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A statistical study on ELF-whistlers/emissions and $M \geq 5.0$ earthquakes in Taiwan

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[1] In this paper, we conduct statistical approaches to study the potential relation between ELF-whistlers/emissions below 100 Hz and 20 $M \geq 5.0$ earthquakes occurred in Taiwan in the period from 26 August 2003 to 13 July 2004. Occurrence ratios of the ELF-whistler and ELF-emission of the entire study period are computed as the reference backgrounds. Our study shows that the ELF-whistlers and ELF-emissions during the earthquake period appear less and more frequently than their associated backgrounds, respectively. For the ELF-emission, the larger earthquakes generally yield the higher occurrence ratios. The statistical analyses confirm that the occurrence ratios of the ELF-emission significantly enhance 5–7 days before the earthquakes and are proportional to the earthquake magnitude but inversely to the distance from the observatory to the epicenter.

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1. Introduction

[2] Electromagnetic signals from 10^{-3} to 10^{8} Hz associated with earthquakes have been studied for several decades [see, e.g., *Parrot*, 1990; *Hayakawa and Fujinawa*, 1994; *Hayakawa*, 1999; *Hayakawa and Molchanov*, 2002a, 2002b, 2008]. *Hayakawa et al*. [1993] studied the influences of seismic activity on the propagation of magnetospheric whistlers at low latitudes and found that whistlers with anomalously increased dispersions frequently occur before and after earthquakes. Moreover, there have been several convincing reports of ULF/ELF emissions for recent $M \geq 7.0$ large earthquakes [*Fraser-Smith et al*., 1990; *Molchanov et al*., 1992; *Hayakawa et al*., 1996; *Hayakawa et al*., 2000; *Ohta et al*., 2001; *Du et al*., 2002; *Hayakawa et al*., 2005; *Schekotov et al*., 2007; *Huang* 2011; *Rong et al*., 2012]. Although event studies of ULF/ELF whistlers and emissions prior to large earthquakes are reported, more efforts should be taken in studying general and detailed phenomena of electromagnetic signals ranging from 50 to 100 Hz corresponding to earthquakes.

[3] Taiwan is located in an active part of the Circum-Pacific seismic belt. The interaction between the northwestward moving Philippine Sea plate and Eurasia plate results in an intense and complicated geological structure; therefore, a large number of earthquakes often occur in a rather small region during a relatively short time period. The average recurrence time of the $M \geq 5.0$ earthquakes in Taiwan is about 2 weeks, 12–16 days [for example, see *Liu et al*., 2004; *Liu et al*., 2006a]. The high occurrence rate of such large earthquakes provides an excellent chance to statistically examine seismo-electromagnetic signals.

[4] The ELF system in Taiwan has been established for the global monitoring of lightning activities and ELF events since August 2003. Up to now, in addition to the lightning and Schumann resonance signatures, other two major types of signals below around 100 Hz have been observed. *Wang et al*. [2005], for the first time, reported low-latitude ELF whistler-like events with frequencies between 60 and 100 Hz, and termed them to be "ELF-whistlers". Similar events had also been observed in Alaska, California, and the South Pole; several mechanisms including the tail of lightning-generated VLF whistlers have been suggested, but there are no solid conclusions [*Heacock*, 1974; *Sentman and Ehring*, 1994; *Kim et al*., 2006]. Recently, *Wang et al*. [2011] had proposed the wave mode of these observed whistler-like events to be Class III ion-cyclotron ELF-whistlers,

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Table 1. $M \geq 5.0$ Earthquakes in Taiwan During 26 August 2003 to 13 July 2004

No.	Year	Month	Day	Hour	Minute	Latitude (°N)	Longitude (°E)	Depth (km)	M	Group Type
1	2003	09	11	06	55	22.709	121.399	85.36	5.76	CLA
2	2003	10	10	20	51	24.006	122.555	37.62	5.07	ORP
3	2003	11	12	08	02	24.453	121.953	21.29	5.39	ORP
4	2003	12	06	14	34	23.074	121.360	37.82	5.14	CLA
5	2003	12	10	12	38	23.066	121.398	17.73	6.42	CLA
6	2003	12	11	08	01	22.791	121.391	33.58	5.39	CLA
7	2003	12	16	21	56	23.116	121.341	20.27	5.02	CLA
8	2003	12	18	00	27	22.605	121.311	32.2	5.43	CLA
9	2003	12	29	21	41	24.595	121.964	68.19	5.21	ORP
10	2004	01	01	11	15	23.335	121.711	24.88	5.35	ORP
11	2004	01	29	03	13	22.992	120.952	6.69	5.15	TCM
12	2004	02	04	11	23	23.380	122.149	17.36	5.64	ORP
13	2004	05	01	15	56	24.075	121.528	21.55	5.25	TCM
14	2004	05	08	16	02	21.925	121.639	6.61	5.59	CLA
15	2004	05	10	04	06	24.569	121.766	69.16	5.49	TCM
16	2004	05	15	13	07	24.860	121.900	91.59	5.12	ORP
17	2004	05	16	14	04	23.050	121.979	12.85	5.72	ORP
18	2004	05	19	15	04	22.713	121.369	27.08	6.03	CLA
19	2004	06	03	00	56	23.637	121.289	14.65	5.17	TCM
20	2004	07	06	15	32	24.897	122.265	5.96	5.22	ORP

yet the source mechanism is still not determined. Therefore, the source of these events has remained unsolved. The other type of observed signals is named as "ELF-emissions", following the name "VLF emissions" given in *Helliwell* [1965] for their similar features on the *f-t* spectrograms. The shapes of these emissions on the *f-t* spectrograms are not as regular as the observed ELF-whistlers. Though the wave–particle interaction occurred at the ionosphere and

