Current State of Precise Point Positioning and Future Prospects and Limitations

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Abstract. The Precise Point Positioning Working Group within the Next Generation RTK Sub-Commission of IAG Commission 4 has been involved with Precise Point Positioning (PPP) developments for the past few years. The information presented here summarizes the Working Group's findings concerning the state of PPP technology, and discusses the probable near-term future potential and limitations of the technique. The broad question of the place of PPP within the future spectrum of space geodetic measurement techniques is addressed by investigating specific aspects of the method.

Keywords. GPS. Precise Point Positioning. Navigation.

1 Introduction

The main goal of this paper is to describe the current performance of what has become known as the Precise Point Positioning (PPP) technique, and to discuss the future potential of the technique, along with its technical limitations. The basic methodology and algorithms of the approach are assumed known, and hence will not be discussed. Interested readers can review, e.g., Zumberge et al. (1997) and Kouba and Héroux (2001).

The paper begins with a review of the current state of PPP, covering performance and usage. Current technical limitations of the approach are then discussed, including solution convergence period, accuracy and integrity of solutions. The next section considers potential improvements upon the current approach, in terms of integer ambiguity resolution, integration with other data, e.g., from RTK solutions and inertial navigation systems (INSs), and the use of other external modelling data, e.g., atmospheric refraction models. Equally important are PPP infrastructure challenges, including the availability of precise satellite orbits and clock offsets, precise orbit and clock prediction, real-time dissemination of predicted obits and clocks, and reference frame realizations. Given the great changes due to GPS Modernization and the development of other Global Navigation Satellite Systems (GNSSs), we would be remised not to speculate on the potential significant positive impacts of these added signals on future PPP performance. Finally we end with a discussion of the potential of PPP to perform in a similar manner as RTK.

2 Current State of PPP

This section is designed to summarize current PPP performance using a number of metrics, and to set the technique's impact within the context of the wider field of positioning and navigation. What is meant by PPP is the state space solution to the processing of pseudorange and carrier phase measurements from a single GNSS receiver, utilizing satellite constellation precise orbits and clock offsets determined by separate means. Typically, a dual-frequency GNSS receiver is utilized with dual-frequency code and phase measurements linearly combined to remove the first-order effect of ionospheric refraction and the real-valued carrier phase ambiguity terms estimated from the measurement model. The tropospheric refraction is also estimated along with the position and ambiguity parameters from the measurements. PPP using a single-frequency GNSS receiver has also been investigated with great promise for certain applications which however will not be further exploited in this paper (see, e.g. Gao et al., 2006; Le and Tiberius (2006)). To achieve the best position accuracy possible from PPP, effects such as carrier phase wind-up and transmitter antenna

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phase offset must be corrected using models. Residual terms such as receiver noise and multipath are generally ignored or handled minimally via stochastic means. Refer to, e.g., Kouba and Héroux (2001) for a full parameterization discussion.

A somewhat unique aspect of PPP is that it is an area of research being actively pursued by academia, government and industry, in concert and individually. As is typical, early development occurred in research settings for scientific goals. Governments, as service providers, have in some cases engaged in providing PPP services to the public, given the socioeconomic benefits. Industry has embraced and advanced the technology to better serve its clients. The results are: a) rapid development and use of PPP in a variety of application areas, and b) significant overlap between the three groups in terms of research and development, and service models. The latter point will be discussed further in the infrastructure section.

2.1 Performance Specifications

The standard metrics used here to describe the performance of conventional PPP services are: accuracy, precision, convergence period, availability and integrity. With PPP solutions showing very little in the way of biases – typically a few centimetres for the most (Bisnath et al., 2003), there is very little difference between the accuracy and precision metrics. In terms of north, east and up component accuracies at the 1σ level, PPP is able to provide few centimetre-level results in static mode and decimetre-level results in kinematic mode, both could be achieved in either post-mission or real-time (see, e.g., Dixon, 2006; Bisnath et al., 2003; Muellerschoen et al., 2001; and Gao and Shen, 2002).

