GPS seismometers with up to 20 Hz sampling rate

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The large near-field displacements before and during an earthquake are invaluable information for earthquake source study and for the detection of slow/silent quakes or pre-seismic crustal deformation events. However due to bandwidth limitations and saturation current seismometers cannot measure many of these displacements directly. In a joint experiment between the University of New South Wales (UNSW) and the Meteorological Research Institute (MRI), two Trimble MS750 GPS receivers were used in the Real-Time Kinematic (RTK) mode with a fast sampling rate of up to 20 Hz to test the feasibility of a "GPS seismometer" in measuring displacements directly. The GPS antenna, an accelerometer, and a velocimeter were installed on the roof of an earthquake shake-simulator truck. The simulated seismic waveforms resolved from the RTK time series are in very good agreement with the results from the accelerometer and the velocimeter, after integrating twice and once respectively. Moreover, more displacement information are revealed in the GPS RTK results although they are noisier.

1. Introduction

Because the GPS satellites are not affected by earthquakes, the GPS constellation can be considered an "ideal pendulum". Therefore, a GPS receiver on the Earth can be used as a seismometer to recover the signature of the antenna displacement.

The first experiment on GPS seismometers was reported as early as 1994. It was carried out by the Disaster Prevention Research Institute (DPRI), Kyoto University, Japan (Hirahara *et al.*, 1994). The experiment was performed at a rover site equipped with a GPS antenna on a slider, and two reference sites at distances 160 m and 160 km away from the rover site. The slider oscillated horizontally with periods of 25–300 sec and amplitude of 15 cm. The sampling interval of the receivers was 1 sec. A horizontal accuracy of 1–2 cm was achieved in post-processing and it was concluded that using GPS as a strain seismometer to obtain large amplitude, near-field ground motion was possible. Another GPS seismometer experiment was carried out by the Geographical Survey Institute (GSI) of Japan, involving the kinematic processing of some GEONET data to derive ground motion due to the 4 October 1994, M8.1 Hokkaido-Toho-Oki earthquake (Hatanaka *et al.*, 1994). The sampling rate of this continuous GPS (CGPS) data was 30 sec. The P-wave arrival was successfully resolved in this case. Again, the experiment suggested the feasibility of a GPS seismograph if the receiver can observe with a high enough sampling rate. Even at the 30 sec sampling rate, GPS could detect slow/silent quakes or pre-seismic events. Short-term afterslip in the 1994 Sanriku–Haruka-Oki earthquake was an example of slow earthquake detection by GPS at 30 sec sampling rate (Heki and Tamura, 1997). One Hz sampling GPS was also proposed to be used as an ultra-long-period seismograph by Miyazaki *et al.* in 1997.

Recent research developments in GPS seismometer include a UNSW experiment performed on 11 November 1998 (Ge, 1999). In that experiment two Leica CRS1000 receivers were used. One functioned as the rover, the other as the reference receiver, both sampling at 10 Hz. The vibrations of 2.3 Hz and 4.3 Hz on the GPS antenna were generated using a mechanical shaker with amplitude of up to 12.7 mm. An accelerometer sensor was co-located on the GPS antenna fixture so that an independent measurement could be used in comparison. Experimental results were in good agreement. An adaptive filter based on the Least-Mean-Square algorithm was developed to extract displacements from the GPS RTK series.

2. The UNSW-MRI GPS Seismometer Experiment

The current wide dynamic range, broadband seismic networks are sensitive to the frequency band from 10 Hz to 1/300 Hz. Therefore a GPS system with 10 Hz sampling rate (i.e. up to 5 Hz frequency coverage) seems still not sufficient to justify a GPS seismometer network. However, very recently GPS receivers have achieved 20 Hz sampling rates. This means that such GPS receivers may be able to detect signals with frequencies from DC to 10 Hz.

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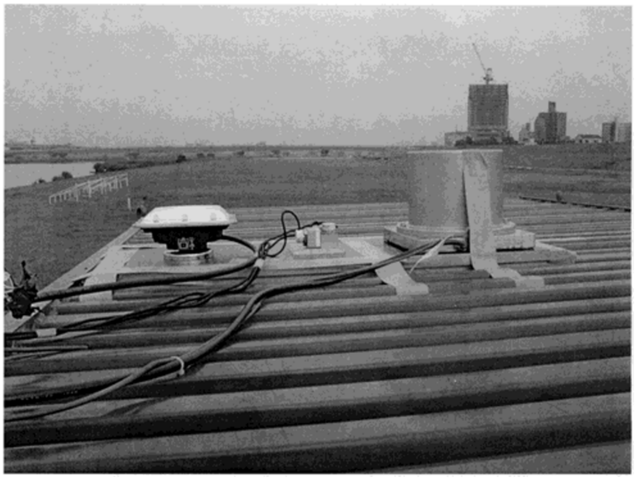

Fig. 1. Setup of the UNSW-MRI GPS Seismometer Experiment.

