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Evaluation of the Applicability of the Chapman-Miller Method on Variation of the Geomagnetic Total Intensity Field in Taiwan from 1988 to 2007

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ABSTRACT

The solar (S) and lunar (L) variations of geomagnetic fields at the horizontal (H), declination (D), and the downward vertical component data (Z) are modeled by the Chapman-Miller method with four order harmonics. In this paper, we compare S and L variations of the geomagnetic total intensity field using a consistent method with 3-component data for seasonal variations (summer, winter, and equinox) for three distinct phases during the years 1988 - 2007. The results show that consistency in the S and L variations for geomagnetic total intensity indicates normal stations and discrepancies are occurred due to data quality. In application, consistent results also prove that the function of the magnetometers at TW was normal and that large anomalies were certainly in existence during the Chia-Yi earthquake.

Key words: Solar and lunar variations, Chapman-Miller method, Geomagnetic field

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1. INTRODUCTION

For observing the geomagnetic field surrounding Taiwan, a network of eight geomagnetic stations (listed in Table 1 and shown in Fig. 1) was installed at the beginning of 1988. During the period 1988 - 2001, the first phase of the geomagnetic survey was conducted at stations equipped with G-856 magnetometers (sensitivity = 0.1 nT) that had sampling rates of 5 or 10 min.; these stations routinely recorded variations in the geomagnetic total intensity field (Yen et al. 2004). Locations of the stations were chosen carefully away from populated areas to diminish interference from visible iron objects and power lines. Because Taiwan is located in the Circum-Pacific seismic zone, the stations are generally set in areas with high seismicity or crustal activity except for the reference station, Lunping (LP), which is located in a seismically quiet zone. After the Chi-Chi earthquake, surprising pre-earthquake anomalous phenomena were observed at the Liyutan (LY) and Tsengwen (TW) stations (Yen et al. 2004). Hence, since 2001 the new auxiliary Lunping (LN) station was set about 10 m away from the sensor of LP to supplement its records providing a continuous reference source. During 2002 - 2004, the second phase of the geomagnetic survey commenced (Yen et al. 2008). New magnetometers were installed in the station network. Due to the close of the LP and LN stations, the Kinmen station (KM) was used as the new reference station. Meanwhile, from north to south, three new stations, Yeheng (YH), Shuanlung (SL), and Pingtung (PT) were established in central Taiwan to improve coverage. Consequently, for this phase, the geomagnetic network was comprised of 11 stations (listed in Table 1) and the sampling rate was dramatically shortened to one min. and after 2007, the sampling rate was modified to only 1 second for acquiring still more detailed data.

The geomagnetic research data observed by the network

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Table 1. The locations and disturbance degrees in the three seasons of the three observation phases. The numbers in the columns of the three phases explaining the disturbance degrees of the related study periods are second standard deviations ($STD_{nd}S$). The NaN denotes that there are no observed data during related study periods.

Station	Code	Long.	Lat.	Observation period	Phase 1 (1988 - 2001)			Phase 2 (2002 - 2004)			Phase 3 (2007)		
					Equinox (E) season	Summer (S) season	Winter (W) season	E season	S season	W season	E season	S season	W season
Lunping	LP	121.1667	25.0000	1988 - 2002	12.08	16.38	10.44	NaN	NaN	NaN	NaN	NaN	NaN
Lunping new	LN	121.1667	25.0000	2001 - 2002	8.26	8.50	8.66	NaN	NaN	NaN	NaN	NaN	NaN
Liyutan	LY	120.7675	24.3467	1988 - now	10.18	10.38	7.23	1.81	2.05	1.45	0.04	0.04	0.10
Tsengwen	TW	120.5167	23.2514	1988 - now	15.42	12.40	9.22	1.94	2.12	1.64	0.19	0.19	2.75
Hengchun	HC	120.8008	21.9350	1988 - now	16.98	25.41	15.83	5.76	3.86	3.70	0.09	0.12	0.14
Yeheng	YH	121.3671	24.6710	2002 - now	NaN	NaN	NaN	4.05	0.00	6.65	0.06	0.07	0.08
Shuanlung	SL	120.9441	23.7902	2002 - now	NaN	NaN	NaN	2.16	3.45	2.50	NaN	0.00	NaN
Pingtung	PT	120.6496	22.7035	2002 - now	NaN	NaN	NaN	2.54	2.33	2.81	0.12	0.08	0.07
Neicheng	NC	121.6681	24.7181	1988 - now	11.36	11.23	8.57	1.83	2.52	1.18	0.03	0.03	0.05
Hualien	HL	121.6006	24.0678	1988 - now	9.65	12.31	7.10	10.62	6.43	21.42	0.12	0.12	0.11
Yuli	YL	121.2856	23.3506	1988 - now	9.94	10.48	7.43	17.14	3.47	6.24	0.10	0.44	0.18
Taitung	TT	121.0519	22.8019	1988 - now	10.45	10.33	7.77	9.52	6.31	7.84	2.54	0.06	5.23
Kinmen	KM	118.4164	24.4471	2002 - now	NaN	NaN	NaN	1.39	1.25	1.83	0.71	0.15	0.33