The convergence period, namely the length of time required from a cold start to a decimetre-level positional solution, is typically about 30 minutes under normal conditions and will be significantly longer before the position solution can converge to the few centimetre-level, if at all (Gao and Shen, 2001; Héroux et al., 2004). This period is determined by the measurement strength of the observables for a GPS-only solution, the geometry of the problem, and the redundancy available for the estimation problem. Initial solutions rely almost exclusively on noisy pseudorange measurements, the uncertainties of which are magnified via the ionosphere-free linear combination. The availability of solutions is usually high, given that application areas for this technique are open sky, continuously unobstructed environments. Otherwise PPP would typically not be used. Finally, the availability of integrity measures for the PPP solution is considered. Aside from filter covariance estimates, quantitative quality measures of the obtained results are limited. For example, knowledge of biases in correctors (e.g., precise transmitter orbit and clock products), the potential for biases in estimated coordinates, and measurement outliers are typically not considered (that is, rigorously specified and accounted for) in solutions.

2.2 Usage and Applications

PPP can be used for processing of static and kinematics data, both in real-time, if the dissemination mechanisms are in place to construct, transmit, receive and process precise satellite orbit and clock products, and in post-processing mode. The caveat for all such usage is that there needs to be *uninterrupted GNSS signal availability*, as loss of tracking lock on a minimum number of satellites requires processing filter re-initialization, resulting in tens of minutes of greater than decimetre resolution positioning, until filter re-convergence. This constraint severely limits the utility of PPP, in so far as it can only be robustly (i.e., successfully) used in environments with *continuous* open sky coverage.

One of the first uses of a prototype PPP approach was for the post-processing of static geodetic data for, e.g., rapid processing of GNSS tracking station data, or crustal deformation monitoring (Zumberge et al., 1997). Other scientific uses have included precise orbit determination of Low Earth Orbiters (e.g., Bisnath and Langley, 2002). The main commercial applications of PPP have been in agricultural industry for precision farming (see, e.g., Dixon, 2006), marine applications, for sensor positioning in support of seafloor mapping and marine construction (see, e.g., Bisnath et al., 2003, and Arroyo-Suarez et al., 2005), and airborne mapping (e.g. Gao et al., 2005).

Further growth in current active areas is underway, and the technique is making inroads into other application areas such as atmosphere remote sensing, precise time transfer, land surveying, construction and military (e.g., Gao et al., 2004, and Dixon, 2006). Fundamentally, wherever precise positioning and navigation is required in isolated locations or expansive areas, and reference station infrastructure is not available, or very costly to temporarily erect, for, e.g., natural resource mapping and retrieval, PPP is being strongly considered as a positioning and navigation solution.

3 Technical Limitations

3.1 Convergence Period

Although the PPP approach presents definite advantages for many applications in terms of operational flexibility and cost-effectiveness, it requires a long initialization time as phase ambiguities converge to constant values and the solution reaches its optimal precision, taking full advantage of the precise but ambiguous carrier phase observation. PPP convergence depends on a number of factors such as the number and geometry of visible satellites, user environment and dynamics, observation quality and sampling rate. As these different factors interplay, the period of time required for the solution to reach a pre-defined precision level will vary.

Shown in Figure 1 are the convergence times with respect to different position accuracies from processing data at an IGS tracking station over seven consecutive days (Héroux et al., 2005). The station data collected at a 30 second interval for each 24 hour session was processed using IGS precise orbits and 5 minute clocks, and the position error was computed every 15 minutes. The results show a high degree of day-to-day variability, despite the similar satellite geometry one would expect given a common daily session start time. For example, the solution crosses the 10 cm threshold within 30 minutes on several days, but also takes more time to do so on other days. Shown in Figure 2 are the average weekly convergence time series at four different IGS tracking stations (separated by 1000 km or more and therefore subject to different satellite geometries). Significant differences in positioning accuracy and convergence time exist, likely caused by varying satellite geometry and / or station specific tracking conditions, such as multipath environment.

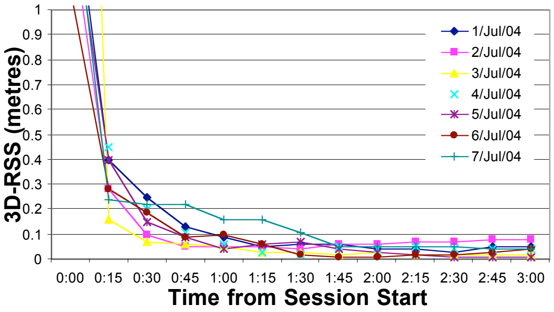

Fig 1 Convergence time of different days (Héroux et al., 2005).

