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Displacement analysis of the GPS station of Sampali, Indonesia

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The displacement of the SAMP GPS station located in Medan City, Indonesia, is analyzed by means of an on-line point positioning method, the Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP). Based on the comparison of the results obtained with those from previous studies, we propose that CSRS-PPP can be applied to analyses of the displacement of a GPS station. Previous studies have focused solely on the "Sumatra-Andaman Islands Earthquake of December 26, 2004"; in contrast, we provide here an in-depth analysis of the crustal movements at the SAMP station for an expanded period of 2.5 years. CSRS-PPP, an Internet data processing service of the Department of Natural Resources Canada (NRCan), was used to process the data obtained at the SAMP station from January 2004 to July 2006. The data show a clear displacement in the southwestern direction from December 26, 2004 to March 28, 2005 when two major earthquakes occurred. However, after the midpoint of 2005, the data show displacement at a regular speed. In particular, the "Sumatra-Andaman Islands Earthquake ($M_w = 9.0$) of December 26, 2004" led to a displacement of 0.1387 m ($dn = -0.0122$ m, $de = -0.1382$ m) to the southwest. The earthquake ($M_w = 8.7$) that occurred on March 28, 2005 led to a displacement of 0.1921 m ($dn = -0.1400$ m, $de = -0.1315$ m) to the southwest. Starting from December 26, 2004, displacement to the southwest continued. From April 2005, however, the speed of the displacement gradually slowed down. The dn variation shows a displacement at a regular rate (−55.69 mm/year) from April 28, 2005 to July 2006, while the de variation shows a displacement at a regular rate (−23.66 mm/year) from July 5, 2005 to July 2006.

Key words: Displacement, GPS station, Indonesia, CSRS-PPP, dn variation, de variation.

1. Introduction

On average, about 1000 earthquakes with intensities of 5.0 or greater are recorded each year. Of these, only an average of one per year is classified as a great earthquake (intensity ≥ 8.0), major earthquakes (intensity 7.0–7.9) occurring 18 times a year on average, strong earthquakes (intensity 6.0–6.9) occurring ten times a month, and moderate earthquakes (intensity 5.0–5.9) occurring more than twice a day (Bolt, 1993; Lomnitz, 1994). Because most of these earthquakes occur under the ocean or in underpopulated areas, they pass unnoticed by all but seismologists. Major earthquakes are important keys to understanding crustal deformation phenomena, including coseismic (main rupture and early aftershocks) and postseismic effects (including a short-term afterslip phase and a long-term viscoelastic relaxation phase) (Ergintav *et al.*, 2002). In order to conduct in-depth geodetic research, several hundred GPS stations are being installed or are already in operation all around the world. Daily data from these GPS stations are transferred to the GPS analysis centers of the International GNSS service (IGS) for analysis and management (Beutler *et al.*, 1995a). GPS networks, such as the Sumatran GPS Array (SuGAr), the Southern California Integrated GPS Network (SCIGN), and the Australian Regional GPS Network (ARGN) are in operation and constantly monitoring the movement of the Earth's crust (Fialko, 2006; Kreemer *et al.*, 2006b). Many researchers have conducted displacement analyses on GPS permanent stations that fell under the influence of large-scale earthquakes (Table 1).

After the large-scale earthquakes occurred along the Sumatra seashores in December of 2004 and in March of 2005, the displacement analysis along the GPS permanent stations of the Sumatra seashores became more intensive. In particular, research on the SAMP GPS permanent station, located in Medan City, Indonesia, is continuing to this day (Banerjee *et al.*, 2005; Kreemer *et al.*, 2006a).

This aim of this study was to process GPS data observed at the SAMP GPS permanent station from January 2004 to July 2006 and to analyze the result of the displacement by comparing the data obtained before and after the outbreak of the earthquakes. While previous studies focused on the "Sumatra-Andaman Islands Earthquake of December 26, 2004", we focus more closely on analyzing the crustal movements at SAMP station for the expanded period of 2.5 years. Furthermore, this study uses a web-based GPS processing software, denoted the Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP) (Tétreault *et*

Table 1. Recent earthquakes for which coseismic displacements have been determined by GPS.

Earthquake Magnitude (Date)	Site	Lat. (°)	Long. (°)	North (mm)	East (mm)	Displacement (mm)	Processing software	References
7.6 (28 Dec. 1994)	KUJI	40.1	141.5			92	GAMIT	Heki *et al.* (1997)
					77.5 ± 10		GIPSY OASIS II	Melbourne *et al.* (2002)
8.1 (30 July 1995)	Antofagasta	−23.6	−70.3	−300	−750		GIPSY OASIS II	Melbourne *et al.* (2002)
8.0 (9 Oct. 1995)	MANZ	19.0	−104.2			45 ± 10	GIPSY OASIS II	Melbourne *et al.* (2002)
7.5 (17 Aug. 1999)	BEST	40.8	30.2	−16.5	92.8		GAMIT/GLOBK	Ergintav *et al.* (2002)
8.4 (23 June 2001)	AREQ	−16.4	−71.4	−309	−446			Cerveira and Weber (2004)
						500		Perfettini *et al.* (2005)
						500 ± 108	GIPSY OASIS II	Melbourne *et al.* (2002) Melbourne and Webb (2002)
9.0 (26 Dec. 2004)	SAMP	3.6	98.7	−14.8	−135.0	138 ± 6	GAMIT/GLOBK	Banerjee (2005) Banerjee *et al.* (2005)
				−9.0	−139.0		GIPSY OASIS II	Kreemer *et al.* (2006b)
						138	GAMIT/GLOBK	Subarya *et al.* (2006)
8.7 (28 Mar. 2005)	SAMP	3.6	98.7	−136.9	−114.7			Kreemer *et al.* (2006a)

al., 2005). Although some other well-known software packages, such as GIPSY-OASIS, Bernese, GAMIT, among others, produce better results on positioning in terms of accuracy, the processing of the data from these scientific software packages is not easy for a non-GPS expert. As a matter of fact, for the analysis of the co-seismic motion, the accuracy from PPP would be satisfactory in most cases, as shown in many previous studies (Melbourne *et al.*, 2002; Kreemer *et al.*, 2006b). In summary, PPP is potentially faster, more efficient, and more straightforward.

