Simulation case study of deformations and landslides using real-time GNSS precise point positioning technique

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\textbf{ABSTRACT}

The precise point positioning (PPP) is a Global Navigation Satellite System (GNSS) computation technique that performs precise positioning using a single receiver. This is the main advantage over the traditional differential positioning for geodesy and geomatics which requires, at least, two receivers to get a precise position or a single receiver connected to a network of reference stations. The main goal of this work was to study the real-time PPP technique for deformation and landslides monitoring. A custom designed device was used for the simulation of landslides, and several test campaigns were performed at field. A control unit was designed based on open-source software and Python libraries implemented in this research. The conclusion of the study shows that real-time PPP allows solutions for deformation monitoring with mean offsets of 2 cm in north, east and up components, and standard deviations of 2 cm. It demonstrates the reliability of real-time PPP monitoring systems to detect deformations up to 5 cm of magnitude when the double constellation (GPS+GLONASS) was used. Finally, an improvement in the results with the recovery of fixed ambiguities in the PPP algorithms is outlined.

\textbf{ARTICLE HISTORY}

Received 22 September 2015
Accepted 27 December 2015

\textbf{KEYWORDS}

Global Navigation Satellite Systems; real-time; precise point positioning; landslides; deformations

\section{Introduction}

Global Navigation Satellite System (GNSS) observations have been used for ground movements monitoring for a long time (Jäger & González 2006; Blewitt et al. 2008; Cina & Piras 2015). The precise point positioning (PPP) technique in real-time, is a recent method that provides several advantages over the traditional differential GNSS solutions. A single receiver can obtain an instantaneous navigation position but without precision. However, PPP approach with a single receiver can achieve accuracy without simultaneous GNSS observations of other stations (Zumberge et al. 1997), or without a real-time connection to differential or real-time kinematics corrections, computed by a local or regional GNSS network of reference stations.

The theoretical basis of PPP consists of determining the position of a single receiver using pseudo-range and carrier phase GNSS measurements, together with precise satellite clocks and orbit state models, signal biases and, if possible, atmospheric propagation models derived from a global network. As a consequence, it is the only possible precise technique in isolated areas and it can be used in a remote location to monitor possible landslides and movements or deformations due to
natural hazards (De Agostino & Piras 2010; Caissy et al. 2013; Kalita et al. 2014). This topic is also of interest in previous research works, with post-processing PPP (Wang 2013), or in real-time PPP (RT-PPP) approach with or without integer ambiguity resolution (Chen et al. 2009). In an RT-PPP scenario, it can be very useful as a tool to support early warning systems at the time when a phenomenon is happening and as an additional prevention mechanism. As an experimental technique, PPP has a potential interest that must be analyzed in several fields, and, even more so, in the real-time case study.

However, precise absolute positioning with centimetre accuracy with a single GNSS receiver was considered unfeasible until recently. The reason of this limitation was the difficulty in cancellation of errors, the phase ambiguity resolution and the dependence on external information, in order to model the GNSS error sources. That is to say: it depends on the performance of the orbit and clock products, and the effects of the un-modelled or un-calibrated errors (Gao & Chen 2005). Moreover, in RT-PPP, precise streams of products and state models are needed, and they must meet certain requirements of latency and continuity. In the case study of real-time positioning, the technique is very sensible to gaps and outliers in a product and fluctuations in the constellation. As a consequence there appear delays in initialization, losses of convergence and a lack of accuracy in the results.

In this paper, the analysis of RT-PPP potential and the possibility of using the technique for the continuous monitoring are presented in order to complement results obtained by mentioned researchers. The capacity of RT-PPP for deformation monitoring is evaluated based on the simulation of several deformations performed in different field campaigns. In order to have a clear idea about the precision and accuracy of the technique, the RT-PPP results were compared with the known values of the simulated deformations and with the quasi-real-time post-processing PPP approach. Double differences post-processing solutions with high-ratio products are also presented for the same campaigns.

Different methods for the ambiguity resolution problem in PPP have been proposed by several researchers, like the decoupled clock model (Collins 2008), the fractional cycle bias determination (Ge et al. 2008; Li et al. 2015) and the integer recovery clocks (IRC) technique (Laurichesse et al. 2008). The proof of the concept of real-time ambiguity resolution is also introduced for the case study of deformation monitoring.

2. Experimental and test campaigns

It is important to emphasize that PPP does not depend on the simultaneous GNSS observations of other points or on the development of a local GNSS network infrastructure, so it can be applied everywhere on earth. On the contrary, in relative positioning, one GNSS receiver should be installed on the place with the motions that are of interest, called rover, and there must be at least another receiver on a stationary place as the reference station. The reference station must typically be placed in a stable area. Such a place could be difficult to find: in the case of strong earthquakes, for example, the reference station may also be displaced. The processing and the monitoring tasks have no dependence on a particular reference station, if a network of reference stations is available. However, its development and maintenance are always more expensive and such infrastructures are not available in all cases in remote locations. The use of PPP can solve these limitations, RT-PPP computations can also be more immediate and simpler to obtain.

