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Precise Point Positioning: Where are we now?

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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, and several PPP online services and software packages have been developed. This research has shown that centimetre-level point positioning is not only achievable in post-processed static mode, but potentially also for real-time applications, with a single GNSS receiver.

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. Real-time and near real-time 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) allow PPP to potentially offer a viable alternative to RTK solutions in some circumstances, while maintaining the advantages of PPP over differential real-time products. 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 PPP and reviews the advances made in PPP in the last two decades with an emphasis on the potential to utilise PPP as a ‘fill-in’ service for existing CORS networks in areas where dense CORS coverage is not justified, e.g. due to low population density. This paper also outlines the current limitations and possible future direction of PPP.

KEYWORDS: Precise Point Positioning, GNSS, CORS, precise orbits, precise clock corrections.

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 (Table 1) (Kouba, 2009).

Table 1: Precise satellite orbits and clock corrections, provided by the International GNSS Service (IGS, 2005).

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	

PPP methods differ from differential positioning methods in that differential techniques require access to the observations of one or more reference stations with known co-ordinates. 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. This in turn reduces labour and equipment costs and simplifies operational logistics (Goa, 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 co-ordinates are used at the Continuously Operating Reference Station (CORS) station.

The use of a single GNSS receiver for PPP invokes significant disadvantages as well, the most significant being the long convergence times necessary (> 20 minutes) for the float solution to converge to centimetre accuracy, thus limiting its use in real-time applications. Since the ambiguity terms of the un-differenced carrier phase observations are no longer of an integer nature due to the initial phase biases (differenced out in double-differencing techniques), fixed ambiguity resolution capable of reducing the time needed for a centimetre-accurate solution (i.e. initialisation time) is much harder to solve for (see section 5) (Goa, 2006).

As differencing techniques are not used, no relative ionospheric effects can be cancelled out, and consequently expensive dual-frequency receivers (capable of providing the ionosphere-free linear combination) are required for decimetre-level accuracy positioning (although this is also needed in differential techniques exceeding 10-15 km).

PPP also requires a number of corrections to limit the effects of centimetre-variations to un-differenced code and phase observations. 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 differential positioning techniques (i.e. short/medium length static baselines, kinematic and Real-Time Kinematic (RTK) techniques). Table 2 compares the correction types used for improving PPP and differential positioning techniques.

This paper provides a brief history of the development of PPP and reviews the advances made in PPP in the last two decades, with an emphasis on the last five years. Initially, post-processed static PPP and the availability of post-processed online services are examined. A technique that can be used to improve PPP accuracies by using combined GPS/GLONASS satellite orbit and clock corrections is also examined. Subsequently, the advances in fixed integer ambiguity resolved PPP is reviewed, including the utilisation of the yet to be finalised Galileo constellation in both static and kinematic PPP. Finally, medium and low-cost single-frequency GNSS receivers and their availability for use in PPP are analysed.

Table 2: Comparing correction types used by typical PPP and differential 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	✓	✗
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		
Troposphere	✓	✓
Ionosphere	✓ (L1 only)	✗

2. A BRIEF OF HISTORY OF 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. This research has shown that centimetre-level point positioning is achievable in post-processed static mode, and potentially also for RTK applications (e.g. Gao, 2006; Zumberge *et al.*, 1997a; Choy, 2009).

Recently, increased attention has focused on accessing accurate satellite ephemerides with short latency and frequent updates (such as ultra-rapid orbits, cf. Table 1) with the aim of supporting real-time or near real-time kinematic PPP applications. Discussions within the IGS have investigated the generation of a real-time service to support an increasing demand in real-time products. 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 Real-Time Working Group, 2007).

With the advent of cost-effective, accurate, RTK positioning provided by an increasing number of CORS networks around the world, the focus of PPP has shifted to real-time or near real-time solutions. Advances have been made in PPP in the last two decades with an emphasis on the potential to utilise PPP as a 'fill-in' service for existing CORS networks, such as CORSnet-NSW (Janssen *et al.*, 2010, 2011), in areas where dense CORS coverage is not justified due to low population density or for economic reasons (such as in developing nations). Limitations still remain, currently restricting the use of PPP for real-time applications, primarily the long convergence times of typically more than twenty minutes needed for the float solution to converge to centimetre-level accuracy (Gao, 2009).

