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High-rate real-time PPP for dynamic motion detection in vertical direction

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ABSTRACT

Nowadays, with the developments in GNSS (Global Navigation Satellite System) technology, the data storage and data processing capacity of GPS (Global Positioning System) receivers has been gradually increased. This situation is widely used in the detection and monitoring of horizontal and vertical vibrations that occur in the structure when high temporal resolution geodetic GPS receivers are under the influence of dynamic loads such as earth crust motions, wind load, traffic load, which affect man-made engineering structures. In the study, RT DF-PPP (Real Time Dual Frequency-Precise Point Positioning) method was applied together with a GPS sensor with a sampling interval of 20 Hz, using a steel bar mounted on a steel tree model designed as a structure model, and a steel bar on which different sensors can be integrated and can provide simulation of vertical motions in detecting vertical motions occurring in structures. To evaluate the performance of the method used and to test the performance of capturing vertical displacements, the DF-RP (Dual Frequency-Relative Positioning) method was taken as reference and the results were compared with the PP-PPP (Post Process-PPP) method using the IGS-Final (International GNSS Service-Final) product. When the results are compared with the RP and PP-PPP solutions in the frequency domain of vertical motions as a result of harmonic oscillations of the high-rate RT-PPP method, it has been seen that the amplitudes and frequencies are compatible with each other. Therefore, dynamic motions that occur as a result of natural events such as earthquakes, tsunamis, landslides and volcanic eruptions can be instantly and reliably monitored and detected by the high-rate RT-PPP method. When the results were evaluated in the time domain, an improvement was observed in the RMSE (Root Mean Square Error) and maximum values of RT-PPP and PP-PPP methods according to RP after filtering. When the statistical results are examined, vertical harmonic motions of the solutions made by using both RT-PPP and PP-PPP methods can be detected with accuracy below centimeters. These results clearly show that it can detect vertical dynamic motions in engineering structures such as bridges, skyscrapers and viaducts with RT-PPP method to evaluate. Thus, by detecting the effects of dynamic motions occurring in the structure on the health of the structure, a safe environment will be provided by making a rapid hazard assessment for life safety.

I. Introduction

High temporal resolution GPS receivers have been widely used in the monitoring and detection of instantaneous displacements as a result of natural events, the monitoring of dynamic motions in the structure and the detection of deformations that occur in the structure (Larson *et al.*, 2003; Larson, 2009; Kouba, 2003; Yi *et al.*, 2013; Moschas and Stiros, 2015; Wang *et al.*, 2016; Yu *et al.*, 2016; Yigit and Gurlek, 2017). Nowadays, the ability of high-rate GPS receivers used in many areas to capture dynamic motions occurring horizontally and vertically with Precise Point Positioning (PPP) technique (Zumberge *et al.,* 1997; Kouba and Heroux, 2001) using precise satellite orbit and clock corrections produced by analysis centers without being connected to a fixed point has been evaluated in many studies. In addition, the Relative Positioning (RP) technique was taken as a reference for comparison in the studies.

In many studies conducted with the PPP method, IGS-Final, IGS-Rapid and IGS-Ultra-rapid products produced by the International GNSS Service (IGS) analysis center were used. Although these products differ in terms of broadcasting time and accuracy, they have been evaluated with the post-process PPP method in areas such as GPS seismology and structural health monitoring (SHM) (Kouba 2003; Avallone *et al.,* 2011; Xu *et al.,* 2013; Nie *et al.,* 2016; Paziewski *et al.,* 2018; Xu *et al.,* 2019; Moschas *et al.,* 2014; Yigit, 2016; Yigit and Gurlek, 2017; Tang *et al.,* 2017; Kaloop *et al.,* 2018). The use of the products produced by the IGS analysis center in the monitoring of instantaneous dynamic motions due to the delay time limits these products. For this reason, real-time satellite orbit and clock correction information are provided free of charge to the user through the Real Time Service (RTS), which was established by IGS in 2013, in order to ensure the instantaneous data stream continuously. In this case, the idea of real-time monitoring of dynamic motions has emerged and these studies have begun to be carried out in many areas today. In the studies, the performance of the Real Time (RT)-PPP method and the correction products used were tested by monitoring the displacements that occur in natural events such as earthquakes and tsunamis. (Hadas and Bosy, 2015; Krzan and Przestrzelski, 2016; Elsobeiey and Al Harbi, 2016; El-Mowafy *et al.*, 2016; Alcay and Turgut, 2017; Alcay, 2019; Takahaski *et al.*, 2014, Tu *et al.*, 2017, El-Mowafy and Deo, 2017; Li *et al.*, 2019; Li *et al.*, 2014; Zheng *et al.*, 2019; Zhang *et al.*, 2021). This method, which is also used in deformation monitoring of engineering structures, has been emphasized as an alternative method to the RP method (Martin *et al.,* 2015; Tang *et al.*, 2017). In addition to the real-time data stream offered by IGS, it offers satellite orbit and clock products with a sampling interval of 30 seconds, which are derived from the IGC01 data stream presented under real-time conditions and can be used for post-evaluation PPP solutions. However, the use of these products has been tested for near real-time rapid hazard assessment in order to detect the oscillations caused by the motions of the earth's crust in the structures and the damage to the structure. It has been tested that under real-time conditions, correction products produced from IGC01 can be detected at the centimeter or even millimeter level in the detection of earthquake-induced surface wave motions (Li *et al.,* 2019; Li *et al.*, 2014; Zheng *et al.*, 2019; Zhang *et al.*, 2021).

