satellites, and the future looked bleak. Ambitious plans to revitalize the constellation were established in late 2001, with the announced intention to have the GLONASS constellation back to 24 satellites in 2009. An impressive series of launches from 2002 to 2011 restored the GLONASS constellation, and by the end of 2011 the GLONASS constellation again reached 24 healthy satellites in orbit, for the first time since 1996 (FSA 2011).

GLONASS, like its counterpart GPS, continues to evolve and modernize. The GLONASS satellites never had an intentional degradation such as SA. The GLONASS-M series of satellites (launches from 2003-2016) feature open signals on L1 and L2. A third open signal (L3OC) will be included on GLONASS-M satellites launched from 2015. The upcoming GLONASS-K1 will also support this third open signal. The GLONASS-K2 satellites will support legacy L1 and L2 signals that use Frequency Division Multiple Access (FDMA) for signal separation. They will also support Code Division Multiple Access (CDMA) signals on L1, L2 and L3, although the CDMA implementation will not be the same as that used for modernized GPS or Galileo satellites. GLONASS-KM satellites may eventually transmit signals that are compatible with modernized GPS and Galileo satellites (Inside GNSS 2010).

The GLONASS constellation has generally been performing quite well, although it did suffer a major system disruption in early April. The entire system was unusable for almost 12 hours. Initial speculation was that an incorrect upload of corrections to satellite ephemerides (used to compute orbital positions) was to blame (Inside GNSS 2014).

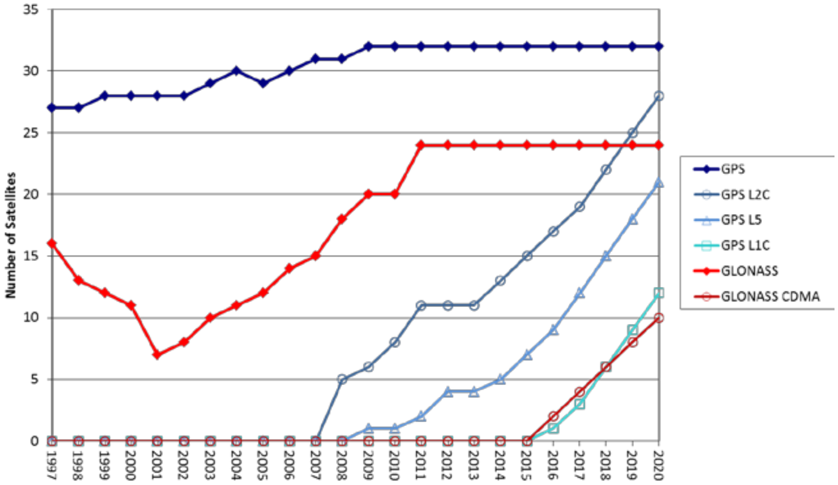


Figure 2 – Number of satellites and number of modernized signals for GPS and GLONASS from 1997 to 2020 (planned)

Upcoming Constellations: Galileo and BeiDou

Significant changes due to the modernization efforts for GPS and GLONASS is only half the story. Two new GNSS constellations are scheduled to be operational by the end of 2020: Europe's Galileo and China's BeiDou. The first two experimental satellites for Galileo (GIOVE-A and GIOVE-B) were launched in 2005 and 2008, respectively. Four In-Orbit Validation (IOV) satellites were launched in October 2011 and October 2012. The first two launches of four fully operational Galileo satellites are scheduled for late summer and fall of 2014, with 2020 a target date for a 30-satellite constellation in orbit (Figure 3).

China also has invested heavily in creating its own GNSS constellation, known as BeiDou. The final configuration for the constellation will include 27 mid-Earth orbit (MEO) satellites (similar to GPS, GLONASS and Galileo), 3 satellites in an inclined geosynchronous orbit, and 5 satellites in geostationary orbit. The geosynchronous and geostationary satellites will provide enhanced coverage over all of China and as far south as southern Australia. China currently has several geosynchronous and geostationary satellites in orbit, and four MEO satellites were launched in 2012. Like Galileo, BeiDou is scheduled for completion around 2020 (Figure 3).

