Precise Point Positioning With Ambiguity Resolution In Real-Time

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ABSTRACT

We have developed and implemented a method to resolve carrier phase ambiguities in precise point positioning (PPP) mode at the satellite single difference (difference between two satellites observed from one receiver) level. The corrections needed for PPP with single difference ambiguity resolution can be generated in real-time and transmitted to static or moving dual frequency GPS client users. We call the real-time point positioning with ambiguity resolution "PPP-RTK".

We demonstrate that "PPP-RTK" has several significant advantages over PPP positioning without ambiguity resolution or standard PPP. Compared to PPP, PPP-RTK converges significantly faster to the correct position in static and kinematic applications. In kinematic applications PPP RTK provides superior positions of the moving platform compared to standard PPP. PPP-RTK has the main advantage over traditional network RTK techniques that the client user of the PPP RTK corrections can be in a highly kinematic environment like a buoy or an airplane at a significant distance (several 100 to 1000 km) from the reference network and still achieve 1-2 cm horizontal position accuracy.

This paper summarizes the technique to obtain PPP and PPP RTK corrections and shows representative example results.

INTRODUCTION

Carrier phase ambiguity resolution is of critical importance for high accuracy GPS applications. Generally carrier phase ambiguities are resolved on the double difference level, when epoch phase data from two GPS stations and two GPS satellites are differenced. The double difference cancels noninteger terms in the GPS phase observation due to clock and/or hardware delays in the transmitter and receiver, enabling that the double difference ambiguity can be rounded to the nearest integer value.

In precise point positioning (PPP) analysis mode [1] it is not possible to form double differences, thus, even if ionospheric effects were negligible, the ambiguities cannot be rounded to a nearest integer. Ambiguities in PPP processing remain real-valued. Using precise GPS satellite clock estimates, it has been shown that static PPP solutions can achieve solution precision comparable to differential processing (except in the east coordinate component which is slightly better in ambiguity resolved baseline solutions). The main disadvantage of PPP with good clocks, compared to differential processing, is that the solutions generally take longer to converge than ambiguity-resolved differential solutions. Another important disadvantage for kinematic PPP rovers is that the correlation between ambiguity parameters and coordinate parameters degrades the position solution. Thus for time critical applications such as real-time kinematic (RTK) surveying and deformation monitoring, differential methods are generally used.

Differential RTK solutions are limited by the distance between the base station and the rover, because RTK ambiguity resolution becomes increasingly unreliable as baselines exceed 50 km and tropospheric and ionospheric errors at the base and the rover decorrelate. Network RTK solutions mitigate this shortcoming but they require that the rover is located within the reference network or at least close to it. Furthermore they require two-way communications in the virtual reference station (VRS) implementation [2a, 2b], or they rely on the assumption that the ionospheric delay can be represented as a plane or low order surface in the surface correction parameterization (FKP) implementation [3].

PPP corrections of satellite positions and clock errors are in principle independent of the client user position and the same corrections can be applied to clients over large areas. (Some position dependent error remains in the PPP corrections due to residual satellite orbit errors.) Thus to combine the advantages of network RTK differential GPS and PPP positioning it is desirable to develop corrections that allow PPP positioning with ambiguity resolution [3b]. These corrections can be determined from a regional network and broadcast to cover an area the size of a country or even a continent.

PPP requires precise satellite position and corresponding clock information. For post processing PPP applications this can be obtained, for example, from the International GPS Service final (IGS) or rapid (IGR) products. For real-time applications the IGS provides an ultra-rapid product with predicted satellite positions and predicted clocks (IGU). While the satellite positions can be predicted well, (10 cm level over several hours,) the corresponding GPS clock behavior cannot be predicted with equivalent accuracy and frequently have m-level errors. In our approach we assume the IGU satellite positions to be correct and use the dual frequency data from a ground-based reference network to estimate corresponding satellite clock corrections. For this estimation we assume that the coordinates of the stations in the reference network are known and we tightly constrain or fix their positions. We estimate tropospheric delays, receiver clocks, satellite clocks and ambiguity parameters. For the estimation of PPP RTK clock corrections it is necessary that carrier phase ambiguities are resolved when processing the reference network data. This is not required for standard PPP clock corrections.