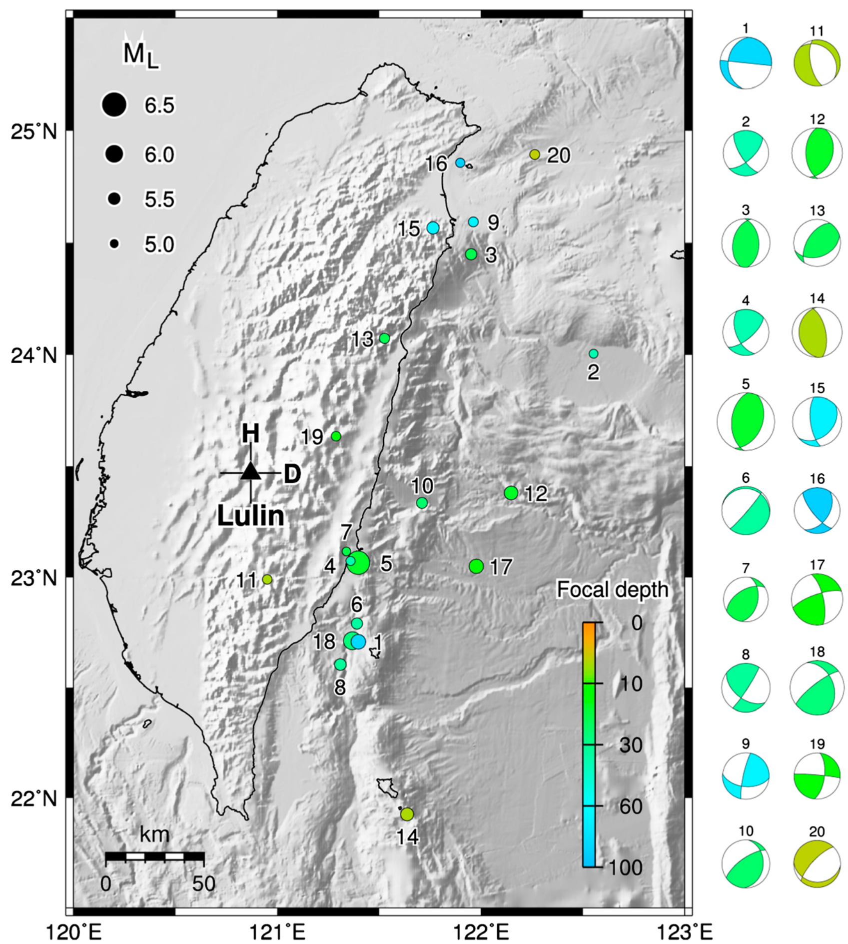

Figure 1. Locations of the ELF system at Lulin and 20 $M \geq 5.0$ earthquakes in Taiwan during 26 August 2003 to 13 July 2004.

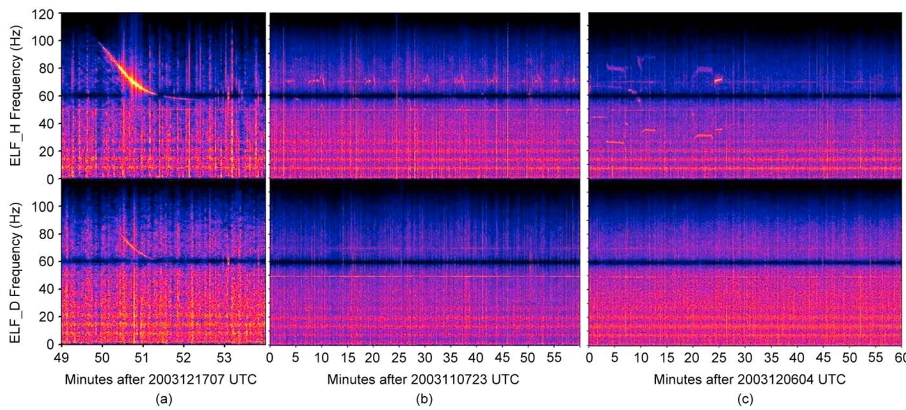

Figure 2. A typical ELF-whistler and ELF-emission observed in Taiwan. (top row) H component (north-south). (bottom row) D component (east-west) of the magnetic field signals. (a) ELF-whistlers 07 UT, 17 December 2003; (b) quasi-periodic ELF-emissions, 23 UT, 07 October 2003; and (c) discrete ELF-emissions, 04 UT, 06 December 2003.

magnetosphere has been the mostly discussed mechanism to produce VLF emissions in *Helliwell* [1965], the possibility for the ELF-emissions to relate to the earthquakes cannot be ruled out for there have been relevant reports regarding ULF/ELF emissions below 50 Hz [*Dea et al*., 1991, 1993; *Ohta et al*., 2002, 2003]. In this paper, simply out of curiosity, we would like to find out if there is any relationship between ELF-whistlers/emissions observed by the system and the 20 $M \geq 5.0$ earthquakes (Table 1) that occurred in Taiwan from 24 August 2003 to 13 July 2004 (Figure 1).

