GPS Seismometers with up to 20Hz Sampling Rate

Linlin Ge[1], Shaowei Han[1], Chris Rizos[1], Yuzo Ishikawa[2], Mitsuyuki Hoshiba[2], Yasuhiro Yoshida[2], Mitsuma Izawa[3], Narihiro Hashimoto[4], and Shigeru Himori[5]

[1]School of Geomatic Engineering, The University of New South Wales, Sydney, Australia
[2]Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
[3]Trimble Japan, Japan
[4]Hitachi Zosen Information Systems Co. Ltd., Japan
[5]Katsujima Co. Ltd., Japan

ABSTRACT

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 current seismometers cannot measure large near-field 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 20Hz to test the feasibility of a "GPS seismometer" in measuring displacements directly. The GPS antenna, an accelerometer, and a velometer 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 velometer, after integrating twice and once respectively. Moreover, more displacement information are revealed in the GPS RTK results although they are noisier.

In order to develop an operational GPS seismometer network, implementation issues such as the layout of reference and rover stations, noise reduction using measurements from adjacent days, correlation between measurements, data communication, etc., are briefly discussed.

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 160m and 160km away from the rover site. The slider oscillated horizontally with periods of 25-300sec and amplitude of 15cm. The sampling interval of the receivers was 1sec. A horizontal accuracy of 1-2cm 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 30sec. 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 30sec sampling rate, GPS could detect slow/silent quakes or pre-seismic events.

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 10Hz. The vibrations of 2.3Hz and 4.3Hz on the GPS antenna were generated using a mechanical shaker with amplitude of up to 12.7mm. 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. This is an important step toward the development of an operational GPS seismometer.

2. THE UNSW-MRI GPS SEISMOMETER EXPERIMENT

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

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 20Hz 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 velometer were installed on the roof of an earthquake shake-simulator truck. The earthquake shake-simulator truck is shown in Fig. 2.

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

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

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

Session	Time (JST15h m s)	Intensity	GPS
		Horizontal	
1	1314-1344	2	
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	20Hz
		Up & 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	
28	4142-4202	3	
29	4212-4232	4	
30	4242-4302	5L	
31	4312-4332	5H	
32	4352-4402	6	10Hz
		Up & down	
33	4442-4502	4	
34	4512-4532	5L	
35	4542-4602	5H	
36	4627-4637	6	
		Horizontal	
37	4857-4917	2	
38	4927-4947	3	
39	4956-5017	4	
40	5026-5046	5L	
41	5056-5116	5H	5Hz
42	5132-5142	6	
		Up & down	
43	5156-5216	4	
44	5226-5246	5L	
45	5256-5316	5H	
46	5326-5336	6	
47	5517-5707	1923 Kanto	20Hz
48	5813-5840	1995 Kobe	

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

3. RESULTS AND COMPARISON

The GPS RTK results for the experiments were recorded in real-time in files, in the GGK message format. Acceleration and velocity data from the seismometers were recorded concurrently. A number of programs were written to process the results.

In Figure 3, the GPS RTK time series of selected segments in the 20Hz session are compared with acceleration integrated twice and velocity integrated once. 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 Figure 4, the three results were bandpass filtered (passband: 0.1 to 8Hz) and superimposed. The GPS result is much better than expected. The focus has now shifted to investigating some of the implementation issues.

