

Precise Point Positioning: Is the Era of Differential GNSS Positioning Drawing to an End?

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SUMMARY

For three decades the differential GPS (DGPS), and subsequently DGNSS, technique has been the dominant operational mode for precise positioning for the geoscience, geospatial and navigation communities. All DGNSS techniques perform positioning relative to one or more reference GNSS receivers located at points of known coordinates. Depending upon the type of GNSS measurement, user equipment, reference receiver infrastructure, data processing algorithm, ancillary products or services, and operational requirements (e.g. real-time or post-mission, moving or static user equipment, good or poor satellite and reference receiver geometry, etc.), different levels of performance are obtained. For example, the basic DGNSS technique using single-frequency pseudo-range measurements can deliver few-metre to sub-metre positioning accuracy, in either local-area DGNSS or wide-area DGNSS implementations. The processing of carrier phase data enables sub-decimetre-level accuracy, with the highest operational accuracy being possible (at the few-centimetre level) using the most sophisticated receiver equipment and algorithms, even in real-time and with the user equipment in motion (the so-called RTK mode). RTK techniques are now indispensable for precise navigation, machine automation, surveying and mapping. Over the last decade many government agencies and private companies have established permanent reference receiver networks (or CORSs – continuously operating reference stations) to support RTK users. This positioning infrastructure is expensive to establish and maintain at the appropriate density (e.g. number and distribution of CORS), quality (e.g. monumentation), functionality (e.g. multi-GNSS receivers), integrity (e.g. signal quality monitoring and datum) and robustness (e.g. terrestrial or satellite communications link between CORS and users). Over the same time period the technique of Precise Point Positioning (PPP) has been touted as an alternative for the “infrastructure-hungry” carrier phase-based DGNSS techniques. Although PPP suffers from several disadvantages – slow convergence times, no user equipment supports real-time algorithms, no real-time satellite orbit and clock data streams, uncertain coordinate datum – recent PPP developments could address most of these disadvantages. This paper describes the current knowledge of PPP, progress in the development of software, algorithms and data standards, and the provision of real-time services to support PPP, with a particular focus on the IGS (and commercial) products and the new role of CORS to provide augmentation services to PPP users. The paper also speculates on the evolving role(s) of CORS networks in the context of future PPP, and whether DGNSS techniques will be largely replaced by PPP techniques.

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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 – <http://igs.org>), to perform point positioning using a single GNSS receiver.

PPP methods differ from differential GNSS (DGNSS) positioning methods in that differential techniques require access to the observations of one or more reference stations with known coordinates (Grinter and Roberts, 2011). This suggests that the PPP technique has an advantage over differential methods in that only a single receiver is necessary (at the user's position), removing the need for the user to establish their own local reference station or to have access to observations from one (or more) reference station(s) operated by others. Consequently, the spatial operating range limit of differential techniques is overcome, as well as the need for simultaneous observations at both user and reference receivers. The "operating limit" for DGNSS varies from about 10 km in the case of the centimetre-level accuracy, carrier phase (CPH) based positioning techniques that use a single reference station, to perhaps several tens of kilometres in the case of network-based CPH techniques, to several hundreds of kilometres for metre-level accuracy, pseudo-range (PR) based positioning techniques (Rizos, 2010). (In this paper the focus will be on CPH-based GNSS positioning techniques.) Furthermore, PPP obviates the need for the user to obtain the reference station(s) observation data either in real-time or post-mission. Hence, overall, there is a reduction in labour and equipment costs, as well as simplified operational logistics (Gao, 2006).

PPP also provides a positioning solution in a dynamic, global reference frame such as the International Terrestrial Reference Frame (ITRF, see Altamimi et al., 2011), negating any local distortions associated with differential positioning techniques when local coordinates are used at the Continuously Operating Reference Station (CORS). However, it is important to fully understand the implications of transforming between a global and a national or local datum. This issue will not be dealt with in this paper, and the reader is referred to discussion in, for example, Haasdyk and Janssen (2011, 2012).

