ORIGINAL PAPER

Assessment of long-term variation in displacement for a GPS site adjacent to a transition zone between collision and subduction

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Abstract A transition and subduction zone adjacent to the Ryukyu Arc, Ryukyu Trench, and Okinawa Trough, extends between southern Japan and northeastern Taiwan. It is generated during the northwestward subduction of the Philippine Sea Plate, which lies the Eurasian Plate along the Ryukyu Trench. The movement of the Philippine Sea Plate is hindered at the northeastern corner of Taiwan, which causes complicated structure of the Philippine Sea Plate at the western end of the Ryukyu subduction zone. Development of the active subduction and transition boundary near the western Ryukyu Arc is evaluated statistically by using displacements derived from GPS site data. The statistical model shows that the absolute displacement derived from GPS measurements of nearly 8 years indicates a maximum spatial variation of 0.625 m. Three trends are observed for such long-term progress, and use of linear regression also reveals quite good consistency between the data and statistic models. Such rate is also elevated following the trend development. Southeastern and nearly horizontal movement is suggested to the main development of for the site movements, it is likely related to the tensional activity adjacent to this boundary.

Keywords GPS · Uncertainty · Statistics · Ryukyu Arc · Taiwan

1 Introduction

Taiwan lies about 150 km east the Fukien coast of the mainland China, separated from the latter by the Taiwan Strait (Fig. 1). Taiwan Province is comprised of 81 islands and islets. Geographically, Taiwan Province is represented by the main island with 13 islands and scattered islets. Taiwan is a member of the Ryukyu–Taiwan–Luzon arc chain rimming the western border of the Pacific Ocean (Fig. 2). The tectonic evolution of Taiwan can be attributed either to the development of classic geosynclinal cycles or to the interaction of crustal plates. In the geosynclinal model, Taiwan is formed by a typical mobile or organic Cenozoic geosynclinal deposition on a pre-Tertiary metamorphic basement filled with Tertiary sediments to a thickness of more than 10,000 m. In the plate tectonic model, the main island of Taiwan is situated on the junction between the continental Eurasian Plate on the west and the oceanic Philippine Sea Plate on the east. Taiwan can thus be divided into two major geologic or tectonic provinces, separated by a linear and narrow fault-bounded valley that marks the collision suture of the two converging plates (Ho 1982).

Knowledge of the major tectonic features and structural elements of this particular island chain is essential for interpretation of the plate tectonic evolution of Taiwan. The important structural elements in this region are the Asian continent, Ryukyu Arc, Luzon Arc, South China Sea,

