Terr. Atmos. Ocean. Sci., Vol. 22, No. 5, 521-533, October 2011 doi: 10.3319/TAO.2011.05.18.01(T)

NOTES AND CORRESPONDENCE

Continuous CWB GPS Array in Taiwan and Applications to Monitoring Seismic Activity

Tzay-Chyn Shin[1], Kai-Wen Kuo[2], Peih-Lin Leu[2], Chun-Hsiung Tsai[2], and Juen-Shi Jiang[2,*]

[1] *Central Weather Bureau, Taipei, Taiwan*
[2] *Seismological Center, Central Weather Bureau, Taipei, Taiwan*

Received 10 March 2011, accepted 18 May 2011

ABSTRACT

GPS observations have revealed important information for studying active tectonics and plate motion and are a useful tool for monitoring crustal deformation. The CWB continuous GPS array consists of approximately 150 stations with dense spatial coverage throughout Taiwan and can be used not only to monitor crustal deformation and seismic activity, but also to analyze the earthquake precursors in Taiwan.

Key words: GPS, Crustal deformation, Seismic activity, Earthquake precursor

Citation: Shin, T. C., K. W. Kuo, P. L. Leu, C. H. Tsai, and J. S. Jiang, 2011: Continuous CWB GPS array in Taiwan and applications to monitoring seismic activity. Terr. Atmos. Ocean. Sci., 22, 521-533, doi: 10.3319/TAO.2011.05.18.01(T)

1.INTRODUCTION

The Central Weather Bureau (CWB) initiated its permanent Global Positioning System (GPS) network in 1993 to investigate the relationships between seismic activity and crustal deformation in Taiwan. Utilizing satellite positioning techniques, each station can provide precise global coordinates for its antenna position which can be used to monitor the horizontal and vertical crustal movement at the site (Altamimi et al. 2002). This approach provides important information about crustal deformation caused by plate motion in the region. Using these data allows further studies to be carried out on related questions about seismic activity, stress accumulation or release, and mechanisms of earthquake formation (Dixon 1991; Segall and Davis 1997).

2. CONTINUOUS CWB GPS ARRAY IN TAIWAN

After the 1999 Chi-Chi earthquake, CWB enhanced data collection in its network to scrupulously monitor crustal deformation in Taiwan. The total number of the GPS stations was increased to 150 between 2001 and 2006. Presently, the CWB GPS array consists of about 150 stations (Table 1 and Fig. 1), with dense spatial coverage in Taiwan, and operates continuously.

GPS observations have provided important information about tectonic deformation (Seno et al. 1993; Yu et al. 1997, 1999, 2001; Hu et al. 2001; Rau et al. 2008). The continuous CWB GPS array is used to monitor site displacement, site velocity, and crustal deformation and can be used to study earthquake precursors in Taiwan. In order to analyze earthquake precursors and improve efforts to predict future crustal activity and strong earthquakes, just as in the case of weather forecasting, GPS observations must be mathematically connected with the physical processes of earthquake generation. Crustal deformation data are important for this purpose. Previous research has shown that dislocation theory works well for describing co-seismic, post-seismic and inter-seismic deformation (Wdowinski et al. 1997; Yu et al. 2001, 2003; Hu et al. 2007; Cheng et al. 2009; Hsu et al. 2009b). The dense continuous GPS array provides daily GPS site coordinates, and the spatial coverage in Taiwan is now satisfactory.

* *Corresponding author*
E-mail: jim@scman.cwb.gov.tw

Table 1. Site locations for the CWB continuous GPS array in Taiwan.

Stations	Longitude (deg)	Latitude (deg)	Antenna type	Receiver type	Starting date
AKND	120.3572607	22.8033134	TRM 41249.00	Trimble 5700	2005 311
ALIS	120.8132958	23.5081718	TRM 41249.00	Trimble 5700	2006 061
ANKN	121.5247287	24.9591011	TRM 41249.00	Trimble 5700	2005 311
BALN	121.4261202	24.6994866	TRM 41249.00	Trimble 5700	2006 360
BANC	121.4421054	24.9976575	TRM 41249.00	Trimble NetRS	2006 267
BANP	120.3054070	22.6931355	TRM 41249.00	Trimble 5700	2007 093
BLOW	121.5712484	24.1717565	TRM 41249.00	Trimble 5700	2005 311
CHEN	121.3735835	23.0974047	TRM 41249.00	Trimble NetRS	2006 296
CHIA	120.4332019	23.4959793	TRM 41249.00	Trimble NetRS	2006 292
CHIH	121.2059846	23.1158414	TRM 41249.00	Trimble 5700	2005 196
CHIN	120.5821503	24.2710204	LEIAT504 SCIT	Leica RS500	2001 318
CHIU	120.8289093	23.9453861	TRM 41249.00	Trimble 5700	2008 140
CHNT	121.6618972	24.1492109	TRM 41249.00	Trimble 5700	2003 001
CHUA	120.5573023	24.0660529	LEIAT504 SCIT	Leica RS500	2001 318
CHUL	121.1256878	23.1323685	TRM 41249.00	Trimble 5700	2005 355
CHUN	121.3931036	23.4528551	TRM 41249.00	Trimble 5700	2006 019
CLAN	121.5120060	24.6022513	TRM 41249.00	Trimble 5700	2005 005
CLON	120.5796053	22.4300519	TRM 41249.00	Trimble 5700	2006 116
CTOU	120.2778453	22.7546898	TRM 41249.00	Trimble 5700	2004 069
DAHU	120.8718357	24.4228817	TRM 41249.00	Trimble 5700	2004 334
DAJN	120.8649784	22.3113048	TRM 41249.00	Trimble 5700	2004 156
DANL	120.7519109	22.2041398	TRM 41249.00	Trimble 5700	2010 088
DASI	120.9444151	22.4784281	TRM 41249.00	Trimble 5700	2005 160
DCHU	121.2805748	23.2131806	TRM 41249.00	Trimble 5700	2005 311
DNAN	120.4479916	23.6738074	TRM 41249.00	Trimble 5700	2004 347
DNFU	121.4822889	23.6851291	TRM 41249.00	Trimble 5700	2007 005
DPIN	120.9328048	24.0430813	TRM 41249.00	Trimble 5700	2003 157
DSIN	121.3980350	23.6312177	TRM 41249.00	Trimble 5700	2006 121
DULI	121.3305994	23.0256676	TRM 41249.00	Trimble 5700	2004 337
ERLN	120.4195559	23.7975935	LEIAT504 SCIT	Leica RS500	2001 317
FENP	121.5194230	23.5984498	TRM 41249.00	Trimble 5700	2006 061
FIVE	121.7810771	25.0710532	TRM 41249.00	Trimble NetRS	2006 269
FKDO	120.8562789	23.6835597	TRM 41249.00	Trimble 5700	2005 322
FLON	121.9374829	25.0203745	TRM 41249.00	Trimble 5700	2004 106
FUNY	120.3201699	23.9223196	TRM 41249.00	Trimble 5700	2005 143
FUSN	121.3314661	24.7990453	TRM 41249.00	Trimble 5700	2003 116
GAIS	120.5906224	23.0802936	TRM 41249.00	Trimble NetRS	2006 303
GUKN	120.5887808	23.6458652	TRM 41249.00	Trimble 5700	2003 001
GUKW	121.0065506	24.2022011	TRM 41249.00	Trimble 5700	2005 322
HANS	121.6871412	24.6095142	TRM 41249.00	Trimble 5700	2004 058
HENC	120.7464525	22.0039359	TRM 41249.00	Trimble NetRS	2006 296
HERI	121.5809192	25.2944433	TRM 41249.00	Trimble 5700	2004 152
HLIU	120.9941719	23.7930312	TRM 41249.00	Trimble 5700	2003 100
HNSN	121.3080666	24.3377038	LEIAT504 SCIT	Leica RS500	2001 326
HOPN	120.8948811	24.1707809	LEIAT504 SCIT	Leica RS500	2001 319
HRGN	121.4051075	23.5552869	TRM 41249.00	Trimble 5700	2006 229

