

The development of enhanced algorithms for rapid precise point positioning



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Abstract

Within the last decade, Precise Point Positioning (PPP) has been discussed by GNSS (Global Navigation Satellite System) experts and research groups all over the world. PPP uses code or phase observations on zero-difference level in combination with precise orbits and clock corrections to achieve highly accurate point coordinates. PPP in comparison to Differential GPS (DGPS) and Real-Time Kinematic (RTK) based techniques has no need for nearby reference stations, since the corrections used for PPP are globally valid. Still, PPP is suffering from long convergence times, which makes it rarely used for real-time applications.

Therefore, the project RA-PPP (Rapid Precise Point Positioning) was started in 2009 to conduct detailed investigations on new algorithms for PPP. Several techniques to reduce the convergence time and to increase the accuracies were developed and finally implemented into a PPP client for evaluation purposes. This paper will present the investigations and results of the project, as well as the developed PPP client. Finally, a first glance on a PPP real-time implementation is provided.

Keywords: GNSS, Precise Point Positioning, convergence time, software module

Kurzfassung

Seit einigen Jahren beschäftigt sich eine Vielzahl von GNSS (Globales Navigations satellitensystem) Experten und Forschungsgruppen mit dem Thema Precise Point Positioning (PPP). Diese Positionierungstechnik verwendet undifferenzierte Phasen- und Codebeobachtungen in Kombination mit präzisen Orbits und Uhrkorrekturen, um hochgenaue Positionslösungen zu erhalten. Dabei benötigt PPP im Vergleich zu differentiellen und relativen Positionierungstechniken keine Referenzstation, da global gültige Korrekturdaten von diversen Organisationen angeboten werden. Jedoch wird PPP derzeit aufgrund relativ langer Konvergenzzeiten noch selten für Echtzeitanwendungen eingesetzt.

Aus diesem Grund wurde 2009 ein Projekt namens RA-PPP (Rapid Precise Point Positioning) gestartet, dessen Hauptaugenmerk auf der Erforschung und Evaluierung neuer Algorithmen und Methoden für PPP lag. Einige Ansätze zur Verringerung der Konvergenzzeit als auch zur Verbesserung der Positionsgenauigkeit wurden untersucht und entwickelt, um schließlich im Rahmen eines PPP Software Clients evaluiert zu werden. Dieser Artikel präsentiert einige Aspekte dieser Projektarbeit sowie den Aufbau und die Ergebnisse der entwickelten Software. Am Ende des Papers wird ein Ausblick auf eine derzeit laufende Echtzeit-Implementierung gegeben.

Schlüsselwörter: GNSS, Precise Point Positioning, Konvergenzzeit, Software Modul

1. Fundamentals

1.1 The principle of PPP

Compared to the lifetime of Global Navigation Satellite Systems (GNSS), Precise Point Positioning (PPP) is a relatively new positioning technique aiming at high accuracies by processing data of only one receiver. While the concept of PPP was first mentioned in the 1970's, the theoretical foundation of PPP has not been published until 1997. At that time, the Jet Propulsion Laboratory (JPL) presented its first investigations on positioning within a few cm level using dual-frequency data from single GPS receivers in post-processing [1]. Since then PPP has become a well-known technique to process data of isolated GPS receivers.

In contrast to the Single Point Positioning (SPP) technique, for PPP code and phase measurements are supported by precise orbits and precise clock corrections to compute precise positions on zero-difference level. In the case of dual-frequency observations, an ionosphere-free linear combination is used to remove influences of the ionosphere. Single-frequency users need additional information on the ionosphere, since neglecting its influence could result in errors in the range of some meters. Therefore, ionospheric maps as well as precise orbits and clocks are provided by organizations like the IGS (International GNSS Service), which is a voluntary federation of more than 200 agencies worldwide pooling re-

sources and permanent GPS (Global Positioning System) and GLONASS (Globalnaja Nawigazionnaja Sputnikowaja Sistema) station data to generate precise GPS and GLONASS products. IGS products comprise GPS ephemerides, satellite and station clock corrections, earth rotation parameters, and atmospheric parameters. Detailed information on IGS products and services can be found on the IGS website [2].