3. POST-PROCESSED PPP

At present post-processed PPP offers the most comparable accuracies to differential positioning techniques. PPP post-processing services from organisations such as JPL's Auto-GIPSY (JPL, 2006) and Natural Resources Canada's (NRCan's) CSRS-PPP, which provide converged float solutions at the centimetre-level, have allowed PPP to offer a viable alternative to post-processed differential GNSS solutions.

A comparable product to CSRS-PPP, AUSPOS (AUSPOS, 2011) which uses differential techniques is offered by Geosciences Australia (GA). AUSPOS is a free online service that processes static GNSS observations (AUSPOS processes a regional network solution using the scientific Bernese software). The service provides both International Terrestrial Reference Frame (ITRF) and Geocentric Datum of Australia (GDA94) coordinates and takes advantage of both the IGS product range and the IGS GNSS network to determine co-ordinates anywhere on the Earth. The GDA94 co-ordinates produced by AUSPOS do not take into account local distortions at the observed site and may not 'fit' the local datum.

Ebner and Featherstone (2008) compared a network solution across a 550 km by 440 km area in Western Australia composed of 46 points with 5-day GNSS occupations, which was processed using the Bernese software. This was compared with PPP solutions processed using CSRS-PPP's online service (NRCan, 2011). The Bernese-processed co-ordinates were used as the 'true' co-ordinates for comparison. All co-ordinates determined were in ITRF2000.

Table 3 shows the co-ordinate differences of CSRS-PPP compared to the Bernese-processed solutions. At a 99% confidence level, only one CSRS-PPP solution was significantly different to the Bernese solution (in the North component only).

Whilst the authors acknowledged that PPP is inherently less accurate than network-processed GNSS due to the inability to fix carrier-phase integer ambiguities, this was balanced against the cost-effective 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 PPP post-processing, which involves sending the observed Receiver Independent Exchange (RINEX) format data to a third party for position determination.

Table 3: ITRF2000 co-ordinate differences obtained with CSRS-PPP vs. a Bernese network solution (Ebner and Featherstone, 2008).

	Δ E (m)	**Δ N (m)**	**Δ U (m)**
Min	0.000	-0.001	0.000
Max	0.012	-0.014	-0.029
Mean	0.003	-0.005	-0.012
STD	0.005	0.003	0.007

Ebner and Featherstone (2008) concluded that the PPP approach 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 are required to achieve reliable results, in this case interpreted as a PPP solution within 20 mm of the Bernese solution.

At present, no online PPP service provides GDA94 co-ordinates (as provided by AUSPOS or differential static techniques), instead providing co-ordinates in ITRF, as such at an observed site within Australia a transformation is required to provide GDA94 co-ordinates. This extra step in the process can lead to the propagation of further errors in the final co-ordinates (Haasdyk and Janssen, 2011).

It is worth noting that more recent initial testing undertaken by the author using the CSRS-PPP online service in New South Wales has obtained similar accuracies with shorter data sets (< 24 hours) at five CORSnet-NSW stations when compared to the Regulation 13 values (a recognised value standard issued by GA) of the stations, which are processed using a Bernese network solution with seven days of continuous data.

4. IMPROVING PPP USING COMBINED GPS/GLONASS ORBIT AND CLOCK CORRECTIONS

4.1 Static Post-Processed PPP

The availability, reliability and positional accuracy of PPP are particularly dependent on the number of visible satellites. Currently PPP processing software and online services only process GPS observations, using the precise GPS satellite orbits and clock corrections available from services such as the IGS. Even with a 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 with differential techniques). The ability to utilise extra satellites available in the GLONASS constellation enhances the capabilities of PPP and its possible applications (Cai and Gao, 2007).

Since the international GLONASS Experiment (IGEX-98) and the GLONASS Service Pilot Project (IGLOS), conducted in 1998 and 2000 respectively, precise GLONASS orbit and clock data have become available (Weber *et al.*, 2005). The precise GLONASS orbit and clock data now available can be used to improve PPP positional accuracy and reliability. Currently there are 32 operational GPS satellites and 23 operational GLONASS satellites, amounting to 55 operational satellites in total available to the user for PPP.

Currently four IGS analysis centres routinely provide GLONASS precise orbit products. These include CODE (Centre of Orbit Determination in Europe, University of Berne, Switzerland), IAC (Information Analytical Centre, Russia), ESA/ESOC (European Space Operations Centre, Germany) and BKG (Bundesamt für Kartographie und Geodäsie, Germany). 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, at the 1.5 ns accuracy level.