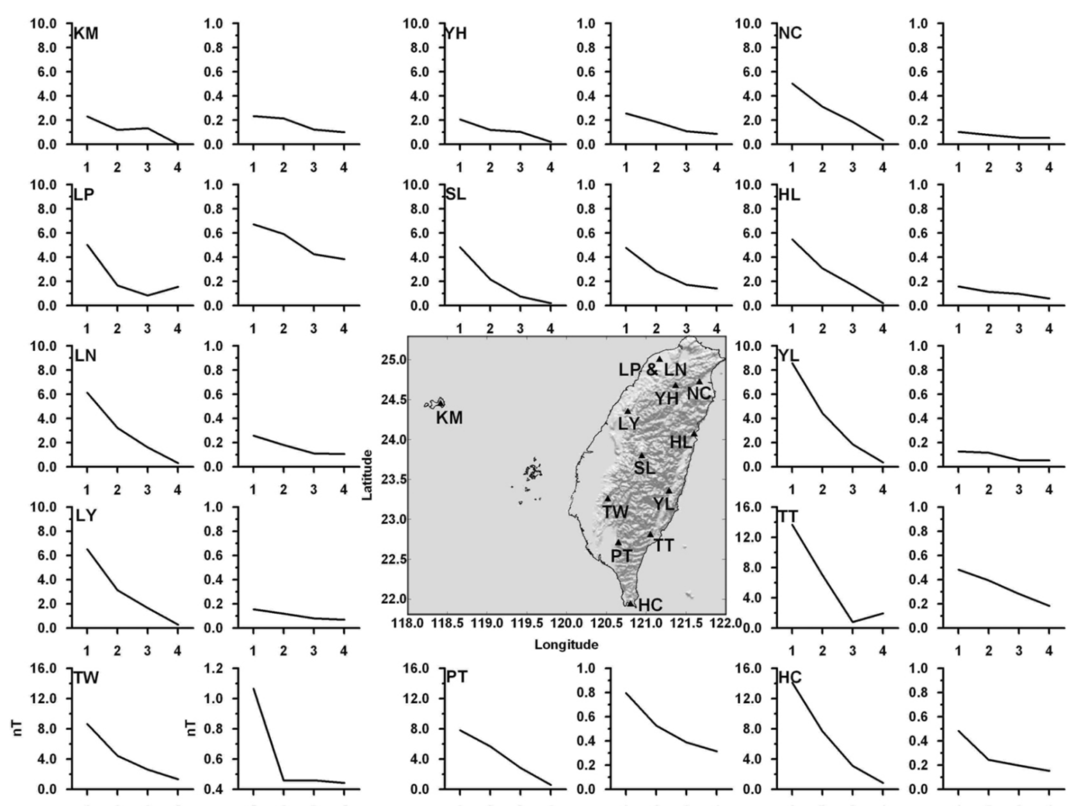

Fig. 1. The amplitudes and errors of the 4 harmonics in the S variation during 1988 - 2007. The right and left panels show the respective the amplitudes and errors of the harmonics at each station. The x-axis denotes the orders of the harmonics.

are widely used in Taiwan, such as in geomagnetic surveying (Hsu et al. 1998; Wang et al. 2002; Yen et al. 2008), analyzing long term change rate associated with the Chi-Chi earthquake (Chen et al. 2004) and examining anomalous pre-earthquake phenomena (Yen et al. 2004). However, replacement of the magnetometers and environmental changes could possibly result in disturbances potentially compromising data over long temporal periods. This possibility needs to be accounted to enhance data quality. Here, the data are analyzed using the Chapman-Miller method for determining the parameters of the solar and lunar variations by four harmonics (Chapman and Miller 1940). We also compare the obtained parameter amplitudes with three-component data to make sure the method works within the geomagnetic total intensity field. If these results are in agreement, the obtained phases and errors of the parameters are employed in detecting any distorted data.