1.2 Mathematical Model

Figure 1 visualizes the main error contributions to undifferenced GNSS observables relevant for PPP processing.

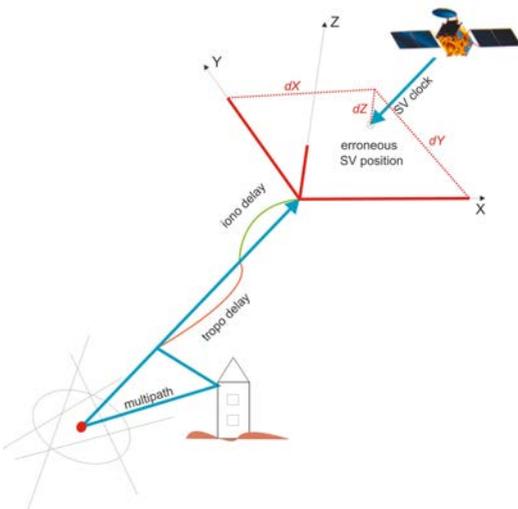


Fig. 1: Overview of the main GPS errors sources

After virtually eliminating satellite clock and orbit errors by using precise orbits and clock products, the standard mathematical model underlying PPP is defined by the ionosphere-free combination of code pseudoranges R_i (1) and phase measurements Φ_i (2) according to [3].

$$\frac{R_1 f_1^2}{f_1^2 - f_2^2} - \frac{R_2 f_2^2}{f_1^2 - f_2^2} = \rho + cdt_r + \Delta_{trp} \tag{1}$$

$$\begin{aligned} \frac{\lambda_1 \Phi_1 f_1^2}{f_1^2 - f_2^2} - \frac{\lambda_2 \Phi_2 f_2^2}{f_1^2 - f_2^2} &= \\ &= \rho + cdt_r + \Delta_{trp} + \frac{\lambda_1 N_1 f_1^2}{f_1^2 - f_2^2} - \frac{\lambda_2 N_2 f_2^2}{f_1^2 - f_2^2} \end{aligned} \tag{2}$$

The term c stands for the speed of light, f_i is the frequency on carrier i and λ_i is the respective wavelength. The unknown parameters to be determined are the point position contained in ρ , the receiver clock error denoted by cdt_r , the

tropospheric delay Δ_{trp} , and a phase bias term including the ambiguities N and calibration biases. To solve the equations for these parameters, several strategies are possible, relying on least-squares adjustment or Kalman filtering. The receiver clock solution contains further error terms like noise and multipath, which cannot be accessed individually. The determined geocentric coordinates are directly linked to the reference frame of the precise orbits.

It can be further distinguished between static PPP where the coordinates are assumed to be stable over the whole observation period and kinematic PPP where the coordinates are estimated every epoch. Today's PPP systems can provide accuracies up to centimeter level after long observation periods with static dual-frequency approaches. Decimeter accuracy, which is sufficient for many applications, is achieved after an initialization time of some 15 to 30 minutes. These accuracies mainly depend on the quality of the orbit and the clock data. Orbit predictions by the IGS, being available within real-time, are reported to have dm accuracy within the first hours of prediction. Further information on IGS products can be found in [4].

1.3 Constraints and Limitations

On the one hand, PPP can be considered as a rather cost-efficient technique compared to common techniques like RTK or DGPS, since it is based on observations of single GNSS receivers. Due to globally valid correction data being freely provided by analysis centers, there is no need for simultaneous observations of a nearby reference station and, thus, there is no restriction in operational range.