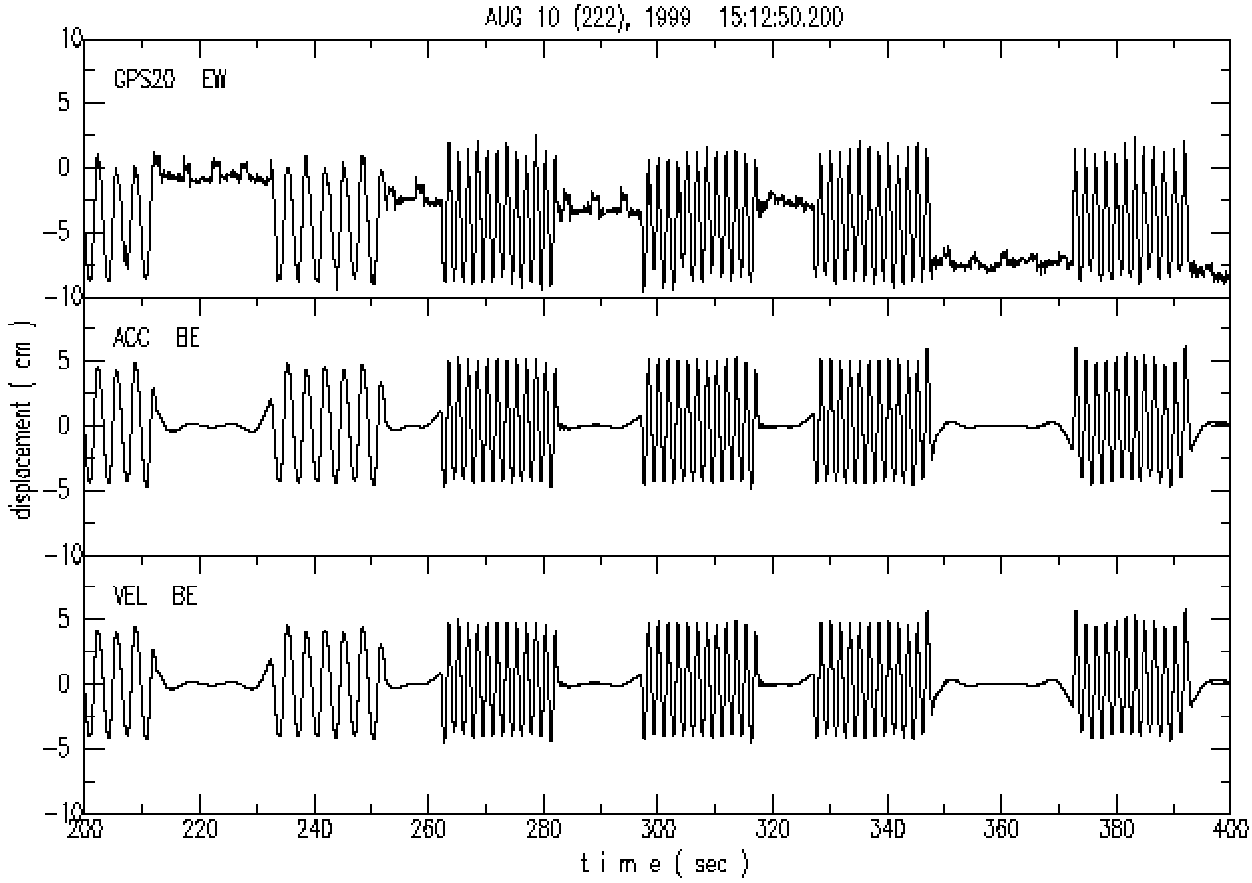

Figure 3. GPS RTK result compared with acceleration integrated twice and velocity integrated once.