2. METHODOLOGY

The earth's geomagnetic field is simultaneously affected by the Sun and Moon (Chapman and Bartels 1940). Changes in the geomagnetic field caused by the Sun and Moon are respectively named solar and lunar variations. To separate the Sun and Moon effects, Chapman and Miller (1940) developed the Chapman-Miller method for determining the solar and lunar variations in the geomagnetic field, and probable vector errors were derived by Malin and Chapman (1970). The solar (S) variation, the most conspicuous daily effect, can be easily presented by four harmonics functions:

$$S = \sum_{n=1}^{4} S_n \sin(nt + \sigma_n) \tag{1}$$

Here, S_n and σ_n are respectively the amplitudes and the phases of the nth harmonic, and t denotes the mean solar time measured from local midnight.

Likewise, the small lunar (L) variation is described by similar harmonics. Due to a phase difference, the L variation is given by the harmonics, as follows

$$L = \sum_{n=1}^{4} L_n \sin[(n - 2)t + 2\tau + \lambda_n)] \tag{2}$$

where L_n and λ_n of the nth harmonic are the amplitudes and the phases of the L variation, respectively. The τ is a mean of lunar time measured from the mean local lower transit of the Moon and related to t by

$$\nu = t - \tau = 23^h \cdot 3827 + 29684 \cdot 4748T + 0.000112T^2 \tag{3}$$

The ν is the phase of the Moon measured by the hour angle between the Sun and Moon increasing from 00 at one new moon to 24 at the next, and T is time in the Julian centuries (36525 solar days) measured from the same standard from midday of 31 December 1899. In terms of ν, the L variation can be rewritten as:

$$L = \sum_{n=1}^{4} L_n \sin[(nt - 2\nu + \lambda_n)] \tag{4}$$

It is worth mentioning that L_2, which is a purely lunar daily variation, with a period of a half lunar day is the most important component of the L variation and is expressed by

$$L_2 \sin(2\tau + \lambda_2) \tag{5}$$

The other part ($L - L_2$) of the L variation is dependent on the Sun and Moon, and named the luni-solar component.

Malin and Chapman (1970) suggests that S_1 and L_2 are respectively the major components of the S and L variations in the declination (D), horizontal (H). and vertical downward (Z) components. Because the geomagnetic total intensity field is a joint force of H and Z, variations of L_n and S_n in the geomagnetic field are very similar. Therefore, we analyzed the geomagnetic total intensity field by the Chapman-Miller method, first, and then compared with D, H, and Z results. If the relationship between them is consistent, three seasonal divisions are tested to look for further evidence. Note that the three seasons, summer, winter and equinoxes, denote May, June, July and August, January, February, November and December, and March, April, September and October, respectively (Huang 1990). Based on the inclinations of the Earth's axis, the greatest S and L variations of D, H, and Z are generally observed in summer and the least in winter (Gupta and Malin 1972; Shiraki 1977, 1981; Huang 1990). This suggests that S_1 and L_2 of the geomagnetic total intensity field have a maximum in summer and a minimum in winter. To examine whether or not this method is appropriate, we compare $_1$, $_2$, and errors in S_1 and L_2 with expected results (normal) and the data with/without disturbance during the three phases, 1988 - 2001, 2002 - 2004, and 2007.

3. DESCRIPTION

Figure 1 shows the amplitudes and errors of the 4 harmonics in the S variation between 1998 and 2007. In general, S_1 is the largest response of the S variations with S_n decreasing with the order of harmonics at most stations, except for at KM, LP, YH, and Taitung (TT) (Fig. 1). Patterns in S_1, S_2, and S_3 variations for KM and YH are quite different from those of the other stations (normal stations) suggesting severe disturbance. By contrast, the discrepancy happening in S_4 implies weak noise at LP and TT. It is worth mentioning that station TW has a normal pattern for S_n but with large errors. With respect to the minor L variation from 1988 to 2007, the Hengchun (HC), Hualien (HL), LY, LN, Neicheng (NC), TT, and Yuli (YL) stations all have L_2 as being largest a result that agrees with previous studies (Fig. 2). Incongruity patterns in L_n are found at KM, LP, TT, and YH. These results are consistent with the compromised stations given in Fig. 1 for the S variations. Stations SL and TW have normal S_n and abnormal L_n suggesting that they have been somewhat compromised by a small noise factor.