We modify the standard PPP satellite clock correction by a receiver independent term that makes it possible to resolve the wide lane and narrow lane single difference ambiguities in PPP RTK mode to integer values. Below we describe first how we generate standard PPP clock corrections, followed by additional information for deriving the modified satellite clock corrections (MSCCs) needed for PPP RTK.

ESTIMATING CLOCK CORRECTIONS FOR STANDARD PPP POSITIONING

Real-time Precise Point Positioning (PPP) requires accurate satellite clocks in real-time. The following discussion shows that precise relative clock corrections as estimated from a regional or continental size network are adequate for PPP.

Satellite clocks can be estimated using either the pseudorange (code) observations, the phase observations, or a combination of both. Usually a so-called ionosphere-free linear combination (either phase or code) is used in order to eliminate the effect of the ionosphere. In all cases the satellite clocks can be precisely estimated in a relative sense only. However, the meaning of the word "relative" depends on whether or not the code observations are used.

If the code measurements are used, it is necessary to choose one "reference clock" which may be a selected receiver clock or a selected satellite clock or any single linear combination of clocks. E.g. it is possible to constrain the sum of all satellite clock corrections towards zero. The resulting clock estimates then refer to this reference. The disadvantage of using code measurements is that additional biases (so-called differential code biases) are introduced into the estimation.

In our approach for estimating clock corrections for standard PPP we use the phase observations only. Consequently (due to correlations between estimated clocks and ambiguities), the resulting satellite clocks δ^i are correct only on the double-difference level between satellites and between epochs

$$(\delta^i - \delta^j)_{tk} - (\delta^i - \delta^j)_{tl}$$

with δ^i, δ^j ... satellite clock corrections, satellites i,j
t_k, t_l ... epochs

This means that our resulting satellite clocks are "relative" in this double (between satellites and between epochs) sense. Fortunately, just such a relative accuracy is required if only the phase observations are used for the computation of the client rover's position in PPP mode. In that case the observation equations for two satellites i,j and two epochs t_1, t_2 are

$$\begin{aligned}
L^i_3(t_1) &= \rho^i(t_1) + c\delta_r(t_1) - c\delta^i(t_1) + \lambda_3 n^i_3 \\
L^j_3(t_1) &= \rho^j(t_1) + c\delta_r(t_1) - c\delta^j(t_1) + \lambda_3 n^j_3 \\
L^i_3(t_2) &= \rho^i(t_2) + c\delta_r(t_2) - c\delta^i(t_2) + \lambda_3 n^i_3 \\
L^j_3(t_2) &= \rho^j(t_2) + c\delta_r(t_2) - c\delta^j(t_2) + \lambda_3 n^j_3
\end{aligned} \tag{1}$$

with

L_3 ... ionosphere-free linear combination
ρ ... geometric distance rover-satellite
δ_r ... receiver clock
δ^i ... satellite clock
n_3 ... formal L_3 ambiguity (real valued, constant in time)

Eliminating the clock parameters $\delta_r(t_1)$, $\delta_r(t_2)$ and the ambiguities n^i_3, n^j_3 is equivalent to forming a double difference (between satellites and between epoch)

$$L_3^{ij}(t_1) - L_3^{ij}(t_2) = \rho^{ij}(t_1) - \rho^{ij}(t_2) - c\,[(\delta^i(t_1) - (\delta^j(t_1)) - (\delta^i(t_2) - (\delta^j(t_2))] \tag{2}$$

Receiver clocks and ambiguities disappear in this equation, only double-difference clocks remain. Thus, only double-difference satellite clock corrections are relevant for PPP.

ESTIMATING ADDITIONAL CORRECTIONS FOR PPP RTK POSITIONING

It is well known that due to observation delays only the double-difference ambiguities preserve their integer character and can therefore be resolved to integers. Resolving single-difference ambiguities in PPP mode requires therefore additional information (concerning the observation delays) provided by the server together with the satellite clock corrections.