Cai and Gao (2007) studied the performance of combined GPS and GLONASS PPP, comparing the positional accuracy and convergence times between GPS-only and combined GPS/GLONASS processing. As part of their analysis, four processing sessions were used, each with 3-hour data from three IGS stations (HERT, GOPE and YARR). A dual-frequency GPS/GLONASS receiver was used at a 30-second sampling rate. A total of 12 GLONASS satellites were available in the constellation on the day of testing (however, on average only 2-3 were used in the solution).

Figure 1 shows the 3-dimensional positional accuracy comparisons between GPS-only observations and combined GPS/GLONASS observations at the three IGS stations. A marginal improvement in the positioning accuracy is evident in 58% of cases, with one instance of a 12 cm improvement (Cai and Gao, 2007).

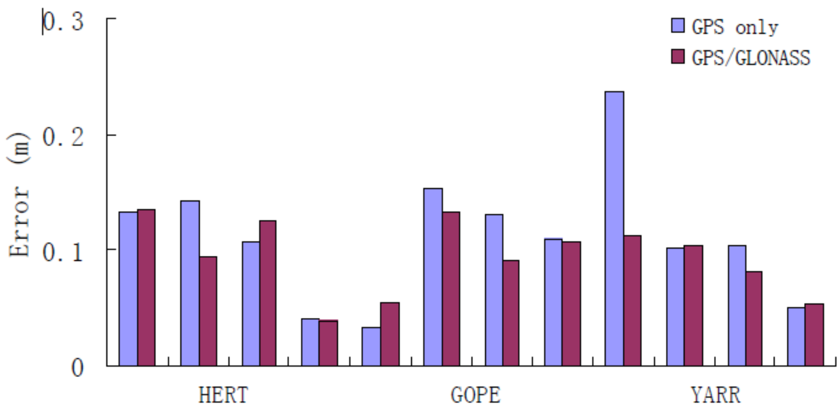

Figure 1: 3-dimensional positional accuracy comparison between GPS-only observations and combined GPS/GLONASS observations for four 3-hour sessions at three IGS stations (Cai and Gao, 2007).

The authors concluded that there was no significant impact to the positioning results with the inclusion of the GLONASS constellation since only two or three GLONASS satellites were observed at any specific time. It was stated, however, that the results indicate the positioning accuracy can be improved by additional GLONASS observations in most cases when more GLONASS satellites become available in the constellation. Further, their research indicated that improvement of the positional convergence times is dependent on the satellite geometry, which is improved with additional visible satellites.

4.2 Kinematic PPP

The use of GLONASS in kinematic PPP can further enhance the potential applications available to PPP. Currently the two analysis centres of IGS offering GLONASS clock corrections provide tabular clock 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) densified the GPS/GLONASS clock corrections produced by

ESOC to 1-second corrections and analysed several PPP processing algorithms with kinematic GNSS observations. The interpolation procedure used 1-second carrier-phase observations from the IGS CORS network and starting with ESOC's 5-minute tabular GNSS clock values, PPP residuals were computed for the carrier-phase observations. A linear interpolation was then used to determine 1-second clock corrections. Furthermore, piece-wise fitting of the carrier-phase residuals to the 5-minute clock corrections and linearly interpolated values achieved a new improved set of 1-second clock corrections.

As part of the study, a kinematic measurement campaign was undertaken to investigate the convergence time and accuracy of co-ordinates, comparing GPS-only and combined GPS/GLONASS solutions. The results, reproduced in Table 4, refer to 4 hours of continuous kinematic data, in which interpolated satellite clock correction intervals include 10 seconds, 30 seconds and 5 minutes (there was no improvement in positioning results based on 1- and 5-second intervals of tabular clock values).

Table 4: RMSvalues of North/East/Up errors comparing GPS-only and GPS/GLONASS precise corrections (Hesselbarth and Wanninger, 2008).