To double check, Fig. 3 shows S_1 and errors in equinoxes, summer and winter to understand seasonal effects in geomagnetic total intensity within the whole study period. Roughly, S_1 in equinoxes is larger than for winter and smaller than for summer because solar wind directly impacts the Northern Hemisphere in summer. However, a discrepancy in Fig. 3 is found for winter at LP and for equinoxes at TT. We also examine L_2 within the three seasons between 1988 and 2007 as shown in Fig. 4. Clearly, the patterns for S_n in Fig. 3 and for L_n in Fig. 4 are similar because the connection between the Sun and Earth is almost the same. The patterns for L_2 versus the seasons at stations KM, SL, and YH are certainly different to those at other 'normal' stations. Meanwhile, the discrepancies in L_2 for seasonal periods given at stations LP and TT are also consistent with the results of Fig. 3 for the S variations.

In short, the discrepancies in results given at stations KM, LP, SL, TT, and YH with the 'normal' expected station results as demonstrated in Figs. 1 to 4 and the consistency in discrepancies between the S and L variations leads to the conclusion that the analyzed results are consistent. The patterns for S_n and L_n at 'normal' stations (Figs. 1 to 4) agree with those of previous studies in three-component data indicating that this method can be employed successfully in geomagnetic total intensity field measurement. Given that the method can be used successfully, we try to determine data disturbances for 1988 - 2001, 2002 - 2004, and 2007. Figures 5 and 6 respectively show the S and L variations for the three phases. In fact, $_n$ and $_n$ should be very similar at all stations during the three phases because they are all located in a small area and all harmonic functions are counted into the same initial time. Surveying Figs. 5 and 6, it is evident that $_1$ and $_2$ are roughly distributed within a range between 190 and 240 and small errors in the S and L variations are conspicuously during the first and third phases. Except for station TW, the results show that disturbances generally appear in the second phases.

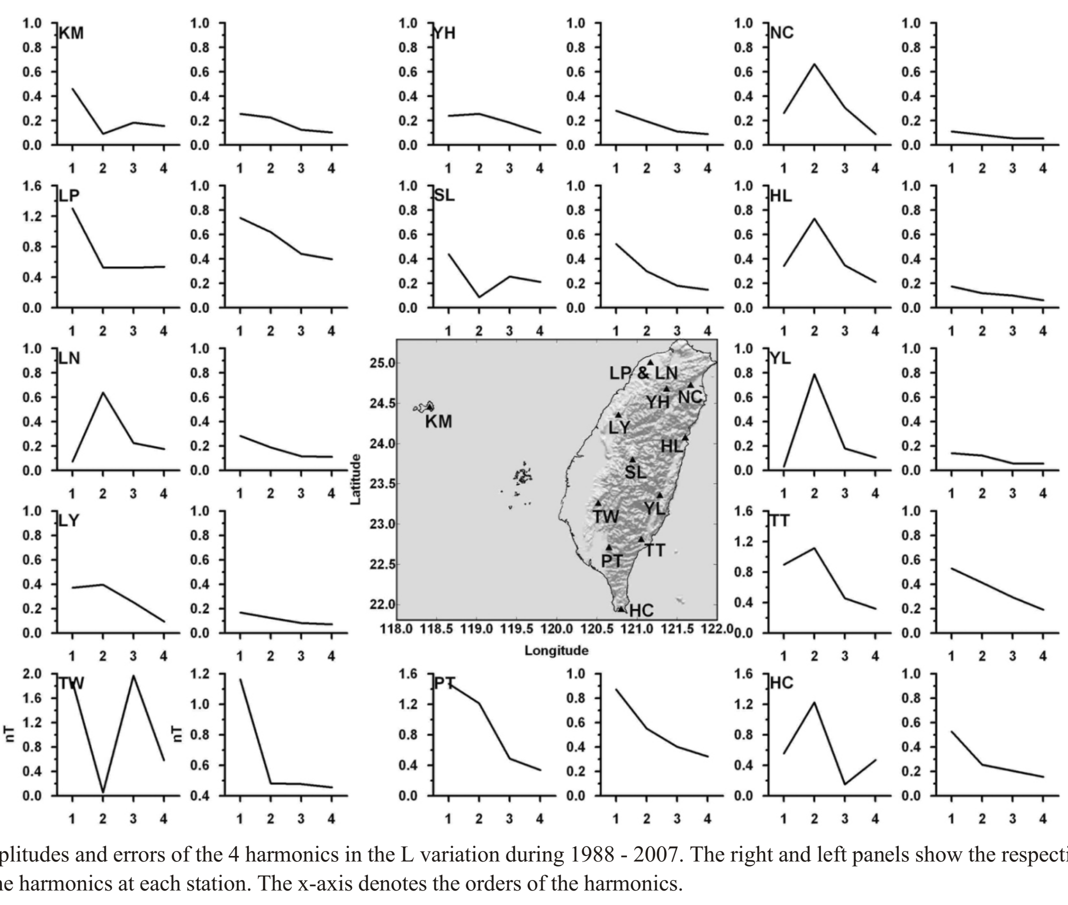

Fig. 2. The amplitudes and errors of the 4 harmonics in the L variation during 1988 - 2007. The right and left panels show the respective amplitudes and errors of the harmonics at each station. The x-axis denotes the orders of the harmonics.

