Daytime and nighttime mid-latitude ionospheric disturbances and their delayed occurrence after geomagnetic activity

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For a mid-latitude station the occurrence rates on ionograms of nighttime spread-F, daytime first-hop distortions (produced by medium-scale travelling ionospheric disturbances) and daytime second-hop spread are considered over a five-year period. Superposed-epoch analysis has been used to investigate the second-hop spread relative to days of enhanced activity in the other two parameters. The results show that all three parameters are closely related, with the second-hop spread being related to spread-F occurrence on the night following the daytime occurrence of this second-hop spread. Additional superposed-epoch analyses show that all three parameters are related to enhanced geomagnetic activity which is found to occur during an early-morning period which is displaced by three such periods from the days of enhanced activity for these parameters. Two peaks occur in this early-morning period, one at 0400 local time, and the other close to local midnight. The paper concentrates particularly on this daytime second-hop phenomenon and sample ionograms are presented to illustrate some of the characteristics of the spread traces which are recorded.

1 Introduction

For mid-latitude regions this paper considers the delayed occurrence of nighttime spread-F, daytime first-hop distortions and daytime second-hop spread following increased geomagnetic activity in auroral-zone regions. It seems likely that all three parameters result from the passage of medium-scale travelling ionospheric disturbances (MS-TIDs) (Refs 1 and 2). Interrelationships between these three parameters (which are recorded on ionograms) will also be considered. Particular attention will be paid to the daytime second-hop spread which has received little or no attention by investigators in the past, possibly due to the reason that it was thought to result from backscatter from ground irregularities. However recent results\(^1\)\(^-\)\(^2\), which indicate weaker first-hop signals when this second-hop spread is recorded, as well as evidence of associations with nighttime spread-F (Ref.3) and daytime MS-TIDs (Ref.2), suggest that irregularities in the ionosphere are involved.

Absorption events in the D region delayed by a number of days after increased geomagnetic activity at specific local times (in the early morning hours)\(^6\) are apparently associated with similar delayed occurrences of mid-latitude spread-F (Ref.5). Therefore in view of the relationships between daytime and nighttime disturbances, which will be explored further in this paper, analyses have been performed to investigate whether or not daytime disturbances can be related to geomagnetic activity with similar delayed occurrences. In the past it has not been possible to associate with any certainty daytime disturbances with geomagnetic activity\(^6\)\(^-\)\(^8\). This could be due possibly to the fact that delayed occurrence was not considered and/or to the fact that daily geomagnetic indices were used rather than the hourly values which are available with the AE indices.

2 Experimental details and method of analysis

The special features of a modern ionosonde\(^9\) located on Bribie Island (36.1°S, 118.1°E — corrected geomagnetic coordinates) at a site 55 km magnetically north of Brisbane, Australia, have been used to record on ionograms some of the characteristics of the second-hop daytime spread. These characteristics will be considered in the next section. This paper will also consider statistically the occurrence rates of the three parameters which were mentioned in section 1. These occurrence rates have been determined from ionograms recorded routinely every 15 minutes at Moggill, another recording site situated approximately 60 km magnetically south of Bribie Island. The Moggill ionograms from 1979 to 1983 (inclusive) were used, although recordings for several months of 1982 were unavailable or unsuitable.

For each day or night of each month used, counts
were made of the number of ionograms showing (a) nighttime spread-F between the local times of 1800 and 0600, (b) first-hop daytime trace distortions between local times of 0600 and 1800, and (c) second-hop daytime spread, again from 0600 to 1800. The local time is 10 h ahead of Universal Time. The counts obtained for the month of June 1981, which are quoted in Fig. 1, show the variability of these three parameters from day to day. The spread-F counts for each night were allocated the date of the first half of the night (i.e., from 1800 to 0000). Sets of controls were obtained from each parameter determined by considering those counts in each month which were greater than 1.33 times the average count for that month. The days of these controls for June 1981 are indicated by circles on Fig. 1. These controls have been used not only to investigate further relationships between these three parameters, but also to determine what associations, if any, these days of enhanced occurrence for each parameter might have with geomagnetic activity. Hourly values of the AE, AL and AU indices have been used for geomagnetic activity, and superposed-epoch methods were employed to investigate these relationships.

