IONOSPHERIC IRREGULARITIES AND HIGH-MULTIPLE REFLECTIONS

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Summary

The occurrence of high-multiple reflections (10 hops and more) from the F_2 layer of the ionosphere at night is considered. Sunspot-cycle, annual, and diurnal variations are presented. The sunspot-cycle and annual variations are similar to those for the upper-atmosphere neutral particle density. Periodicities in occurrence of around 60 min are found. Associations are found between high-multiple trace occurrence and sunset and sunrise times at the 90 km level. Ionospheric irregularities which are present at the time of high-multiple reflections indicate that these reflections are probably not due to focusing effects. Evidence is presented to support a mechanism involving the reduction of non-deviative absorption to explain these reflections. This reduction may be caused by acoustic waves propagating in the high atmosphere.

I. Introduction

Pierce and Mimno (1940) reported high-multiple (H.M.) reflections, up to about 10 hops, from the F_2 layer at night and concluded that they were the result of suitable curvatures in the F_2 layer producing focusing effects. Subsequently Baird (1954) extended their work and showed that small tilts in the ionosphere, of about 1°, could explain the staggered timing of successive multiple-hop traces, when recorded by fixed-frequency techniques. Diurnal and annual variation estimates were also made. Bowman (1960*a*) dealt with the peak in occurrence around (90 km level) sunrise and measured the azimuths-of-arrival of these signals at sunrise, and also after an eclipse.

The present work gives an annual variation resulting from the analysis of ionograms taken over a period of 19·5 years at Brisbane. Diurnal and sunspot-cycle variations are also considered. Evidence is presented to support an alternative mechanism to that of focusing by the F_2 layer, to explain the H.M. trace occurrence.

II. Nature of High-multiple Reflections

At Brisbane (geomagnetic latitude 36° S.) spread-F occurrence has a maximum in winter months, while the H.M. occurrence peaks in the equinoctial months. Nevertheless, on occasions both these phenomena occur together. Simultaneous occurrence is also observed at Hobart (geomagnetic latitude 52° S.). Plate 1, Figure 6, shows an ionogram from Hobart during an ionospheric storm. H.M. traces were seen regularly on this night and their occurrence seemed to be unaffected by the transition from quiet conditions early in the night to severe storm conditions after

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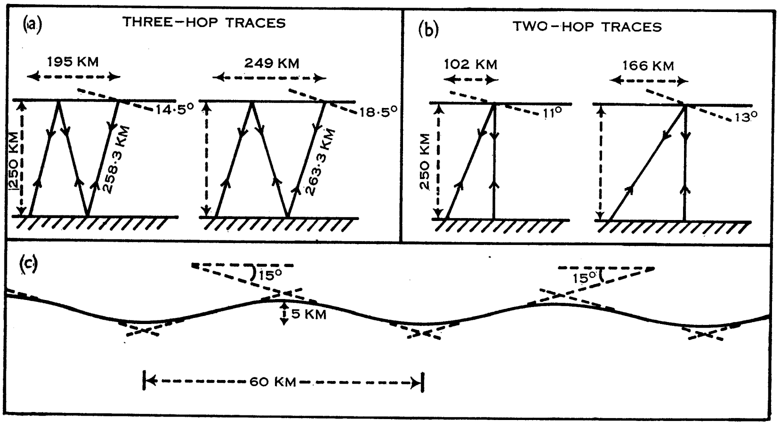
2130 Eastern Australian Standard Time (E.A.S.T. = U.T.+10 hr). However, as Plate 1, Figure 6, shows, during the storm each H.M. trace showed a certain amount of spreading in range.

Spread-F conditions at Brisbane seem to result from off-vertical reflections from a ripple structure in the contours of equal ionization density (Bowman 1960*b*). Wavelengths vary from 20 to over 100 km. A shallow ripple structure will not give the off-vertical signals sufficient range to distinguish them from the normal incidence signals of the first multiple trace. However, second- and third-hop reflections can show satellite traces (spread-F) from such a ripple structure. This is indicated in Plate 1, Figures 3 and 4, where the H.M. traces also have "spread" characteristics. In Plate 2, Figure 3(*a*), the second- and third-hop satellite traces are sufficiently well defined to allow an approximate calculation on the ripple structure after certain simplifications are made. The method of determining wavelength and amplitude



Figs. 1(*a*) and (*b*).—Methods illustrated for determination of approximate wavelengths and amplitudes of ionospheric irregularities from three-hop and two-hop traces.