The satellite single differences (SSDs) of GNSS phase L^{ij}_{1k}, L^{ij}_{2k} and code P^{ij}_{1k}, P^{ij}_{2k} observations, for example for GPS, of station k and can be described by the following equations

$$L^{ij}_{1k} = \rho^{ij}_k - I^{ij}_k - c\delta^{ij} + \lambda_1\left(n^{ij}_{1k} + l^{ij}_1\right) \tag{3a}$$

$$L^{ij}_{2k} = \rho^{ij}_k - \frac{f_1^2}{f_2^2} I^{ij}_k - c\delta^{ij} + \lambda_2\left(n^{ij}_{2k} + l^{ij}_2\right) \tag{3b}$$

$$P^{ij}_{1k} = \rho^{ij}_k + I^{ij}_k - c\delta^{ij} + p^{ij}_1 \tag{3c}$$

$$P^{ij}_{2k} = \rho^{ij}_k + \frac{f_1^2}{f_2^2} I^{ij}_k - c\delta^{ij} + p^{ij}_2 \tag{3d}$$

where l^{ij}_1 , l^{ij}_2 are the uncalibrated phase delays for the L1 and L2 GPS frequencies f_1 and f_2 respectively, p^{ij}_1, p^{ij}_2 are the uncalibrated code delays. These (single-difference) delays do not depend on station k and are assumed to change slowly in time.

We developed an efficient way to estimate the uncalibrated observation delays on the server side. The server-estimated resulting delays are then added to the estimated satellite clock corrections in such a way that the rover using these so-called modified satellite clock corrections (MSCCs) is able to resolve the integer ambiguities n^{ij}_{1k} n^{ij}_{2k} on the satellite single-difference level in PPP mode.

SOFTWARE DESCRIPTION

Software used for the estimation of satellite clock corrections has been developed by GPS Solutions, Inc. It is the RTNet (acronym for Real-Time Network) program, see *Figure 1* for a flow-chart diagram.