Six GNSS campaigns were executed during a year, between Doy (day of year) 107/2013 and Doy 135/2014. Every day a deformation simulation was performed, in north, east, north-east (NE) or vertical direction. The graphs and figures in section 3 reflect a summary of the six campaigns, with special emphasis on the moments of induced deformations. The tables in section 4 show the statistical results of the deformation magnitude of the six simulations and the application of RT-PPP ambiguity resolution.
Field GNSS receivers and hardware available in the market were not prepared for direct decoding of the clock and orbit products, in the recent standard format for RT-PPP, during the period of the campaigns. This format is called RTCM-SSR (Radio Technical Commission for Maritime Services - state space representation format) (RTCM State Space Working Group 2007; Wübbena 2012). Additionally, the software and firmware versions of the single receiver did not allow the application of PPP algorithms to solve the position (as PPP is a methodology still in development). For this reason a custom designed control unit and software were integrated in order to solve PPP algorithms with a GNSS single receiver. The purpose of the control unit was to monitor and compute PPP positions and detect induced ground landslides.

2.1. Design of the field control unit

The components of the control unit (figure 1) were a dual-frequency L1/L2 Trimble R8 GNSS receiver measuring data at 1 Hz, mobile hardware such as a tablet or laptop, open-source C++ experimental libraries and other self-programmed software in the high level programming language Python, which has a free and open-source community-based development model (Python Software Foundation 2015).

The own-developed open-source software based on Python libraries provides a more immediate, quick and simpler analysis in real-time of possible deformations, and in addition, it can be used in quasi-real-time case study with hourly processing. Thus, it can be considered as an important complement to the actual tools for deformation detections. This self-programmed software in Python provides easily interpretable results in real-time and allows data analysis in coordination with external tools for PPP real-time resolution problem. It provides epoch-by-epoch connection with a GNSS device or with other data streams. It also allows a direct comparison with known coordinates, a direct alignment with the desired regional reference frame ETRF2000 (European Terrestrial Reference Frame 2000), and finally, statistical analysis of convergence time and accuracy. The control unit was evaluated in the calibration geodetic network of the Polytechnic University of Valencia (Spain), used in several research works (Berné et al. 2008).

As previously mentioned, an important part of the control unit was the mobile hardware (laptop, tablet or similar) which was connected to the GNSS single receiver by a USB serial port adapter. In this case, we set up the programmed libraries in a tablet that performed an internet GPRS/3G connection with the International GNSS Service (IGS) products server (Dow et al. 2009), in order to receive state space representation models. These models contain GNSS satellite clock corrections, orbit corrections and GNSS signal biases to be applied in real-time.

![Figure 1. Control unit with the stream of data products of the International GNSS Service (IGS) and data flow from the receiver.](image)
2.2. Clock product application and PPP algorithm resolution

Data processing of a global network can give real-time clock and orbit products, also with fixed ambiguities. That is to say, analysis centres or service providers estimate the state models in advance with a global GNSS network, then implement the distribution of the streaming, and finally, users can apply these state models in real-time (Agrotis et al. 2010; Thaler & Weber 2010; Mervart & Weber 2011; Hauschild & Steigenberger 2012). Nowadays, there exist individual state models from analysis centres (CLKxx) and combined solutions from analysis centres from the International GNSS Service (IGSyy). As shown in Hadas and Bosy (2015), one of the main problems of the IGS real-time combined products, is still the latency, which can present values of more than 20 seconds. It also increases the age of the corrections; as a consequence, this problem degrades initialization period, the convergence and the final accuracy. At the moment, an optimal alternative consist of using an individual state model from an analysis centre, with this choice, it is possible to minimize significant latency effects.

A global state product CLK91 (GPS+GLONASS), supplied by the Centre National d’Etudes Spatiales of France (CNES) (Laurichesse et al. 2013), was used. The reason for choosing this clock and orbit model was because in previous analysis with GNSS measurements it proved to be highly stable. The differences for GPS orbit corrections, between this product and other state models from different analysis centres were usually about few millimetres until 10 cm. For GLONASS satellites the differences can reach values of about 50 cm. In addition, CLK91 was chosen because the same analysis centre (CNES) can provide state models with the capacity of ambiguity resolution in real-time. It provided excellent initializations, accuracies and periods of convergence with good repeatability in coordinates in comparison to other IGS and analysis centre models (figure 2) in north (N), east (E) and up (h) components. This clock model is accessible via streaming.

Other real-time reports and relative differences between several state models from different analysis centres can be seen in the monitor of the GNSS data centre hosted by the Bundesamt für Kartographie und Geodäsie from Germany (http://igs.bkg.bund.de/ntrip/ppp). In the case of other IGS products (like IGS01, IGS02) they provide only GPS orbit and clock corrections, and corrections were needed to both GPS+GLONASS constellations.