Fig. 1(*c*).—Estimate of irregularity dimensions using results from (*a*) and (*b*).

from second-hop and third-hop traces independently is shown in Figures 1(*a*) and 1(*b*). Averaging the results gives a wavelength of 60 km and a peak to peak amplitude of 5 km (Fig. 1(*c*)). The multiplicity of H.M. traces on Plate 2, Figure 3, also testifies to the presence of these irregularities.

When H.M. traces occur there is often a simultaneous increase in the signal strength of the lower order multiples (e.g. first-, second-, and third-hop). Two sensitive indications on ionograms of first-hop signal strength are the x-ray reflection below the electron gyro frequency and the x-ray "tail" above the electron gyro frequency. The sudden burst of H.M. traces on Plate 2, Figure 1(*b*), is accompanied by enhanced signal strength for first-, second-, and third-hop traces, and an x-ray "tail" enhancement. Also, on this occasion a small patch of E_s appears. Plate 1, Figure 2, is an ionogram taken 10 min after the one shown by Plate 1, Figure 1. It shows H.M. traces, first-, second-, and third-hop enhancement, and enhancement of the x-ray signal below the electron gyro frequency.

Sometimes two sets of H.M. traces are seen on an ionogram; one set, the more common, represents group ranges between 3000 and about 4000 km, while the other set represents group ranges between 6000 and about 7000 km. During the analysis to determine the diurnal variation of H.M. traces, when about 50 000 ionograms were inspected, on one occasion only, three sets were present, the third set representing signals with ranges in excess of 9000 km. An example of reflections with ranges in excess of 6000 km (extra-high-multiple or E.H.M. traces) is shown in Plate 1, Figure 5. During the months of September 1947 and September 1948 at Brisbane, H.M. traces were present for 46% of the night hours, while E.H.M. traces were present for 2·4% of the night hours. Additional features of the ionograms were examined when E.H.M. traces were present. On 90% of these occasions H.M. traces were also present; for 51% of the time the first-, second-, and third-hop traces showed enhancement and for 20% of the time the x-ray below the electron gyro frequency was enhanced. Satellite traces on second- and third-hop traces were present for 46% of the time. These indicate a certain degree of roughness in the F_2 layer.

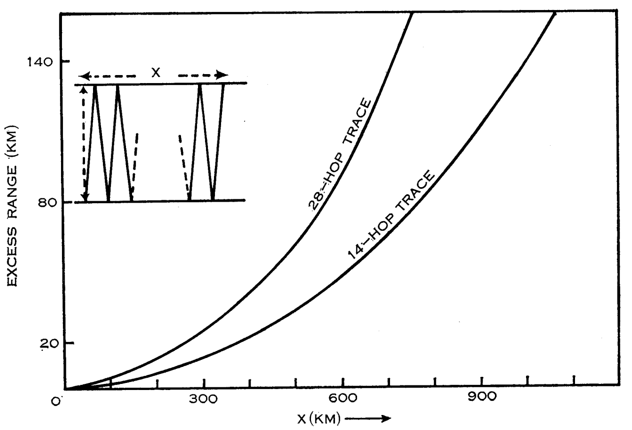


Fig. 2.—Plots of excess ranges above those for vertical incidence for 14-hop and 28-hop traces for a layer height (virtual) of 250 km, against extreme horizontal displacements of signals for off-vertical reflections.

If we assume a perfectly flat layer, except at the last point of reflection, an estimate can be made of the horizontal distance the signals travel before they return to the transmitter-receiver site. For a vertical-incidence group range of 250 km, the fourteenth-hop reflection should have a range of 3500 km provided all ray paths are vertical. Assuming that the changes in group retardation can be neglected for ray paths slightly away from the vertical, a calculation has been made of ranges in excess of 3500 km as the horizontal displacement (defined above) varies. These and similar calculations for the 28-hop trace are shown in Figure 2. For the H.M. and E.H.M. traces of Plate 1, Figure 5, and the H.M. traces of Plate 2, Figure 1(b), no discrepancy could be detected between observed and calculated ranges, if it is assumed that all ray paths for H.M. and E.H.M. traces are vertical. If it is claimed that these ranges can be read with an accuracy of 5 km, Figure 2 gives an indication that the furthermost reflection point is not more than about 150 km for the H.M. traces and 100 km for the E.H.M. traces.

