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Real Time Precise Point Positioning: Are We There Yet?

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ABSTRACT

The concept of Precise Point Positioning (PPP) using Global Navigation Satellite System (GNSS) technology was first introduced in 1976, however it took until the 1990s for PPP to generate interest amongst the greater GNSS community. Over the last two decades, dual-frequency PPP has been extensively researched, culminating in the availability of PPP post-processed correction products from organisations such as the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL), the International GNSS Service (IGS) and Natural Resources Canada (NRCan). With the advent of cost-effective, accurate, Real-Time Kinematic (RTK) positioning provided by an increasing number of Continuously Operating Reference Station (CORS) networks around the world, the focus of PPP has shifted to real-time or near real-time solutions. A real-time or near real-time PPP solution would potentially allow for a viable alternative to RTK solutions in some circumstances. However, several limitations still remain, primarily the long convergence times needed to resolve ambiguities, currently restricting the use of PPP for real-time applications.

This paper provides a brief history of the development of real-time PPP and reviews the recent advances made in PPP with an emphasis on the development of a real-time or near real-time PPP solution.

KEYWORDS: Precise Point Positioning, GNSS, CORS, RTK, IGS.

1. INTRODUCTION

Precise Point Positioning (PPP) is a positioning method that employs widely and readily available Global Navigation Satellite System (GNSS) orbit and clock correction products, e.g. obtained via the International GNSS Service (IGS), to perform point positioning using a single GNSS receiver (Kouba, 2009).

PPP methods differ from differential positioning methods in that differential techniques require access to the observations of one or more reference stations with known coordinates. This provides PPP with an advantage over differential techniques in that only a single receiver is necessary (at the user's end) removing the need for the user to establish a local base station. Consequently, the spatial operating range limit of differential techniques is negated, as well as the need for simultaneous observations at both rover and base for real time applications (it should be noted that a sparse CORS network such as the IGS network is still needed to provide the necessary corrections for a PPP solution). PPP also has an advantage in that it provides a positioning solution in a dynamic, global reference frame such as the International Terrestrial Reference Frame (ITRF, see Altamimi *et al.*, 2011), rather than a local reference frame. However, one large disadvantage of PPP over differential GNSS techniques remains; large convergence times are needed to determine accurate coordinates due to the un-differenced errors (un-calibrated/un-modelled satellite and receiver hardware delays) within the PPP solution.

In recent years, the focus of PPP has shifted from determining an accurate post-processed un-differenced solution, to determining an accurate un-differenced solution in real time. The advent of the IGS Real-Time Pilot Project in 2007 has pressed the development of real-time clock and orbit streams by IGS (Ge *et al.*, 2008). The development of these correction streams allows 'end users' to determine an accurate Real-Time PPP (RT-PPP) solution (albeit with a slight delay of a few seconds) anywhere in the world.

The availability of RT-PPP solutions elevates PPP as a potentially viable alternative to differential GNSS techniques, in particular the highly productive and practical Real-Time Kinematic (RTK) solution. However, the long convergence times necessary to obtain an accurate position continue to hinder PPP potential. Recently, several methods have been developed to allow ambiguity-resolved (AR) PPP solutions in real-time, including the Centre National d'Etudes Spatiales (CNES) Real-Time PPP demonstrator (CNES, 2013) and Nexteq's AR PPP system. These methods allow for slightly faster, accurate cm-level solutions compared to converged float solutions.

Finally, with the introduction of a third frequency such as the L5 signal on the GPS constellation and equivalent third frequency on the Galileo constellation, the potential exists to reduce the time taken to resolve the ambiguities on a PPP solution to times comparable to differential positioning techniques.

This paper provides a brief history of the development of RT-PPP and reviews the advances made in PPP in the last few years, including some of the real-time products available on the market, the advances in ambiguity-resolved PPP solutions and finally the recent progress made in single frequency PPP.

2. A BRIEF HISTORY OF REAL TIME PPP

The evolution of PPP dates back to Anderle (1976), but it was not until the late 1990s that this technique was vigorously researched and studied at the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) (Zumberge *et al.*, 1997b). Over the last two decades, dual-frequency PPP has been extensively researched, and several PPP software packages have been developed. These studies have shown that centimetre-level point positioning is achievable in post-processed static mode, and decimetre-level positioning in post-processed PPP kinematic-mode (e.g. Zumberge *et al.*, 1997a; Gao, 2006; Choy *et al.*, 2009).

Recently, increased attention has focused on accessing accurate satellite ephemerides and clock corrections in real-time with the aim of supporting real-time or near real-time kinematic PPP applications. As a result of these discussions, the IGS Real Time Working Group (RTWG) was established to govern and address issues relevant to the development of the IGS real-time infrastructure (IGS RTWG, 2007). In April of this year, the IGS unveiled real-time clock and orbit products allowing users to stream corrections enabling real-time PPP solutions.

With the advent of real-time products such as satellite orbit and clock corrections as well as the advances that have been made in the last few years in relation to AR PPP solutions, PPP is beginning to offer a viable addition/alternative to differential positioning techniques, particularly in areas where dense CORS coverage is not justified due to sparse population or for economic reasons (such as in developing nations). There also exists the potential to utilise PPP as a 'fill-in' service for existing CORS networks, in which GNSS station density is not analogous throughout the whole network, such as CORSnet-NSW (Janssen *et al.*, 2011, 2013).

3. THE IGS REAL TIME SERVICE

The International GNSS Service (IGS) recently announced the launch of its Real Time Service (RTS) in April 2013. Traditionally, the IGS distributed its satellite orbit and clock corrections with a delay based on the stated accuracies of the corrections with the intention that they were to be used for post-processed positioning, e.g., the final IGS orbit and clock corrections have a ~14 day delay. The IGS already had produced 'ultra rapid' correction products for use in near real-time and real-time positioning, however the prediction part of this correction was based on earlier observations and was significantly less accurate than the other IGS products (Caissy *et al.*, 2012).