In the field control unit, the model was also encapsulated in a standard file as an ultra-rapid product. Moreover, if the single receiver L1/L2 observations are transferred to a computer in RINEX

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**Figure 2.** N, E and vertical offsets of the comparison between real-time PPP results and known positions with different clock and orbit products: (a) CLK91 clock with GPS, (b) CLK91 with GPS+GLONASS and (c) IGS03 with GPS+GLONASS.
format, they can be post-processed with hourly or sub-hourly latency to obtain near-real-time results with PPP and/or doubles differences.

The resolution of the position with RT-PPP can provide kinematic solutions, using sequential algorithms in the field campaigns. These algorithms were executed with an extension of C++ libraries of the NTRIP Client software distributed by Bundesamt für Kartographie und Geodäsie (BNC) (Mervart 2012), and libraries distributed by the CNES (Laurichesse & Privat 2015). Also, the self-programmed open-source Python libraries allowed real-time connection with the RTCM receiver stream, real-time clock and orbit products, or NMEA streams with positions as output of BNC, by means of a sockets library. All observations were recorded with a sampling interval of 1 second. These algorithms solve the PPP position with the ionosphere-free pseudo-range \( P_c \) and carrier phase combinations \( \Phi_c \), between GNSS frequencies \( L_1 \) and \( L_2 \) (equations (1) and (2)):

\[
P_c = \frac{f_{L_1}^2P_{L_1} - f_{L_2}^2P_{L_2}}{f_{L_1}^2 - f_{L_2}^2}
\]

\[
\Phi_c = \frac{f_{L_1}^2\Phi_{L_1} - f_{L_2}^2\Phi_{L_2}}{f_{L_1}^2 - f_{L_2}^2}
\]

Input state models from the provider have an estimated accuracy better than 0.5 cm for orbits and 0.1 nanoseconds for clocks standard deviations (www.igs.org). The sampling of the received state model was every 5 seconds. It was considered that the initial position of the receiver was known, but after the initial period new positions need to be estimated at each time step in the PPP computation because of the induced movements. The initial \( \sigma \) values for the estimated coordinates were adjusted depending on the receiver dynamics (figure 3), and the process noise for the tropospheric delay was determined from standard tropospheric activity. The phase ambiguities were considered as a constant per pass in the PPP approach without ambiguity resolution and the sequential algorithm was solved without iterations. The initial sigma value for known coordinates was 1 cm. For the expected variations of the position (white noise and induced movements), it was assigned 100 m. For the tropospheric delay estimation a value of 0.1 m was chosen, and the expected variation of the tropospheric effect was about 1 cm/hour.

![Figure 3. Computation scheme for PPP algorithm resolution.](image-url)
2.3. Physical device for induced deformations

A physical device was designed for the simulation of the north-east landslides or horizontal deformations. This physical device acted as an antenna mount for the GNSS engine. Another device was also set up to study deformations on the vertical component. In the case study on horizontal deformations, the device consisted of a sliding steel guide which supported a sliding track of 232 mm. In this device, part of the guide can remain fixed and the other part supports the movement, as shown in figure 4. Previously, the torsion of the guide that supports the GNSS antenna was checked. Millimetre graduation rod was fixed to the guide in order to measure the magnitude of every displacement. In every session, a time of 25–40 minutes was set with the antenna in a static position in order to start from a PPP solution which was as accurate as possible. Following this interval (initialization time) the antenna began to move and slipped along the guide, keeping a constant altitude. The magnitudes of the induced deformations were of the order of centimetres and decimetres between 5 and 24 cm. The maximum displacement was due to the maximum deformation allowed for the physical device. The minimum induced magnitudes were chosen in order to be compliant with the expected accuracy of the PPP technique in real-time. After a few epochs in this position, new displacements can be induced again either in the same direction or returning to the initial position.

3. Results of the real-time PPP deformation detection

3.1. Evaluation of two-dimensional displacement components of the deformation

The results with RT-PPP for the two-dimensional component were analyzed, and the following figures represent the differences between fixed coordinates of the centre of the pillar and the RT-PPP measurements. All the comparisons were made using the ETRF2000 frame at the epoch of observations. In some cases, a horizontal NE error component was introduced, formed by the square root of sum of the squares of offsets in north (N) and east (E) directions. The NE component represents the distance observed from the antenna to the centre of the pillar. In other words, the error committed can also be analyzed directly on this component, since the distance is known.