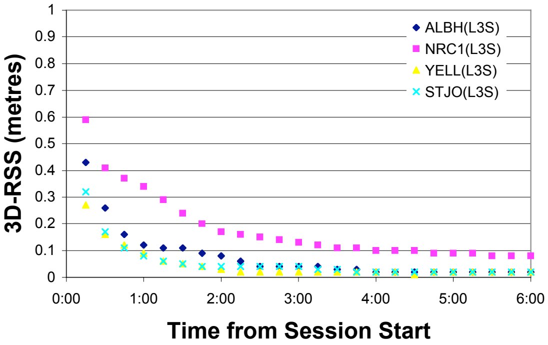

Fig. 2 Convergence time of different user locations (Héroux et al., 2005).

3.2 Accuracy

The primary factors that limit the accuracy of PPP are the limited precision of current precise orbit and clock products and the effects of unmodelled error sources. PPP is currently able to provide few centimetre-level results in static mode and decimetre-level results in kinematic mode. Shown in Figure 3 are the positioning results of a high-quality, static dataset from an IGS station (ALGO) using the JPL real-time orbit and clock products. It can be seen that the coordinate estimates could converge to the centimetre-level within 30 minutes. After convergence, all position coordinate components are accurate at the sub-centimetre level and the positioning accuracy statistics are given in Table 1. Shown in Figure 4 are the positioning results of a kinematic dataset acquired from an airborne platform flying at an altitude of approximately 250 m above the ground at 50 knots. The precise orbit and clock correction are again from JPL's real-time orbit and clock product. The short baseline, double-differenced, ambiguity-fixed position solutions were used as ground-truth and the positioning accuracy statistics are given in Table 2. The results indicate that it takes about 20 to 30 minutes for the positioning solution to converge to the decimetre-level.

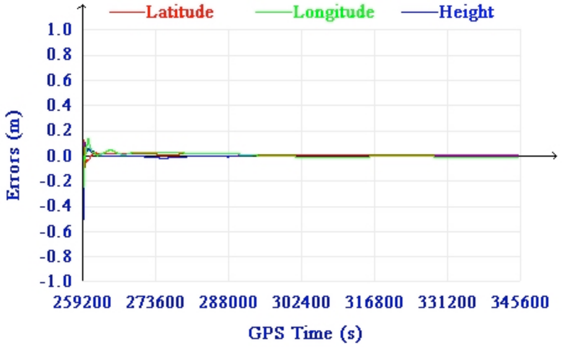

Fig. 3 Static Positioning Using IGS Dataset.

Table 1 Accuracy statistics for static positioning results after filter convergence (in cm).

	Latitude	Longitude	Height
RMS	0.9	1.0	0.7
BIAS	0.8	0.3	0.0
STD	0.3	0.9	0.7

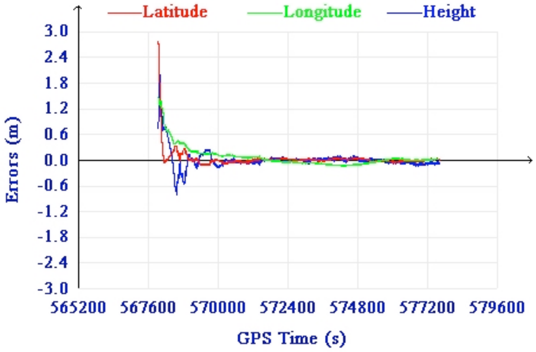

Fig. 4 Positioning with aircraft dataset.

Table 2 Accuracy statistics for kinematic positioning results after filter convergence (in cm).

	Latitude	Longitude	Height
RMS	2.8	6.8	4.9
BIAS	-0.2	-1.5	-1.5
STD	2.8	6.7	4.6

In addition to further improvement of the precise orbit and clock products, the ability to exploit the integer property of phase ambiguities can further improve the obtainable position accuracy of PPP. Minor error sources including initial satellite and receiver phase biases would need to be estimated and removed (as they cannot be eliminated in undifferenced processing) in the measurement model.

3.3 Integrity

Integrity monitoring is an essential component of any positioning / navigation system. Given that in PPP processing some parameters are estimated, while others are eliminated via estimates derived from a separate process, without multiple solutions (e.g., as in the case with network RTK), providing integrity information for PPP single receiver estimates is all that more important. An industrial example is that at least one service provider has clients who are willing to pay for two independent solutions: PPP and long-range RTK (with float ambiguities). The independent solutions are used to judge accuracy of the solutions.

