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The bottomside mid-latitude ionospheric trough

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Abstract—The measured power losses and Doppler shifts of h.f. radio waves propagated over a long, west–east, sub-auroral path are found to exhibit features which cannot be explained by simple predictions and models. Both theory and the limited available data indicate that a bottomside *F*2-layer depletion should be present below the topside mid-latitude trough. Introducing this into the models (using the mean statistical positions of the trough deduced from ALOUETTE I and II soundings) is shown to explain many of these features. From the Doppler shifts and a simple ray-tracing model the height of the depleted *F*2-peak inside the trough is deduced to be greater than its value outside the trough by an amount of the order of only 30–80 km.

1. INTRODUCTION

The majority of observations of the mid-latitude trough in the nocturnal *F*-region have been made using topside measurements (AHMED *et al.*, 1979) or in total electron content (MENDILLO and KLOBUCHAR, 1975). The presence of the trough in both topside profiles and T.E.C. indicates that the trough is a depletion of ionisation and not a redistribution. The trough is seen at all altitudes down to the *F*2-peak (THOMAS *et al.*, 1966), however relatively few observations of a trough below the *F*2-peak have been made.

The theories of the formation of the trough indicate that the trough should be present in the bottomside ionosphere. The poleward wall lies just equatorward of the boundary of diffuse auroral precipitation (TURUNEN and LISZKA, 1972: CHACKO and MENDILLO, 1977). BATES *et al.* (1973) therefore suggested that the poleward wall is caused by ionisation by the soft component of auroral particles. This ionisation is produced at altitudes around 100–150 km and moved upwards along geomagnetic field lines by the effects of auroral heating. Thus the observed field-aligned 'cliff' of ionisation is formed. The majority of ionisation caused by auroral particles is formed beneath the *F*2-peak where it is affected primarily by chemical and not diffusive processes (ROBLE and REES, 1977).

Statistically, the centre of the ionospheric trough is associated with the position of the geomagnetic field line of the equatorial magnetospheric plasmapause (KOHNLEIN and RAITT, 1977). However, at any instant the two do not coincide in a consistent way (GREBOWSKY *et al.*, 1978). Thus, the theory that the equatorward trough wall is the simple ionospheric manifestation of the plasmapause, with diffusive equilibrium along the field lines (THOMAS and DUFOUR, 1965) is inadequate (nor can this explain the depth of the trough). A more complex theory by SCHUNK *et al.* (1976) suggests the 0–N_2 ion–atom interchange reaction rate is increased by plasma convection. Figure 1 shows the approximate positions of the ionospheric trough and the polar plasma convection pattern. The trough wall positions are predicted by regression equations given by HALCROW and NISBET (1977) at a low K_p value. The convection pattern shown is the model adopted by KNUDSEN (1974). The polar wind outflow of protons enhances the loss at night (RAITT *et al.*, 1977) and such flows have been observed to be large at night in the polar cap region and between the plasmapause and the auroral oval (BANKS, 1971; LOCKWOOD and TITHERIDGE, 1979), and hence in the trough centre and poleward wall. SPIRO *et al.* (1978) have been able to extend this theoretical work by adding: a dawn/dusk asymmetry into the convection potential distribution (HEPPNER, 1973); a 5° asymmetry in the polar cap boundary (towards the nightside; STERN, 1977) and a narrow 'throat' of plasma flow into the polar cap on the dayside (HEELIS *et al.*, 1976). They were then able to produce trough cross-sections very similar to those observed as well as explain features of plasma convection such as the reversals of flow observed in the post dusk sector as seen by the AE-C satellite, and the stagnation point shifted into the pre-midnight sector (HEPPNER, 1977).

The 0–N_2 ion-atom interchange reaction rate is also faster for vibrationally excited N_2 molecules which are formed in the auroral zones and may be

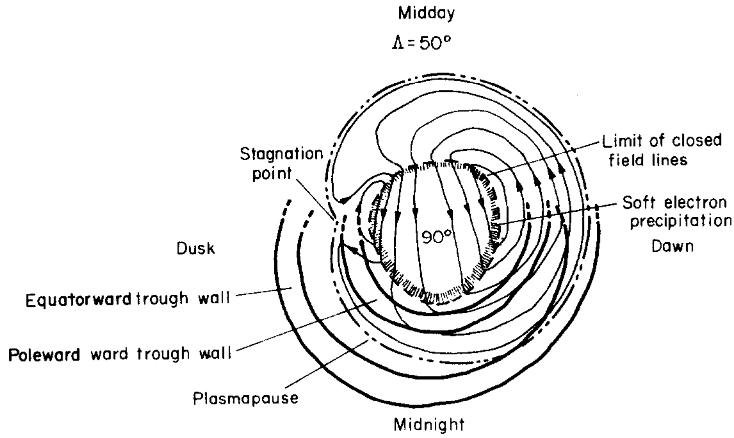

Fig. 1. Invariant latitude: local time plots of the model plasma convection pattern above 200 km by KNUDSEN (1974) and the mean positions of the walls of the trough in the *F*2-peak density at low K_p (between the solid lines) from regression equations by HALCROW and NISBET (1977).

moved equatorward by the thermospheric neutral winds (SCHUNK and BANKS, 1975). Both these mechanisms would give maximum depletions near the *F*2-peak (MAYR and HARRIS, 1979).