Table 1. (Continued)

Stations	Longitude (deg)	Latitude (deg)	Antenna type	Receiver type	Starting date
HSIN	121.0142576	24.8277543	TRM 41249.00	Trimble NetRS	2006 293
HSUE	121.0264544	24.2805971	TRM 41249.00	Trimble 5700	2003 125
HUAL	121.6135174	23.9753858	TRM 41249.00	Trimble NetRS	2006 291
HUAN	121.2726259	24.1434786	LEIAT504 SCIT	Leica RS500	2001 326
HUAP	121.7494479	24.3090014	TRM 41249.00	Trimble 5700	2004 145
HUWE	120.2866275	23.7294034	TRM 41249.00	Trimble 5700	2005 097
HUYS	121.0294100	24.0923325	TRM 41249.00	Trimble 5700	2006 081
ICHU	120.2793092	23.3606612	TRM 41249.00	Trimble 5700	2004 001
ILAN	121.7566207	24.7640449	TRM 41249.00	Trimble NetRS	2006 292
JLUT	120.6227875	22.3299626	TRM 41249.00	Trimble 5700	2004 156
JSUI	121.4238909	23.4919816	TRM 41249.00	Trimble 5700	2003 133
JYAN	121.2263472	24.2424728	TRM 41249.00	Trimble 5700	2004 142
KASU	120.6329822	22.8101928	TRM 41249.00	Trimble 5700	2005 239
KSHI	121.1760383	24.7766684	LEIAT504 SCIT	Leica RS500	2001 310
KUAN	121.1642538	23.0496855	TRM 41249.00	Trimble 5700	2006 094
KYIN	121.0804212	25.0410513	TRM 41249.00	Trimble 5700	2004 142
LANY	121.5581069	22.0373097	TRM 41249.00	Trimble NetRS	2006 292
LAOL	120.6872978	22.4119215	TRM 41249.00	Trimble 5700	2007 009
LGUE	120.6353833	22.9929058	TRM 41249.00	Trimble 5700	2005 319
LIKN	120.5279090	22.7586127	TRM 41249.00	Trimble 5700	2004 058
LIUC	120.3690760	22.3466818	TRM 41249.00	Trimble NetRS	2006 296
LIYU	120.7818075	24.3430626	LEIAT504 SCIT	Leica RS500	2001 330
LNKO	121.3781813	25.0763739	TRM 41249.00	Trimble 5700	2005 311
LONT	121.1305623	22.9063190	TRM 41249.00	Trimble 5700	2003 001
LTUN	121.7716273	24.7000306	TRM 41249.00	Trimble 5700	2004 049
LUKN	120.4351326	24.0600112	LEIAT504 SCIT	Leica RS500	2001 317
LUSN	121.1860541	24.0351935	TRM 41249.00	Trimble 5700	2006 355
MATZ	119.9230685	26.1693978	TRM 41249.00	Trimble 5700	2005 311
MFEN	121.1724785	24.0821631	TRM 41249.00	Trimble 5700	2005 292
MIAO	120.8102681	24.5834546	TRM 41249.00	Trimble 5700	2003 146
MITO	120.2631593	22.7958603	TRM 41249.00	Trimble 5700	2004 153
MLO1	120.5538208	22.8999567	TRM 41249.00	Trimble 5700	2007 008
NAAO	121.8102123	24.4493496	TRM 41249.00	Trimble 5700	2004 097
NANK	120.2743958	23.1019937	TRM 41249.00	Trimble 5700	2003 106
NCKU	120.2758121	22.9384544	TRM 41249.00	Trimble NetRS	2006 298
NDHU	121.5508182	23.8972435	TRM 41249.00	Trimble 5700	2005 089
NEMN	120.4200821	22.9081248	TRM 41249.00	Trimble 5700	2006 249
NHSI	121.4530156	23.4062140	TRM 41249.00	Trimble 5700	2005 242
NIUT	121.5615823	24.6347818	TRM 41249.00	Trimble 5700	2004 191
NJOU	120.5714119	22.5038990	TRM 41249.00	Trimble 5700	2004 058
NSAN	121.3828065	24.4282024	TRM 41249.00	Trimble 5700	2006 339
NSHE	120.8009077	24.2257967	LEIAT504 SCIT	Leica RS500	2001 319
PAKU	120.6360389	23.9156843	TRM 41249.00	Trimble 5700	2008 001
PANG	119.5637405	23.5652071	TRM 41249.00	Trimble NetRS	2006 292
PAOS	120.9502799	24.7149268	TRM 41249.00	Trimble 5700	2003 002
PEI1	120.1685928	23.2938366	TRM 41249.00	Trimble 5700	2005 311

Table 1. (Continued)