2. GPS Data

We focus on the "Sumatra-Andaman Islands Earthquake of December 26, 2004" and on March 28, 2005. The epicenter (3.316°N, 95.854°E) of the "Sumatra-Andaman Islands Earthquake of December 26, 2004" is the northwestern seashore of the Sumatra island of Indonesia, and the epicenter (2.074°N, 97.013°E) of the earthquake that occurred on March 28, 2005 is the northern Sumatra (http://earthquake.usgs.gov/regional/world/historical.php). The SuGAr network and Badan Koordinasi Survei dan Pemetaan Nasional (BAKOSURTANAL)'s site SAMP are located around the epicenters (Fig. 1). The SuGAr network and site SAMP data can be obtained from SOPAC. SOPAC is the IGS data and analysis center that supports high-precision geodetic survey and geophysical observation using GPS. In addition, SOPAC provides data that can be used for evaluating earthquake danger, the movement of the Earth's crust, the deformation of plate borders, and meteorological processing. SOPAC not only includes the SCIGN network, which consists of 250 stations, but also stores daily GPS data on more than 800 GPS permanent stations from more than 20 networks around the world (http://sopac.ucsd.edu/other/sopacDescription.html). Unfortunately, the GPS data observed in 2004 by the SuGAr network are not open to the public. Among the GPS data observed around December 26, 2004 and around March 28, 2005, the SOPAC center can only provide SAMP GPS data. Therefore, this study conducted the displacement analysis only around the site SAMP. The Site SAMP is the GPS permanent station located about 330 km to the east of

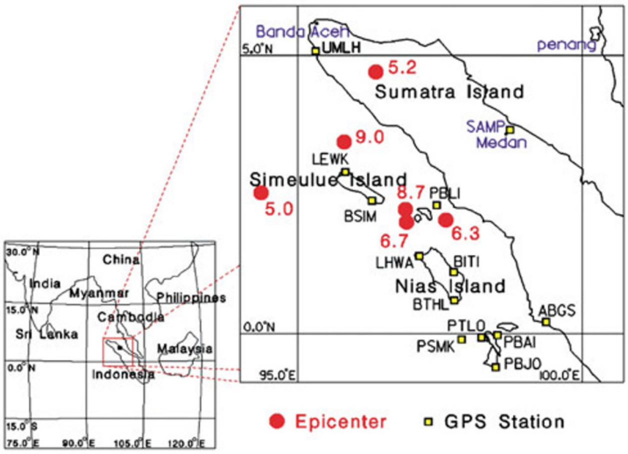

Fig. 1. The distribution of the GPS sites around the epicenter area of the earthquakes of magnitude >5.0 that occurred between 2004 and 2006.

Table 2. SAMP GPS Data.

Year	Common data	Additional data (Day of year)
2004	15-day intervals	341–366
2005		005, 006, 007, 023, 024, 025, 048, 052, 067–069, 080–105, 134, 152, 186, 187, 229, 268, 321, 323, 324
2006		146–148, 197–201, 208

the epicenter of the "Sumatra-Andaman Islands Earthquake of December 26, 2004" (Blewitt *et al.*, 2006).

First, in order to examine the rough displacement of the site SAMP, the GPS data for the 15th and 30th of every month from January 2004 to July 2006 were downloaded from the SOPAC center via the Internet. In order to look into the displacement from the two earthquakes that occurred on December 26, 2004 and on March 28, 2005, the SAMP GPS data were acquired before and after the date of the earthquake events (Table 2).

Table 3. Internet-based GPS data processing services.

Service	Agency	Processing type	Area	Upload system	Upload file	Results
OPUS	NGS	Relative	The USA	Web	RINEX	email
SCOUT	SOPAC	Relative	Anywhere on Earth	Anonymous Ftp	RINEX	email
AUSPOS	Geoscience Australia	Relative	Anywhere on Earth	Web	RINEX	email
Auto-GIPSY	JPL	Absolute	Anywhere on Earth	Anonymous Ftp	RINEX	email
CSRS-PPP	NRCan	Absolute	Anywhere on Earth	Web	RINEX	email

Table 4. RMS errors (cm).

Software		6 hour	12 hour	24 hour	Average
GIPSY	H	2.65	2.04	2.64	2.44
	V	2.65	2.04	2.64	2.44
OPUS	H	1.20	1.56	1.56	1.42
	V	1.20	1.56	1.56	1.42
SCOUT	H	1.06	1.23	1.25	1.18
	V	1.06	1.23	1.25	1.18

H: Horizontal RMS error, V: Vertical RMS error.

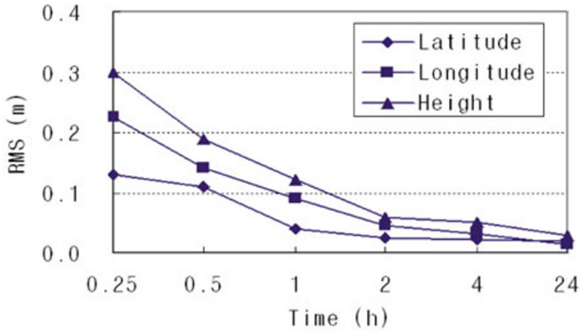

Fig. 2. Expected positioning accuracy of CSRS-PPP as a function of time (Geodetic Survey Division).

Table 5. The list of datasets processed in this study.

Data set	GPS data	Processed results
1	15-day intervals (2004.01–2006.07)	Tables 6, 7
2	DOY 340 (2004)–DOY 366 (2004)	Table 8
3	DOY 80 (2005)–DOY 105 (2005)	Table 9
4	additional data	Table 10

3. GPS Data Processing

With the development of high-precision GPS technology, both the data processing and the analysis software have become more elaborate and more automated. GPS processing services, based on the Internet, are a good example. In 2001, the Auto-GIPSY service made its debut. Representative examples of Internet-based processing services, which are current in service include Auto-GIPSY, OPUS, SCOUT and AUSPOS (Dawson *et al.*, 2001) (Table 3).

When the accuracies of GIPSY, OPUS, and SCOUT were compared (MacDonald, 2002), SCOUT was determined to have the best accuracy on the horizon and on the vertical on average. GIPSY was better than OPUS in terms of horizontal accuracy, but the vertical accuracy was less than that of OPUS (Table 4).

It is known that the accuracy of the CSRS-PPP is comparable to that of the other services described above (Fig. 2). In addition, CSRS-PPP is more stable than auto-GIPSY, and faster and more efficient than OPUS and SCOUT, both of which perform relative positioning, not absolute positioning.

For data processing, this study uses the CSRS-PPP service. CSRS-PPP allows GPS users in Canada (and abroad) to recover more accurate positions from a single GPS receiver by submitting their observed data over the Internet. CSRS-PPP can process GPS observations from single or dual-frequency GPS receivers. Compared to uncorrected point positioning using broadcast GPS orbits, this application can improve the results by a factor of 2 to 100 (Tétreault *et al.*, 2005), depending on user equipment, dynamics, and duration of the observing session. CSRS-PPP provides improved positions in the NAD83 (CSRS) reference frame as well as in the International Terrestrial Reference Frame. The PPP application can process GPS observations only when precise GPS orbits and clock products are available (Geodetic Survey Division, 2004). It will use the best products available at the time the data are submitted. Since CSRS-PPP processing is based on the IGS final orbit and clock products that are global in nature, it may be used to process GPS observations made anywhere on or near Earth, at any time of a day. IGS final orbits are made available with a delay of between 10 to 12 days (Beutler *et al.*, 1999). It is the orbit information that should be used if the highest accuracy is required.

Table 5 shows the list of the experiments conducted in this study. In total, four datasets are processed, and the results are presented in Tables 6–10.