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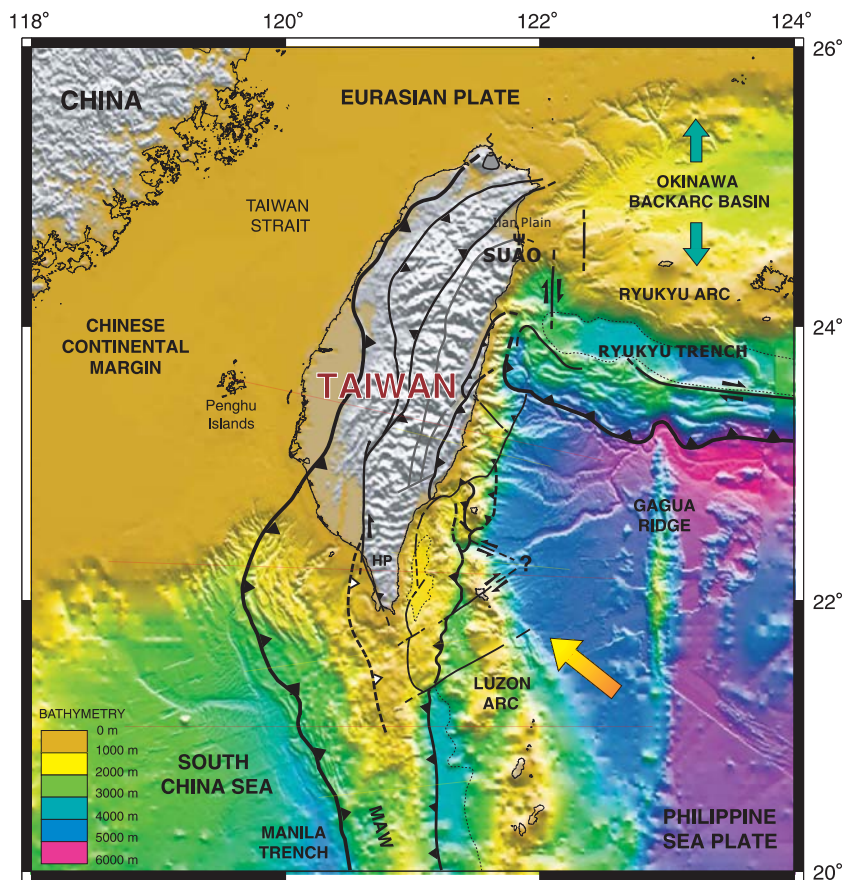C.-H. Chang
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**Fig. 1** Map showing studied GPS site and schematic tectonic boundaries (Google 2006)
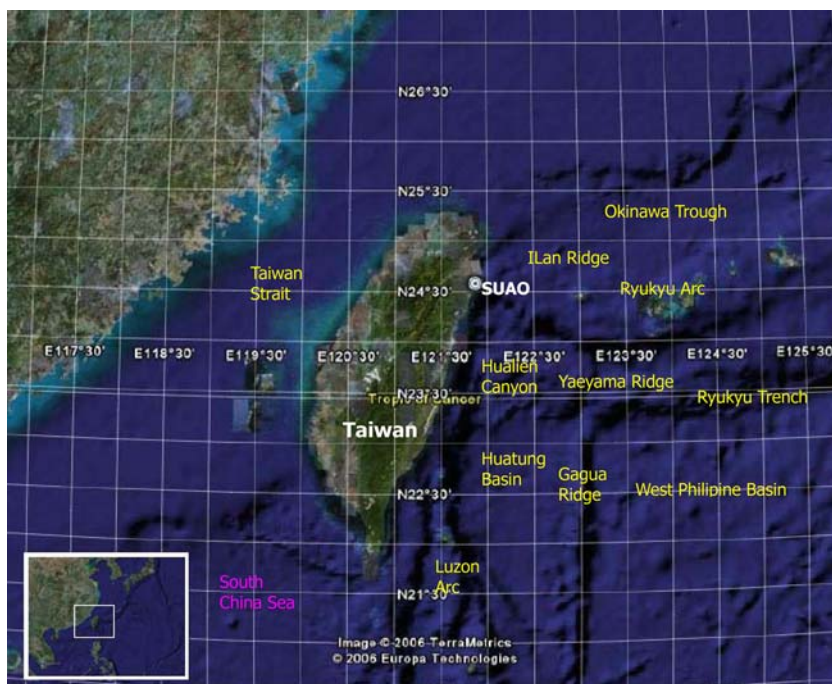
Fig. 2 Schematic model showing continent–arc collision and plate tectonic setting of Taiwan (redraw after, Angelier et al. 2001)
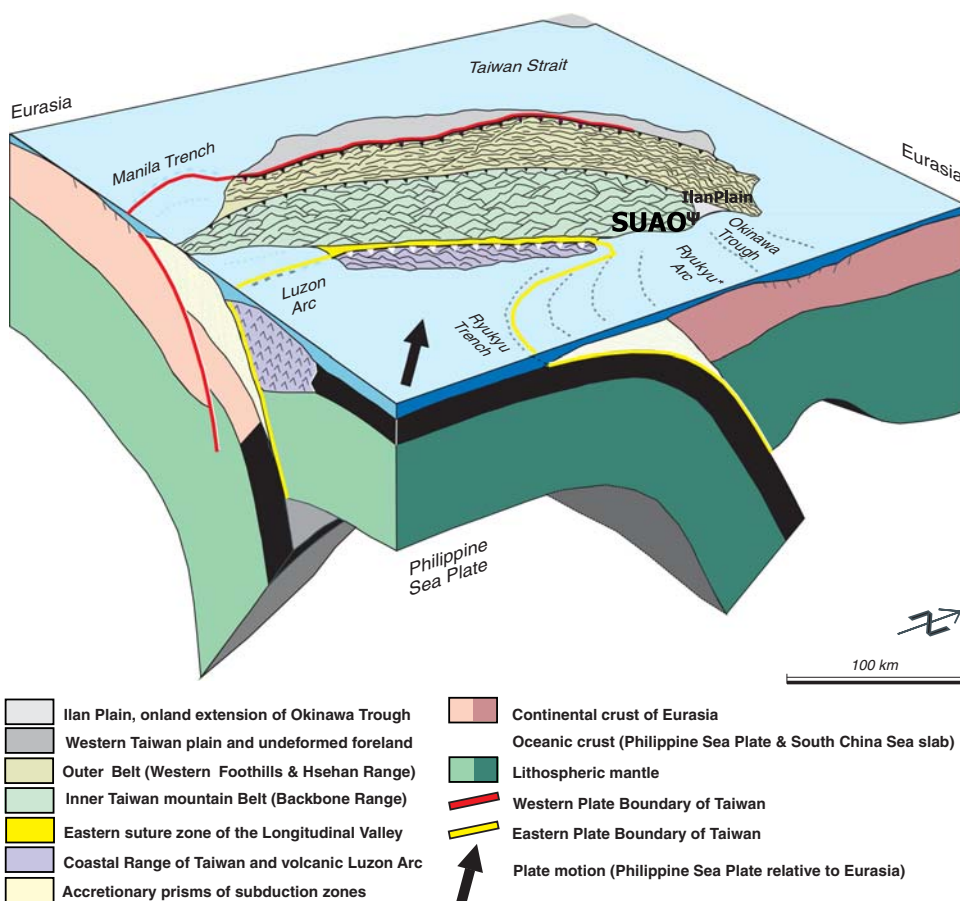
Fig. 3 Active and extent plate
boundaries in Taiwan–Luzon
region (redraw after,
Malavieille et al. 2002)