However, the use of a single GNSS user receiver for PPP traditionally has also had a number of severe disadvantages, the most significant being the long convergence times (of the order of 20 minutes or more) necessary for the ambiguity float solution to converge so as to ensure centimetre-level positioning accuracy. This has limited its use in real-time applications. Since the ambiguity terms of the undifferenced CPH observations are no longer integers due to the initial phase biases (which are differenced out in the "double-differencing" of data, as in the

case of DGNSS techniques), reducing the time for resolving integer ambiguities (as required for centimetre-accurate solutions) is much harder to achieve.

Furthermore, because differencing techniques are not used in PPP algorithms, no relative ionospheric measurement delays can be assumed to cancel (or at least be significantly mitigated), and consequently dual-frequency receivers (capable of generating the 1st order ionosphere-free linear combination) are required for decimetre-level accuracy positioning (although this is also the case for differential techniques when the inter-receiver distance typically exceeds a few tens of kilometres).

PPP also requires a number of corrections to be applied to account for centimetre-level variations in undifferenced PR and CPH observation biases. In addition, phase wind-up corrections, satellite antenna phase centre corrections, solid earth tide corrections and ocean loading corrections are all necessary for accurate PPP solutions, but not considered for standard DGNSS techniques (i.e. short/medium-length static baselines, kinematic and Real-Time Kinematic (RTK) techniques) (Rizos, 2010). Table 1 lists the correction biases or errors to be modelled or otherwise accounted for in the case of PPP compared to differential positioning techniques.

Table 1: Biases and errors that need to be applied or accounted for in typical PPP and differential GNSS positioning techniques.

Correction Type	PPP	Differential GNSS
Satellite Specific errors		
Precise satellite clock corrections	✓	✗
Satellite antenna phase centre offset	✓	✓
Satellite antenna phase centre variations	✓	✓
Precise satellite orbits	✓	✓/✗
Group delay differential	✓ (L1 only)	✗
Relativity term	✓	✗
Satellite antenna phase wind-up error	✓	✗
Receiver Specific Errors		
Receiver antenna phase centre offset	✓	✓
Receiver antenna phase centre variations	✓	✓
Receiver antenna phase wind-up	✓	✗
Geophysical Models		
Solid earth tide displacements	✓	✗
Ocean loading	✓	✗
Polar tides	✓	✗
Plate tectonic motion	✓	✗
Atmospheric Modelling		
Tropospheric delay	✓	✓
Ionospheric delay	✓ (L1 only)	✗

This paper gives a brief history of the development of PPP and reviews the advances made in PPP over the last two decades, with an emphasis on the past few years. The paper introduces post-processed online services, planned real-time PPP implementations as well as current commercial services, advances in integer ambiguity resolution for PPP, and the emergence of so-called “network-based” PPP techniques. The evolution of the IGS and commercial service providers in the context of supporting post-processed and real-time PPP techniques, now and in the future, will be briefly discussed. The paper also speculates on the evolving role(s) of CORS networks in the context of future PPP.

2. BRIEF HISTORY OF PPP

Whilst the evolution of PPP dates back to Anderle (1976), it was not until the late 1990s that this technique was seriously studied. Over the last two decades, dual-frequency PPP has been extensively researched, and several PPP software packages have been developed. It has been demonstrated that centimetre-level point positioning is achievable in post-processed, static receiver mode, and potentially also for kinematic applications (e.g. Zumberge et al., 1997; Gao and Kongzhe, 2004; Choy, 2009).

Recently, increased attention has focused on accessing accurate satellite orbits that have been computed with low latency and are available with frequent updates, or even orbits that have been “predicted” – such as the IGS ultra rapid orbits, cf. Table 2 – with the aim of supporting real-time or “near” real-time kinematic PPP applications. Discussions within IGS have been concerned with the provision of a real-time service to support an increasing demand in real-time products such as orbits, satellite clocks, and atmospheric parameters. The IGS Real Time Working Group (RTWG) was established to address issues relevant to the development of IGS real-time infrastructure and products. It has been running a pilot project for the past two years (<http://www.rtigs.net>), which has been such a success that the IGS may launch a real-time service in mid-2012 (Rizos, pers. comm.).