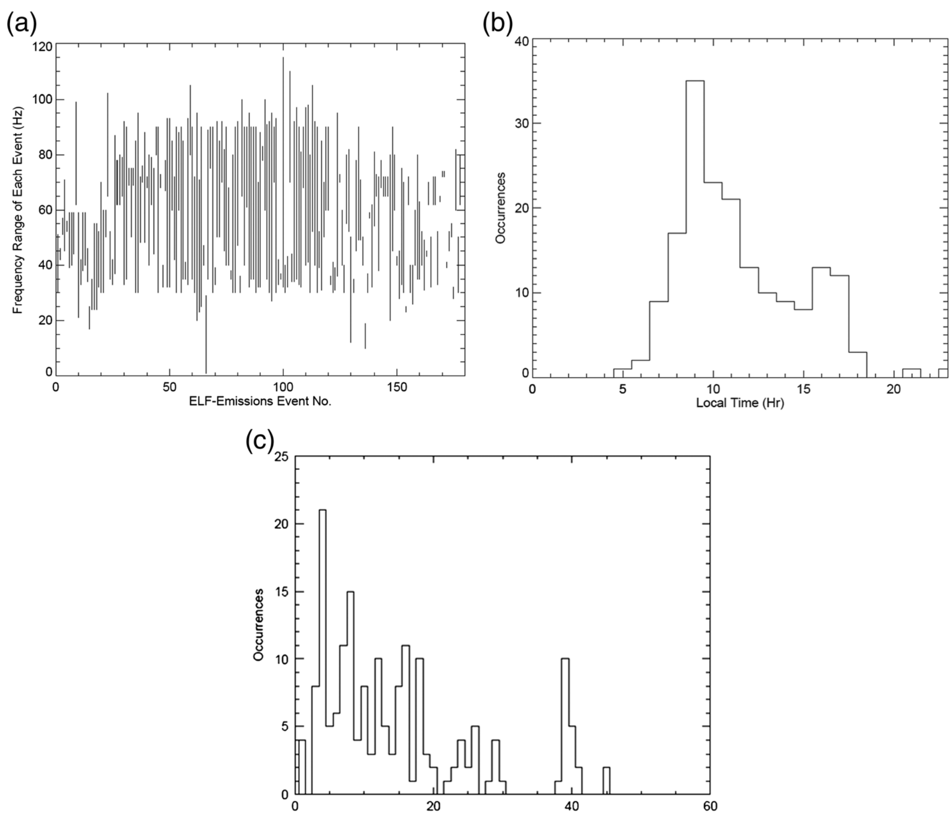

Figure 3. Characteristics of the observed 178 ELF-emissions. (a) The frequency range for each detected event. (b) Distribution of the local hour of occurrence for the events. (c) Numbers of occurrence for these events and the values of *Ap* at the corresponding occurrence day.

Table 2. Comparison of ELF-Whistlers and ELF-Emissions Observed in the Lulin Station

Observations	ELF-Whistlers	ELF-Emissions
Frequency	60–100 Hz	1–115 Hz
Patterns on *f-t* Spectrograms	Frequency Generally Decreases as Time Increases	No Regular Tendency
Local Time	Daytime Maximum	Daytime Maximum
Amplitude	A Few pT to 70 pT	A Few pT to 30 pT
Magnetic Field	N-S Dominates	N-S Dominate
Correlation with *Ap*	Not Obvious	Not Obvious

2. Instrument and Observation

[5] The ELF system consists of both the magnetic and electric antennas. The BF-4 magnetic field induction sensors with its antenna is located at Lulin Observatory (23.47°N, 120.87°E; 2862 m altitude; 16.76°N geomagnetic) on the central ridge of Taiwan (Figure 1). The range of receiving frequency is from 1 to 200 Hz and notch-filtered at both 60 and 120 Hz. The response of the receiver drops below 10% for signals with frequencies higher than 100 Hz. The signals are sampled by a 16-bit analog to digital converter at a rate of 400 Hz. Both north–south (H) and east–west (D) components of magnetic fields on the horizontal plane are measured. The 60 m long wire ELF electric field antenna is located at National Cheng Kung University (23.00°N, 120.22°E, 32 m altitude) about 100 km south of Lulin. The preamplifier has a gain of 100 and 50 dB notch filters at 60 and 120 Hz. The system receives electric fields at the same frequency range as the magnetic ELF system by using the same signal conditioning and notch filtering module.