To examine rough displacements of the Site SAMP, GPS data were processed at 15-day intervals from January 2004 to July 2006 (Tables 6, 7). To investigate the influence of the earthquake that occurred on December 26, 2004, we processed the DOY (Day of Year) 340 (2004)–DOY 366 (2004) GPS data (Table 8); the influence of the earthquake that occurred on March 28, 2005 was investigated by processing the DOY 80 (2005)–DOY 105 (2005) GPS data (Table 9). In addition, to examine the postseismic motion, DOY 5, 6, 7, 15, 23, 24, 25, 30, 48, 52, 67–69, 134, 152, 186, 187, 229, 268, 321, 323, 324 (2005), DOY 146–148, 197–201, 208 (2006) GPS data were processed (Table 10).

4. Displacement Analysis

The position differences (dn, de, and du) of the processed result were calculated by taking the DOY 340 (lat 3°37′17.8000″N, long 98°42′52.9894″E, height 1.999 m) of the year 2004 as the reference epoch. The period between January 2004 and July 2006 shows almost similar re-

Table 6. The processed results of the dataset 1.

Day	Lat (DMS)	Long (DMS)	Height (m)	RMSE (lat)	RMSE (lon)	RMSE (height)	dn (m)	de (m)	du (m)	Comment
20040015	3 37 17.7998	98 42 52.9886	2.043	0.003	0.012	0.019	−0.0061	0.0247	0.044	
20040030	17.7999	52.9893	2.042	0.003	0.010	0.018	−0.0031	0.0031	0.043	
20040045	17.8001	52.9884	2.050	0.003	0.011	0.017	0.0031	0.0309	0.051	
20040060	17.8002	52.9894	2.045	0.003	0.011	0.020	0.0061	0.0309	0.046	
20040075	17.8000	52.9888	2.038	0.004	0.013	0.021	0.0000	0.0185	0.039	
20040090	17.8002	52.9889	2.019	0.003	0.011	0.018	0.0061	0.0154	0.020	
20040105	17.8000	52.9893	2.057	0.003	0.010	0.018	0.0000	0.0031	0.058	
20040120	17.8001	52.9894	2.043	0.003	0.013	0.018	0.0031	0.0000	0.044	
20040135	17.8002	52.9892	2.021	0.003	0.013	0.018	0.0061	0.0062	0.022	
20040150	17.8000	52.9892	2.020	0.003	0.010	0.017	0.0000	0.0062	0.021	
20040165	17.8002	52.9895	2.016	0.003	0.009	0.017	0.0061	−0.0031	0.017	
20040170	17.8005	52.9892	2.029	0.003	0.009	0.016	0.0154	0.0062	0.030	
20040195	17.8001	52.9890	2.028	0.002	0.009	0.017	0.0031	0.0123	0.029	
20040210	17.8000	52.9898	2.034	0.003	0.010	0.016	0.0000	−0.0123	0.035	
20040225	17.8000	52.9893	2.025	0.002	0.010	0.015	0.0000	0.0031	0.026	
20040240	17.8001	52.9897	2.014	0.002	0.010	0.015	0.0031	−0.0093	0.015	
20040255	17.8000	52.9896	2.019	0.003	0.012	0.017	0.0000	−0.0062	0.020	
20040270	17.8000	52.9899	2.018	0.002	0.009	0.016	0.0000	−0.0154	0.019	
20040285	17.8003	52.9897	2.008	0.002	0.009	0.016	0.0092	−0.0093	0.009	
20040300	17.8004	52.9899	2.012	0.002	0.009	0.016	0.0123	−0.0154	0.013	
20040315	17.8001	52.9902	2.025	0.003	0.010	0.018	0.0031	−0.0247	0.026	
20040330	17.8005	52.9898	1.982	0.003	0.010	0.019	0.0154	−0.0123	−0.017	
20040345	17.7998	52.9899	2.013	0.003	0.010	0.020	−0.0061	−0.0154	0.014	
20040360	17.8002	52.9900	2.007	0.003	0.009	0.017	0.0061	−0.0185	0.008	
20050015	17.7998	52.9853	1.998	0.003	0.010	0.019	−0.0061	−0.1265	−0.001	
20050030	17.7996	52.9847	2.024	0.003	0.009	0.016	−0.0123	−0.1450	0.025	
20050045	17.7999	52.9843	2.023	0.002	0.009	0.016	−0.0031	−0.1574	0.024	
20050075	17.7994	52.9846	2.019	0.003	0.011	0.017	−0.0184	−0.1481	0.020	
20050090	17.7948	52.9798	2.029	0.002	0.008	0.013	−0.1597	−0.2963	0.030	
20050105	17.7942	52.9804	2.030	0.003	0.011	0.016	−0.1782	−0.2777	0.031	
20050120	17.7936	52.9794	2.047	0.003	0.010	0.017	−0.1966	−0.3086	0.048	
20050135	17.7773	52.9699	10.002	0.033	0.068	0.092	−0.6973	−0.6018	8.003	bad data
20050149	17.7934	52.9789	2.038	0.002	0.008	0.017	−0.2027	−0.3240	0.039	
20050165	17.7933	52.9789	2.012	0.002	0.007	0.015	−0.2058	−0.3240	0.013	
20050180	17.7932	52.9788	2.006	0.002	0.007	0.015	−0.2089	−0.3271	0.007	
20050195	17.7931	52.9789	2.007	0.002	0.007	0.015	−0.2119	−0.3240	0.008	

sults, with the exception of between March 2005 and April 2005. However, between March 2005 and April 2005, the deviation of the results increases dramatically. For example, in the case of the DOY 103 of the year 2005, the dn, de, and du are 0.144 m, 29.340 m, and 137.323 m, respectively (Table 9). The root mean squared errors (RMSEs) are 0.609 m (x), 2.526 m (y), and 1.725 m (z), which is about 100-fold larger than the general RMSE. There are ten values that are about eightfold larger than the general RMSE; otherwise, the RMSE is, on average, 0.003 m (dn), 0.009 m (de), and 0.016 m (du). The reason for those poor RMSEs was found to be that the quality of the associated data was poor. While there were no large RMSEs in the processed results of the 2004 GPS data, there were ten large RMSEs in the processed results of the 2005 and 2006 GPS data sets. The 2004 GPS data was a typical RINEX file which has extension *.04o. However, the 2005 GPS data and 2006 GPS data were a compact RINEX file having extension *.05d, *.06d. The compact RINEX files were converted to the normal RINEX files to examine the data record order (Table 11). The C1 and P2 pseudoranges in the converted SAMP1350.05o ranged from about 15,000 km to about 19,000 km, which is unreasonable considering that the normal distance between GPS satellite to GPS receiver is about 20,200 km. Therefore, it is obvious that those poor RMSEs are caused by the bad datasets.

Among the results that were processed from January 2004 to July 2006, the results for which the RMSE exceeds 0.003 m (dn), 0.009 m (de), and 0.016 m (du) were excluded. In processing the GPS data, we focused around the time that earthquakes occurred in an attempt to look more closely at the transition of the displacement (Fig. 3).