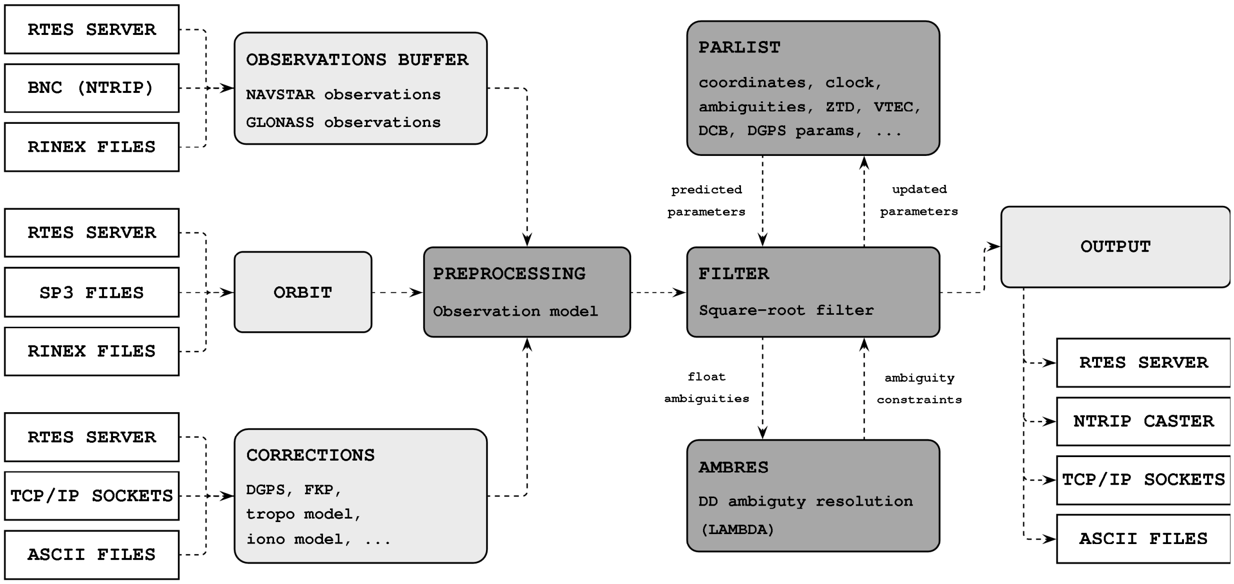

Figure 1 : *Flow-chart diagram of the RTNet program.*

This software has been primarily designed for the processing of real-time GNSS data with the utmost accuracy. Important characteristics are

- implemented for GNU Linux operations system (MS Windows version available)
- real-time GPS and GLONASS data processing
- post-processing possible with RINEX files
- processing of un-differenced data, ambiguity resolution on double-difference or (in PPP mode) on single-difference level (in PPP RTK mode).

The software is very general and can be used in several modes [4], [5], [6], [7], e.g. in a network mode for real-time deformation monitoring, in server mode for the computation of satellite clock corrections, or in PPP client mode that uses the clock corrections for the estimation of the rover position or tropospheric delay.

PPP AND PPP RTK STATIC POSITIONING

Since RTNet uses zero-difference observations, receiver clocks and ambiguities are estimated in PPP mode. Any initial satellite clock error is compensated by the ambiguity estimation. A common satellite clock error drift is absorbed by the drift of the estimated receiver clock.

RTNet estimates the satellite clock corrections in real time. A typical comparison of RTNet real-time estimated clocks with IGS satellite clocks estimation shows rms agreement of ~0.02 ns at the double difference level which corresponds to about 6 mm. Observations from regional networks can dramatically reduce the errors in PPP resulting from inaccurate predicted clock estimates. To prove this statement, the estimated satellite clock corrections have been used for processing data of a single static station in PPP mode. In this case, the RTNet software was also used in client PPP positioning mode. We computed PPP clock corrections from a network in Japan and used those clocks to estimate the coordinates of GEONET station 0200 in static mode. The results for this example are shown in *Figure 2*.

Figure 2 clearly shows the position error of the different processing modes compared to the known position. The solution with RTNet improved clocks converges faster towards the correct position than the IGU orbits/clock solution. In fact the real-time improved clocks perform comparable to the post-processed final IGS products. The convergence time of the standard PPP solutions with IGS or RTNet improved clocks is over 30 minutes in the horizontal components.

Figure 2 also shows that this convergence time is much reduced in PPP RTK mode (denoted SDAMB for single difference ambiguity resolution in that figure) as the solution appears to snap into its correct place within ~10 minutes.

