Precise Point Positioning – Towards Real-Time Applications



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Abstract

Precise Point Positioning (PPP) denotes a GNSS (Global Navigation Satellite System) based positioning technique, where dual-frequency code and phase measurements from a single receiver are used to calculate precise site coordinates at the sub-decimeter level. The data processing relies on precise satellite orbits and clock correction information determined from observation data of a global reference station network provided by organizations such as the International GNSS Service (IGS). Typically, the ionospheric delay is almost completely eliminated by means of the ionosphere-free linear combination, while the tropospheric delay and the receiver clock bias are estimated parameters along with the site coordinates.

Introduced for the first time about 14 years ago the PPP technique was mainly used in post-processing applications. Barriers for a more intense use of PPP were a lack of accurate real-time orbit and clock products, the still poor knowledge of receiver and satellite calibrations biases and last, but not least, long coordinate filter convergence times due to complex or incomplete integer ambiguity fixing. However, to meet the increasing demand of upcoming real-time (RT) applications IGS has initiated a real-time working group to investigate the feasibility of real-time GNSS data distribution and the generation of derived products such as precise clock corrections and orbits. Scientific organizations and companies operating reference stations can participate in the working group either by delivering their data-streams via a central service or by providing real-time GNSS products.

This article deals with the contributions of the Institute of Geodesy and Geophysics, Technical University of Vienna (TUW) to the IGS Real-Time Working Group and with the quality of PPP positioning obtained using the RT-data stream established at our institute. Aside from the positioning aspect the potential of PPP to derive related products such as tropospheric delays to contribute to weather forecast models is discussed. Finally prospects as well as current barriers of PPP in view of the upcoming new GNSS systems and signals are highlighted.

Keywords: GNSS, Precise Point Positioning, IGS Real-Time Working Group

Kurzfassung

Mit Precise Point Positioning (PPP) wird eine GNSS- (Global Navigation Satellite System) basierte Positionierungstechnik bezeichnet, welche unter Nutzung von 2- Frequenz Code- und Phasenbeobachtungen eines einzelnen Empfängers die Berechnung präziser Stationskoordinaten mit sub-dm Genauigkeit erlaubt. Die Datenprozessierung stützt sich dabei auf präzise Satellitenbahn- und Uhrinformation welche von Organisationen wie dem International GNSS Service (IGS) aus Daten eines globalen Netzwerkes berechnet und bereitgestellt wird. Die ionosphärische Verzögerung wird bei PPP im Allgemeinen durch Bildung der ionosphärenfreien Linearkombination eliminiert, die troposphärische Verzögerung und der Stationsuhrfehler werden als Parameter neben den Koordinaten geschätzt.

Seit rund 14 Jahren wird PPP als Punktbestimmungstechnik eingesetzt, vor allem geeignet für Postprozessierung Applikationen. Als Hindernis für die verstärkte Nutzung erwiesen sich die echtzeitnahe Verfügbarkeit von präziser Bahn- und Uhrinformation, eine bis heute unzulängliche Kenntnis der Empfänger- und Satellitenhardwarekalibrierung („calibration biases“) und nicht zuletzt die lange Konvergenzzeit der Koordinatenlösung. Um der stark steigenden Nachfrage nach in Echtzeit verfügbaren Beobachtungsdaten und Bahn- und Uhrprodukten zu begegnen, wurde von IGS die Real-Time Working Group ins Leben gerufen. Die Arbeitsgruppe setzt sich aus Forschungsinstituten aber auch kommerziellen Unternehmen zusammen, welche einerseits GNSS Referenzstationen betreiben oder Echtzeitprodukte aus deren Beobachtungen ableiten.

Dieser Artikel beschäftigt sich vorrangig mit dem Beitrag des Instituts für Geodäsie und Geophysik (TU-Wien) zur IGS Real-Time Working Group und mit der erreichbaren Positionierungsgenauigkeit bei Nutzung der intern berechneten und bereitgestellten Echtzeit-Korrekturdatenströmen. Neben dem Positionierungsaspekt wird auch kurz auf das Potenzial der ebenfalls mittels PPP geschätzten troposphärischen Signalverzögerungen eingegangen. Der Beitrag schließt mit einem Ausblick auf Stärken aber auch Problembereiche von PPP in Hinblick auf die demnächst verfügbaren neuen Navigationssysteme und Signale.