While post-processed PPP has many applications in geodesy – such as determination of the coordinates of receivers for the densification of the ITRF datum, or of static receivers in the context of earthquake studies (for determining pre-, co- and post-seismic motion), and the estimation of tropospheric delay – its use as an alternative positioning technique to DGNSS for surveying and mapping applications has been limited. This fact can be attributed to several reasons. Firstly, with the advent of cost-effective, centimetre-level accuracy, RTK-GNSS positioning provided by an increasing number of CORS networks around the world, there has been little need for PPP, a technique that does not (directly) use CORS services. Secondly, the availability of data products (i.e. orbits and satellite clock information) could, until recently, only support decimetre-level accuracy PPP via post-processed solutions. Thirdly, the RTCM message and data product standards to support PPP positioning are comparatively immature. Fourthly, no commercial off-the-shelf GNSS receivers have been marketed capable of generating positioning solutions using the PPP algorithm in real-time.

Nevertheless the PPP technique can be considered as a useful “fill-in” service for existing regional CORS networks, such as CORSnet-NSW (Janssen et al., 2011), in areas where dense

CORS coverage is not justified due to low population density or economic reasons (such as in developing countries). Will PPP be anything more than a niche high-accuracy GNSS technique? Advances have been made in PPP, especially in the past few years, which address the abovementioned limitations of PPP, and have the potential to increase the applicability of PPP techniques.

3. PPP SERVICES

3.1 Post-Processed PPP

At present, post-processed PPP (PP-PPP) offers the most comparable accuracies to DGNSS positioning techniques. Free PPP post-processing services such as Auto-GIPSY (<http://apps.gdgps.net/>) and CSRS-PPP (http://www.geod.nrcan.gc.ca/products-produits/ppp_e.php) provide converged float solutions at the centimetre-level, thereby allowing PPP to offer a viable alternative to post-processed DGNSS solutions. Users upload their observed RINEX data files to such online services, and the coordinate solution for the (static or kinematic) GNSS receiver's position is computed automatically. Note, however, that long observation session times (several hours) are required to obtain "comparable accuracies", and therefore the applications are typically restricted to the establishment of geodetic control using GNSS technology. This is in contrast to "high-productivity" GNSS techniques which are used to determine the coordinates of points (or a user receiver's trajectory) with centimetre accuracy, with just a few seconds or minutes of measurement epoch data (Rizos, 2010).

Ebner and Featherstone (2008) investigated a geodetic network solution across a 550 km by 440 km area in Western Australia composed of 46 points with 5-day GNSS receiver occupations. It was found that CSRS-PPP solutions were generally not significantly different from using the Bernese software (processing data in differential-network GNSS mode) solution used as ground truth. Whilst it was acknowledged that PPP was inherently less accurate than network-processed GNSS due to the inability to fix CPH integer ambiguities, this was balanced against the advantages of PPP. As PPP requires only a single dual-frequency GNSS receiver, this significantly reduced the equipment and personnel needed, as well as the pre-planning and logistics involved in a conventional network-based static GNSS geodetic survey. Furthermore, the processing time and skills needed to process conventional GNSS baselines is greater, compared to PP-PPP which involves sending the observed data files to a third party for coordinate determination. It was concluded that PPP yields a "slightly lower accuracy" but is a more cost-effective alternative to establishing geodetic control, particularly applicable in remote areas or developing countries. The authors also noted that at least two continuous days of observations were required to achieve reliable results, in this case interpreted as a PPP coordinate solution within 20 mm of the Bernese solution.

Grinter and Janssen (2012) compared PPP results from 1-hour, 2-hour, 4-hour, 12-hour and 24-hour observation datasets collected at 20 sites against coordinates derived from a Bernese network solution. It was found that PP-PPP was able to provide comparable results to DGNSS techniques for survey-accuracy (assumed to be within 25 mm in Easting/Northing and 35 mm

in Ellipsoidal Height), static applications using observation spans of 4 hours. The risk of outliers was minimised by utilising a longer observation window, while no further improvement was apparent between the 12-hour and 24-hour solutions within the specifications set for the study.

