THE ANALYSIS OF GPS DOPPLER VELOCITY ON EARTHQUAKE MONITORING

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Abstract

A large earthquake often induces a strong but rapid transient ground motion. Previous studies have shown that GPS technique is capable of inferring the transient ground displacement due to earthquake. The main purpose of this study is to extend the technique to detect instantaneous ground surface velocity. The GPS Doppler data sets from three earthquake events have been processed. The least-squares method is used to obtain time-to-time velocity estimates. The results show that the applied GPS approach is capable of detecting surface velocity in the level of one centimeter. The GPS velocity estimates in both the time and magnitude are consistent with the seismometer solutions. As a result, the GPS Doppler velocity technique has the potential to assist the CWB tracking network in monitoring the high dynamic ground deformation.

Key word: Earthquake Monitoring, GPS Doppler, Instantaneous Velocity

1. Introduction

Applying GPS technique to explore the Earth motion has been quite successful in recent years (e.g. [3, 10]). As a result, the term of GPS velocity is commonly used to describe the crustal deformation or fault slip rate (e.g. [1, 10]). Due to the dynamic behavior of an earthquake [2], a GPS technique, referred to as Kinematic GPS (KGPS), is applied to infer transient displacements induced by earthquakes with a typical GPS sampling rate in one hertz [7, 8]. One way to improve the observation of the dynamic response, a much faster data sampling can be used with GPS [9]. Consequently, the potential of GPS as seismometers can be expected [4].

The second approach in improving the observation of earthquake-induced dynamic behavior is to infer the instantaneous velocity. The previous research has shown a promising potential with ground site horizontal speed accuracy in the level of several centimeters [6]. The level is the typical magnitude of earthquake-induced ground wave speed when the corresponding earthquake measure is over 6.0 on the Richter scale.

Taiwan is located on the boundary between the Eurasian and Philippine Sea Plates. Central Weather Bureau (CWB) in Taiwan has been operating a continuous earthquake-monitoring network with more than 140 GPS tracking sites since Year 2000 [7]. The main purpose of this study is to apply the GPS technique in observing the ground surface motions due to earthquakes. To improve the GPS technique, the instantaneous velocity determination from GPS Doppler has been implemented in this study. The GPS Doppler data of three earthquake cases have been processed. The GPS satellite velocity has been computed from GPS broadcast ephemeris [11]. In addition, the least-squares method [5] has been applied to estimate GPS site instantaneous velocity.

2. Methodology

The GPS Doppler measurement model has been analyzed in the previous study and the measurement can be modeled as follows [6]:

$$D = -\left(\frac{\dot{PR}}{c}\right) \times f + \varepsilon \,, \dot{PR} = \dot{\rho} + c(\dot{\delta t} - \dot{\delta T}) + \dot{\delta\rho}_{trop} + \dot{\delta\rho}_{ion} \,, \quad (1)$$

where D is Doppler measurement, $\dot{PR}$ is pseudo-range rate, f is the carrier frequency, c is the speed of light, is the measurement noise, $\dot{\rho}$ is range rate, $\dot{\delta t}$ is the user clock drift, $\dot{\delta T}$ is the satellite clock drift, $\dot{\delta\rho}_{trop}$ is the troposphere delay rate, and $\dot{\delta\rho}_{ion}$ is the ionosphere delay rate.

In the data processing, the troposphere delay rate and ionosphere delay rate are usually small and can be ignored. The satellite velocity and clock error drift can be computed from broadcast ephemeris. In this study, the computation approach of GPS satellite velocity in [11] has been adopted. To be able to use the GPS Doppler data, at least four measurements have to be observed simultaneously to compute four unknown parameters (3D site velocity and site clock error rate). In general, there are more than four GPS satellites in view, so a least-squares method [5] is applied.

To improve the accuracy, the correction for each GPS Doppler is computed with using Equation (1) by assuming zero velocity for the fixed site receiver. The correction term will include the satellite velocity error due to the inaccurate velocity computation, fixed site receiver clock drift error, satellite clock drift error from broadcast message, and troposphere and ionosphere delay rates. To reduce the solution error, one-minute average from pre-earthquake solutions has been computed to correct the solutions after.

3. Results and Analysis

Due to the precision of GPS Doppler-derived instantaneous velocity, only the earthquakes measured greater than 6.0 in Richter scale have been considered. The corresponding velocity results from CWB seismometers have been published over CWB website. The seismometer velocity estimates will be served as independent references in assessing GPS Doppler results.