Figure 3 shows that the displacement was clearly visible using the data from December 26, 2004, March 28, 2005,

Table 7. The processed results of the data set 1 (continued).

Day	Lat (DMS)	Lon (DMS)	Height (m)	RMSE (lat)	RMSE (lon)	RMSE (height)	dn (m)	de (m)	du (m)	Comment
20050210	3 37 17.7927	98 42 52.9787	2.019	0.002	0.008	0.015	−0.2242	−0.3302	0.020	
20050225	17.7927	52.9784	2.003	0.002	0.007	0.014	−0.2242	−0.3395	0.004	
20050240	17.7927	52.9780	2.019	0.003	0.008	0.013	−0.2242	−0.3518	0.020	
20050255	17.7928	52.9783	2.002	0.003	0.008	0.015	−0.2212	−0.3426	0.003	
20050270	17.7927	52.9782	2.024	0.002	0.008	0.015	−0.2242	−0.3456	0.025	
20050285	17.7926	52.9781	1.999	0.002	0.007	0.014	−0.2273	−0.3487	0.000	
20050300	17.7924	52.9782	2.005	0.002	0.007	0.014	−0.2334	−0.3456	0.006	
20050315	17.7925	52.9780	2.022	0.002	0.007	0.015	−0.2304	−0.3518	0.023	
20050330	17.7923	52.9780	2.019	0.002	0.007	0.015	−0.2365	−0.3518	0.020	
20050345	17.7923	52.9784	2.011	0.002	0.007	0.015	−0.2365	−0.3395	0.012	
20050360	17.7922	52.9780	2.019	0.002	0.006	0.015	−0.2396	−0.3518	0.020	
20060015	17.7920	52.9783	2.012	0.002	0.007	0.014	−0.2457	−0.3426	0.013	
20060030	17.7921	52.9779	1.999	0.002	0.007	0.015	−0.2427	−0.3549	0.000	
20060045	17.7920	52.9786	2.022	0.002	0.007	0.014	−0.2457	−0.3333	0.023	
20060060	17.7922	52.9784	1.986	0.002	0.007	0.015	−0.2396	−0.3395	−0.013	
20060075	17.7919	52.9778	1.988	0.002	0.007	0.015	−0.2488	−0.3580	−0.011	
20060090	17.7920	52.9780	2.019	0.002	0.008	0.015	−0.2457	−0.3518	0.020	
20060104	17.7918	52.9777	2.001	0.003	0.008	0.016	−0.2519	−0.3611	0.002	
20060120	17.7913	52.9779	2.024	0.002	0.006	0.014	−0.2672	−0.3549	0.025	
20060135	17.7916	52.9779	2.007	0.002	0.006	0.014	−0.2580	−0.3549	0.008	
20060150	17.7916	52.9778	2.019	0.003	0.008	0.017	−0.2580	−0.3580	0.020	
20060165	17.7915	52.9779	2.017	0.002	0.007	0.015	−0.2611	−0.3549	0.018	
20060180	17.7912	52.9776	2.016	0.002	0.007	0.016	−0.2703	−0.3642	0.017	
20060195	17.7916	52.9773	1.999	0.002	0.006	0.013	−0.2580	−0.3734	0.000	
20060210	17.7914	52.9775	1.986	0.002	0.007	0.014	−0.2642	−0.3672	−0.013	

Table 8. The processed results of data set 2

Day	Lat (DMS)	Lon (DMS)	Height (m)	RMSE (lat)	RMSE (lon)	RMSE (height)	dn (m)	de (m)	du (m)	Comment
20040341	3 37 17.8000	98 42 52.9899	2.012	0.003	0.010	0.018	0.0000	0.0154	0.013	
20040342	17.8001	52.9900	2.017	0.003	0.010	0.019	0.0031	0.0185	0.018	
20040343	17.8000	52.9897	2.023	0.003	0.009	0.018	0.0000	0.0093	0.024	
20040344	17.8000	52.9897	1.997	0.003	0.010	0.018	0.0000	0.0093	−0.002	
20040345	17.7998	52.9899	2.013	0.003	0.010	0.020	−0.0061	0.0154	0.014	
20040346	17.8000	52.9899	2.017	0.003	0.009	0.018	0.0000	0.0154	0.018	
20040347	17.7999	52.9897	2.011	0.003	0.010	0.019	−0.0031	0.0093	0.012	
20040348	17.8001	52.9898	1.995	0.003	0.009	0.017	0.0031	0.0123	−0.004	
20040349	17.8002	52.9891	2.001	0.003	0.010	0.018	0.0061	−0.0093	0.002	
20040350	17.8003	52.9895	2.003	0.003	0.009	0.018	0.0092	0.0031	0.004	
20040351	17.8000	52.9899	2.005	0.003	0.011	0.018	0.0000	0.0154	0.006	
20040352	17.8002	52.9901	2.013	0.003	0.009	0.018	0.0061	0.0216	0.014	
20040353	17.8001	52.9900	1.997	0.003	0.009	0.018	0.0031	0.0185	−0.002	
20040354	17.8001	52.9900	2.021	0.003	0.009	0.017	0.0031	0.0185	0.022	
20040355	17.8001	52.9899	2.025	0.002	0.008	0.016	0.0031	0.0154	0.026	
20040356	17.7999	52.9899	2.029	0.003	0.008	0.016	−0.0031	0.0154	0.030	
20040357	17.7999	52.9899	2.027	0.003	0.009	0.017	−0.0031	0.0154	0.028	
20040358	17.8001	52.9897	2.009	0.002	0.008	0.017	0.0031	0.0093	0.010	
20040359	17.8002	52.9898	2.002	0.003	0.009	0.016	0.0061	0.0123	0.003	
20040360	17.8002	52.9900	2.007	0.003	0.009	0.017	0.0061	0.0185	0.008	
20040361	17.7996	52.9854	2.032	0.003	0.009	0.017	−0.0123	−0.1234	0.033	
20040362	17.7996	52.9854	2.013	0.003	0.009	0.017	−0.0123	−0.1234	0.014	
20040363	17.7997	52.9853	2.007	0.003	0.010	0.019	−0.0092	−0.1265	0.008	
20040364	17.7996	52.9856	2.016	0.003	0.009	0.018	−0.0123	−0.1173	0.017	
20040365	17.7998	52.9852	2.008	0.003	0.010	0.019	−0.0061	−0.1296	0.009	
20040366	17.7996	52.9853	2.012	0.003	0.010	0.018	−0.0123	−0.1265	0.013	

and July 5, 2005 as the starting points. The dn led to a little displacement starting from December 26, 2004, the day when the earthquake occurred. However, in the period from March 28, 2005 to March 30, 2005, the displacement occurred on a very large scale. In addition, starting from April 28, 2005, the displacement is seen to be increasing at a regular level (Fig. 3(b)). Compared with the dn, which occurred on December 26, 2004, the de variation led to a very

Table 9. The processed results of dataset 3.