[6] From 24 August 2003, the station started to provide analyzable data. It is discovered that the electric field signals are rather weak; therefore, we focus on the magnetic fields. During about a 12 month period of observation until 13 July 2004, when the system was damaged by lightning, 310 events of ELF-whistlers that featured frequencies from 60 to 100 Hz were detected [*Wang et al.*, 2005]. They generally resemble conventional lightning-generated VLF whistler patterns: descending frequencies with increasing time (Figure 2a), but the related theory cannot interpret their long dispersion (5500 s $Hz^{1/2}$). The relation between these observed ELF-whistler occurrence times versus local times was found to appear between 05 and 20 LT,(local time, LT = UT + 8 h), with three peaks during 09–10, 14–15, and 18–19 LT.

[7] Figures 2b and 2c show examples of detected ELF-emissions. It can be seen that their patterns in the *f-t* spectrograms are markedly different from those of the ELF-whistlers. Some events are quasi-periodic (Figure 2b), but most are discrete emissions with combination forms (Figure 2c), mixtures of rising, falling, and hook patterns, as classified in *Helliwell* [1965]. In total, 178 emission events are detected; among them, 53 are quasi-periodic, and 125 are discrete. The frequencies of these emissions are found to range from as low as 1 to up to 115 Hz, but most of them are between 30 and 90 Hz (Figure 3a). No preferential trend is found between frequency and time for these ELF-emission events. All 178 events possess H component of magnetic field; among them, only 40 events also possess a weak D component. Therefore, the detected magnetic field signals have linear polarizations dominated in north-south direction. The average polarization direction is east to north 76.44° with standard deviation of 24.7°. If the source waves of these signals have propagated perpendicularly to the measured polarization direction, they could cover a wide range approximately from east to southeast where the earthquakes mostly occur (also see Figure 1). Figure 3b is the histogram of numbers of occurrences versus the occurred local time, which displays that the ELF-emissions occur mainly at the daytime from 05 to 18 LT with a few events at 21 and 23 LT. This is very different from the occurrences of ELF-

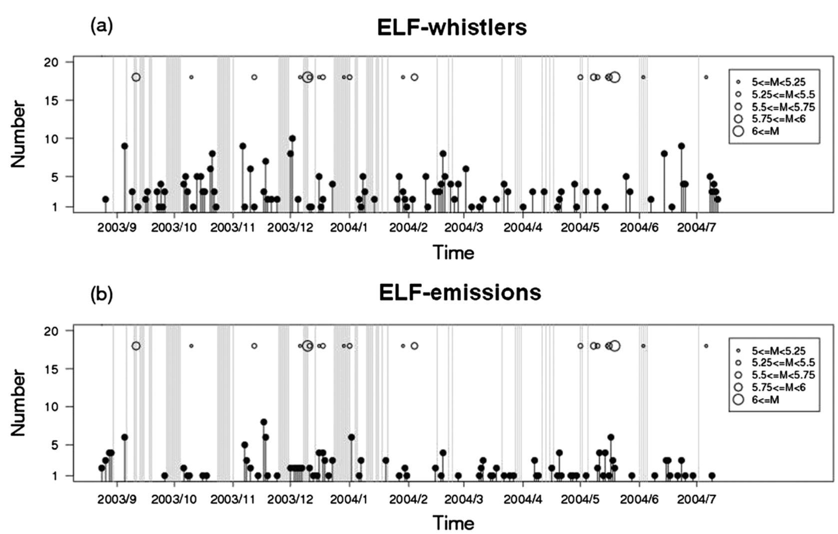

Figure 4. The $M \geq 5.0$ earthquakes and occurrence numbers of the (a) ELF-whistlers and the (b) ELF-emissions observed in Taiwan during the study period of 26 August 2003 to 13 July 2004. There are 323 days in the study period, and the ELF system has several data gaps (denoted by gray lines) and is operated in 253 days. The dotted solid lines display the 310 ELF-whistlers and 178 ELF-emissions which appear in 93 and 82 days during the study period, respectively.