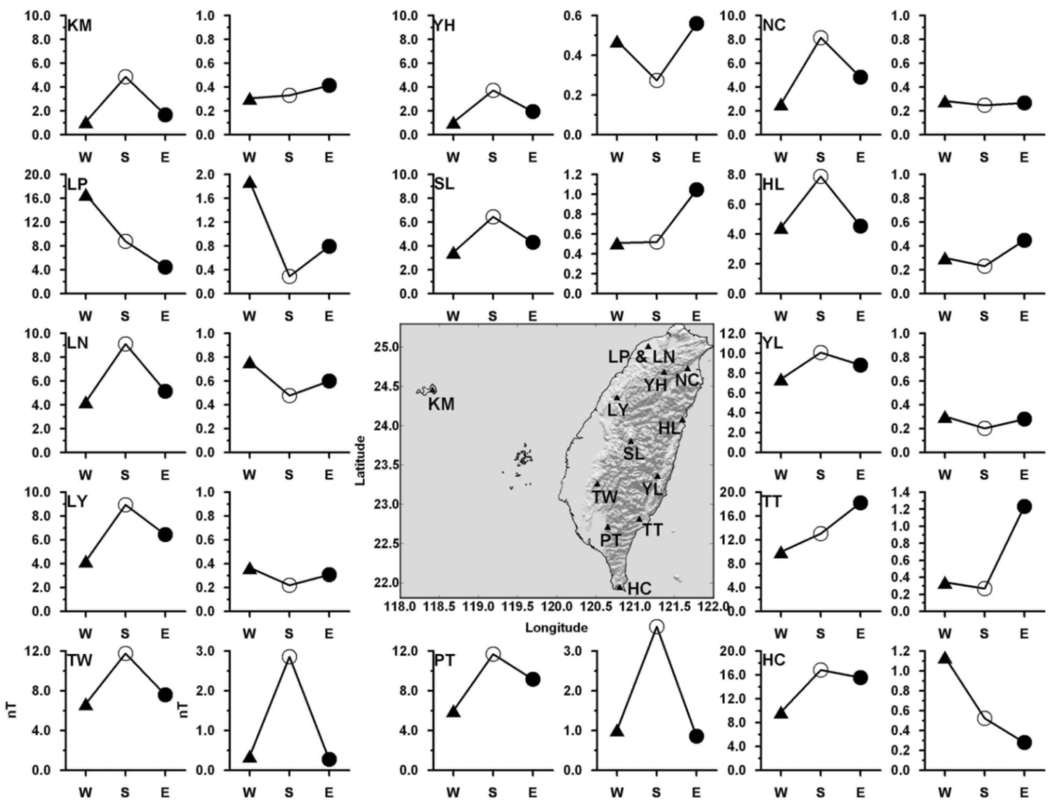

Fig. 3. The S_1 and its error during three seasons. The right and left panels at each station respectively show S_1 and its error. The W (▲), S (○), and E (●) on x-axis are the winter, summer, and equinox seasons.