It seems desirable to explain in some detail why it has been necessary to consider controls relative to monthly averages rather than yearly averages. It has been shown² for the parameters considered here and for spread-F generally from mid- and low-latitude stations¹⁰ that modulation of occurrence rates by changing levels of the neutral-particle density of the upper atmosphere (UA-NPD) most likely controls the annual distributions of these parameters. As this appears to result from control of the MS-TID wave amplitudes by the neutral-particle density, it seems reasonable (in the absence of any other information) to assume a uniform distribution of disturbances throughout the year even though the MS-TID wave amplitudes will vary significantly. As Bowman² shows, the occurrence rate around the June solstice is at least 4 times greater than during the equinoctial periods.

3 Some characteristics of second-hop daytime spread

The modern ionosonde⁹ mentioned in section 2 was responsible for the swept- and fixed-frequency ionograms which are presented in Figs 2 and 3, as representative of second-hop daytime spread conditions. These conditions are most prevalent in sunspot-minimum years. In 1990 and 1991 when the solar cycle was near its maximum, ionograms such as those which appear in Figs 2 and 3 were almost never recorded. Except for Fig. 3(a) all the ionograms on Figs 2 and 3 record primarily O-ray traces. However sometimes weak X-ray traces are also recorded [see Fig. 2(a)].

The second-hop spread conditions during a short interval of time near 1420 LT on 23 June 1988 are shown in Fig. 2 by (a) the full-scale swept-frequency ionogram, (b) a limited-scale ionogram with limited height and frequency parameters (a frequency range of about 300 kHz), and (c) an ionogram similar to (b)
Fig. 2—Ionograms which illustrate some of the characteristics of daytime second-hop spread (The time quoted on each ionogram is the local time and the number appearing after decimal point shows seconds, e.g. 1419.25 means 14 hrs 19 min 25 s).
but with swept-gain used. In addition, Figs 2(d), 2(e) and 2(f) are fixed-frequency ionograms (at 5.8 MHz) over a period less than 2 min showing three 10-s sections again for a limited-height range appropriate for second-hop reflections. As discussed previously, Fig. 2(b) shows that the spread appears as quasi-horizontal (QH) patches while in Fig. 2(c) where the gain is swept 30 dB every second the signal strengths of these patches are shown to be significantly weaker than the second-hop main-trace signals. The fixed-frequency recordings [Figs 2(d), 2(e) and 2(f)] illustrate that each patch is ephemeral in that it is recorded for only a short time, being replaced at other ranges by other patches. As reported by Bowman, Figs 2(g) and 2(h) illustrate (for events on 16 June 1988) that as first-hop distortions move to lower frequencies the second-hop spread is found to follow this movement. Figure 2(i) is a limited-range swept-frequency ionogram of the second-hop spread for this event on 16 June 1988. This figure shows clearly that reflection from the ionospheric structures responsible for these QH patches is almost
certainly specular because of the phase coherency observed on these patches.

Figure 3(a) is a full-range ionogram (recorded on 6 Sep. 1989) showing second-hop spread associated with the O-ray. Figure 3(b) was recorded approximately 2 min later using limited height and frequency scales and a gain sweep of 60 dB every 0.5 s. The signal strengths of the patches are significantly lower than the second-hop main trace which is easily recognized. As illustrated and explained elsewhere, the patches are also recorded at frequencies in excess of $f_{\nu}F2$ and have an approximate straight underedge characteristic of signals reflected from locations which, as the frequency recorded increases, move further away from the zenith position. Another pair of a full-range ionogram [Fig.3(c)] and a limited-range ionogram [Fig.3(d)] again indicate the details available on limited-range ionograms which are not available on full-range ionograms. This pair were recorded within a short time of each other on 30 May 1985. Approximately 10 min later two additional limited-range ionograms [Figs 3(e) and 3(f)], which show the spread well developed, were recorded 32 s apart. The spread in range is at least 80 km. The QH patches in Fig.3(f) are in different positions on the ionogram than those on the ionogram in Fig.3(e), illustrating the fact that individual patches exist only for a short interval of time. A careful inspection of Figs 3(b), 3(d), 3(e) and 3(f) again shows that specular reflection is involved in patch formation because of the coherent phase recorded on the patches.

4 Interrelationships between the parameters

It has already been shown by using controls for both daytime first-hop distortions and daytime second-hop spread, that a close association exists between nighttime spread-F and these daytime parameters. It can be inferred from this and also by using specific events that daytime first-hop distortions and second-hop spread are closely related. However it seems appropriate to check this proposed relationship by more quantitative information. The controls for first-hop distortions for the months of May, June, July and August have been used in a superposed-epoch analysis to determine the average level of second-hop-spread activity on these days and for 25 days before and after these centre days. The mean and standard deviation of the resulting 51 average values were determined. On the plot shown by Fig. 4(a) the points are plotted as standard-deviation displacements from the mean. The maximum displacement of 4.8 standard deviation on the centre day establishes a significant relationship between these parameters.