Fig. 4 Seismicity activities
near the studied site. Spatial
scatter of seismic events show
that a boundary-related
distribution is demonstrated
near the studied area
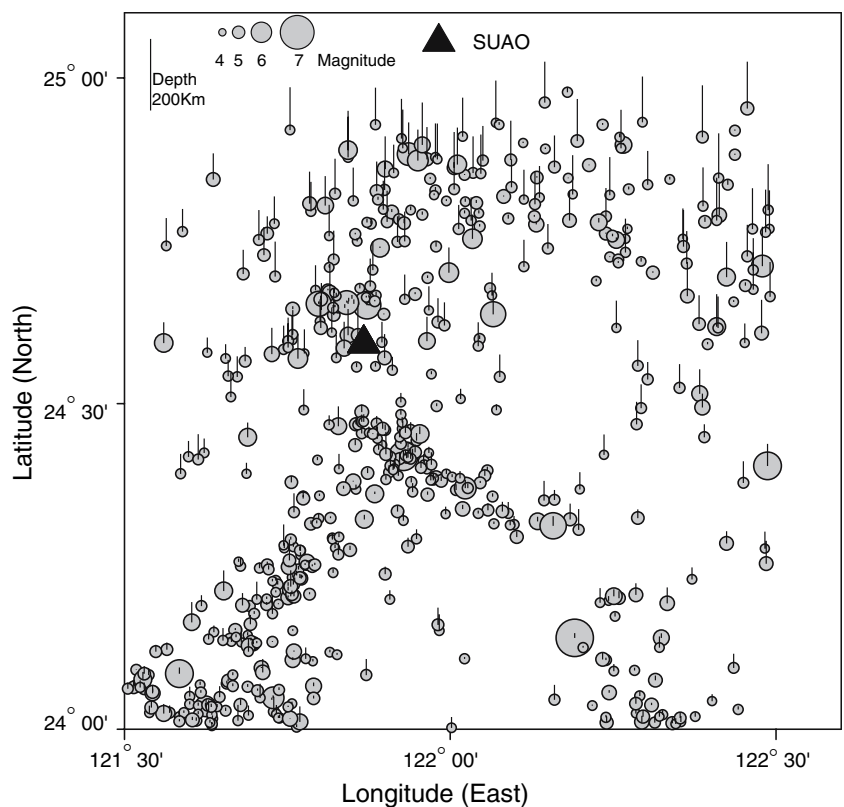
and Philippine Sea Basin. Among them are three major marginal basins, which are the South China Sea, Philippine Sea Basin, and Okinawa Trough behind the Ryukyu Arc. The Ryukyu Arc system is situated on the southeast of the East China Sea continental slope of the East China Sea and includes from north to south, Okinawa Trough, Ryukyu Ridge, and Ryukyu Trench, respectively. This island arc joins the northeastern part of Taiwan and tectonic units of the Ilan Plain and its related volcano group. The Okinawa Trough is located inside of the Ryukyu Arc and is a marginal sea or an extensional of the back-arc basin (Bowin et al. 1978). The western extension of the trough is the Ilan Plain in northeastern Taiwan. From the theory of lithospheric plate tectonics or new global tectonics, Taiwan is situated at a convergent and compressive boundary between two major tectonic plates, resulting from an active collision of an island arc (the Luzon Arc on the edge of Philippine Sea Plate) with the continental margin of Asia (on the Eurasian Plate). The collision is a very young tectonic event and the present rate of plate convergence is estimated about 7 cm/year in a northwest–southeast direction (Seno 1977) (Fig. 3). Using seismicity as well as other geophysical and geological data in the Taiwan region, Wang et al. (2001) have investigated the lithospheric structure of the Philippine Sea Plate beneath the western end of the Ryukyu subduction zone and its tectonic effects. A geodynamic model developed by Sibuet and Hsu (2004) addressed the notion of a continuum from subduction to collision, traces of the Miocene volcanic arc, and plate activity adjacent to this transition area.

The main objective of this study is to realize possible development in the current status near this active plate boundary area using long-term statistical assessment of position variation measured from GPS site. A major early implementation of GPS was in the study of ground trust. Aircraft are used to photograph areas on the Earth's surface. Index marks are often surveyed on the ground to provide reference locations on these photographs, which can assist in determining their scale and orientation; GPS can be used to survey these locations. Based on its characteristics, high positional accuracy is expected from GPS survey measurements. This research uses data of geodetic coordinate to identify the uncertainty of site position from the viewpoint of the spatial and temporal location, or the nature of environmental changes. Displacement derived by GPS is processed by the Bernese software (Bernese 2006); the average root-mean-square (rms) values of residuals for all stations were used to correct after removing the co-seismic offsets and, periodic variations. Residual value is can be taken as the tolerating precision of continuous GPS measurement. A statistical method (Cressie 1993; Hann 1977) is available to characterize the three components of a geodetic coordinate, which are longitude, latitude, and height. Regression analysis is also used to evaluate trends in position. Spatial scatter of seismic events has shown that, more or less, a boundary-related distribution is demonstrated near this transition area (Fig. 4). Resultant statistical significance infers the possible cause of variations may be due to the nature of seismic events which often occur in conjunction with tectonic activity.