Fig. 2. Earthquake shake-simulator truck used in the UNSW-MRI GPS Seismometer Experiment.

In a joint experiment between UNSW and MRI, two Trimble MS750 GPS receivers were used in the Real-Time Kinematic (RTK) mode with a fast sampling rate of up to 20 Hz to test the feasibility of the "GPS seismometer" in measuring displacements directly. As can be seen from Fig. 1, the GPS antenna, an accelerometer, and a velocimeter were installed on a metal plate, which was mounted with bolts and adhesive tapes on the roof of an earthquake shake-simulator truck shown in Fig. 2.

Table 1 outlines the 48 experiment sessions in which earthquakes of different intensities (in JMA (Japan Meteorological Agency) Scale), including some past quakes such as the 1923 Kanto Quake and the 1995 Kobe Quake (recorded at Kobe Kaiyou Meteorological Observatory of JMA), were simulated. GPS sampling rates used were 20 Hz, 10 Hz and 5 Hz while the sampling rates for the seismometers were 100 Hz (acceleration data logging started at 14:03:50 JST and velocity data logging started at 14:27:29 JST).

Table 1. UNSW-MRI experiment sessions (10 August 1999).

Session	Time (JST 15 h m s)	Intensity	GPS
		Horizontal	
1	1314–1344	2	20 Hz
2	1417–1447	2	
3	1532–1552	3	
4	1602–1622	3	
5	1642–1702	3	
6	1712–1732	4	
7	1748–1808	4	
8	1817–1837	4	
9	1902–1922	5L	
10	1932–1952	5L	
11	2002–2022	5L	
12	2032–2052	5H	
13	2102–2122	5H	
14	2132–2152	5H	
15	2212–2222	6	
		Up and down	
16	2402–2422	4	
17	2512–2532	4	
18	2542–2602	4	
19	2612–2632	5L	
20	2642–2702	5L	
21	2712–2732	5L	
22	2742–2802	5H	
23	2812–2832	5H	
24	2842–2902	5H	
25	2932–2942	6	
26	3341–		
		Horizontal	
27	4112–4132	2	10 Hz
28	4142–4202	3	
29	4212–4232	4	
30	4242–4302	5L	
31	4312–4332	5H	
32	4352–4402	6	
		Up and down	
33	4442–4502	4	
34	4512–4532	5L	
35	4542–4602	5H	
36	4627–4637	6	
		Horizontal	
37	4857–4917	2	5 Hz
38	4927–4947	3	
39	4956–5017	4	
40	5026–5046	5L	
41	5056–5116	5H	
42	5132–5142	6	
		Up and down	
43	5156–5216	4	
44	5226–5246	5L	
45	5256–5316	5H	
46	5326–5336	6	
47	5517–5707	1923 Kanto	20 Hz
48	5813–5840	1995 Kobe	

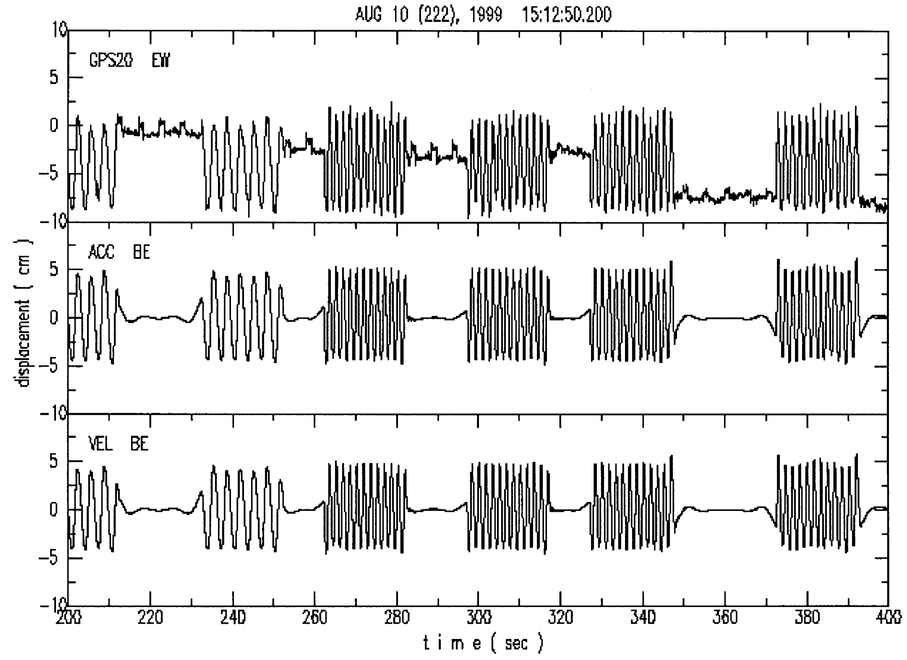

Fig. 3. GPS RTK result compared with acceleration integrated twice and velocity integrated once.