III. Diurnal, Annual, and Sunspot-cycle Variations (Brisbane)

Figure 3 shows diurnal variations for certain days in summer, equinoctial, and winter periods. These days were consecutive and embraced a period in each case in which the sunset and sunrise times did not vary by more than 10 min. This was done because previous work (Bowman 1960*a*) had shown that a sunrise peak occurred about the time of sunrise at the 90 km level. Several years of records were used here. The sunrise peaks are well defined in the distributions. Throughout the night the summer and winter distributions show no marked variations, but the equinox distribution has a maximum at 0100 E.A.S.T. The equinox and winter distributions show what appear to be small peaks in occurrence about 40 min after ground sunset. Examples of sunset and sunrise H.M. traces are given by Plate 2, Figures 1 and 2 respectively.

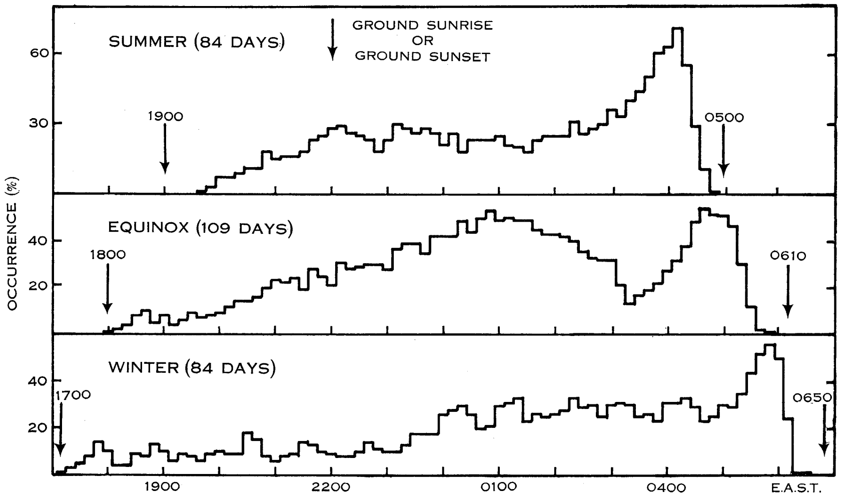


Fig. 3.—Histograms of diurnal distributions of H.M. traces at Brisbane for summer, equinox, and winter.

Figure 4 gives the percentage occurrence of H.M. traces relative to ground sunset or ground sunrise times for the three seasons. Plotting the distributions in this way allowed the use of more data. Each histogram represents data for the years 1948–50 inclusive. During these years occurrence rate was relatively high and did not vary greatly (Fig. 6).

As the phenomenon is confined to the night hours (Fig. 3), and the length of night hours varies throughout the year, some allowance must be made for this when considering the annual variation. The average percentage occurrence per night hour (at 90 km level) has been used in Figure 5 for the annual-variation histogram. Ionograms from Brisbane for 19·5 years have been used here. Maxima occur in the equinoctial periods. The minimum in winter is lower than that in summer. The distribution shows reasonably good agreement with the annual variation of the upper-atmosphere neutral particle density, as deduced from artificial satellite data

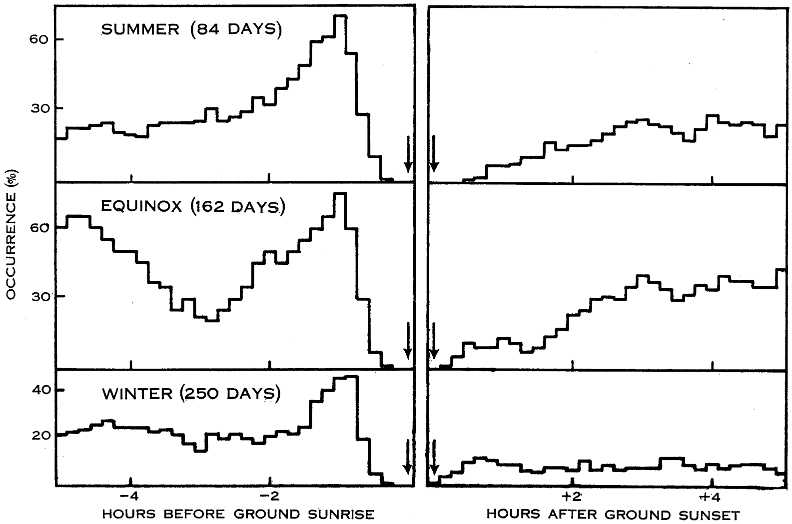


Fig. 4.—Histograms of distributions of H.M. trace occurrence at Brisbane for the 5 hr before ground sunrise and the 5 hr after ground sunset for summer, equinox, and winter.