Figure 5 shows the different periods of the receiver dynamics initialization time, convergence period, epoch of movement, convergence after deformation and/or other instants of induced deformation (dashed lines).
For Doy 107/2013 the convergence time required was 12 minutes and 23 seconds for a solution in the range of 20 cm, for the NE components. After initialization, all positions were below a range of 20 cm during the entire time span. The standard deviation of RT-PPP positions was about 2.6 cm, before the first induced movement (at epoch 310270 in GPSWEEK time scale). All values were as expected considering the accuracy of the RT-PPP method. In figure 5(b), the theoretical position of the NE component (corresponding to a movement of 23.2 cm) is represented with a continuous line. On the one hand, it is possible to compare the mean offset of RT-PPP positions with respect to the expected coordinates after the displacement; in this case the mean offset was 5.8 cm for horizontal components. On the other hand, it is necessary to analyze the mean offsets and statistics of the detected displacement with respect to the real displacement; this is done in section 4.

Figure 5. (a) Real-time PPP epoch-by-epoch differences for Doy 107/2013. N, E components and NE component. (b) Period after the initial movement. (c) Second simulation of deformation and convergence. Units in metres, time referred to GPSWEEK seconds in X axis.
The solution maintains the standard deviation after the induced movement but the graph shows a displacement in the coordinates. The last part of the session is represented in figure 5(c), which shows the return of the GNSS antenna to its initial position. The standard deviation and the outliers in the reception of the real-time state model must be estimated or known every time in order to discriminate observation noises from real movements. This is possible with the implemented Python libraries and it is also applicable to the loss of tracked satellites, which is controlled epoch by epoch, and the dilution of precision analysis. As in the previous cases another simulation was conducted for Doy 135/2014, which included short undersize deformations in one direction and in another. The induced displacements were similar in magnitude to the accuracy of the technique to evaluate minimum detection capacity of the phenomenon. Dashed lines represent the instant at which the landslides were induced (figure 6) and the circles remark the instants of deformations in the extended figure. In this case, the mean offset with respect to the expected positions was 7.1 cm.

Finally, the data were post-processed with quasi-real-time latency for the same sessions using high-rate measurements data (1 Hz). The same product of clock corrections, orbits and biases applied in real-time was used in the quasi-real-time processing. The combination of frequencies was the ionosphere-free solution, and the PPP algorithm was solved sequentially in order to give kinematic solutions, as in previous cases. A post-processed PPP solution with GPS+GLONASS constellations and another solution with only GPS were obtained in every campaign (figure 7).

Dashed lines represent the moments with induced landslides. The main differences observed between the post-processing scenarios were the initial convergence time and the difference between computed positions, which was more than 5—10 cm in some epochs. More stability was also detected in the GPS+GLONASS solution in all sessions. Additionally, the differences between the RT-PPP approach (figure 6) and the quasi-real-time post-processed PPP approach (figure 7) are mainly due to the elimination of the real-time latency in the post-processing computation. As it can be seen, quasi-real-time post-processing provides solutions with better biases.

Figure 6. (a) Real-time PPP epoch-by-epoch differences for Doy 135/2014, north (N) component. (b) 10 cm induced movement in north direction. (c) 5 cm induced movement in north direction. (d) 9 cm induced movement in south direction. Units in metres, time referred to GPSWEEK seconds.
Other field campaigns were conducted, and we also obtained similar deformation detections at centimetre level to the real displacement of the guide as in previous cases. In addition, the accuracy of the measured deformations with the RT-PPP and post-processed PPP approaches was calculated and is shown in section 4, after the evaluation of the vertical deformation.

3.2. Evaluation of the vertical displacement component of the deformation

In this case study, there was an induced movement along the vertical h component. The reference point with known coordinates was an eccentric point of the pillar. Sliding steel rod was fixed to the antenna at this point. The steel rod was anchored to the pillar with cross clamps, which were screwed together to ensure stability (figure 8). Static GNSS observations were used with the double-difference post-processing technique in order to determine its coordinates.

The induced magnitudes were of some centimetres as in the previous cases, because they were consistent with the expected accuracy of the RT-PPP technique. The next picture (figure 9) shows the differences between the known position and the positions with RT-PPP in the initial and final moments after an induced movement. After the displacement, it remained in the same position until the end of the observation.

Figure 9(c) shows the detected movement in vertical direction (23.2 cm), which is similar at centimetre level to the real displacement of the GNSS antenna (25 cm). In order to compute the
displacement with RT-PPP, the positions were averaged during 5 minutes before the displacement and also after the displacement. As it can be seen, the standard deviation remained around 6.5 cm with the desired stability, in spite of the induced deformation.

Other campaigns were done with more simulations. In the next case the induced movements were 5 and 10 cm (figure 10), and the circles represent the moment of the displacement. The dispersion of the RT-PPP solution shows high stability after the initial convergence, with a standard deviation around 3.1 cm during all session. This fact allows a clear detection of the deformation magnitude.