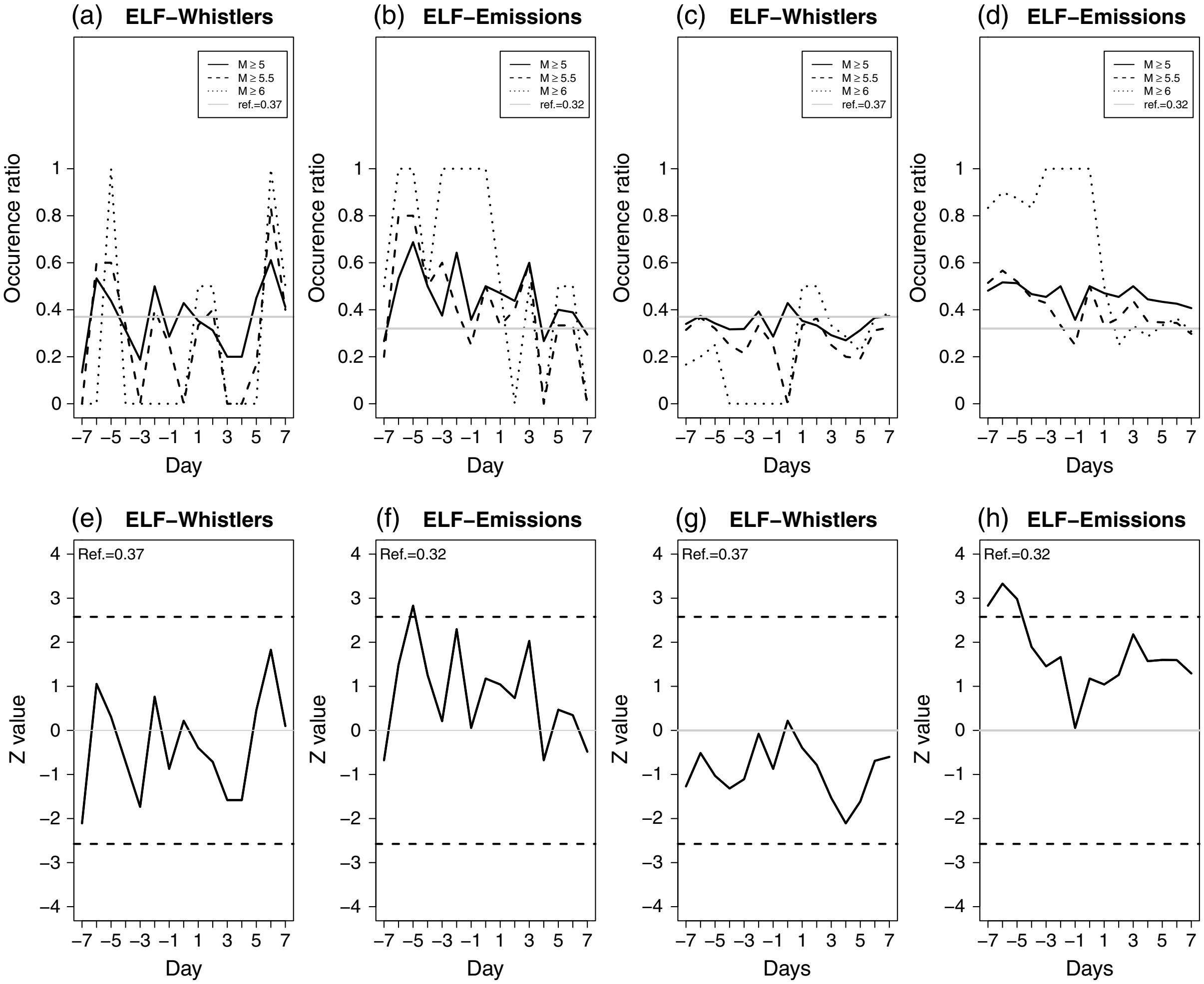

Figure 5. Occurrence ratios and the corresponding *z*-test of the ELF-whistlers and ELF-emissions for 20 $M \geq 5.0$, 6 $M \geq 5.5$, and 2 $M \geq 6.0$ earthquakes. Occurrence ratios of the (a) ELF-whistlers and (b) ELF-emissions of the (c) individual-day study as well as those for the (d) cumulative-day study, respectively. (e–h) The corresponding *z*-test results, where dash lines are the upper and lower critical values of the level of significance $\alpha = 0.01$. To perform a sufficiently statistical analysis, it requires a certain amount of sample size. In such concern, we made the statistical test on those of the $M \geq 5$ earthquakes only.

whistlers which are never detected after 20 LT. Moreover, the correlation of these events and geomagnetic activities are also examined by comparing with the corresponding *Ap* and *Dst* indexes for all the observational days. The correlation coefficient is around zero so that these detected events are not essentially related to the geomagnetic disturbances. Figure 3c displays the distribution of occurrences versus the corresponding *Ap* index. Approximately 90% of the events occurred at quiet time ($Ap < 29$), only 10% occurred at minor storm time ($29 < Ap < 50$). Table 2 summarizes the comparison of ELF-whistlers and ELF-emissions observed at the ELF system of Lulin station.

3. Data Analysis

[8] The 20 $M \geq 5.0$ earthquakes occurred from 24 August 2003 to 13 July 2004 (325 days), while the ELF system had some data gaps and was operated in 253 days during the 325 day study period (Figure 4). During the ELF observation period, 310 ELF-whistler and 178 ELF-emission events appear in 93 and 82 days, respectively. Consequently, the associated overall (background) occurrence ratios are 0.37 (93 days/253 days) and 0.32 (82 days/253 days), respectively. Figure 4a reveals no clear relationship between the ELF-whistlers and the earthquakes. Vice versa, in Figure 4b, it is interesting to find cluster features of the two quantities that the occurrence number of ELF-emissions increases few days before the larger magnitude earthquakes, which are rather clear for the earthquakes before 11 September 2003 (M5.76), 10 December 2003 (M6.42), and 19 May 2004 (M6.03). Other time, with less/smaller earthquakes, the occurrences of ELF-emissions are not that many. Although the origins from artificial interference may not be completely excluded, the preferential clustered occurrences suggest their association with earthquakes being worth to be examined. Since the average recurrence of the 20 $M \geq 5.0$ earthquakes is 16.25 days (=325 day/20 earthquakes), we examine the occurrences of the ELF-whistlers and the emissions within 7 days before and after the earthquakes to avoid possible confounded effects.