A similar analysis has been performed to investigate the relationship between daytime second-hop spread and controls for nighttime spread-F, again using the controls for May, June, July and August. Figure 4(b) shows a peak on the centre day of 2.8 standard deviation. As with the earlier results, since spread-F occurrence on the night following daytime second-hop spread occurrence is allocated the same date as the daytime events, daytime second-hop spread is shown to be associated with spread-F on the night following but not to any degree associated with spread-F on the night preceding. This observation will be considered in section 6 (Discussion).

5 Associations with geomagnetic activity

Superposed-epoch analyses using controls for all the months of the years 1979, 1980, 1981 and 1983 and some of the months of 1982 have been performed with the resulting plots showing standard-deviation displacements from the mean as was described in section 4. For these particular superposed-epoch analyses an array of 1401 average values was obtained, consisting of 700 values before and 700 values after the average central control value. Analyses performed earlier have shown that nighttime spread-F appears to be associated with geomagnetic activity at particular local times which are centred on local sunrise. Furthermore it has been proposed that charged particles entering the radiation belt at times of enhanced geomagnetic activity diffuse radially to lower $L$ shells some of which are subsequently precipitated to produce D-region absorption (see Spjeldvik and Thorne and Bowman). These precipitated particles possibly generate the atmospheric gravity waves (AGWs) which are responsible for travelling ionospheric disturbances (TIDs) and spread-F.

In view of this apparent local-time dependence, hourly values of the AE, AL and AU indices have been used here for geomagnetic activity. Although controls for the parameters were determined for 12-h intervals for both daytime and nighttime hours, a reference time of 0000 UT or 1000 LT (LT = UT + 10h) for each control day was used in each superposed-epoch analysis. Although all three geomagnetic indices have been investigated for possible association with the three parameters, only the plots for the AL indices will be presented. The results are more significant for these indices. It is important to note that in the analyses it has been found convenient to use positive values in place of the
negative AL indices. To compensate for diurnal
variations for any particular month (not so much for
geomagnetic activity but for other parameters which
might be investigated, such as $f_{min}$ absorption values)
a computer programme subtracts the average
monthly value for each hour of the day from the actual
hourly values. Therefore data used in any
superposed-epoch analysis have been normalized to
allow for diurnal variations. This means that any
information on geomagnetic-index levels is not
retained for these analyses.

5.1 AL index versus nighttime spread-F

Figures 5 and 6 show the results from
superposed-epoch analyses which investigate the
AL-index levels relative to the nighttime spread-F
control days. For this parameter (spread-F) two sets
of controls were used to investigate which set
produced the more significant results. Set 1 used values
greater than 1.1 times the average monthly values
while set 2 (subsequently adopted for all analyses and
as illustrated by Fig.1) used values greater than 1.33
average monthly values. It can be seen from Fig.5,
which involves 426 set 1 controls, that the levels of
significance of the peak displacements are marginally
less than those shown in Fig.6, which involves 335 set 2
controls. Thus all other similar analyses for this
investigation have used set 2 controls. When this is

Fig. 4—Superposed-epoch plots of second-hop spread using (a) controls for first-hop distortions and (b) controls for
spread-F.

Fig. 5—A superposed-epoch plot of the AL index using controls (values > 1.1 times monthly averages) for spread-F.

Fig. 6—A superposed-epoch plot of the AL index using controls (values > 1.33 times monthly averages) for spread-F.
done it is found that the controls come from approximately the top third of the occurrence values. For Figs 5 and 6 (and for other similar analyses reported here) only the central sections of the resulting 1401 values from the superposed-epoch analyses are shown (from 9 days before the central hour to 2 days after). Peaks occur in the distributions of points at 0400 and 2300 at or close to the third early-morning period before the control interval. The 0400 peak registers 3.07 while the second peak at 2300 records 2.39 standard deviation displacements. In addition a significant peak which registers 3.91 at 0400 is found in the early-morning period immediately preceding the control interval. The two significant peaks which occur in sunset periods between positions marked - 4 and - 5 and also the single peak between positions - 5 and - 6 in Fig.6 are not found when the AL index is investigated relative to either the second-hop-spread controls or the first-hop-distortions controls (see sections 5.2 and 5.3).