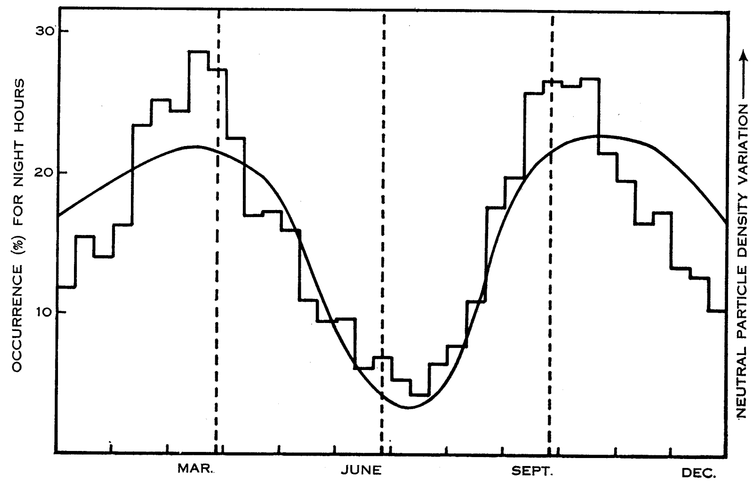


Fig. 5.—Annual variation of H.M. traces (percentage occurrence per night hour at 90 km level) from analysis of ionograms for 19·5 years from Brisbane. Also plotted is the annual variation of upper-atmosphere neutral particle density.

(Paetzold and Zschörner 1961). Both distributions show a minimum in mid July (not at the time of northern solstice). The slow fall to, and quicker rise from, this minimum is also consistent in these distributions.

The maximum occurrence rate associated with the sunrise is approximately the same for summer and the equinox but is somewhat reduced for the winter (Fig. 4). The small peak in occurrence at sunset is the same for winter and the equinox but is absent for summer (Fig. 4).

The sunspot-cycle variation shown on Figure 6 reveals a marked change in occurrence from sunspot maximum to sunspot minimum. Over this interval the occurrence rate drops by a factor of about 50, the H.M. trace phenomenon showing a direct relationship with the sunspot number.

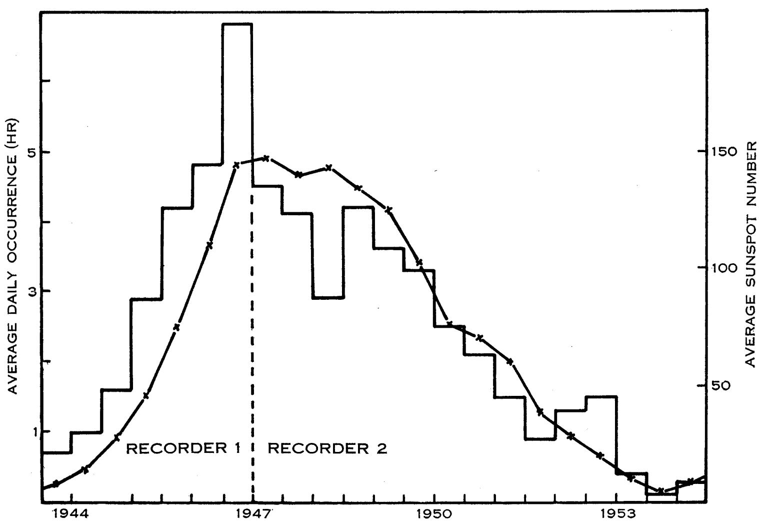


Fig. 6.—Sunspot-cycle variation for H.M. traces at Brisbane from 1944 to 1954 (inclusive). Note that two different ionosondes were used. Sunspot-number variation is also indicated (—×—).

IV. Periodicities in Occurrence

Examination of ionograms on nights when H.M. traces occur reveals periodicities ranging from 30 to about 90 min. During periods of continuous occurrence the signal strength (as determined by the appearance of the ionogram) seems to oscillate with periods of about 40 min. Figure 7(*a*) gives examples of this. For the last example (March 25–26, 1960) the $h'F_2$ variation at the time (illustrated) does not appear to be associated in any way with the periodicity in occurrence.