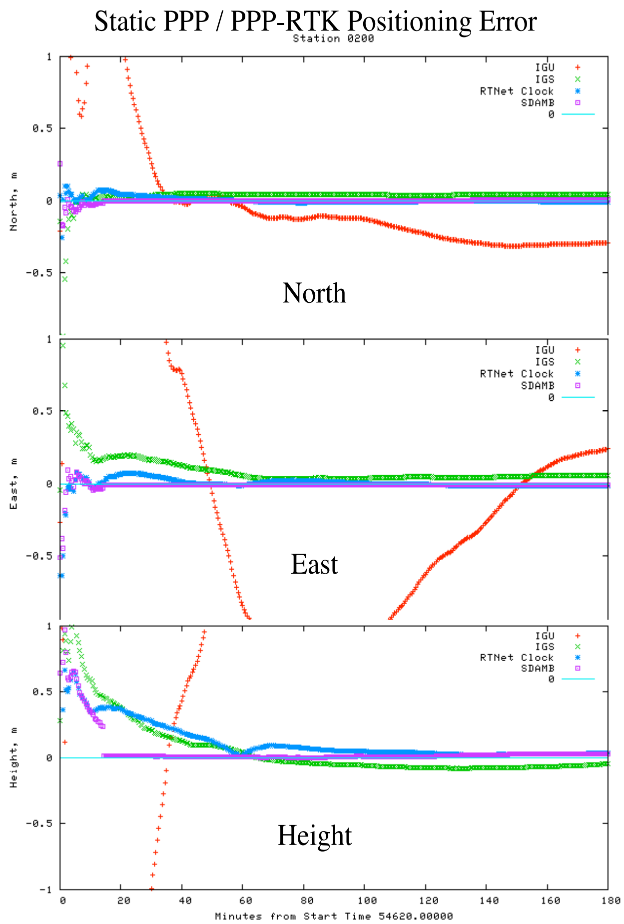

Figure 2 *This figure compares the initial 180 minutes of static positioning for GEONET station 0200. The solution modes that are compared are PPP with IGU predicted orbits and clocks (red), PPP with IGS final orbits and 30-sec clocks (green), PPP positioning with RTNet clocks (which are real-time improvements of the IGU clocks as described above) (blue) and PPP RTK solutions with RTNet determined MSCCs (purple).*

ADVANTAGES OF PPP RTK IN KINEMATIC POSITIONING

In this section we will demonstrate several advantages of PPP RTK in kinematic mode.

(1) Faster convergence of the solution than PPP
(2) Better Kinematic solution
(3) Large distance from reference network

The MSCCs can be generated in real-time or in post-processing. For the test results shown in this paper we provided this information either through TCP/IP socket communication, or – for post-processing – through a file. On the rover side the RTNet program is then capable of utilizing the additional information for the ambiguity resolution on the single-difference (between satellites) level.

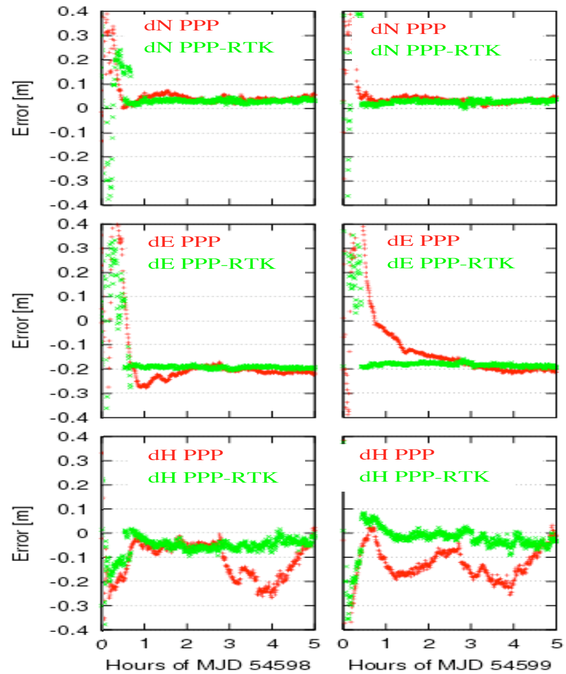

Figure 3 *compares PPP (red) and PPP RTK (green positioning solutions for a fixed site that was estimated in kinematic mode. The first 5 hours of processing for two days (MJD 54598, 54599) are shown. The main points are the shorter convergence time and the more stable height component for the PPP RTK solution compared to the PPP solution.*

In *Figure 3* we compare positions estimated in kinematic mode for a client station with and without ambiguity resolution in PPP mode. This fixed station's position was determined as if it was moving freely with a motion constraint of 100 m/sec. The clocks and MSCCs were estimated based on a 15-receiver network at a distance of ~ 200 km from the fixed PPP client station. Especially for the east component it is obvious that ambiguity resolution reduces convergence time of the position. It should be noted that convergence time for PPP is over 1 hour on both days in this case. This long time is presumably related to very loose motion constraints that we placed on this solution. With such loose motion constraints PPP RTK also takes 15-30 minutes until ambiguities can reliably be resolved. This is significantly slower than network or baseline RTK, which achieves ambiguity resolution usually after a few measurement epochs.

