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# Ionospheric coupling, especially between ionogram-recorded spread-F and sporadic-E enhancements at an equatorial-anomaly crest station, Chung-Li

G. G. Bowman and I. K. Mortimer

Department of Physics, University of Queensland, Brisbane, Queensland, Australia

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[1] The analysis of ionograms recorded at Chung-Li, a station situated near the crest of the equatorial ionosphere anomaly, finds that there is coupling between the nighttime $F_2$ and $E_s$ layers at the onset of spread-F, as is the case in midlatitudes. The results were obtained using isolated patches of spread-F occurrence of duration 2 hours or less and for sunspot-minimum years. It is suggested that the medium-scale traveling ionospheric disturbances (TIDs), which are responsible for the spread-F occurrence, influence both the $F_2$ and $E_s$ levels almost simultaneously, as their travel is consistent with the evidence from these analyses, as well as that already available for midlatitudes. Some comments are made on the possibility that these medium-scale TIDs may be responsible directly for some of the small-scale irregularities observed at these equatorial latitudes. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2435 Ionosphere: Ionospheric disturbances; 2487 Ionosphere: Wave propagation (6934); *KEYWORDS:* sporadic-E, spread-F, coupling, TIDs

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## 1. Introduction

[2] The literature on equatorial spread-F (ESF) is dominated by considerations of the small-scale irregularities (SSIs) and electron-density depletions created by the Rayleigh-Taylor instability (RTI). However, certain aspects of the ionogram-recorded spread-F phenomenon which relate to electron-density undulations created by passing medium-scale traveling ionospheric disturbances (MS-TIDs) have been found to be similar to spread-F characteristics recorded for midlatitudes. *Bowman* [2001] has shown that these similarities apply to the after midnight (AM) recordings from an equatorial-ionospheric-anomaly (EIA) crest station (Chung-Li). This present paper will mainly be concerned with evidence from Chung-Li that supports an additional similarity involving coupling between the $F_2$ and $E_s$ regions. This coupling is known to exist between these ionospheric levels in midlatitudes at times of spread-F occurrence. The analyses will use data from monthly booklets (from Chung-Li) of ionospheric parameters at hourly intervals and f-plots at 15 minute intervals for some of these parameters.

[3] There is some evidence for coupling between ionospheric levels and ground level, the results being obtained using microbarographs. The associations involve (1) ionospheric absorption and sporadic-E events [*Khan*, 1970; *Shrestha*, 1971a, 1971b], (2) nighttime $F_2$-region MS-TID fluctuations [*Bowman*, 1968; *Bowman and Shrestha*, 1997, reporting on work by *Khan*, 1973], and (3) large-scale TIDs [*Bowman and Shrestha*, 1966]. As mentioned, it is the $F_2$-layer–sporadic-E layer coupling which is considered here. An early report [*Bowman*, 1960] showed that often the related $F_2$-region structure consisted first of h′F shifted lower followed by a significant height rise. Sporadic-E enhancements were recorded particularly for the suppression but also sometimes separately for the height rise. Experimental evidence for a relationship between spread-F occurrence and sporadic-E enhancement for midlatitudes has been available for sometime [*McNicol et al.*, 1956; *Bowman*, 1960, 1968, 1985, 1986; *Bowman and Dunne*, 1981]. Also for midlatitudes, a recent paper [*Mathews et al.*, 2001] reports on new evidence for this association. This early work is discussed briefly by *Bowman et al.* [1994], with a diagram illustrating this relationship.

[4] Chung-Li (geomagnetic coordinates, 14.3N, 191.6E) has a local time (LT) 8 hours ahead of universal time (UT). In sunspot-maximum years the type 1 spread-F occurrence, as classified by *Bowman* [2001] and related to the post-sunset height rises, is only about one fourth that at Manila which is in the same longitude zone and close to the geomagnetic equator. In sunspot-minimum years there is little or no evidence of this type 1 spread-F occurrence at Chung-Li [*Bowman*, 2001]. The years examined here are 1983 to 1987 and 1993 to 1995 when the average sunspot number for each year was less than 70.