On the other hand, PPP is a zero-difference technique being influenced by errors cancelling in double-difference approaches. Examples of effects degrading PPP accuracy are the quality of orbit and clock products, the tie to the appropriate reference frame, the noise amplification of the ionosphere-free combination used and the inability to fix integer phase ambiguities due to non-integer calibration phase biases that vanish in difference-mode. Furthermore, the quality of single-frequency PPP strongly depends on the quality of information on the ionospheric activity to account for the signal delay within this dispersive part of the atmosphere. Due to long convergence times and the limited quality of real-time PPP products, the technique is rarely used for real-time positioning by now.

2. Project work

As already stated, there is still a need for further developments on the PPP technique and its algorithms. Therefore, a research project called 'Innovating Algorithms for Rapid Precise Point Positioning' (RA-PPP) was started in 2009 concentrating on the development and improvement of PPP algorithms and techniques to reduce convergence times and to increase position accuracy. The Graz University of Technology, Institute of Navigation (lead), the Vienna University of Technology, Institute of Geodesy and Geophysics, as well as the companies TeleConsult Austria GmbH and Wien-Energie Stromnetz GmbH contributed to this research which has been successfully completed in 2010.

2.1 Aims and goals

RA-PPP stands for the need of faster and more accurate algorithms for PPP and, therefore, comprises the refinement of this technique towards real-time capability. Thus, in a first step the strengths and deficiencies of currently used PPP processing algorithms and products were identified. Based on this pre-information, the following four approaches were considered to be the most promising enhancements for the PPP technique:

- The derivation of improved Total Electronic Content (TEC) models for single-frequency users,
- the use of so called 'regional clocks', which will be explained later,
- the use of new ionosphere-free linear combinations with reduced phase noise, and
- the simulation to solve for ambiguities under special conditions.

To establish a basis for the evaluation of the algorithms, a PPP client was developed enabling the processing of single- and dual-frequency measurements. The client's output parameters consist of positions and quality parameters for static and kinematic users. Finally, a test environment was set up to evaluate the user module and the algorithms' performance concerning convergence time, accuracy, and availability. The relevant concepts are shortly presented.

2.2 Concepts

Derivation of improved TEC models for single-frequency users

If only single-frequency observations are available, the user needs additional information on ionospheric refraction, since the ionospheric influence cannot be eliminated as in the case

of dual-frequency measurements. Hence, the derivation of accurate TEC models is required to achieve enhanced position accuracy for single-frequency PPP. In the context of the RA-PPP project, various TEC models were evaluated. The global models are based on high resolution spherical harmonics while the local models are obtained by Taylor series expansion of the electron content from local reference station networks. The spherical harmonics are of degree and order 15 to 30 resulting in a wavelength > 1500 km. This is still too sparse to cover high resolution features of the ionosphere but allows for catching a time varying scale factor for extended regions. The local models based on Taylor series expansion are able to catch smaller features of the ionospheric delay such as ionospheric disturbances, but are representative for small areas only. A detailed description of global and local ionospheric modeling can be found in [5].

'Regional clocks'

The 'regional clocks' (also denoted as 'pseudo clocks') concept was first introduced by Leandro [6], and provides a possibility to add corrections accounting for regional effects like troposphere to clock corrections to improve the convergence time of a PPP solution.

Assuming at least two successfully tracked signals at different carrier frequencies, we start with the ionosphere-free linear combination Φ_{if} . After linearization and a slight reformulation of formula (2),

$$\begin{aligned} \Phi_{if} - \rho^0 - \Delta_{trp}^0 - \lambda_{if} N_{if}^0 &= \\ &= c(dt_s - dt_r) + \delta G + \delta \Delta_{trp} + \lambda_{if} \delta N_{if} + m + n \end{aligned} \quad (3)$$

is obtained where, on the left-hand side of the equation, the superscript ⁰ indicates approximate values for geometric effects like orbits and tropospheric delay as well as an initial bias parameter N per individual satellite. On the right-hand side we solve for the satellite clock dt_s with respect to the receiver clock dt_r . Residual effects are the orbit errors δG , the remaining tropospheric delay $\delta \Delta_{trp}$ and a residual bias parameter δN_{if} as well as the environmental multipath m and the noise n . Since the only parameters to solve for are the clocks, all further effects on the right hand side map onto these parameters. This procedure produces a kind of virtual clock differences covering regional effects and being clearly correlated with clocks at nearby stations (see Figure 2). Therefore, we call these clock differences 'regional clocks', which are different from clock solutions provided for instance by