In this study, real-time evaluation of vertically damped harmonic motions with the RT-PPP method and the performance of the method are tested. The raw observation data collected from the geodetic quality GNSS receiver with 20 Hz sampling interval integrated into the steel bar capable of producing vertical damped harmonic motion has been solved with the RT-PPP method based on the IGC01 product offered by IGS-RTS. Moreover, the results were compared with the PP-PPP method, with reference to the RP method, which is widely used in many studies on the evaluation of dynamic motions occurring in engineering structures.

II. Traditional PPP method and description of experiments

A. *Methodology*

Dual frequency GNSS raw code and undifferenced carrier phase observation equations:

$$P_{r,j}^{s} = \rho_{r}^{s} + c.\delta t_{r} - c.\delta t^{s} + T_{r}^{s} + I_{r}^{s} + m_{r,j}^{s} + \varepsilon_{r,P}^{s} \tag{1}$$

$$\Phi_{r,j}^{s} = \rho_{r}^{s} + c.\delta t_{r} - c.\delta t^{s} + \lambda_{j} N_{r,j}^{s} + T_{r}^{s} - I_{r}^{s} + m_{r,j}^{s} + \varepsilon_{r,\Phi}^{s} \tag{2}$$

Defined by the Equations 1 and 2. The symbols used in the equations are respectively:

$P_{r,j}^{s}$ = Pseudorange observation of the carrier frequency (j) with respect to the satellite (s) of the GPS receiver(r) (m)
$\Phi_{r,j}^{s}$ = Carrier-phase observation of the carrier frequency (j) with respect to the satellite (s) of the GPS receiver (r) (m)
ρ = Geometric distance between satellite and receiver (m)
c = Speed of light (m/s)
δt_{r} = Receiver clock correction (s)
δt^{s} = Satellite clock correction (s)
T_{r}^{s} = Tropospheric delay between satellite and receiver (m)
I_{r}^{s} = Ionospheric delay between satellite and receiver (m)
λ_{j} = Carrier-phase wavelength (m)
$N_{r,j}^{s}$ = Integer ambiguity (cycle)
$m_{r,j}^{s}$ = multipath effect of code and phase observations (m)
ε_{r}^{s} = noise effect of code and phase observations (m)

In the equation, using both code and carrier phase observations increases the point positioning accuracy of the Traditional-PPP method, and dual-frequency observation models are proposed to reduce the effect of ionospheric errors.

B. *Experiment Design for RT-PPP method*

In order to detect vertical displacements of engineering structures under the influence of dynamic loads, a vertical steel flat simulation bar, which can produce vertically damped harmonic motion and on which measurements can be made by integrating different sensors, has been used throughout the experiment. In addition, the steel flat simulation bar is mounted on the steel tree model, as seen in Figure 1 to produce harmonic oscillations by fixing one edge and applying force to the other free edge. The main purpose of using this model is to simulate the multipath effect caused by bridge elements (tower, main cable, suspension cables) while measuring in engineering structures such as bridges. Morever, the building seen in Figure 1 causes the most multipath effect in the experiments.

Damped harmonic motions with different initial amplitude are produced by the steel flat simulation bar. Among these motions, example one case was selected. It was chosen to test the performance of RT-PPP in applications such as structural health monitoring of vertical displacements due to the effect of dynamic loads in engineering structures, earthquake early warning system and rapid hazard assessment.