The IGS RTS produces and publishes real-time GPS orbit and clock corrections globally (free via subscription, consistent with IGS's open data policy), that can be streamed in the Radio Technical Commission for Maritime Services (RTCM). The RTCM–State Space Representation (SSR) format will be capable of supporting sub-decimetre RT-PPP anywhere in the world, 24 hours per day. Currently the RTS products are offered as GPS constellation only; however the real-time corrections will include the Russian GLONASS constellation from the end of 2013 (they can be accessed currently on an experimental basis), which is also supported by the RTCM-SSR format. Other constellations will be added when they become available. Table 1 outlines the IGS RTS products, their formats and frequency.

Product	Format	Frequency
GNSS Data	RTCM 3	1 second
GPS orbit corrections	RTCM-SSR	5 or 60 seconds
GPS clock Corrections	RTCM-SSR	5 seconds

Table 1: Outline of the IGS RTS products, their formats and frequency (Caissy *et al.*, 2012).

The IGS RTS network consists of 130 globally distributed real-time tracking stations maintained by local and regional operators observing 1-second data with latencies of 1 – 3 seconds. Figure 1 shows the IGS RTS global network. The IGS RTS correction products are delivered to users via the Network Transport of RTCM by Internet Protocol (NTRIP).

Figure 1: IGS RTS global network of stations (IGS, 2013).

The IGS does not guarantee the accuracy or availability of the RTS. However, the IGS has taken steps to ensure that it continues to meet GNSS community expectations in reliability, accessibility and accuracy by:

- Offering reliable data flow throughout the data delivery, reducing the likelihood of total failure of the system, including redundant data paths as part of the solution by including as many reference stations as possible. The real-time product flow offers a reliable product flow throughout the delivery chain including redundant paths as part of the solution.

- Offering global coverage, including redundant stations in geographical regional.

- All real-time data are transmitted to a minimum of two separate real-time data centres.

Figure 2 illustrates the IGS GNSS data centre and product distribution architecture.

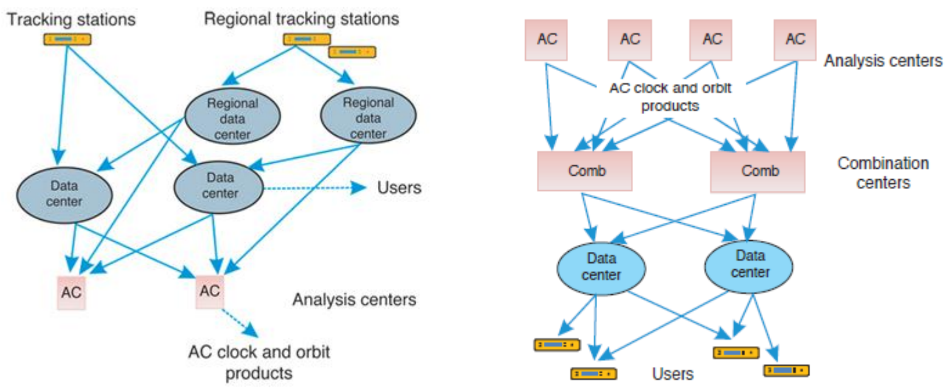

Figure 2: IGS GNSS data centre and product distribution architecture (Caissy *et al*., 2012).

The IGS Multi-GNSS Experiment (M-GEX) aims to allow the RTS to improve the tracking network, including the addition of new GNSS receivers that can track additional GNSS constellations such as Galileo, BeiDou and QZSS. Currently some Real Time Analysis Centres (RTACs) do produce GLONASS orbits and clock corrections and will provide these corrections to users. Most of the RTACs that currently do not, are working towards producing

GLONASS corrections as well as corrections for the Galileo constellation, with the additional aim of eventually adding the QZSS and BeiDou constellations (Caissy *et al*., 2012).

The completion of the IGS RTS is instrumental in enabling RT-PPP to progress into a viable positioning technique that is comparable to differential GNSS positioning techniques. The development of the various correction streams used for the IGS RT products allow for other corrections to be added such as fractional biases and various atmospheric corrections which in turn will allow for faster convergence times and integer AR PPP solutions.

3.1 IGS RTS BKG Ntrip Client PPP Demonstrator

To access the data streams that contain the satellite orbit and clock corrections produced by the IGS RTS, an NTRIP client application must be used. The Bundesamt für Kartographie und Geodäsie (BKG) NTRIP Client (BNC) and the RTKLIB software (developed by T. Takasu) both allow access to these data streams. Both are open source applications and both support a variety of GNSS positioning applications (Caissy *et al*., 2012).

Several correction streams are available to load into the NTRIP client from various combination centres in which the data has been sourced from RTACs. Raw data in the form of RINEX observations are also needed as input, as well as the RTCM ephemeris stream which is available from the IGS website at http://www.igs-ip.net/home.

The BNC includes a PPP engine, capable of producing a RT-PPP solution globally. Figure 3 shows an example of a PPP solution on the BKG Ntrip Client (BNC) Version 2.8. In this example, the IGS03 stream (GPS+GLONASS, Kalman-generated combination from Bundesamt für Kartographie und Geodäsie (BKG), the Centre National d'Etudes Spatiales (CNES), the German Aerospace Centre (DLR) & GMV (a privately owned technological business group)) is being used from the BKG/CTU combination centre. In this case, raw data is being sourced from TBOB (in Tibooburra, Australia) which forms part of the CORSnet-NSW network. For this example, the solution took 32 minutes to converge to a horizontal accuracy of 0.023 metres (when compared to a 24hr Bernese-processed differential AUSPOS solution (AUSPOS, 2012)), however the ellipsoidal height accuracy never improved past an accuracy of 0.150 metres (possibly a systematic bias due to improper modelling).