The effects of a trough on bottomside ionograms remain unclear because of 'off-vertical' reflections as simulated by HELMS and THOMPSON (1973) and NYGRÉN (1977) using ray tracing. Some trough observations have been reported with ionosondes, however, when the trough is wide under quiet conditions (CHACKO and MENDILLO, 1977). The trough in ion concentrations was observed by SHARP (1966) both above and below the *F*2-peak by satellite ion-trap experiments. STANLEY (1966) was able to explain 'oblique echoes' on bottomside soundings as reflections from the poleward wall of the trough which is very steep (BATES *et al.*, 1973). NICHOL (1973) interpreted spread-*F* on mid-latitude ionograms as multiple reflections from the walls of the trough, and mid-latitude spread-*F* has been correlated with the trough walls (TURUNEN and LISZKA, 1972).

TAYLOR (1973) was able to observe the trough at heights above and below the *F*2-peak as it moved over an incoherent scatter radar, and BOWMAN (1969) observed the trough in the bottomside nocturnal iso-ionic contours using an ionosonde with direction finding capabilities. The theories and available data hence indicate that the trough should persist to altitudes below the *F*2-peak.

2. OBSERVATIONS OF RADIO WAVES

7.335 MHz c.w. radio waves transmitted from CHU, Ottawa (geographic coordinates: 45°18'N, 75°45'W) were received at the Norman Lockyer Observatory, Sidmouth (50°41'N, 3°13'W), a great circle distance of 5212 km. The power losses suffered by the signals in propagating over this path, L_{T0}, were measured (LOCKWOOD, 1978; LOCKWOOD and MITCHELL, in press). The Doppler shift of the received signal was also measured, the frequency stability of the local oscillators at the transmitter and receiver being 1 part in 10^9. The accuracy of the power loss measurements was checked by direct calibrations.

Figure 2 shows *n*, the number of hourly observations of observed loss between L_{T0} and $(L_{T0}+1)$ dB

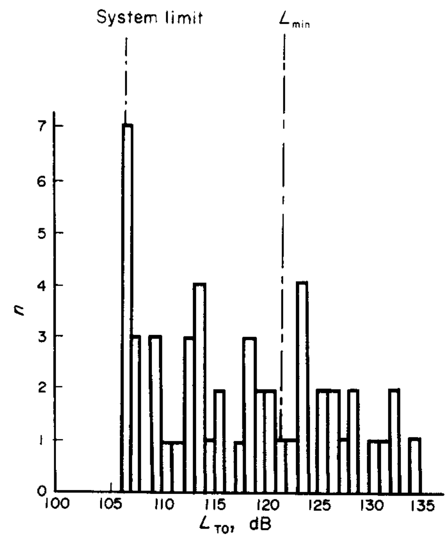

Fig. 2. Histogram of *n*, the number of observations for which the measured loss is between L_{T0} and $(L_{T0}+1)$ dB In April, May and June, 1976. L_{min} is the minimum loss of a hypothetical link using the same apparatus over a path of length 5212 km.

as a function of L_{T0}, for all the usable recordings taken in April, May and June 1976. In 33 of these 77 cases the observed loss was less than L_{min}, the minimum loss for a hypothetical link using the same apparatus over a free-space, straight-line path of length equal to the Ottawa–Sidmouth great circle distance. To investigate these low losses further, these measured values of L_{T0} were compared with predicted values obtained using a method based on that of BARGHAUSEN *et al.* (1969). Such predictions can, of course, differ greatly from the actual loss at any instant due to effects not included in the prediction and because the values used in making the prediction are medians of large statistical spreads due to the variability of *F*-layer propagation. To eliminate these factors (as possible explanations of results of the kind shown in Fig. 3) the minimum possible loss for each time of recording was predicted, L_m. This was done by using relevant decile values in some terms of the total loss equation and by omitting others completely. The only gain factor included was focusing due to a spherical ionosphere. Other possible gain factors include: 'maximum range focusing' as described by CROFT (1969); unresolved multipath interference, and ducting or focusing due to tilts of the iso-ionic contours. It can be shown that only the last of these can consistently explain the results (LOCKWOOD, 1978).

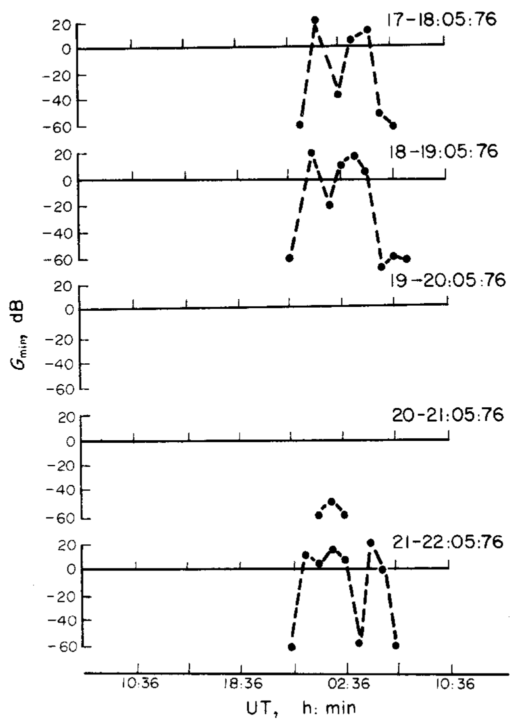

Fig. 3. Diurnal variation of the additional gain of the predominating predicted ionospheric mode, G_{min} for five consecutive days. No usable recordings were made during the night of 19–20/05/76 and no positive values of G_{min} were observed during the following night.