the IGS. When introducing the ‘regional clocks’ via a PPP solution to process the coordinates of a nearby isolated station (rover station), we remove the impact of the remaining master station clock which will be absorbed by the rover station clock. The satellite-specific bias at the master station will be absorbed as well by the ambiguity parameter at the rover station. This concept differs from DGPS techniques concerning the calculation model, since for DGPS differences between simultaneous observations at master station and rover are calculated and passed to the user, while ‘regional clock’ corrections are manipulated clock differences calculated independently at the master station.

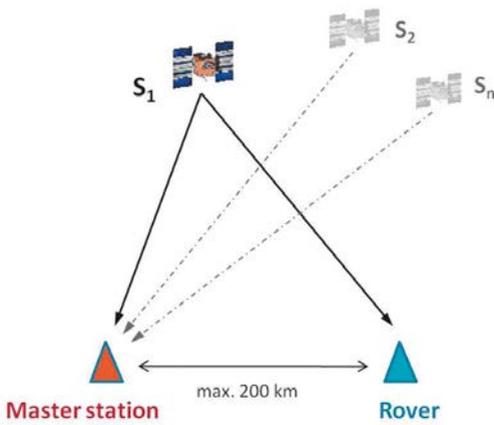


Fig. 2: Spatial correlation of atmospheric and orbit effects

The convergence time will be reduced in any case down to 30 minutes or less which demonstrates the strength of this procedure. The accuracy reaches dm level which is quite comparable with state-of-the-art PPP procedures. Nevertheless, this approach cannot compete in fixing times with double-difference approaches; however, the correlation holds over hundreds of kilometers distance to the master station and the clock differences can easily be obtained, even in real-time.

This approach was evaluated by feeding the PPP algorithm with ‘regional satellite clocks’ recovered from a master station with observation data of well-known rover stations in the vicinity (50 km up to 150 km distance) of the master station. On the one hand, the ‘regional clocks’ approach was tested with the Bernese software using a least-squares adjustment, on the other hand, the same tests were performed with the RA-PPP client based on a Kalman filter (cf. [7]).

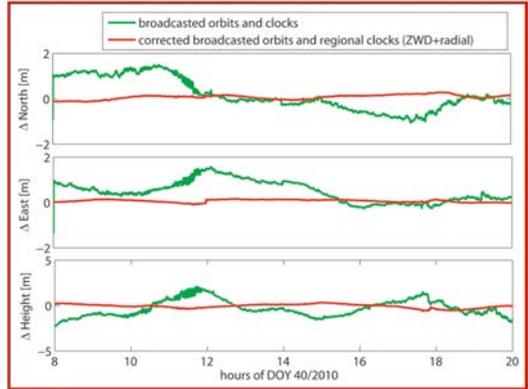


Fig. 3: Comparison of pseudorange PPP solutions with broadcast orbits and clocks and broadcast orbits and ‘regional clocks’

Figure 3 shows the effect of ‘regional clock corrections’ with a tropospheric zenith wet delay correction calculated at a nearby reference station and orbit corrections in the radial component. It is shown, that the PPP solution can be dramatically improved with ‘regional clocks’ if only broadcast ephemerides are available to the user. These types of corrections can be applied especially in situations, where the bandwidth for data communication is low, or if communication is too expensive to forward standard RTCM range and phase corrections. The validity span of ‘regional clock corrections’ is quite long due to medium term variation of orbital errors and ZWD. Regional Clock corrections might therefore be interpolated and extrapolated (in case of stable satellite clocks). Further information on the ‘regional clocks’ concept can be found in [8].