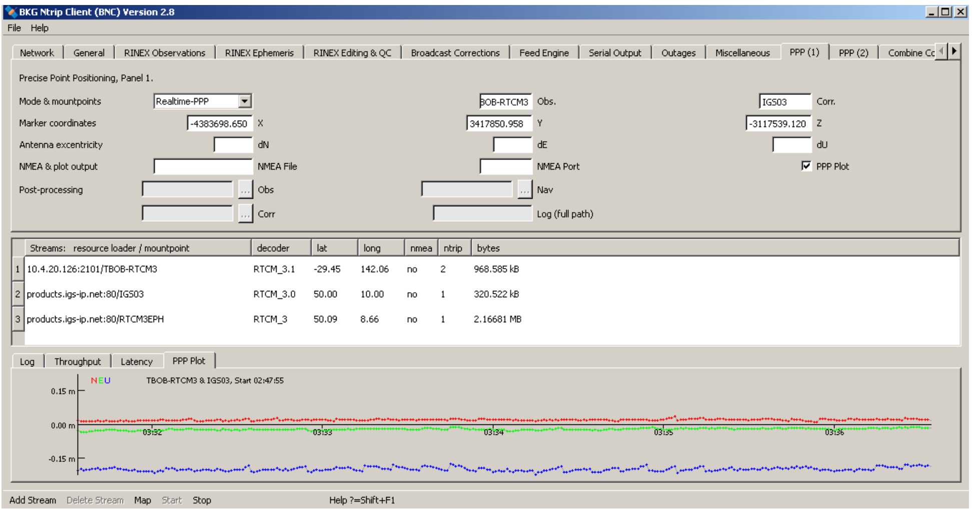

Figure 3: Example of a PPP engine solution on the BKG Ntrip Client (BNC) Version 2.8

4. CURRENT REAL TIME PPP SERVICES

With the availability of real-time satellite orbit and clock corrections, several products/services have emerged that take advantage of these corrections to deliver a RT-PPP solution. The biggest obstacle in delivering a RT-PPP solution once the corrections are readily available is the convergence time necessary to compute accurate PPP coordinates. In an effort to reduce convergence time and to also increase the accuracy of a RT-PPP solution, these services have sought to resolve the integer ambiguity of the RT-PPP solution. The ability to do this is also beneficial to the production of a kinematic PPP solution.

4.1 Integer Ambiguity-Resolved PPP Solution

Conventional PPP has involved the use of float solutions, which require long observation time, upwards of 20 minutes, to converge to centimetre accuracy. Whilst this is a relatively short observation time for static positioning, it is currently restricting the use of PPP for real-time applications. The fixing of integer ambiguities is usually only applied to differential techniques, as all unknown non-integer biases are eliminated in the differencing process. The fixing of integer ambiguities is a particularly difficult challenge in un-differenced measurements (Laurichesse *et al.*, 2009).

Several methods have been developed, in which fixed ambiguity resolution (or integer ambiguity resolution) is possible for un-differenced single receiver positioning utilising a CORS network (at a variety of network densities). Integer ambiguity resolution reduces the time it takes to achieve centimetre-level accuracy, allowing for more efficient PPP real-time applications.

To achieve this goal, the hardware biases of the receiver and the satellites need to be considered. The between-satellite hardware delays and initial phases (also called hardware delays or Fractional Cycle Biases (FCBs)) have to be separated from the between-satellite integer ambiguities (Odijk *et al.*, 2012). Two different approaches that allow for integer ambiguity resolution at a single GNSS receiver are; the fractional phase biases method (Ge *et al.*, 2008, Geng *et al.*, 2010), and the (similar techniques) integer recovery clock and decoupled satellite clocks methods (Collins *et al.*, 2008; Laurichesse *et al.*, 2009). These two methods differ in the approach taken to estimate the hardware delays and initial phases biases (Gao and Kongzhe, 2004; Geng *et al.*, 2010; Odijk *et al.*, 2012). Both approaches are based on linear combinations of dual-frequency GPS data.

Both methods allow the provision for the satellite products (FCB corrections) to be used in conjunction with other products, in this case the precise satellite clock corrections, to provide an integer ambiguity resolved precise point position at a single receiver.

4.2 CNES Real Time Integer PPP Demonstrator

The Centre National d'Etudes Spatiales (CNES) has developed a process in which the Melbourne-Wübbena (MW) combination is used to fix the difference between the ambiguities on the two frequencies. Following this the ionosphere-free phase combination is used to fix the remaining ambiguity in a global network solution. During this process clock corrections associated with the ionosphere-free phase combination are estimated, resulting in the integer nature of the ambiguities being revealed. A Kalman Filter is then used in mixed mode (with both real and integer-valued phase ambiguities) to produce GPS orbits and clocks with integer properties (used for corrections at the user receiver). CNES also developed algorithms that perform RT ambiguity-resolved PPP solutions (Laurichesse, 2011).

To demonstrate that this solution is possible, CNES has developed a demonstrator that includes a modified version of the BNC NTRIP client that allows for ambiguity fixing.

Figure 4 illustrates the architecture behind the CNES demonstrator including the network side in which raw data is collected, the zero difference measured wide-lane are fixed for each receiver in the network followed by the carrier phase ambiguity for the network. From this, the ‘integer’ clock by-products are determined. At the user side, the zero difference measured wide-lane are fixed for the receiver and then the determined ‘integer’ clock by-products are used to fix the carrier phase ambiguity and from there a centimetre level PPP is solved for.