Figure 3, shows the diurnal variations of G_{min} (the difference between the predicted minimum loss, L_m, and the observed loss, L_{T0}) for 5 consecutive days. it was found G_{min} was frequently positive and large at night. In the three months used to compile Fig. 2, values of G_{min} up to +35 dB were observed and in 27 of the 77 recordings in this period G_{min} was greater than +10 dB. At these times the lowest loss propagation mode predicted was invariably the 2*F*2 mode.

The hourly observations of the Doppler shift, Δf, usually show a regular diurnal variation of the type shown in Figs. 4, 5 and 6. Like G_{min}, the Doppler shift shows two maxima during a night with an intermediate minimum. The second peak occurs between 04 and 06 UT and varies in amplitude from 0.20 to 0.50 Hz (±0.01).

The continuous lines of Figs 4(i), 5(i) and 6(i) are ray tracing model predictions of the Doppler shift. These were produced by a Snell's law-type, two-dimensional, ray-tracing program. Parabolic *E*- and *F*2-layers were used with the values of the peak heights and densities along the path being those used in the power loss predictions. The semi-thicknesses used were kept constant over the path for simplicity. The phase path (ROBINSON and DYSON, 1975) of the lowest loss mode, *P*, was evaluated at intervals of one minute and the Doppler shift taken from the rate of change of *P*. Groups of 15 values were then averaged to give quarter-hourly means.

It can be seen that these simple predictions do not agree well with the observed variations and in particular the shifts observed between 04 and 06 UT are considerably larger than predicted.

3. DISCUSSION OF POWER LOSS RESULTS

The independent Doppler shift and power loss measurements vary considerably from their simple model predictions. Although there are many possible causes of these deviations there is one possible cause which is common to both in that sharply tilted iso-ionic contours of the bottomside ionsphere have not been allowed for.

Tilts of the *F*-layer are expected at the latitudes of this path due to the walls of the mid-latitude trough. To evaluate their possible role in the propagation of these signals results were used concerning the mean morphology of the trough. Various

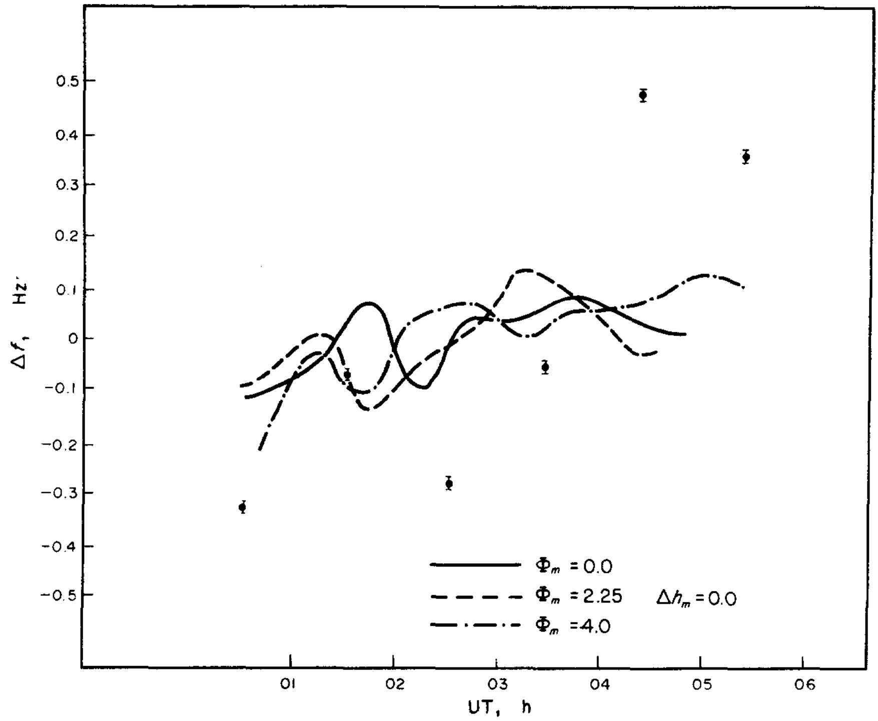

Fig. 4. Model Doppler shift variations for the night of 22–23/06/77 (mean $K_p = 2.5$) for (i) $\Phi_M = 0.0$; (ii) $\Phi_M = 2.25$ and (III) $\Phi_M = 4.0$. The points show the observed values.