Stations	Longitude (deg)	Latitude (deg)	Antenna type	Receiver type	Starting date
PEIN	121.1231336	22.8010763	TRM 41249.00	Trimble 5700	2005 238
PENL	120.9760414	24.5388419	TRM 41249.00	Trimble 5700	2004 245
PEPU	121.6103418	24.0178851	LEIAT504 SCIT	Leica RS500	2001 304
PLAN	121.0866044	24.5789550	LEIAT504 SCIT	Leica RS500a	2001 348
PLIN	121.7139515	24.9336272	TRM 41249.00	Trimble 5700	2004 035
PNCY	122.0794375	25.6275002	TPSCR.G3 TPSH	TOPCON	2009 001
PTUN	120.4596878	22.6498538	TRM 41249.00	Trimble 5700	2004 058
PUSN	120.5201134	23.9649432	TRM 41249.00	Trimble 5700	2003 001
RENI	120.5085707	23.4589440	TRM 41249.00	Trimble 5700	2006 268
SALU	120.5783066	24.1444539	TRM 41249.00	Trimble 5700	2006 079
SAND	120.6406475	22.7172711	TRM 41249.00	Trimble 5700	2005 320
SANI	120.7687291	24.4143578	TRM 41249.00	Trimble NetRS	2006 293
SANJ	121.5008733	25.2607988	TRM 41249.00	Trimble 5700	2005 195
SANL	120.7685580	23.6644839	TRM 41249.00	Trimble 5700	2006 338
SFON	121.0101618	24.9328990	LEIAT504 SCIT	Leica RS500	2001 332
SGAN	120.3496594	22.5812753	TRM 41249.00	Trimble 5700	2006 139
SGUN	120.6918845	24.2716346	TRM 41249.00	Trimble 5700	2006 113
SHUL	121.5627361	23.7876178	TRM 41249.00	Trimble 5700	2005 185
SHWA	120.3478113	23.0214341	TRM 41249.00	Trimble 5700	2005 357
SINL	121.2546300	22.9082908	TRM 41249.00	Trimble 5700	2005 159
SLIN	121.4414068	23.8118585	LEIAT504 SCIT	Leica RS500	2001 305
SLNP	121.6356352	24.7531200	TRM 41249.00	Trimble 5700	2004 057
SONA	120.9858475	24.3978178	LEIAT504 SCIT	Leica RS500	2001 311
SPAO	121.4848682	24.2050170	TRM 41249.00	Trimble 5700	2004 098
SSUN	120.3777769	23.4141530	TRM 41249.00	Trimble 5700	2005 325
STA1	120.9792566	24.6356036	TRM 41249.00	Trimble 5700	2008 024
SUAN	120.2998831	23.4775789	TRM 41249.00	Trimble 5700	2003 001
SUAO	121.8670734	24.5923974	TRM 41249.00	Trimble NetRS	2006 272
SUCH	120.9075844	24.2910739	TRM 41249.00	Trimble 5700	2005 322
SUN1	120.9083521	23.8812423	TRM 41249.00	Trimble NetRS	2006 290
SYAN	120.9867543	23.2480069	TRM 41249.00	Trimble 5700	2009 001
TAIP	121.6731717	25.0345264	TRM 41249.00	Trimble 5700	2004 133
TANS	121.4268949	25.1815043	TRM 41249.00	Trimble 5700	2005 102
TATA	120.8870513	23.4814032	TRM 41249.00	Trimble 5700	2004 002
TEGS	120.6549887	24.3562107	TRM 41249.00	Trimble 5700	2003 001
THAI	121.2955986	24.6071217	TRM 41249.00	Trimble 5700	2009 163
TMAL	120.9598750	22.6489236	TRM 41249.00	Trimble 5700	2007 005
TOFN	120.9248050	24.6620435	TRM 41249.00	Trimble 5700	2004 335
TSHI	121.6327637	25.2569143	TRM 41249.00	Trimble 5700	2004 139
TSIO	120.7041036	24.4727972	TRM 41249.00	Trimble 5700	2006 073
TSLN	120.7193882	23.6343285	TRM 41249.00	Trimble 5700	2007 115
TTUN	121.0807088	22.7645525	TRM 41249.00	Trimble 5700	2003 007
TUCN	121.4961328	24.5748421	TRM 41249.00	Trimble 5700	2004 069
TUNM	121.4935822	23.9652105	LEIAT504 SCIT	Leica RS500	2001 305
TUNS	120.4040473	23.3172429	TRM 41249.00	Trimble 5700	2003 001
WANC	120.5263385	23.1868434	TRM 41249.00	Trimble 5700	2004 128

Table 1. (Continued)

Stations	Longitude (deg)	Latitude (deg)	Antenna type	Receiver type	Starting date
WANL	121.6375620	25.1693882	TRM 41249.00	Trimble 5700	2004 139
WANS	120.8851949	23.6075069	TRM 41249.00	Trimble 5700	2005 126
WDAN	120.5043185	22.6060642	TRM 41249.00	Trimble 5700	2005 272
WFEN	120.6994726	24.0419480	TRM 41249.00	Trimble 5700	2006 129
WIPN	121.0585550	24.6746368	TRM 41249.00	Trimble 5700	2004 344
WUKU	121.4006646	25.1172808	TRM 41249.00	Trimble 5700	2004 106
WUST	120.3681700	23.2052417	TRM 41249.00	Trimble 5700	2003 047
YAME	121.1852987	24.9084554	TRM 41249.00	Trimble 5700	2004 036
YENL	121.6018494	23.9035041	TRM 41249.00	Trimble 5700	2003 001
YNTS	121.7789336	24.8617439	TRM 41249.00	Trimble 5700	2004 070
YSAN	120.0859831	23.1465514	TRM 41249.00	Trimble 5700	2004 330
YUL1	121.3011356	23.3409313	LEIAT504 SCIT	Leica RS500	2010 354
YUSN	120.9591475	23.4873021	TRM 41249.00	Trimble NetRS	2006 288
ZEND	120.2175679	22.9432766	TRM 41249.00	Trimble 5700	2005 311
ZWEN	120.4973496	23.2197402	TRM 41249.00	Trimble 5700	2006 174

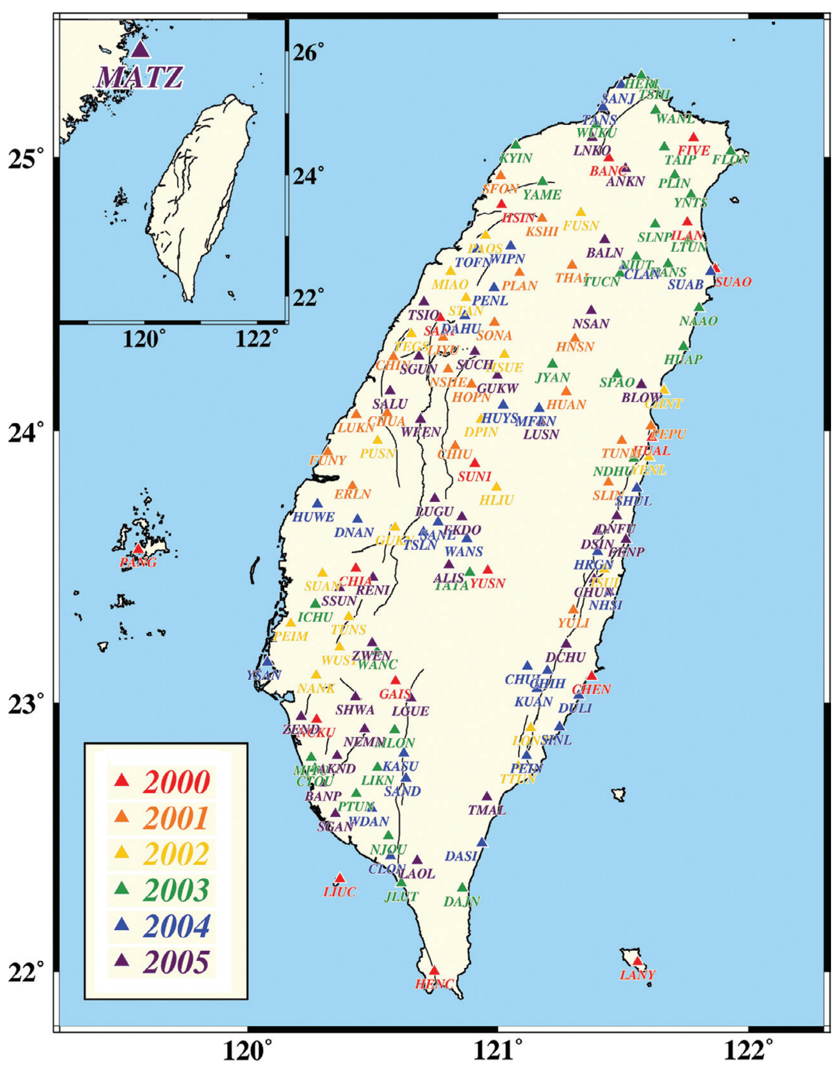

Fig. 1. Site location in the CWB GPS Network.