Obviously, post-fit residuals from a PPP epoch solutions can be analyzed to detect individual measurement outliers, or more significant problems. This should be standard practice. More complex examples of integrity monitoring exist in other GNSS applications and should be considered for PPP processing. Potentially, Receiver Anonymous Integrity Monitoring (RAIM)-type of screening can be implemented for PPP estimates. This would be a straightforward design, and would provide users with additional confidence in their PPP solutions, beyond covariance estimates and post-fit residuals. More elaborate, it may be possible to contemplate a Wide Area Augmentation System (WAAS)-type of space-space grid error approach be used to evaluate PPP orbit and clock corrector products, which could be specified when generated from tracking stations and integrated into the PPP processing.

4 Potential For Improvement

4.1 Ambiguity Resolution

Convergence time can be improved as demonstrated in Gao and Shen (2001), through stochastic model refinement and higher sampling rate. The improvement level however was found insignificant. Exploiting the integer property and the application of integer resolution techniques to PPP have the potential to reduce convergence time to several minutes or even several seconds. In double-differenced GPS processing, where integer ambiguity resolution has been widely utilized, the double-differenced ambiguity parameters are integers, which can render the position solution accuracy to the few centimetre-level or better after they have been fixed to their correct integer values.

For PPP with undifferenced observations, the ambiguity parameters are not integers as they are corrupted by the initial fractional phase bias in the GNSS satellites and receivers. Significant progress is being made in understanding the characteristics and the estimation of the abovementioned initial phase biases (e.g., Ge et al., 2006; Wang and Gao, 2007). This research will shed light on the recovery of the integer property of the ambiguities.

4.2 Integration with RTK

Integration of PPP with network RTK techniques may lead to improved position accuracy and performance, particularly reduction in convergence time. A concept of network RTK-based PPP was described in Wubbena et al. (2005). A hybrid system of optimal integration of PPP and RTK solutions has also been implemented into a global differential positioning system (Dixon, 2005). As PPP can be an efficient alternative to RTK in certain applications, it is expected that more work will be carried out to investigate the seamless integration of PPP and RTK methods.

4.3 Integration with INS

The integration of stand-alone and double-differenced GNSS and INS has been extensively investigated in the past as the coupling has benefits such as improved cycle slip detection, smoothed trajectory and increased reliability. An integrated PPP GPS/INS system has been developed by Zhang and Gao (2005) to support geo-referencing in airborne mapping, which offers similar performance to a differential GPS/INS system. An integration of PPP with INS can also reduce re-initialization time, since INS can supply accurate position and velocity information during short periods and subsequently reduce the position convergence time. This is particularly important for real-time kinematic applications, as frequent signal blockages are common in the field.

4.4 Ingestion of Precision Atmospheric Models

A tropospheric parameter unknown is usually estimated along with the position and ambiguity parameters from the measurements in dual-frequency GNSS receiver-based PPP, while several ionosphere parameters are estimated in single-frequency GNSS receiver based PPP (Gao et al., 2006). Ingestion of precision atmospheric models can reduce the total number of unknown parameters that need to be estimated from the measurement model, potentially remove the need for noise propagating linear combinations of observables, and potentially improve positioning performance (e.g., Dodd et al., 2006; Keshin et al., 2006). As a result, it can reduce the convergence time of PPP. The challenge is that range corrections from such measurement and physics-based atmospheric models have to be very accurate, e.g. better than a few centimetres.

5 Infrastructure Issues

Infrastructure refers to the satellite orbit and clock information (products) being generated and used in PPP parameter elimination schemes, and the information and processes related to the collection, generation and dissemination of these products.

5.1 Availability of Precise Orbits and Clock Offsets

Precise orbit and clock products have improved significantly in recent years. And post-processed and predicted products are freely available over the Internet. As such, PPP processing can be performed by anyone who can develop the processing software. This comment is particularly applicable to post-processing of single receiver data sets. The phenomena which impact satellite orbit and clock estimates include transmitter antenna models, antenna phase centres, satellite radiation models and eclipse periods.

5.2 Precise Orbit and Clock Prediction

As can be seen in Table 3, post-processed (final) orbit and clock IGS products are produced at quiet a high level of accuracy. However, improvements in IGS predicted products for real-time usage is desirable, in order to marginally improve PPP solutions. The greatest disparity between the final and predicted products is the 50 times worsening of the clock product coupled with a 3 times enlarging of the data rate. Comparable positioning accuracy, however, has been demonstrated using IGS final products and JPL real-time orbit and clock correction products by Gao and Chen (2005).