While *Figure 3* demonstrates the advantage of PPP RTK compared to standard PPP in terms of solution convergence it also shows that the ambiguity-resolved solution is more stable in the vertical component. Next we demonstrate the improved kinematic solution for stations that move. Kinematic PPP is, for example, important for the monitoring of seismic deformation. In the case of large earthquakes it can be difficult to find a fixed reference site that did not move during the earthquake to determine absolute deformation. Such absolute real-time deformation information is critical for decision making by emergency response agencies.

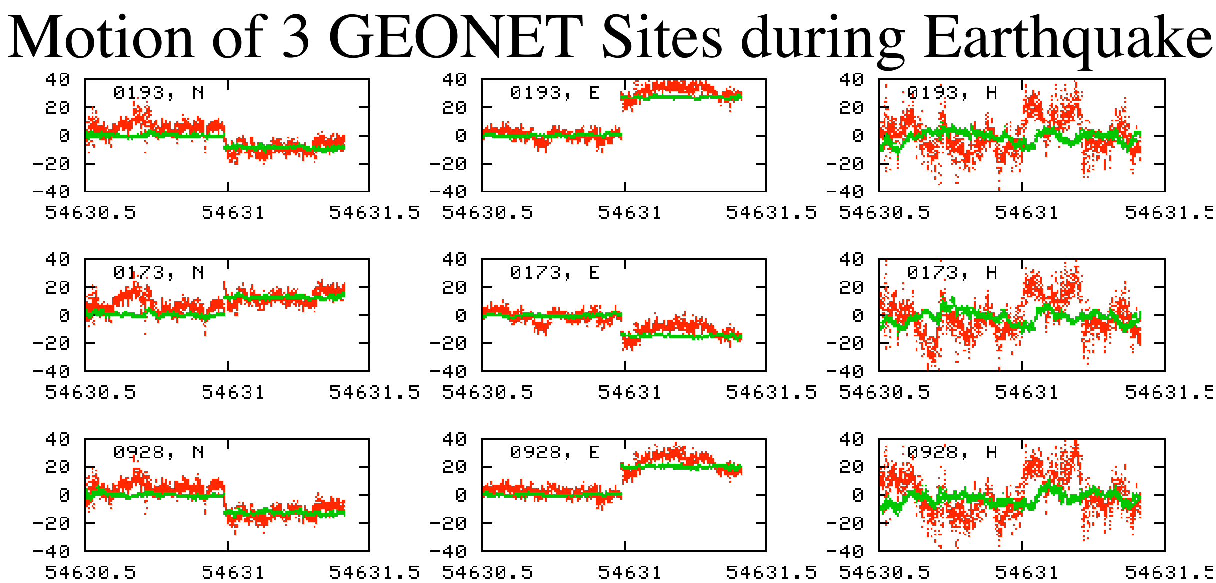

Figure 4 *Shows the standard PPP solution (using final 30-sec IGS orbits and clocks) in red and the PPP RTK solution (using IGU orbits and clocks corrected by RTNet computed MSCCs) in green for three GEONET stations affected by the magnitude 6.8 June 13, 2008 Iwate earthquake. From top to bottom: station 0193, 0173, 0928; From left to right: north, east, up component. The co-seismic displacement can be seen in both PPP solutions but the PPP RTK solution is lower noise and shows the seismic offset more clearly. Seismic waves cannot be resolved because of the 30-sec sampling rate.*

The solutions in *Figure 4* were obtained in PPP kinematic mode with a very loose 100 m / sec constraint on station motion. The solutions were computed for 30-sec GPS data from three GEONET stations. The standard PPP solutions used IGS final orbits and corresponding 30-sec clocks. The PPP RTK solution was computed in real-time mode using the predicted portion of the IGU orbits/clocks and RTNet - computed MSCCs. The reference network for computation of the MSCCs consisted of a network of 15 sites at a distance of 200 km from the epicenter of the earthquake. Because of this separation and because the of the 6.8 earthquake magnitude these reference stations were not significantly affected by the ground motion.