3. ROUTINE GPS DATA PROCESSING AND ANALYSIS

All GPS stations in the CWB GPS network are equipped with dual-frequency geodetic receivers. The receiver instruments and antenna types include: (1) Leica RS500 and LEIAT504 SCIT (20 stations), (2) TRIMBLE 5700 and TRM41249.00 (113 stations), (3) TRIMBLE NETRS and TRM41249.00 (17 stations). The sampling interval for data collection is either 30 or 1 sec. Raw data from each station are converted to Receiver Independent Exchange Format (RINEX) and the continuous GPS data are processed independently using both Gamit/Globk and Bernese software to obtain the precise coordinates (Hugentobler et al. 2001; Herring et al. 2008).

GPS phase data acquired at continuous stations are transferred to the central control system at the CWB main office. All the station coordinates are used to obtain the final solution using the IGS (International GNSS Service) precise orbit after a few weeks. Data screening, editing and double differencing of phase observations between sites are performed in order to estimate their relative positions. Regional and global adjustment for daily solutions can improve the accuracy, and an example of the site position time series is plotted in Fig. 2. For some special cases, such as the occurrence of a strong earthquake, data are processed at intervals of 30 or 1 sec. and the baseline components are calculated using broadcast orbits in a quasi-real time manner to monitor crustal activity. This approach can quickly provide rough information about co-seismic displacement. The database system stores daily coordinate solutions, their covariance matrices, and raw phase data for further analyses. Time series plots of station coordinates and velocity vector plots can be used for routine monitoring of crustal deformation.

GPS time series data are analyzed using the following formula (Nikolaidis 2002):

$$\begin{aligned} y(t_i) &= a + bt_i + c\sin(2\pi t_i) + d\cos(2\pi t_i) + e\sin(4\pi t_i) \\ &+ f\cos(4\pi t_i) + \sum_{j=1}^{n_g} g_j H(t_i - T_{gj}) + \sum_{j=1}^{n_h} h_j H(t_i - T_{hj}) t_i \\ &+ \sum_{j=1}^{n_k} k_j \exp[-(t_i - T_{kj})/\tau_j] H(t_i - T_{kj}) + v_i \end{aligned} \quad (1)$$

where

- a, b represent the intercept and slope of linear trend of inter-seismic crustal movement,
- c, d, e, f are coefficients for annual and semi-annual periodic deformation,
- g_j is the co-seismic displacement of jth earthquake,
- h_j is the change of trend after the jth earthquake,
- k_j, τ_j are the constant and relaxation time for post-seismic deformation of jth earthquake,
- $H(\tau)$ is a step function where $H(\tau < 0) = 0$ and $H(\tau \geq 0) = 1$, and v_i is the random error term.

In Fig. 2, the blue circle indicates the daily coordinate variation and the magenta line shows the regression curve for the above formula. Furthermore, the average inter-seis-

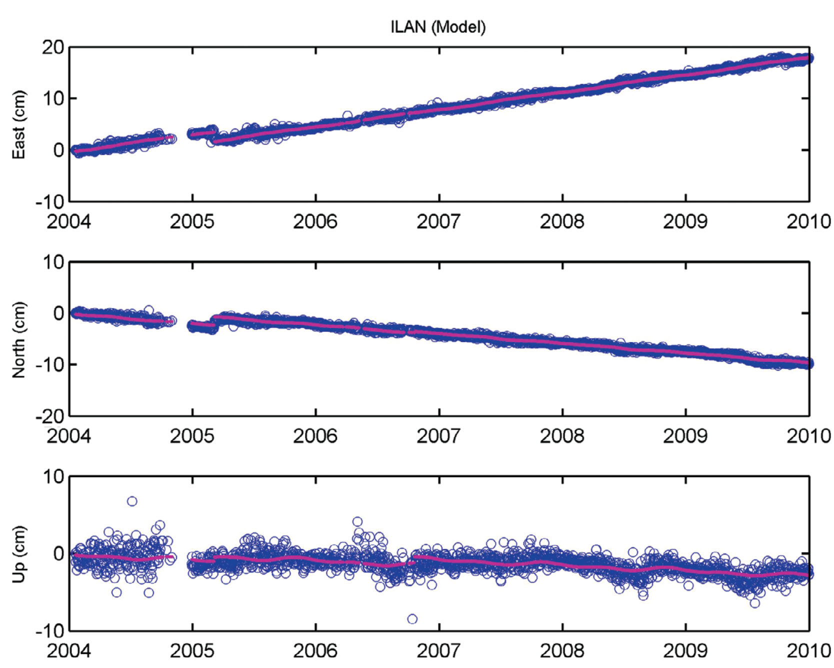

Fig. 2. Time series showing the coordinate component variation of ILAN GPS station from 2004 to 2009. The magenta curves are the best-fitting lines of each component using the Nikolaidis (2002) regression model.

mic site velocity can be estimated from the time series of each station as shown in Fig. 3 and Table 2 (for horizontal velocity). The horizontal strain field can be derived from horizontal site velocities and is also plotted in Fig. 3. The coseismic site slip for the 26 December 2006 strong earthquake in Taiwan is shown in Fig. 4.