Day	Lat (DMS)	Long (DMS)	Height (m)	RMSE (lat)	RMSE (lon)	RMSE (height)	dn (m)	de (m)	du (m)	Comment
20050080	3 37 17.7997	98 42 52.9851	2.011	0.003	0.010	0.017	−0.0092	−0.1327	0.012	
20050081	17.7997	52.9847	2.016	0.003	0.010	0.019	−0.0092	−0.1450	0.017	
20050082	17.7994	52.9848	2.024	0.003	0.010	0.017	−0.0184	−0.1420	0.025	
20050083	17.7996	52.9844	2.016	0.003	0.009	0.015	−0.0123	−0.1543	0.017	
20050084	17.7995	52.9851	2.016	0.002	0.009	0.016	−0.0154	−0.1327	0.017	
20050085	17.7996	52.9844	2.023	0.003	0.010	0.017	−0.0123	−0.1543	0.024	
20050086	17.7997	52.9847	2.021	0.002	0.009	0.013	−0.0092	−0.1450	0.022	
20050087	17.7989	52.9837	2.028	0.003	0.010	0.017	−0.0338	−0.1759	0.029	
20050088	17.7951	52.9810	2.019	0.003	0.008	0.015	−0.1505	−0.2592	0.020	
20050089	17.9100	52.8732	14.712	0.037	0.092	0.135	3.3790	−3.5860	12.713	bad data
20050090	17.7948	52.9798	2.029	0.002	0.008	0.013	−0.1597	−0.2963	0.030	
20050091	17.7947	52.9798	2.018	0.002	0.007	0.014	−0.1600	−0.2960	0.030	
20050092	17.7841	52.8646	16.008	0.035	0.106	0.139	−0.4880	−3.8510	14.009	bad data
20050093	17.7945	52.9805	2.019	0.003	0.009	0.016	−0.1690	−0.2750	0.020	
20050094	17.7943	52.9797	2.040	0.002	0.01	0.015	−0.1750	−0.2990	0.041	
20050095	17.7415	53.0081	22.819	0.063	0.127	0.24	−1.7970	0.5770	20.820	bad data
20050096	17.7945	52.9796	2.015	0.002	0.01	0.015	−0.1690	−0.3020	0.016	
20050097	17.8344	53.0108	14.202	0.029	0.069	0.112	1.0570	0.6600	12.203	bad data
20050098	17.7942	52.9800	2.036	0.002	0.008	0.015	−0.1840	−0.2900	0.037	
20050099	35.6245	0.5133	0.000	10.413	8.356	33.519	—	—	—	bad data
20050100	17.8612	52.9802	13.492	0.035	0.067	0.109	1.8800	−0.2840	11.493	bad data
20050101	17.7943	52.9797	2.015	0.003	0.009	0.015	−0.1750	−0.2990	0.016	
20050102	17.7793	53.0032	22.170	0.043	0.087	0.184	−0.6360	0.4260	20.171	bad data
20050103	17.8047	53.9401	139.322	0.609	2.526	1.725	0.1440	29.3400	137.323	bad data
20050104	17.7689	52.9459	13.624	0.032	0.079	0.099	−0.9550	−1.3420	11.625	bad data
20050105	17.7942	52.9804	2.030	0.003	0.011	0.016	−0.1782	−0.2777	0.031	

Table 10. The processed results of dataset 4.

Day	Lat (DMS)	Long (DMS)	Height (m)	RMSE (lat)	RMSE (lon)	RMSE (height)	dn (m)	de (m)	du (m)	Comment
20050005	3 37 17.7995	98 42 52.9856	2.012	0.003	0.010	0.019	−0.0154	−0.1173	0.013	
20050006	17.7994	52.9852	2.017	0.003	0.009	0.018	−0.0184	−0.1296	0.018	
20050007	17.7997	52.9849	2.015	0.003	0.010	0.020	−0.0092	−0.1389	0.016	
20050023	17.7997	52.9843	2.011	0.002	0.009	0.017	−0.0092	−0.1574	0.012	
20050024	17.7997	52.9845	2.016	0.003	0.009	0.018	−0.0092	−0.1512	0.017	
20050025	17.7996	52.9849	2.028	0.003	0.009	0.016	−0.0123	−0.1389	0.029	
20050048	17.7996	52.9848	2.047	0.003	0.011	0.019	−0.0123	−0.1420	0.048	
20050052	17.7999	52.9846	2.041	0.003	0.011	0.019	−0.0031	−0.1481	0.042	
20050067	17.7998	52.9844	2.004	0.003	0.011	0.018	−0.0061	−0.1543	0.005	
20050068	17.7996	52.9846	2.037	0.003	0.011	0.018	−0.0123	−0.1481	0.038	
20050069	17.7995	52.9847	2.030	0.003	0.011	0.017	−0.0154	−0.1450	0.031	
20050134	17.7936	52.9792	2.030	0.002	0.007	0.015	−0.1966	−0.3148	0.031	
20050152	17.7932	52.9794	2.027	0.002	0.007	0.014	−0.2089	−0.3086	0.028	
20050185	17.7933	52.9786	2.031	0.002	0.007	0.014	−0.2058	−0.3333	0.032	
20050186	17.7931	52.9783	2.013	0.002	0.007	0.015	−0.2119	−0.3426	0.014	
20050229	17.7928	52.9787	2.018	0.002	0.007	0.014	−0.2212	−0.3302	0.019	
20050268	17.7928	52.9784	2.013	0.002	0.006	0.014	−0.2212	−0.3395	0.014	
20050314	17.7925	52.9780	2.015	0.002	0.007	0.015	−0.2304	−0.3518	0.016	
20050321	17.7923	52.9779	2.012	0.002	0.007	0.015	−0.2365	−0.3549	0.013	
20050323	17.7923	52.9776	2.011	0.002	0.007	0.014	−0.2365	−0.3642	0.012	
20060031	17.7921	52.9779	1.997	0.002	0.007	0.014	−0.2427	−0.3549	−0.002	
20060059	17.7916	52.9781	1.998	0.002	0.007	0.014	−0.2580	−0.3487	−0.001	
20060106	17.7918	52.9777	2.016	0.003	0.008	0.016	−0.2519	−0.3611	0.017	
20060146	17.7914	52.9780	1.998	0.002	0.008	0.015	−0.2642	−0.3518	0.001	
20060147	17.7915	52.9779	2.005	0.002	0.007	0.014	−0.2611	−0.3549	0.006	
20060198	17.7910	52.9783	1.967	0.002	0.007	0.014	−0.2764	−0.3426	−0.032	
20060208	17.7910	52.9773	2.003	0.002	0.007	0.014	−0.2764	−0.3734	0.004	

large-scale displacement. The displacement that occurred between March 28, 2005 and July 5, 2005 is clearly visible. From July 5, 2005, the displacement is increasing steadily (Fig. 3(c)). On January 23, 2005, the dn is -0.0031 m and the de is -0.0222 m, which clearly demonstrates the larger displacement on de. The du variation does not show a large transition (Fig. 3(d)).