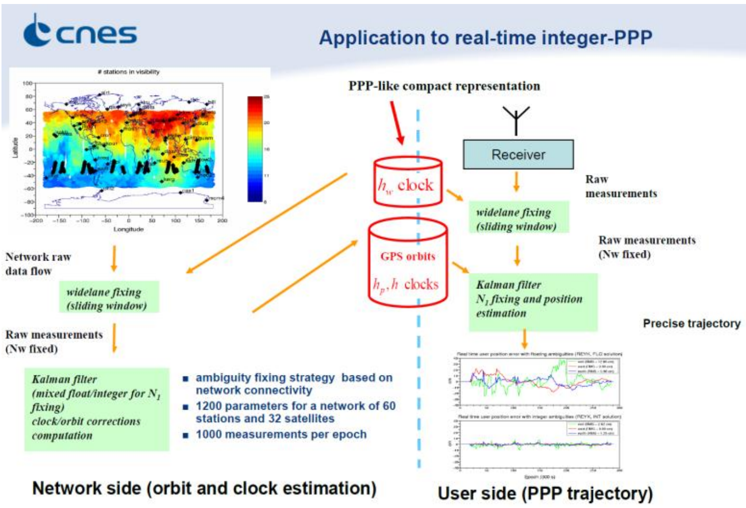

Figure 4: Diagram of the architecture of the CNES demonstrator (Laurichesse, 2011).

In practice, the CNES demonstrator is used in the same way as the BNC NTRIP Client (it is a modified version of this to incorporate AR). It is a matter of simply selecting the relevant streams, in this case the modified correction stream from the CNES caster, an IGS ephemeris stream, and raw observation data. Similar to the BNC Ntrip Client, the PPP engine will determine a PPP solution (AR in this case) and can be compared to ‘true’ coordinates for station monitoring. The demonstrator can also be used to measure an AR PPP solution in kinematic mode, and is able to determine an AR PPP solution globally.

Figure 5 shows the horizontal and vertical accuracy of the AR PPP solution using the CNES Real Time Integer PPP Demonstrator at IGS station FFMJ. This example can be found on the CNES website dedicated to the demonstrator http://www.ppp-wizard.net which states this example as a ‘typical example’.

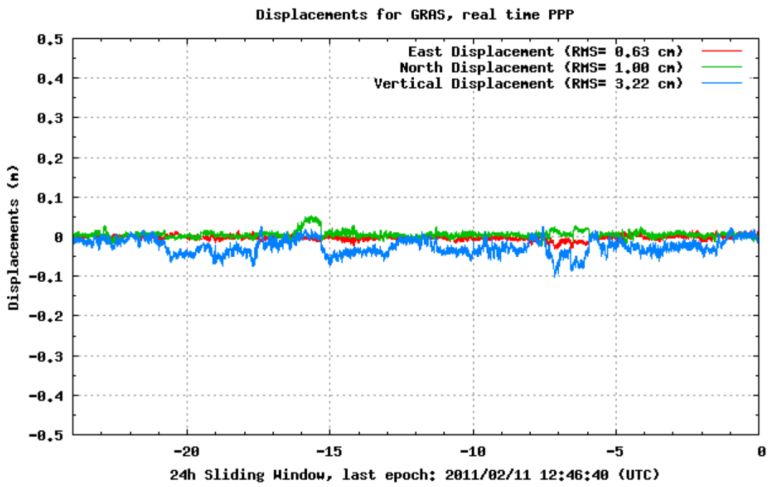

Figure 5: AR PPP accuracy for station FFMJ using CNES demonstrator (Laurichesse, 2011).

4.3 Nexteq's Ambiguity-Resolved PPP System.

Nexteq (a private company) has developed a similar approach to that of the CNES AR PPP method (however not in real-time), whereby the FCBs are established over a global network of receivers. By taking advantage of the stable-nature of the FCBs over a large area and using the ionosphere-free carrier-phase, ionosphere-free code and the MW observable, the FCBs of the narrow lane ambiguities can be obtained. Once the network FCBs have been determined then the FCBs for both the narrow and wide lane observables are sent to the user.

To demonstrate this method, Urquhart *et al*. (2012) processed 6 hours of data in kinematic mode, using FCBs determined from a global tracking network. Figure 6 shows the results at two stations, in which the AR PPP solution (in red) out-performs the float PPP solution (in blue). The time taken for the ambiguities to converge to their final integer value was typically 20-30 minutes.

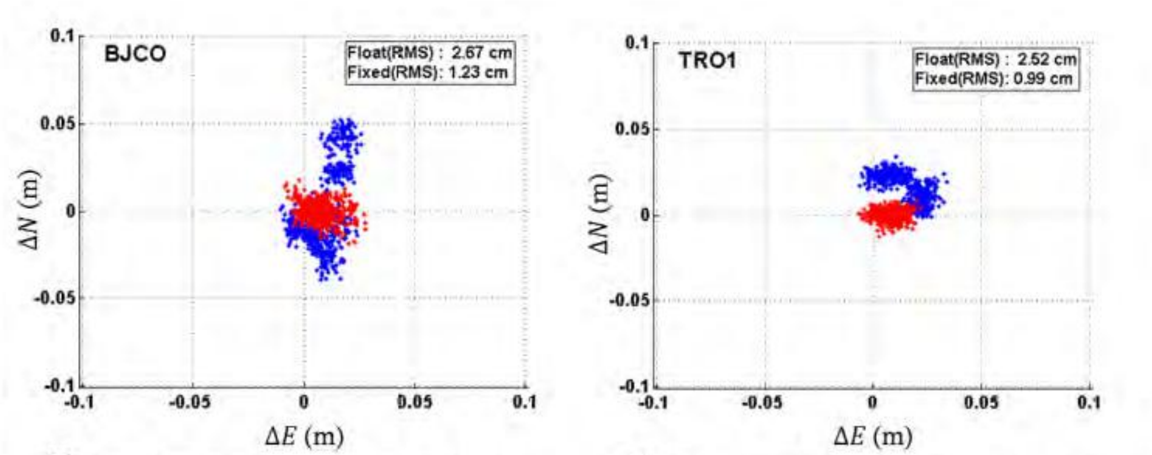

Figure 6: AR PPP (Red) Vs Float PPP (Blue) accuracy for station BJCO and TRO1 using Nexteqs FCB estimates from a global network of stations (Urquhart *et al*., 2012).