Table 3 IGS ephemeris products (IGS products, 2007).

Product		Accuracy	Interval	Latency
Final	Orbits	<5 cm	15 min	~13 days
	Clocks	<0.1 ns	5 min	
Predicted	Orbits	***~10 cm***	15 min	Real-time
	Clocks	***~5 ns***	***15 min***	

5.3 Real-time Dissemination of Predicted Orbits and Clocks

The production of orbit and clock information for real-time processing, hence prediction of quantities, is a major focus of current research efforts. The IGS, for example, has been studying the generation and dissemination of real-time data products for the past few years and has recently begun a real-time data products pilot project (IGS real-time, 2007). A number of other institutes are now providing predicted orbits and clocks for real-time PPP use.

Dissemination of products in the form of corrections can be done in a variety of ways that can primarily be grouped into satellite-based or Internet-based. Satellite-based transmission is the usual choice of commercial service providers, as the correct signals can be received by an antenna built into the GPS receiver package (see Bisnath et al., 2003). Internet-based correction transmission can be made with much lower cost and therefore has been used as the model for academic prototypes, with great potential to be widely adopted in applications (see, e.g., NTRIP, 2007).

The manner of development of PPP and PPP infrastructure leads to an interesting question of provider model: free versus paid real-time corrections. That is, an academic / government model of infrastructure support, or a commercial model of paid service provider.

5.4 Reference Frame

Satellite orbit and clock products refer to a particular realization of ITRF. This realization depends on data from numerous GNSS, VLBI, and SLR stations distributed heterogeneously around the world, and the non-uniform weighting of the varying-length data records from each station. When a new version of ITRF is established and published, and data products redefined with respect to that frame, PPP user coordinates are affected (altered). The end-user must be aware of this link, and furthermore, that the coordinates generated by PPP are referred to ITRF and a coordinate transformation is necessary to bring the PPP solution into the "flavour" of coordinates the user requires.

6 Effects of GNSS Evolution

GPS-only PPP has its limitations, such as insufficient number of visible satellites due to signal blockages and insufficient reliability for 'safety of life' applications. An integration of GPS with other navigation systems such as the Russian GLONASS, European Galileo and Chinese COMPASS could provide many more observations and is expected to have a significant impact on position accuracy, reliability and convergence time of PPP. Shen and Gao (2006) have compared GPS-only and GPS/Galileo-based PPP and the simulation results demonstrate that combined system can reduce convergence time by half over GPS-only PPP. In Cai and Gao (2007) it was demonstrated that combined GPS/GLONASS PPP greatly improves positioning accuracy and reduces convergence time (see Figures 5 and 6). These improvements are dependent on the enhanced level of satellite availability and geometry for position determination. Issues such as interoperability and compatibility however must be addressed for integration of data from hybrid navigation systems.

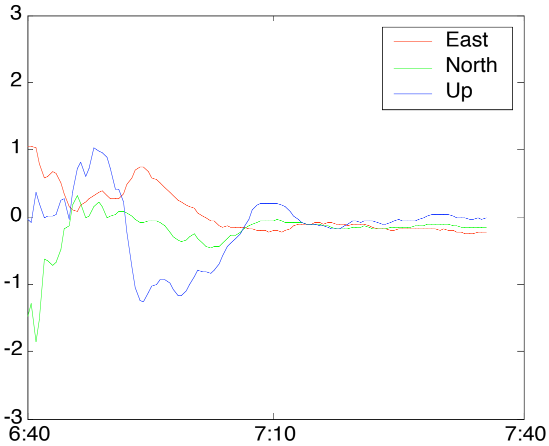

Fig. 5 Simulated GPS-only PPP convergence period and accuracy performance.

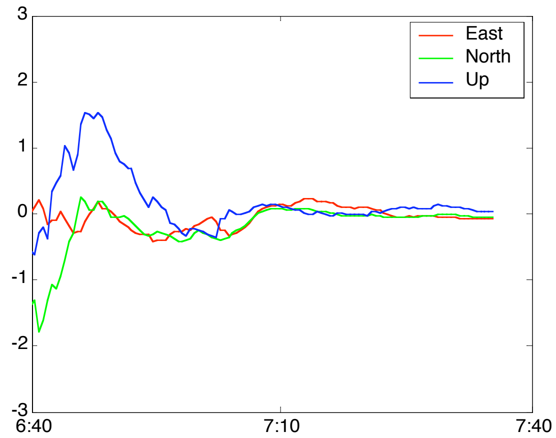

Fig. 6 Simulated GPS / GLONASS PPP convergence period and accuracy performance.