The dn is increasing at a regular level from April 2005 to

Table 11. Comparison of the two RINEX data records showing good (left) and bad (right) quality.

4 L1 L2 C1 P2 #/TYPES OF OBSERVATION							
SAMP1200.05d → SAMP1200.05o				SAMP1350.05d → SAMP1350.05o			
05 4 30 0 0 30.0000000 0 7G08G10G27G04G28G02G07				05 5 15 4 0 59.9830000 0 9G 2G 6G10G26G 5G29G30G 9G18			
				−58722585.421	−45706555.860	17890804.316	17890811.768
−36664678.443	−28203951.000	22926316.311	22926320.294	−13709063.273	−9926588.839	17726226.369	17726235.841
−4893527.064	−3780676.462	24098533.072	24098537.003	−38329482.883	−29470402.133	18707904.216	18707912.766
−38629218.811	−28551393.465	24322342.552	24322348.031	−44944836.327	−34054730.951	15003571.871	15003578.996
−40791205.970	−31756538.541	21052757.456	21052760.858	−33092906.208	−25394017.981	17815452.234	17815462.835
−48729047.057	−37342981.608	20586580.688	20586583.587	−43559837.103	−32811126.770	15596173.028	15596180.140
−29005295.867	−22209512.716	22392036.815	22392038.499	−20438782.145	−15297248.827	18263873.315	18263883.658
−37367905.174	−29071516.361	23296224.579	23296231.105	−29938469.981	−23313306.838	19143182.556	19143193.645
				−10729736.027	−7795933.720	19219379.096	19219390.441

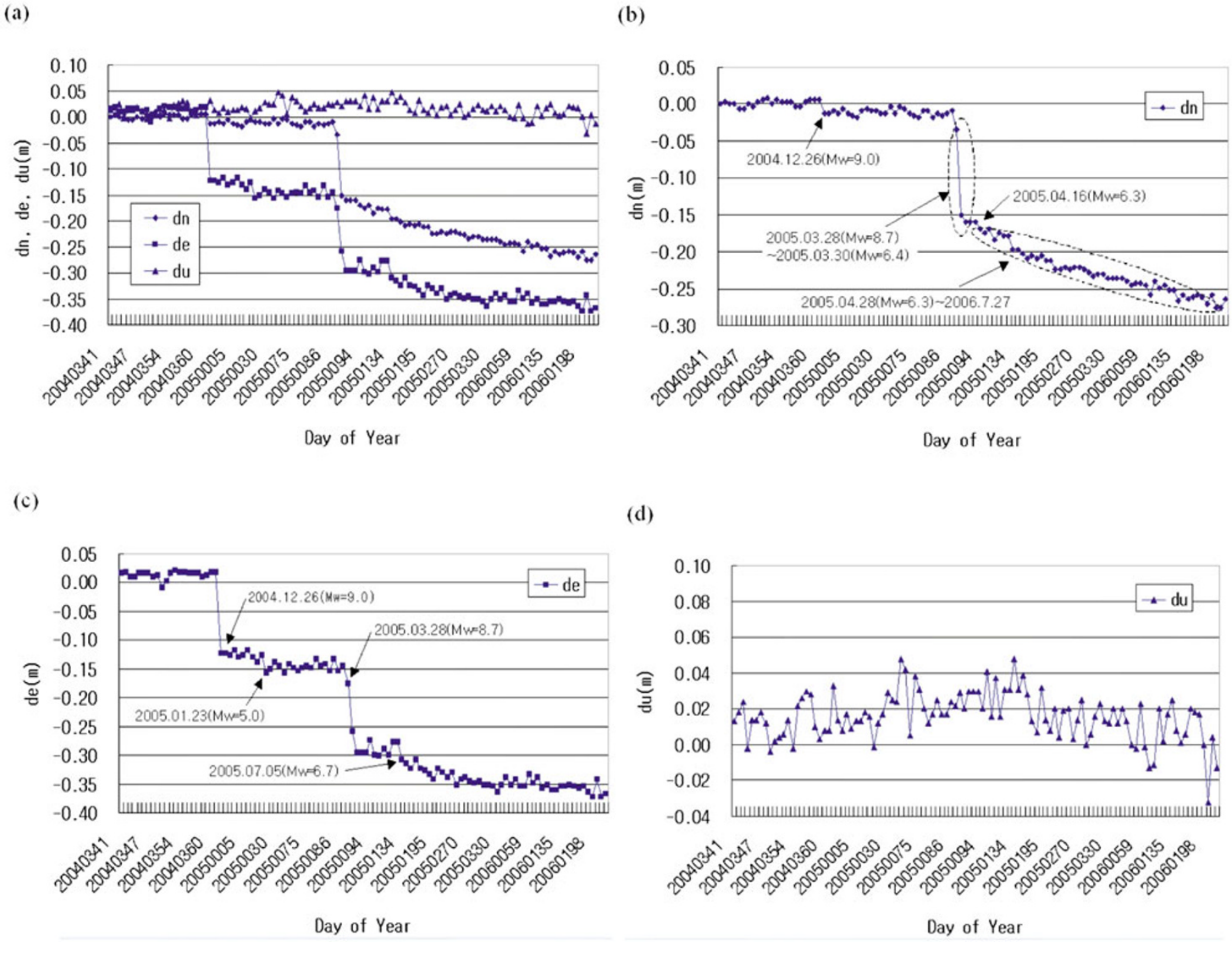

Fig. 3. The distribution after the results that exceed RMSE 0.003 m (dn), 0.009 m (de), and 0.016 m (du) were excluded.

July 2006, and the rate of increase is about −55.69 mm/year (Fig. 4(a)). The de variation increases on a regular basis from July 2005 to July 2006, and the rate of increase is about −23.66 mm/year (Fig. 4(b)).

The de variation can be seen to be undergoing large changes relative to the dn and de variations. The offsets at the time of the earthquake were estimated by noting the differences in the mean positions of the 5 days before and after the earthquake, respectively (Fig. 5). The mean of dn in the 5 days before the earthquake is 0.0018 m, and that of dn in the 5 days after the earthquake is −0.0104 m (Table 8). Therefore, the offset (−0.0122 m) at the time of the earthquake was calculated by differencing (Fig. 5(b)). The mean of de in the 5 days before the earthquake is 0.0142 m and that of de in the 5 days after the earthquake is −0.1240 m (Table 8). Therefore, the offset of de is −0.1382 m (Fig. 5(c)). The du variation does not change substantially (Fig. 5(d)).