## 2. Results

[5] Mainly for the AM period the analyses will involve two different investigations, one comparing the nightly


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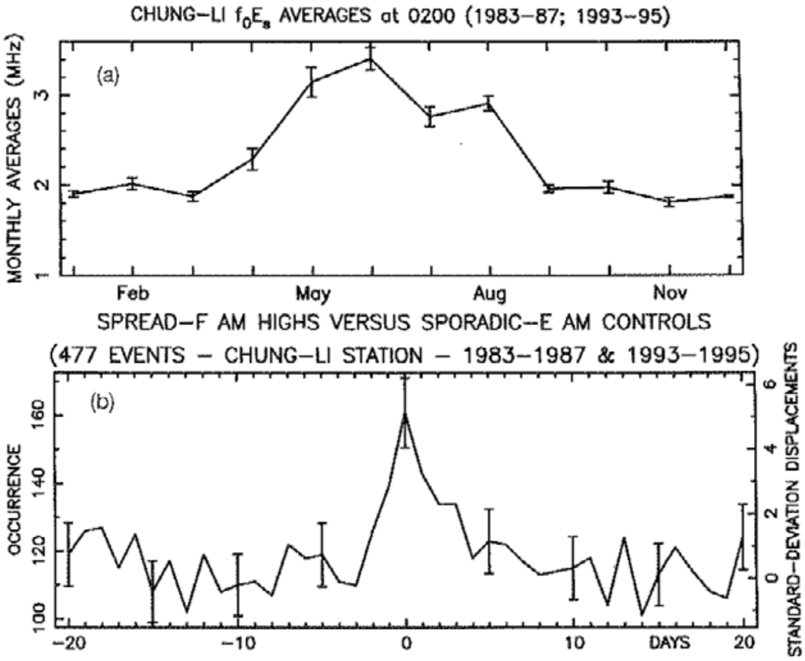


**Figure 1.** At Chung-Li (a) monthly averages of $f_oE_s$ averages at 0200 (LT) for sunspot-minimum years, and (b) spread-F occurrence relative to sporadic-E controls.

occurrence of spread-F with $E_s$ enhancements, while the second will concentrate on individual spread-F events and related sporadic-E occurrence.

### 2.1. Daily AM Spread-F Maxima and Enhanced $f_oE_s$ Values (0000–0600 LT)

[6] An extended superposed-epoch analysis has been used. Because of the severe modulation, presumably by the influence of the neutral-particle density on MS-TID wave amplitudes [see *Bowman*, 2001, Figure 1], the spread-F occurrence has been normalized by dividing each entry in a month by the average occurrence for that month. A data file has been made consisting of days in the period investigated when spread-F occurrence (in hours per night) was $\geq$1.5 times the average occurrence for each month. The key days for the superposed-epoch analysis consisted of $f_oE_s$ values (at any hour of the AM period), which were greater than or equal to twice the monthly average for each month and for the 0200 LT hour. As Figure 1a shows, these monthly averages maximize in summer [*Whitehead*, 1970]. The extended analysis embraced the center day ±365 days. For analysis of this kind it has been found that the final averages of the columns are distributed normally. This allows displacements on any day to be evaluated in terms of standard-deviation displacements from the mean, thus giving a reliable measure of its importance on that day.

[7] The final plot (Figure 1b) shows only a small section of the results (center day ±20 days). Standard-error bars have been computed and are placed at 5 day intervals relative to the center day. The spread-F events are displaced significantly on the center day indicating a relationship with the $f_oE_s$ key days at a level of 5.2$\sigma$. There is a 2.0. $\times$ $10^{-6}$ percent probability that this result is fortuitous [*Croxton*, 1949]. Figure 1b establishes a relationship between the levels on a night by night basis. The next subsection will consider the individual times of spread-F occurrence at Chung Li and related $E_s$ enhancements around these times.