Interval of clock correction	Correction Type	Northing (m)	Easting (m)	Up (m)
10-second	**GPS-only**	0.013	0.017	0.032
	GPS/GLONASS	0.012	0.016	0.032
	Difference	-0.001	-0.001	0.000
30-second	**GPS-only**	0.013	0.018	0.033
	GPS/GLONASS	0.015	0.018	0.035
	Difference	0.002	0.000	0.002
5-minute	**GPS-only**	0.029	0.027	0.064
	GPS/GLONASS	0.030	0.030	0.059
	Difference	0.001	0.003	-0.015

Hesselbarth and Wanninger (2008) noted that adding GLONASS satellites (on average 7.5 GPS and 3.5 GLONASS satellites were visible during observation times) to GPS reduces PPP convergence times by about a factor of two. There was no improvement in convergence times at intervals less than 30 seconds. It was also noted that precise satellite clock corrections at 5-minute intervals do not fully exploit the full potential of kinematic PPP. Furthermore, there was no significant increase in positional accuracy using combined GPS/GLONASS precise corrections. The authors also acknowledged that a further reduction of convergence times can be expected when the GLONASS space segment is complete.

5. FIXED INTEGER AMBIGUITY RESOLUTION IN PPP

5.1 A Comparison of Methods for Fixed Integer Ambiguity Resolution

Conventional PPP has involved the use of float solutions which require long observation times, 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 double-differencing, 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.*, 2008). 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. Integer ambiguity resolution reduces the time it takes to achieve centimetre-level accuracy, allowing PPP real-time applications.

Geng *et al*. (2010a) compared two methods for integer ambiguity resolution at a single GNSS receiver. The methods involve separating the Fractional Cycle Biases (FCBs) from the integer ambiguities in a network solution. This provides satellite products which can be used in conjunction with other products such as precise satellite orbits and precise satellite clock corrections to provide an integer ambiguity resolved precise point position at a single receiver.

This approach differs from conventional PPP methods in which ambiguities are not fixed to integers but converged float ambiguity solutions are used, as the integer properties are destroyed due to the absorption of the FCBs in the GNSS measurements by the un-differenced ambiguity estimates (Ge *et al*., 2008). These FCBs are presumed to be hardware-dependent and are present in all GNSS receivers and satellites (Geng *et al*., 2010a). However, the temporal property of the FCBs is not exactly known, and the time-invariant parts of the FCBs cannot be separated from the un-differenced ambiguity estimates in conventional PPP (Zumberge *et al*., 1997b; Geng *et al*., 2010b). There is some conjecture about whether FCBs and initial phase biases are the same and whether or not they are hardware related. The initial phase biases, or the FCBs, will always exist as part of the un-differenced carrier-phase observation equation. This is because for a carrier-phase observation, at any time of signal lock, the distance from the satellite to receiver consists of a number of complete cycles and some fractions of cycle. In some cases, the FCB's, the initial phase biases and the hardware delays (in particular the satellites') are 'treated' as the same.

The first method, proposed by Ge *et al*. (2008), involves un-differenced ambiguities which are decomposed into wide-lane and narrow-lane ambiguities and removed from the receiver-dependent FCBs by applying the difference between the satellites. A CORS network is used to determine the wide-lane FCBs by averaging the fractional parts of wide-lane ambiguity estimates derived from Melbourne-Wübbena combination measurements. Narrow-lane FCBs are determined by averaging the fractional parts of all narrow-lane ambiguity estimates derived from the wide-lane ambiguities as well as the ionosphere-free observable ambiguities. At the single receiver end, once the FCBs (wide- and narrow-lane) have been determined, they are used to correct the ambiguity estimates, allowing integer ambiguity resolution.

Laurichesse *et al*. (2009) used a similar method that includes applying the same decomposition; however, the un-differenced ambiguities are directly fixed to integers. In this case, an arbitrary value is assigned to the FCBs of a specific receiver to obtain the satellite-specific FCBs. The wide-lane FCB determination in this method is the same as that of Ge *et al*. (2008). The narrow-lane integer ambiguities can then be fixed over a CORS network. The GPS integer phase clocks estimated during this process can be used by a single receiver both inside and outside of this CORS network for improved accuracy. Laurichesse *et al*. (2009) concluded that the integer phase clocks could be used by any receiver in the area around the network to perform absolute real-time kinematic positioning with an accuracy of about 2 cm. However, initialisation of the ambiguity resolution filter in the user receiver can take up to one hour and still requires some improvements. Table 5 shows the success rate for correct initial ambiguity estimation for three scenarios at various initialisation periods.

Table 5: Success rate for correct initial ambiguity estimation for three scenarios at various initialisation periods (Laurichesse *et al*., 2009).