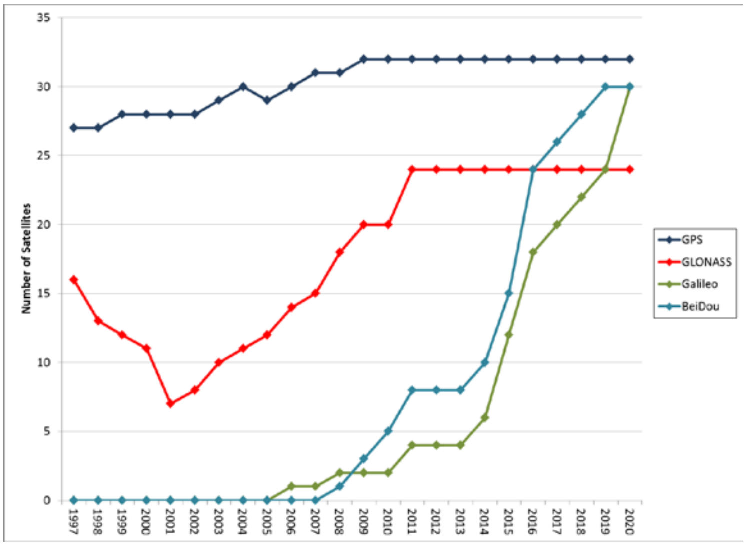


Figure 3 – Number of satellites for GPS, GLONASS, Galileo and BeiDou from 1997 to 2020 (planned)

NovAtel's Role in Supporting Precision Agriculture

NovAtel's role as a technology developer is to provide systems integrators with scalable GNSS products in a variety of form factors, from cards to enclosures to an integrated antenna/card combination. Equally as important, NovAtel's role is also to manage the chaos as GNSS evolves. There are legacy signals on legacy frequencies, there are new signals on legacy frequencies, there are new signals on new frequencies, and there are entirely new constellations to add into the GNSS solution. None of these enhancements are scheduled to happen at the same time or on the same schedule, and it will take GNSS well over a decade to transition from where we are today to where we will ultimately be.

GNSS OBSERVATIONS AND ERROR SOURCES

There are two fundamental measurements of the received satellite signals that are made by a GNSS receiver: the pseudorange and the carrier phase (also known as code and phase). In a perfect world, the signals are received at the antenna exactly as transmitted by the satellites, and essentially error-free measurements are passed to the positioning engine. In reality, the received signals contain a combination of several significant errors (Figure 4), resulting in a degraded GNSS position. The effect of the ionosphere generally has both the greatest magnitude and greatest variation out of all of the error sources.

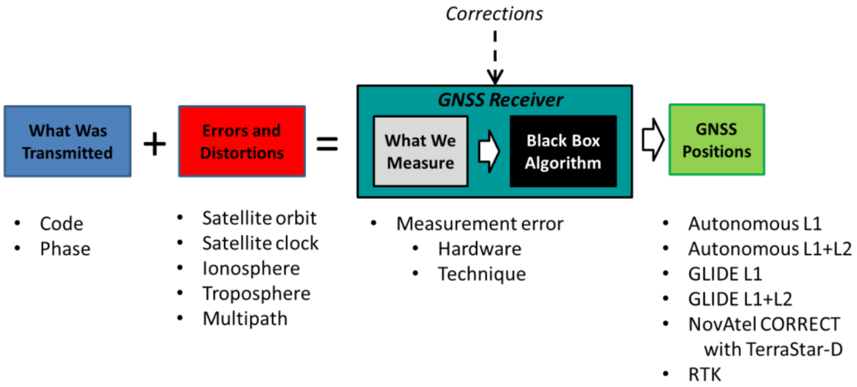


Figure 4 – GNSS Signals, Error Sources, Processing Techniques and Resulting Position Types.

GNSS Errors and Mitigation Strategies

Many different processing techniques have been developed to try and account for the various error sources (Table 1). The most straightforward approach is to essentially do nothing, and rely upon a single-frequency receiver to measure the pseudorange and compute its position in an unassisted (autonomous) fashion. No corrections are applied to try and account for the satellite orbit or clock errors, a very coarse correction (global model) for the ionosphere is applied, and a standard atmospheric model for the troposphere is assumed. The global model for the ionosphere does not account for local variations in the ionosphere, and generally only removes around half of the error due to the ionosphere. A dual-frequency receiver is able to measure, in real time, the relative signal delay between the L1 and L2 frequencies.