Table 1 Descriptive statistics for the position displacement obtained from GPS

	Size	Missing	Mean	Standard deviation	Standard error	C.I. of mean
East	2,268	0	0.1710	0.1320	0.00276	0.00542
North	2,268	0	−0.2350	0.1470	0.00309	0.00606
Altitude	2,268	0	−0.0241	0.0252	0.00053	0.00104
Displacement	2,268	0	0.2950	0.1940	0.00406	0.00797

	Range	Maximum	Minimum	Median	25%	75%
East	0.454	0.4090	−0.0452	0.1800	0.0409	0.2830
North	0.482	0.0004	−0.4820	−0.2610	−0.3560	−0.0940
Altitude	0.237	0.0654	−0.1720	−0.0263	−0.0424	−0.0055
Displacement	0.625	0.6250	0.0000	0.3210	0.1040	0.4560

|	Skewness	Kurtosis	K-S distance	K-S probability	Sum	Sum of squares
East	0.10400	−1.391	0.1250	<0.001	388.155	105.669
North	−0.00174	−1.411	0.1270	<0.001	−532.505	174.164
Altitude	0.03150	0.555	0.0405	<0.001	−54.589	2.758
Displacement	0.06700	−1.416	0.1350	<0.001	669.593	282.592
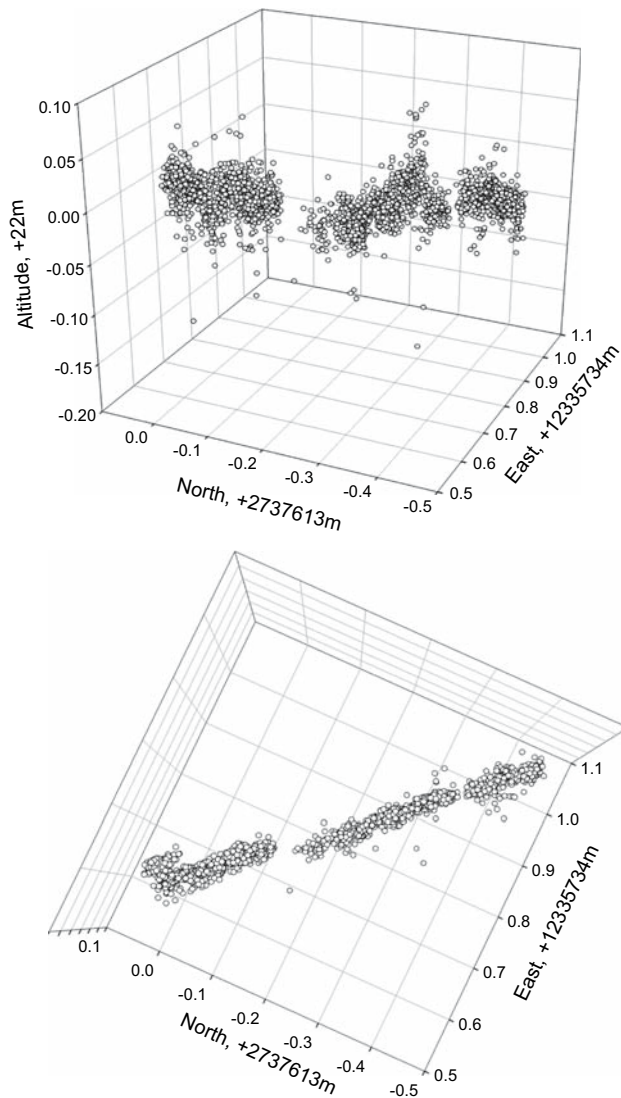
Fig. 5 Position obtained from GPS for SUAO station. A total of 2,268 discontinuous daily GPS data are collected over nearly 8 years. Deviation and absolute displacement of the longitude, latitude, and height components are referred to 1 January 1999