	Initialisation Time						
Configuration	**5 min**	**10 min**	**15 min**	**30 min**	**45 min**	**60 min**	**90 min**
Static receiver, position known	75 %	82 %	87 %	90 %	-	-	-
Static receiver, position unknown	-	-	61 %	80 %	88 %	91 %	-
Kinematic receiver	-	-	17 %	43 %	62 %	76 %	81 %

The main difference in the methods described by Ge *et al.* (2008) and Laurichesse *et al.* (2009) is how the narrow-lane FCBs are separated from the integer ambiguities. In the first method, the narrow-lane FCBs are estimated using float ambiguity estimates. In the second method, the narrow-lane FCBs are amalgamated into the clock estimates.

Geng *et al*. (2010a) compared these two methods in regards to the Root Mean Square (RMS) statistics of residuals of daily ambiguity-float and daily ambiguity-fixed position estimates against the IGS weekly solutions of 350 IGS stations over one year in 2008. The results of this comparison are summarised in Table 6. It is evident that the differences between the two methods are minimal. Geng *et al*. (2010a) noted that both methods showed slightly inferior results in areas with a less dense IGS station network.

Table 6: Mean RMS statistics of daily ambiguity-float and ambiguity-fixed position estimates against the IGS weekly solutions in 2008 (Geng *et al.*, 2010a).

Method	**Ambiguity-Float Solution (m)**			**Ambiguity-Fixed Solution (m)**		
	East	**North**	**Up**	**East**	**North**	**Up**
Ge *et al.* (2008)	0.0034	0.0022	0.0062	0.0020	0.0021	0.0059
Laurichesse *et al.* (2009)	0.0035	0.0023	0.0063	0.0019	0.0021	0.0058

A similar method to the Laurichesse *et al.* (2009) method, developed by Collins *et al.* (2008), is the ‘decoupled clock model’. In this method, dual-frequency carrier-phase and pseudo-range measurements are processed by specifying the clock parameters separately for both the carrier-phase and the pseudo-range measurements. Estimates of the carrier-phase clock errors are randomly biased with respect to the pseudo-range estimates, and ambiguity parameters are constrained to be integer-valued. To compute the satellite code and phase clocks required as fixed parameters in single-user PPP solutions a CORS network is used. In the decoupled clock model method all the user-required information is contained in a satellite-only correction.

Collins *et al.*, (2008) found that using this method to process 5-minute static data over 24 hours, only a small improvement in position error is gained. However, there is a significant reduction in convergence time, and with 30-second static processing after 60 minutes, 90% of solutions approach 2 cm horizontal error, compared to 10 cm for standard PPP.

Figure 2 presents a schematic depicting the network and PPP processing of the decoupled clock method developed by Collins *et al.* (2008). Alternatively, the process ‘Satellite decoupled clock estimates’ could be replaced with FCB estimates or initial phase-bias estimates to explain the network and PPP processing of method one (Ge *et al.*, 2008) or method two (Laurichesse *et al.*, 2009), respectively.

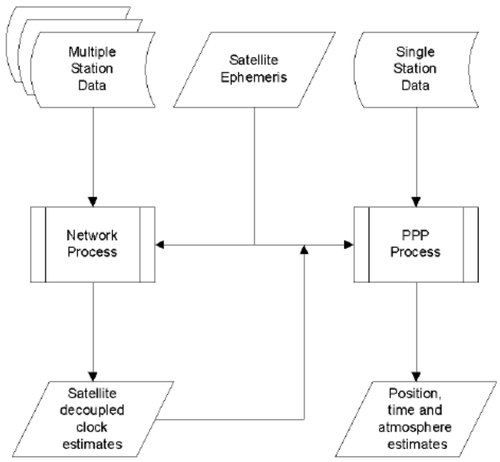

Figure 2: Schematic depicting the network and PPP processing of the decoupled clock method (Collins *et al.*, 2008).

5.2 Improving PPP using the Galileo Constellation

Two new approaches to integer ambiguity resolution in PPP, using the Galileo constellation and supported by a CORS network, have been proposed by Henkel and Günther (2008). These approaches take advantage of the different frequencies available on the Galileo signals.

The first approach is based on an ionosphere-free mixed code-carrier combination with a large-length/low-noise wavelength. The biased estimates from a reference station (provided to the PPP user) are directly applicable for positioning as the linear combination preserves geometry. The large wavelength increases the reliability of ambiguity resolution.