The results show that it is possible to detect minimum displacements of about 5 cm also for the vertical component. Quasi-real-time post-processing PPP was also performed for the up component. Some of the results are shown in the following pictures (figure 11). In the post-processing PPP approach the real-time latency is eliminated. As a consequence, the elimination of the age of the corrections improves the offset of the solution that appeared in the RT-PPP approach.
4. Discussion of the approaches

These sessions were done during one year. As it can be seen, it is possible to determine the value and accuracy of the two-dimensional and vertical deformations with RT-PPP. Induced movements occurred very quickly in time, so it was necessary to average the position before the induced deformation during 5 minutes, in order to know the computed position in advance. The time span used to average RT-PPP positions was also about 5 minutes when the solution achieved convergence after the movement (in the case there was loss of convergence). The computation of the average positions is necessary in order to quantify as accurate as possible the magnitude of the deformation, so it was important to average coordinates before and after the phenomenon happens. In the field campaigns a threshold in the algorithms of Python libraries was included. This threshold controlled the offset in the solutions. If an offset in the position was bigger than a certain threshold and the standard deviation of positions remained constant, a possible deformation had occurred, and the recursive operation of averaging the positions was done, in order to estimate the displacement.

Table 1 shows the statistical results if the detected displacements are compared with the true deformations, in the real-time sessions with GPS+GLONASS, as well as the statistical results for quasi-real-time post-processing using GPS and GLONASS, and with only GPS.

The difference in the bias for the three solutions was of the order of a few millimetres in the case study of the horizontal deformation. The maximum difference with the known induced displacement was around 4 cm in the case of RT-PPP. The deformation can be detected with a mean offset of 1.6 cm in RT-PPP technique for all campaigns. Obviously, the quasi-real-time post-processing, including GPS and GLONASS constellations, was the most accurate PPP approach of the three solutions in all field tests.

The comparison of the displacements for the height component gives differences of centimetres. As in the case study of induced horizontal movements, the maximum discrepancy with the real displacement was around 4 cm (table 2).
The average offset was 2.4 cm when comparing the known displacement with RT-PPP. Again, the best solution was achieved in the quasi-real-time post-processing PPP solution with GPS and GLONASS constellations. Furthermore, the displacement detected with the RT-PPP technique had a standard deviation between 1.5 and 2 cm (1σ values), and deformations of 5 cm were detected closely in all campaigns. It has to be noted that deformation occurs very quickly in these campaigns. That is, they do not occur gradually over long periods. Fast movements allow the use of relative values to determine the differences in position, because the offset in PPP solution that exists before and after induced displacement remains similar in magnitude. However, it has been demonstrated in successful investigations that it is possible to determine the magnitude of landslides or deformations over long periods of time with post-processing PPP (Wang 2013).

Recovering integer ambiguities for RT-PPP was also checked in order to determine whether there was an improvement in the results. The standard PPP solution with ionosphere-free combination gives floating ambiguities, but PPP with fixed ambiguities is also possible. PPP with ambiguity resolution (AR) is called PPP-AR or PPP-RTK. Several authors have made important contributions in order to compare the different proposals for PPP-AR as stated before, and in spite of the practical differences and parameterizations of the approaches (Teunissen & Khodabandeh 2015), they produce equivalent results once the integer ambiguity has been achieved (Shi & Gao 2014). However, the IRC method for RT-PPP ambiguity resolution is a relatively simple method to apply with optimal performance (Geng et al. 2010), and it can be applied with existing open-source software. For this reason, in this paper, the computation with integer ambiguities was based on the IRC approach and developed versions of the libraries of the PPP client with integer and zero-difference ambiguity resolution demonstrator of the CNES (Laurichesse & Privat 2015).

The specific configuration in the experiment used the integer bootstrap (IB) method, implemented in the PPP client of the CNES (Laurichesse et al. 2008), in order to provide correct integer estimation. In spite of the fact that integer least-squares (ILS) is considered the best method for integer estimation (Teunissen 1999), the IB method can be simpler to implement.

| Table 1. Statistical results of the series with horizontal deformation simulation. Mean bias, standard deviation and maximum and minimum differences of the differences with respect to the known values in the detected displacements using different computation techniques and constellations. |
| --- | --- | --- |
| | Real-time PPP (GPS + GLONASS) | Ultra-rapid post-processing (GPS + GLONASS) | Ultra-rapid post-processing (GPS) |
| Mean bias (metres) | 0.01617 | 0.01236 | 0.01387 |
| Standard deviation (metres) | 0.02179 | 0.01513 | 0.01936 |
| Maximum (metres) | 0.04300 | 0.03040 | 0.03460 |
| Minimum (metres) | 0.00040 | 0.00070 | 0.00300 |

| Table 2. Statistical results of the sessions with vertical movement simulation. Mean bias, standard deviation and maximum and minimum differences of the differences with respect to the known values in the detected displacements using different computation techniques and constellations. |
| --- | --- | --- |
| | Real-time PPP (GPS + GLONASS) | Ultra-rapid post-processing (GPS + GLONASS) | Ultra-rapid post-processing (GPS) |
| Mean bias (metres) | 0.02480 | 0.01117 | 0.02208 |
| Standard deviation (metres) | 0.01900 | 0.01622 | 0.03528 |
| Maximum (metres) | 0.04600 | 0.02683 | 0.06440 |
| Minimum (metres) | 0.00600 | 0.00200 | 0.00100 |
for the application with real-time computations from a practical point of view, and the bootstrapped success rate is very easy to compute in certain case studies (Teunissen 2001). IB principle can also provide very useful approximations to the ILS solution. In the PPP client solution, it uses the values of V-C matrix and it considers that ambiguities that have the lowest covariance and are close to an integer must be fixed iteratively. The covariance value of the candidate values must also be below a threshold.