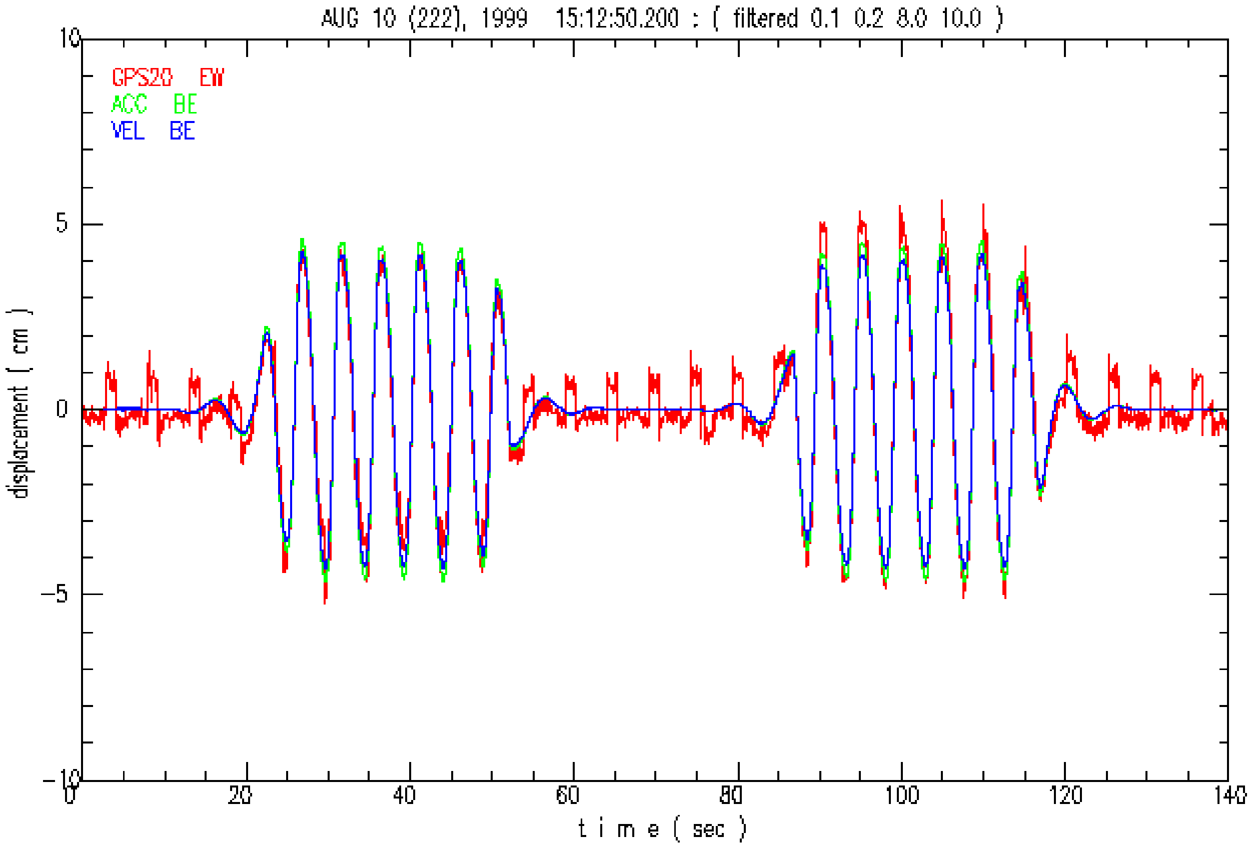

Figure 4. GPS RTK, acceleration and velocity after bandpass filtering.

4. GPS SEISMOMETER: IMPLEMENTATION ISSUES

Several implementation issues concerning the possible use of GPS as seismometer are discussed below.

The first issue is the design of network of reference and rover stations. Ideally seismic waves arrive at the rover first and the reference station remains stationary during the entire earthquake event. Since unlike tsunamis earthquakes can arrive from any direction relative to the rover and reference receivers, and the waves travel as fast as 8km/s, neither of the above two conditions can be satisfied. But for distant events, a configuration consisting of a reference station in the centre of a ring formed by a few rover stations, which is very similar to the first seismoscope invented by Zhang Heng in A.D. 136, will function well for earthquake location. For events local to the ring, combined processing of moving baseline RTK and point positioning have to be used.

To test the possibility of noise reduction using measurements from adjacent days, two Trimble MS750 GPS receivers were connected with a null modem to collect data at UNSW for about 3 hours everyday on 5 successive days beginning 3 March 1999. Fig. 5 is a plot of the variations of the RTK positions around the known position of the rover antenna from Day1 (bottom) to Day5 (top) (vertically shifted for clearance). The multipath effect is clearly presented in the series. Fig. 6 is an example of noise reduction using an adaptive filter [Ge, 1999]. In this particular case, the noise is reduced by about 30%. Table 2 is a summary of noise reduction results from different combinations.

To address the problem of correlation between measurements, a zero-baseline test using two Leica CRS1000 GPS receivers, sampling at 10Hz, was carried out on 2 November 1999 for a 2 hour period at UNSW. Data analysis indicates that the L1 phase measurements are independent, L2 phase measurements are partially independent and the P1 and P2 pseudo-range measurements are correlated. More tests will need to be carried out in order to determine whether GPS receivers can provide independent measurements at up to 20Hz sampling rates.