2 Conceptual model of studied site

The study site is located at Suao (SUAO station), the northeastern corner of Taiwan with a coordinate of E121°52′1.56″ and N24°35′32.64″, in the near the south of Ilan Plain (Fig. 1). The Ilan Plain is a triangular shape along the northeastern coast of Taiwan, facing the Pacific Ocean. The two other sides are fringed by high mountains composed mainly of Miocene to Paleogene slate (Ho 1982). Each side of this triangular plain has a length of about 30 km and the total area is nearly 320 km². By tectonic analysis, the Ilan Plain marks the western termination of the Okinawa Trough, which extends from Japan towards the north end of Taiwan. The extensional opening
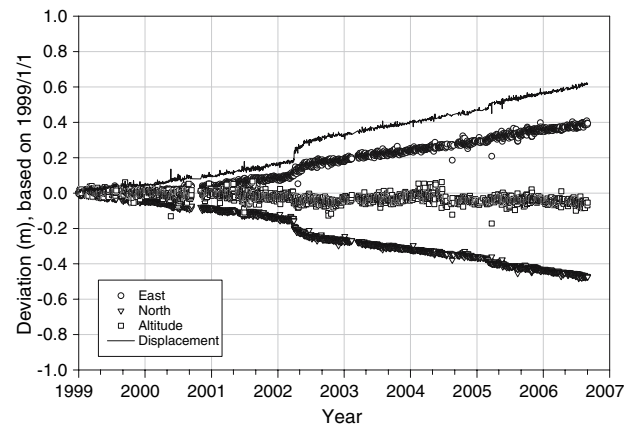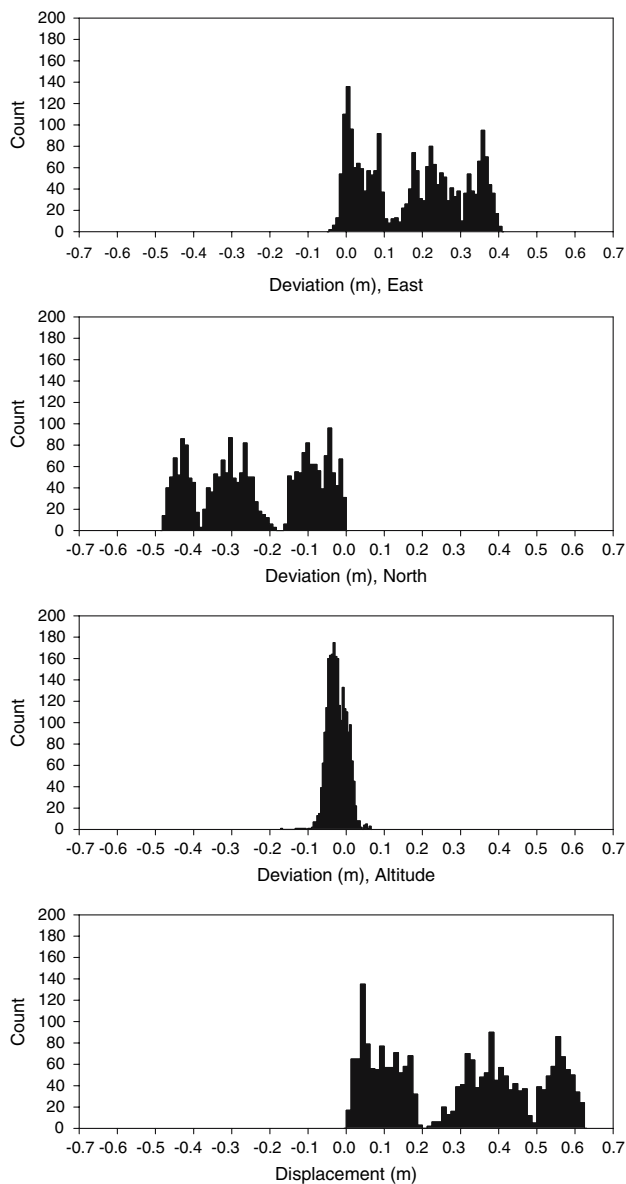

Fig. 6 Time series of position components and displacement at SUAO station. It shows that a linear trend is progressively increased and reveals two jumps in March 2002 and May 2005, respectively

of the Okinawa Trough thus projects westward into Taiwan to form the Ilan Plain. The pre-Tertiary metamorphic complex is the oldest geologic-tectonic element of Taiwan and constitutes the basement of the Tertiary fold-and thrust belts of western Taiwan. Various basement rocks are exposed extensively along the eastern flank of the Central Range and form the eastern margin of the Eurasian Plate. All of these rocks were deformed and altered principally during the late Mesozoic orogenesis so that this tectonic unit is termed the Mesozoic tectonized basement of Taiwan. This metamorphic belt is in a north–south trend with length of 250 km and varies in width from 30 km in the north to about 10 km on the south. All the metamorphic rocks in the basement complex are grouped under the general stratigraphic term ''Tananao Schist'' (Yen 1954a, b; 1960). The GPS site at SUAO is constructed on this basement rock. As can be expected, local sloping or subsidence is ignored. A total of 2,268 discontinuous daily GPS data have been collected at SUAO over nearly 8 years (Table 1; Fig. 5). Time series for the longitude, latitude, and height components of deviation and absolute displacement are referred to 1 January 1999.

3 Quantitative analysis

The data shows that a linear trend is progressively increased and reveals two jumps in March 2002 and May 2005, respectively (Fig. 6). Three sections of trend variation, i.e., trend 1, 2 and 3, are marked for the statistical modeling. Descriptive statistics first quantitatively is used to analyze the displacement for the three directional components of GPS data (Table 1). Deviation of three position components of GPS data is observed to maintain in the eastern and southern direction with downward displace-
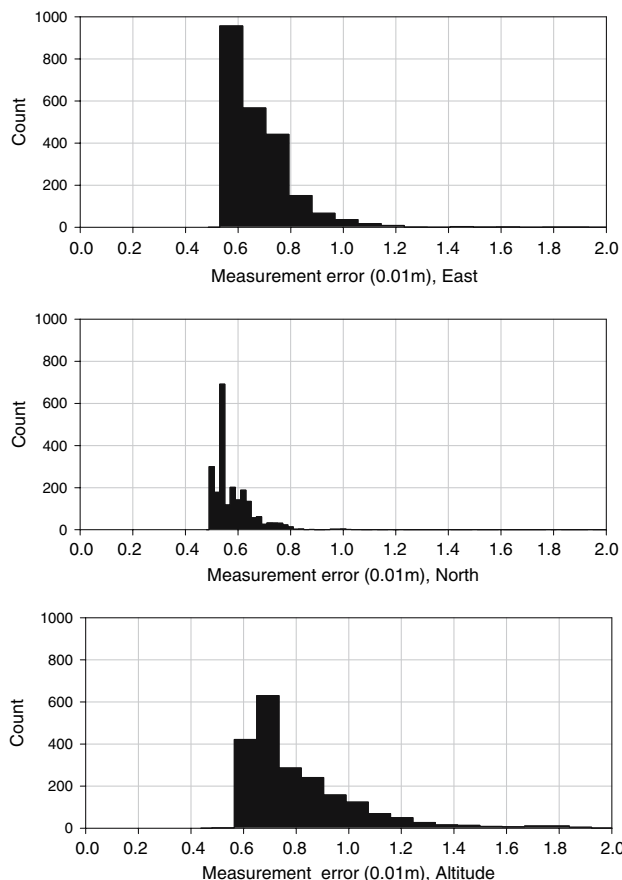
Fig. 7 Histogram of position components and displacement at SUAO station. It indicates that the combination of deviation in the east and the south likely dominate absolute displacement