Figure 4 clearly shows that PPP RTK kinematic solutions are more stable and less noisy than standard PPP solutions. Therefore the earthquake displacement can be detected much more reliably. This is especially remarkable because the standard PPP solutions are based on the best and final IGS orbits and clocks which would generally not be available in real-time while the PPP RTK is computed in a way that is possible in real-time. The same applies for motion detection in deformation monitoring, positioning of ocean platforms, vehicles or airplanes.

The apparent motion of the vertical component in *Figure 4* is highly correlated for the three stations. We do not believe that this motion is signal. The reason for this correlation could be residual clock error or common tropospheric error but it is not yet fully understood.

ROVER DISTANCE FROM REFERENCE NETWORK IN PPP RTK

One of the key advantages of PPP RTK is that client users can be at a large distance from the reference network. *Figure 5* illustrates this difference between network RTK and PPP RTK. In one case the client must be within the reference network or at least close to its boundaries, in PPP RTK the client user of the corrections can be far away from the reference network. This is especially important for covering large areas with a limited number of reference stations and for covering areas where it is difficult or impossible to establish reference stations like in remote forests or the ocean.

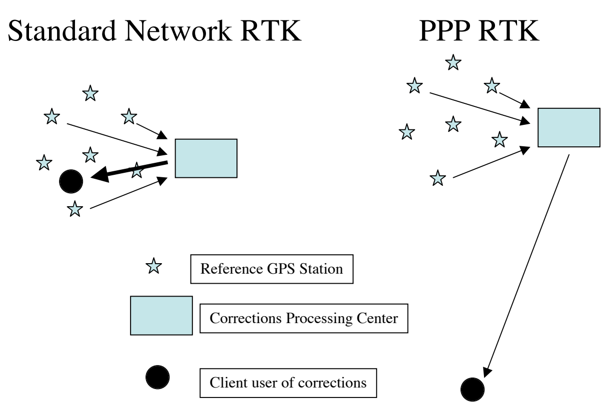

Figure 5 *illustrates one of the main differences between standard network RTK and PPP RT. In the case of PPP RTK the client user of the corrections can be at a great distance from the reference network.*

We investigated the quality of PPP RTK and standard PPP kinematic positioning as a function of the separation from a reference network. To do this we again estimated kinematic positions with a very loose 100 m /sec motion constraint every 30 seconds during 2 weeks for a large number of stations of Japan's GEONET.