5.2 AL index versus daytime second-hop spread

The results for the superposed-epoch analysis for the AL index relative to daytime second-hop control days (320 controls were used) are shown in Fig.7. If the 3rd early-morning period before the control period is considered, significant standard-deviation displacements are found to peak at 0000 and 0400 local time (see arrows). At 0400 the displacement is 3.04 standard deviation while at 0000 it is 3.30. Thus along with nighttime spread-F (Refs 5, 12 and 13), Fig. 7 shows that daytime events are also associated with enhanced geomagnetic activity which occurred several days before the daytime events.

5.3 AL index versus daytime first-hop distortions

Figure 8 shows results of a superposed-epoch analysis of the AL index relative to daytime first-hop-distortion controls (306 controls were used). The display, which is similar to that of Figs 6 and 7, shows a significant peak at 0000 and a peak of lower significance at 0400, both peaks being displaced (as before) by 3 early-morning periods from the control interval (see arrows). The 0400 peak registers a standard-deviation displacement of 1.99 while the 0000 peak records a value of 3.14. As might be expected from Fig.4(a), Fig.8 gives results which are similar to those of Fig.7. In addition, during the second early-morning period before the control interval, Fig.8 shows a peak at 0700 of 3.14 standard deviation.

5.4 Combined daytime and nighttime controls

The plots for the three parameters presented in the previous section (Figs 6, 7 and 8) show significant displacements during an early-morning period which is displaced by 3 such periods from the control intervals. One such displacement occurs at 0400 local time and the other at or near 0000 local time. These facts suggest that it may be profitable to combine all the controls (for the three parameters) in one superposed-epoch analysis in the hope of obtaining peaks of even greater significance at these particular early-morning times. Only one control was used for those days when more than one parameter registered a control. This procedure gave 670 controls in a superposed-epoch analysis with AL indices.

Figure 9 shows selected points from the complete superposed-epoch analysis array similar to those shown on Figs 6, 7 and 8, this time however for the AL index relative to control days for all three parameters. A well-defined peak at 0400 is recorded at 4.24 standard deviation while a second broad peak records 3.63 at 0100, 3.74 at 0000 and 3.82 at 2300 local times. Displacements of lower significance are observed at

![Fig. 7](image1.png)

Fig. 7 - A superposed-epoch plot of the AL index using controls for second-hop spread.

![Fig. 8](image2.png)

Fig. 8 - A superposed-epoch plot of the AL index using controls for first-hop distortions.
Discussion

It seems worth noting that of the two daytime parameters the one which is more closely associated with nighttime spread-F is the daytime second-hop spread. The annual variations of these two parameters (nighttime and daytime spread) are similar\(^2\) and somewhat different from the annual variation for first-hop distortions\(^2\). Furthermore, the delayed occurrence after enhanced geomagnetic activity in the early-morning hours is more significant and the two peaks are more clearly defined for daytime second-hop spread (Fig.7) than for nighttime spread-F (Fig.6) or for daytime first-hop distortions (Fig.8). An early report by Bowman\(^4\) showed that for Brisbane the width of second-hop range spread increased gradually after ground sunrise. The average width reached a maximum value (of approximately 40 km) about 100 min after ground sunrise.

The arguments for suggesting that the annual and sunspot-cycle variations of the two daytime parameters are controlled by the UA-NPD have been put by Bowman\(^3\), and therefore will not be repeated here. It has also been proposed\(^2\) that breaking atmospheric gravity waves (AGWs) may be responsible for the small-scale irregularities which are detected as daytime second-hop spread. One particular investigation\(^5\) has found that daytime small-scale structures have some field-alignment but not as pronounced as the nighttime field-aligned structures. It is suggested here that (as has been proposed for nighttime field-aligned irregularities\(^6\)) non-linear effects of AGWs of sufficiently large wave amplitudes may be responsible for these daytime small-scale structures. Those occasions which record first-hop distortions without second-hop spread would then (if these ideas are correct) results from AGWs of lesser wave amplitudes. These arguments are consistent with the fact that the annual variation of the second-hop spread is close to being in anti-phase with the annual variation of the UA-NPD while the annual variation of the first-hop distortions is only approximately in anti-phase\(^2\).

