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IONOSPHERIC *foF2* VARIATIONS PRIOR TO STRONG EARTHQUAKES IN TAIWAN AREA

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ABSTRACT

Many studies of the seismo-ionospheric coupling effects have been reported. On 17 July 1998(M=6.2), 20 September 1999 (M=7.3) and 22 October 1999 (M=6.4) three large earthquakes respectively struck Rei-Li, Chi-Chi and Chia-Yi in central Taiwan. The three earthquakes severely damaged structures, heavily changed landforms and disturbed geophysical environments. This paper examines variations of the ionospheric penetration frequency, *foF2*, observed by Chung-Li ionosonde station (25.0° N, 121.1° E) several days before the three earthquakes. The mean- and median-based statistical techniques are introduced to investigate the ionospheric electron density prior to the three earthquakes. Results show that the *foF2* decrease significantly before the three earthquakes.

INTRODUCTION

One goal of interest in seismology is to determine whether fault zones generate any hint of impending earthquakes. Recent discussions in the literature on this topic have been mixed, with some question as to whether large earthquakes are by their very nature unpredictable (e.g., Geller, 1991b; Geller *et al.*, 1997a, 1997b), or whether we simply need a more complete record of geophysical and geochemical data in earthquake prone areas (Aceves and Park, 1997).

The existence of "earthquake lights" associated with seismic events has been observed and discussed often (Derr, 1973; Lockner *et al.*, 1983; Hedervari and Noszticzius, 1985; Lockner and Byerlee, 1985; Derr and Persinger, 1986; Oullet, 1990). These scientists suggest lights before, during and after the earthquakes are associated with the electromagnetic radiation of rock during the period of earthquake. While Brady and Rowell (1986) suggested, based on laboratory studies of rock fracture, optical emission via an excitation process to be responsible for both electrical and optical effect, Kirschvink (2000) presumed the cause is some form of crack propagation coupled with ion flow and perhaps fluid movement.

Recently, various methods have been used to detect seismic electromagnetic signals over a wide frequency range from ULF to VHF bands (see papers listed in Enomoto *et al.*, 1997; Hayakawa, 1999). Liu *et al.* (2000) applied a median-based technique to study seismo-ionospheric signatures prior to M$\geqq$ 6.0 earthquakes in Taiwan, which is in a seismic active zone, between January of 1994 and September of 1999. They found that the ionospheric electron density between 1200 and 1700 LT could be significantly disturbed prior to such strong earthquakes. In this paper, to further understand the density perturbation, we employ both mean- and median-based techniques to study the ionospheric penetration frequency, *foF2*, prior to the three most serious earthquakes, Rei-Li (M=6.2, 17 July 1998), Chi-Chi (M=7.3, 21 September 1999) and Chia-Yi (M=6.4, 22 October 1999) during 1998-1999.

EXPERIMENT AND TECHNIQUE

An IPS-42 ionosonde at Chung-Li (25.0°N, 121.1°E) has been routinely operated recording ionogram every 15 minutes to observe the ionosphere in Taiwan area. For a typical vertical sounding, an ionogram displays the variation of virtual height of reflection with frequency, where the virtual height is equivalent to the product of one-half the time-of-flight of the transmitted radio wave and the speed of light c. Figure 1 reveals a typical ionograms recorded by the IPS-42 ionosonde at 1400LT on 20 September 1999, where the vertical and horizontal axes represent the virtual height in km and plasma frequency in MHz, respectively. Notice that there are two traces, O- and X-mode appearing on the ionogram. Based on the magneto-ionic theory (for example, see Budden, 1985), the plasma frequency is equal to the vertically reflected O-mode frequency. The greatest frequency of an O-mode trace, *foF2*, is considered to be the penetration (or largest) plasma frequency (or electron density) of the ionosphere. Since the ionosonde is routinely operated, *foF2* scaled from the ionograms can be used to monitor variations of the greatest electron density in the ionosphere with a 15-minutes time resolution.

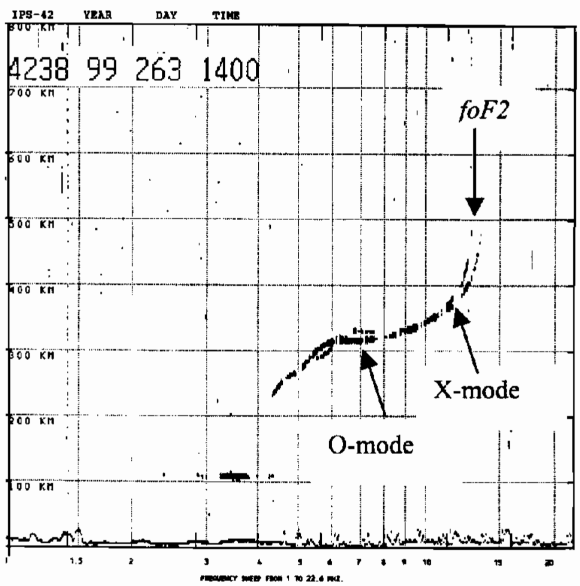

Figure 1. A typical ionogram recorded at Chung-Li on 20 September 1999.