There are a number of PPP software packages that are capable of post-processing GPS (and in some cases GLONASS) data files. Most of these are software written by individuals at universities or research organisations. A well-known open source package is RTKLIB (<http://gpspp.sakura.ne.jp/rtklib/rtklib.htm>). As far as the authors are aware, there is no PP-PPP software offered by the mainstream GNSS instrument manufacturers. In addition, it must be emphasised that it is the availability of accurate satellite orbit and clock information from organisations such as the IGS (cf. Table 2) that makes PP-PPP viable at all.

3.2 Real-Time PPP

Operating in real-time is far more challenging than in post-processed mode. The critical issues are availability of measurement (and other) data, in real-time, over a wireless communications link, in a standard format that would allow GNSS receivers to operate reliably with minimum constraints and with comparative ease.

In the case of DGNSS techniques, the data that must be transmitted to user receivers is essentially the “raw” PR and CPH measurements from one or more reference receivers. Typically these are provided by a CORS network or user-operated reference receivers, either by a direct wireless link from the nearest reference receiver to the user, or via a link to a central network command centre (that itself monitors a network of reference receivers on a continuous, epoch-by-epoch basis). The broadcasts to users are by any physical means, such as short-range VHF/UHF, WiFi, mobile telephony or satellite communications link, and the data message format is in an industry standard such as RTCM (<http://www.rtcn.org>). There is no need for the transmission of ancillary data, such as precise satellite orbit or clock information, as the broadcast navigation message (modulated on the GNSS satellite L-band transmissions) contains system information accurate enough to support centimetre-level relative positioning. There are a number of implementations of high-accuracy DGNSS techniques such as RTK-GNSS and “network-based” RTK-GNSS (or NRTK-GNSS) (e.g. Rizos, 2010).

Contrast that to real-time PPP (RT-PPP). In conventional PPP (real-time or post-processed modes) the only raw PR and CPH measurement data that is required is that of the user’s own receiver. Here lies the attraction of PPP – no CORS or user-operated temporary reference receiver, and hence obviously no requirement for a wireless communications link to external receivers, is required. But unlike DGNSS techniques, operating over inter-receiver distances of several tens of kilometres (in RTK-GNSS and NRTK-GNSS implementations), in order to ensure centimetre-level accuracy PPP results, sub-decimetre accuracy GNSS orbit information and sub-nanosecond accuracy satellite clock information are required. Furthermore, this information is required in real-time (or very low latency, perhaps no more than several seconds delay) at the user receiver (running the RT-PPP algorithm). This is a

significant impost, both in terms of the provision of real-time satellite system data, and the wireless communications to access such data products. (It must be acknowledged that precise satellite orbit and clock information need not be computed “locally”, as such a process requires a relatively sparse ground reference station infrastructure and the data analysis capability can be centralised at a few computational facilities with the relevant expertise.)

The IGS RTWG has been investigating the issues associated with real-time CORS infrastructure and data products, and has been running a pilot project for the past two years (<http://www.rtiigs.net>). The IGS plans to launch a Real-Time Service (IGS-RTS) in mid-2012. However, there are a number of issues that must be addressed in RT-PPP were it to be based on IGS products, not the least of which is (a) the mode of distribution of the real-time orbit and clock products, and (b) the format for such messages. To encourage user uptake of RT-PPP, the provision of IGS-RTS products on its own is not a sufficient condition (though it is an essential condition unless there is a commercial alternative to IGS-RTS products). Instrument manufacturers must implement RT-PPP algorithms inside GNSS receivers. This is generally presaged by the development of appropriate RTCM standards for the broadcast of precise orbit and clock information.

In an interesting development, recently a new, commercial real-time positioning product known as “Trimble RTX” has been released in the United States, bridging the “gap” between RT-PPP and NRTK-GNSS (Chen et al., 2011). A global CORS network (similar to the IGS’s) allows for the computation of precise satellite orbit and clock corrections, while a regional CORS network is used to determine local atmospheric corrections. It is claimed that this technique is capable of providing real-time positioning at the 4-centimetre level horizontally (95%), with initialisation times of less than one minute, delivering the necessary orbit and clock information via an L-band satellite downlink from a geostationary satellite. However, this is a proprietary system using non-industry standard message formats, and hence only Trimble brand user receivers (with special antennas able to track the necessary satellite communications link) can use such a RT-PPP service. Note, however, such a “network-based” RT-PPP technique may boost the popularity of PPP because it addresses several of the drawbacks of conventional PPP, although it must use some CORS infrastructure in order to do so.