Table 2 Descriptive statistics for the error of GPS positioning

	Size	Missing	Mean	Standard deviation	Standard error	C.I. of mean
East	2,268	0	0.00696	0.00334	0.0000702	0.0001380
North	2,268	0	0.00580	0.00106	0.0000222	0.0000436
Altitude	2,268	0	0.01000	0.00733	0.0001540	0.0003020

	Range	Maximum	Minimum	Median	25%	75%
East	0.0877	0.0930	0.00530	0.00640	0.00590	0.00730
North	0.0200	0.0249	0.00490	0.00550	0.00530	0.00610
Altitude	0.0849	0.0897	0.00480	0.00750	0.00660	0.00970

	Skewness	Kurtosis	K-S distance	K-S probability	Sum	Sum of squares
East	15.221	298.451	0.319	<0.001	15.792	0.1350
North	6.645	82.908	0.198	<0.001	13.148	0.0788
Altitude	3.900	20.803	0.290	<0.001	22.737	0.3500

variation, while the error of altitude is more uncertain (Fig. 8). First-order linear regression is conducted to demonstrate the association of absolute displacement and

ment. Absolute displacement is then computed from these components and demonstrates a maximum range of 0.625 m. Three obvious groups of the histogram indicate that the combination of deviation in the east and the south likely dominate absolute displacement (Fig. 7). A normality test is used to establish a centralized histogram for altitude deviation. That test fails, which indicates that the data varies significantly from the pattern expected for a normal population distribution. Median and 75th-percentage values show that the error for estimating position with the GPS is less than 1 cm for all components (Table 2). Note that the north-south component manifests the least

Fig. 8 Histogram of the positioning error derived from GPS at SUAO station

Fig. 9 Analysis of linear
regression for the displacement
at SUAO station
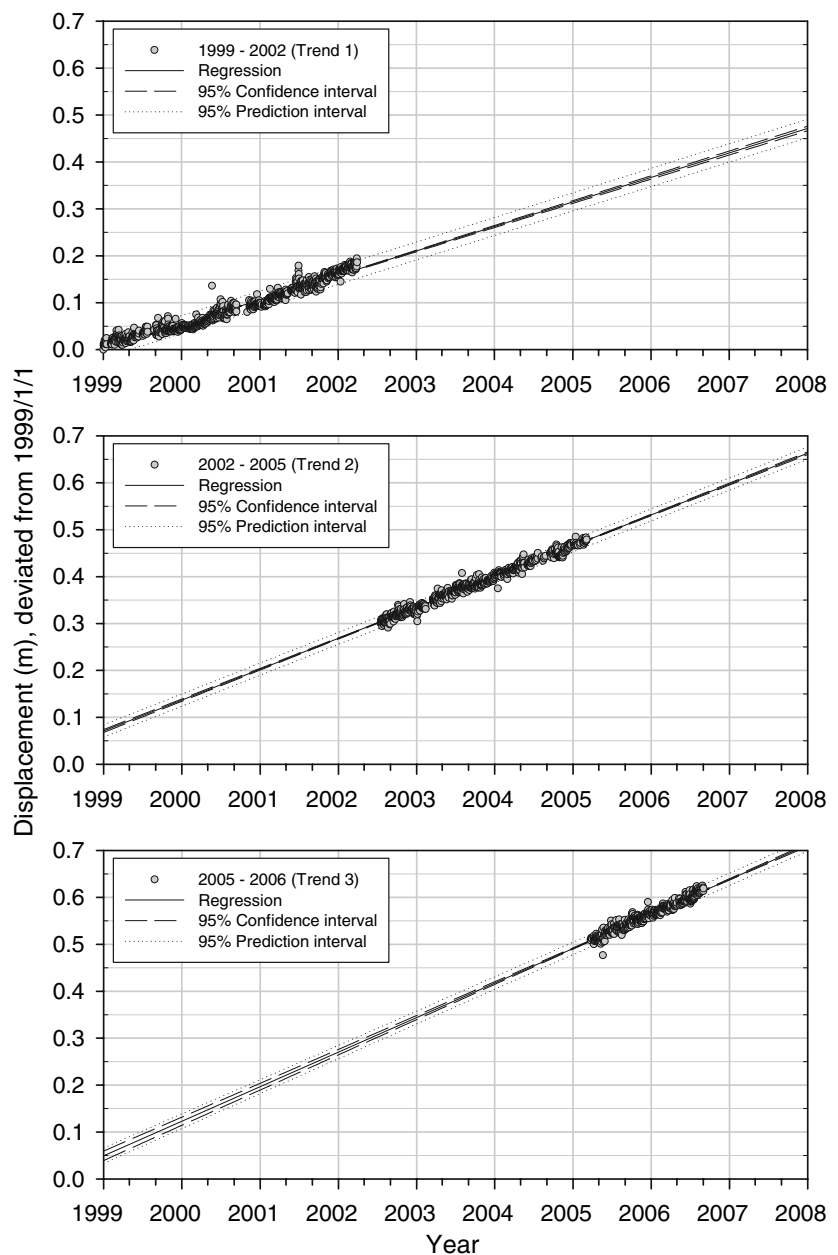
time frame (Fig. 9). Regression statistics are modeled for
three time periods (Table 3). Table 3 shows that regression
parameters (y_0, a) intercept and slope for displacement
versus date is analyzed with very high R^2, adjusted-R^2
value and t-statistic. Good consistency is thus established
between the regression model and the observed displace-
ment. Note also that the increasing rate (a) represents an
increase on the order of 10^{-4} m/day from trend Sect. 1–3.