Data communication is not such a significant problem in the case of the GPS seismometer. Many seismic stations around the world are accessed using technologies varying from long distance phone lines, commercial Internet, INMARSAT satellites, and VSAT systems. Although the amount of data transferred in this manner varies, typically 4 - 10 megabytes are transmitted per day. Moreover Frame Relay circuits can also be used which can handle a data flow of about 5 - 10 terabytes / year. A GPS seismometer array could be cost-effective because the real-time, high-rate capability can be used to address other applications such as atmospheric studies [Ware et al., 1999].

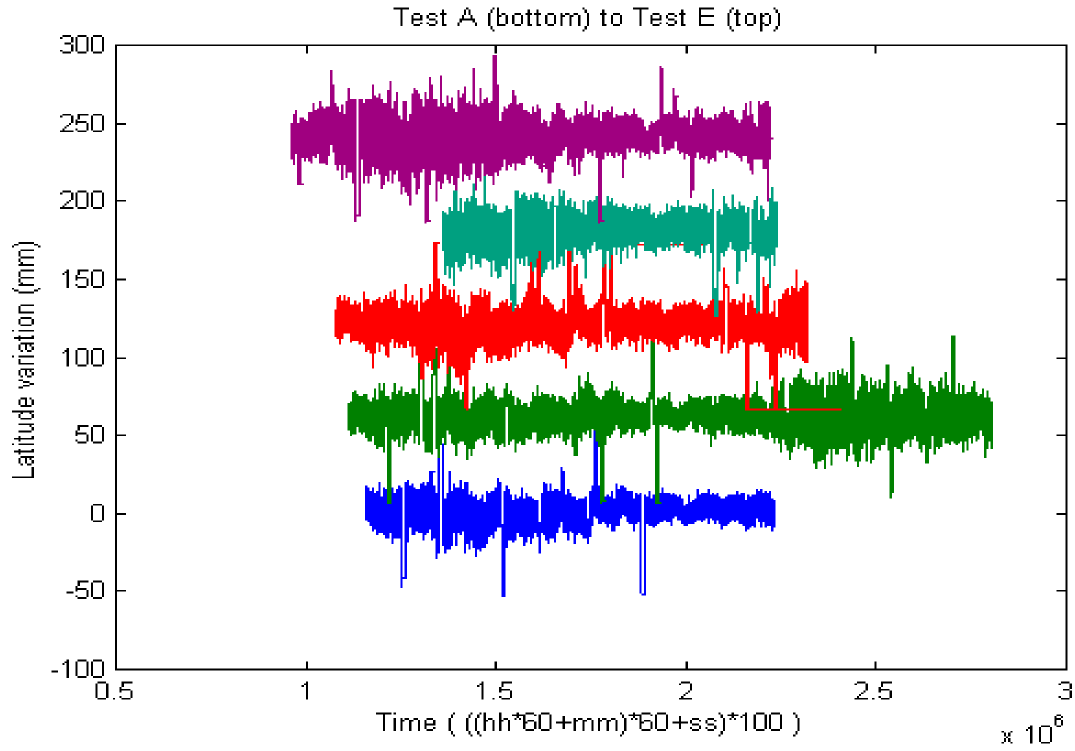

Figure 5. Latitude variations of the rover RTK series for 5 successive days.