### 2.2. Sporadic-E Related to Specific Spread-F Events

[8] Simple superposed-epoch analyses have been performed to investigate possible relationships between elevated $E_s$ or h′F events and specific spread-F events. The onset times of isolated spread-F events were determined from f-plots where the resolution is 15 min. Except for one event with an onset time of 2115 LT, spread-F events lasting two hours or less were considered between the times of 2130 and 0215 LT and subsequently $f_oE_s$ and h′F values were determined at the nearest hour. These parameters were also recorded for 4 hours before and 4 hours after the onset times. Since, as mentioned in the Introduction, postsunset height rises are not expected to be dominant in the periods investigated, the interval used for analyses extended into the premidnight (PM) period so that the onset times ±4 hour periods avoided as much as possible the high $f_oE_s$ values found in daylight hours. The h′F values have been changed to $\Delta$h′F values by subtracting the medium values for the hour of the recorded h′F values.

[9] For the years 1985, 1986 and 1987, 106 isolated spread-F occurrences (as defined) have been found, and listings made of $f_oE_s$ and $\Delta$h′F values for the onset times and 4 hours before and after. Of these cases, on 44 occasions (i.e., for 42 percent of events) there was some evidence of $f_oE_s$ enhancement at the onset time or 1 hour either side. The average values for an analysis involving 44 $f_oE_s$ enhancements are given in Figure 2a along with calculated standard-error bars. A maximum is recorded for hour zero. Some indication of the statistical significance for an association between spread-F onsets and $E_s$ increases

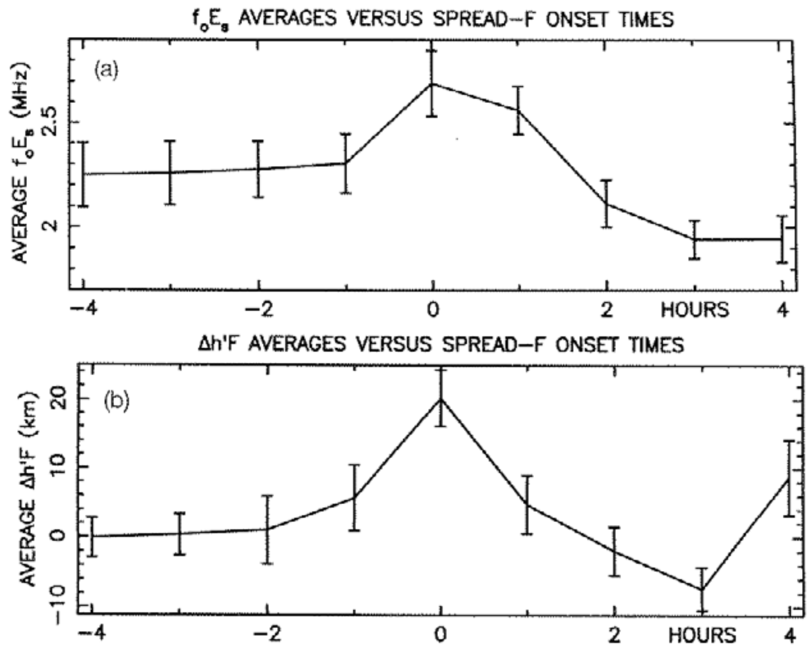


**Figure 2.** At Chung-Li, averages of (a) $f_oE_s$ increases and (b) $\Delta h'F$ values, both relative to onset times of isolated spread-F occurrence.

comes from the fact that for 42 percent of the onsets $E_s$ is enhanced as shown by Figure 2a. It would have been preferable to analyze $E_s$ occurrence levels generally relative to all the spread-F onset key days. Sometimes $E_s$ disturbance conditions extend into the postsunset period where although less pronounced than during daylight hours are nevertheless significant when compared with the more modest events associated with spread-F occurrences. Even for these selected events Figure 2a indicates the influence of these postsunset disturbances when a comparison is made with the results for the presunrise period. Apart from the 44 events chosen there may be additional $E_s$ enhancements of relevance here whose subtle increases are overshadowed by more intense $E_s$ occurrence (as mentioned) making identification difficult. The $\Delta h'F$ values were subjected to a similar analysis (again using the 44 key days), the results of which are presented in Figure 2b, where a well-defined central maximum is recorded. Thus the selected 44 sporadic-E values that indicate a maximum when averaged (Figure 2a) are related to an increase in $F_2$-region $\Delta h'F$ values on day zero (Figure 2b).