3.1. 2009/10/04 Hualien Earthquake (Case 1) Result and Analysis

In the first earthquake case, the estimated 3D Doppler velocity from CWB Hualien City GPS site is shown in Figure 1. The horizontal speed (east in blue line and north in green) picks occur close to 100 seconds with largest east speed around -5.8 cm/s and the largest north speed around -8.5 cm/s. However, the vertical speed result shows no sign of obvious speed pick. Showing in Figure 2 is the result from independent CWB seismometer in Hualien City. The largest speed of 6.27 cm/s occurs in north direction and maximum east speed is 5.39 cm/s. The comparisons of horizontal pick values indicate that the GPS instantaneous velocity is consistent with the independent result.

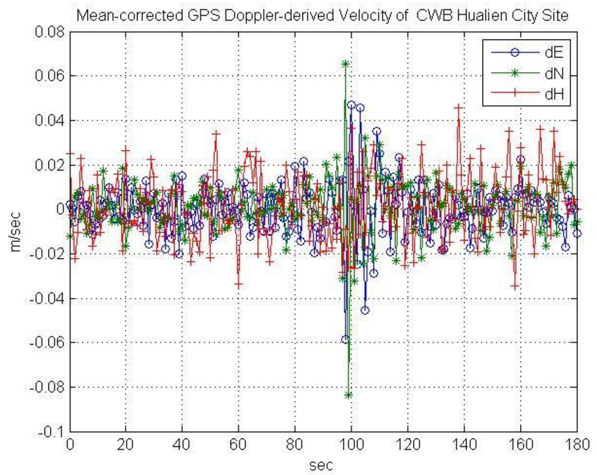

Figure 1: 2009/10/04 Hualien Earthquake: Doppler velocity estimates of Hualien City GPS site

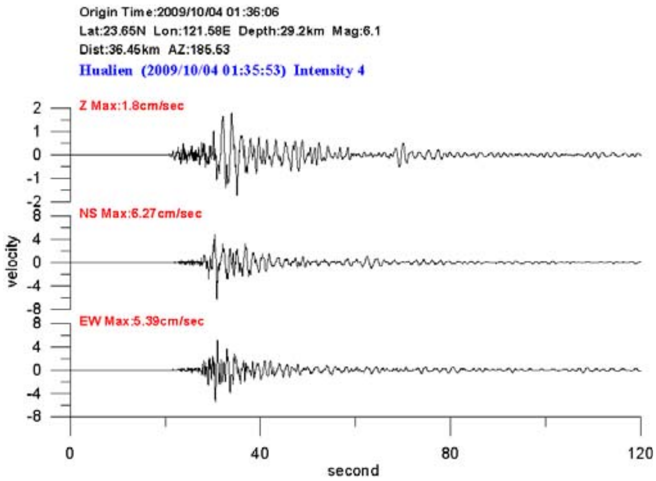

Figure 2: 2009/10/04 Hualien Earthquake: seismometer velocity of Hualien City Site.

3.2. 2009/11/05 Nantou Earthquake (Case 2) Result and Analysis

Showing in Figure 3 is the 3D GPS Doppler velocity from CWB Sun Moon Lake GPS site. As noted in Figure 3, the largest GPS speed is 26 cm/s (at 84 seconds) in the east direction (blue line) while the pick value in the north direction (green line) is 7.6 cm/s.

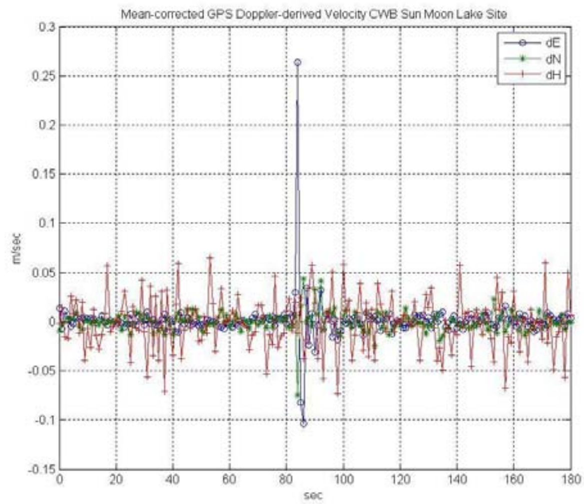

Figure 3: 2009/11/05 Nantou Earthquake: Doppler velocity estimates of Sun Moon Lake GPS site

The velocity result in Figure 4 is from the corresponding CWB seismometer. It shows pick values of 20.14 cm/s in east and of 5.69 cm/s in north. The result in the north direction is compatible with GPS Doppler solution shown in Figure 3. However, a further study is needed to clarify the large discrepancy in the east direction.