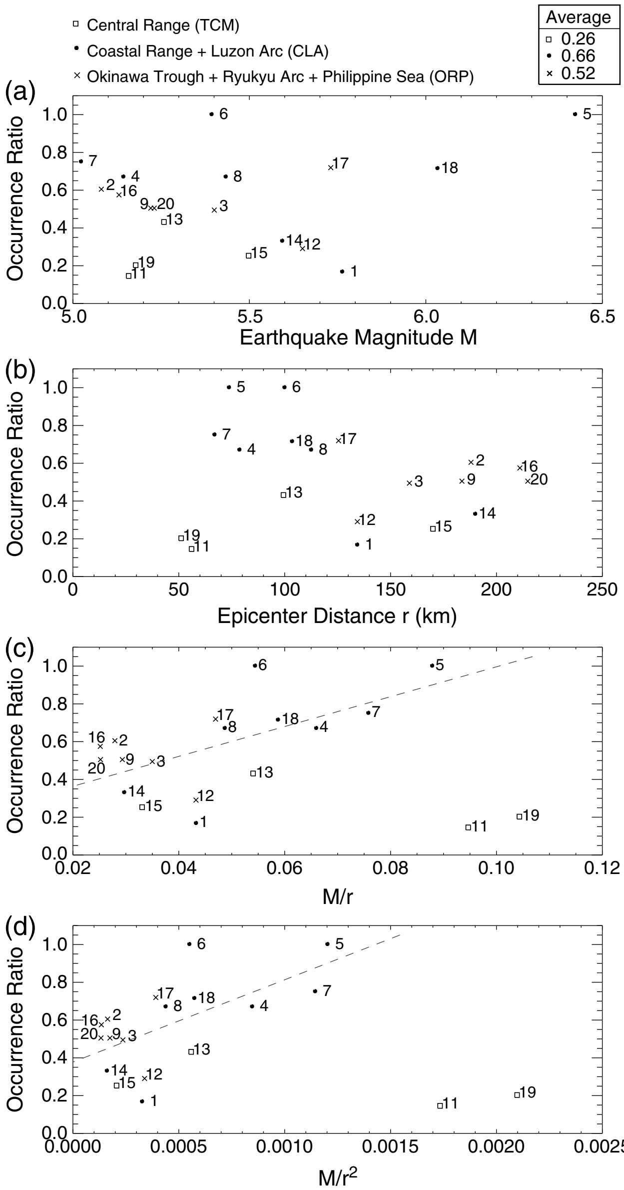

Figure 6. The average occurrence ratio within 7 days prior to each earthquake categorized by the epicenter's geographical location as denoted at the top. The ratio is the proportion of the numbers of occurrence days to the data of valid days within 7 days. The average ratio for each category is shown at the right top corner. The ratio versus (a) earthquake magnitude M, versus (b) the distance (r) from the station to the epicenter, versus (c) M/r, and versus (d) M/r^2. The earthquake numbers from Table 1 are marked. The distance r is derived from Table 1 for each earthquake. Note that there are no valid observational days prior to event no. 10. The dashed line ($OR = 435.330\,M/r^2 + 0.377828$) denotes the linear correlation without nos. 11 and 19, where *RO* is the average occurrence ratio.

[9] Our study considers two types of the occurrence ratios for both the ELF-whistlers and ELF-emissions during the 14 day period regarding to the earthquakes: individual-day study and cumulative-day study. Furthermore, we group the earthquakes into three categories: 20 $M \geq 5.0$, 6 $M \geq 5.5$, and 2 $M \geq 6.0$. The individual-day study focuses on the occurrence ratios on each individual day (Figures 5a and 5b) from the earthquake day denoted as day 0. In contrast, the cumulative-day study considers the occurrence ratios in the period between a specific day and the earthquake day (Figures 5c and 5d). It is interesting to find that for either the individual-day or cumulative-day study, the occurrence ratios of the ELF-whistlers during the earthquake period are slightly less than the associated backgrounds (Figures 5a and 5c), while those of the ELF-emissions are greater than the associated backgrounds (Figures 5b and 5d). In detail, for the individual-day study, the occurrence ratios of the ELF-whistlers fluctuate around or below the background but show no clear difference before and after the earthquakes (Figure 5a). However, the occurrence ratios of the ELF-emissions generally are greater than the associated background and show a decreasing tendency that the occurrence ratios of the ELF-emissions before the earthquake are greater than those after (Figure 5b). Similar results are also observed in the cumulative-day study (Figures 5c and 5d). For either the individual-day or cumulative-day study, greater occurrence ratios of the emissions usually accompany with larger earthquakes.