Schlüsselwörter: GNSS, Precise Point Positioning, IGS Real-Time Working Group

1.Introduction

Precise Point Positioning (PPP) is a positioning technique that uses undifferenced single- or dual-frequency pseudorange and carrier phase observations of a single receiver along with the precise satellite orbit and clock error information to achieve a few centimeter-level precision (see [1], [6], [10]). The concept of PPP was first introduced in the 1970's by R.R. Anderle, and was characterized as a single station positioning with fixed precise orbit solutions and Doppler satellite observations [7]. Nevertheless, the relative positioning mode has dominated the field of GPS data processing until the late 1990's, when the Jet Propulsion Laboratory (NASA) showed that the achievable precision of PPP can be comparable to that from relative positioning and implemented this new technique in their GIPSY/OASIS-II GPS processing software [10]. Consequently, the achievable positioning accuracy for a static receiver provided by PPP is at the cm-level accuracy with 24 hours of observations for a static receiver [2].

In contrast to relative positioning, in PPP no regional network correlations will be introduced and no reference station data is explicitly required for data processing. Aside from the fact that this makes PPP cost effective, the technique also allows to check the consistency of the introduced orbit, clock and atmosphere error models irrespective of environmental station biases propagated by differencing techniques.

The PPP dual-frequency functional model for code and phase reads

$$P_{if} = \rho - c\left(\Delta t^S - \Delta t_R\right) + \Delta\rho_{Trop} \qquad (1)$$

$$\Phi_{if} = \rho - c\left(\Delta t^S - \Delta t_R\right) + \Delta\rho_{Trop} + \lambda_{if} b_{if} \qquad (2)$$

where P_{if} stands for the ionosphere-free combination of pseudorange measurements and Φ_{if} is the ionosphere-free combination of carrier phase measurements in metric units. The term ρ denotes the geometric distance between the satellite and the receiver antenna and c is the speed of light. Δt^S and Δt_R are the satellite and the receiver clock errors respectively, and $\Delta\rho_{Trop}$ denotes the tropospheric delay. The phase equation (Eq. (2)) contains in addition the ionosphere-free effective carrier phase wavelength λ_{if} and the ambiguity parameter b_{if}. This ambiguity parameter b_{if} contains instrumental biases, and is therefore no longer an integer number not even in the zero-difference basic phase observables on L1 and L2. Remaining effects such as phase wind-up, relativity corrections, tidal corrections, phase antenna center variations, etc., have to be introduced through appropriate models.

Dependency of PPP on precise IGS (International GNSS Service) orbit and clock products [4] restricts the use of this technique to post-processing applications, since the latency of these products is at least 17 hours after the observed epoch in the case of the IGS "rapid" products. Real-time applications, on the other hand, rely on broadcast information or precise