[10] Using satellite recordings and spaced stations on Taiwan, *Huang* [1985, 1990] has detected on 125 occasions, movements that were called drifts, involving scintillation patches (SSIs) and total-electron-content depletions. Of these events 90 were found to have velocities comparable with those for MS-TIDs, and the movements were generally toward east-northeast directions. For reasons explained earlier [*Bowman*, 2001] particularly because of similarities found with midlatitude events, hereafter these events will be regarded as produced by MS-TIDs.

[11] The scaling of ionograms involves recording hourly values of a number of ionospheric parameters. In addition so-called f-plots are made which display graphically some of these parameters at 15 minute intervals, thus giving better resolution than the hourly values. Sporadic-E is not one of these parameters although associated blanketing sporadic-E ($f_bE_s$) is. Five specific MS-TID events will be considered here, four of which will be illustrated by sections of f-plots in Figures 3 and 4. Of interest on these plots are the blanketing frequencies ($f_bE_s$) recorded on the ordinate scale, and times of occurrence of both $f_bE_s$ and spread-F (vertical lines) on the abscissa scale. Table 1 lists these 5 events labeled A to E, with MS-TID onset times being noted. Tables 2 and 3 list the relevant $f_oE_s$ and $\Delta h'F$ values, relative to the onset times listed as hour zero with average values for the five events also being listed. The MHz values of $f_oE_s$ in Table 2 have been multiplied by 10. Other aspects of Figures 3 and 4 need explanations. The readings for both $FF_2$ and FE are represented by crosses for X rays and circles for O rays. Doubtful values are indicated by black dots in Figure 3 and asterisks in Figure 4. The $f_bE_s$ is represented by lines joining black dots in Figure 3 and lines joining framed crosses in Figure 4. The descriptive letter q is used for range spread-F. The ''fenced'' region at low frequencies locates the 1.6 MHz limit below which ionosonde readings could not be made. Doubtful $f_{min}$ values are also shown in Figure 4a as asterisks.

[12] Most routinely operated ionosondes cannot record $f_oE_s$ below 1.6 MHz, although it is practical to use this figure when such low recordings are not possible. Consequently the frequent occurrence of 1.6 values on Table 2 (particularly for event B) is further evidence for the isolation of events near the zero hour. A good indication that coupling might exist comes from an examination of $f_oE_s$ and $\Delta h'F$ values for the Taiwan events illustrated by Figure 2 of *Huang* [1990] and Figure 9 of *Huang* [1985]. These have been listed in Table 1 as events A and B respec-