GPS data in Taiwan have demonstrated related information and time series of coordinate variation for each site

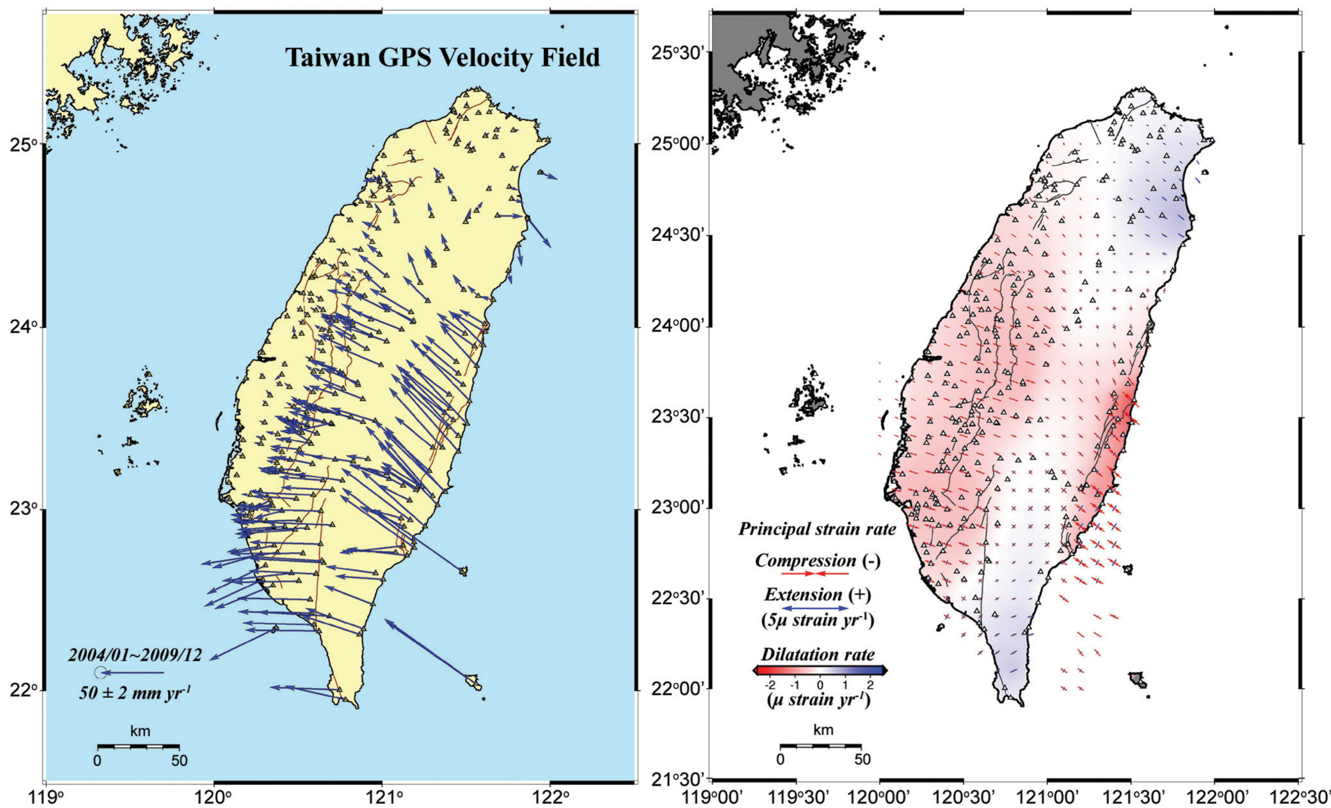

Fig. 3. GPS site deformation map: horizontal velocity field (2004 ~ 2009, left) and crustal strain rate (right). The magnitude and direction of principal strain rates are shown by arrows. Color scale shows magnitudes of dilatation rates. Red color denotes contraction and blue color represents extension.

Table 2. Velocity field for CWB GPS stations with respect to Penghu station.

Stations	Longitude (deg)	Latitude (deg)	V_E (cm yr^{-1})	V_N (cm yr^{-1})	V_U (cm yr^{-1})
AKND	120.357261	22.803313	-3.51	-0.67	0.16
ALIS	120.813296	23.508172	-2.90	0.66	0.21
ANKN	121.524729	24.959101	0.15	0.31	0.01
BALN	121.426120	24.699487	-0.47	1.00	-0.07
BANC	121.442105	24.997658	0.03	0.33	0.22
BANP	120.305407	22.693135	-4.66	-2.28	0.21
BLOW	121.571248	24.171756	-0.87	0.81	0.85
CHEN	121.373583	23.097405	-4.73	5.14	0.76
CHIA	120.433202	23.495979	-0.98	0.28	0.10
CHIH	121.205985	23.115841	-2.83	1.76	-0.57
CHIN	120.582150	24.271020	-0.16	-0.03	0.10
CHIU	120.828909	23.945386	-2.32	1.37	0.42
CHNT	121.661897	24.149211	-1.06	0.27	-0.36
CHUA	120.557302	24.066053	-0.28	0.32	0.12
CHUL	121.125688	23.132369	-2.81	1.39	0.20

Table 2. (Continued)

Stations	Longitude (deg)	Latitude (deg)	V_E (cm yr^{-1})	V_N (cm yr^{-1})	V_U (cm yr^{-1})
CHUN	121.393104	23.452855	-4.52	4.20	-0.69
CLAN	121.512006	24.602251	0.22	0.69	0.55
CLON	120.579605	22.430052	-5.82	0.10	-0.87
CTOU	120.277845	22.754690	-3.87	-1.10	0.25
DAHU	120.871836	24.422882	-0.66	0.08	-0.14
DAJN	120.864978	22.311305	-4.65	1.51	-0.09
DASI	120.944415	22.478428	-3.86	1.48	-0.03
DCHU	121.280575	23.213181	-4.43	4.04	0.85
DNAN	120.447992	23.673807	-0.41	0.32	-1.10
DNFU	121.482289	23.685129	-3.59	2.87	-0.54
DPIN	120.932805	24.043081	-2.34	1.24	0.60
DSIN	121.398035	23.631218	-2.95	2.26	-0.74
DULI	121.330599	23.025668	-4.74	5.00	1.02
ERLN	120.419556	23.797593	-0.22	0.14	-1.10
FENP	121.519423	23.598450	-4.67	4.83	-1.10
FIVE	121.781077	25.071053	0.43	0.02	0.15
FKDO	120.856279	23.683560	-2.45	1.58	-0.10
FLON	121.937483	25.020374	0.36	0.02	-0.07
FUNY	120.320170	23.922320	0.01	-0.13	-3.43
FUSN	121.331466	24.799045	-0.11	0.67	0.21
GAIS	120.590622	23.080294	-4.88	0.23	0.53
GUKN	120.588781	23.645865	-0.78	0.49	-0.22
GUKW	121.006551	24.202201	-1.58	1.33	0.79
HANS	121.687141	24.609514	1.99	-0.05	0.08
HCHM	120.984613	24.792527	-0.21	0.40	0.16
HENC	120.746452	22.003936	-5.53	0.20	-0.61
HERI	121.580919	25.294443	0.09	0.19	0.14
HLIU	120.994172	23.793031	-3.71	1.54	0.85
HNSN	121.308067	24.337704	-0.78	1.29	1.18
HOPN	120.894881	24.170781	-1.84	0.69	-0.01
HRGN	121.405107	23.555287	-3.95	3.18	-0.65
HSIN	121.014258	24.827754	-0.24	0.36	0.03
HSUE	121.026454	24.280597	-2.22	1.70	-0.92
HUAL	121.613517	23.975386	-2.62	1.53	-0.78
HUAN	121.272626	24.143479	-1.98	1.96	0.56
HUAP	121.749448	24.309001	0.29	-1.08	-0.41
HUWE	120.286627	23.729403	-0.17	0.26	-2.99
HUYS	121.029410	24.092333	-2.68	1.30	0.87
ICHU	120.279309	23.360661	-0.55	0.10	-0.50
ILAN	121.756621	24.764045	0.68	-0.25	-0.52
JLUT	120.622788	22.329963	-5.84	0.07	-0.31
JSUI	121.423891	23.491982	-4.54	4.40	0.17
JYAN	121.226347	24.242473	-0.99	2.40	0.47
KASU	120.632982	22.810193	-5.59	0.15	0.55
KSHI	121.176038	24.776668	-0.19	0.57	0.10
KUAN	121.164254	23.049686	-2.54	1.27	0.21