Urquhart *et al*. (2012) also tested the quality of the narrow lane FCB estimates over various sized networks. Their testing included a global network of 35 stations, a regional network of 10 stations with inter-station distances in the order of 1000 km, and a local network comprising 10 stations with inter-station distances of 80-150 km. In this case all wide lane biases used for fixing wide lane ambiguities were determined from a global network.

It was found that the narrow lane fixing success rate was approximately 90% for the global network, 93% for the regional network and 98% for the local network, from this it was concluded that for larger areas, the FCBs are contaminated with residual errors such as atmospheric and orbit errors, which could pose more of an issue when using less precise orbits such as real-time orbits. Furthermore, performing AR-PPP at test stations in North America using narrow lane FCBs determined in a global and regional network showed that regional AR-PPP performed slightly better than global AR-PPP in both the Northing and Easting components.

4.4 GMV's *Magic*PPP Real Time Demonstrator Service.

GMV (a privately owned technological business group) has been developing its own infrastructure aimed at providing real-time GPS and GLONASS orbits and clocks. In GMV's approach, GPS and GLONASS satellites are processed together to ensure a consistent solution is provided. Due to GLONASS satellites transmitting individual frequencies (FDMA as opposed to CDMA used by GPS), an inter-channel bias must be estimated when processing GLONASS data. The final products, i.e. real-time satellite orbits and clocks, are available as a real-time data stream in standard formats and may be used for RT-PPP using GMV's *magic*GNSS PPP service. The network used to determine the orbit and clocks provides global coverage with some redundancy and is comparable to the IGS service; the clock RMS is around 0.3 nanoseconds compared to the IGS rapid product (75ps RMS) and the prediction orbit is around 6cm of the IGS rapid orbit product (~2.5 cm) (Mozo *et al.*, 2012).

The GMV *magic*PPP demonstrator was developed to evaluate RT-PPP performance in realistic scenarios (kinematic and static). Its aims included providing an end to end process including communications, robustness and reliability and the ability to implement on portable devices.

GMV has used its *magic*PPP demonstrator to test a PPP solution in several scenarios including in kinematic mode. As part of the testing, a receiver was mounted onto the roof of a car to test the RT-PPP solution in kinematic mode. This test showed that during the collection of data (a 15 km route around a base station) the solution degraded when a lower amount of satellites were in view due to obstacles such as trees and buildings. This degradation can result in a re-estimation of the ambiguities which can take up to 20 minutes to achieve. It was noticed that the inclusion of both GPS and GLONASS observations during this testing was an advantage as more satellites were in view, limiting the instances of a re-estimation of the ambiguities being needed (Mozo *et al.*, 2012).

Currently research is being carried out at GMV into developing strategies to reduce convergence times (non-integer ambiguity-resolved techniques). One such strategy that is used is the 'quick start' feature which involves starting at a point that has coordinates known within a few centimetres. Use of this feature can lead to convergence within a few seconds (Mozo *et al.*, 2012).

Other researchers and groups are working at improving RT-PPP including using differing techniques. One such technique involves the resolution of ambiguities in a RT-PPP solution by developing a PPP algorithm for L1 and L2 raw observations in which the ionospheric delay parameters are constrained by a derived real-time Global Ionospheric Maps (GIMs) model. Li (2012) carried out testing using this technique in which real-time products including orbits, clocks and GIMs were generated by GMV based on the IGS and EUREF (Regional Reference Frame Sub-Commission for Europe) data streams. RTK PPP using traditional and this new method was carried out at 60 sites globally. It was shown that this new method shortened the observation times for a reliable ambiguity fixed solution by 25% (20 to 15 minutes). It also showed that this method could eliminate the re-convergence time needed (normally 20 minutes) after a data gap or cycle slip, provided the gap length is only a few minutes in length (due to the acquired knowledge of the ionospheric delay within the system).

Collins et al. (2012) used a similar technique in which external ionospheric constraints are applied. In this method AR RT-PPP is possible but instead of receiving the external ionospheric delays from a source utilising a network of receivers (regional or global), the delays are sourced through peer-to-peer type communication, i.e. if another user is in an area close enough to experience similar ionospheric delays, then the ionospheric delay already estimated by that receiver can be used to allow for fast convergence times by the new user. Although this method may seem unconventional, with the progression being experienced by the precise positioning industry it may not be long before this type of mechanism becomes feasible.

4.5 Trimble's CentrePoint RTX Global Service

As well as the much publicised Trimble RTX regional solution, which uses a global CORS network (similar to the IGS's) for the computation of precise satellite orbit and clock corrections and a regional CORS network to determine local atmospheric corrections, Trimble Terrasat has also been working on a full global RTX service. Following principles similar to that of Li (2012) in which the ionospheric delays are constrained to resolve ambiguities, Trimble have devised a product that provides a global RT-PPP service with a convergence time between 10-45minutes. The advantage of this method (as with the method described by Li, 2012) is that using the knowledge within the system of the ionospheric behaviour, re-convergence after a short outage (3-minutes) can be almost instantaneous. Figure 7 shows the comparison between a cold start convergence and a re-convergence using the global RTX system.

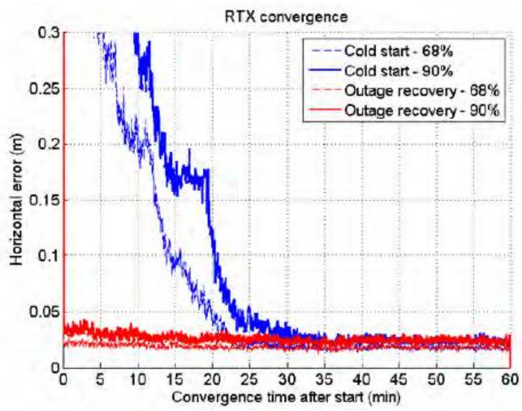

Figure 7: RTX re-convergence results (Leandro *et al.*, 2012).