4 Discussion

Daily displacement derived from GPS data for approxi-
mately 8 years of data are quantitatively analyzed and

summarized. The results show that GPS displacement of
each of the three components is less than one half meter.
The resultant absolute displacement represents a maxi-
mum value of 0.625 m. An outline of absolute displace-
ment versus seismic event with focal depth is
demonstrated on Fig. 10. There are two jumps of absolute
displacement shown, which are also accompanied by a
multitude of seismic events at shallow depths, i.e., less
than 20 km, especially for March 2002 and March 2005.
By determining horizontal and vertical angle from the
displacement components, it is found that the mean
absolute displacement of trend 1 is aimed at E73.5°S with
a mean vertical angle upward by 1° (Table 4). Note that
the trend 2 and trend 3 are concentrated on the mean

Table 3 Regression analysis for the position displacement

Linear regression $y = y_0 + at$, where t in day and deviated from 1/1/1999						
	Trend 1		Trend 2		Trend 3	
Date range	1/1/1999–30/3/2002		17/7/2002–5/3/2005		24/3/2005–2/9/2007	
Regression parameter	y_0	a	y_0	a	y_0	a
Number of data	947		717		490	
Value	1.65×10^{-3}	1.43×10^{-4}	7.09×10^{-2}	1.80×10^{-4}	4.94×10^{-2}	2.02×10^{-4}
Standard error	6.55×10^{-4}	9.21×10^{-7}	1.58×10^{-3}	9.01×10^{-7}	5.17×10^{-3}	2.03×10^{-6}
t-Statistic	2.522	155.268	44.979	200.058	9.557	99.118
P value	0.012	<0.001	<0.001	<0.001	<0.001	<0.001
Correlation coefficients (R)	0.981		0.991		0.976	
R^2	0.962		0.982		0.953	
Adjusted R^2	0.962		0.982		0.953	
Standard error of estimate	0.010		0.007		0.007	
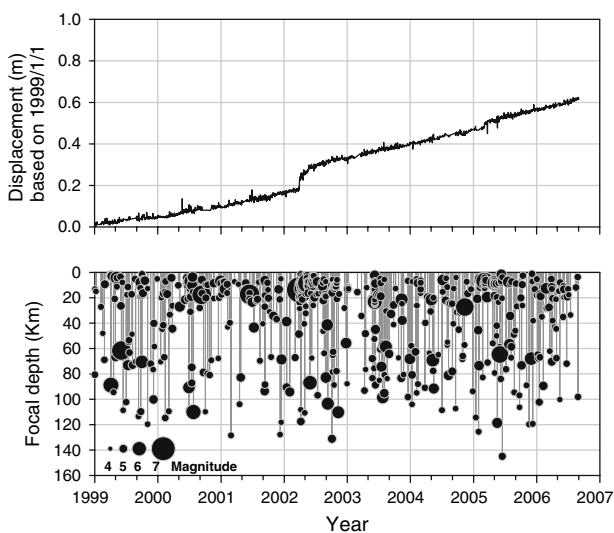
Fig. 10 Comparison for the time series of displacement and seismicity activities shown on Fig. 4
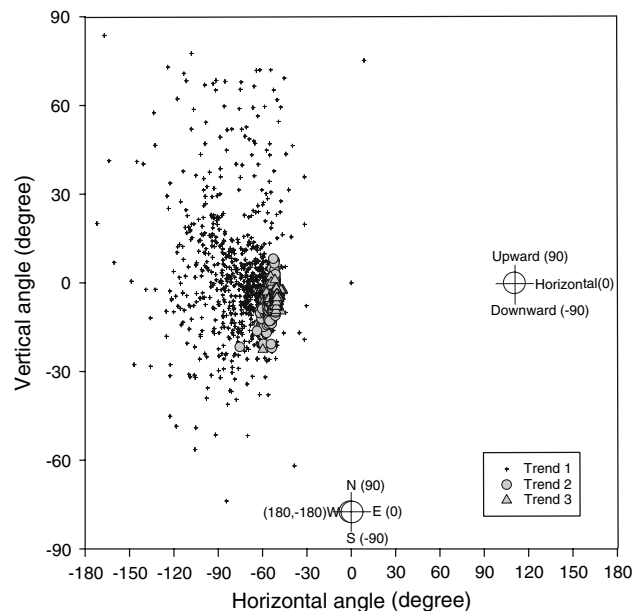
Fig. 11 Vertical and horizontal angle of displacement demonstrated in the observed trends