The NovAtel GLIDE algorithm combines the pseudorange measurements (accurate but not precise) with the carrier phase measurements (precise but not accurate) to remove some of the noise and discontinuities inherent with pseudorange-based positions. The GLIDE algorithm was designed specifically for agricultural applications where multi-decimeter pass-to-pass performance is required. The GLIDE solution can operate with a single- or dual-frequency receiver, and it can operate with or without information provided by Space-Based Augmentation System (SBAS) satellites such as North America's Wide Area Augmentation System (WAAS) or the European Geostationary Navigation Overlay Service (EGNOS).

Externally derived corrections are required to achieve decimeter or even centimeter level performance from a GNSS receiver. Two of the most common methods are Precise Point Positioning (PPP) and Real-Time Kinematic (RTK) positioning. Both methods are capable of producing excellent performance, but the method by which they achieve this performance is very different. A PPP solution relies upon a global network of monitoring stations that are used to compute, in near real time, the corrections for the satellite orbits and clocks. These corrections must then be transmitted to the user's receiver, typically by L-band satellite downlink (services such as OmniSTAR's HP and G2, John Deere's StarFire2 or NovAtel's CORRECT with TerraStar-D) or delivery via the Internet.

An RTK solution relies upon a reference receiver set up over a surveyed point in close proximity (generally less than 15-20km) to the user's area of operation. The reference receiver observes satellite signals that are highly correlated to the signals received by the rover receiver.

Table 1 – Typical GNSS Error Sources and Mitigation Strategies

		Satellite Orbit	Satellite Clock	Ionosphere	Troposphere
Typical magnitude of error		<2m	<2m	1-20m, depending on region	<0.5m
Position Style	Autonomous L1	✗	✗	Global model	Standard atmospheric model
	Autonomous L1+L2	✗	✗	Measured delay	Standard atmospheric model
	GLIDE L1	✗	✗	Global model	Standard atmospheric model
	GLIDE L1+L2	✗	✗	Measured delay	Standard atmospheric model
	NovAtel CORRECT with TerraStar-D (PPP)	✓	✓	Measured delay	Derived via Kalman filter model
	RTK	✓	✓	✓	✓

GNSS POSITIONING TECHNIQUES AND RESULTS (STATIONARY)

To be able to make a fair comparison, it was important to use the exact same data, but processed in several different ways. For this comparison, the data were collected in late March 2014 in the middle of the state of São Paulo, Brazil. Equatorial regions such as Brazil can be particularly challenging for precision with GNSS, as there tends to be much more intensity and daily variation of the ionosphere, resulting in significant and variable delays in the received signals. Despite its challenges, Brazil is an excellent location to be able to illustrate the differences between various processing strategies and techniques.

The NovAtel equipment at the temporary base location consisted of a GPS-702-GGL antenna and a ProPak6 receiver running a release candidate version of 6.4 firmware. Raw data were logged at 1Hz to the internal memory. The antenna was located on a metal hand rail for the duration of the data collection (Figure 5). The coordinate for the temporary base station was established by using the Waypoint software package to produce a static Precise Point Position (PPP) solution using International GNSS Service (IGS) orbit and clock corrections (final version). Using this technique the horizontal accuracy for the temporary base station coordinates are around two centimeters or less.

Figure 5 – Location of the temporary GPS-702-GGL base antenna (left) and rover antenna (right) for the Brazil campaign.

The rover was located approximately 14km to the west of the base station's location. The NovAtel equipment at the rover location consisted of a GPS-702-GGL antenna and a FlexPak6 receiver running a release candidate version of 6.4 firmware. Raw observable data (dual-frequency GPS and GLONASS) were streamed at 10Hz to a laptop. The antenna was installed on a sturdy pillar, with a clear view of the sky (Figure 5). The coordinate of the rover antenna were established with respect to the temporary base antenna using the Waypoint software package. The estimated relative accuracy of this baseline is one centimeter.