4. DEVELOPMENTS IN PPP TECHNIQUES

Reference will only be made to those developments that improve the PPP technique so as to challenge the utility of DGNSS techniques for high-accuracy, high-productivity positioning (including in kinematic mode) applications.

4.1 From GPS to GNSS

The availability, reliability and positional accuracy of PPP are strongly dependent on the number of visible satellites. Currently, PPP processing software and online services often only process GPS observations, using the precise GPS satellite orbits and clock corrections available from organisations such as the IGS (Table 2). Apart from the “ultra rapid

(predicted)” (URP) product, the others only support PP-PPP. Note that although the predicted orbits are accurate enough for decimetre-level PPP (by assuming that the URP products have been downloaded hours in advance and are available for use by the receiver/computer at the instant measurements are made, i.e. in “real-time”), the predictability of the satellite clock corrections is relatively poor. A RT-PPP service would require an order of magnitude improvement in satellite clock estimates by effectively shortening the time between measurements being made by the PPP service provider’s CORSSs, transferred to an analysis centre where the clock parameters are estimated, and then disseminated to RT-PPP users. This, of course, is the basis of the planned IGS-RTS as well as commercial alternatives such as Trimble’s RTX (Chen et al., 2011).

Table 2: Precise GPS satellite orbits and clock corrections provided by IGS (<http://igs.org/components/prods.html>).

Product	Parameter	Accuracy	Latency
Ultra Rapid (predicted)	Orbit	10 cm	Real Time
	Clock	~ 5 ns	
Ultra Rapid (estimated)	Orbit	< 5 cm	3 hrs
	Clock	~ 0.2 ns	
Rapid (estimated)	Orbit	< 5 cm	17 hrs
	Clock	0.1 ns	
Final (estimated)	Orbit	< 5 cm	~ 14 days
	Clock	< 0.1 ns	

Despite the full constellation of GPS satellites, the number of visible satellites may be insufficient in areas such as urban canyons and mountainous regions. Even in open areas, poor satellite geometry may degrade the positional accuracy of PPP (as is the case of differential techniques). The ability to utilise extra satellites available in the GLONASS constellation enhances the capabilities of PPP and its possible applications (e.g. Cai and Gao, 2007; Azab et al., 2011). Currently four IGS analysis centres routinely provide GLONASS precise orbit products. The independent GLONASS orbits are of 10-15 cm level accuracy, and orbits from the four organisations are combined to generate the IGS final GLONASS orbits. Only two data analysis centres, IAC and ESA/ESOC, provide GLONASS clock data, accurate at the 1.5 ns level.

The use of GLONASS in *kinematic* PPP can further enhance the potential applications available to PPP. Currently the two IGS analysis centres offering GLONASS clock corrections provide satellite clock correction values with 5-minute intervals. Since this temporal density is not sufficient for most kinematic PPP applications, interpolation of the satellite clock corrections is necessary. Hesselbarth and Wanninger (2008) interpolated the GPS/GLONASS clock corrections produced by ESA/ESOC to 1-second corrections and analysed several PPP processing algorithms with kinematic GNSS observations. It was found that adding GLONASS satellites reduces PPP convergence times by about a factor of two. At intervals less than 30 seconds, no improvement in convergence times was evident.

The Galileo and Beidou constellations are currently being deployed. The IGS has launched a new initiative, the “Multi-GNSS Experiment” or M-GEX (see Call for Participation at ftp://igs.org/pub/resource/pubs/IGS_M-GEX_VF.pdf), seeking to establish a global tracking network of multi-GNSS capable tracking receivers and to encourage the analysis of the M-GEX data in order for the IGS analysis centres to gain valuable experience in computing satellite orbits and satellite clock products. M-GEX is a global project, commenced on 1st February 2012 and running to the end of August 2012 (at least in its first phase), that incorporates the regional multi-GNSS initiative of the Japanese Aerospace Exploration Agency (JAXA), seeking to promote the use of GNSS (including the JAXA Quasi-Zenith Satellite – the first of Japan’s GNSS augmentation satellites, see http://www.satnavi.jaxa.jp/e/news/qz-1109222_e.html). However, it is still too early to confidently predict the full benefits of multiple GNSS constellations – where over 100 satellites broadcast up to four times that number of signals on which PR and CPH measurements can be made.