The second method uses phase and code observations on four frequencies without employing linear combinations. Phase and code biases cannot be estimated independently on each frequency. However, the Galileo E5 band is split into the E5a, E5b and E5c signal which are modulated onto a carrier wave, thus motivating the assumption of a common bias, leading to the L1 and E5 code and phase biases being determined separately.

It was found that a standard deviation of less than 1 cm was achievable for the estimation of the biases at a single reference station within 5 minutes (which is applicable for PPP users up to several hundred km away). Also, both mixed code/carrier combinations suppress the L1 code noise and multipath by more than two orders of magnitude.

5.3 Overcoming Cycle Slips in PPP

Even with the realisation of fixed-ambiguity PPP, On-The-Fly (OTF) ambiguity resolution is not yet available, and since most ambiguity resolution approaches involve the averaging of wide-lane ambiguities, ambiguity resolution is not instantaneous. In the case of RTK PPP where the interruption of signal tracking is particularly problematic, long delays as a new ambiguity resolution is attempted will lead to untenable practices, as well as the weakened geometry brought about by single-satellite cycle slips.

Banville and Langley (2010) proposed a method using a time-differenced solution which allows estimation of the size of the cycle slip in a least squares adjustment to instantaneously diminish the impacts of any cycle slips. The method involves a time-differenced (TD) functional model, in which TD positioning uses variations in the carrier-phase and code observations over certain time intervals to estimate receiver position and receiver clock offsets. The next step involves wide-lane ambiguity fixing using the LAMBDA method (Teunissen *et al*., 1995). The time-differenced geometry-free ambiguities are then used with the introduction of the previously fixed wide-lane ambiguities to determine the size of the cycle slips on L1. An extra step, the bootstrapping technique, is used to increase the precision of the remaining unfixed cycle slips. Once the size of the cycle slips on the frequencies L1 and L2 has been determined, the effects of the cycle slips can be removed by modifying the predicted values of the ambiguity parameters.

In order to test this method, virtual cycle slips were introduced onto all of the carrier-phase observations at every epoch in a processed RINEX file, i.e. the carrier-phase measurements cannot contribute to a PPP solution unless the introduced cycle slips are corrected. All original RINEX files used in the following tests contained observations at a 1-second sampling interval and the impact of data gaps were analysed by decimating the files to produce 10-, 20- and 30-second sampling intervals. Banville and Langley (2010) tested three different scenarios to assess the effects on multipath and noise. The results, shown in Table 7, include fixing the wide-lane (WL) and geometry-free (GF) ambiguities, as well as the extra bootstrapping step (BS). The success rate is defined as the ratio of the number of corrected cycle slips introduced in the data sets. The three scenarios included static 4-hour data from IGS station ALGO, 2.5-hour data from a moving boat, and 30-minute data from a moving car.

Table 7: The success rates of the corrected cycle slips of various intervals in three separate scenarios, using all three methods (WL, GF and BS) (Banville and Langley, 2010).

Scenario	Data Gap			
	1 sec	**10 sec**	**20 sec**	**30 sec**
Static	99.8 %	99.7 %	99.6 %	99.0 %
Kinematic (boat)	100.0 %	98.9 %	16.9 %	7.1 %
Kinematic (car)	99.4 %	61.7 %	32.4 %	32.6 %

Due to the complexity associated with fixed-ambiguity PPP and especially OTF-fixed ambiguity resolution, it is increasingly apparent that the ability to account for cycle slips is essential. The inability to account for interruptions to the satellite signals will degrade the quality of the PPP solution and limit the potency of RTK PPP. This method showed that cycle slips of 1-second intervals could be corrected 99% of the time in the three scenarios tested. When data gaps exceeded 1 second, the performance of this method decreased because the method is sensitive to any un-modelled changes in the ionospheric delay variations, to the receiver component of the phase wind-up effect, to quick variations in the multipath characteristics, and to the weak geometric strength of the time-differenced solution, which is especially apparent for delays greater than 20 seconds in the kinematic scenarios (Banville and Langley, 2010). The authors are currently investigating ways to account for the ionospheric effects to the described method.