Comparing the result of Banerjee (dn = −14.8 mm, de = −135.0 mm; Table 1) and Kreemer (dn = −9.0 mm, de = −139.0 mm; Table 1) with that of this study, the dn (−12.2 mm) value of this study is placed around the

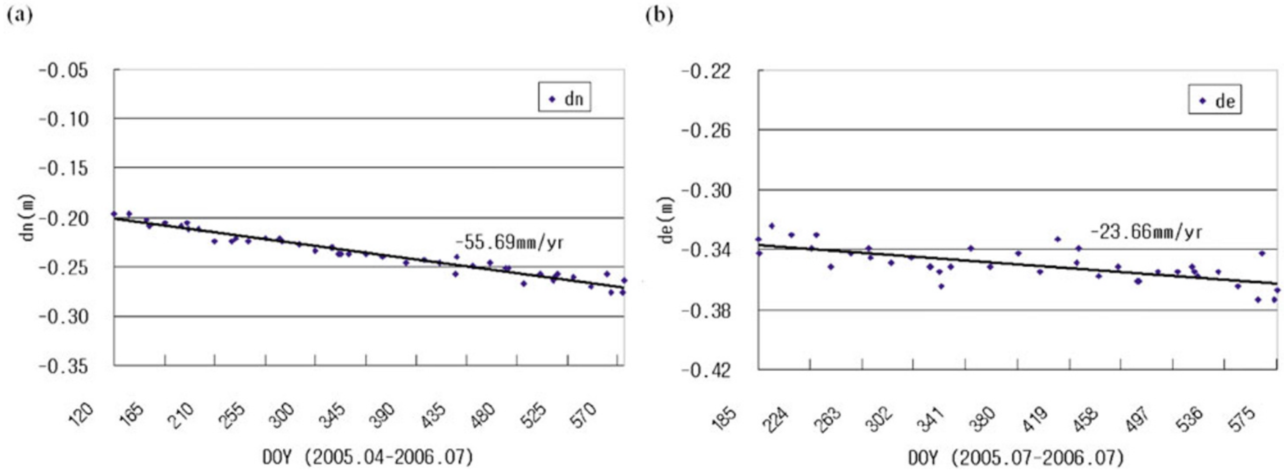

Fig. 4. Regression analysis in a steady increased period.

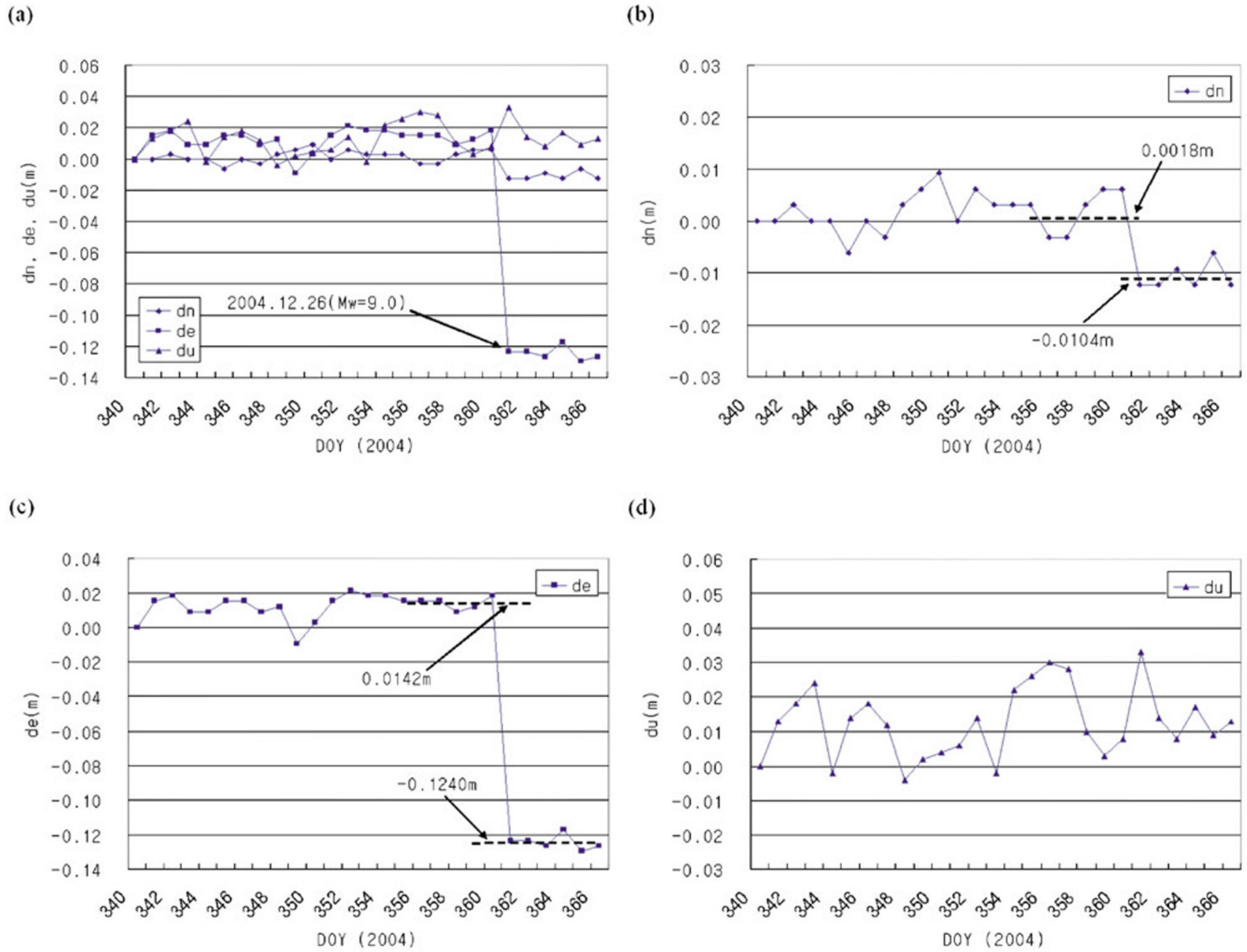

Fig. 5. The distribution of the results from December 5, 2004 to December 31, 2004.

mid-point of the values of the results by the two researchers. Meanwhile, the de (-13.8 mm) value of this study precisely corresponds to that of the two researchers (Fig. 5).

We can see that the increase of the dn and de variations start from March 27, 2005. The offsets at the time of the earthquake were estimated by differencing the mean positions in the 5 days before and after the earthquake, respectively (Fig. 6). The mean of dn in the 5 days before the earthquake is -0.0166 m, and that of dn in the 5 days after the earthquake is -0.1566 m (Table 9). Therefore, the offset (-0.1400 m) at the time of the earthquake was calculated by differencing (Fig. 6(b)). The mean of de in the 5 days before the earthquake is -0.1524 m, and that of de in the 5 days after the earthquake is -0.2839 m (Table 9).