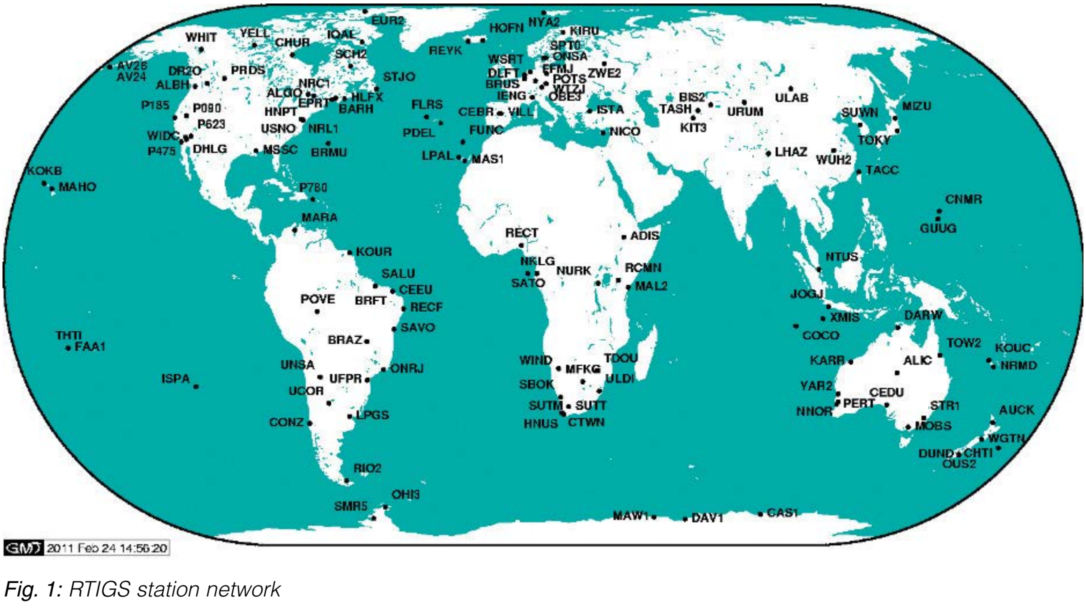

Fig. 1: *RTIGS station network*

predictions. While the GNSS broadcast messages are unsuitable for single point positioning at the sub-meter level, the IGS products have sub-dm orbit accuracy but the accompanying clock corrections are still at the 2-4 ns level after a 6 hours prediction period. These range errors map directly into the PPP solution. Therefore the IGS has investigated potential improvements of orbit and clock correction product generation for RT purposes and established an appropriate Working Group focusing on GNSS real-time data flow and product development in 2002.

After the successful Data and Analysis Center Workshop "Towards Real-Time Network," in Ottawa, Canada in April 2002, the main goal of the IGS Real-Time Working Group (RTWG), led by Mark Caissy of National Resources Canada, was to establish a global GNSS station network (the RTIGS network) consisting of stations which are delivering their observation data in real-time (at most a delay of a few seconds) to central processing facilities, and subsequently to potential users. The data transmission is performed using the internet and the User Datagram Protocol (UDP). Nowadays (2011) this global real-time station network consists of approximately 80 stations (see Fig. 1).

In parallel, appropriate real-time PPP software has to be developed to investigate the potential of RT-PPP. These software packages are mainly developed by private companies or research institutes, and few of them are publicly available. Examples are the software BNC (BKG Ntrip Client) developed by the Federal Agency of Cartography and Geodesy (BKG - Bundesamt für Kartographie und Geoinformation [11]) in Germany, or an open-source program package RTKLib developed at the Tokyo University of Marine Science and Technology. Both packages process broadcast ephemeris corrections for satellite orbits and clocks provided in the RTCMv3 format.

2. Software RTIGU-Control

Besides establishing RT products one task of the IGS RTWG is to monitor the quality of the issued IGU (IGS ultra-rapid) products. This is of special interest as IGU clock corrections experience a considerable degradation in quality with increasing prediction periods, and there is a need for a quick detection of outliers. For that purpose the Institute for Geodesy and Geophysics of the Technical University of Vienna (TUW) contributes to the RTWG by developing the software RTIGU-Control [8]. Based on the software RTIGS Multicast Receive (RTIGSMR) provided by NRCAN [12] and by introducing the RTIGS network observations, RTIGU-Control is able to calculate orbits and clock corrections for the whole GPS satellite constellation in "near" real-time (delay of approximately 15 – 20 seconds). RTIGSMR is already able to decode and prepare the incoming real-time observations for further use and serves as a development platform for creating RTIGU-Control. The three main features of RTIGU-Control can be summarized as followed:

- monitoring of the predicted IGU products, especially the predicted satellite clock corrections;
- calculation of individual daily RTIGU-Control clock and orbit products (TUW-products) for later comparison with other RTIGS center products; and
- assisting real-time positioning applications by providing real-time satellite orbit and clock correction data (see Sec. 3).

The functionality of RTIGU-Control shall be briefly described below. The program calculates, in a first step, the real-time clock corrections and clock drifts with respect to GPS time for the GPS satellites and tracking stations by means of carrier-smoothed observations. This may be regarded as an initial step of an iterative process, because the calculated clock corrections are based on the predicted IGU orbits. A subsequently applied Kalman Filter step (kinematic approach) introduces again the carrier-smoothed observations, this time correcting for the clock corrections of step 1 to calculate the positions and velocities of the satellites. Although the procedure is not totally independent of the IGU solution it still performs a consistency check of the IGU predictions. Clock corrections and orbit information are loaded every 30s to clock – RINEX and SP3 – files. Results and comparisons to IGU products are displayed online on the operator screen but also stored in clock RINEX and SP3 file formats, e.g. for validation of the performance of the IGU-predicted products. Furthermore the established orbit and clock parameters are used to calculate corrections to the broadcast ephemeris, which can finally be fed into a real-time PPP algorithm. The calculation scheme of RTIGU-Control for one epoch is displayed in Fig. 2. The following general steps are performed.