4.2 PPP and Ambiguity Resolution

Conventional PPP involves the use of float solutions which require long observation times (>20 minutes) to converge to centimetre accuracy. Whilst this is a relatively short observation time for static positioning, it restricts the use of PPP for real-time and so-called “high-productivity” positioning applications. The fixing of integer ambiguities is usually only applied to double-differencing, as all unknown non-integer biases are eliminated or significantly mitigated in the measurement differencing process. Although the fixing of integer ambiguities is a particularly difficult challenge in undifferenced measurements, several methods have been developed to address this (e.g. Ge et al., 2008; Laurichesse et al., 2009; Collins et al., 2010; Geng et al., 2010; Laurichesse, 2011). *In all cases, a CORS network is utilised to aid fixed integer ambiguity resolution.* This, in turn, reduces the time it takes to achieve centimetre-level positioning accuracy, in principle allowing RT-PPP operations. However, the ability to constrain and correctly predict the ionospheric delay remains a key factor in enabling integer ambiguity resolution for PPP (Collins and Bisnath, 2011). It is therefore unlikely that a PPP solution using a global or wide-area CORS network will ever become as effective as short/medium-baseline RTK-GNSS or NRTK-GNSS techniques, due to the difficulty in providing sufficiently precise ionospheric corrections.

The Galileo constellation, once fully operational, is expected to enhance fixed integer ambiguity resolution for PPP (there are currently four satellites in orbit) because of the broadcast of signals in three frequency bands. Again relying on the use of a CORS network, Henkel and Günther (2008) proposed two methods taking advantage of the different frequencies available from Galileo. China’s Beidou constellation will also transmit on a minimum of three frequencies (there are already more than ten satellites in orbit). However, there is no 100% interoperability between the four GNSS constellations on three frequencies (i.e. it is not possible to mix PR or CPH measurements from GPS, GLONASS, Galileo and Beidou in triple-frequency combinations). Nevertheless, one would expect that the

widespread availability of triple-frequency GNSS signals by the end of the decade will significantly speed up ambiguity resolution for *both* PPP and DGNSS techniques.

4.3 Single-Frequency PPP

Although the prospect of triple-frequency PPP is tantalising, such a capability is many years away from being a reality. On the other hand, dual-frequency PPP has already demonstrated the capability of providing accurate position solutions at the sub-decimetre level for kinematic positioning and sub-centimetre level for static positioning. However, since the majority of the mass-market GNSS users (navigation and GIS) operate single-frequency GPS receivers, PPP using a single-frequency GPS receiver has the potential to open up PPP to a broader range of applications. The large errors in single-frequency PPP, after the application of precise GPS orbit and clock products, are mainly due to ionospheric effects which cannot be mitigated effectively using single-frequency measurements (Chen and Gao, 2005).

Using the Klobuchar model, based on the ionospheric coefficients broadcast from the GPS satellites, is the simplest way to mitigate the ionospheric delay on measurements in single-frequency PPP. However, only about 50-60% of the total ionospheric effects are mitigated (Klobuchar, 1996). IGS has generated products with information on the Total Electron Content (TEC) of the ionosphere on a global scale since 1998 (<http://igs.org/projects/iono/index.html>). These Global Ionospheric Maps can provide better results than the Klobuchar model (Ovstedal, 2002), although the resolution is generally not sufficient to model ionospheric delay at a regional (let alone local) scale. Choy et al. (2009) investigated the achievable single-frequency PPP positioning accuracy using different types of receivers, in both post-processing and “simulated” real-time modes. It was found that single-frequency PP-PPP with a geodetic-quality GPS receiver is capable of achieving accuracies of 0.1 m horizontally and 0.4 m vertically (RMS, 1 sigma). In comparison, a medium-cost (GIS-grade) GPS receiver delivered 0.3 m horizontally and 0.7 m vertically, while a low-cost (hand-held) GPS receiver achieved 1.7 m horizontally and 3.3 m vertically. In RT-PPP mode, the achievable accuracies were considerably worse. Such performance is unlikely to challenge high-accuracy DGNSS techniques.