C. *Processing Strategy*

Trimble MB-2 OEM receiver with dual frequency, GPS observation data collection and 20 Hz sampling interval was used for the RT-PPP method in the experiments. In addition, in order to evaluate the performance of this method, data was collected throughout the experiment with a CHC I80 GNSS receiver with 2 dual-frequency 20 Hz sampling intervals and a solution was made with the RP method. Another GNSS receiver was fixedly installed at approximately 75 meters from the experiment location, and the other GNSS receiver was mounted on a vertical steel flat simulation bar as a rover, as shown in Figure 1 and data was collected. GPS observation data were collected by setting the cut-off angle of these two receivers to 10° and the data sampling interval to 20 Hz. The experiments were carried out in front of the Civil Engineering Department of the Gebze Technical University campus on July 13, 2021 for approximately 1 hour.

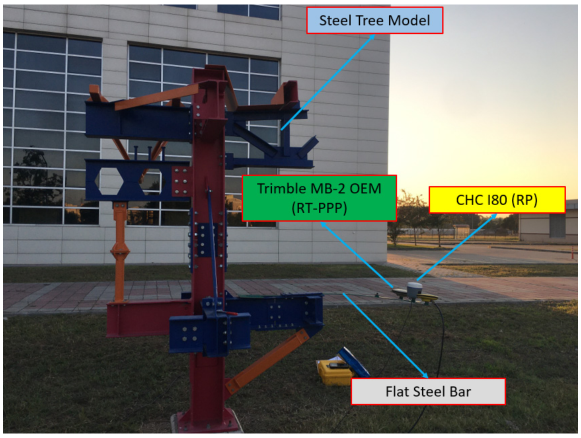

Figure 1. Experiment setup in which damped vertical harmonic motions are performed.

For the RT-PPP solution, a RT-PPP solution was made with the satellite orbit and clock corrections obtained by broadcasting the IGC01 product, which is the RTS product, and the raw observation data recorded from the Trimble MB-2 OEM GNSS receiver. The rtknavi application of RTKLIB demo5_34a software, which is an open source software package, was used to evaluate the RT-PPP method in real time. In addition, to evaluate the performance of RT-PPP after the experiments, PP-PPP solutions were made in the rtkpost application of the RTKLIB software based on the IGS-Final products produced by IGS, with reference to the RP method.

III. Results and Discussion

In this section, the results obtained from 5 cases of damped harmonic motion experiments with different initial amplitudes are examined in the time and frequency domain. In the experiments, the vertical oscillations obtained from the solution of the RT-PPP method and the vertical oscillations obtained from the PP-PPP method based on the satellite orbit and clock correction of the IGS-Final product were compared with reference to the RP method. In order to produce damped harmonic motions, a downward thrust of approximately 3-10 cm was applied to the free end of the steel bar during the experiment.

During the experiment, the oscillation motions were instantly monitored by the RT-PPP method. Figure 2 shows the displacements of 5 free-decayed vertical harmonic motions in the instantaneous time domain. Figure 2 contains the dataset of vertical harmonic motions performed on 13 July 2021. In all methods, solutions were made with only-GPS observations. Experiment time lasted approximately 2.5 minutes. The characteristics of all experimental cases shown in Figure 2 are summarized in Table 1.

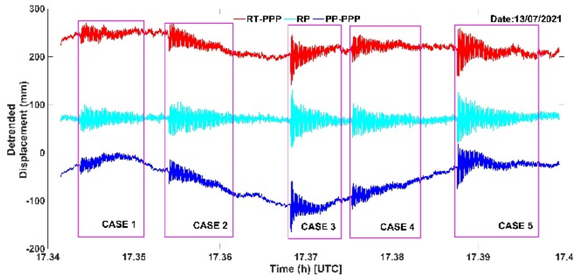

Figure 2. Vertical displacements obtained from the RT-PPP method, RP method and the PP-PPP method.