6. PPP USING A SINGLE-FREQUENCY GNSS RECEIVER

PPP has demonstrated the capability of providing accurate position solutions at 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) use single-frequency GNSS receivers, 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. The large errors in single-frequency PPP, after the application of precise GNSS 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 with ionospheric coefficients broadcast from the GNSS satellites is the simplest way to mitigate the ionospheric effects to single-frequency PPP. However, only about 50-60% of the total ionospheric effects are mitigated (Klobuchar, 1996). IGS has been providing the total electron content of the ionosphere on a global scale since 1998. The resulting Global Ionospheric Model (GIM) can provide better results than the Klobuchar model using the same GNSS dataset and ephemeris (Ovstedal, 2002).

Choy *et al*. (2009) investigated the achievable single-frequency PPP positioning accuracy using a geodetic-quality GPS receiver, a medium-cost GPS receiver, and a low-cost handheld consumer grade GPS receiver.

For the geodetic-quality receiver analysis, a data set was extracted from Mount Stromlo (STR1), an Australian Regional GPS Network (ARGN) site. For the medium- and low-cost receiver analyses, 4-hour single-frequency GPS receiver data sets were processed in simulated real-time and post-processing modes. The IGS ultra-rapid satellite orbit and clock corrections were applied to the simulated real-time processing. The ionospheric error was partially eliminated using the broadcast ionospheric coefficients. IGS rapid precise orbits and clock corrections were used in post-processing mode. In order to remove the ionospheric errors in post-processing mode, IGS GIMs were used. For both modes the Hopfield model was used to correct for the tropospheric Zenith Path Delay (ZPD).

Choy *et al*. (2009) showed that single-frequency PPP is capable of achieving horizontal accuracies of 0.1 m and a vertical RMS of 0.35 m using a geodetic-quality GPS receiver. For medium-cost, single-frequency GPS receivers point positioning accuracies of better than 0.5 m horizontally and 0.75 m vertically were obtained in post-processing mode (Table 8). Horizontal coordinate accuracies of about 1.3 m were achieved in real-time mode. For the low-cost, single-frequency GPS receivers point positioning accuracies of 1.5 m to 3.6 m were achieved in both real-time and post-processing modes. A 30-minute observation time was needed for the solutions to converge to decimetre-level accuracy.

Table 8: RMS of the horizontal and height components in both post-processing and real-time scenarios using medium-cost and low-cost single-frequency GPS receivers (Choy *et al*., 2009).

Receiver Type	**RMS (m)**			
	Post Processing		**Real-Time Processing**	
	2D	**Height**	**2D**	**Height**
Medium Cost	0.33	0.72	1.28	1.64
Low Cost	1.73	3.29	2.22	3.59

7. CONCLUSION

PPP’s main benefit over differential positioning techniques is the ability to provide an accurate position within a global reference frame, anywhere in the world 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. Comparisons in Western Australia give differences in Easting, Northing and Height of 3.3 mm, -4.8 mm, and -11.5 mm, providing a lower-accuracy but more cost-effective alternative to establishing geodetic control. The ability to utilise the GLONASS constellation further enhances the capability of PPP. Studies indicate that the positioning accuracy can be slightly improved by additional GLONASS observations. Furthermore, in kinematic mode, the addition of GLONASS has increased the convergence times of PPP by a factor of two.

A major advancement in PPP is the ability to fix integer ambiguities. Several techniques have been put forward with promising results, in particular the use of a CORS network to correct for the receiver and satellite initial phase biases. These techniques have shown improved accuracies and convergence times. However, challenges still remain, primarily reducing initialisation times (< 15 minutes).

With the advent of fixed-ambiguity PPP for real-time applications, steps have been taken to tackle the problem of cycle slips which become more frequent with a moving receiver. A technique has been reviewed in this paper, showing reliable results when gaps of one second appear. However, when data gaps exceeded one second, the performance of this method decreased quite dramatically.

PPP using single-frequency GPS receivers shows promising results for geodetic, medium-cost and low-cost single-frequency GPS receivers, in particular medium-cost receivers with horizontal point positioning accuracies of better than 0.5 m and vertical point positioning accuracies of better than 0.75 m (post-processed). The use of single-frequency GNSS receivers provides an alternative, cost-effective positioning technique, which could be useful for a variety of low/medium-accuracy GNSS applications, including those in remote locations, where budgetary operational cost is essential. However, 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), may negate the benefits of any advances made in single-frequency PPP.

PPP faces several challenges in order to realise its full potential, particularly in real-time applications. However, with increased research and investment, PPP and its various applications can continue to provide a practical and viable alternative (not replacement) to conventional forms of GNSS positioning.

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