5. THE EVOLVING ROLE OF CORS NETWORKS

This paper sought to speculate on the evolving role(s) of CORS networks in the context of future PPP, and whether DGNSS techniques will be replaced by PPP techniques. We must again analyse the crucial advantage(s) that PPP proponents claim over DGNSS techniques *and* consider the obstacles that must be overcome for PPP to be used for high-accuracy, high-productivity position determination for *all* market scenarios in which current DGNSS techniques such as RTK-GNSS, NRTK-GNSS and wide-area DGNSS are applied. (*It is conceded that there will always be a role for PP-PPP in geodesy, however these applications are not the mainstream surveying, mapping and precise navigation requirements for which standard DGNSS techniques have to date been so successful.*)

The authors contend that the availability of triple-frequency GNSS measurements *may* improve the speed with which ambiguity resolution can be achieved in PPP, because it is the relatively poor “time to first fix” that is currently the most significant shortcoming of PPP. But is the availability of multi-frequency PR and CPH measurements a sufficient condition to elevate PPP to a level of popularity that seriously challenges differential GNSS techniques? It is difficult to give an answer to that question. On the one hand ambiguity resolution for PPP will indeed be sped up, however it must also be emphasised that multi-frequency signal availability (and the resulting PR and CPH measurements) will benefit DGNSS techniques as well. One advantage of next generation multi-frequency measurements will be the *relaxing* of the inter-receiver – i.e. user to reference receiver(s) – distance constraint for high-accuracy, high-productivity DGNSS. This is currently of the order of several-to-many tens of kilometres in the case of NRTK-GNSS (or its equivalent, post-processed network-based DGNSS), and several simulation studies have reported that the density of CORS networks can be reduced such that reference receivers every few *hundreds* of kilometres would be sufficient (e.g. Feng et al., 2007). However, given the significant increase in the number of CORSs established over the last few years, the reduction in cost of upgrading CORS infrastructure (from GPS-only receivers to multi-GNSS receivers) compared to their initial deployment, the predicted “thinning” of CORS networks in the multi-frequency GNSS era, and the many other advantages of CORSs themselves (e.g. monitoring of ground or structural deformation and estimation of atmospheric parameters), the requirement for CORS infrastructure to support DGNSS may not be the significant disadvantage, or constraint, that it once was.

It has to be emphasised that the requirement for almost-ubiquitous wireless communications so that all users wishing to operate in real-time have access to broadcast RTCM correction messages is a critical requirement not only for real-time GNSS, but also for RT-PPP. However, satellite communications (SatComs) via the GNSS receiver “front-end”, as in the case of wide-area DGNSS such as Space-Based Augmentation Systems (SBASs) – e.g. the Wide Area Augmentation System (WAAS) in North America and the European Geostationary Navigation Overlay Service (EGNOS) (Prasad and Ruggieri, 2005) – is an attractive proposition.

Commercial implementations of RT-PPP, apart from Trimble’s RTX, will require access to data products such as those to be generated by the IGS-RTS from mid-2012. The CORS network infrastructure is already deployed, and under M-GEX will be upgraded to have multi-GNSS tracking capability. The analysis and real-time data product dissemination systems have been developed and are undergoing testing, and appear to be robust through the use of redundant analysis centres and broadcasters. Furthermore, industry data message standards are currently being finalised (Rizos, pers. comm.). All of these developments give confidence to GNSS receiver manufacturers that RT-PPP could be easily implemented at the in-receiver algorithm level, and that users could take advantage of RT-PPP if they have access to the real-time data product streams.

Similar to the IGS-RTS, Trimble’s RTX uses a global CORS network to provide the data used to compute satellite orbit and clock corrections. However, it is reported that a regional CORS network (120 km spacing) is used to determine local tropospheric and ionospheric corrections,

and to deliver “several” centimetre-level of positioning accuracy with a “few” minutes of initialisation (ambiguity resolution or ambiguity filter convergence – it is not clear from the published literature which is the case). What distinguishes this service from any that could be implemented via IGS-RTS products is that the necessary data stream (orbit, satellite clock and atmospheric delay parameters) comes via a SatCom downlink, obviating the need for a separate wireless communications link.