The reoccurrence of M≧5.0 earthquakes in Taiwan area is about 15 days (Chen *et al.*, 1999). In the search for a seismic-ionospheric perturbation (earthquake precursor), to avoid the after effects and consider the average reoccurrence interval of earthquakes, Liu *et al.* (2000) and Chuo *et al.* (2000) constructed monitoring techniques by comparing *foF2* value with *foF2* median and mean values based on the previous 15-days. Liu *et al.* (2000) considered a possible earthquake precursor to be when the value of *foF2* between 1200 and 1700 LT on the 16th day previous, X_{16} were less than the associated lower bound, $LB = \tilde{X} - IQR$, where $\tilde{X}$ is the median value and IQR is the associated inter-quartile range between the upper and lower quartiles of *foF2* for the previous 15-days. Instead of median and IQR, Chuo *et al.* (2000) constructed the measure $LB = \overline{X} - \sigma$, where $\overline{X}$ and σ, respectively, are the mean and the standard deviation of *foF2* for the previous 15 days. When X_{16} is less than the associated $\overline{X} - \sigma$ between 1200 and 1700 LT, they consider that a possible earthquake related perturbation is detected.

Notice that the prediction level of $\tilde{X} - IQR$ is roughly 95%, while that of $\bar{X} - \sigma$ is only about 68%. Therefore, in this paper, we applied the techniques employed by Liu *et al.* (2000) and Chuo *et al.* (2000), except that a roughly 95% lower bound $\bar{X} - 1.5\sigma$ was used for detecting an earthquake precursory signal.

OBSERVATIONS AND RESULTS

Figure 2 illustrates the locations of IPS-42 ionosonde as well as Rei-Li, Chi-Chi and Chia-Yi earthquakes. Table 1 lists the occurrence time, location, depth and magnitude of the three earthquakes in detail. Note that the three earthquakes occurred on land with relative shallow depths. For simplicity, we plot X_{16} (solid lines) and the associated $LB = \tilde{X} - IQR$ and $LB = \bar{X} - 1.5\sigma$ (gray lines) during 0-6 days prior to each earthquake. To have a clear presentation, when the earthquake precursors, which are $X_{16} < LB$ between 1200 and 1700 LT, detected, the solid lines are marked by the bold markers. Figures 3 and 4 display results obtained by using the median and mean based techniques, respectively. It can be seen that either technique detects the precursors (denoted by "p" character) within four days prior to the three earthquakes, and the *foF2* significantly decrease during precursory days of Chi-Chi earthquake. For Rei-Li earthquake, both techniques yield the same result. However, the precursor one day before Chi-Chi earthquake and two/three days before Chia-Yi earthquake observed by the median-based technique is not detected by the mean-based method.

Table 1. The Parameters of Earthquake

YY	MM	DD	Hr	Min	Sec	Lat.(°N)	Long.(°E)	Depth(km)	M
1998	07	17	04	51	15.0	23.503	120.662	2.8	6.2
1999	09	21	01	47	12.6	23.850	120.780	8.0	7.3
1999	10	22	10	18	56.9	23.520	120.420	16.6	6.4

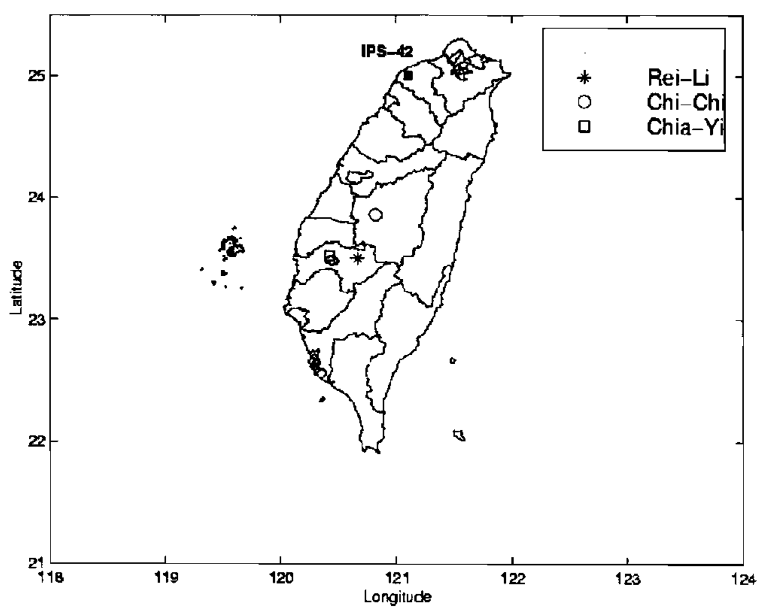

Figure 2. The locations of IPS-42 ionosonde and Rei-Li, Chi-Chi and Chia-Yi earthquakes.