Carrier-smoothing: The carrier-smoothing algorithm is based on a weighting procedure of temporal phase differences together with

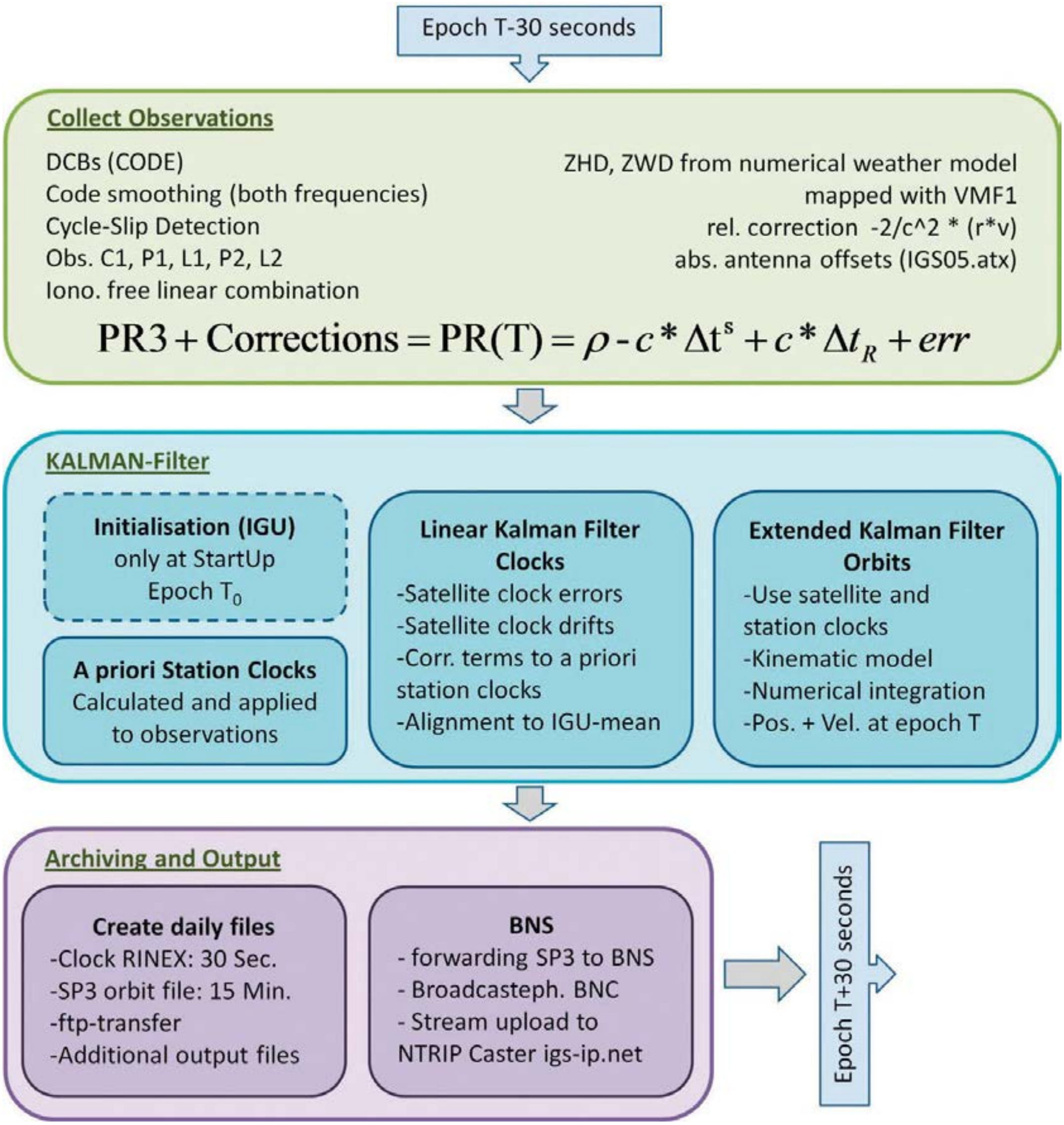

Fig. 2: RTIGU-Control calculation scheme

raw code observations [5]. Code DCBs (Differential Code Biases) provided by the IGS Analysis Center CODE are applied to the observations at both frequencies. Also, cycle-slip detection is performed within this calculation step.

Ionosphere-free linear combination: The smoothed pseudoranges (PRs) at both frequencies are merged by means of the ionosphere-free linear combination (PR3) to reduce the ionospheric delay of the signals.

Apply corrections: The tropospheric delay is corrected using gridded ZHD (zenith hydrostatic delay) and ZWD (zenith wet delay) information calculated from numerical weather models (predictions). They are mapped into the specific elevation using the VMF1 mapping function [3]. The 2^{nd} order relativistic effect is applied and the absolute antenna offsets (IGS05.atx) are included. Additionally solid earth tide corrections are applied to the fixed coordinates of the reference stations.