The data were post-processed using an offline version of the real-time positioning engine used by NovAtel OEM6-series GNSS cards. The number of GPS and GLONASS satellites in view varied between approximately 13 and 20. Four different position solutions that rely principally on the pseudorange measurements are shown at Figure 6. The data were collected from approximately 11 a.m. March 20 to 9 a.m. March 21, 2014. The autonomous L1 solution (lime green line) shows a gradual increase in error throughout the day as the ionosphere becomes charged throughout the day. The ionosphere becomes disturbed from approximately GPS time 430000-440000 (corresponding to 8 p.m. to 10:30 p.m.). The addition of L2 observations results in much improved performance (royal blue line), particularly throughout the daytime hours when the charge in the ionosphere is building. There also is a noticeable improvement during the period when the ionosphere is disturbed.

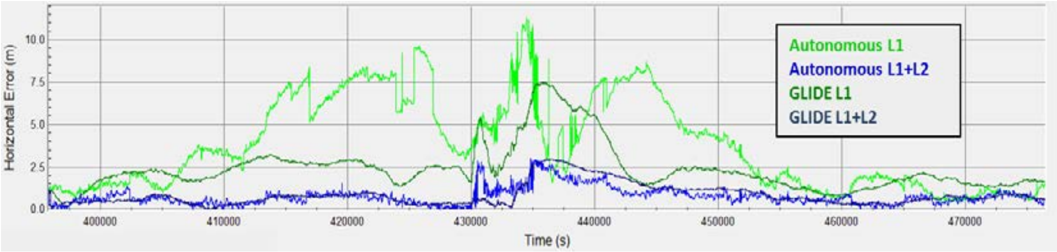


Figure 6 – Plot showing the horizontal errors over 22 hours for four different positioning styles in a region with an active ionosphere.

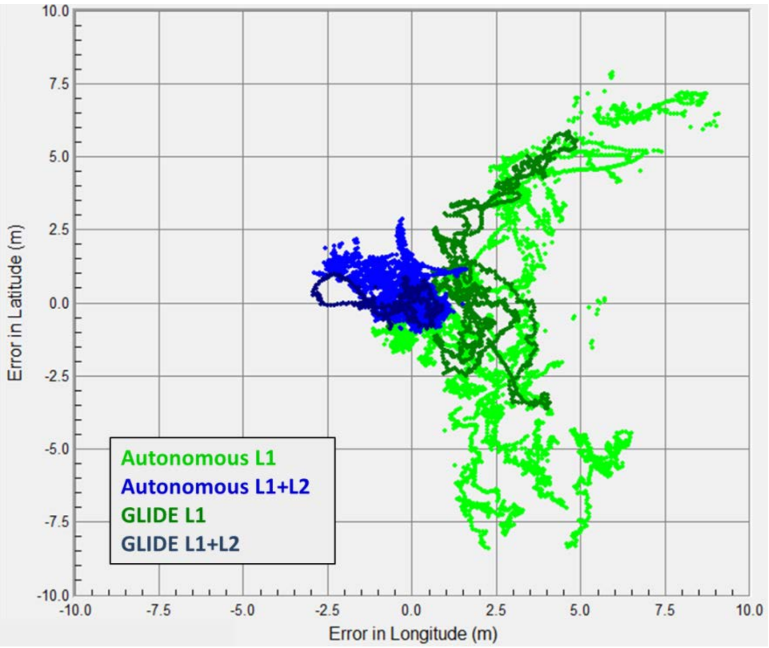


Figure 7 – Scatter plot of horizontal errors over 22 hours for four different positioning styles in a region with an active ionosphere.

Base station data were available for several hours on the morning of March 21, allowing for a comparison of the fully converged PPP solution with an initialized RTK solution (on a 14km baseline). Approximately four hours of PPP and RTK data are shown at Figure 8.

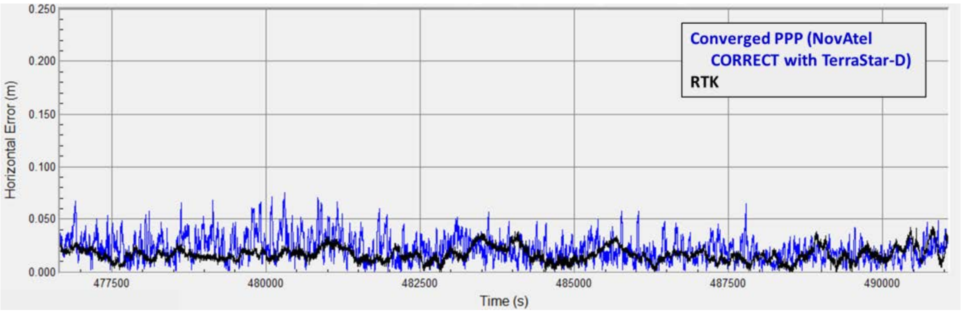


Figure 8 – Horizontal errors for fully converged PPP solution (NovAtel CORRECT with TerraStar-D) and RTK (14km baseline).