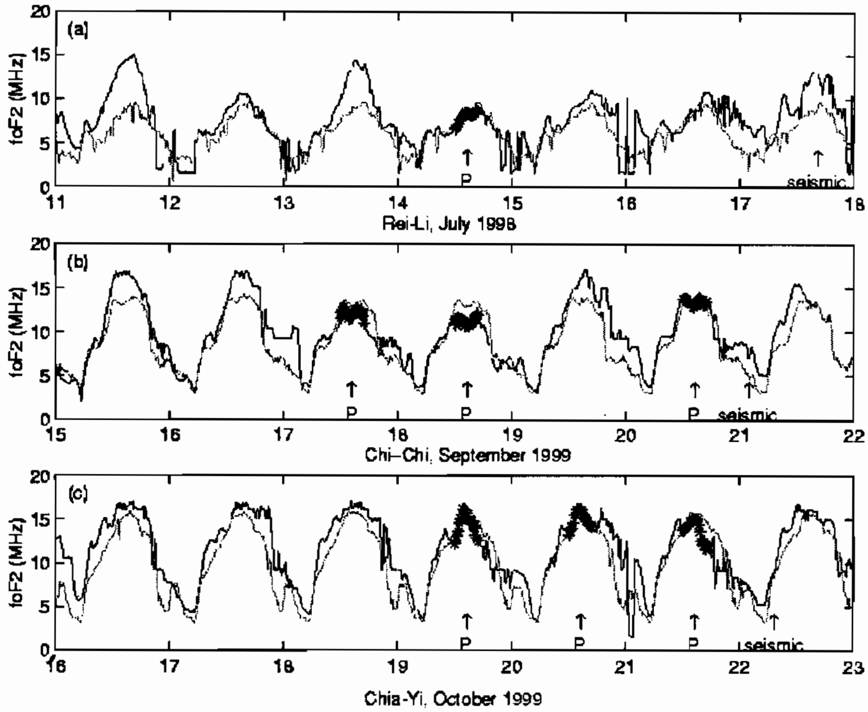

Figure 3. Observation of *foF2* and their associated median-based lower bound during 0-6 days prior to (a) Rei-Li, (b) Chi-Chi, and (c) Chia-Yi earthquakes. The solid and gray lines represent the recorded *foF2* and their associated lower bound, where the bold mark denotes the earthquake precursor.

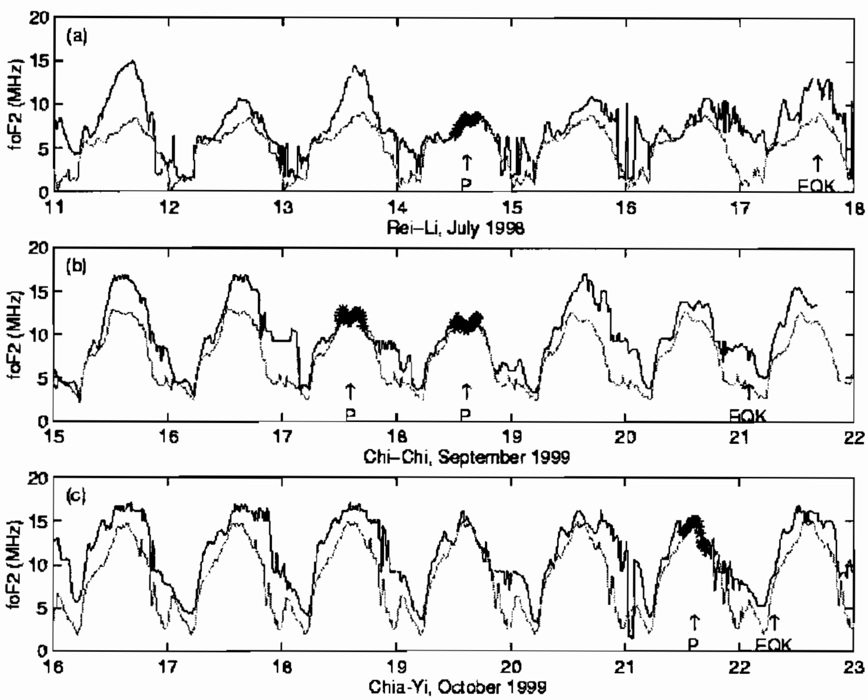

Figure 4. Observation of *foF2* and their associated mean-based lower bound during 0-6 days prior to (a) Rei-Li, (b) Chi-Chi, and (c) Chia-Yi earthquakes.