Linear Kalman Filter - clocks: Within this calculation step the satellite clock corrections with respect to GPS Time as well as their linear drifts are calculated. Because of the unpredictable behavior of most station clocks, approximate a priori values are calculated by introducing the satellite clock corrections of the previous epoch. The filter solely estimates correction terms to these a priori station clock corrections. The mean of all satellite clock corrections is aligned to the IGU clock mean (reference).

Extended Kalman Filter - orbits: Introducing again the observations corrected for the satellite and station clock errors, the orbits of the satellites are estimated. The kinematic model that is used considers the attraction due to the central term for earth gravitation plus the oblateness (J2) of the Earth. The predicted values are generated using a numerical integration process. After this step the positions, as well as the velocities, of all available satellites are obtained. The clock estimation has been separated from the orbit estimation to limit the required processing time of each processing step. In general, and in case of available adequate computer power, it is advisable to estimate all parameters in a single step which allows for proper stochastic modeling.

Archiving and streaming: All calculated results are coded in clock RINEX and SP3 orbit files for further analysis and stored on the ftp server of the Institute. Additionally SP3 files containing the calculated orbits and clocks are generated every epoch and forwarded to BNS (see Sec. 3).

3. Data Flow and PPP Field Test

Typically real-time PPP applications make use of continuously available observation and broadcast information data from a GNSS receiver together with actual corrections to satellite orbit and clock parameters. To perform the task of calculating corrections to the broadcast ephemerides and satellite clock errors use is made of the software BNC (BKG NTRIP Client) and BNS (BKG NTRIP State Space Server) provided by the BKG as well as the real-time orbit and clock information calculated by RTIGU-Control. BNC receives the GPS broadcast information from the NTRIP-Caster igs-ip.net and forwards it to BNS. RTIGU-