The purpose of the analysis of AR performance was to check if the loss of precise solutions or lack of convergence due to multipath, atmospheric noises or constellation tracking was mitigated with the entire ambiguities (figure 12).

Specific values for GPS ambiguity success rates were obtained in the campaigns using a window length of 5 hours. They were computed as the ratio between the number of fixed ambiguities and the total number of ambiguities which were not fixed in the integer estimation (table 3).

It is important to remark that the receiver was suffering induced movements, so, in the kinematic computations, the ambiguity resolution can be affected. Figure 13 shows the epoch-by-epoch evolution of success rates percentage, and the tracked satellites (GPS+GLONASS) for different campaigns.

Table 3. Mean success rate (%) for every campaign and mean RMS in ambiguity estimation. Units in metres.

| Day   | Success rate | Mean RMS |
|-------|--------------|----------|
| Day 1 | 73.815       | 0.015    |
| Day 2 | 70.438       | 0.014    |
| Day 3 | 79.516       | 0.012    |
| Day 4 | 74.226       | 0.056    |
| Day 5 | 60.264       | 0.019    |
| Day 6 | 79.182       | 0.032    |
About the improvement of the solution convergence, real-time ambiguity resolution monitoring over long periods led to only one outlier, with a bias worse than 10 cm in 24 hours in X,Y, taking into account the average of the observations performed over 1 month. In the vertical component there were 43 outliers/day (as average) with a bias worse than 10 cm. Results of PPP without ambiguity resolution were improved, where there were 10 outliers/day for N, E, components during 1 month, and almost 100 gaps for the vertical component. Solution offsets with PPP-AR were inside the range of 5 cm in the 93% of the positions obtained. The accuracy of the PPP positions with fixed ambiguities gave improvements of about 3 cm as an average, but epoch by epoch maximum improvements of 10 cm were detected, with PPP-AR.

The offsets and the accuracy in the position can reflect the strength of the approach model and give a quantitative idea of the probability of correct fixing. Nevertheless, ambiguity validation methods are an important and a critical factor in order to detect degraded solutions with real-time PPP-AR. Different methods and ratio tests for ambiguity validation have been investigated for several research works (Verhagen & Teunissen 2013). A further development is possible if a validation test would be considered for the fixed ambiguities. The tests must also be effective in real-time because immediate positions are required and natural or induced movements can degrade ambiguity resolution.

4.1. Comparison analysis with the double-differences high-rate processing approach

An interesting point of discussion is the comparison between PPP approaches and double-differences processing solutions. GNSS relative positioning technique has also been used for a long time for kinematic and geodynamic applications, as well as for the determination of landslides or movement detections due to seismic or volcanic phenomena. Final high-rate and normal rate clock products obtained from the analysis centres of the IGS allow the use of the double-differences post-processing technique for this purpose. For instance, there are high-rate clock corrections with 5 seconds
sampling provided by the Center for Orbit Determination in Europe, with a latency of 1–2 weeks. A modified and re-compiled version of Bernese 5.0 software was used (Dach et al. 2007) in order to obtain the double-differences solution with a high-rate product. The modifications in Bernese 5.0 consisted of changing certain values and parameters in the FORTRAN code. It is essential in BERN- ESE 5.0 software to use these parameters to specify the maximum dimensions of the array of entry values (such as the number of satellites), or the quantity of unknowns to be estimated in every pass, in the sequential processing. The dimensions of these arrays are limited by default to a certain number (depending also on the allowed memory model). So, it was necessary to increase the dimensions. For instance, it must be defined in advance the use of high-rate sampling of clock corrections or the maximum number of used satellites of more than one constellation. In the double-differences approach, the epoch-by-epoch estimated parameters for the kinematic positioning may become very large and also the number of observations types or the number of parameters which are simultaneously processed, so they must be specified by certain magnitudes of the corresponding arrays. The sigma-dependent ambiguity resolution method of Bernese 5.0 was performed in order to fix integer ambiguities. No statistical tests or ambiguity validations were performed over the quadratic form of the residuals associated with the set of ambiguities, as all ambiguities were fixed correctly by the software.

The statistical results of the double-differences solution were computed for all sessions, and are shown in tables 4 and 5.

The double-differences approach or relative positioning also leads to a better calculation of the real displacement, as expected. However, there is a high degree of agreement with PPP technique, which confirms that the PPP approach could be a future alternative to relative positioning.