For times when occurrence was not continuous, Figure 7(*b*) illustrates cases chosen with periodicities of about 60 min in the occurrence of H.M. traces. Other periodicities also exist.

V. Spatial Extent of High-multiple Disturbances

Calculations using the ranges of H.M. traces on Plate 1, Figure 2, indicate that on this occasion the H.M. reflections were slightly oblique and that radiation would have covered a horizontal distance of about 500 km before returning to the transmitter-receiver site. These traces appear suddenly and on the same ionogram the x-ray signal below the gyro frequency, which must be reflected from positions close to the zenith, is also enhanced. The disturbance responsible for these phenomena appears to have a spatial extent of at least 500 km.

Ionograms taken at Cape York for five months in 1945 (geomagnetic latitude 20° S. and 2100 km from Brisbane) have been analysed so that daily occurrence of H.M. traces can be compared with that at Brisbane. A similar comparison has been made between occurrences at Hobart (geomagnetic latitude 52° S. and 1800 km from Brisbane) and Brisbane for 5 months of 1946. Figure 8 shows these results. At all three stations occurrence is variable. No relationship in occurrence between each pair is apparent.

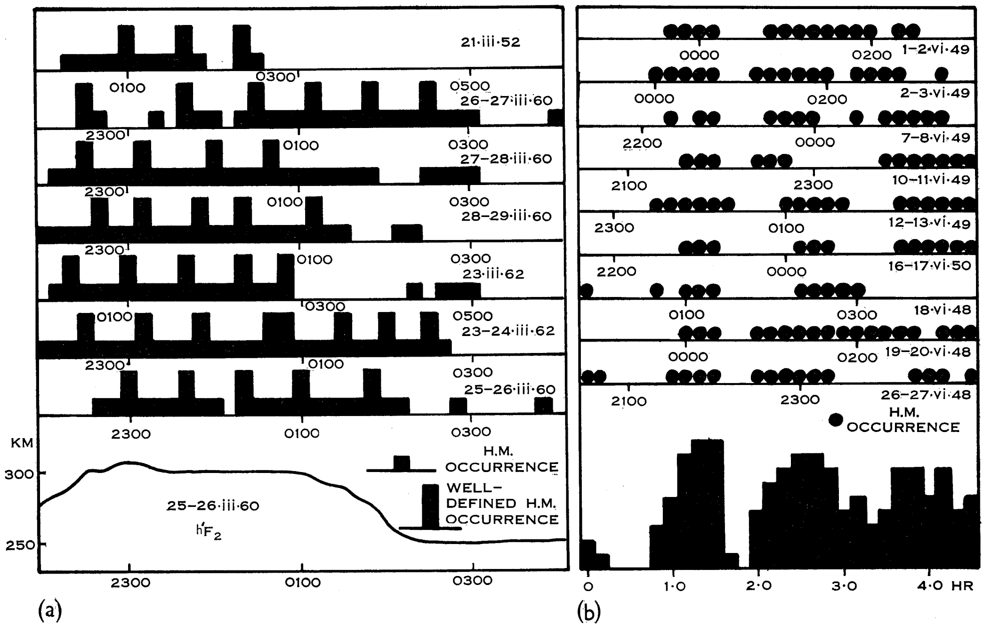


Fig. 7(a).—Illustrations of a number of cases during almost continuous occurrence of H.M. traces (Brisbane) when periodicities occur in enhanced signal strengths for the H.M. traces. Fig. 7.(b).—Illustrations of a number of cases when the occurrence of H.M. traces (Brisbane) shows a periodicity of about 60 min.

For the Hobart-Brisbane pair, times when sunrise and sunset H.M. traces are identifiable, are indicated. Again no relationship between stations is obvious.

VI. Azimuths-of-arrival of High-multiple Reflections

Rotating-loop records taken during 1958 allowed, on occasions, the measurement of the azimuth-of-arrival of H.M. signals. This system gave an ambiguity of 180° in direction. Only 21 readings were possible. The results indicated no preferred azimuth-of-arrival. Six readings gave directions in the north-west or south-east quadrants and the remaining 15 were located in the north-east or south-west quadrants.