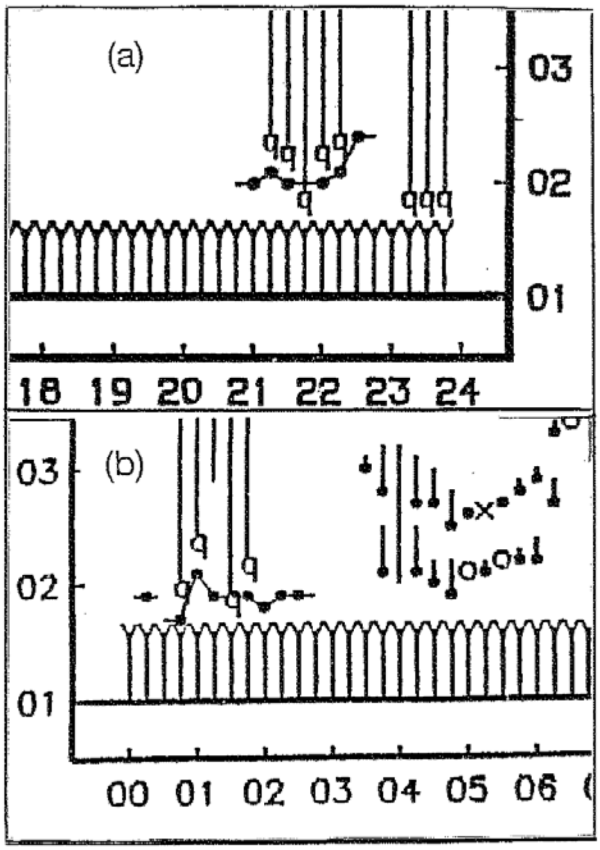


**Figure 3.** Sections of Chung-Li *F* plots showing isolated spread-F occurrence (vertical lines) and related blanketing for (a) 2115 LT, 1 March 1988 (Event A) [*Telecommunication Training Institute*, 1988] and (b) 0045 LT, 19 Jan. 1994 [*Telecommunication Training Institute*, 1994] (Event C). The ordinate measures frequency in MHz and the abscissa local times.

tively. Table 2 indicates onset times of $f_oE_s$ enhancements for both events and Table 3 shows that for event B there is a $\Delta h'F$ increase at onset time plus 1 hour. For event A the central $\Delta h'F$ values are not dominant although they are slightly larger than most of the other values listed. The f-plot section in Figure 3a for event A shows isolated $f_bE_s$ values associated with the Es enhancement. Event B needs special mention. As Figure 9 of *Huang* [1985] shows a well-defined although relatively weak MS-TID crosses Taiwan around 2200 (LT) with individual events lasting only for about 15 min. No spread-F was recorded which is not unusual for weak MS-TIDs [*Bowman*, 1995]. At 2215 (LT) an isolated $f_bE_s$ enhancement is recorded at the level of 2.2 MHz. In addition, Figures 3b, 4a and 4b give f-plot sections (with some $f_bE_s$ values) of the spread-F associated with events C, D and E. The $\Delta h'F$ increases are registered at hour +1 for both B and E events with the relevant $E_s$ enhancement coinciding with this time for event E, but occurring an hour before for event B. As can be seen from the figures illustrated by *Bowman* [1960], although the $\Delta h'F$ increases are usually delayed by a few tens of minutes after the initial $E_s$ enhancement, on some occasions the delay is longer extending sometimes to at least an hour. Figure 4b shows for event E that isolated blanketing does not always occur. The postsunset $E_s$ enhancements mentioned earlier are illustrated by event D of Table 2 and also the $f_bE_s$ recorded in Figure 2a, thus suggesting that on some occasions spread-F related $E_s$ enhancements may be masked. Table 2 also shows postsunset enhancements events for A, B and C at hour −4.

## 3. Discussion and Conclusions

[13] The experimental evidence presented here for an EIA crest ionosonde station is consistent with the existence of a coupling between nighttime $F_2$ layers and $E_s$ layers during the passage of the MS-TIDs which are responsible for the spread-F traces on ionograms. This is the case for midlatitudes. The arguments for regarding the AM spread-F occurrence during sunspot-minimum years at an EIA crest station to be no different from midlatitude spread-F (as proposed by *Bowman* [2001]) is strengthened by these results. At midlatitudes there is evidence for breaking AGWs (associated with the MS-TIDs) at times of spread-F occurrence due to the evidence of stratification seen on spread-F traces [*Bowman et al.*, 1988]. This mechanism is also proposed by *Kvavadze et al.* [1988] to explain the SSIs they found moving with the spread-F disturbances. Because of the similarities between midlatitudes and EIA regions for night-