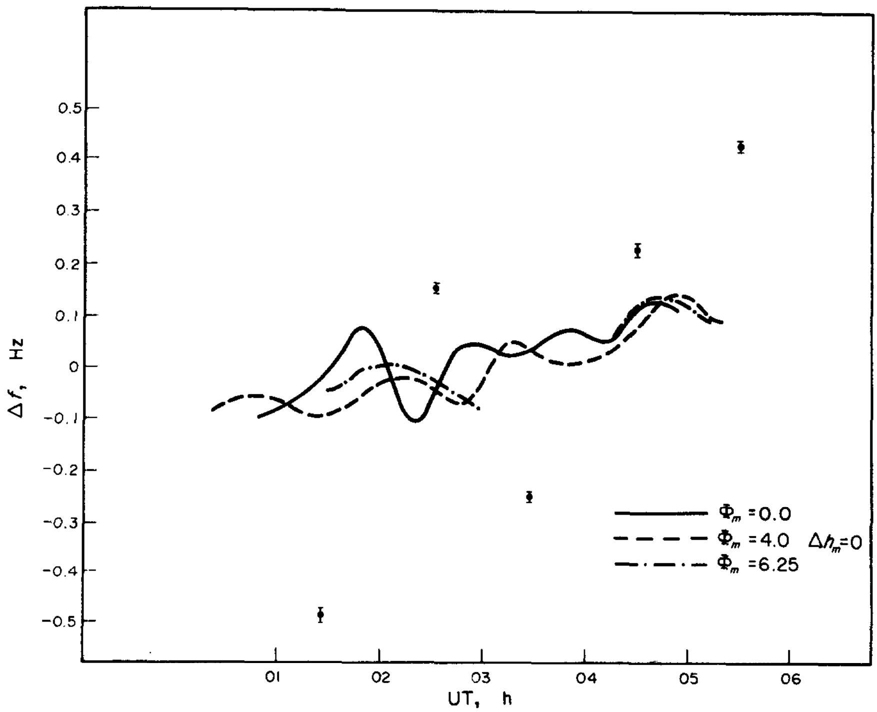

Fig. 5. Model Doppler shift variations for the night of 05–06/06/77 (mean $K_p = 1.6$) for (i) $\Phi_M = 0.0$; (ii) $\Phi_M = 4.0$ and (iii) $\Phi_M = 6.25$. The points show the observed values.

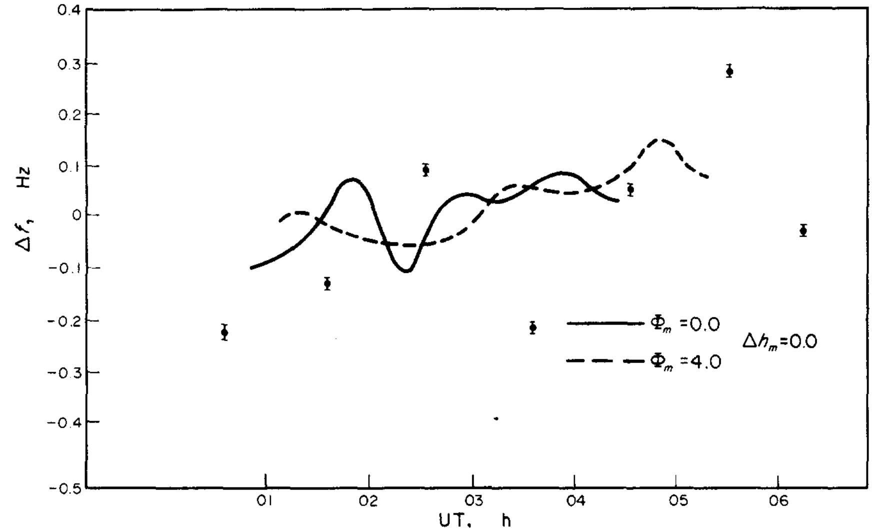

Fig. 6. Model Doppler shift variations for the night of 04–05/06/77 (mean $K_p = 1.4$) for (i) $\Phi_M = 0.0$; (ii) $\Phi_M = 4.0$. The points show the observed values.

such models of the trough with varying K_p index and local time have been developed from existing data (FEINBLUM, 1973; HALCROW and NISBET, 1977). It must be remembered that there are several pitfalls in the use of such statistical morphological results (MENDILLO and CHACKO, 1977) and the regression equations cannot be used to predict the actual boundary locations of the trough at any one instant (MENDILLO *et al.*, 1978). Hence their use here can only indicate that any one hypothesis is consistent with mean statistical positions of the trough.

The mean invariant latitude of the walls of the trough in the F-layer peak are shown in Fig. 7 for various K_p values as a function of local time. These are given by equations by HALCROW and NISBET (1977) based on eight years' ALOUETTE I and II topside sounder data. Also shown are the invariant latitudes of the points A and B, which are the points one and three quarters of the way along the Ottawa–Sidmouth path at 200 km altitude. In practice, of course, the reflection points of the $2F2$ mode could be considerably removed from the points A and B, but they are sufficiently accurate indicators, considering the inaccuracies of the wall positions. It can be seen at low K_p both A and B lie within the trough walls for the times at which the trough would be open at them. The mean times that the trough opens at A and closes at B are calculated from the mean zenith angles given by FEINBLUM (1973), and are shown in Fig. 7. At higher K_p values the point B remains within the trough walls, but the steeper and more equatorward position of the poleward wall cause A to be outside the trough for most of the night. Thus this path is at the right latitudes to be affected by any bottomside trough at low K_p values.