Use of new ionosphere-free linear combinations with reduced phase noise

It is well known that the use of the ionosphere-free combination (equations (2) and (3)) for dual-frequency observations significantly increases the noise of code and phase observations compared to isolated signals. Due to new carrier bands and signals being available in the near future, advantages for the data processing are expected. It is obvious that the use of new Galileo signals or the new civil signal at GPS L5 will allow for the formation of additional linear combinations with phase and code based on three to five individual frequencies. This will enable a better ambiguity resolution as well as reduced noise amplification within the combination of different signals. Unfortunately, the Galileo system will not become fully operational until 2015 (see [9]). Concerning GPS L5, the number of satellites in orbit, emitting the L5 signal, is insufficient to evaluate the noise

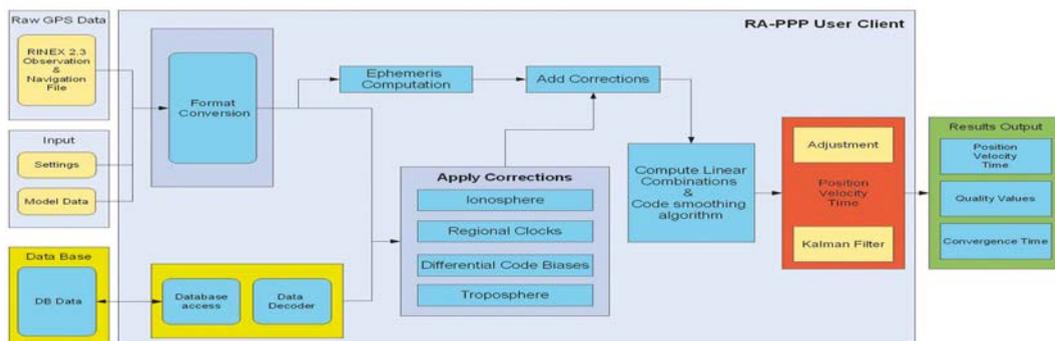


Fig. 4: Architectural Design of the RA-PPP user client

behavior of the new linear combinations with real data. Further considerations concerning new linear combinations can be found in [10] and [11].

Simulation to solve for ambiguities under special conditions

The probably most effective approach to improve convergence time of PPP solutions is to determine the initial satellite and station bias parameters and to subsequently fix the remaining integer ambiguities as described in [12]. So far, this approach was investigated only from a theoretical point of view, but not yet implemented in the PPP user-client.

3. RA-PPP client

Based on the previously described concepts a PPP user client for post-processing was developed by TeleConsult Austria GmbH. This client obtains the necessary correction data from a data base on a correction data server which contains not only publicly available corrections (precise ephemerides, global ionospheric maps, differential code biases) from providers like IGS or CODE (Center for Orbit Determination in Europe) but also local ionospheric maps and 'regional clocks' calculated in a correction data computation module.

The actual position computation is carried out in the PPP client. RINEX files are used as raw data input source for the client. The key element of the RA-PPP user client is the processing module which includes the previously designed algorithms. The module is capable of calculating the user's positions as well as quality parameters by means of Kalman filtering. An overview of the processing module is given in Figure 4.

The RA-PPP client is implemented in C/C++, since a real-time capability is envisaged for the

future. The processing module consists of two core modules – the correction computation and the PVT (Position, Velocity and Time) module. Before the actual computation occurs, all incoming data are converted into an internal format and plausibility checks are performed. The correction module accesses the data server and requests the necessary correction parameters in dependence on the user input. The corrections to each observation are calculated. Then the corrected observations together with the computed satellite positions are forwarded to the PVT module. Within this module the actual position calculation is carried out. For evaluation purposes, either a least-squares adjustment or a Kalman filter algorithm can be used. In case of pseudorange and phase observations, a time-dependent code smoothing by means of phase observations, in order to reduce the measurement noise, is applied. Along with the processed position of the rover, also accuracy and quality parameters as well as the convergence time are provided to the user.