Table 1. Properties of five Cases discussed in the study

Case	Time [s]	Init. Amp. [mm]	Freq. [Hz]
1	25.5	20	1.64
2	38	30	1.64
3	20	60	1.65
4	32	30	1.64
5	28	55	1.62

During the experiments, data loss was experienced in some epochs while solving with the RT-PPP method. This is due to the fact that the receiving antenna cannot collect data at intervals of 0.05 seconds in some cases. These data losses were eliminated with the spline interpolation method. The same situation was applied to the PP-PPP method since the raw observation data used in the RT-PPP method were also used in the PP-PPP method. As seen in the figure, fluctuations are seen in the displacement time series of all cases in both RT-PPP and PP-PPP methods. The reason for this behavior is due to the convergence time of the PPP, the limitations of the models used, and the accuracy of the products (Cai, 2009). The offsets and fluctuations in displacements is not a major problem, as the aim of this study is focused on detecting short-term (15 - 35 s) dynamic motions with the RT-PPP approach. In addition, it was observed that the displacements obtained by the RP method were straight along the center of the motions during the oscillation case.

Different filters can be used to eliminate the short-term and long-term fluctuations in the RT-PPP and PP-PPP seen in Figure 2. For this, in the time domain of the experiments with five different harmonic oscillations and all the methods used in the study, a Butterworth high-pass filter with a stop frequency of 0.5 Hz and a pass frequency of 1 Hz was applied. The filtered time series of all methods is shown in Figure 3. Case 2 was chosen as a representative example to examine the performance of real-time PPP in capturing vertical damped harmonic oscillations and compare it with post-process PPP with reference to RP. In Figure 4, the detrended displacement time series obtained from the RT-PPP, RP and PP-PPP methods is shown in the upper part of the figure. The initial amplitude of the harmonic motion is about 30 mm and the total time is 38 seconds. In cases where the time series of the three methods whose displacements were obtained were consistent with each other, but the oscillation decreased, fluctuations occurred. These fluctuations seen in short-term motions are corrected by applying a high-pass filter as seen in the middle of Figure 4.

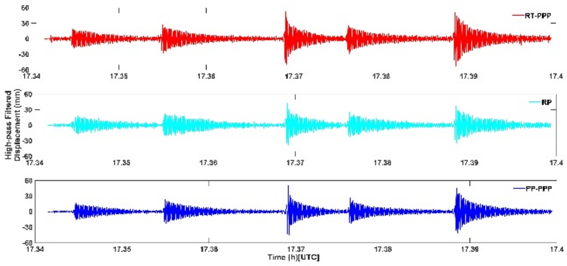

Figure 3. Displacement time series filtered by applying a Butterworth high-pass filter.

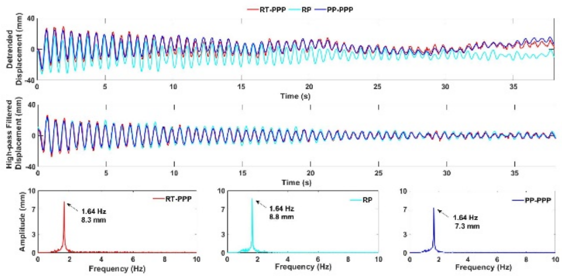

Figure 4. Displacement time series and FFT spectrum of the RT-PPP, RP and PP-PPP methods for Case 2.

The main purpose of this study is to evaluate the performance of the methods used in capturing vertical dynamic motions. Therefore, the frequency and amplitude values corresponding to the Fast Fourier Transform (FFT) spectrum in the frequency domain of the three methods were compared with each other. As can be seen in the figure, the harmonic oscillation frequencies obtained by the three methods are equal and 1.64 Hz. There are small differences at the level of milimeter in the amplitude values corresponding to the dominant frequency. The results show that the amplitude value obtained by the RT-PPP method is close to the RP. The reason for this difference is the noise level of methods due to the accuracy of products used and different GNSS antenna/receiver, among others.

When the FFT results of all the cases selected in Table 2 are examined, it is observed that the displacements can be captured under centimeters with the RT-PPP method and give similar results when compared to other methods. In addition, in cases where the dominant amplitude values are at the centimeter level, it was seen that the dominant frequency values were the same in all 3 methods, and the amplitude values were compatible with each other. Considering these results, the RT-PPP method gave reliable results compared to the RP method, which is the ability to capture vertical motions occurring in engineering structures. In order to analyze the time domain accuracy of the RT-PPP and PP-PPP methods, the RMSE was calculated with reference to the RP method and shown in Table 3.