VII. Discussion

If it is maintained that focusing is the primary cause of H.M. trace occurrence, one would expect an ionosphere with a ripple structure, the ripples having radii of curvature of roughly 3000 km, and at times exceeding 6000 km. This curvature would be superimposed on the curvature already existing (radius about 6700 km) due to the shape of the Earth. Any additional and smaller-scale ripple structure would tend to counteract this focusing effect. However, on occasions H.M. traces are present when the ionosphere is most disturbed due to spread-F irregularities. At Brisbane the ionosphere is seldom completely smooth at night. Irregularities, which can cause spreading on second- and third-hop traces, with the first-hop trace remaining clean, are nearly always present. Figure 1(c) gives an example of the structure on these occasions.

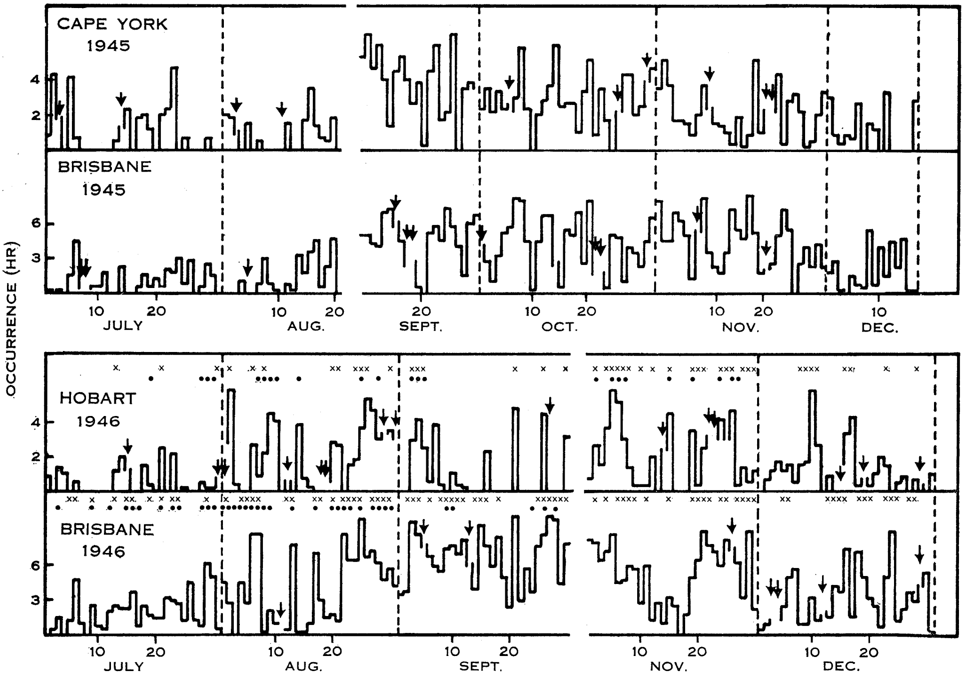


Fig. 8.—Comparison between daily occurrence of H.M. traces between Cape York and Brisbane for 5 months of 1945. Similar comparison between Hobart and Brisbane for 5 months of 1946. × indicates sunrise H.M. trace occurrence and ● indicates sunset H.M. trace occurrence. ↓ indicates no record.

Although a smooth layer may be an advantage for H.M. reflections, the foregoing suggests that it is not vital for their occurrence. H.M. traces still occur when the layer is disturbed. In fact the "spread" nature of some H.M. traces gives some indication of the presence and size of F_2-layer irregularities. The analysis of E.H.M. traces supports this view. In 90% of the cases of E.H.M. traces considered, H.M. traces were also present. A significant proportion of occasions when E.H.M. traces were found showed a simultaneous enhancement for low-order reflections (first-, second-, and third-hops). Plate 1, Figure 2, and Plate 2, Figure 1(*b*), illustrate cases where H.M. traces and low-order multiple traces show simultaneous enhancements. Simultaneous focusing effects covering a range of curvatures from 300 to 3000 km, and even to 6000 km, are extremely unlikely, particularly when the relatively small-scale spread-F structures are also present.

The alternative is to explain H.M. traces in terms of a reduction in non-deviative absorption. A redistribution of ionization at any level below the F_2 layer by travelling disturbances of some kind might temporarily reduce this absorption. However, due to the exponential change in electron–neutral particle collision frequency with height, this mechanism would be more effective in the lower regions (D and lower E regions). The sudden enhancement of the E_s trace on Plate 2, Figure 1(*b*), supports the view that the effect occurs below the E_s layer.