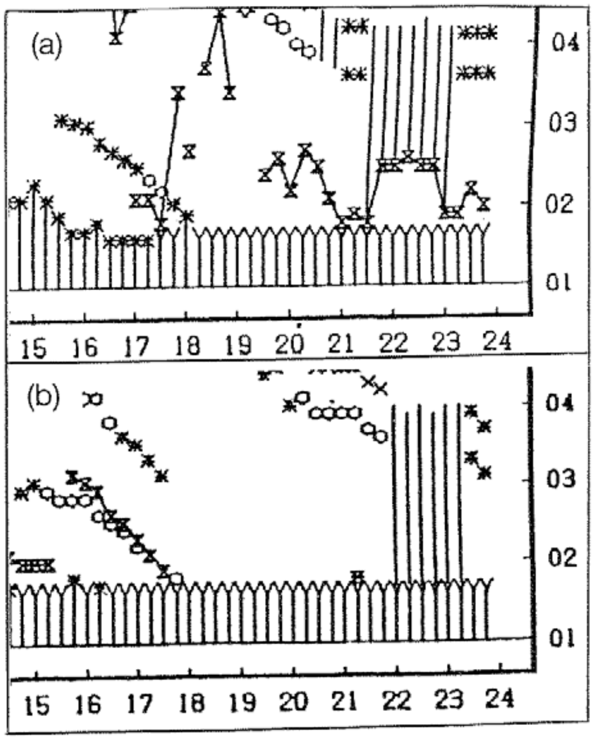


**Figure 4.** Sections of Chung-Li *F* plots showing spread-F occurrence (vertical lines) and related blanketing for (a) 2130 LT, 14 July 1985 (Event D) [*Telecommunication Training Institute*, 1985] and spread-F only for (b) 2200, 29 March 1986 [*Telecommunication Training Institute*, 1986] (Event E). The ordinate measures frequency in MHz and the abscissa local times.

**Table 1.** Spread-F Occurrence (≤2 hours)

| Event | Figure | MS-TID Onset |
|---|---|---|
| A | 3a | 2115, 1 March 1988 |
| B | - | 2200, 11 Feb. 1983 |
| C | 3b | 0045, 19 Jan. 1994 |
| D | 4a | 2130, 14 July 1985 |
| E | 4b | 2200, 29 March 1986 |

time disturbed conditions after midnight, it is proposed here that some of the SSIs in this equatorial region may result from breaking AGWs. For this region, *Huang* [1985, 1990] recorded on 125 occasions moving SSIs associated with moving larger-scale $F_2$-layer disturbances. Furthermore, it seems worth considering breaking AGWs as a mechanism for the generation of some of the SSIs that are present in equatorial regions in the postsunset period. At these times the MS-TIDs will have wave amplitudes that will be considerably enhanced due to the large height rises which occur at these times. Of relevance here are comments by *Hines* [1963, p. 24], who states referring to AGWs, that "because of their increase of amplitude with height (in the absence of strong dissipation) these waves would be more effective in the production of spread-F when the *F* layer is high."

[14] Events A and B which are well illustrated by *Huang* [1985, 1990] involve movements of scintillation patches (involving SSIs) and total-electron-control depletions which can be regarded as produced by MS-TIDs, as the occurrence characteristics are very similar to those found for midlatitudes [*Bowman*, 2001]. The associated $E_s$ enhancements for these events A and B (Table 2) also, it seems likely, are generated progressively as the MS-TIDs propagate. The other alternative, which seems unlikely, is that at Chung-Li $E_s$ enhancements occur intermittently along the MS-TID path and that they, along with the other 44 events just happen by chance to be recorded at Chung-Li. This leads to the hypotheses that for both EIA and midlatitude regions MS-TIDs, except for delays of the order of minutes, are located simultaneously as they propagate at both the $F_2$ and $E_s$ layers. The disturbance at the $F_2$-layer level does not necessarily have to produce spread-F as it will depend on the magnitude of the wave amplitudes [*Bowman et al.*, 1987]. Average directions of travel for midlatitude MS-TIDs for both $F_2$- and $E_s$-layer events are the same, the directions being (a) northwest in the southern hemisphere and (b) southwest in the northern hemisphere. For the $F_2$-layer events the relevant references are for (a) *McNicol et al.* [1956] and (b) *Behnke* [1979], *Kvavadze et al.* [1988], *Bowman et al.* [1994], and *Garcia et al.* [2000]. For the $E_s$-layer events the relevant evidence can be found for (a) in Figure 1 of *Bowman* [1985] after *Clarke* [1965] and for (b)

**Table 2.** $f_oE_s$ Sporadic-E Occurrence (MHz × 10)[a]

| Event | −4 | −3 | −2 | −1 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| A | 31 | 16 | 16 | 16 | 34 | 29 | 16 | 19 | 16 |
| B | 20 | 16 | 16 | 16 | 22 | 16 | 16 | 16 | 16 |
| C | 25 | 19 | 16 | 16 | 32 | 26 | 16 | 16 | 16 |
| D | 39 | 44 | 35 | 23 | 32 | 32 | 16 | 16 | 16 |
| E | 16 | 16 | 16 | 22 | 21 | 31 | 16 | 16 | 16 |
| Average | 26 | 22 | 20 | 19 | 28 | 27 | 16 | 16 | 16 |

[a] Hours from onset time.