5. Conclusions

In this paper several field campaigns were used to demonstrate the suitability of RT-PPP measurements for the detection of induced deformations and landslides. In other words, a single receiver can work autonomously with PPP algorithms and can reach enough accuracy when clock products are available.

As it can be seen, RT-PPP must use solutions that have reached the previous convergence. It is better to use GPS+GLONASS constellations, since they add robustness to the solution. Recovering fixed phase ambiguities is very useful because it can compensate losses of convergence in the observations and it improves the accuracy of the solution. Future investigations can focus on integer ambiguity validation by means of ratio tests for the RT-PPP case study, as it can be crucial in order to avoid biased solutions.
It is also necessary to monitor the clock model used, in order to have a parallel system to differentiate the loss of accuracy due to real-time clock outliers with respect to a true deformation. The continuous computation of other parameters, such as the standard deviation positions with respect to the known position, or the control of satellites tracked is also important in order to differentiate the observation noises from real movements. In the present case study, the RT-PPP technique gives accuracies within 2 cm in the detection of deformations or landslides, and there are differences of only a few centimetres when we compare detected movements with the known values. Applying standardized models for ionosphere corrections (Hernández-Pajares et al. 2011), will be essential in the future to achieve faster initialization. As the real-time state models are in continuous development, future analyses will be developed with improved IGS products and new state models from analysis centres.

It can be concluded that the PPP approach has great future potential and it can also be used, in addition to other geophysical instruments, in real-time monitoring systems to detect movements in certain areas, in order to aid in setting up early warning systems. PPP greatly could have an influence on disaster prevention or management, particularly in those areas where a nearby network infrastructure does not exist.

Acknowledgements

The authors want to thank Denis Laurichesse from the Centre National d’Etudes Spatiales (France) for the availability of tools and products for precise point positioning ambiguity resolution. The authors would like to thank the reviewers for the interesting and valuable contributions and suggestions during the revision of the paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Agrotis L, Alfaro P, Dow J, Zandbergen R, Svehla D, Ballereau A. 2010. ESOC’s RETINA system and the generation of the IGS RT combination. Poster session presented at: International GNSS Service Workshop; 2010 Jun 28 to Jul 2; Newcastle, UK.
Berné JL, Garrigues P, García-Asenjo L, Baselga S. 2008. Base de calibración de la Universidad Politécnica de Valencia: Descripción y medición [ Calibration network of the Polytechnic University of Valencia: description and survey]. Revista de la CECEL 7 — II. Proceedings of the International Congress of Geomatic and Topographic Engineering IX — Topcart; 2008 Feb; Valencia, Spain; p. 277—284.

Blewitt G, Hammond WC, Kreemer C, Plag HP, Stein S, Oka E. 2008. GPS for real-time earthquake source determination and tsunami warning systems. J Geodesy. 83:335—343.

Caissy M, Agrotis L, Weber G, Fisher S. 2013. IGS real-time service meeting the needs of the IGS real-time PPP user community. Presented at: GNSS PPP Workshop: Reaching Full Potential; Ottawa, Canada. Available from: ftp://geodesy.noaa.gov/dist/steveh/PPPSlides/

Chen J, Ge M, Dousa J, Gendt G. 2009. Evaluation of EPOS-RT for real-time deformation monitoring. J Global Position Syst. 8:1—5.

Cina A, Piras M. 2015. Performance of low-cost GNSS receiver for landslides monitoring: test and results. Geomat Nat Haz Risk. 6:497—514.

Collins P. 2008. Isolating and estimating un-differenced GPS integer ambiguities. Proceedings of the 2008 Institute of Navigation National Technical Meeting; Fairfax, VA; p. 720—732.

Dach R, Hugentobler U, Frídez P, Meindl M. 2007. Bernese GPS software version 5.0. Astronomical Institute, University of Bern-AIUB, Switzerland. Bern: Stämpfli Publications AG; [Digital print 2011]. Available from: http://www.bernese.unibe.ch/docs50/DOCU50.pdf.

De Agostino M, Piras M. 2010. Different PPP strategies in the case of natural disasters. Disaster Adv. 10/2012. 5:509—513.

Dow J, Neilan R, Rizos C. 2009. The international GNSS service in a changing landscape of global navigation satellite systems. J Geodesy. 83:191—198.

Gao Y, Chen K. 2005. Performance analysis of precise point positioning using real-time orbit and clock products. J Global Position Syst. 3:95—100.

Ge M, Gendt G, Rothacher M, Shi C, Liu J. 2008. Resolution of GPS carrier-phase ambiguities in precise point positioning (PPP) with daily observations. J Geodesy. 82:389—399.

Geng J, Meng X, Dodson AH, Teferle FN. 2010. Integer ambiguity resolution in precise point positioning: method comparison. J Geodesy. 84:569—581.