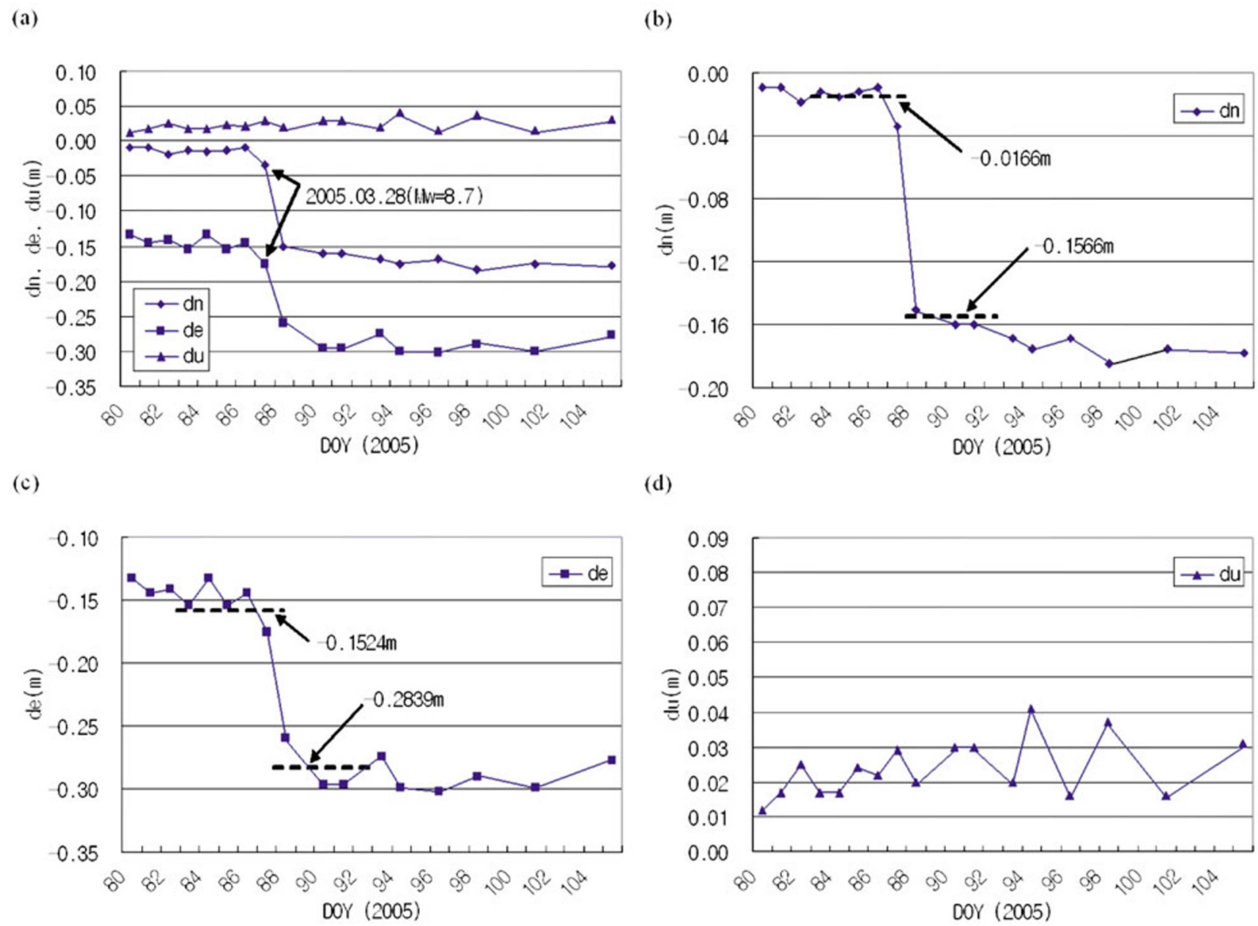

Fig. 6. The distribution of results from March 21, 2005 to April 15, 2005.

Table 12. The displacement of the Site SAMP by the earthquakes.

Time	*dn* (m)	*de* (m)	Displacement (m)
2004.12.26	−0.0122	−0.1382	0.1387
2005.1.23	−0.0031	−0.0222	0.0224
2005.3.28	−0.1400	−0.1315	0.1921
from April 2005 to July 2006	−0.0660	−0.0224	0.0697

Therefore, the offset of de is −0.1315 m (Fig. 6(c)). The du variation does not show a significant change (Fig. 6(d)).

RMSEs with high values appeared in the period from March 21, 2005 to April 15, 2005; otherwise, the RMSEs are 0.003 m (dn), 0.009 m (de), and 0.016 m (du) on average. As the values of the results were excluded, taking the average RMSE as the reference, the result values of the 5 days after the earthquake outbreak were three. Comparing the result of Kreemer *et al.* ($dn = -0.1369$ m, $de = -0.1147$ m; Kreemer *et al.*, 2006a, Table 1) with the result of this study ($dn = -0.1400$ m, $de = -0.1315$ m), the dn and de values of this study are comparable with each other, although some parts of the results were excluded in the RMSE calculation.

The displacement that occurred from the "Sumatra-Andaman Islands Earthquake of December 26, 2004" was 0.1387 m in the southwest direction ($dn = -0.0122$ m, $de = -0.1382$ m). The displacement by the earthquake on January 23, 2005 and January 24, 2005 was 0.0224 m in the southwest direction ($dn = -0.0031$ m, $de = -0.0222$ m). The displacement by the earthquake on March 28, 2005 was 0.1921 m in the southwest direction ($dn = -0.1400$ m, $de = -0.1315$ m). The displacement from April 2005 to July 2006 was 0.0697 m in the southwest direction ($dn = -0.0660$ m, $de = -0.0224$ m) (Table 12).

5. Conclusion

The aim of this study was to process the GPS data of the SAMP GPS permanent station located in Medan City, Indonesia, from January 2004 to July 2006 and to analyze the result of displacement before and after the earthquakes of the same period. The GPS data of the SAMP permanent station was processed using the on-line CSRS-PPP, and the RMSE was found to be 0.003 m (dn), 0.009 m (de), and 0.016 m (du) on average. These values were used to exclude results from days with poor data. The data showed a clear displacement in the southwestern direction from December 26, 2004 (earthquake $M_w = 9.0$)

to March 28, 2005 (earthquake $M_w = 8.7$), which was the period when the earthquakes occurred. However, after the midpoint of 2005, the data show displacement at a regular speed. The "Sumatra-Andaman Islands Earthquake of December 26, 2004" led to a displacement of 0.1387 m ($dn = -0.0122$ m, $de = -0.1382$ m) to the southwest. The earthquakes that occurred on January 23, 2005 and on January 24, 2005 led to a displacement of 0.0224 m ($dn = -0.0031$ m, $de = -0.0222$ m) in the southwestern direction. The earthquake that occurred on March 28, 2005 led to a displacement of 0.1921 m ($dn = -0.1400$ m, $de = -0.1315$ m) to the southwest. Starting from December 26, 2004, displacement to the southwest continued. However, from April 2005, the speed of the displacement gradually slowed down. The dn shows a regular rate of displacement (-55.69 mm/year) from April 28, 2005 to July 2006. The de variation shows a regular rate of displacement (-23.66 mm/year) from July 5, 2005 to July 2006. Comparing previous studies of the SAMP station with the results of this study, the dn and de values of this study are comparable with each other. Therefore, we propose that on-line tools such as CSRS-PPP can be used to analyze co-seismic displacement of a GPS station in a simple and effective way.

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