**Table 3.** $\Delta h'F$ Displacements in Kilometers[a]

| Event | −4 | −3 | −2 | −1 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| A | −15 | −10 | −5 | −10 | −10 | −30 | −30 | −15 | −10 |
| B | −20 | −20 | 30 | 10 | 0 | 30 | −30 | −20 | 0 |
| C | 20 | −10 | 40 | 0 | 90 | 10 | −50 | 20 | 25 |
| D | 0 | 0 | 20 | 20 | 60 | 20 | 0 | −10 | −30 |
| E | 0 | −5 | 0 | 25 | 15 | 35 | 35 | 25 | −5 |
| Average | −3 | −9 | 17 | 9 | 31 | 13 | −15 | 0 | −4 |

[a] Hours from onset time.

in *Harwood* [1961] and *Tanaka* [1979]. Furthermore, the distributions of speeds for the $E_s$ layer [*Harwood*, 1961; *Sinno et al.*, 1964; *Tanaka*, 1979] are virtually the same as found for the $F_2$ layer [*McNicol et al.*, 1956; *Bowman*, 1991, Figure 2a, reproduced from work of *Lamb*, 1954]. Further evidence of simultaneous movements at the two levels comes from an early report. *McNicol et al.* [1956] (see their Plate 5 and a reproduction of this diagram by *Bowman* [1990, p. 270]) state "in a few cases there is excellent simultaneity between *F* satellites and $E_s$ curved traces . . ." Curved sporadic-E traces indicate $E_s$-level disturbances arriving and departing from an overhead position. Similarly the term "satellites" refers to extra $F_2$-layer ionograms traces indicating the passage of a MS-TID. It is of interest to note here, that two disturbances have already been reported, the MS-TIDs traveling simultaneously at both levels in a southwest direction across Japan, with SSIs being generated at the MU radar site in central Japan [*Bowman et al.*, 1994].

[15] Information on the F-layer characteristics of daytime MS-TIDs is reported by *Heisler* [1963], *Bowman* [1992], and *Bowman et al.* [1987]. There is some evidence in other reports that these MS-TIDs also sometimes couple with the $E_s$ layer, as has been considered here for nighttime events. These daytime disturbances are identified on ionograms by F-layer trace distortions in the form of cusps, which drift down the ionograms trace during the passage of the MS-TIDs. *Heisler* [1959] has detected at three or four midlatitude ionosonde stations and on three occasions, daytime MS-TIDs that have traveled across the Australian continent distances of at least a thousand kilometers. All stations indicated the F- and $E_s$-layer levels being affected at the same time, thus representing disturbances traveling at both levels. The relevant ionograms at three stations for one of these disturbances are illustrated by *Heisler and Whitehead* [1960]. *Castel and Faynot* [1964, p.985] have found coupling between satellite recordings of the ionosphere above the F-layer maximum and ionosonde recordings. Referring to the ionograms cusps, they state that "this fork moves gradually downwards, first along the *F* normal trace, then along the E region trace, to disappear finally in a weak, short-lived sporadic-E ionization." The speeds found (100-200 $ms^{-1}$) are similar to those for midlatitude MS-TIDs [see *Bowman*, 1991, Figure 2c, reproduced from *Munro*, 1958]. Also, *Schodel et al.* [1973] have reported an association between daytime *F* layer ionization fluctuations (determined from total-electron-control variations) and ground-level microbarograph recordings.

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G. G. Bowman and I. K. Mortimer, Department of Physics, University of Queensland, Brisbane, Queensland 4072, Australia. (ian@physics.uq.edu.au)