DISCUSSION AND SUMMARY

It has been known, that the *foF2* is sensitive to daily variation of the solar (EUV, F10.7) and the magnetic activities. To avoid the *foF2* anomalies come from the two activities, we check the geomagnetic Dst index and F10.7. Figure 5 show that the geomagnetic condition (solid line) and solar activity (dot line) are relatively quiet before the three earthquakes, respectively. Liu *et al.* (2000) use the median-based technique to identify the precursor of Chi-Chi earthquake, while Chuo *et al.* (2000) employ the mean-based method to detect the precursor of Chi-Chi and Chia-Yi earthquakes. This paper examines the precursors of Rei-Li, Chi-Chi and Chia-Yi earthquakes by the two techniques. Note that, due to the heavy-tailed distribution, which data yields extremely large and/or small values, of *foF2*, the URSI (International Union of Radio Science) usually report the robust statistics, including the median of *foF2*. Since the mean of *foF2* is more sensitive to the extreme small values of *foF2*, the mean-based technique is less powerful in the detection of earthquake precursors. Therefore, the detected rates of the two techniques are quite different. However, both techniques lead to the same results that Chi-Chi earthquake of magnitude M=7.3 yields the largest number of the precursors and that Rei-Li earthquake of magnitude M=6.2 has the smallest precursory number. Moreover, the strength of the precursors prior to Chi-Chi earthquake detected by using the two techniques reaches the greatest value. Therefore, it is interesting to note that the precursory strength and number are possibly related to the earthquake magnitude.

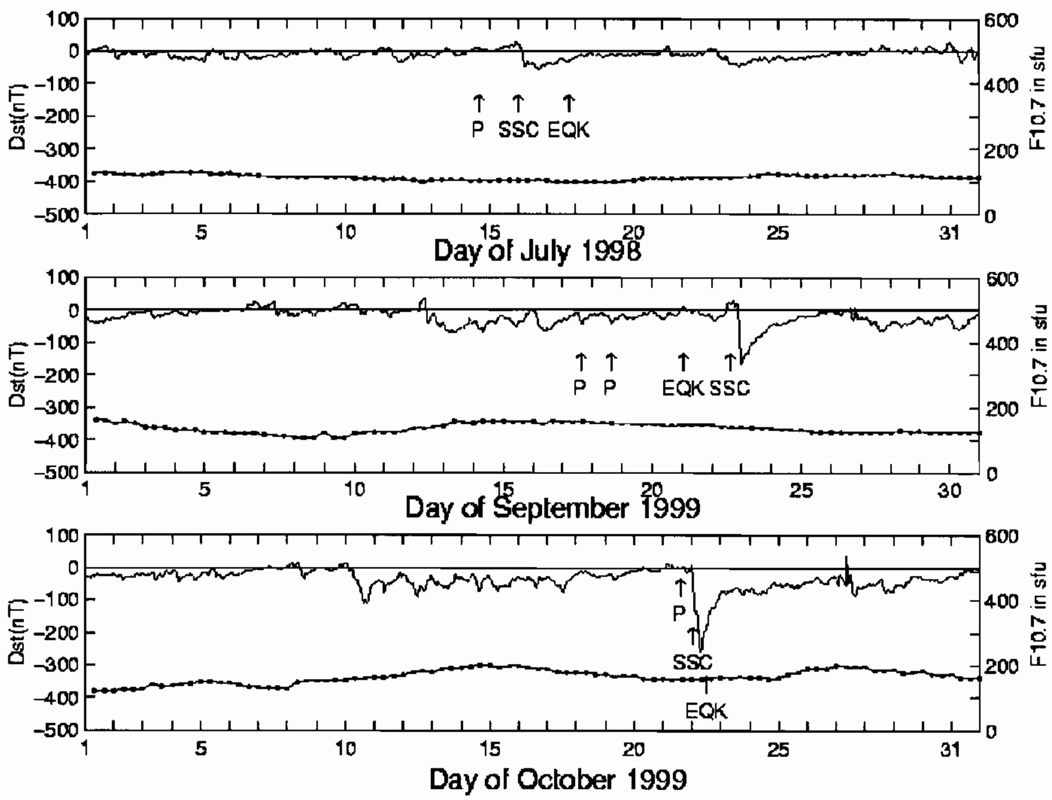

Figure 5. The Geomagnetic Dst index variation (solid line), and Solar radio emission F10.7 (dot line), during the periods of three earthquakes.

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