Apart from general tests on the user client, also the performance of the algorithms was investigated. Two different groups of data sets were used during the tests. The first group was generated by a GNSS constellation and performance simulator (cf. [13]) in order to evaluate the positioning algorithm itself. The second group represents real data recorded by a Javad Sigma receiver, capable of receiving GPS L1, L2, and L5 signals. The receiver, as well as the GNSS constellation simulator, provided the raw observation data (pseudoranges and phases, as well as ephemeris data) in the RINEX format.

As mentioned before, no linear combinations with the new GPS L5 carrier could be tested within the RA-PPP client due to a lack of L5 ca-

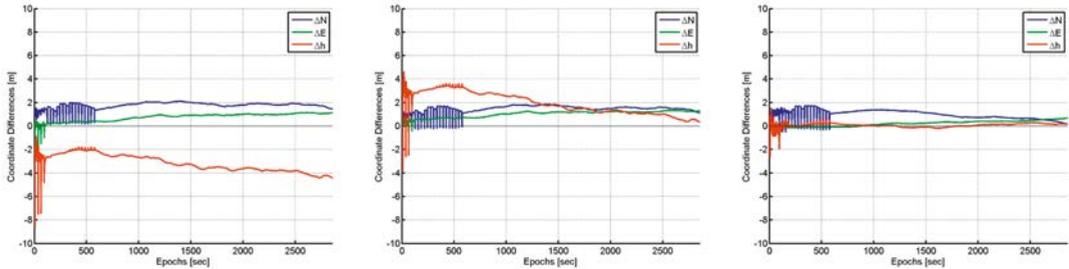


Fig. 5a-c: UTM coordinate differences for single-frequency solution (a) with code-smoothing, Klobuchar ionosphere model and Hopfield troposphere model applied (b) with code-smoothing, global ionosphere model and Hopfield troposphere model applied (c) with code-smoothing, precise ephemeris and ‘regional clock’ data

pable satellites. Nevertheless, tests in December 2009, January, March and July 2010 showed a maximum number of five L2C observations (new civil code on L2) out of up to twelve visible satellites. This is sufficient for position computation, but tests would have been more significant with a higher number of L2C measurements. For a critical investigation of the performance of the linear combinations the P2 (precise code on L2) measurements were used instead. Comparing P2 with L2C showed the same performance, when all satellites transmitted dual-frequency data.

All real data were recorded at the roof of the Geodesy building in Graz on geodetic pillars with known coordinates in WGS84. The algorithms’ performance was evaluated by comparing the calculated coordinates with the reference coordinates of the pillar.

Figure 5a shows the coordinate differences with respect to the reference coordinates when applying the broadcast ionospheric model (Klobuchar) and a Hopfield tropospheric model to the phase-smoothed code observations. The blunders, which are visible during the first 500 seconds, mainly result from rapid changing satellite geometry. This causes the smoothing algorithm for the specific satellites to restart. The height offset is caused by the coarse ionospheric model, which obviously overcompensates for the ionospheric delay during calm phases.

As an alternative to the broadcast ionosphere model, the user can choose either a global or a local ionospheric map model. Figure 5b shows the coordinate differences with respect to the reference coordinates when using code-smoothed single-frequency data with a Hopfield model for troposphere, but now, with a global ionosphere map model. It is obvious that the calculated model parameters fit much better than the broadcast model before.

		Mean [m]	Median [m]	Std [m]
Figure 5a	dN	1.769	1.827	0.293
	dE	0.749	0.905	0.339
	dh	-3.165	-3.302	0.736
Figure 5b	dN	1.479	1.532	0.313
	dE	1.014	1.166	0.299
	dh	1.936	1.781	0.950
Figure 5c	dN	1.000	1.078	0.393
	dE	0.213	0.242	0.246
	dh	0.070	0.096	0.187

Tab. 1: Statistical mean, median and standard deviation of time series in Figure 5a-c

One main goal of RA-PPP was the development and implementation of so called ‘regional clocks’. The use of ‘regional clocks’ within the user client is very similar to the use of precise clocks. Again, the clock biases are given in a certain time interval and a cubic interpolation is used to obtain the corrections for a specific time. Due to fact that regional effects are taken into account, a benefit within the obtained coordinates is visible. Figure 5c shows the coordinate differences with respect to the reference coordinates when using precise orbits, precise clock corrections and on top regional effects converted to further clock information. As expected the statistical values of the presented time series (see Table 1) reflect the benefit of using ‘regional clocks’ especially in the height component. All further results of the RA-PPP client can be found in [7].