Table 2. (Continued)

Stations	Longitude (deg)	Latitude (deg)	V_E (cm yr^{-1})	V_N (cm yr^{-1})	V_U (cm yr^{-1})
KYIN	121.080421	25.041051	-0.18	0.27	0.26
LANY	121.558107	22.037310	-7.27	5.17	-0.10
LAOL	120.687298	22.411922	-5.69	0.32	0.54
LGUE	120.635383	22.992906	-4.81	0.13	0.89
LIKN	120.527909	22.758613	-5.74	-0.04	-0.10
LIUC	120.369076	22.346682	-5.33	-2.57	0.23
LIYU	120.781808	24.343063	-0.55	0.20	0.38
LNDO	121.918075	25.097378	0.34	0.22	-0.10
LONT	121.130562	22.906319	-3.49	1.61	0.88
LTUN	121.771627	24.700031	0.93	-0.34	-0.36
LUKN	120.435133	24.060011	-0.26	0.06	-0.28
LUSN	121.186054	24.035193	-2.56	1.30	0.27
MATZ	119.923068	26.169398	-0.22	-0.01	-0.02
MFEN	121.172479	24.082163	-3.27	1.90	0.93
MIAO	120.810268	24.583455	-0.31	0.26	-0.31
MITO	120.263159	22.795860	-2.50	-0.44	-0.15
MLO1	120.553821	22.899957	-5.18	-0.25	0.04
NAAO	121.810212	24.449350	0.26	-1.66	-0.66
NANK	120.274396	23.101994	-0.84	0.01	0.36
NCKU	120.275812	22.938454	-2.05	-0.06	-0.02
NDHU	121.550818	23.897244	-2.81	1.97	-0.86
NEMN	120.420082	22.908125	-3.75	-0.26	0.92
NHSI	121.453016	23.406214	-4.54	4.86	-0.13
NIUT	121.561582	24.634782	0.47	0.72	0.18
NJOU	120.571412	22.503899	-5.80	0.12	-0.87
NSAN	121.382806	24.428202	-0.41	1.20	0.99
NSHE	120.800908	24.225797	-1.29	0.60	0.33
PAKU	120.636039	23.915684	-0.50	0.29	0.02
PANG	119.563741	23.565207	0.00	0.00	0.00
PAOL	120.702872	23.108625	-4.07	0.21	1.48
PAOS	120.950280	24.714927	-0.27	0.55	0.13
PEI1	120.168593	23.293837	-0.32	0.10	-1.66
PEIN	121.123134	22.801076	-5.02	-0.57	-0.43
PENL	120.976041	24.538842	-1.27	0.54	-0.48
PEPU	121.610342	24.017885	-1.98	1.15	0.06
PLAN	121.086604	24.578955	-0.27	1.04	0.30
PLIN	121.713952	24.933627	0.14	0.25	0.03
PTUN	120.459688	22.649854	-5.49	-0.61	1.12
PUSN	120.520113	23.964943	-0.23	0.10	-1.05
RENI	120.508571	23.458944	-1.31	0.29	0.22
SALU	120.578307	24.144454	-0.31	0.21	-0.10
SAND	120.640648	22.717271	-5.87	0.35	0.17
SANI	120.768729	24.414358	-0.54	0.19	-0.80
SANJ	121.500873	25.260799	-0.04	0.16	0.02
SANL	120.768558	23.664484	-2.60	1.17	0.54
SFON	121.010162	24.932899	-0.13	0.26	-0.10

Table 2. (Continued)

Stations	Longitude (deg)	Latitude (deg)	V_E (cm yr^{-1})	V_N (cm yr^{-1})	V_U (cm yr^{-1})
SGAN	120.349659	22.581275	-4.62	-1.86	-0.14
SGUN	120.691884	24.271635	-0.45	0.27	-0.17
SHUL	121.562736	23.787618	-2.88	3.25	-1.38
SHWA	120.347811	23.021434	-1.96	-0.30	0.38
SINL	121.254630	22.908291	-5.05	4.45	0.90
SLIN	121.441407	23.811858	-2.43	2.05	0.13
SLNP	121.635635	24.753120	0.21	0.24	-0.05
SONA	120.985848	24.397818	-1.01	0.78	0.29
SPAO	121.484868	24.205017	-0.85	1.22	0.98
SSUN	120.377777	23.414153	-0.94	0.20	-0.03
STA1	120.979257	24.635604	-0.32	0.55	0.35
SUAN	120.299883	23.477579	-0.42	0.15	0.02
SUAO	121.867073	24.592397	1.85	-2.31	-0.18
SUCH	120.907584	24.291074	-0.89	0.42	1.00
SUN1	120.908352	23.881242	-2.50	1.43	0.58
TAIP	121.673172	25.034526	0.26	0.19	-0.05
TANS	121.426895	25.181504	-0.33	0.24	-0.38
TATA	120.887051	23.481403	-5.22	1.80	-0.16
TEGS	120.654989	24.356211	-0.29	0.18	-0.20
THAI	121.295599	24.607122	-0.30	1.03	0.57
TMAL	120.959875	22.648924	-3.93	0.54	0.16
TOFN	120.924805	24.662044	-0.35	0.47	0.17
TSHI	121.632764	25.256914	0.11	0.20	0.20
TSIO	120.704104	24.472797	-0.26	0.23	0.19
TSLN	120.719388	23.634329	-2.05	0.66	0.87
TTUN	121.080709	22.764552	-4.19	0.15	-0.50
TUCN	121.496133	24.574842	0.43	0.86	0.80
TUNH	121.300222	23.075160	-3.81	4.43	1.83
TUNM	121.493582	23.965211	-2.21	1.60	0.36
TUNS	120.404047	23.317243	-0.88	0.24	-0.09
WANC	120.526338	23.186843	-2.92	0.42	0.29
WANL	121.637562	25.169388	0.26	0.23	-0.02
WANS	120.885195	23.607507	-3.14	1.19	0.90
WDAN	120.504319	22.606064	-5.27	-0.10	-0.14
WFEN	120.699473	24.041948	-0.84	0.35	-0.18
WIPN	121.058555	24.674637	-0.28	0.69	-0.10
WUKU	121.400665	25.117281	0.00	0.36	-0.15
WUST	120.368170	23.205242	-1.24	0.11	0.30
YAME	121.185299	24.908455	-0.14	0.49	0.22
YENL	121.601849	23.903504	-2.75	2.74	-1.08
YNTS	121.778934	24.861744	0.45	0.24	0.21
YSAN	120.085983	23.146551	-0.14	-0.10	-0.38
YULI	121.301136	23.340931	-3.00	2.46	-1.11
YUSN	120.959147	23.487302	-3.56	1.05	0.49
ZEND	120.217568	22.943277	-1.56	0.02	0.38
ZWEN	120.497350	23.219740	-2.45	0.10	1.01

