Intercontinental Geoinformation Days

igd.mersin.edu.tr

The efficiency of high-rate RTK for structural health monitoring

Güldane OKU TOPAL*[1], Burak AKPINAR [1], Vahap Engin GÜLAL[2]

[1] *Yildiz Technical University, Department of Geomatics Engineering, Istanbul, Turkey*
[2] *Atlas University, Rectorate, Turkey*

Keywords
Structural Health Monitoring
High-Rate RTK
Shake Table
Time Series

ABSTRACT

The purpose of Structural Health Monitoring (SHM) is to monitor the conditions of important structures, to determine natural behaviors, and to take necessary precautions in advance by determining the possible accidents. In recent years, Global Navigation Satellite Systems (GNSS) are widely used because of their high accuracy and ease of use in SHM applications. The purpose of this study is to show that high-rate RTK GNSS measurement methods can detect the behavior of engineering structures with high accuracy and to investigate that they can be used effectively in SHM. Experiments were carried out with a single-axis shake table to determine the performance of the RTK GNSS method in SHM studies. The shake table was moved harmonically to simulate possible structural movements and it is aimed to determine these movements with the 20 Hz multi-GNSS equipment. The obtained data were analyzed by time series analysis and fast Fourier transform techniques, and the frequency and amplitude values of the movements were calculated. The accuracy of the results was determined by comparing GNSS displacements with the results obtained by LVDT (Linear Variable Differential Transformer) which is the position sensor of the shake table. As a result of experiments, it was determined that the high-rate RTK GNSS method can be used in observing the behavior and natural frequencies of engineering structures with a precision of a few mm.

1. INTRODUCTION

Improving technology, increasing population due to increased construction and these areas' largest economy has increased the importance of structural observation. These observations have great importance in terms of structural health monitoring (SHM) and disaster management.

There are many different methods and equipments used in SHM applications. However, today High Rate Global Navigation Satellite Systems (GNSS) method has been widely used to detect dynamic deformations and determine structural vibrations for long bridges, towers and tall buildings (Wells et al. 1987).

GNSS is a three-dimensional positioning system with the help of radio signals broadcast from GNSS satellites, in all weather conditions, day and night, quickly, accurately and economically, without the need for sight between points. The system, designed for the navigation need, offers a very sensitive time and speed determination as well as positioning (Wells et al. 1987). With the help of the developing GNSS Method, SHM studies have also gained a new dimension and have become able to present instant results with the help of data obtained simultaneously. So last years, Real-time GNSS positioning methods have been used to detect dynamic displacement of tall slender structures and long or short span bridges frequently (Çelebi and Şanlı 2002; Li et al. 2006; Meng and Roberts 2007; Park et al. 2008; Moschas and Stiros 2011; Xu et al. 2017; Górski 2017). Besides, various shake table tests have been carried out to simulate the natural frequencies of engineering structures, create high oscillations and determine these displacements with GNSS equipment. (Wang et al. 2012 ; Önen et al. 2014; Nie et al. 2016; Akpınar et al. 2017; Dindar et al. 2018)

There are 3 main techniques used in broadcasting corrections and point coordinates in RTK positioning which can be used effectively and practically in SHM. These are Virtual Reference Station Method (VRS), Field Correction Parameters Method (FKP), Main-Auxiliary Reference Station Method (MAC) techniques. In this study, the results of the high-rate RTK GNSS measurements performed with the single-axes shake

* **Corresponding Author**

*(guloku@yildiz.edu.tr) ORCID ID 0000-0001-7548-2276
(bakpinar@yildiz.edu.tr) ORCID ID 0000-0002-3076-1578
(engingülal@gmail.com) ORCID ID 0000-0002-5397-3303

Cite this study

Oku Topal G, Akpınar B & Gülal V E (2021). The efficiency of high-rate RTK for structural health monitoring. 2nd Intercontinental Geoinformation Days (IGD), 24-27, Mersin, Turkey

table will be analyzed using Time Series and Fast Fourier Transform Analysis. The results of these three Network RTK (NRTK) GNSS methods have been analyzed and the advantages and disadvantages of the methods compared to each other have been determined.

2. METHOD

Spectra Precision SP80 GNSS Receiver was mounted on the shake table and experiments were carried out in the field of Yıldız Technical University Davutpaşa Campus Faculty of Civil Engineering to determine whether structural vibrations can be determined by NRTK GNSS methods. Data on the movements of selected amplitudes and frequencies were collected from the GNSS receiver mounted on the shake table while the shake table was stationary and in motion. The measurement results obtained from GNSS were compared with the position sensor (LVDT) data of the shake table and the results were examined. For each of the VRS, FKP and MAC methods, GNSS data was collected with a sampling rate of 20 Hz for a total of ten minutes, with the first and last 4 minutes being still and 2 minutes moving ''Table 1''.