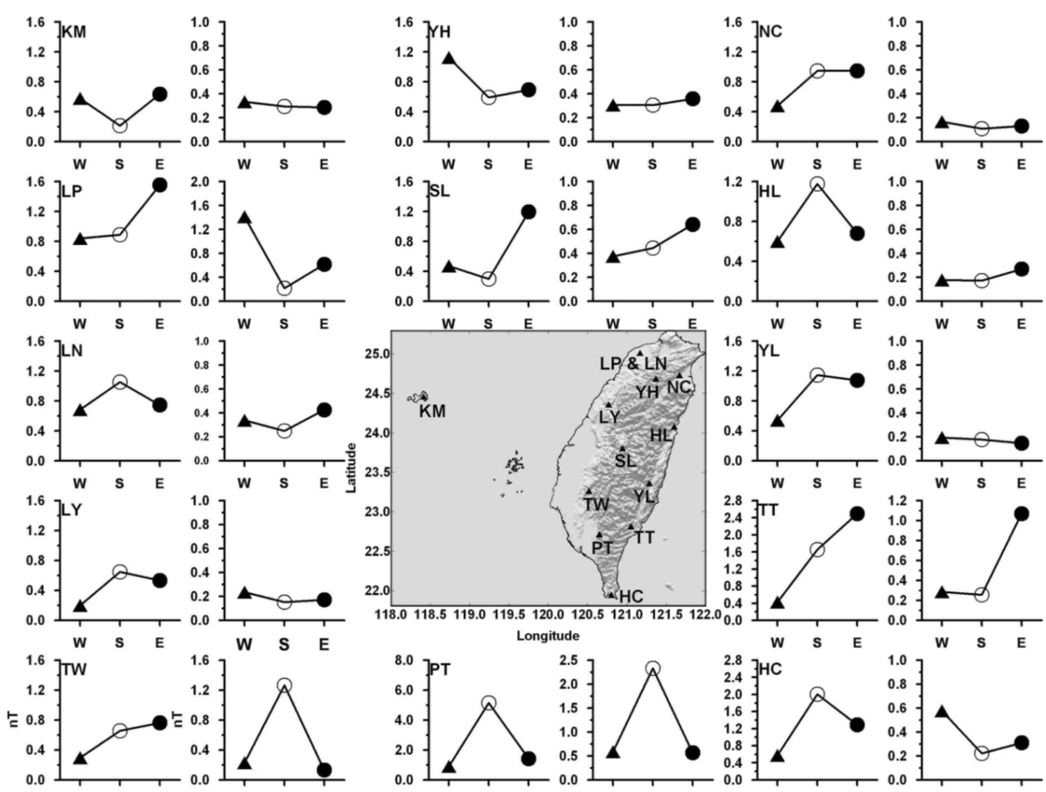

Fig. 4. The L_2 and its error during three seasons. The right and left panels at each station respectively show L_2 and its error. The W (▲), S (○), and E (●) on x-axis are the winter, summer, and equinox seasons.

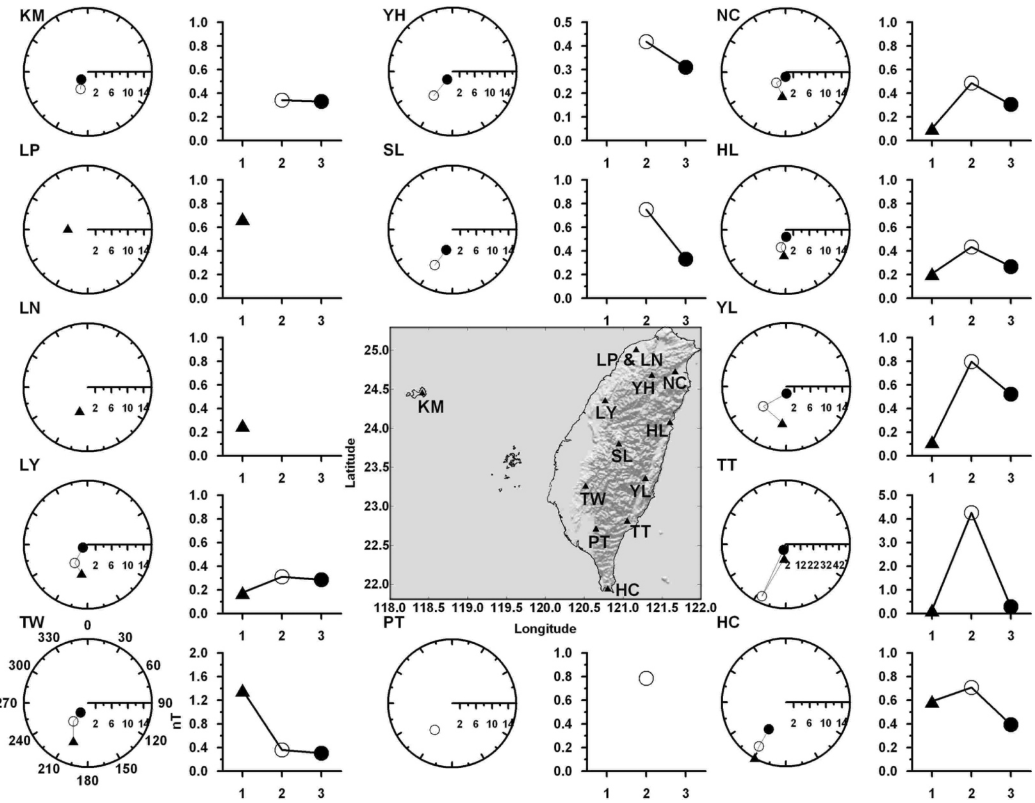

Fig. 5. The ${}_1$, S_1, and error during the three phases. The radius and azimuths of the right panels respectively denote S_1 and ${}_1$. The errors are shown in the left panels at each station. The symbols, ▲ (1), ○ (2), and ●(3), indicate the first, second, and third observation phases.