Trimble’s RTX is therefore in many respects very similar to SBAS implementations of wide-area DGNSS, except that it uses the CPH measurements to assure sub-decimetre-level (and potentially several-centimetre-level after “initialisation”) positioning accuracy, as all PPP techniques do. Hence this implementation addresses the requirement of ubiquitous wireless communications for users. However, CORS receiver spacing of 120 km (or so) seems to be a retrograde step vis-à-vis “pure” PPP, which has claimed there is no requirement for local/regional CORSs, except the few dozen global receivers needed to enable the computation of real-time orbit and satellite clock correction information.

Such a “network-based” PPP technique was demonstrated by Japanese investigators (Saito et al., 2011). They used the LEX signal transmitted by the Quasi-Zenith Satellite (http://qzss.jaxa.jp/index_e.html) to broadcast *both* the IGS-derived orbit and satellite clock data (i.e. based on the current URP product, not the IGS-RTS which is not yet operational) and atmospheric parameter information used to mitigate the tropospheric and ionospheric delay error on PR and CPH measurements. The latter were computed using those GEONET CORS receivers surrounding the test receiver. Few centimetre-level accuracy was achieved, in real-time, and used to control a driverless tractor. However, note that Japan’s CORS receiver spacing is on average about 30 km (http://www.gsi.go.jp/ENGLISH/page_e30030.html).

6. CONCLUDING REMARKS

PPP’s main advantage over DGNSS positioning techniques is the ability to provide an accurate position within a global reference frame, anywhere in the world with a single GNSS user receiver. Post-processed products and services from organisations such as the IGS and Natural Resources Canada have enabled PPP to offer a viable alternative to post-processed differential solutions, while maintaining the advantages of PPP, for geodetic users. The ability to utilise additional satellite constellations, such as GLONASS, Galileo and Beidou, will further enhance the capability of PPP. However, the fact that the reference frame of PPP results is not the datum of a nation or region does raise its own management issues (see, e.g., Haasdyk and Janssen, 2012, for some discussion on this matter).

A major advancement in PPP is the ability to fix integer ambiguities. Several techniques have been developed with promising results – supported by bias corrections derived from a CORS network – to correct for the receiver and satellite initial phase biases. These techniques have shown improved accuracies and reduced convergence times. However, challenges still remain, primarily reducing initialisation times and correctly accounting for the ionospheric delay in the GNSS measurements. It is therefore unlikely that a PPP solution using a global or sparse CORS network will ever be as effective as short/medium-baseline RTK/NRTK-GNSS,

due to the difficulty in providing sufficiently accurate ionospheric corrections. A regional CORS network with an inter-receiver spacing of the order of a “few” hundred kilometres (and preferably much less), however, has the potential to significantly improve the modelling of the spatial variability of the ionosphere’s TEC.

High-performance (i.e. high-accuracy and high-productivity) RT-PPP has been demonstrated, both in a commercial sense (Trimble’s RTX) and by researchers (QZS testing). However, CORS network densities similar to those for RTK/NRTK-GNSS techniques are required. While the provision of real-time IGS products and the finalisation of industry-agreed data formats will give a significant boost to RT-PPP, the challenge of transmitting such data to user receivers remains. Furthermore, it is debateable that RT-PPP will ever challenge RTK/NRTK-GNSS techniques *on the grounds that it requires less or no CORS infrastructure*. The results so far suggest that the reduction in CORS infrastructure is not significant if “network-based” PPP techniques are used. Paradoxically, CORS networks will play a large role in providing the corrections required to achieve RT-PPP results with centimetre-level accuracy. Because the need for CORS networks will not disappear, the authors contend that while PPP will be a useful addition to the GNSS “toolkit”, DGNSS-based techniques and services will still be a popular user option for many years to come because the justification for the establishment of CORS has *not* been weakened by recent developments in PPP.

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