Table 1. All events same frequencies and equal observation times on the shake table

	Shake Table			
GNSS	Stationary	Motion	Stationary	Duration
VRS	4 min	2 min(5 Hz)	4 min	11.00-11.10
FKP	4 min	2 min(5 Hz)	4 min	11.10-11.20
MAC	4 min	2 min(5 Hz)	4 min	11.20-11.30

2.1. The Network-RTK

In the Network-RTK measurement technique, corrections are not from a single reference station, but a system consisting of multiple reference stations. The biggest advantage of the method is that the 15 km working area limit required to obtain cm accuracy is pulled to a 100 km base distance. In Turkey national CORS-TR system (TUSAGA-AKTİF) is operating according to the Network-RTK measurement principle. The CORS-TR system has a total of 146 stations spread across the country (Yıldırım et al. 2011). Some other networks work in the Network-RTK technique, not nationally, but regionally. For example, the ISKI-UKBS network, which has 8 fixed stations covering the whole of Istanbul, is one of these local networks. In our study ISKI-UKBS network has been used to compare VRS, FKP, and MAC methods.

2.1.1. VRS, FKP and MAC methods

The VRS (Virtual Reference Station) method is based on the determination of the position of mobile receivers with respect to a virtual reference station created using data of reference stations covering the working area. In the VRS method, it is assumed that there is a virtual station without equipment installed on it only a few meters away from the roaming receiver. With this method, even if there is a malfunction in the operation of any reference station in the network, the necessary GNSS corrections can be calculated using other station data (Arslan et al 2002).

FKP (Field Correction Parameters Method) is the same as the basic principle VRS method. In FKP method, which is the German translation FKP (Flächen Korrektur Parameter), surfaces are used as a reference in the calculation of correction parameters. The transfer of data at the reference stations to the browsing receiver requires that the approximate location of the browsing receiver be known (Eren et al. 2009).

The basic principle of the MAC Method is based on determining the location of the mobile receiver within the network, which consists of one master station and several auxiliary stations. The critical point of this method is that most of the calculations are made in the mobile receiver (Kahveci and Yıldız 2001)

2.2. Shake Table

A shake table is called a platform that realizing harmonic motion at defined frequencies and imitates earthquake movements by artificially generating vibration movements. The QUANSER Shake Table II (SHII) used in the experiments is an earthquake simulator with a single-axis 9.5 cm displacement capability. The range of motion of the table is determined with the help of LVDT sensors that provide precise position feedback integrated into the hardware ''Fig. 1''. The LVDT measures the position of the table at 0.0006 mm accuracy with 50 samplings per second (50 Hz). The movements created by the shaking table can be determined as harmonic and random values. Harmonic motions are the function of a sinusoidal wave defined by amplitude, frequency, and number of cycles (Yiğit et al. 2018). In this study, results regarding a harmonic motion was observed.

Figure 1. Shake Table

2.3. Time Series and Fast Fourier Analysis

In the time series analysis, it is ensured that the time-dependent graph of the series is generated, filtering operations to eliminate blunders, then the trend, periodic and stochastic components in the series are analyzed and removed from the series. A detected trend component in the series represents the long time changes in the series and is defined as a polynomial function which is given below:

$$Y\,(ti)\text{Trend} = \sum_{k=1}^{m} Ckti^{k-1} \tag{1}$$

Where Ck, (k=1,2,...,m) are the parameters that depend on the degree of function(Erdoğan and Gülal 2013). By separating these calculated trends from the series, de-trended series and graphs are created. Then, the spectral analysis should be done to determine the frequency and amplitude of the series.
The transformation of series from the time domain to frequency domain is done by Fast Fourier Transform (Erdoğan 2006). The basis of the Fourier Technique is based on the separation of the signals that make up the time series. In the FFT, as in other time series, the series should be de-trended. In FFT a function with period T can be approached as the sum of sine and cosine functions.

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos\frac{n\pi x}{L} + b_n \sin\frac{n\pi x}{L} \right) \quad (2)$$

After the Fast Fourier Transform is applied to the time series, the frequency and amplitude values of the motion will be given in the results section.

3. RESULTS

The 5 Hz harmonic oscillation data of all 3 network RTK methods were analyzed by time series and fast Fourier analysis. The amplitude and frequency values are expressed in "Table 2".