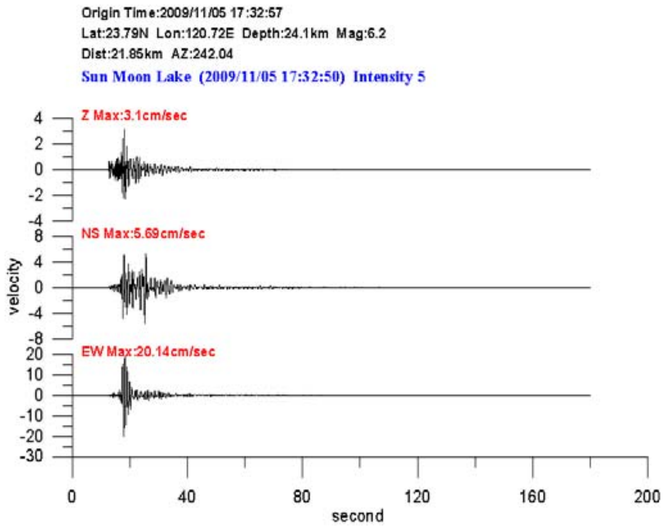

Figure 4: 2009/11/05 Nantou Earthquake: seismometer velocity of Sun Moon Lake Site

3.3. 2009/12/19 Hualien Earthquake (Case 3) Result and Analysis

In previous two cases, only the seismometer information over web site was used to assess GPS results. In Case 3 of 2009/12/19 Hualien earthquake, the seismometer velocity of 200 Hz was available. And hence, more details regarding the magnitude and epoch time of the earthquake-induced surface motion can be analyzed.

In the following figures, the 0 second represents the epoch time of UTC 2009/12/19 13:02:00. Figure 5 shows the largest east speed of -16 cm/s from Yanliao GPS site (blue) at 34 seconds. The east speed result from the corresponding CWB seismometer (red) shows a pick value of -21.8 cm/s at 33.77 seconds. The differences in magnitude maybe due to data sampling rate difference. The GPS only recorded (one Hz) two pick values while the seismometer with 200-Hz sampling recorded at least six obvious pick values.

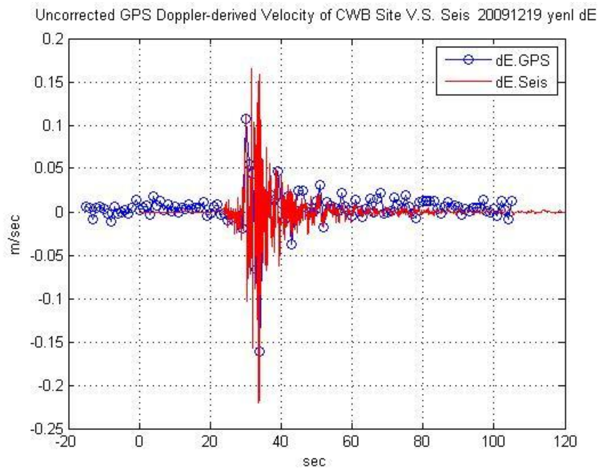

Figure 5: 2009/12/19 Hualien Earthquake: Doppler <u>east</u> speed estimates (blue) of Yanliao GPS site (YENL) VS east speed (red) of Yanliao seismometer (HWA060)

Showing in Figure 6 are the north speed results from Yanliao GPS site (blue line) and from CWB seismometer (red line). The largest north speed of -9.5 cm/s at 32 seconds from Yanliao GPS site (blue) and that of -12.3 cm/s at 31.71 seconds from Yanliao seismometer (red) can be observed. The GPS solutions are noisier in one cm/s level. As a result, both the magnitude and epoch time are considered to be consistent in these two solutions.