The Trimble global RTX system also employs a fast-start system that allows semiinstantaneous convergence by using a known starting position. This allows geometric distance within the equation to be known, leaving only the neutral atmosphere delay and the receiver clock as the only unknowns. The RTX system will store the last position of the antenna, e.g. if precision farming where the tractor stopped, and use this as the known starting position when a new initialisation is needed (Leandro *et al.*, 2012).

4.6 Real Time Kinematic PPP

The aim of AR RT-PPP is to deliver RTK performance whilst maintaining the advantages of PPP. The recent progress being made on AR PPP outlined above, allows for an easier kinematic solution. To demonstrate the ability to perform kinematic AR RT-PPP, an experiment was conducted to compare the performance of conventional RTK and kinematic RT-PPP by GMV using the CNES PPP-wizard demonstrator (Laurichesse, 2011). In this experiment, the receiver was kept stationary until initialisation was gained then moved in a loop trajectory. The trajectory was computed in real-time by the CNES demonstrator and later reconstructed using RTKLIB (differential GNSS RTK technique) using a nearby reference station. The measurements were output at 1 Hz, however the PPP-wizard trajectory was only available every 5 seconds (due to the clock corrections). Figure 8 shows the two trajectories; the PPP-wizard solution in red and the RTKLIB (differential) solution in green.

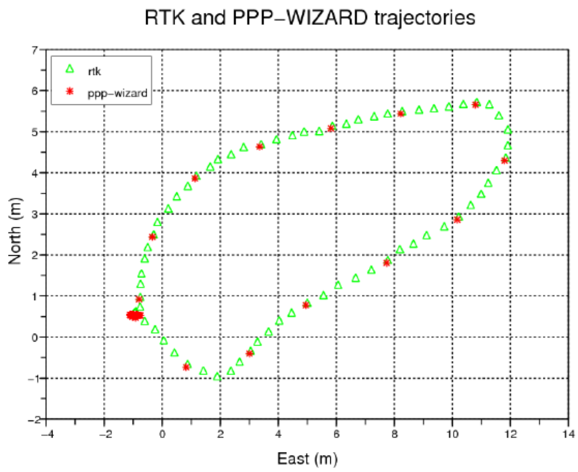

Figure 8: Antenna trajectories of RTK and PPP-wizard (Laurichesse, 2011).

During the kinematic part of this experiment, the two trajectories were within centimetres of each other, highlighting the ability of AR RT-PPP to perform accurate kinematic positioning, albeit at a maximum rate of 5 seconds.

5. IMPROVING RT-PPP USING TRIPLE FREQUENCIES

Triple frequency measurements, available now on the GPS constellation (L5 signal; restricted to four satellites at present in May 2013) and the Galileo constellation (four satellites available at present in May 2013) can potentially mitigate the issue of slow convergence/fix times for RT-PPP in that they allow for three choices for the ionosphere-free pseudorange (between P1, P2 and P5). This allows for manipulation of the various combinations that can assist in accelerating the narrow lane ambiguity (Geng and Bock, 2012).

These authors have devised a method whereby an ambiguity-fixed extra wide lane carrier phase on L2 and L5 (fixed almost instantaneously) is combined with the wide lane carrier phase on L1 and L2 to form an ionosphere-free observable with a 3.4 m wavelength, which allows for very efficient narrow lane ambiguity resolution.

Table 2 shows the RMS in East, North and Up components between ground truth and positions derived from ionosphere-free pseudorange and the wide lane carrier phase (using three frequencies) method from a simulated study. This highlights the improvement in the accuracy of this technique particularly in the Up component. These improvements reduce the search space required to fix the narrow lane ambiguities and hence reduce the convergence times needed to reach a fixed ambiguity PPP solution.

Session	Pseudorange			Carrier-phase		
	East	North	Up	East	North	Up
1	2.4	2.5	11.5	1.6	1.5	2.9
2	3.9	4.2	17.7	1.8	1.9	3.8
3	6.8	8.0	31.7	2.7	3.0	5.9

Table 2: RMS in East, North & Up components (in metres) between ground truth and positions derived from ionosphere-free pseudorange and wide lane carrier phase (using three frequencies) (Geng and Bock, 2012).

Furthermore Geng and Bock (2012) showed from their simulations that wide lane ambiguity resolution was possible within 2, 4 and 20 seconds (3 simulated sessions), and concluded that as rapid wide lane ambiguity is crucial to narrow lane ambiguity resolution and due to the improved accuracy of the wide lane ambiguity resolution, narrow lane ambiguity resolution could be achieved in a few minutes (this was in a simulation test only, where ionosphere effects and FCBs were not specifically accounted for). The study also simulated multipath effects and concluded that triple frequency demonstrated superiority over dual frequency in processing multipath-contaminated GPS measurements.

5.1 Triple Frequency Real Time PPP demonstration

Fugro has recently demonstrated RT-PPP based solely on Galileo signals (Galileo currently consists of a constellation of four satellites, the minimum required to permit calculation of a Galileo-only position). Fugro achieved this task on March 18, 2013 which was within a week of all four Galileo satellites being activated. Fugro generates Galileo orbit and clock corrections which can be used in conjunction with the Fugro G2 decimetre level corrections to achieve a RT-PPP solution. Figure 9 plots the accuracy of the Galileo/GPS/GLONASS solution at a station in Oslo, Norway over a 2-hour time period. From this plot it can be seen that the noise level of the position is better with Galileo alone than when GPS and GLONASS satellites are also used even though the satellite geometry is much worse in the Galileo-only solution (only four satellites available).