Table 2. Peak frequency and amplitude difference from LVDT value for all methods

Methods	GPS		LVDT		Difference	
	Amp. (mm)	Freq. (Hz)	Amp. (mm)	Freq. (Hz)	Amp. (mm)	Freq. (Hz)
VRS	14.6	5.00	16.1	5.00	1.5	0.0
FKP	15.0	5.00	17.0	5.00	2.0	0.0
MAC	15.0	5.00	16.4	5.00	1.4	0.0

When the differences are examined, it is seen that the best result from the NRTK GNSS methods is obtained with the VRS and MAC method. Lower accuracy was obtained from the FKP method with the highest difference value compared to the other two methods.

During the RTK measurements, data were collected in stationary time with GNSS for four minutes after the oscillations started and the oscillations ended. The data regarding this period when the shake table is at rest were determined by time series analysis and the amplitude and frequency values were calculated. The expected frequency and amplitude of the motion for the stationary time is zero. Results belonging to stationary time were used as RMSE (root-mean-square-error) in our measurements. When ''Table 3'' is examined, it is seen that the lowest RMSE belongs to the VRS method and the highest RMSE belongs to the FKP method. The RMSE results are consistent with the accuracy of the LVDT differences for harmonic motion.

Table 3. Peak frequency and amplitude of stationary time

STATIONARY	VRS	FKP	MAC
Amplitude(mm)	1.5	2.2	1.6
Frequency(Hz)	0.01	0.04	0.01

Figure 2 shows the LVDT and GNSS detrended time series and the Fast Fourier Transform (FFT) spectra of a representative event selected for comparing the methods. It can be seen in ''Fig. 2'' all three methods of displacement show good agreement with the LVDT displacements.

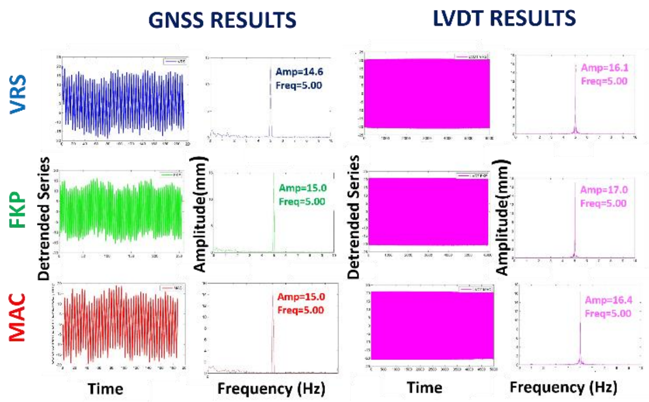

Figure 2. Ground motion test: free vibration responses of GNSS (VRS, FKP, MAC) derived time series and FFT spectrum.

4. DISCUSSION & CONCLUSION

Exactly the same analysis procedures were applied to RTK GNSS and LVDT measurement data and the differences between the determined frequency and amplitude values were calculated. The same frequency values were obtained for all methods with LVDT and GNSS methods. The differences between the amplitude values were determined as 1.5 mm for VRS, 2 mm for FKP, and 1.4 mm for MAC. Although frequency values can be determined with high accuracy in all measurement methods, differences were detected in the amplitudes compared to LVDT measurements, but these differences are exceptionally low. In this study, the relative accuracy of the methods were determined as below cm. Also, the data when the shake table was stationary was analyzed by time series analysis, and the amplitude and frequency values were calculated. Since the differences between these values and the amplitude and frequency values calculated during motion are very close to each other, these differences are found to be meaningless.

The natural frequencies of large engineering structures are in the range of 0.5 - 1 Hz. The determination of oscillations at a frequency of 5 Hz with high accuracy with high rate RTK measurement methods has shown that the RTK-GNSS method can be used effectively in monitoring the structural behaviors.

In conclusion, Network-RTK GNSS methods are potentially good methods for determining the natural frequencies of engineering structures. All test results revealed that all three Network RTK GNSS methods are efficient in SHM studies.

ACKNOWLEDGEMENT

We would like to thank Ahmet Anıl Dindar, and Fahri Karabulut for their support for this work.

REFERENCES

Akpınar B, Aykut N O, Dindar A A, Gürkan K & Gülal V E (2017). Ağ RTK GNSS Yönteminin Yapı Sağlığı İzleme Çalışmalarında Kullanımı, Afyon Kocatepe University Journal of Science and Engineering 2017. 035504. (1030-1040).