Table 2 – Horizontal errors for various positioning styles in a region with an active ionosphere.

		Horizontal Error (m)			
		50%	70%	90%	95%
Positioning Style	Autonomous L1	3.20	5.30	7.60	8.17
	Autonomous L1+L2	0.67	0.86	1.41	1.84
	GLIDE L1	2.10	2.50	4.10	5.80
	GLIDE L1+L2	0.65	0.87	1.4	1.85
	NovAtel CORRECT with TerraStar-D (PPP)	0.019	0.026	0.038	0.044
	RTK (14km baseline)	0.015	0.020	0.025	0.030

GNSS POSITIONING TECHNIQUES AND RESULTS (DYNAMIC)

Significant insight into GNSS positioning can be derived by evaluating the GNSS solution while the antenna is moving. Conducting data collection and analysis when the antenna is stationary is relatively easy: collect data, establish the unchanging coordinate of the antenna, then compare the computed positions against this coordinate to determine the horizontal and vertical errors. The scenario becomes more complex when the antenna is moving, although it is somewhat straightforward to determine the changing coordinate using RTK. It becomes even more complicated when you are trying to assess the performance of several integrated antennas. NovAtel goes through considerable effort to validate the GNSS performance while in a dynamic mode. Farmers don't do much farming when their equipment is sitting still.

Data were collected in October 2013 and February 2014 in an agricultural setting in the Midwest United States. A FlexPak6 GNSS receiver and GPS-702-GGL and antenna were installed at the reference station, and raw observable data were logged for post-processing. The reference station was located in close proximity (100m-600m) to the area of operation of the dynamic test vehicle (Figure 9).

Figure 9 – Location of GNSS base station (yellow star, top right) and trajectory of test vehicle.

A comprehensive set of equipment was installed on the roof of the test vehicle, as shown at Figure 10. A post-processed RTK solution was used to establish the dynamic coordinates of the GPS-702-GGL antenna (indicated by the red circle). The virtual coordinates for the remaining antennas (indicated by the green circles) were computed by combining the GNSS observable data with yaw (heading), pitch and roll parameters derived using a NovAtel SPAN (Synchronized Position Attitude Navigation) system as well as the measured physical offsets of the antennas with respect to the Inertial Measurement Unit's (IMU) center of navigation (indicated by the yellow circle). The IMU used in this test is the SPAN-CPT that features fiber optic gyro and Micro Electromechanical Systems (MEMS) technology. The SPAN-CPT can produce highly accurate 100Hz heading, pitch and roll to a post-processed accuracy of 0.030, 0.15 and 0.15 degrees, respectively (NovAtel SPAN 2014). The post-processed trajectories were computed using Inertial Explorer, and the resulting virtual coordinates will be of RTK quality.

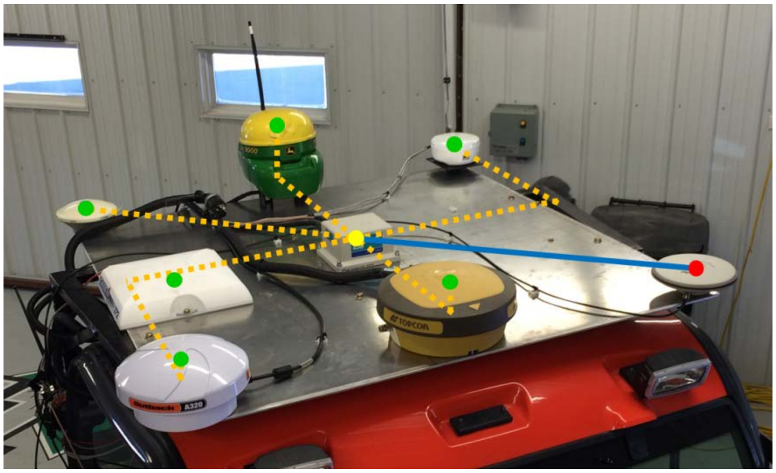


Figure 10 – GNSS equipment installation showing RTK antenna (red circle), IMU Center of Navigation (yellow circle) and derived coordinates (green circles).