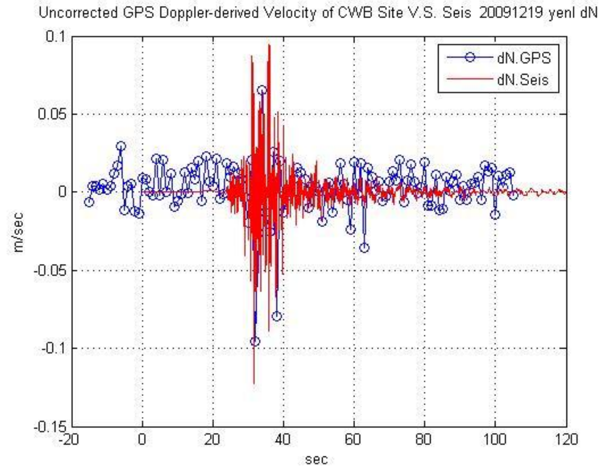

Figure 6: 2009/12/19 Hualien Earthquake: Doppler <u>north</u> speed estimates (blue) of Yanliao GPS site (YENL) VS north speed (red) of Yanliao seismometer (HWA060)

The second studied GPS site, Chiayi, is about 100 km away from Yanliao. Showing in Figure 7 is the east speed result from Chiayi GPS site with a maximum pick value of 7.0 cm/s at 61 seconds (blue). The result is close to CWB seismometer east speed pick result (red) of 7.3 cm/s at 60.7 seconds. As a result, both the magnitude and epoch time are more consistent in these two solutions.

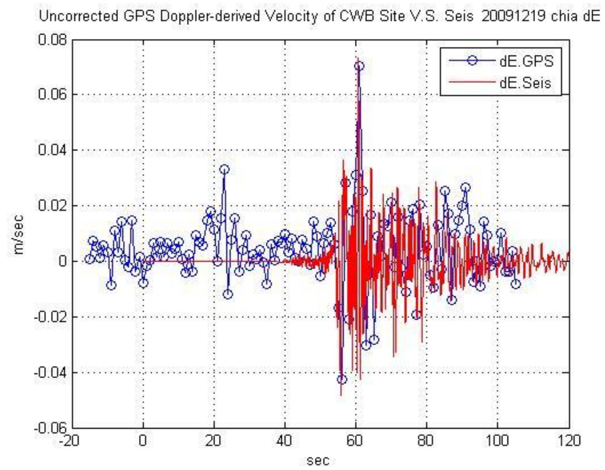

Figure 7: 2009/12/19 Hualien Earthquake: Doppler <u>east</u> speed estimates (blue) of Chiayi GPS site (YENL) VS east speed (red) of Chiayi seismometer (HWA060)

The comparison of pick value time tags between Figures 5 and 7 shows that the time difference in GPS east picks between Chiayi and Yanliao sites is about 27 seconds apart. The time gap recorded in CWB seismometer results is about 26.93 seconds apart. It indicates that the time gap is consistent in GPS Doppler and seismometer east speed solutions.

Showing in Figure 8 are the north speed results from Chiayi GPS site (blue line) and from CWB seismometer (red line). The maximum pick north value in GPS solution is of 5.9 cm/s at 61 seconds (blue) and that from Chiayi seismometer is of 6.5 cm/s at 60.01 seconds (red). The GPS solutions are noisier in one cm/s. The result also indicates that these two solutions are considered to be consistent in both magnitude and epoch time.

The time gap between Figures 6 (Yanliao) and 8 (Chiayi) recorded in both north speed results are also computed. Time difference in GPS north speed pick is 29 seconds apart while that in seismometer is about 28.3 seconds apart. As a result, the time gap is consistent in GPS Doppler and seismometer north speed solutions.

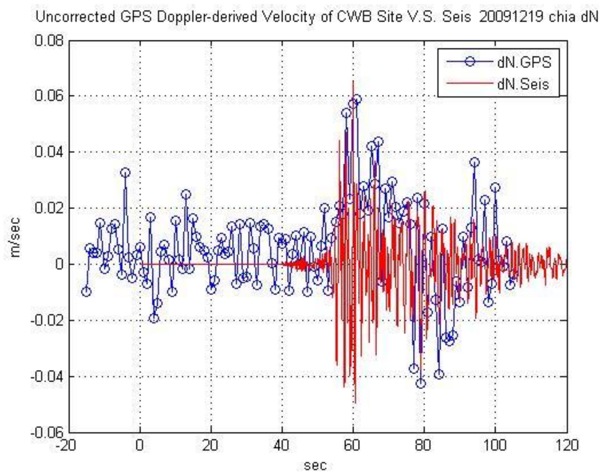

Figure 8: 2009/12/19 Hualien Earthquake: Doppler north speed estimates (blue) of Chiayi GPS site (CHIA) VS north speed (red) of Chiayi seismometer (HWA060)