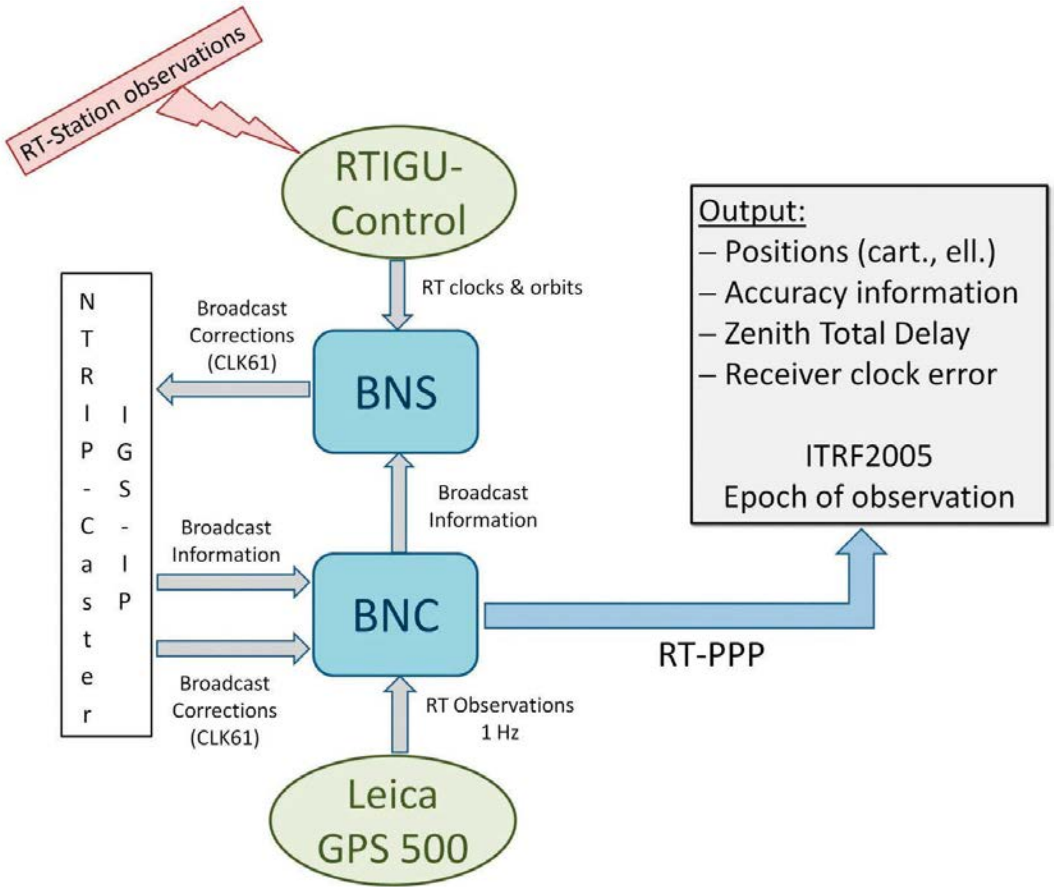

Fig. 3: Processing scheme of the RT-PPP experiment

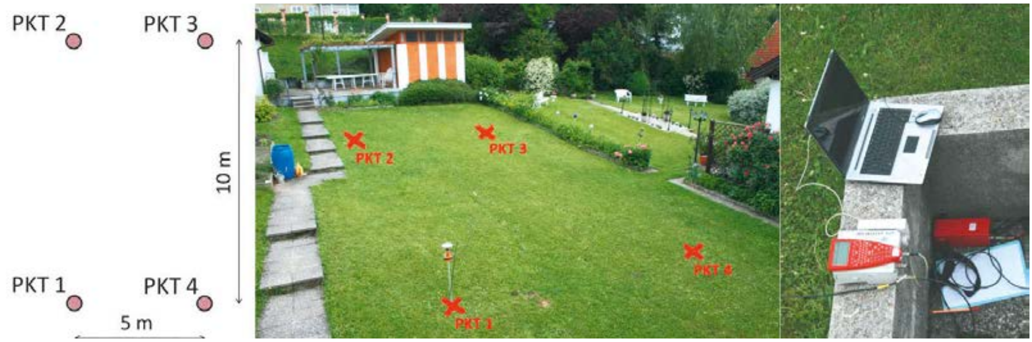

Fig. 4: *Setup of the RT-PPP test scenario*

Control calculates the satellite orbits and clock errors and forwards them in SP3 file format to BNS.

BNS calculates the correction terms to the broadcast ephemerides and clock errors using the forwarded data sets and delivers these corrections in a RTCMv3 format back to the NTRIP-Caster within the correction data stream CLK61. Finally, besides various other correction data streams provided by several other institutions, this CLK61 stream applied to the underlying broadcast information is used within the built-in real-time PPP client of BNC to calculate site coordinates. The processing scheme is shown in Fig. 3.

To study the achievable accuracy using RTIGU-Control products with RT-PPP, both static as well as a kinematic test scenario were set up [9]. Current observation data were collected by a Leica GPS 500 receiver. The test area comprised four static points forming a rectangle with dimensions of approximately 5 to 10 meters. The Leica GPS 500 receiver was connected to a AT502 Antenna and delivered measurements with a data rate of 1Hz to the serial port of the notebook where BNC was installed. The broadcast information and the correction data stream CLK61 were received via WLAN from the NTRIP-Caster igs-ip.net. Parallel to the RT-PPP solutions calculated by BNC, the raw observation data were stored for post-processing. An external power supply unit completed the necessary equipment (see Fig. 4).

After initializing the RT-PPP algorithm at PKT 1 static measurements were carried out at PKT 2 – PKT 4 for about half an hour at each point. Afterwards several kinematic tests were carried out, for example one kinematic trajectory described a "figure eight", another one involved moving randomly between the four points.

Tab. 1 shows the schedule of the different tasks performed in RT-PPP experime

The RT-PPP results were recorded within the log file of BNC, the raw measurements as RINEX v2.11 observation file. The reference coordinates of PKT1 – PKT4 were calculated by means of the Leica GeoOffice (LGO) software using the static observations together with rapid IGS products and observations from a nearby reference station. The kinematic trajectories and the static

Measurement time (MESZ) Date: June,12th 2010	Measurement scenario	BNC RT-PPP (kin.)	LGO Baseline	NRCan PPP (kin.)	Comments
12:11 – 13:43	Static, PKT 1	X	X	X	Initialising RT-PPP
13:45 – 14:23	Static, PKT 2	X	X	X	
14:26 – 15:57	Static, PKT 3	X	X	X	
14:59 – 15:32	Static, PKT 4	X	X	X	
From 15:35	Kinematic	X	—	X	figure eight
From 15:37	Kinematic	X	—	X	random movement
From 15:42	Kinematic	X	—	X	loop