The mean times that the trough opens at A and closes at B are shown in Fig. 8 for a few typical days when G_{min} was consistently positive. The times that G_{min} was positive are also indicated in Fig. 8, and those points marked 'm' are also maxima in G_{min}. The trough end positions are evaluated using the mean K_p value for that day (from noon to noon). This was done because the plasmapause (and hence trough) behaviour is determined by not only the current K_p value but also the recent K_p value history (GREBOWSKY *et al.*, 1974; MENDILLO *et al.*, 1978). The mean K_p values are shown at the bottom of the diagram. 89% Of the observed positive G_{min} values were between the mean times that the trough was open at both A and B and all were within an hour of these times. Therefore the low power losses were observed at the times predicted by a hypothesis of focusing due a bottomside trough. The maxima in G_{min} tend to occur near the times that the trough opens at A and closes at B. This is qualitatively consistent with this hypothesis in that at such times focusing would occur in the plane parallel to the trough as well as in the one perpendicular to it (due to the end and walls of the trough respectively; NYGRÉN, 1977).

It can be seen in Fig. 8 that no positive values of G_{min} were observed on the nights of 19–20/05/76

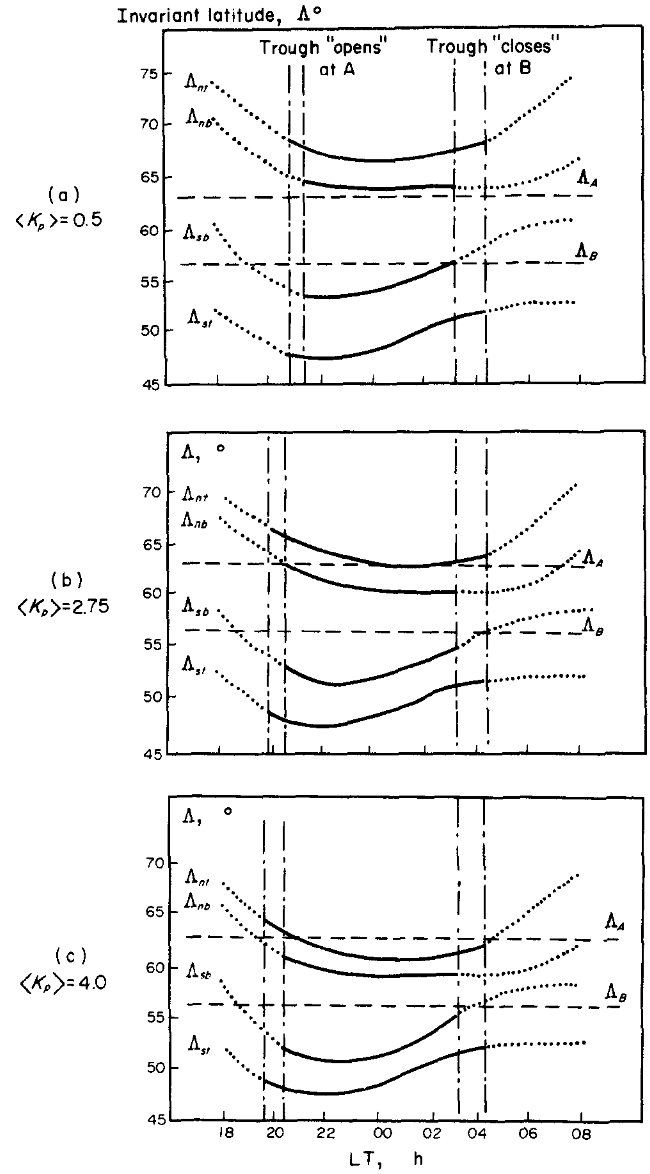

Fig. 7. Variations of mean invariant latitudes of top and base of north and south walls (Λ_{nt}, Λ_{nb}, Λ_{st} and Λ_{sb} respectively) of north hemisphere trough, for 17–18/05/76 for a mean K_p value of (a) 0.5, (b) 2.75 and (c) 4.0.

nor 20–21/05/76 and the mean K_p values on these nights were larger. In fact, no positive G_{min} values were observed when the K_p value exceeded 2.75 (Fig. 9) and there is a sharp cut-off in G_{min} around this K_p. At this K_p the point A lies roughly in the middle of the mean position of the poleward trough wall (Fig. 7b). Thus, at this (and higher) K_p the first hop of a $2F2$ mode would be defocused by the trough (Helms and Thompson, 1973). The possibility of a $2F2$ mode being focused by the trough therefore agrees well with the observed cut-off in G_{min} values at this K_p.