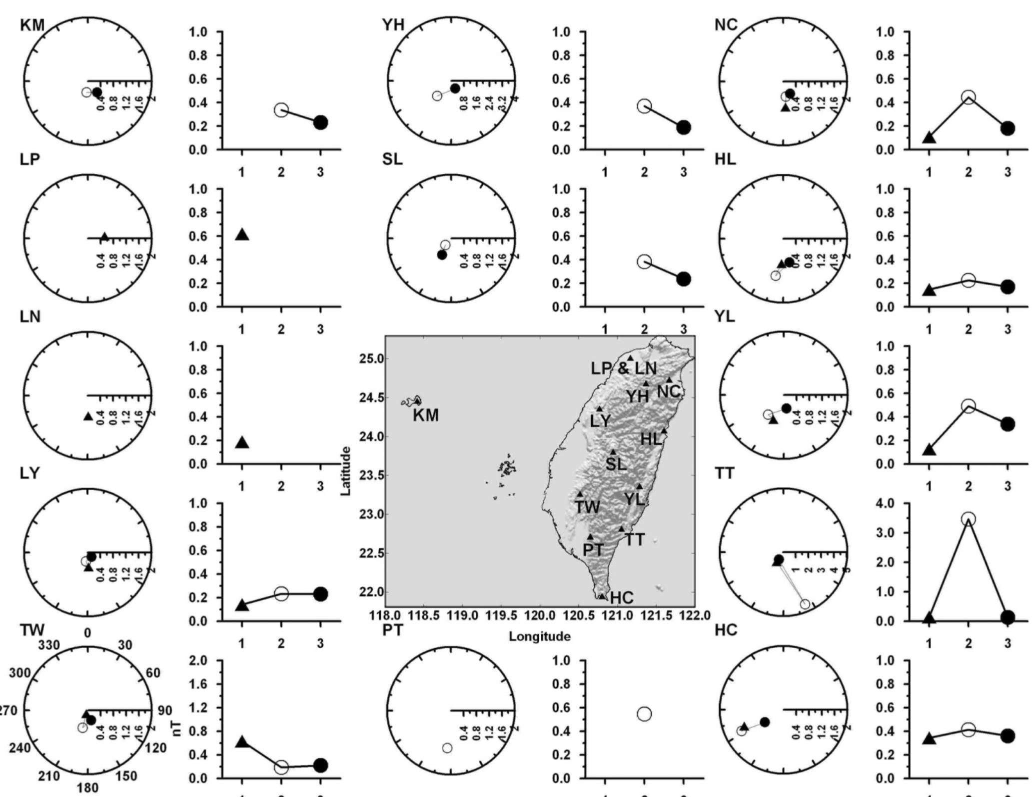

Fig. 6. The ${}_2$, L_2, and error during the three phases. The radius and azimuths of the right panels respectively denote L_1 and ${}_1$. The errors are shown in the left panels at each station. The symbols, ▲ (1), ○ (2), and ● (3), indicate the first, second, and third observation phases.

4. DISCUSSIONS AND CONCLUSIONS

To prove our results, we count the standard deviations (STDs) from the 24 hourly values of a single day to represent daily disturbance degrees. Then, second standard deviations (STD_{nd}s) (listed in Table 1) as determined by the STDs reveal the disturbance degree in the analyzed temporal periods. Note that station HC, which has the largest daily variations, is located along the seashore at the southern end of Taiwan and has large STD_{nd}s. During the first phase, small STD_{nd}s are found at HL, LN, LY, NC, TT, and YL. LP and TW have large STD_{nd}s, this is consistent with the results analyzed by the Chapman-Miller method (Figs. 3 and 4). The STD_{nd}s in the second phase are generally smaller than them in the first one due to the short observation period. However, STD_{nd}s in HC, HL, PT, SL, TT, YH, and YL are larger than the mode of the stations implying disturbance interference in the second phase. By contrast, large STD_{nd}s are only obtained at TT and TW indicating that most stations become normal in the third phase. Although, when examining the data, we can roughly count STD_{rd}s, it is difficult to determine a critical value for declaring a disturbance due to differences in the temporal periods.