7 PPP versus RTK

Given the previous discussions about the capabilities and potential of PPP, an obvious place to termination this paper is with a comparison of PPP and the industry standard RTK technique. Or more precisely, the question: Can PPP ever replace RTK? To address this overall issue, we pose a series of logically ordered questions. Some queries may be answered quite readily, while others can only be partially addressed.

7.1 Can PPP algorithms, data and operation be improved to the point where the technique obtains the same level of performance as RTK? And if so, what specific improvements are required for PPP to perform like RTK?

This result can be seen as a potential final objective of PPP algorithm research – and a recasting of the overall question. All of the measurement strength of the undifferenced PPP observables is used to estimate: i) few-centimetre-level position estimates, ii) with a few seconds worth of measurements, iii) without the need for a reference station. The utility of such a solution would be significant, and is the subject of the last question asked here.

The third characteristic (of removing the need for reference stations) is the one that would make PPP so appealing as compared to RTK. The first characteristic (of attaining centimetre-level positioning accuracy) may be possible, given recent research results related to ambiguity resolution of undifferenced observables. The potential exists to isolate and estimate initial fractional phase biases in order to isolate true integer ambiguities, without over-parameterizing the processing model. The second characteristic (of attaining the desired accuracy with a few seconds of data) is perhaps the most challenging. Given the inherent weaker measurement models of PPP versus RTK (that is, less data in PPP), it will be difficult estimating the correct biases and ambiguities, aside from performing this resolution quickly. Meeting the initialization and re-initialization challenge will be the most difficult hurdle for the PPP technique to receive greater industrial acceptance for real-time applications.

7.2 Can this objective be reached in the near future? In a cost-effective way? In a practical manner?

If the objective of parity between techniques can be reached, it will require significant further algorithm development and perhaps more observables to reduce processing filter convergence period. This latter requirement would delay implementation of an RTK-like PPP processor. Significant infrastructure overhead may be encumbered in order to estimate receiver and satellite code and phase biases, the added complexity of which could increase costs to service providers. If as some research suggests, few minute convergence periods are possible, we are hesitant to state that this limitation will be tolerated by many industries other than the ones currently using PPP.

7.3 Do we even want PPP to work like RTK?

Though it may seem like an odd question, given the context of this paper, it is a reasonable question if theoretically PPP can perform at the level of RTK. The two approaches have been developed independently, for different purposes. This fact makes them very useful as independent, mutual integrity checkers for some scenarios. Though the benefit obtained from the removal of the constraint for the need for reference stations with PPP has obliged researcher to seek out a potential solution.

7.4 If PPP can work like RTK, would it replace RTK / network RTK / DGPS?

It can be speculated that PPP would first be used as a complimentary solution to RTK in positioning and navigation work. But as the approach gained acceptance, it could replace RTK. The only caveat here is that a significant level of integrity would have to be issued along with accurate PPP solutions to gain industrial acceptance.

7.5 How would science, industry and society be affected / impacted by such a result?

RTK-like PPP would positively impact all facets. Relieved of RTK baseline constraints, users would be able to perform few centimetre-level positioning almost anywhere. Though performance would be similar in urban areas, where RTK networks are already established. That said, a two system solutions would enable new applications.

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References

Arroyo-Suarez, E.N., J.L. Riley, G.F. Glang and D.L. Mabey (2005). "Evaluating a global differential GPS system for hydrographic surveying." ION GPS 2005, 13-16 September, Long Beach, CA, pp. 1500-1506.

Bisnath, S. and R.B. Langley (2002). High-precision platform-independent positioning with a single GPS receiver. *Navigation*, Vol. 29, No. 3, pp. 161-169.

Bisnath, S., D. Wells and D. Dodd (2003). Evaluation of commercial carrier phase-based WADGPS services for marine applications. Proceedings of ION GPS/GNSS 2003, 9-12 September, Portland, Oregon, pp. 17-27.

Cai, C and Y. Gao (2007). Positioning model and accuracy analysis of Precise Point Positioning with GPS and GLONASS. Poster paper, Geoide Annual Meeting, 6-8 June, Halifax, Nova Scotia.