Although no positive G_{min} values were obtained when K_p was large the converse was not true in that, as shown in Fig. 9, a low K_p value does not always give a positive G_{min} value. In 42% of the recordings at mean K_p below 2.75 G_{min} was negative. Why the effect is not always observed at low

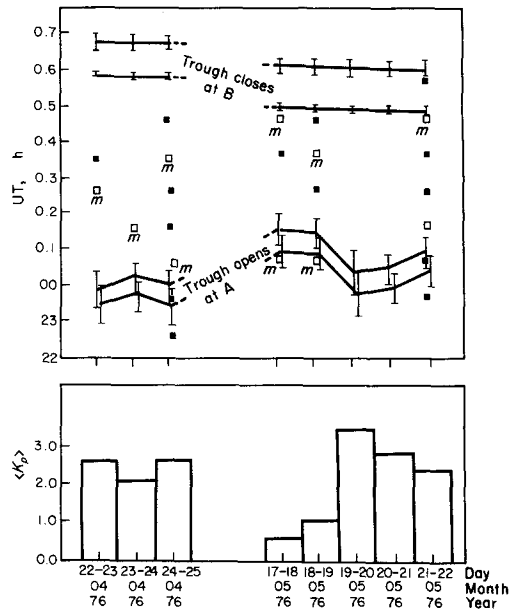

Fig. 8. Times of positive G_{min} observations (both open and closed squares) and daily mean K_p values (from noon to noon) for various days of nearly-continuous usable recordings. The mean times at which the trough opens at A and closes at B are also shown for that mean K_p value (FEINBLUM, 1973). The open squares marked with m denote that the positive G_{min} value is also a maximum in the diurnal variation of G_{min}.

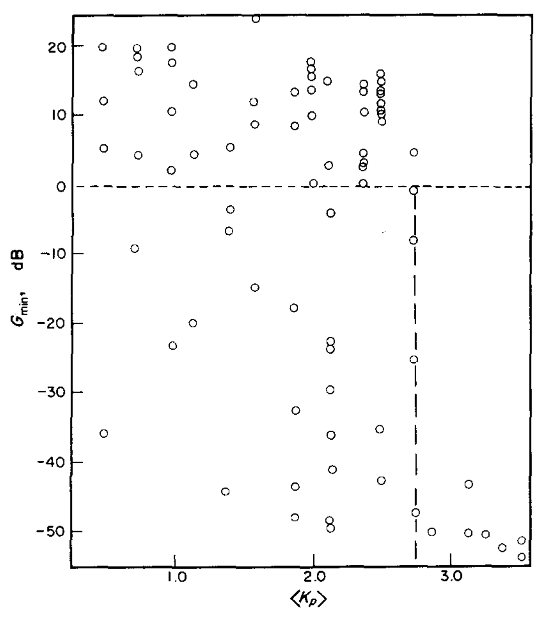

Fig. 9. Values of G_{min} from observations in April, May and June 1976 as a function of the mean K_p value.

K_p remains unclear. The topside trough was found to be present on roughly 95% of all nights in a three year period by AHMED *et al.* (1979), so it is unlikely that this is due to the absence of any ionospheric trough. It may, however, be due to a less well-defined bottomside trough, or a change in its orientation.

4. DISCUSSION OF DOPPLER SHIFT RESULTS

The simple ray tracing predictions of the Doppler shift were repeated allowing for the depletion of the $F2$-peak density in the trough. The model variation used is shown in Fig. 10 and is one adopted by HALCROW and NISBET (1977). The factor Φ (reciprocal of the correction factor used to correct the CCIR global $F2$-peak density maps) is assumed to vary linearly across the walls of the trough, and was given a constant value of Φ_M in the base of the trough, (they found that a constant value of $(1/\Phi_M)$ of 0.25 ± 0.05 fitted all the data at all seasons and sunspot numbers less than 50). Figures 4, 5 and 6 show the predicted Doppler shift variations for several nights recordings made using the ray tracing program as before but also varying the value of Φ_M. The $F2$ semi-thickness is kept at a constant value, as is the peak height across the trough. The results vary in a rather unpredictable

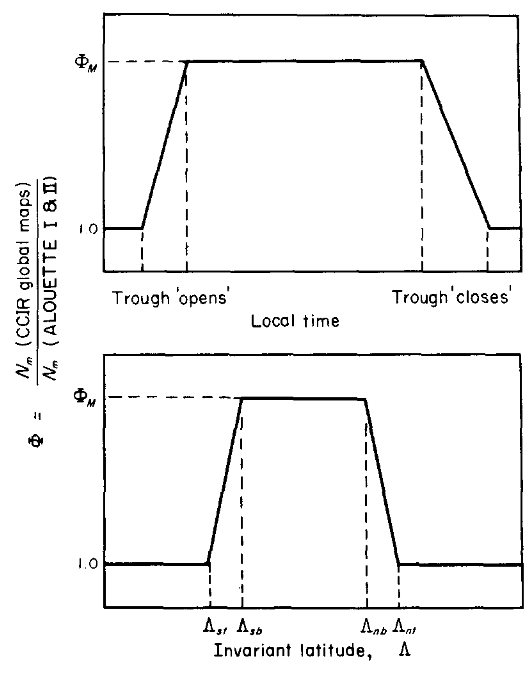

Fig. 10. Model of trough positions (HALCROW and NISBET, 1977).