direction of E54°S to E51°S and are nearly horizontal with a small downward angle of 4–5° (Table 4; Fig. 11). Furthermore, Kurtosis, K-S distance and K-S probability do not support passing the normality test at these orientation angles. The folded rocks of the Ryukyu Arc are connected with the fold belt of southern Japan to the northeast and extend southeastward into Taiwan. There is a remarkable contrast on the north and south of the Ryukyu Arc (Eguchi and Uyeda 1982). Only the south-

western end of the Ryukyu Arc system is related to the tectonic study of the Taiwan region. The western end of the non-volcanic arc in the Ryukyu Arc is interpreted as connected to the east-turning segment of the Central Range in Taiwan (Biq 1981). The Ryukyu Trench situated southeast of the Ryukyu Ridge is one of the deepest portions of Pacific Ocean, and demonstrates an active

Table 4 Descriptive statistics for the orientation of position displacement

	Size	Missing	Mean	Standard deviation	Standard error	C.I. of mean
Horizontal 1	947	0	–73.502	20.341	0.6610	1.297
Vertical 1	947	0	1.056	19.942	0.6480	1.272
Horizontal 2	717	0	–54.113	2.245	0.0838	0.165
Vertical 2	717	0	–5.736	3.944	0.1470	0.289
Horizontal 3	604	0	–50.914	1.074	0.0437	0.0858
Vertical 3	604	0	–4.451	1.714	0.0698	0.137

	Range	Maximum	Minimum	Median	25%	75%
Horizontal 1	180.960	9.090	–171.870	–67.357	–84.862	–58.813
Vertical 1	157.599	83.900	–73.699	–2.797	–9.217	6.957
Horizontal 2	26.530	–49.029	–75.560	–53.583	–55.270	–52.589
Vertical 2	30.176	8.243	–21.933	–5.762	–8.131	–3.450
Horizontal 3	13.612	–46.315	–59.927	–50.820	–51.427	–50.349
Vertical 3	24.651	2.206	–22.445	–4.421	–5.329	–3.397

	Skewness	Kurtosis	K-S distance	K-S probability	Sum	Sum of squares
Horizontal 1	–1.129	2.267	0.126	<0.001	–69606.788	5507676.645
Vertical 1	1.196	2.986	0.135	<0.001	999.600	377263.412
Horizontal 2	–2.105	12.221	0.101	<0.001	–38799.326	2103173.586
Vertical 2	–0.0246	1.481	0.0360	0.028	–4113.010	34732.915
Horizontal 3	–1.618	12.365	0.0832	<0.001	–30751.816	1566381.431
Vertical 3	–1.850	20.328	0.0587	<0.001	–2688.570	13739.912

Orientation in angle (degree)

1 Trend 1; *2* Trend 2; *3* Trend 3

subduction zone. The existence of a major strike-slip zone under the ocean between Taiwan and the Ryukyu Arc is postulated by Wageman et al. (1970) and Wu (1970). A western boundary of the lithosphere exists beneath Taiwan. The boundary almost lies along the 121°E meridian line (Wang et al. 2001). The boundary is migrating westward at a rate of about 6 cm/year along with the movement of the Philippine Sea Plate. The westward migration of the lithospheric boundary of the plate causes the westward extension of the Okinawa Trough, which lags behind Philippine Sea Plate by about 600,000 years. The initial stage of the Okinawa Trough formation, in turn, put the whole northern Taiwan area under tensional stress (Wang et al. 2001). It is apparent that absolute displacement toward the southeast is possibly on account of tensional activity in this boundary. Unfortunately, spatial coherence along the boundary cannot be assessed due to deficient data for the same period for other GPS stations. Nevertheless, this study provides a useful statistical model to effectively assess daily displacement by GPS observation. Although consistent spatial variation can only be derived for the SUAO station, the data shows that the resultant variation is likely related to tectonic activity in this boundary. However, in the future more spatial coherence data is needed to make reliable inferences.

5 Conclusions

Development of an active subduction and transition boundary near the western Ryukyu Arc has been assessed statistically by displacements obtained from a GPS site at Suao, Taiwan. In general, intermittent daily displacement quantitatively summarizes the temporal and spatial variations. This method for analyzing the variation of GPS position can be regarded as an effective approach to detect activity along a ground or spatial boundaries. The conclusions of this research are as follows:

1. The results show that absolute displacement derived by a GPS site for nearly 8 years of intermittent daily movements represents a maximum value of 0.625 m in spatial variation.
2. Three linear trends are concluded for such long-term evolution using time series and histogram analysis.

Result of linear regression reveals consistency between the data and statistic model. Regression analysis also shows an increasing rate on the order of 10^{-4} m/day for such movements. This rate is elevated following the trend development.

3. The 75th-percentage value of population demonstrates that the error in estimating position is less than 1 cm for all components of movement. It did not influence the result of these studies.

4. Southeastern and nearly horizontal movement with very small angle is believed to result from the proposed as the main development of for the site movements; it is likely related to the tensional activity adjacent to this boundary.

5. Moreover, in the future more spatial coherence from GPS data can be used to address more reliable assessments about such activity adjacent to this transition zone.

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