Dixon, K. (2006). StarFireTM: A global SBAS for sub-decimetre precise point positioning. Proceedings of ION GNSS 2006, Fort Worth, Texas, pp. 2286-2296.

Dodd, D., S. Howden and S. Bisnath (2006). Implementation of Ionosphere and Troposphere Models for High-Precision GPS Positioning of a Buoy During Hurricane Katrina. Proceedings of ION GNSS 2006, Fort Worth, Texas, pp. 2006-2016.

Gao, Y. and X. Shen (2001). Improving convergence speed of carrier phase based Precise Point Positioning. Proceedings of ION GPS 2001, 12-14 September, Salt Lake City, Utah, pp. 1532-1539.

Gao, Y. and X. Shen (2002). A new method for carrier phase based Precise Point Positioning. *Navigation*, Vol. 49, No. 2, pp.109-116.

Gao Y., S. Skone, K. Chen, N.A. Nicholson and R. Muellerschoen (2004). Real-time sensing atmospheric water vapor using precise GPS orbit and clock products. Proceedings of ION GNSS 2004, 21-24 September, Long Beach, California, pp. 2343-2352.

Gao, Y., A. Wojciechowski and K. Chen (2005). Airborne kinematic positioning using precise point positioning methodology. *Geomatica*, Vol. 59, No. 1, pp. 275-282.

Gao, Y., Y. Zhang and K. Chen (2006). Development of a real-time single-frequency Precise Point Positioning system and test results. Proceedings of ION GNSS 2006, 26-29 September, Fort Worth, Texas, pp. 2297-2303.

Ge, M., G. Gendt and M. Rothacher (2006). Integer ambiguity resolution for precise point positioning. Proceedings of VI Hotine-Marussi Symposium of Theoretical and Computational Geodesy: Challenge and Role of Modern Geodesy; 29 May – 2 June, Wuhan, China.

Héroux, P., Y. Gao, J. Kouba, F. Lahaye, Y. Mireault, P. Collins, K. Macleod, P. Tétreault and K. Chen (2004). Products and applications for Precise Point Positioning - Moving towards real-time. Proceedings of ION GNSS 2004, 21-24 September, Long Beach, California, pp. 1832-1843.

IGS products (2007). International GNSS Service data products.http://igscb.jpl.nasa.gov/components/prods.html.

IGS real-time (2007). International GNSS Service real time pilot project. http://www.rtigs.net/pilot.

Keshin, M.O., A.Q. Le, and H. van der Marel (2006). Single and dual-frequency Precise Point Positioning: approaches and performances. NAVITEC 2006, Noordwijk, The Netherlands, 11-13 December 2006, 8 pp.

Kouba, J. and P. Héroux (2001). Precise point positioning using IGS orbit and clock products. *GPS Solution*, Vol. 5. No. 2, pp. 12-28.

Le, A. and C. Tiberius (2006). Single-frequency precise point positioning with optimal filtering. *GPS Solutions*, Vol. 11. No. 1, pp. 61-69.

Muellerschoen, R.J., Y.E. Bar-Sever, W.I. Bertiger and D.A. Stowers (2001). NASA's Global DGPS for high precision users. *GPS World*, Vol. 12, No. 1, pp.14-20.

NTRIP (2007). Networked Transport of RTCM via Internet Protocol. http://igs.bkg.bund.de/index_ntrip.htm.

Shen, X. and Y. Gao (2006). Analyzing the impacts of Galileo and Modernized GPS on Precise Point Positioning. Proceedings of ION NTM 2006, 18-20 January, Monterey, California, pp. 837-846.

Wang, M. and Y. Gao (2007). An investigation on GPS receiver initial phase bias and its determination. Proceedings of ION NTM 2007, 22-24 January, San Diego, California, pp. 873-880.

Wubbena, G., M. Schmitz and A. Bagg (2005). PPP-RTK: Precise Point Positioning using state-space representation in RTK networks. Proceedings of ION GNSS 2005, 13-16 September, Long Beach, California, pp. 2584-2594.

Zhang, Y. and Y. Gao (2005). Performance analysis of a tightly coupled Kalman filter for the integration of undifferenced GPS and inertial data. Proceedings of ION National Technical Meeting, 24-26 January, San Diego, California, pp. 270-275.

Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins and F.H. Webb (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks.. *Journal of Geophysical Research*, Vol. 102, No. B3, pp. 5005-5018.