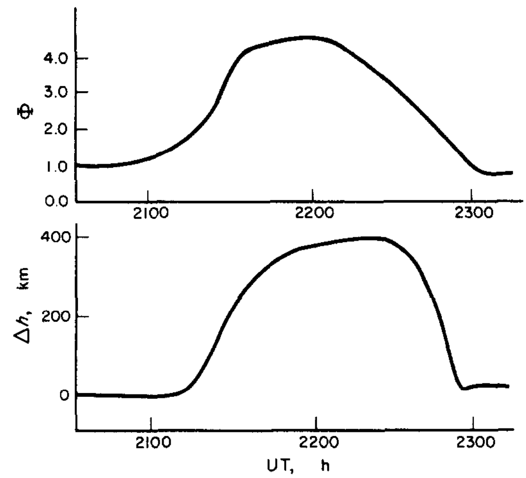

Fig. 11. Variation of peak density correction factor, Φ, and peak height change, Δh, observed by Bowman (1969) on 21/04/58.

way which is to be expected considering the unrealistic discontinuities in the gradient of Φ_M in the model used. However it was found that by varying Φ_M alone this model could still not reproduce the observed Δf variations.

The iso-ionic contours obtained by Bowman (1969) of the bottomside ionospheric trough in the southern hemisphere show that as well as the F2-peak density being reduced, the peak height is increased in the trough region. An example of the variations of Φ and the change in the F2-peak height, Δh, from his results are shown in Fig. 11. To include this effect in the model Δh was given the same model variation as Φ with a constant base value of Δh_m. The ray tracing predictions for fixed values of Φ_M and semi-thickness and varying Δh_m are shown in Figs. 12, 13 and 14 for the same nights as Figs, 4, 5 and 6 respectively. It can be seen that the modelled values now begin to resemble the observed values remarkably well considering the crudeness of the model predictions. The value of Δh_m used in the best fit was found to be largely independent of Φ_M and ranged between 30 and 80 km, considerably less than the 300–400 km reported by Bowman (1969). In the trough passage reported by Taylor (1973) the peak height first increased from 320 to 380 km, but then a second peak appeared at an altitude of 730 km which slowly descended to the usual peak height, which he described as a new irregular F-layer which replaced the first, depleted layer. It seems likely that this new layer may be the peak reported by Bowman (for which Δh_m is of the order of 400 km)

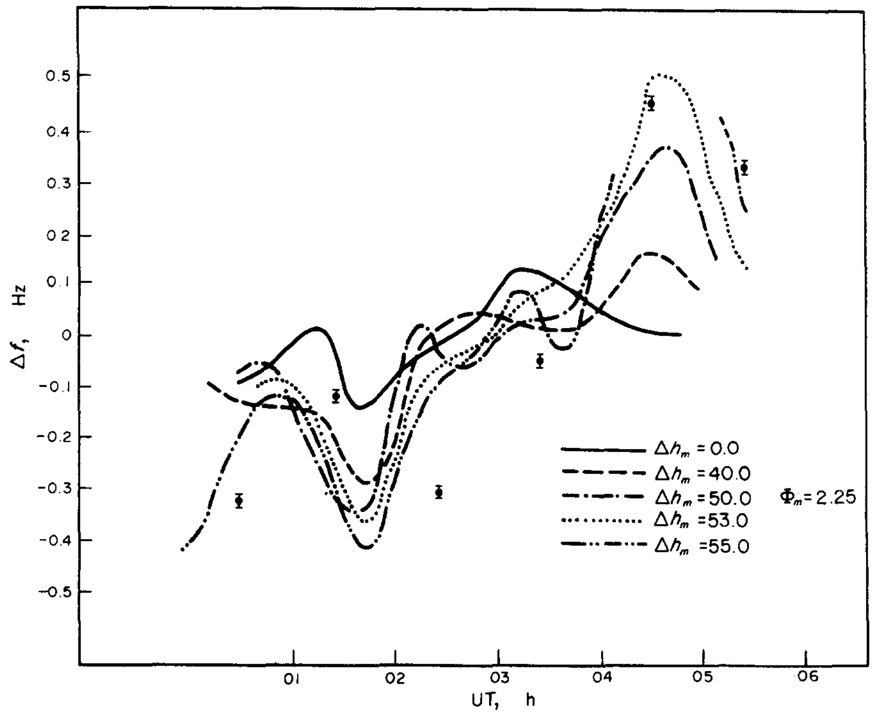

Fig. 12. Model Doppler shift variations for the night of 22–23/06/77 (mean $K_p = 2.5$) for various values of Δh_m and a Φ_M of 2.25. The points show the observed values.