The increase in H.M. occurrence at (90 km level) sunrise time and to a less extent at (90 km level) sunset time is interesting. A previous analysis (Bowman 1960*a*) has shown the existence of irregularities in the D region around this sunrise time. These appear to be concentrations of ionization in lines aligned in the direction of the sunrise line and spaced from one another by about 50 km. It is possible that the electron density in regions between the concentrations has been reduced so that radiation passing through the layer in these regions encounters reduced absorption effects.

Both spread-F and H.M. trace occurrence show close relationships with the annual variation of the neutral particle density of the upper atmosphere (Bowman 1964) except for the fact that the spread-F and H.M. trace variations are inverse. A similar association is found for the sunspot-cycle variation of these parameters (Cook 1962). Since it seems unlikely that F_2-layer changes are primarily responsible for the existence of H.M. traces, spread-F and H.M. trace occurrence are apparently not directly related to each other. If the neutral particle density is important to their occurrence it suggests that the spread-F disturbances propagate better when this density is low and the H.M. disturbances propagate better when the density is high. The H.M. disturbances may possibly be acoustic waves generated above the F_2 layer and propagated through the layer towards the ground. Mitra (1952) shows that in the high atmosphere, attenuation of these waves is proportional to the mean free path of molecules in the region being considered. Higher neutral particle density would favour their propagation.

Apart from the sunset and sunrise occurrence of H.M. traces, the diurnal variation seems to be controlled by the gradual decay through the night of ionization responsible for non-deviative absorption. The absence of the sunset peak in summer is probably due to the presence of E_s blanketing during this period.

VIII. Acknowledgments

The author is grateful for the assistance of Mrs. D. Nielson and Miss B. Ross, who did a considerable amount of the data reduction; and also would like to thank the Ionospheric Prediction Service for making available the ionograms used in the analysis.

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IONOSPHERIC HIGH-MULTIPLE REFLECTIONS

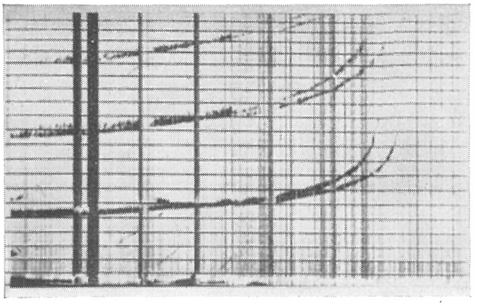


Fig. 1.—Ionogram (Hobart) 0100 18.xii.46.

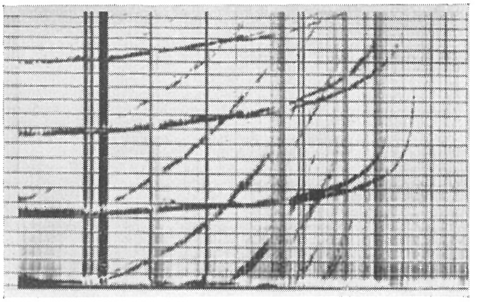


Fig. 2.—Ionogram (Hobart) 0110 18.xii.46.

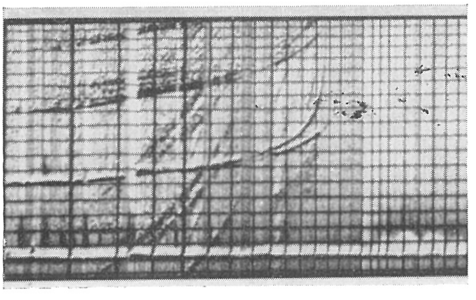


Fig. 3.—Ionogram (Brisbane) 0050 3.ix.47.

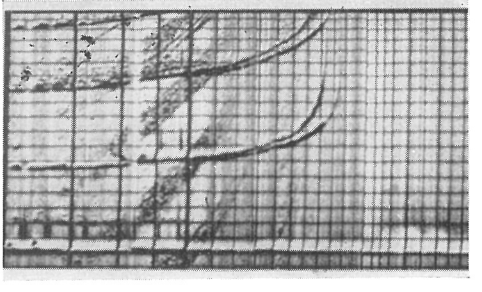


Fig. 4.—Ionogram (Brisbane) 0120 3.ix.47.

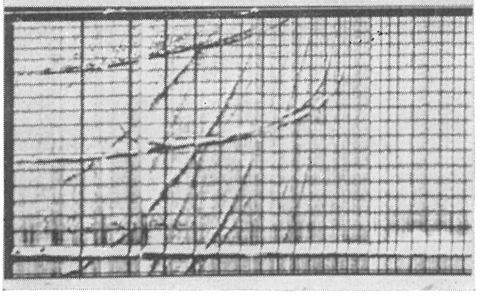


Fig. 5.—Ionogram (Brisbane) 0410 7.ix.47.