Tab. 1: *Tasks and schedule of the RT-PPP test scenarios*

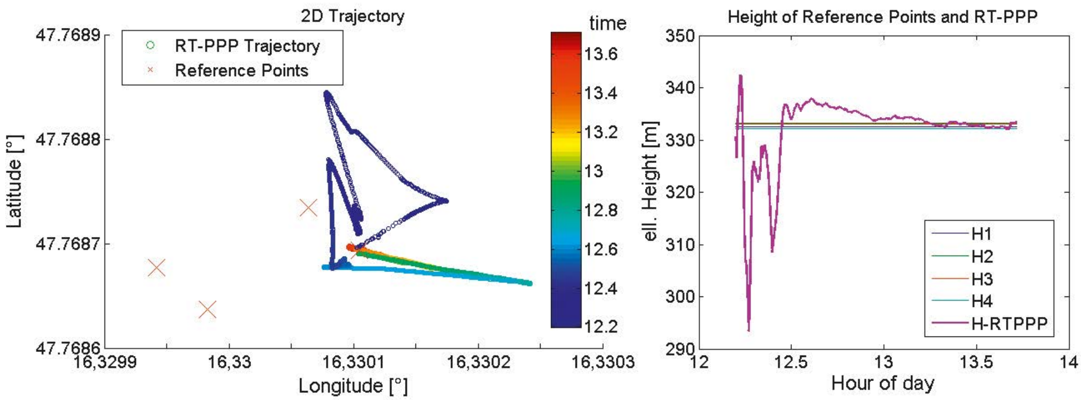

Fig. 5: Initialization step at PKT 1

observations were processed using the online kinematic PPP service of National Resources Canada (NRCan). Finally, these reference solutions were then compared with the achieved RT-PPP solutions.

The convergence time of the BNC PPP algorithm is typically 30 to 45 minutes, but depends also on the quality of the broadcast corrections and the ratio between code and phase measurement noise set by the user. In the worst case, if the quality of the broadcast corrections is extremely bad, the coordinate solution does not converge. Fig. 5 shows the convergence process at PKT 1 for the horizontal position as well as for the height component. The change in the horizontal position with time is color-coded, which means position solutions during the initialization period are plotted with blue circles, positions obtained after convergence of the filter algorithm are plotted with red circles. The heights of the reference points are plotted as horizontal lines. Convergence was achieved about 45 minutes after initialization.

After the convergence of BNC's PPP algorithm at PKT 1 and at the other three corner points of the test rectangle (PKT 2 – PKT 4) RT-PPP measurements were carried out and afterwards compared with the reference position, and additionally with the kinematic solutions of NRCan online PPP service. As an example the solutions obtained from NRCan and by RT-PPP at PKT 3 are shown in Fig. 6.

The horizontal positions it has to be pointed out that the point clouds obtained from both solutions are clearly separated in space. The coordinate rms. of the NRCan point cloud is about 10 cm with an offset to the reference position (red "X") of 10 cm in the southwest direction. In the case of RT-PPP the rms. of about 15 cm is slightly larger with an offset of 25 cm in the southeast direction of the reference position. Another clearly visible detail is that the solutions show an artificial movement with time (color-coded) which can be related to the changing satellite geometry. The offset can be caused by differences in orientation of the introduced orbit represen-