The test vehicle was operated for over four hours in an open-sky environment. The vehicle path orientation was close to east-west (Figure 9), and the vehicle horizontal speed variation is shown at Figure 11. The speed varied between stationary and just over 4 m/s (14.4 kph, 8.9 mph). The resulting horizontal position errors for three different PPP solutions are shown at Figure 12. All three PPP solutions have a period at the beginning (approximately 30 minutes) where the solutions converge. Once this steady-state condition is achieved, all three PPP solutions perform well, and provide a real-time position solution that is of decimeter quality or better.

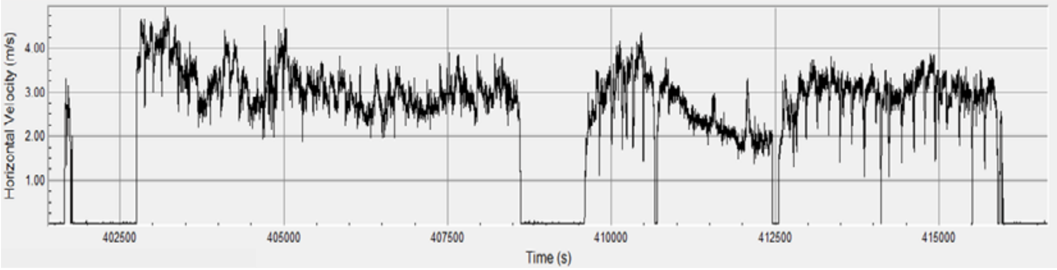


Figure 11 – Horizontal speed of the test vehicle over four hours.

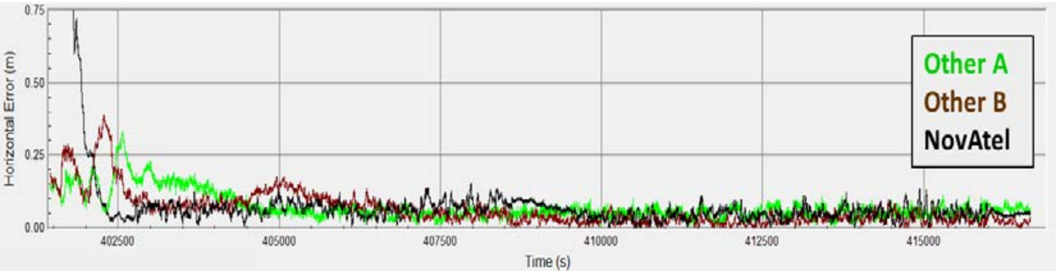


Figure 12 – Comparison of three different PPP solutions (NovAtel CORRECT with TerraStar-D and two non-NovAtel solutions).

Not all results were as expected, however. One prominent GNSS manufacturer that offers different options for PPP solutions had a repeatable bias of over a meter between different solution types. Figure 13 shows two different PPP solutions (“Other A” and “Other B”) offered by the same GNSS provider. One solution shows a consistent bias, whereas the other solution is in agreement with the NovAtel PPP solution. Three additional PPP solutions (not shown in Figure 13) from three other GNSS providers all agree with the NovAtel and “Other B” solutions. Curiously, this meter-level bias was not observed in other tests conducted outside of the United States.

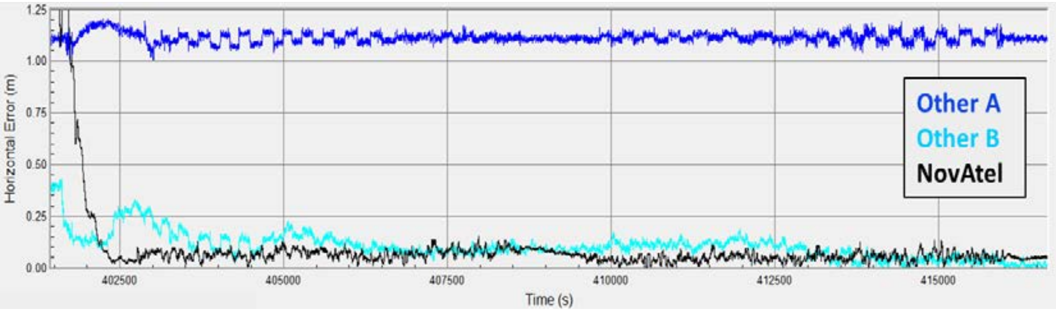


Figure 13 – Comparison of three different PPP solutions (NovAtel CORRECT with TerraStar-D and two non-NovAtel solutions from the same manufacturer).