[10] To see if the occurrence of the ELF-whistlers or ELF-emissions is significantly related to the earthquakes, we apply the z-test [*Neter et al.*, 1988; *Agresti*, 2002] based on the statistic

$$z = \frac{p\text{-}p_0}{\sqrt{\frac{p_0(1\text{-}p_0)}{n}}},$$

where n, P, and P_0 denote the number of days, the occurrence ratio regarding the earthquakes, and the associated background ratio, respectively. Specifically, for the individual-day study, the n of each individual day is equal to the number of the earthquakes, and for the cumulative-day study, the n of each specific period is equal to the sum of the days in the period along with all the earthquakes. In the z-test, we consider a conservative significance level at 0.01, preferring to the fashion of indifference between the occurrence ratio regarding the earthquakes and the associated background ratio. Hence, if the absolute value of z is larger than 2.57, we claim that the occurrence ratio and its background are significantly different. For the individual-day study, all the z-tests show that the occurrence ratio of ELF-whistlers is not significantly different from its background ratio (Figure 5e), while the occurrence ratio of ELF-emissions is significantly different from, in fact, larger than its background ratio on day 5 before the earthquake (Figure 5f). For the cumulative-day study, the occurrence ratio and background ratio of ELF-whistlers are, again, not significant (Figure 5g). However, the occurrence ratio of the emissions is now significantly away from its background ratio on days 5–7 before the earthquake occurred (Figure 5h).

[11] We also examine whether there is a preferential geographical distribution of the epicenters corresponding to higher occurrence ratios of ELF-emissions during the pre-earthquake period (cumulative-7 days before each earthquake). Based on the geographical property in Taiwan, the earthquakes listed in Table 1 or shown in Figure 1 are classified into three groups. First, event nos. 11, 13, 15, and 19

Table 3. Correlations Between the Occurrence Ratio and Magnitude or Distance

EQK Region (No.)	TCM (4)	CLA (8)	ORP (8)	Total (20)	Total – TCM (16)
Occurrence Ratio	0.26	0.66	0.52	0.53	0.60
M	0.25	0.10	−0.13	0.27	0.16
R	0.35	−0.72	0.08	−0.14	−0.55
M/r	−0.58	0.72	−0.05	0.05	0.63
M/r^2	−0.64	0.67	−0.01	−0.08	0.63

are distributed along the central range of Taiwan, which is the mountain (TCM) area. Second, event nos. 1, 4, 5, 6, 7, 8, 14, and 18 are grouped into the coastal range connecting to the Luzon Arc (CLA) and nearby. Third, event nos. 2, 3, 9, 10, 12, 16, 17, and 20 are all located at sea, covering from Okinawa trough, heading south to Ryukyu arc and the Philippine Sea (ORP). Figure 6 depicts the occurrence ratio of ELF-emissions of each earthquake, which is the proportion of the number of days with ELF-emissions to that of observation days within 7 days prior to the earthquake. The average occurrence ratios are denoted at the top right corner of the three geographical groups, which show that CLA yields the highest value (0.66), ORP is the second (0.52), and TCM is the lowest (0.26). Note that the occurrence ratio of TCM is less than that of the associated background (0.32). It can be seen that event nos. 5 and 11 yield the highest and lowest occurrence ratios, respectively, among the 20 studied earthquakes. Although it is rather scattered, Figure 6a (Figure 6b) reveals that the occurrence ratio of the ELF-emission tends to be proportional (inversely proportional) to the earthquake magnitude M (the distance r from the Lulin Observatory to each epicenter). On the other hand, if event nos. 11 and 19 in the central range are degraded, the rest occurrence ratio of the ELF-emission seems to be well correlated with M/r^2, with the correlation coefficient 0.62 and 95% confidence interval (0.45 and 0.69) (Figure 6c).

4. Discussion and Conclusion

[12] Whistlers are the VLF waves which originate in the lightning discharges in the opposite hemisphere and have propagated in the magnetosphere along the magnetic field lines [*Helliwell*, 1965; *Walker*, 1976; *Hayakawa and Tanaka*, 1978; *Park*, 1982]. *Hayakawa et al*. [1993] examined whistlers at Sugadaira (25°N geomagnetic) and found that anomalous whistlers, the dispersion value of which is greater than twice the typical (background) value, exhibit a substantial increase in occurrence during seismic activity in the geographic longitude sector of 100°E–160°E during 1970–1978. However, observations recorded at Lulin (16.76°N geomagnetic) show that the relationship between the ELF-whistlers and the earthquakes within a radius of about 400 km is insignificant in Taiwan during 2003–2004. The discrepancy might be due to the whistler type examined in this study and that in *Hayakawa et al*. [1993] being different, in terms of the frequency range so as to the propagation paths.

[13] *Hayakawa and Tanaka* [1978] found that whistlers at low latitudes (10°–20°N geomagnetic) are also trapped in field line ducts as in the case of high- and middle-latitude whistlers [*Park*, 1982]. Therefore, in *Hayakawa et al*. [1993], it could be possible that seismogenic emissions and/or discharges either trigger the anomalous whistlers or disturb the typical lightning-related whistlers at the conjugate point in the geographic longitude sector of 100°E–160°E of the southern hemisphere, which then propagate along field lines and are recorded at the Sugadaira station. By contrast, *Wang et al*. [2005] found that the observed ELF events at Lulin contain no echoes and, hence, are not likely to be formed from whistlers bouncing along the same field line. Note that the earthquakes occur very near the Lulin station ($L = 1.09$; 16.76°N geomagnetic); therefore, even the local earthquakes somehow trigger and/or disturb the ELF-whistlers, which shall travel away from and can unlikely be observed in Taiwan. This might explain why the occurrence ratios of the ELF-whistlers during the earthquake period are even less than those of the associated background, as shown in Figures 4a and 4c. The results of *Hayakawa et al*. [1993] and of the current study seem to suggest that the seismo-related whistlers are most likely observed at the conjugate points of earthquake epicenters [cf. *Lagoutte et al*., 2006].