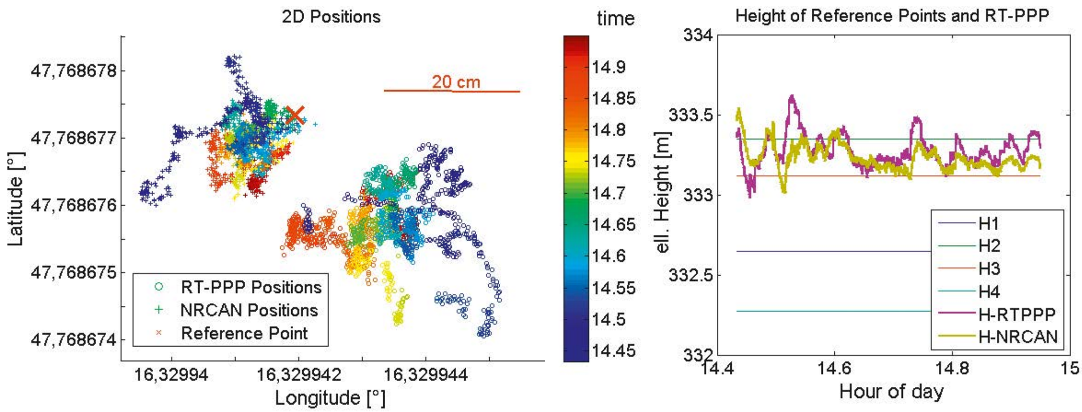

Fig. 6: Reference, NRCan and RT-PPP solutions for PKT 3

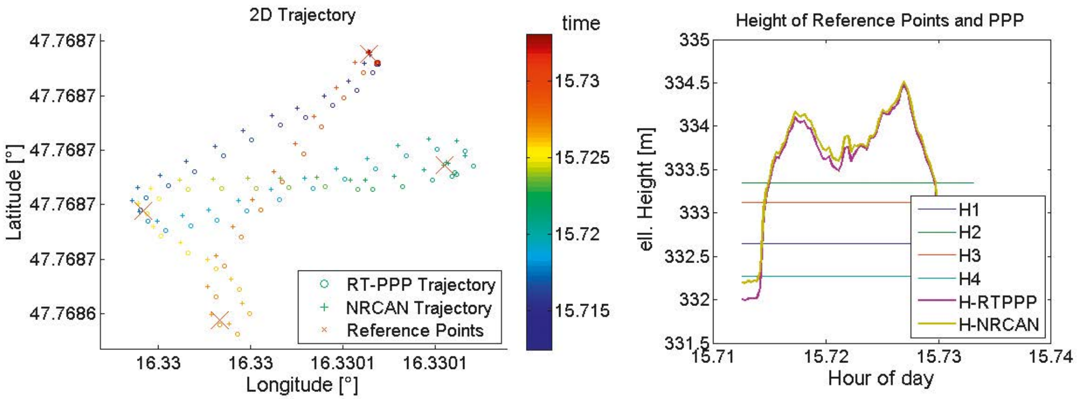

Fig. 7: Results of the kinematic test scenario "loop"

tations, on the one hand real-time orbit information and on the other a precise IGS orbit product for post-processing, well aligned to the underlying reference frame The height time series of both PPP solutions are very similar. In most cases the RT-PPP solution are a few cm above the NRCan solution. Both PPP solutions show a bias of approximately 10-15 cm compared to the reference height. This may be caused in both cases by an insufficient modeling and estimation of the tropospheric path delay.

As a final example, the results of the kinematic "loop" experiment are shown in Fig. 7.

Starting at PKT 4, PKT 3 was circled. Afterwards the receiver was moved along the diagonal of the rectangle until PKT 1 was reached. From there the receiver was moved back to PKT 3 and further on to PKT 2. Finally the chosen path led back to PKT 4 along the other diagonal of the rectangle. In Fig. 7 the horizontal plot contains again the reference positions of the corner points, the trajectory of the NRCan solution obtained from post-processing and the real-time trajectory from BNC obtained with the RTIGU-Control broadcast corrections. Similar to the static experiment one can see an offset of approximately 30 cm in the southeast direction of the RT-PPP solution from the reference position (and also with respect to the NRCan solution). This offset remains constant over the whole observation period of the kinematic test. This would be an indicator of a stable number (and geometry) of visible satellites, although the elevation mask characteristics are significantly changing during the movement of the antenna. A check of the raw observation data confirmed that no change in the number of tracked satellites took place during this experiment.

The conducted RT-PPP experiment confirms that using the real-time orbit and clock correction data-stream obtained from RTIGU-Control for real-time PPP algorithms such as the one used by the BNC software can provide positioning accuracies of 20 – 30 cm in horizontal position as well as height. Therefore, this technique can be integrated into various global navigation applications.

4. Summary and Prospects

PPP has become a valid alternative to network-based GNSS processing, at least for a number of post-processing applications. Currently real-time PPP solutions still suffer from extended coordinate filter convergence times compared to differential techniques, as well as having a limited positioning accuracy at the 10-20 cm-level, primarily caused by missing calibration information preventing integer ambiguity fixing. Nevertheless, there are a number of applications, aside from exclusive positioning tasks, which can be addressed using PPP. In this context "near" real-time troposphere monitoring can be mentioned as an example. The tropospheric delay is a parameter of the PPP process and the variation of atmospheric humidity is of great interest to meteorology. PPP data from a dense reference station network can be processed in short time frames which allows computation of tropospheric delays within a couple of minutes, hence contributing to weather forecasting. For details see [6].

The set of new signals provided by next generation and modernized GNSS programs will allow for improved ambiguity resolution techniques. In terms of PPP these signals will offer the opportunity to choose less noisy ionospheric-free linear combinations and allow for the modeling of higher order ionospheric effects. However, the use of new GNSS signal for PPP will only be possible if the accompanying systematic inter-system biases can be determined to high accuracy.

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