The importance of evaluating GNSS performance while dynamic is illustrated at Figure 14. This plot shows thirty minutes of data, where the test vehicle was stationary for the first half, and dynamic for the second half. When the test vehicle was stationary, the two GNSS position solutions are quite similar: the absolute accuracy is around 25cm (for the non-NovAtel receiver) and around 10cm (for the NovAtel receiver). When the test vehicle was dynamic, however, there was a significant difference in performance. The non-NovAtel receiver’s position solution became much noisier, and there were significant position errors of *several decimeters* that seem to be correlated with a change in speed/direction of the test vehicle.

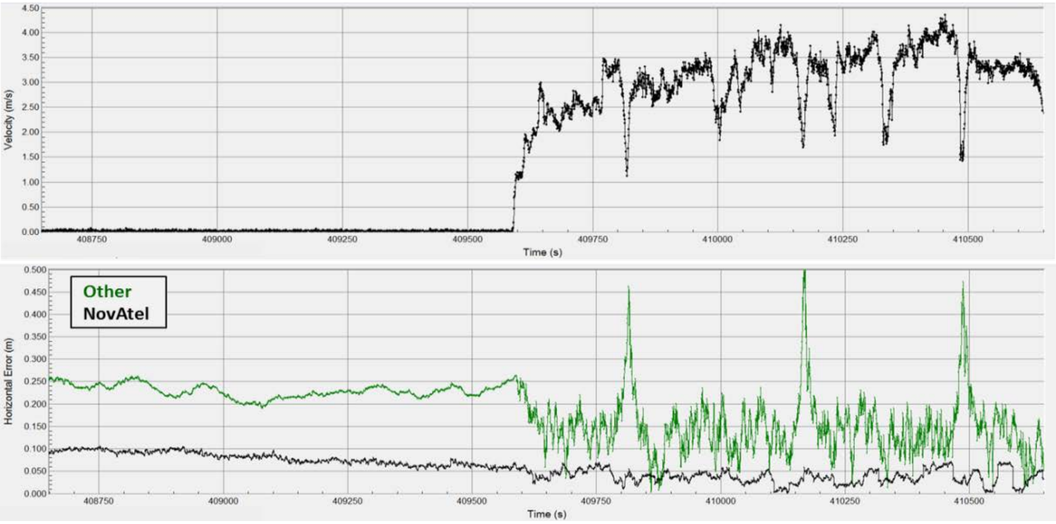


Figure 14 – Comparison of two different PPP solutions (NovAtel CORRECT with TerraStar-D and other).

Conclusions

There will be many significant changes to GNSS over the next ten to fifteen years. New signals and new frequencies will be added to the existing GPS and GLONASS constellations. Two new constellations (Europe's Galileo and China's BeiDou) will become functional. The new signals, frequencies and constellations will result in an improvement in accuracy, availability and robustness of a GNSS-derived position solution.

GNSS signals will be distorted from the time they are transmitted to the time they are received. The method by which the GNSS observables are processed will have a significant effect on the resulting position accuracy and precision. The use of dual-frequency data allows for real-time measurement and compensation of the errors due to the signal propagation through the ionosphere. Corrections (such as PPP or RTK) can be provided to reliably achieve positions with centimeter-level accuracy.

Dynamic testing is essential when evaluating the real-time position accuracy of GNSS positions. Highly accurate virtual trajectories can be generated by combining RTK with attitude information provided by a quality IMU. Dynamic testing in the Midwest United States illustrated that the real-time PPP solutions could provide reliable decimeter-level position solutions. GNSS solutions from several manufacturers were compared, and most were found to be reasonably consistent. One manufacturer offered at multiple options for a PPP solution, but one of these solutions had a consistent and repeatable bias of over a meter. Another manufacturer's PPP solution worked reasonably well when stationary, but showed very noisy and poor performance when moving.

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