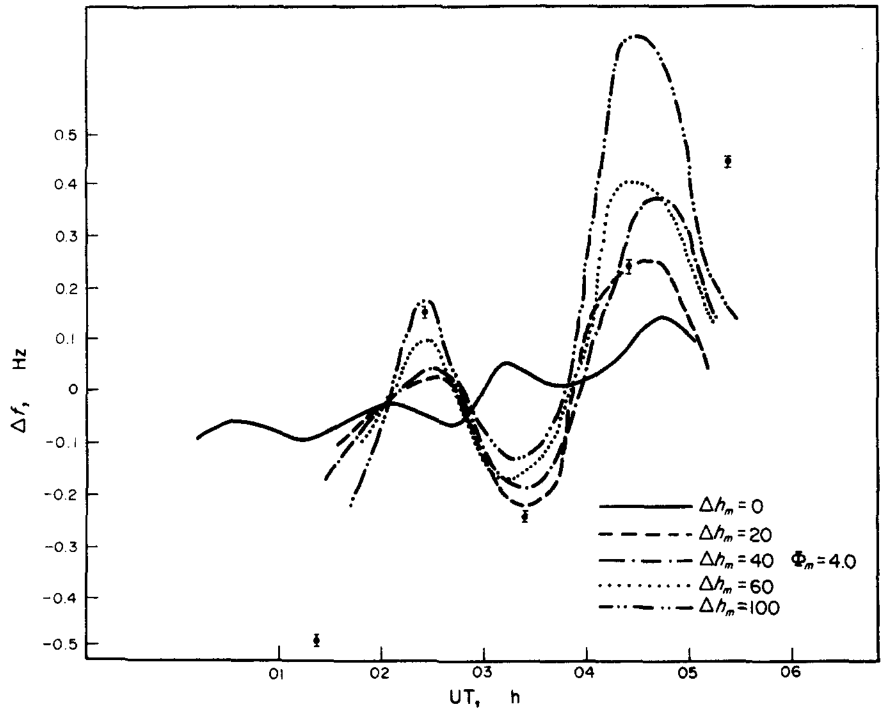

Fig. 13. Model Doppler shift variations for the night of 05–06/06/77 (mean $K_p = 1.4$) for various values of Δh_m and a Φ_M of 4.0. The points show the observed values.

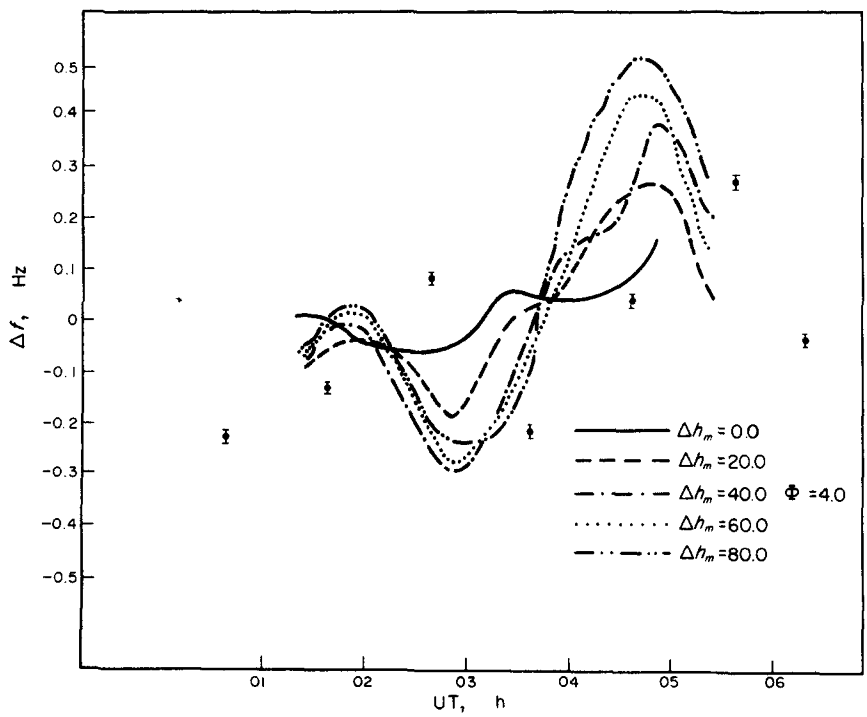

Fig. 14. Model Doppler shift variations for the night of 04–05/06/77 (mean $K_p = 1.6$) for various values of Δh_m and a Φ_M of 4.0. The points show the observed values.

whereas the oblique h.f. waves in this study do not penetrate the 'old' depleted F-layer, which only rises by about 30–80 km. It was found in several examples (Fig. 13) that the observed Δf variation lagged behind the predicted one by up to three quarters of an hour, such a delay, between the walls of the trough in Φ and Δh can also sometimes be seen in Bowman's results although only up to about 30 min duration.

5. CONCLUSIONS

The observed variations of the power losses and Doppler shifts of these signals cannot be explained by simple means. The path lies along the latitudes of the mid-latitude trough. The presence of a bottomside trough at low K_p offers a qualitative explanation of the power loss results. Introducing a crude model of the trough based on its mean statistical positions from ALOUETTE soundings gives Doppler shift variations of the kind frequently observed. The cut-off in the low power losses above a K_p of 2.75 strongly implicates the bottomside trough in the propagation of these signals. From the Doppler shift results and the simple model of the trough it is found that the depleted $F2$-peak is raised by an amount of the order of 50 km inside the trough.

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