[14] By contrast, the results show that the occurrence ratios of the ELF-emissions are generally greater than the associated background during the earthquake period, the occurrence ratios before the earthquake are greater than those after, and the larger the earthquake yields, the greater the occurrence ratio. The detailed study shows that the average occurrence ratio of the earthquakes of CLA yields the highest average value (0.66), ORP takes the second (0.52), and TCM is the lowest (0.26). A common representation of the focal mechanism in seismotectonic studies is shown by means of the projection of the focal sphere with quadrants of compressions and dilations in black and white. This type to various types of faults (strike-slip, vertical, normal, and revise/thrust) is together with projections of the focal sphere onto a vertical plane [*Udías*, 1999]. Figure 1 illustrates the type of fault with the associated depth information of the 20 earthquakes. Event no. 5, the 2003 Chengkung earthquake (*Mw* 6.8), is the largest magnitude event and yields the greatest occurrence ratio in this study, occurred at a focal depth in the range of 10–25 km in eastern Taiwan. The aftershocks show a fault-bend at a depth of 18 km. Estimated coseismic displacements constrain two fault planes: one at 5–18 km depth dipping 60°E, and the other at 18–36 km depth dipping 45°E. The uppermost fault plane of the Chihshang Fault (0–5 km) did not break immediately after the main shock; however, it may have a major role in after-slip and even in interseismic ground deformation [*Wu et al*., 2006]. It can be seen that the two outliers, event nos. 11 and 19, which are the nearest to the Lulin Observatory, are in TCM and yield rather low occurrence ratios among the studied earthquakes (see Figure 6). The extension mechanism of event no. 11 and the strike-slip mechanism of event no. 19 take place beneath the Central Range at a shallow depth (< 15 km). In contrast, the compression mechanism causes the other events in TCM, lying on high occurrence ratios and playing an import role in dominating the ELF-emissions. Therefore,

possible causal mechanisms could be electric field and/or current generated by the crust subjected to physical stress via the piezoelectric effect [*Huang*, 2002]. In the northeastern part of Taiwan, event nos. 3, 9, 15, 16, and 20 can be separated to shallower and deeper groups. Event nos. 9, 15, and 16 that occurred in the Wadati-Benioff zone beneath the southernmost Ryukyu arc show focal mechanisms in downdip extension. However, those events are far away from the Lulin observatory and are in smaller magnitude. Nevertheless, the results suggest that the chance of observing (or occurrence ratio of) ELF-emissions before the earthquakes possibly is related to the underground structure, tectonic environment, focal mechanism [*Liu et al.*, 2006b], stress level [*Uyeda*, 2009], forthcoming earthquake magnitude, distance from the observatory to the epicenter, etc.

[15] One of the problems is the clustering of the catalog. Although, the 7 days before and after the earthquake seems to be a good time interval for unbiased estimates, some of earthquake events included in the analysis have time difference less than 7 days (for example, nos. 4, 5, 6, 7, and 8 and nos. 15, 16, 17, and 18) that might create biased estimate. It is interesting to estimate the occurrence ratio, where there is not less than 7 days between 11 earthquakes (nos. 1–3, 9–14, and 19–20) for spatial distance less than 1°. We compute the occurrence ratio of the cumulative 7 days before and after the 11 earthquake events being 0.51 (=39 / (7 × 11)) and 0.43 (=33 / (7 × 11)), respectively, which is close to that of Figure 5d. In fact, for those earthquakes occurring less than 7 days between each other, most of the associated anomalies contribute to the idea that within 7 days before and after should be nearly equal. For example, for the anomalies that occur between nos. 5 and 6, they are considered as post-anomalies for no. 5 and pre-anomalies for no. 6, respectively. The simple bin adding in Figures 5a–5d and the *z*-test in Figures 5e–5f indicate that even under some possible confounded/contaminated 7-day effects, the occurrence ratio of the emissions is significantly greater than its background ratio on days 5–7 before the earthquake occurred.

[16] Table 3 summarizes correlation coefficients between the occurrence ratio and M, r, M/r, or M/r^2 for the three earthquake groups. CLA yields the most sensible results, in which the occurrence ratio is proportional to the earthquake magnitude but inversely to the distance between the Lulin observatory and the epicenter among the three groups. Note that in CLA, the occurrence ratio vs. M/r or M/r^2 also yields the highest correlation among the groups. Similarly, when the four earthquakes in TCM are discarded (i.e., Total – TCM; or CLA + ORP), we confirm that the occurrence ratio is proportional to the earthquake magnitude but inversely proportional to the distance. Meanwhile, if the seismo-preparation energy is related to the earthquake magnitude, rather high correlations of the occurrence ratio versus M/r or M/r^2 of the events in CRL and Total – TCM (i.e., CLA + ORP) in Table 3 as well as of the overall events, except event no. 11 and 19, in Figures 6c and 6d demonstrate that the occurrence ratio of ELF-emissions is related to the energy with a point (epicenter/hypocenter) or line (fault line) geometry released from the associated earthquake.

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