Experimental evidence indicated by Bowman et al.\(^3\) and Fig.4 of this paper shows that (at least statistically) spread-F occurrence is enhanced on the night following enhanced daytime occurrence of MS-TIDs (responsible for the two daytime parameters) but not to any extent on the night before. At any one time during the daylight hours several disturbances have been found to coexist\(^7\), travelling in different directions with different speeds. In addition there is evidence that similar conditions prevail during the night hours\(^8\). Thus it seems likely that D-region precipitation events in sub-auroral regions, which occur in early-morning periods but displaced in time a few days after enhanced geomagnetic activity\(^4\), are responsible in any particular early-morning period for multiple events. These precipitation events can be imagined as producing AGWs which in turn are responsible for the MS-TIDs\(^9\) which are detected in mid-latitude regions after certain travel times from these sub-auroral regions. The faster disturbances, it is suggested, arrive during daylight hours and the slower disturbances during the night which follows. The average speed during the day of these MS-TIDs (calculated from many observations\(^8\)) is 154 m s\(^{-1}\) (Ref.18), which is somewhat greater than twice the average speed (63 m s\(^{-1}\)) determined for night hours\(^18\). Thus if this speculation is correct, the multiple occurrence of MS-TIDs with possibly spatial resonance\(^20\) being responsible for some disturbances dominating at particular locations makes it difficult to track these disturbances from one location to the next. It is not known whether or not these MS-TIDs reach and cross the geomagnetic equator. This situation (for MS-TIDs) is in contrast to conditions prevailing with large-scale travelling ionospheric disturbances (LS-TIDs) where occurrence is confined to isolated events which seem to be initiated at the onset of substorms. These LS-TIDs can be tracked across continents\(^21\), even right up to the geomagnetic equator\(^22\).

The fact that the associated geomagnetic activity is usually concentrated around local times of midnight and 0400 is particularly interesting. An examination of 60 auroral-absorption substorms (associated with
geomagnetic substorms) by Berkey et al.\textsuperscript{2,3} has found that these substorms occur frequently near midnight. In addition strong absorption is sometimes also recorded in the early-morning sector. Kangas et al.\textsuperscript{2,4}, Lukkari et al.\textsuperscript{2,5} and Hargreaves and Devlin\textsuperscript{26} have also reported on early-morning sector electron precipitation events. Thus at times of geomagnetic substorms, electrons can be expected to be injected into the radiation belt around midnight (local time) and in the early-morning sector. However it is not clear why electron injections at these particular hours influence the delayed absorption events (in sub-auroral locations) a few days later, resulting from radial diffusion and pitch-angle scattering as described by Spjeldvik and Thorne\textsuperscript{11}. Some comment on this problem has been made by Bowman\textsuperscript{5}. It is probably worth noting that the neutral winds which move equatorward have speeds which are enhanced at times of geomagnetic activity, particularly around midnight and in the early morning hours\textsuperscript{27-28}. In fact some observations\textsuperscript{27-28} report wind-speed enhancements with two peaks, one around midnight and another several hours later.

Further investigations are needed to establish why the daytime second-hop spread is recorded regularly on routinely-recorded ionograms while daytime first-hop spread is difficult to detect even by modern research-oriented ionosondes\textsuperscript{1-2,29}. A possible mechanism involving reflection of radio waves perpendicular to the ground after being deflected specularly by field-aligned irregularities is suggested by Bowman\textsuperscript{1}. However, other mechanisms which might relate to the sizes or shapes of these daytime small-scale irregularities need to be explored. Just as it is important to understand the occurrence and generation mechanism for the field-aligned irregularities which are sometimes present in the nighttime ionosphere\textsuperscript{16,30-31}, it would seem equally important to understand these daytime small-scale irregularities, which have, as some measurements have shown\textsuperscript{12}, some degree of field-alignment. Routine ionogram recordings similar to those used for this investigation have been made at many locations around the world for several decades now. Therefore data banks and ionosonde stations have extensive sets of data which would be suitable for statistical analyses similar to the analyses performed for this paper.

7 Conclusions

The results presented here have shown that mid-latitude nighttime disturbances (identified by spread traces on ionograms) should not be considered in isolation, but should be thought of as part of disturbance conditions prevailing during the daytime as well as during night hours. It has been known for some time now that nighttime spread-F (in particular for mid-latitude stations such as Bribie Island) tends to occur a few days after enhanced geomagnetic activity\textsuperscript{5,12,13}. This present investigation indicates (reported probably for the first time) that this delayed occurrence also applies to daytime disturbances, particularly the disturbances which produce the second-hop spread on ionograms. A previous investigation\textsuperscript{5} reported that the geomagnetic activity associated with mid-latitude spread-F a few days later occurred in an early morning period for high mid-latitude stations. For Brisbane\textsuperscript{5} the early morning period is resolved into two components. Further evidence of these components is presented here not only for nighttime spread-F, but also for the two daytime parameters. Thus the results show that maxima in associated geomagnetic activity occur around local midnight and also near 0400 LT.

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References

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