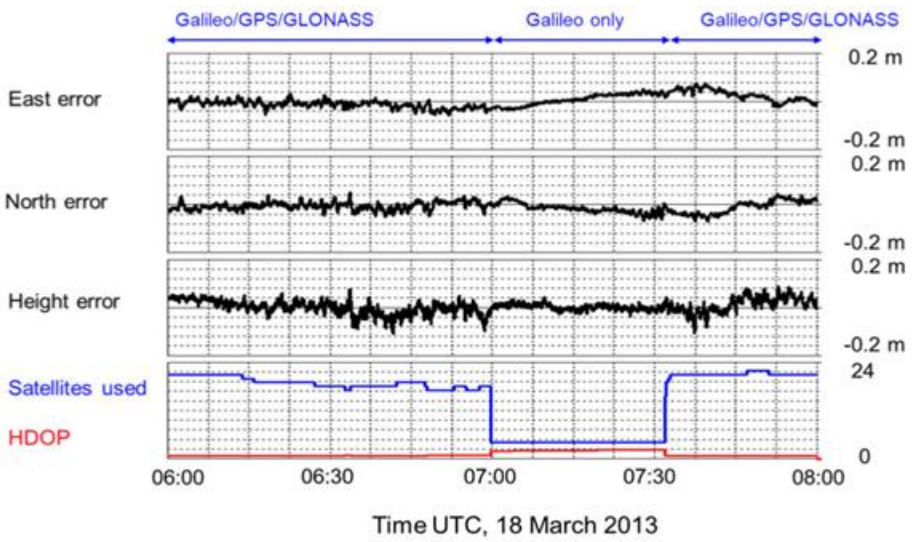

Figure 9: Accuracy of the Galileo/GPS/GLONASS solution at a station in Oslo, Norway over a 2-hour time period (GPS World Staff**,** 2013).

These are encouraging results with only four available Galileo satellites, and should improve the performance of RT-PPP by the time a full constellation (26 satellite constellation by the end of 2015) is completed.

6. PPP USING A SINGLE-FREQUENCY GNSS RECEIVER

Since the majority of the mass-market GNSS users (navigation and GIS) use single-frequency GNSS receivers, RT-PPP using a single-frequency GNSS receiver will open up PPP to a broader range of applications. Accuracies of several metres have been demonstrated for point positioning using single-frequency GNSS observations (Choy *et al.*, 2009).

As an ionospheric-free linear combination cannot be attained when using a single frequency receiver, there are two options that can be used to acquire a sub-metre PPP solution (Bakker *et al*., 2012):

- A linear combination of the L1 code and carrier phase data can be used to eliminate the ionospheric delays, however this requires the carrier phase ambiguity to be estimated, leading to long convergence times.

- Ionospheric delays can be sourced externally, e.g. IGS provides GIM's that can be used to correct for the ionospheric delay, leaving only the receiver position and clocks as the unknown parameters. This leads to much faster convergence times.

In actual fact the single-frequency algorithm can converge much faster than the dual-frequency algorithm when using the latter method. This is due to the noise and multipath on L1 being amplified by a factor of 2.546 by the ionosphere-free combination (on a dual-frequency solution), and the L2 pseudorange being noisier by a factor of 1.546. However, once convergence has been reached the dual-frequency PPP solution will provide a more accurate solution than single-frequency (Bakker *et al*., 2012).

Recently, within the IGS, Associate Analysis Centres (ACC) have been collaborating on the development of a combined global IGS RT-Vertical Total Electron Content (VTEC) product. This collaboration is occurring under the umbrella of the IGS Ionosphere Working Group. From this working group it may be feasible to combine real-time VTEC products from several centres into a robust IGS real-time ionosphere product. Work to compare both solutions is underway with the goal of finding optimal ways to assess and combine these products into an IGS RT-VTEC product. The final aim is to produce a compatible product with ionosphere-correction information delivered in the RTCM-SSR standard (Caissy *et al*., 2012).

The advent of sub-metre accuracy single frequency RT-PPP on a global scale will open up the PPP market to a large number of users who would otherwise rely on standard hand-held GPS receivers that could provide solution that is accurate to only several-metres. This in turn will allow a host of new applications to become available to the mass GNSS market.

7. CONCLUSION

PPP main benefit over differential GNSS positioning techniques is the ability to provide an accurate position within a global reference frame with a single GNSS receiver. However, it must be noted that some form of regional/global CORS network is necessary to provide the correction products needed for PPP to provide high-accuracy positioning.

Post-processed products and services from organisations such as IGS and NRCan have allowed PPP to offer a viable alternative to post-processed differential solutions while maintaining the advantages of PPP.

Recent developments in the real-time distribution of correction products particularly from the IGS RTS have led to several techniques being advanced that allow for ambiguity-resolved RT-PPP solutions, thus offering PPP as a possible alternative to differential GNSS positioning techniques. In particular, the techniques exemplified in this paper (i.e. the CNES demonstrator, external ionospheric constraint technique and techniques taking advantage of triple frequencies) are working toward ways to provide an AR RT-PPP solution with reduced convergence times as a rival to existing differential GNSS positioning techniques.

The advent of real-time single-frequency PPP corrections such as ionospheric corrections opens up sub-metre accurate real-time global positioning to the mass market. This will compete with the differential wide-area augmentation systems offering similar accuracies at low cost (such as Omnistar and Starfire) or in some cases no cost, e.g. Wide Area Augmentation Systems (WAAS) in North America and the European Geostationary Navigation Overlay Service (EGNOS).

It is the authors view that in the near future, as these techniques mature (including advancements in differential GNSS positioning), that hybrid PPP and differential GNSS positioning techniques sourcing corrections from each other will provide a homogeneous, truly global precise positioning solution.

REFERENCES

Altamimi Z, Collilieux X, Métivier L (2011) ITRF2008: An improved solution of the international terrestrial reference frame, *Journal of Geodesy* 85(8): 457-473.