Arslan N, Aydın C, Üstün A & Demirel H (2002). Sanal Referans İstasyonu Sistemi (VRS), 30th Anniversary Symposium in Geodesy and Photogrammetry Education 16-18 October 2002, Selçuk University, Konya

Celebi M & Sanli A (2002). GPS in Pioneering Dynamic Monitoring of Long-Period Structures. Earthquake Spectra, 18(1), 47-61. https://doi.org/10.1193/1.1461375

Dindar A A, Akpınar B, Gurkan K, Aykut N O & Gulal E (2018). Development of LowCost Hybrid Measurement System 16. Europen Confrence on Earthquake Engineering 2018, Thessolaniki.

Erdoğan H (2006). Mühendislik Yapılarındaki Dinamik Davranışların Jeodezik Ölçmelerle Belirlenmesi, PhD Thesis, Yıldız Technical University, Institute of Science and Engineering, İstanbul(in Turkish).

Erdoğan H & Gülal E (2013). Ambient Vibration Measurements of the Bosphorus Suspension Bridge by Total Station and GPS. Experimental Techniques. 37. https://doi.org/10.1111/j.1747-1567.2011.00723.x.

Eren K, Uzel T, Gülal E, Yıldırım O & Cingöz A (2009). Results from a Comprehensive GNSS Test in the CORS-TR Network: Case Study. Journal of Surveying Engineering, 135(1): 10-18.

Górski P (2017). Dynamic characteristic of tall industrial chimney estimated from GPS measurement and frequency domain decomposition. Eng. Struct. 148.

Kahveci M & Yıldız F (2001).Global Konum Belirleme Sistemi Teori-Uygulama. Nobel Yayın Dağıtım, Ankara.

Li X, Linlin G, Ambikairajah E, Rizos C, Tamura Y & Yoshida A (2006). Full-scale structural monitoring using an integrated GPS and accelerometer system. GPS Solutions, 10(4), 233-247

Meng X, Dodson A H & Roberts G W (2007). Detecting bridge dynamics with GPS and triaxial accelerometers. Eng. Struct. 29 (11):3178–3184. https://doi.org/10.1016/j.engstruct.2007.03.012.

Moschas F & Stiros S (2011). Measurement of the dynamic displacements and of the modal frequencies of a short-span pedestrian bridge using GPS and an accelerometer. Engineering Structures, 33(1), 10-17.celerometers, Engineering Structures, 29, 3178-3184, doi: 10.1016/j.enstruct.2007.03.2012.

Nie Z, Zhang R, Liu G, Jia Z, Wang D, Zhou Y & Lin M (2016). GNSS seismometer: Seismic phase recognition of real-time high-rate GNSS deformation waves. Journal of Applied Geophysics, 135, 328-337. https://doi.org/10.1016/j.jappgeo.2016.10.026.

Önen Y H, Dindar A A, Gülal E, Gürkan G, Gürkan K & Akpınar B (2014). Use of High-Frrequency GNSS Sebsors in Dynamıc Motions. Second European Conference on Eartquake Engineering and Seismology, 25-29 August, İstanbul.

Park H S, Sohn H G, Kim I S, & Park J H. (2008). Application of GPS to monitoring of wind-induced responses of high-rise buildings. Struct. Des. Tall Spec. Build. 17 (1): 117–132. https://doi.org/10.1002 /tal.335.

Wang G, Blume F, Meertens C, Ibanez P & Schulze M (2012). Performance of High-rate Kinematic GPS during Strong Shaking: Observations from Shake Table Tests and the 2010 Chile Earthquake. Journal of Geodetic Science, 2(1): 15-30.

Wells D E, Beck N, Delikaraoğlu D, Kleusberg A, Krakiwsky E E, Lachapelle G, Langey R B, Nakiboğlu M, Schwarz K P, Tranquilla J M, Vanicek P (1987). Guide To GPS Positioning, Second Edition, Canadian GPS Associates, New Brunswick, Canada.

Xu Y, Brownjohn J M W, Hester D & Koo K Y (2017). Long-span bridges: Enhanced data fusion of GPS displacement and deck accelerations. Eng. Struct. 147 (Sep): 639– 651. https://doi.org/10.1016/j.engstruct.2017.06.018.

Yıldırım Ö, Bakıcı S & Mekik Ç (2011). TUSAGAAKTİF (CORSTR) Sisteminin Tapu ve Kadastro Genel Müdürlüğüne Katkıları. Journal of HKM Jeodezi, Jeoinformasyon ve Arazi Yönetimi, 11(2), 134-139.

Yigit C O, Dindar A, Bezcioglu M & El-Mowafy A (2018). Evaluation of HighRate GNSS-PPP for Monitoring Structural Health and Seismogeodesy Applications. In XXVI FIG Congress 2018: Proceedings (pp. 1-18).