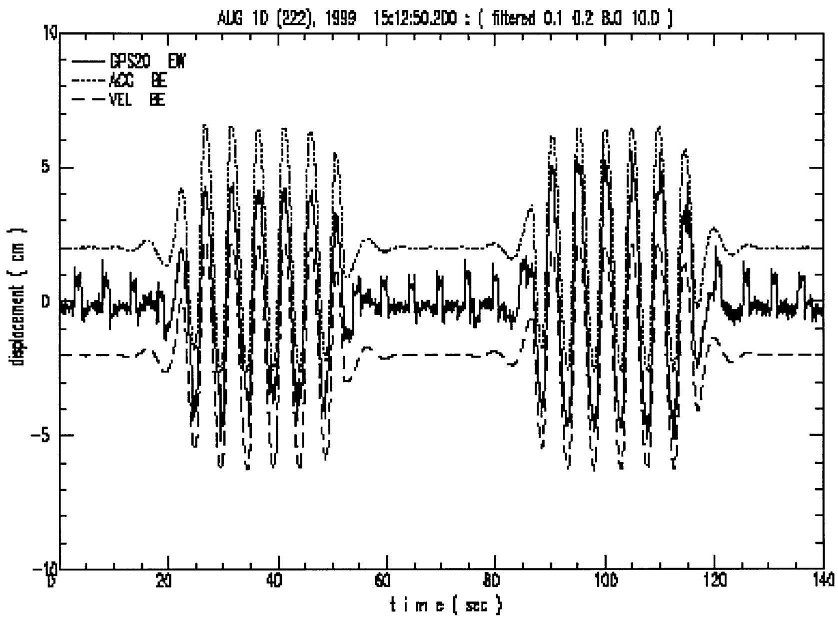

Fig. 4. GPS RTK, acceleration and velocity after bandpass filtering.

3. Results and Comparison

The MS750 GPS receiver on the truck was used as a rover receiver while a reference station was setup 10 m away from the truck also using MS750. The GPS RTK results for the experiments were recorded in real-time in files, in the GGK message format, which includes information on time, position, position type and DOP (Dilution of Precision) values from the rover receiver. Acceleration and velocity data from the seismometers were recorded concurrently. According to the MS750 Manual, the accuracy of MS750 in low latency mode, in which it was configured in the UNSW-MRI experiment, is 2 cm + 2 ppm for horizontal and 3 cm + 2 ppm for vertical.

In Fig. 3, the GPS RTK time series of selected segments in the 20 Hz session are compared with acceleration integrated twice and velocity integrated once. The later two are bandpass filtered (passband: 0.1 to 8 Hz). The three results are in very good agreement in all the experiment sessions (where there were vibrations). But the GPS results indicate that the shaft of the shake-simulator truck did not return to its original position after the sessions, and indeed no effort was made to do so in the experiment.

In Fig. 4, the three results were bandpass filtered (passband: 0.1 to 8 Hz). The acceleration and velocity results were offset 2 cm and −2 cm respectively in the vertical axis direction for better printing effects in black and white. As a matter of fact, when the results were superimposed in a color plot they agree with each other very well. The GPS result is much better than expected, although the origin of the trace offsets in the GPS result that occur every 5 seconds is not clear at the moment. As can be seen from the figure sine waves of 10 cm amplitude peak to peak and 1–5 sec periods were generated by the truck in this session of the experiment.

4. Concluding Remarks

The joint experiment between the University of New South Wales and the Meteorological Research Institute using two Trimble MS750 GPS receivers in the Real-Time Kinematic (RTK) mode with seismic signals generated by an earthquake simulating truck indicated that the GPS RTK result is in good agreement with results of accelerometer and velocimeter, proving that a fast sampling rate (up to 20 Hz) GPS system can be used as a “GPS seismometer” for measuring displacements directly.

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References

Ge, L., GPS seismometer and its signal extraction, Proc. 12th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation GPS ION’99, Nashville, Tennessee, 14–17 September, 1999.

Hatanaka, Y., H. Tsuji, Y. Abe, Y. Iimura, K. Kobayashi, and H. Morishita, Coseismic crustal displacements from the 1994 Hokkaido-Toho-Oki earthquake revealed by a nationwide continuous GPS array in Japan—results of GPS kinematic analysis, Japanese Symposium on GPS (1994), Tokyo, Japan, 15–16 December, 141–147, 1994 (in Japanese).

Heki, K. and Y. Tamura, Short-term afterslip in the 1994 Sanriku-Haruka-Oki earthquake, *Geophys. Res. Lett.*, **24**(24), 3285–3288, 1997.

Hirahara, K., T. Nakano, Y. Hoso, S. Matsuo, and K. Obana, An experiment for GPS strain seismometer, Japanese Symposium on GPS (1994), Tokyo, Japan, 15–16 December, 67–75, 1994.

Miyazaki, S., T. Sagiya, T. Tada, and Y. Hatanaka, One Hz Sampling GPS as an Ultra-Long-Period Seismograph, 1997 AGU Fall Meeting, December 8–12, San Francisco, California, 1997.

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