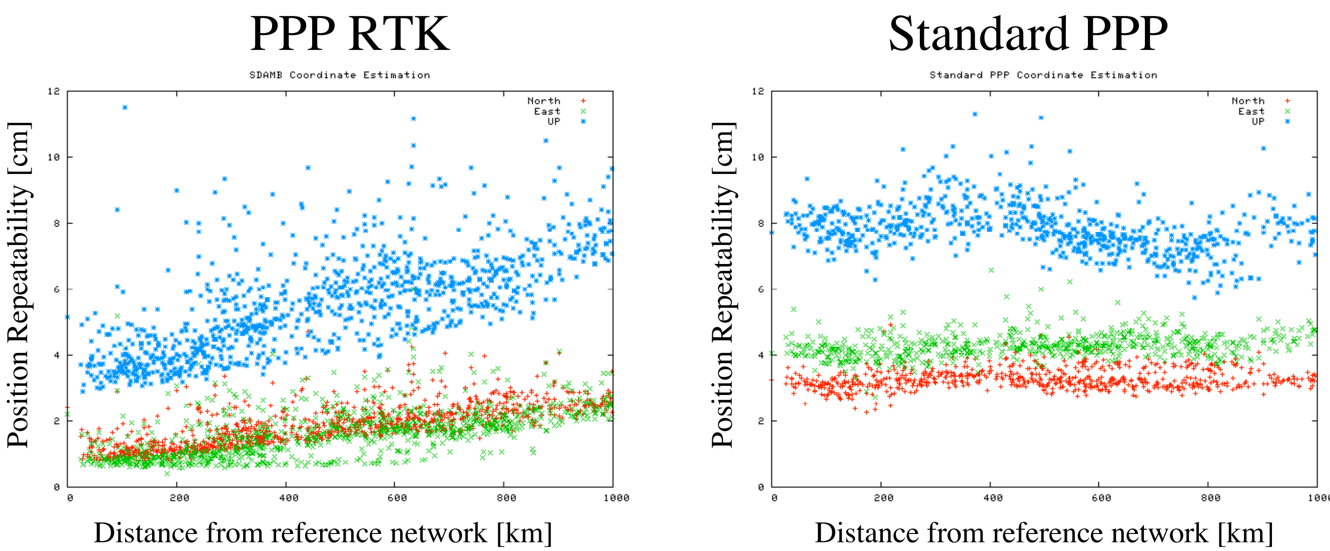

Figure 6 *Two-week kinematic (100 m /sec constraint) position repeatability as a function of distance from the center of the reference network. Each dot (red=North, green-East, blue=Up) represents the rms of about 40,000 kinematic 30-sec position solutions for a station in GEONET. The left panel shows that horizontal repeatability for stations up to 1000 km are better than 2 cm. PPP RTK provides significantly more precise positions than standard PPP positioning.*

In this case the PPP and PPP RTK clock corrections were computed based on a 20-station network in the northern half of the island of Honshu. This network had short (~25 km) baselines so that it was possible to reliably resolve carrier phase ambiguities for server-side real-time reference network data processing. We processed client dual frequency data from stations at varying distances from the midpoint of the 20-station reference network. The positions of the client stations were estimated every 30-sec for a two week period and the position repeatability was computed for the 2-week period. The results are shown in *Figure 6* where we compare the kinematic position error in standard PPP mode versus PPP RTK mode. PPP RTK horizontal position rms is about 1 cm at a distance of 200 km form the reference network and it is about 2 cm at a distance of 1000 km form the reference network. Standard PPP position rms in kinematic mode is ~ 4 cm up to 1000 km with little distance dependence. The vertical component is improved for PPP RTK up to 1000 km from the reference network as compared to standard PPP.

PPP – RTK SYSTEM CONSIDERATIONS

Up to now we have processed server and client data at the same location without the need to transmit the corrections to a remote client. To set up a PPP RTK demonstration with a remote client the following components are needed:

1. A local network of dual frequency stations streaming real-time data to a processing center. The stations in this network should be separated less than 50 km so that we can reliable resolve dual frequency carrier phase ambiguities in real-time.
2. A processing center to process the data from the network (1) in real time using the latest IGU predicted orbit positions. The processing center computes the MSCCs and it determines the differences between IGU orbit positions and broadcast orbit positions. These orbit differences and MSCCs are packaged into a data stream for transmission to the client.
3. A communications mode to transmit the corrections. This could be radio, cell phone, satellite phone, the Internet etc.
4. A dual frequency client receiver and processor. The processor re-combines the broadcast orbits with the transmitted orbit differences and uses these reconstructed IGU orbits and the corresponding MSCCs for PPP RTK positioning with ambiguity resolution.

We are presently implementing transmission of these corrections in a suggested RTCM 3 format and plan to conduct a field demonstration shortly

DISCUSSION AND SUMMARY

We have shown that precise point positioning with ambiguity resolution, so called PPP RTK, is possible and reliable in real-time. The corrections can be estimated with data from a single reference station or from a reference network as long as ambiguities in the reference network are resolved in real-time.

The main advantages of PPP RTK over standard real-time PPP with real-time clock corrections are (a) faster convergence of the solutions for surveying applications and (b) improved kinematic positioning. The key advantages of PPP RTK over standard network RTK are: (a) lower bandwidth requirement since the MSCCs needs to be transmitted only infrequently even if the client has high rate positioning requirements and most importantly, (b) 1-2 cm horizontal positioning accuracy can be achieved even for highly kinematic client users at distances of up to 1000 km from the reference network.

These advantages allow high precision kinematic GPS applications in remote locations such as far-offshore buoys or exploration ships, drill rigs, or surveying/exploration airplanes. They also make it easier to provide GPS corrections for cm positioning on continental scale for large nations with sparse infrastructure.

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