Within the RA-PPP project, a PPP user client was successfully developed. The client is able to use RINEX files as input and has the ability to automatically connect to a correction data base, which provides several models for correcting different error sources. The user client is able to use different models for compensating atmospheric

effects (e.g. Klobuchar model, global VTEC (Vertical Total Electron Content) model, local VTEC model, Hopfield model, Saastamoinen model, Modified Hopfield model). The client uses precise clock and orbit data in order to account for the satellite specific errors as well as 'regional clock' corrections. In case of dual-frequency observations, a linear combination is used to eliminate the ionospheric error.

Currently the software is not capable of processing real-time data. Nevertheless modules have already been established which can handle real-time correction data transfer in future. Tests and evaluations show the performance of the developed algorithms. Especially the 'regional clocks' provide a benefit to the accuracy.

4. Future Work

While within the last years the demand for real-time PPP tailored to the needs of various applications increased, also a handful of commercial and free services providing real-time correction products were brought to life.

Currently, the IGS real-time working group is providing a real-time pilot project to be prepared for the trend towards real-time GNSS data and derived products such as precise clock corrections and orbits. Organizations or reference stations producing real-time GNSS data can participate in the working group to provide their data-streams via a central service (cf. [14]).

Recently, the commercial positioning service called G2, providing real-time orbits and clocks, was initiated. Operated by Fugro, it mainly addresses the vessel navigation market. Using G2, for the first time also GLONASS integration within PPP (see [15]) is possible.

Nevertheless, real-time PPP is only in its starting phase and only few applications make use of the technique. There are still many unsolved problems left, e.g., the integer ambiguity resolution during PPP processing and the insufficient availability of real-time correction data, which again directly influences the position accuracy.

Based on the outcome of the project RA-PPP, the same consortium is currently investigating the adaptation of the developed algorithms to the new challenges within a follow-up project called 'Development of a real-time PPP processing facility' (short title RT-PPP) which started at the beginning of 2011. Within this work, we plan to develop appropriate algorithms for real-time PPP and to modify existing algorithms to comply with

the requirements of modern applications. It is planned to estimate the gain and deficiencies of using GLONASS observations within PPP as a response to the recovered constellation and modernization of the Russian satellite system. Based on an increasing number of GNSS satellites, improvements in accuracy and availability due to a better geometric constellation can be expected. Since a lot of applications are safety or liability critical, it will also be necessary to include investigations on integrity monitoring algorithms, appropriate for PPP.

Enabling real-time PPP processing requires producing and distributing real-time correction data fulfilling the accuracy needs depending on the addressed applications. Therefore, the project consortium plans to strongly focus on that task. Thereby the calculation and application of the 'regional clock' corrections within real-time will be one of the challenges of RT-PPP.

A so called data streamer will concentrate on the dissemination of orbit, clock and atmospheric corrections that will be provided via RTCM data messages. 'Regional clocks' will be calculated for a set of GNSS stations for adequate time intervals and forwarded to a data conversion unit together with the other correction data. The data will be sent to a stream encoder to convert the correction terms for PPP into appropriate RTCM data messages, which will be broadcasted via Ntrip. An Ntrip client within the rover requests and receives the RTCM messages and forwards them to the processing unit of the built in user-client, where the RTCM corrections can be applied to the observations to improve the PPP solution.

For our current project the post-processing software produced in RA-PPP serves as a base platform for the implementations of a real-time processing facility. It will be adapted and upgraded not only with a module enabling the reception of real-time corrections but also with new algorithms and modules in order to serve as a real-time processing device.

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