Table 2. Dominant frequency and amplitude values of 3 methods

Case	RT-PPP		RP		PP-PPP	
	Amp. [mm]	Freq. [Hz]	Amp. [mm]	Freq. [Hz]	Amp. [mm]	Freq. [Hz]
1	8.0	1.64	8.0	1.64	6.8	1.64
2	8.3	1.64	8.8	1.64	7.3	1.64
3	14.4	1.65	12.9	1.65	12.8	1.65
4	8.3	1.64	7.9	1.64	7.0	1.64
5	15.4	1.62	12.3	1.62	12.8	1.62

Table 3. RMSE and Maximum values of difference between RP and PPP methods

Case	RT-PPP		PP-PPP	
	RMSE [mm]	Max [mm]	RMSE [mm]	Max [mm]
1	6.1 [2.6]	17.3 [9.0]	6.7 [2.2]	17.3 [6.7]
2	6.5 [2.6]	19.7 [9.2]	7.3 [2.2]	19.5 [7.1]
3	7.0 [4.4]	22.4 [14.8]	8.7 [2.6]	22.9 [12.3]
4	6.0 [2.8]	23.7 [12.4]	6.0 [2.1]	17.9 [6.2]
5	7.4 [5.3]	22.2 [20.9]	6.8 [2.7]	22.7 [10.8]

The RMSE and maximum values of the PP-PPP and RT-PPP methods calculated with reference to RP for all cases are given in Table 3. Values in square brackets in this table are filtered results, while others show unfiltered results. After applying filtering, RMSE and maximum values decreased. In the RT-PPP approach, after filtering, there is an improvement between 9% and 57% in RMSE values, while there is an improvement between 8% and 48% in maximum values. When the same situation was examined for the PP-PPP approach, an improvement was observed between 16% and 70% in the RMSE values, while an improvement between 9% and 61% in the maximum values. It shows that after filtering, RT-PPP can give reliable results in monitoring vertical short-time dynamic behavior with an accuracy of milimeter-level. In addition, small displacements of about 1 cm were detected with high accuracy at the milimeter level with the RT-PPP approach. These results in the time domain clearly show that the performance of the RT-PPP method for capturing displacements of vertical motions that may occur in engineering structures with a high-rate GNSS receiver gives reliable results without the need for a reference receiver. Thus, it has been revealed that the RT-PPP approach is an alternative method to the RP method in capturing short-term dynamic motions caused by natural events such as earthquake, tsunami, and wind in engineering structures.

IV. Conclusion

In this study, the ability to capture vertical displacements resulting from dynamic motions in engineering structures with real-time PPP technique was investigated. In order to produce these vertical motions occurring in the structures, 5 vertical damped harmonic motion simulation tests were carried out using flat steel bars. In order to test the performance of the RT-PPP method, the RP method, which is widely used in many studies to capture dynamic motions in structures, was taken as reference. In addition, the real-time solutions obtained from the RT-PPP method were compared with the solutions of the PP-PPP method in the time and frequency domain, using precise satellite orbit and clock correction information. When the FFT spectrum analysis of the 5 harmonic oscillation test results was performed, it was clearly seen that RT-PPP gave the same frequency values for each case compared to the other two methods. Although there are small differences at millimeter level in the amplitude values corresponding to the dominant frequencies, it is obvious that the RT-PPP method achieves successful results in vertical harmonic oscillations. These differences are caused by the signal-to-noise ratios caused by the hardware of GNSS receivers, the accuracy of the satellite orbit and clock correction information used in PPP solutions, and the delays caused by real-time broadcast products. Statistical analyzes in the time domain were performed to test the accuracy of monitoring the instantaneous displacements in the structures with the RT-PPP method. Considering the results, it has been seen that the RMSE values of the RT-PPP method varied between 0.4 and 2.5 millimeters compared to the PP-PPP method. In addition, the accuracy of the harmonic oscillations of the 5 cases according to the RT-PPP method was obtained below about 5.5 millimeters. These results in the time domain clearly show that the performance of the RT-PPP method for capturing displacements of vertical motions that may occur in engineering structures with a high-rate GNSS receiver gives reliable results without the need for a reference receiver. Thus, it has been revealed that the RT-PPP approach is an alternative method to the relative positioning method in capturing short-term dynamic motions caused by natural events such as earthquake, tsunami, and wind in engineering structures. After applying a high-pass filter to the RT-PPP approach, it has been observed that the dominant frequencies and amplitudes of vertical dynamic motions can be determined accurately and reliably. In addition, the RT-PPP approach provides reliable results in applications such as structural health monitoring, early warning system, rapid hazard assessment, and real-time products in the detection of short-term vertical dynamic motions that gave similar results compared to IGS-Final products used in post-process.

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