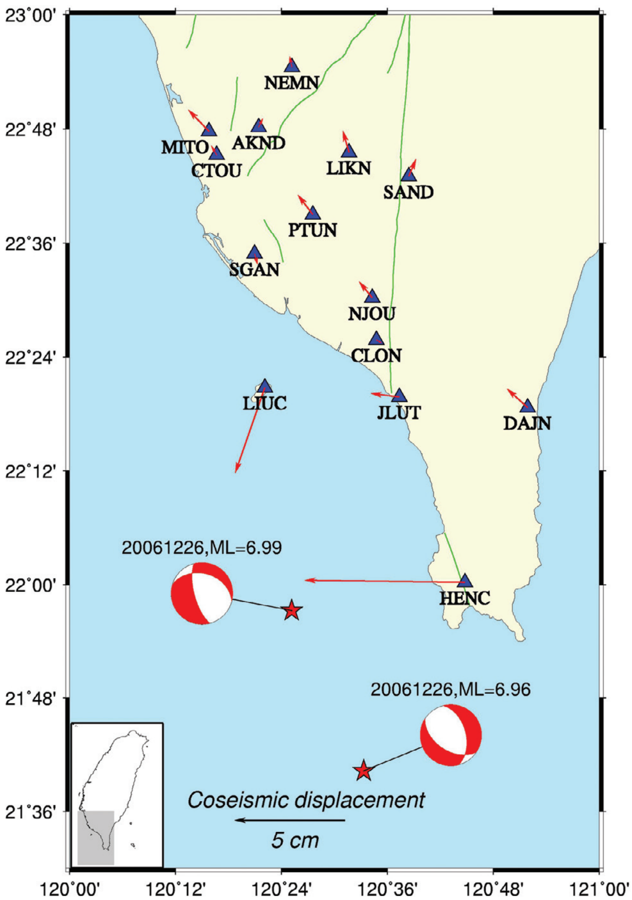

Fig. 4. The coseismic displacement of GPS stations associated with the 26 December 2006 earthquake in southern Taiwan.

in the network. Maps of the site velocity field and horizontal strain field in Taiwan derived from time series data are useful for future analysis. The general public can also learn about crustal deformation and plate motion in Taiwan. GPS-derived velocity/strain field reveal several features of tectonic deformation, which consistently indicate the northwestward movement in the direction of plate convergence (Yu and Chen 1994; Yu et al. 1997; Yu and Kuo 2001; Lin et al. 2006; Hsu et al. 2009a).

4. EARTHQUAKE PRECURSOR ANALYSIS

Taiwan is located at the active plate boundary between the Eurasia Plate and Philippine Sea Plate. The continuous collision results in active seismicity and large earthquakes (Tsai 1986; Wang and Shin 1998). Because earthquakes occur frequently in Taiwan, research on earthquake prediction is vital. Earthquake prediction presents serious challenges, whether the effort is focused on the time of occurrence, epicenter location, magnitude, or intensity. Studies of seismic precursor are actively underway in Taiwan. Research on earthquake precursors is mainly focused on monitoring and analysis of pre-seismic anomalies, collecting data on precursor phenomenon before strong earthquakes occur. GPS data can show steady deformation processes in eastern Taiwan and the seismic deformations associated with some significant events (Yu et al. 2001; Hu et al. 2007; Cheng et al. 2009; Hsu et al. 2009b). The pre-seismic anomalies from GPS time series including the 19 December 2009 earthquake (M 6.9) in eastern Taiwan are shown in Fig. 5.

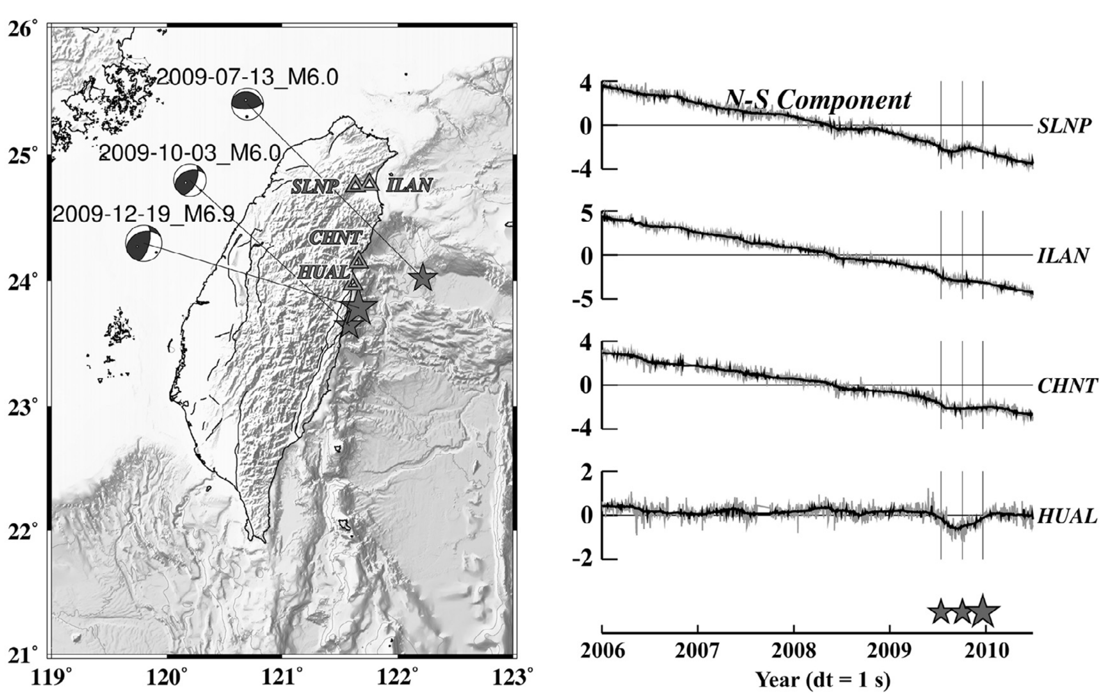

Fig. 5. GPS time series in eastern Taiwan show pre-seismic anomaly of 19 December 2009 strong earthquake (M = 6.9).