Anderle RJ (1976) Point positioning concept using precise ephemeris, *Proceedings of the International Geodetic Symposium*, Las Cruces, New Mexico, 47-75.

AUSPOS (2012) AUSPOS – Online GPS Processing Service, http://www.ga.gov.au/geodesy/sgc/wwwgps/ (accessed May 2013).

Bakker P, Van Der Marel H, Petovello M (2012) Single-versus dual-frequency Precise Point Positioning, *Inside GNSS*, 7(4): 30-35.

Caissy M, Agrotis L, Weber G, Hernandez-Pajares M, Hugentobler U (2012) Innovation: The International GNSS Real-Time Service, GPS World, 23(6): 52-58.

Choy S, Silcock D, Zhang K (2009) Single frequency precise point positioning using a low-cost GPS receiver, *Proceedings of the Surveying & Spatial Sciences Institute Biennial International Conference (SSC2009)*, Adelaide, Australia, 681-695.

CNES (2013) CNES PPP Demonstrator (PPP-Wizard Project), http://www.ppp-wizard.net/caster.html (accessed May 2013).

Collins P, Bisnath S, Lahaye F, Heroux P (2008) Undifferenced GPS ambiguity resolution using the decoupled clock model and ambiguity datum fixing, *Navigation* 57(2): 123-135.

Collins P, Lahaye F, Bisnath S (2012) External Ionospheric Constraints for Improved PPP-AR Initialisation and a Generalised Local Augmentation Concept, *Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation 2012*, Nashville, USA, 3055-3065.

Gao Y, Kongzhe C (2004) Performance analysis of Precise Point Positioning using real-time orbit and clock products, *Journal of Global Positioning Systems* 3(1-2): 95-100.

Gao, Y (2006) GNSS Solutions: Precise Point Positioning and its challenges, Aided-GNSS and Signal Tracking, *Inside GNSS*, 1(8): 16-18.

Ge M, Gendt G, Rothacher M, Shi C, Liu J (2008) Resolution of GPS carrier-phase ambiguities in precise point positioning (PPP) with daily observations. *Journal of Geodesy* 82(7): 389–399.

Geng J, Meng X, Dodson AH, Teferle F (2010) Integer ambiguity resolution in Precise Point Positioning: Method comparison, *Journal of Geodesy* 84(9): 569–581.

Geng J, Bock Y (2012) Triple frequency GPS precise point positioning with rapid ambiguity resolution, *Journal of Geodesy* (87):449-469.

GPS World Staff (2013) Real-time PPP with Galileo demonstrated by Fugro, http://www.gpsworld.com/real-time-ppp-with-galileo-demonstrated-by-fugro (accessed May 2013).

IGS RTWG (2007) The IGS Real-time Working Group Terms of Reference, http://www.rtigs.net (accessed April 2013).

IGS (2013) Real Time IGS Pilot Project Status Report (IGS Workshop presentation June, 2010), http://www.rtigs.net/docs/IGS_Workshop_June_2010_RTIGS_PP_StatusReport_3.pdf (accessed May 2013).

Janssen V, Commins R, Watson P, McElroy S (2013) Using GNSS CORS to augment long-term tide gauge observations in NSW, *Proceedings of the Surveying & Spatial Sciences Institute Conference (SSSC2013)*, Canberra, Australia.

Janssen V, Haasdyk J, McElroy S, Kinlyside D (2011) CORSnet-NSW: Improving positioning infrastructure for New South Wales, *Proceedings of the Surveying & Spatial Sciences Institute Biennial International Conference (SSSC2011)*, Wellington, New Zealand, 395-409.

Janssen V, McElroy S (2010) Coordinates and CORSnet-NSW: Dealing with distortions in GDA94, *Position*, 50, 24-27.

Kouba J (2009) A Guide to using International GNSS Service (IGS) products, Natural Resources Canada, http://igscb.jpl.nasa.gov/components/usage.html (accessed May 2013).

Laurichesse D, Mercier F, Berthais JP, Broca P, Cerri L (2009) Integer ambiguity resolution on undifferenced GPS phase measurements and its application to PPP and satellite precise orbit determination, *Navigation* 56(2): 135-149.

Laurichesse D (2011) The CNES real time PPP with un-differenced integer ambiguity resolution demonstrator, *Proceedings of the 24th International Technical Meeting of The Satellite Division of the Institute of Navigation 2011*, Portland, USA, 654-662.

Leandro R, Gomez V, Stolz R, Landau H, Glocker M, Drescher R, Chen X (2012) Development on global centimeter-level GNSS positioning with Trimble CenterPoint RTX, *Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation 2012*, Nashville, USA, 3089-3095.

Li X (2012) Improving real-time PPP Ambiguity resolution with ionospheric characteristic consideration, *Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation 2012*, Nashville, USA, 3027-3037.

Mozo A, Calle J, Navarro P, Piriz R, Rodriguez D, Tobias G (2012) Demonstrating in-the-field real-time precise positioning, *Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation 2012*, Nashville, USA, 3066-3076.

Odijk D, Teunissen P, Zhang B (2012) Single-frequency integer ambiguity resolution enabled GPS Precise Point Positioning, *Journal of Surveying Engineering* (138):193-202.

Urquhart L, Zhang Y, Lee S, Chan J (2012) Nexteqs integer ambiguity-resolved Precise Point Positioning system, *Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation 2012*, Nashville, USA, 3046-3054.

Zumberge JF, Watkins MM, Webb FH (1997a) Characteristics and applications of precise GPS clock solutions every 30 seconds, *Journal of Navigation* 44(4): 449-456.

Zumberge JF, Heflin MB, Jefferson DC, Watkins MM, Webb FH (1997b) Precise Point Positioning for the efficient and robust analysis of GPS data from large networks, *Journal of Geophysical Research* 102(3): 5005-5017.