4. Conclusions

This study focused on the instantaneous velocity estimation from earthquake-affected GPS Doppler data. From the analyzed results, it is found that the GPS Doppler-derived speed can be in the level of one-centimeter per second accuracy in surface ground motion. The vertical solutions are slightly larger. The results from three earthquake cases show that the GPS Doppler observation is capable of extracting precise instantaneous site velocity. In addition, the time and magnitude are consistent with seismometer ground velocity solutions. As a result, GPS Doppler has the potential to assist the CWB tracking network in monitoring the high dynamic ground deformation caused by earthquakes.

Acknowledgment

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References

[1] Becker, T.W., Hardebeck, J.L., and Anderson, G., 2005:"Constraints on Fault Slip Rates of the Southern California Plate Boundary from GPS Velocity and Stress Inversions", Geophysical Journal International, Vol. 160, Issue 2, pp. 634-650.

[2] Blewitt, G., Hammond, W.C., Kreemer, C., Plag, H.-P., Stein, S., and Okal, E., 2009:"GPS for Real-Time Earthquake Source Determination and Tsunami Warning Systems", Journal of Geodetics, Vol. 83, pp. 335–343.

[3] Bock, Y., Agnew, D.C., Fang, P., Genrich, J.F., Hager, G.H., Herring, T.A., Hdnut, K.W., King, R.W., Larsen, S., Minster, J.B., Stark, K., Wdowinski, S., and Wyatt, F.K., 1993:"Detection of Crustal Deformation from the Landers Earthquake Sequence Using Continuous Geodetic Measurements", Nature, Vol. 361, pp. 337-340.

[4] Ge, L., Han, S., Rizos, C., Ishikawa, Y., Hoshiba, M., Yoshida, Y., Izawa, M., Hashimoto, N., and Himori, S., 2000: "GPS seismometers with up to 20Hz sampling rate", Earth Planets Space, Vol. 52, No.10, pp. 881-884.

[5] Gelb, A., 1974, Applied Optimal Estimation, The M.I.T. Press, Massachusetts, U.S.A..

[6] Ho, C.-S., Chen, J.-Z., and Weng, C.-T., 2001:"Precise Velocity Determination with GPS Doppler Measurements", Proceedings of The 2001 National Technical Meeting of the Institute of Navigation, Long Beach, California, U.S.A., January 22-24, 2001, pp. 223-227.

[7] Ho C.-S., and Tsai, C.-H., 2009:"A GPS Study on Observing Earthquake Ground Displacement", Proceedings of The 27th International Symposium on Space Technology and Science (ISTS), Kyoto, Japan, July 5-12, 2009, Paper No. ISTS 2009-n-17, pp. 1-5.

[8] Irwan, M., Kimata, F., Hirahara, K., Sagiya, T., and Yamagiwa, A., 2004:"Measuring ground deformations with 1-Hz GPS data: the 2003 Tokachi-oki earthquake (preliminary report)", Earth Planets Space, Vol. 56, pp. 389–393.

[9] Roberts, G.W., Cosser, E., Meng, X., and Dodson, A.H., 2004:"Monitoring the Deflections of Suspension Bridges Using 100Hz GPS Receivers", Proceedings of ION GNSS 17th International Technical Meeting of the Satellite Division, Long Beach, California, USA, September 21-24, 2004, pp. 1403-1413.

[10] Tabei, T., Hashimoto, M., Miyazaki, S., and Ohta, Y., 2003:"Present-day deformation across the Southwest Japan arc: Oblique subduction of the Philippine Sea plate and lateral slip of the Nankai forearc", Earth Planets Space, Vol. 55, pp. 643–647.

[11] Zhang, J., Zhang, K., Grenfell, R., and Deakin, R., 2006:"GPS Satellite Velocity and Acceleration Determination using the Broadcast Ephemeris", Journal of Navigation, Vol. 59, Issue 2, pp. 293-305.