We hope to use the GPS time series analysis to identify changes in earthquake precursor signals from background signals. Although GPS data can provide insights on the ongoing deformation only, continuing these kinds of monitoring efforts will lead to much more precise deformation fields and more details on their temporal variations. The typical accuracy as root mean squares error for GPS site coordinates is a few mm in the horizontal and 10 - 20 mm in the vertical. Even though daily site coordinate solutions are not adequate for monitoring the crustal deformation at active plate boundaries, monthly mean solutions might be adequate. Seasonal variation signals still remain in the monthly time series, which presents some obstacles for geodetic or geophysical interpretations. However, daily or hourly analysis is required for monitoring precursory changes for large earthquakes. In this case, we will need to process much noisier data to detect small changes.

Acknowledgements Thanks to all who have communicated to relevant personnel involved in the development of the program, and that indeed help us a lot. The full discussions with Drs. S. B. Yu and C. C. Liu have been very helpful. We would like to thank the referees for their comments and suggestions that improve the presentation of this paper.

REFERENCES

Altamimi, Z., P. Sillard, and C. Boucher, 2002: ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications. *J. Geophys. Res.*, **107**, 2214, doi: 10.1029/2001JB000561. [Link]

Cheng, L. W., J. C. Lee, J. C. Hu, and H. Y. Chen, 2009: Coseismic and postseismic slip distribution of the 2003 Mw = 6.5 Chengkung earthquake in eastern Taiwan: Elastic modeling from inversion of GPS data. *Tectonophysics*, **466**, 335-343, doi: 10.1016/j.tecto.2007.11.021. [Link]

Dixon, T. H, 1991: An introduction to the Global Positioning System and some geological applications. *Rev. Geophys.*, **29**, 249-276, doi: 10.1029/91RG00152. [Link]

Herring, T. A., R. W. King, and S. C. McClusky, 2008: Introduction to GAMIT/GLOBK, report, Massachusetts Institute of Technology, Cambridge.

Hsu, Y. J., S. B. Yu, M. Simons, L. C. Kuo, and H. Y. Chen, 2009a: Interseismic crustal deformation in the Taiwan plate boundary zone revealed by GPS observations, seismicity, and earthquake focal mechanisms. *Tectonophysics*, **479**, 4-18, doi: 10.1016/j.tecto.2008.11.016. [Link]

Hsu, Y. J., S. B. Yu, and H. Y. Chen, 2009b: Coseismic and postseismic deformation associated with the 2003 Chengkung, Taiwan, earthquake. *Geophys. J. Int.*, **176**, 420-430, doi: 10.1111/j.1365-246X.2008.04009.x. [Link]

Hu, J. C., S. B. Yu, J. Angelier, and H. T. Chu, 2001: Active deformation of Taiwan from GPS measurements and numerical simulations. *J. Geophys. Res.*, **106**, 2265-2280, doi: 10.1029/2000JB900196. [Link]

Hu, J. C., L. W. Cheng, H. Y. Chen, Y. M. Wu, J. C. Lee, Y. G. Chen, K. C. Lin, R. J. Rau, H. Kuochen, H. H. Chen, S. B. Yu, and J. Angelier, 2007: Coseismic deformation revealed by inversion of strong motion and GPS data: The 2003 Chengkung earthquake in eastern Taiwan. *Geophys. J. Int.*, **169**, 667-674, doi: 10.1111/j.1365-246X.2007.03359.X. [Link]

Hugentobler, U., S. Schaer, and P. Fridez (Eds.), 2001: Bernese GPS Software, version 4.2, Astronomical Institute, University of Berne, Bern, Switzerland, 515 pp.

Lin, K. C., K. E. Ching, J. C. Hu, T. T. Yu, and R. J. Rau, 2006: Current crustal deformation and strain rate in Taiwan deduced from continuous GPS measurements. *Geophys. Res. Abstr.*, **8**, 07160.

Nikolaidis, R., 2002: Observation of geodetic and seismic deformation with Global Positioning System, Ph.D. Dissertation, University of California, San Diego, 249 pp.

Rau, R. J., K. E. Ching, J. C. Hu, and J. C. Lee, 2008: Crustal deformation and block kinematics in transition from collision to subduction: Global positioning system measurements in northern Taiwan, 1995-2005. *J. Geophys. Res.*, **113**, B09404, doi: 10.1029/2007JB005414. [Link]

Segall, P. and J. L. Davis, 1997: GPS applications for geodynamics and earthquake studies. *Annu. Rev. Earth Planet. Sci.*, **25**, 301-336, doi: 10.1146/annurev.earth.25.1.301. [Link]

Seno, T., S. Stein, and A. E. Gripp, 1993: A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geological data. *J. Geophys. Res.*, **98**, 17941-17948, doi: 10.1029/93JB00782. [Link]

Tsai, Y. B, 1986: Seismotectonics of Taiwan. *Tectonophysics*, **125**, 17-37, doi: 10.1016/0040-1951(86)90005-3. [Link]

Wang, C. Y. and T. C. Shin, 1998: Illustrating 100 years of Taiwan seismicity. *Terr. Atmos. Ocean. Sci.*, **9**, 589-614.

Wdowinski, S., Y. Bock, J. Zhang, P. Fang, and J. Genrich, 1997: Southern California permanent GPS geodetic array: Spatial filtering of daily positions for estimating coseismic and postseismic displacements induced by the 1992 Landers earthquake. *J. Geophys. Res.*, **102**, 18057-18070, doi: 10.1029/97JB01378. [Link]

Yu, S. B. and H. Y. Chen, 1994: Global Positioning System measurements of crustal deformation in the Taiwan arc-continent collision zone. *Terr. Atmos. Ocean. Sci.*, **5**, 477-498.

Yu, S. B. and L. C. Kuo, 2001: Present-day crustal motion along the Longitudinal Valley fault, eastern Taiwan. *Tectonophysics*, **333**, 199-217, doi: 10.1016/S0040-19

51(00)00275-4. [Link]

Yu, S. B., H. Y. Chen, and L. C. Kuo, 1997: Velocity field of GPS stations in the Taiwan area. *Tectonophysics*, **274**, 41-59, doi: 10.1016/S0040-1951(96)00297-1. [Link]

Yu, S. B., L. C. Kuo, R. S. Punongbayan, and E. G. Ramos, 1999: GPS observation of crustal deformation in the Taiwan-Luzon region. *Geophys. Res. Lett.*, **26**, 923-926, doi: 10.1029/1999GL900148. [Link]

Yu, S. B., L. C. Kuo, Y. J. Hsu, H. H. Su, C. C. Liu, C. S. Hou, J. F. Lee, T. C. Lai, C. C. Liu, C. L. Liu, T. F. Tseng, C. S. Tsai, and T. C. Shin, 2001: Preseismic deformation and coseismic displacements associated with the 1999 Chi-Chi, Taiwan, earthquake. *Bull. Seismol. Soc. Am.*, **91**, 995-1012, doi: 10.1785/0120000722. [Link]

Yu, S. B., Y. J. Hsu, L. C. Kuo, H. Y. Chen, and C. C. Liu, 2003: GPS measurement of postseismic deformation following the 1999 Chi-Chi, Taiwan, earthquake. *J. Geophys. Res.*, **108**, 2520, doi: 10.1029/2003JB002396. [Link]