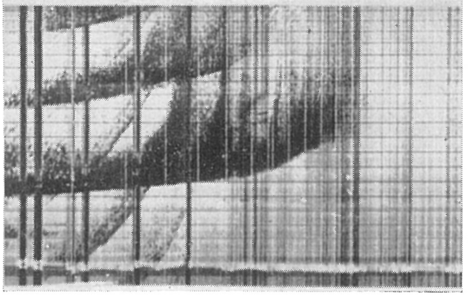
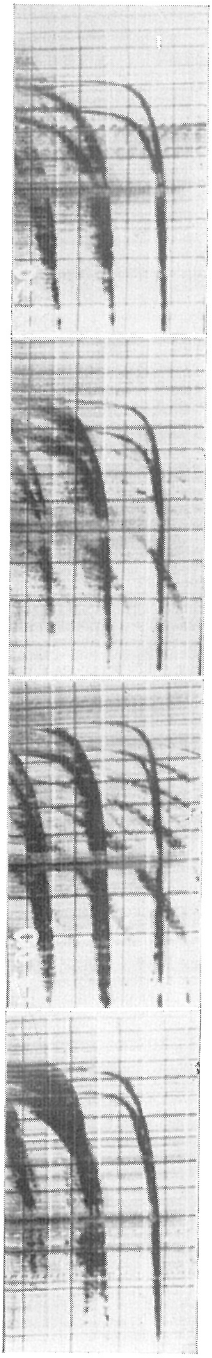


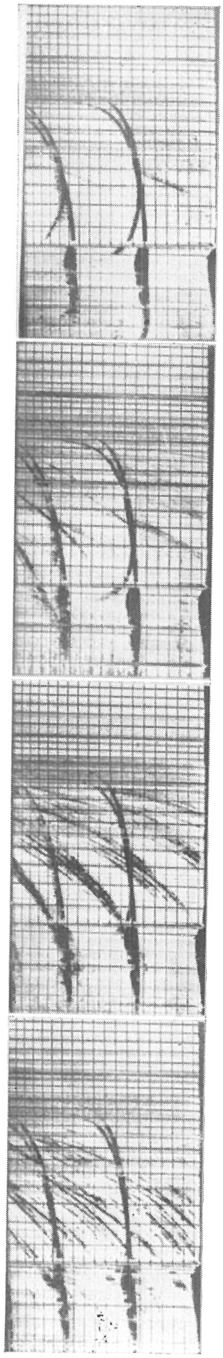
Fig. 6.—Ionogram (Hobart) 2350 14.viii.46.

IONOSPHERIC HIGH-MULTIPLE REFLECTIONS



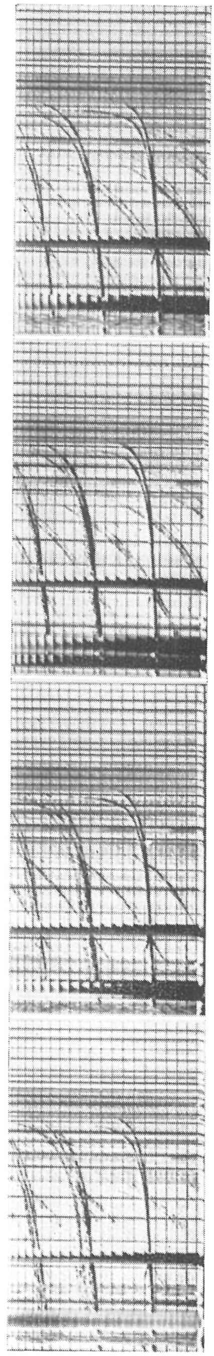
(a) 1745 (b) 1800 (c) 1815 (d) 1830

Fig. 1.—Consecutive ionograms from Brisbane around 1800 on 14.vii.46 showing sunset high-multiple traces.



(a) 0350 (b) 0400 (c) 0410 (d) 0420

Fig. 2.—Consecutive ionograms from Brisbane around 0400 on 17.xii.48 showing sunrise high-multiple traces.



(a) 0000 (b) 0010 (c) 0020 (d) 0030

Fig. 3.—Consecutive ionograms from Brisbane around 0000 on 9.ix.48 showing multiplicity of high-multiple traces.

IX. References

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