GNSS Data Center Germany [Internet]. Germany: Bundesamt für Kartographie und Geodäsie. Available from: http://igs.bkg.bund.de/ntrip/ppp

Hadas T, Bosy J. 2015. IGS RTS precise orbits and clocks verification and quality degradation over time. GPS Solut. 19:93—105.

Hauschild A, Steigenberger P. 2012. Combined GPS and GALILEO real-time clock estimation with DLR’s RETICLE system. Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2012); 2012 Sep; Nashville, TN; p. 302—309.

Hernández-Pajares M, Juan-Zornoza M, Sanz-Subirana J, Samson J, Tossaint M. 2011. Method, apparatus and system for determining a position of an object having a global navigation satellite system receiver by processing undifferenced data like carrier phase measurements and external products like ionosphere data. International patent application PCT/EP2011/001512. European Spatial Agency reference: ESA/PAT/566).

International GNSS Service – Real Time Service [Internet]. c 2015. Available from: www.igs.org

Jäger R, González F. 2006. GNSS/LPS based online control and alarm system – mathematical models and technical realization of a system for natural and geotechnical deformation monitoring and hazard prevention. In: Sansó F, Gil AJ, editors. Geodetic deformation monitoring: from geophysical to engineering roles. Volume 131 series of IAG symposia, Jaén 2005. Berlin: Springer; p. 293—303.

Kalita J, Rzepecka Z, Szuman-Kalita I. 2014. The application of precise point positioning in geosciences. Proceedings of the 9th International Conference on Environmental Engineering; 2014 May 22—23; Vilnius, Lithuania. http://dx.doi.org/10.3846/enviro.2014.215. Available from: http://enviro.vgtu.lt

Laurichesse D, Cerli L, Berthias JP, Mercier F. 2013. Real time precise GPS constellation and clocks estimation by means of a Kalman filter. Proceedings of the 26th International Technical Meeting of the Satellite Division of the Institute of Navigation. ION GNSS; 2013 Sep; Nashville, TN; p. 1155—1163.

Laurichesse D, Mercier F, Berthias JP, Bijac J. 2008. Real time zero-difference ambiguities fixing and absolute RTK. Proceedings of the 2008 Institute of Navigation National Technical Meeting; Fairfax, VA; p. 747—755.

Laurichesse D, Privat A. 2015. An open-source PPP client implementation for the CNES PPP-WIZARD demonstrator. Proceedings of the Institute of Navigation GNSS; 2015 Sep; Tampa, FL.

Li P, Zhang X, Ren X, Zuo X, Pan, Y. 2015. Generating GPS satellite fractional cycle bias for ambiguity-fixed precise point positioning. GPS Solut. 19:1—12.

Mervart L. 2012. Introduction to BKG Ntrip Client (BNC) usage. Presented at: PPP-RTK and Open Standards Symposium; 2013 Mar 12—13; Frankfurt, Germany; p. 12.

Mervart L, Weber G. 2011. Real-time combination of GNSS orbit and clock correction streams using a Kalman filter approach. Proceedings of Institute of Navigation - GNSS; 2011 Sep 20—23; Portland, OR; p. 707—771.
Python Software Foundation. 2015. Python documentation and libraries; [accessed 2015 Jun]. Available from: https://docs.python.org/3/

RTCM State Space Working Group. 2007. RTCM Paper 075-2007-SC104-470 Mission Statement, 2007.

Shi J, Gao Y. 2014. A comparison of three PPP integer ambiguity resolution methods. GPS Solut. 18:519–528.

Teunissen PJG. 1999. An optimality property of the integer least-squares estimator. J Geodesy. 73:587–593.

Teunissen PJG. 2001. GNSS ambiguity bootstrapping: theory and application. Proceedings of KIS2001; 2001 Jun 5–8; Banff, Canada, University of Calgary; p. 246–254.

Teunissen PJG, Khodabandeh A. 2015. Review and principles of PPP-RTK methods. J Geodesy. 89:217–240.

Thaler G, Weber R. 2010. Contribution of the Technical University of Vienna to the RTIGS-pilot-project. Poster session presented at: International GNSS Service Workshop; 2010 Jun 28 to Jul 2; Newcastle, UK.

Verhagen S, Teunissen PJG. 2013. The ratio test for future GNSS ambiguity resolution. GPS Solut. 17:535–548.

Wang Q. 2013. Millimeter-accuracy GPS landslide monitoring using precise point positioning with single receiver phase ambiguity (PPP-SRPA) resolution: a case study in Puerto Rico. J Geodetic Sci. 3:22–31. ISSN (Print) 2081-9943.

Wübbena G. 2012. RTCM state space representation (SSR). Overall concepts towards PPP-RTK. Presented at: PPP-RTK & Open Standards Symposium; 2012 Mar 12–13; Frankfurt, Germany; p. 41.

Zumberge JF, Helfin MB, Jefferson DC, Watkins MM, Webb FH. 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. J Geophys Res. 102:5005–5017.