After denoting the behaviors of the S and L variations in the geomagnetic total intensity field, we have provided an example explaining how to use such data. Geomagnetic anomalies associated with earthquakes have been observed in many studies (Hayakawa and Fujinawa 1994; Hayakawa 1999; Hayakawa and Molchanov 2002). Pre-earthquake anomalous phenomena are generally considered to be the results of pressed rocks producing currents (piezomagnetism effect) (Johnston 1997; Nishida et al. 2004) or a new geomagnetic field existing before an earthquake occurs (Chen et al. 2009). Large pre-earthquake anomalies up to 150 nT were observed two months before the Chi-Chi earthquake and disappeared after the Chia-Yi earthquake (Yen et al. 2004; Liu et al. 2006). Because these large anomalies were observed for the first time, scientists generally question these observed disturbance and the magnetometers used to measure them. However, daily variations are evident in the station records and these can help in answering such questions. In this study, the behavior of the geomagnetic total intensity field in normal functioning magnetometers (as determined by the Chapman-Miller method) can be understood. By ways of a further example, the Chapman-Miller method is again employed here to prove that the magnetometers were normal during the Chia-Yi earthquakes (1999/10/22, M_w = 5.9) (Chan and Ma 2004; Chang and Wang 2006). Figure 7a shows that large S_1 decreases with the order of the harmonics at TW between September and October in 1999. This suggests that daily variations are still in existence and the magnetometer was operating normally during the Chia-Yi earthquake. Because the L variation is small and easily disturbed, L_3 instead of L_2 becomes the largest variation (bottom of Fig. 7a). After the Chia-Yi earthquake occurred, the S and L variations returned to normal as shown in Figs. 7b and c.

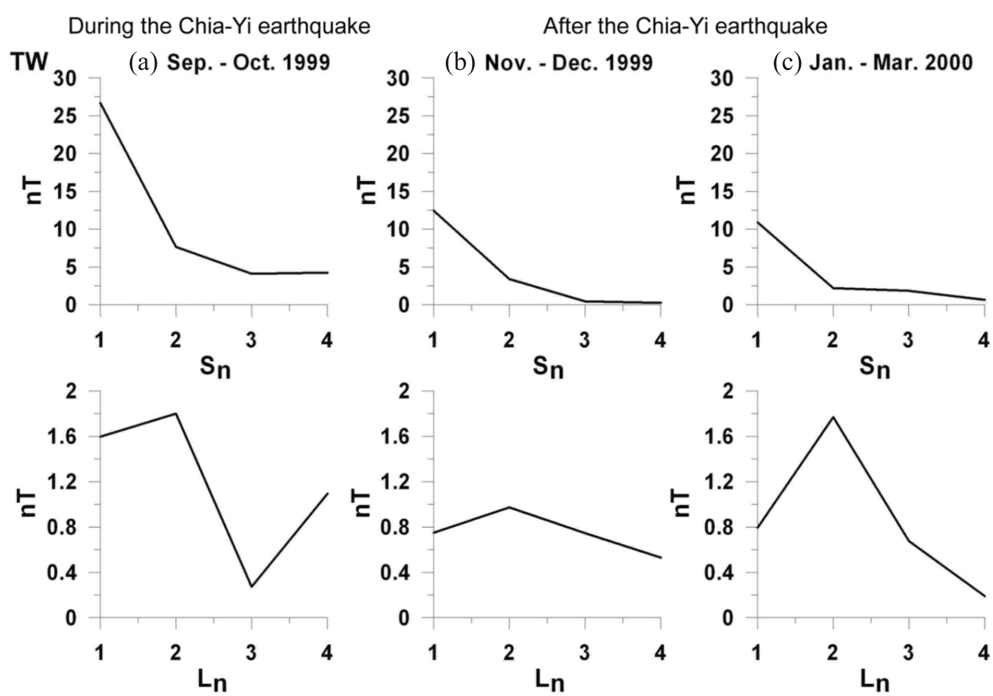

Fig. 7. The S and L variations at TW during the Chia-Yi earthquake. The upper and lower panels respectively denote the S and L variations, the numbers on the x-axis are the orders of harmonics. The variations during the three periods, September - October 1999, November - December 1999, and January - March 2000 are shown with (a) to (c).

In conclusion, the Chapman-Miller method can be employed for geomagnetic total intensity field measurement. The results show that S_1 and L_2 are the major harmonics respectively in the S and L variations. These variations are greatest in the summer and least in winter for geomagnetic total intensity. These results are in agreement with previous studies. It is clear from this study that the Chapman-Miller method can be employed to identify whether or not the geomagnetic field has been disturbed and also if magnetometers are functioning normally.

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