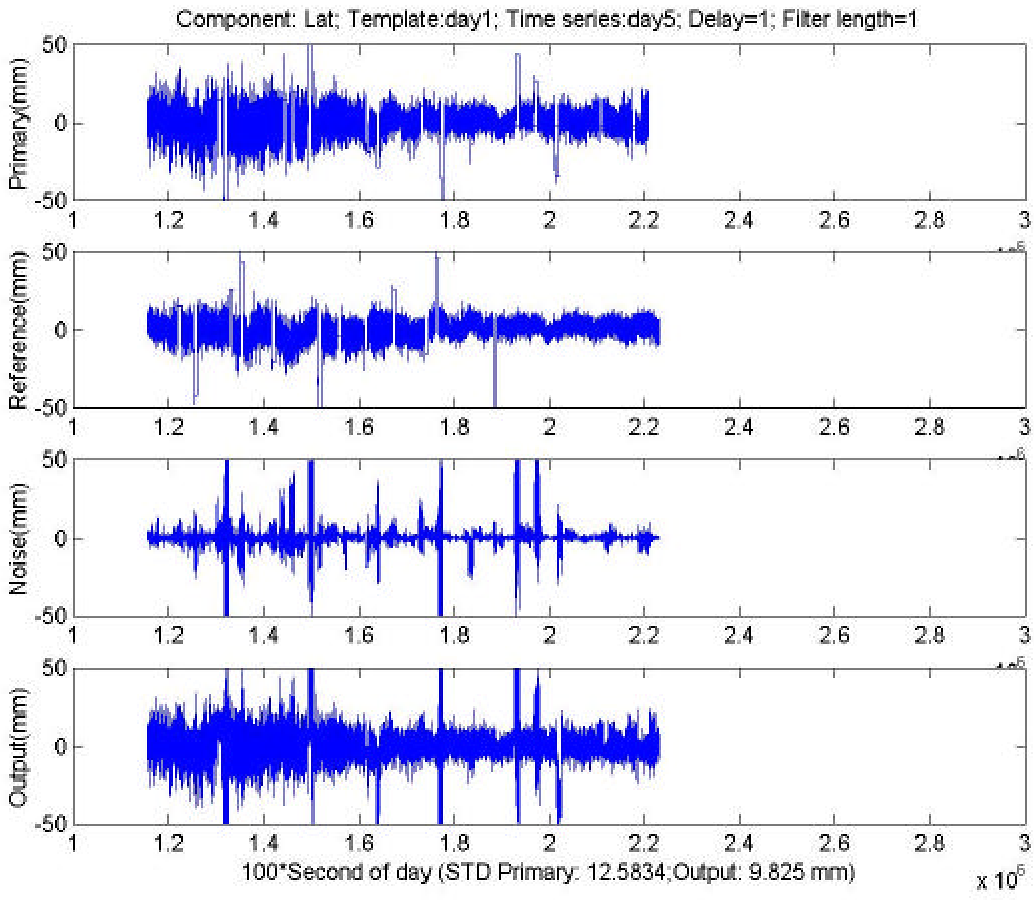

Figure 6. Adaptive filtering used in noise reduction.

Table 2. Summary of noise reduction results using adaptive filtering.

P	R	STDp (mm)	STDo (mm)	LTr (%)	LNr (%)	HTr (%)	Ar (%)	Hr (%)
2	1	13.98	10.99	21			15	18
2	1	11.22	9.49		15			
2	1	25.63	23.5			8		
3	1	17.98	13.58	24			19	21
3	1	14.69	12.11		18			
3	1	28.07	23.52			16		
3	2	19.72	15.96	19*			18*	19*
3	2	15.85	12.85		19			
3	2	29.37	24.83			15*		
4	1	21.41	19.04	11			12	13
4	1	18.35	15.78		14			
4	1	31.05	27.51			11		
4	2	21.46	17.92	16			17	19
4	2	18.28	14.47		21			
4	2	30.76	26.29			15		
4	3	10.2	3.92	62			54	60
4	3	12.49	5.11		59			
4	3	25.5	14.89			42		
5	1	12.58	9.77	22			21	25
5	1	13.93	10		28			
5	1	28.31	25.08			11		
5	2	12.78	9.37	27			20*	25
5	2	13.36	10.27		23*			
5	2	27.29	24.11			12		
5	3	12.81	6.32	51			47	51
5	3	14.15	6.91		51			
5	3	27.29	16.71			39		
5	4	11.31	6.38	44*			44*	50*
5	4	15.01	6.53		56			
5	4	28.12	18.74			33*		

P: primary sequence;
R: reference sequence;
STDp: the standard deviation (STD) of primary sequence;
STDo:the STD of output sequence;
LTr: noise reduction in latitude component;
LNr: noise reduction in longitude component;
HTr: noise reduction in height component;
Ar: averaged noise reduction in three components; and
Hr: averaged noise reduction in horizontal components.

5. 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 proved that a fast sampling rate (up to 20Hz) GPS system can be used as a “GPS seismometer” for measuring displacements directly.

A brief study of implementation issues such as the layout of reference and rover stations, noise reduction using measurements from adjacent days, correlation between measurements, data communication, etc., indicates that there are no major technological obstacles in upgrading current CGPS arrays to also function as GPS seismometer arrays.

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