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# APPARENT DIURNAL MOVEMENTS OF THE TROUGH IN TOTAL ELECTRON CONTENT (TEC) OF THE IONOSPHERE

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## Abstract

The apparent latitudinal movements of the trough in total electron content (TEC) in the course of the day were studied using signals from NNSS satellites. Measurements were made with a chain of four stations (Sodankylä, Uppsala, Lindau, and Graz) using the Difference Doppler method. Data from October and November 1975 were used.

The minimum in each TEC vs. latitude plot was sought, and its position was converted to an $L$ value using the IGRF model. The material was divided into three groups according to the degree of geomagnetic activity. The mean diurnal variation of $L$ in each group was determined. The results are:

1. In each group the minimum in TEC (the trough) appears by day at $L$ values higher than 10 and moves in the afternoon to $L$ values between 3 and 4.
2. With increasing activity the trough moves equatorwards in all local time sectors.

A comparison of the apparent diurnal movement of the TEC trough with the equatorward boundary of the statistical auroral oval suggests that the two might be interconnected but the former appears in all local time sectors a few degrees equatorward of the latter. A relation with the plasmapause might be present in the night sector and with the cusp in the day sector.

## 1. *Introduction*

The high-latitude ionosphere is temporally and spatially highly variable. Among other things, it exhibits latitudinal minima in the critical frequency of the F layer (foF2) (MULDREW, 1965), in the local density of dominant ions (SHARP, 1966), in the total electron content (LISZKA, 1967) and in the light ion density (TAYLOR and WALSH, 1972). All these minima have been called throughs in the literature, and often it is quietly assumed that these throughs more or less coincide. It is possible that this assumption is the source of come conflicting results in trough studies.

The purpose of this report is to give results concerning the apparent diurnal movement of the total electron content (TEC) trough, as determined by means of differential Doppler measurements. These measurements were carried on at a chain of stations from the auroral zone to middle latitudes (Sodankylä, Uppsala, Lindau and Graz) operated in the framework of an international project (LEITINGER *et al.*, 1978). This report covers the period November and December 1975; these are winter months in which the trough is most often observed. I shall compare our results with those obtained by others and try to draw conclusions as to the connections of the trough with other geophysical features.

## 2. *Measurements*

Signals from the NNSS (Navy Navigational Satellite System) satellites were used in this study. These satellites have polar orbits at an altitude of about 1100 km and radiate two coherent beacon frequencies, 150 and 400 MHz. The differential Doppler effect on these frequencies, normalized to 50 MHz, was measured. This effect gives information on the integrated number of electrons between the satellite and the ground station, and this quantity is converted to vertical total electron content (TEC) at the location where the radio ray intersects the ionosphere at a chosen altitude (Fig. 1). The intersection is called the subionospheric

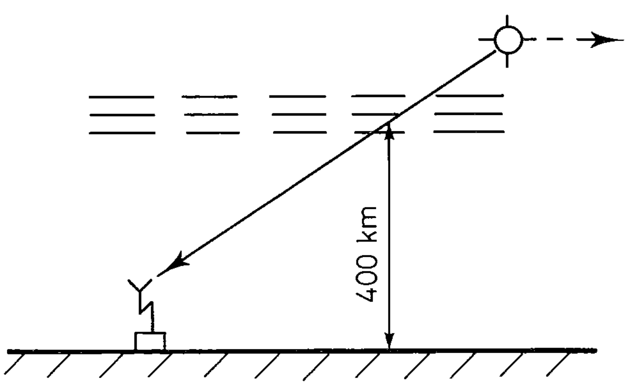


Fig. 1. The principle of TEC measurement schematically.

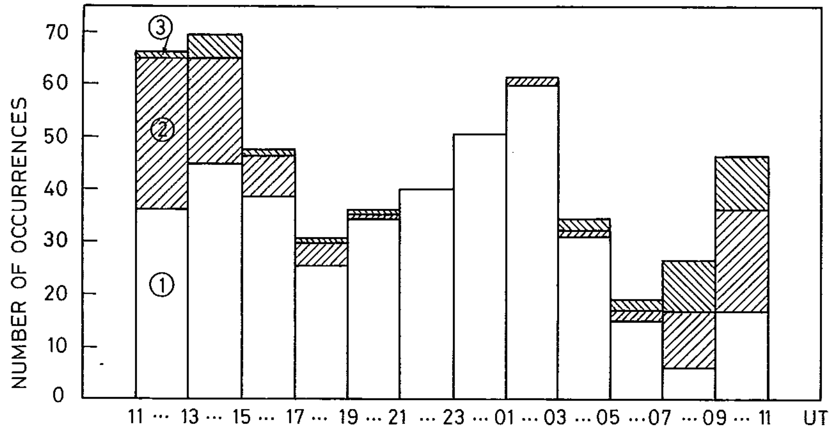


Fig. 2. The daily variation in the occurrence of the trough.
1 = recording with a trough present
2 = recording obtained for part of the latitude range only; no trough seen in this range but it might have been located at high latitudes.
3 = no trough visible in spite of complete latitude coverage.

point. The altitude used in this study was 400 km, corresponding to the most common altitude for the center of gravity of the ionospheric electron density profile.

The recordings giving the differential phase of the signals at the two frequencies were scaled. The results from the different stations were combined to TEC vs. latitude plots and plots of subionospheric tracks. Most of the TEC plots show a minimum, the TEC trough.

We have studied in the Appendix what relation the latitude of the TEC trough, as measured by means of our method, has with the actual minimum. The result is that if the subionospheric altitude has been chosen properly, the errors remain well below one degree. On the other hand, if the subionospheric altitude is (say) 100 km too high, and the measuring station is several degrees away from the minimum, errors up to one degree will be obtained. We think that our value of 400 km for the subionospheric altitude is in most cases sufficiently correct to justify the conclusions drawn here, especially in light of the large latitude excursions of the trough.

The occurrence of the trough at different times of day is shown by means of a histogram in Fig. 2. It is obvious that the trough is relatively frequent from 11 UT to 05 UT: Almost all recordings where the whole latitude range could be covered show a trough. After 05 UT the number of recordings drops, and a smaller fraction of them contain a trough.

The trough seems to be an afternoon and night phenomenon and less well developed in the morning hours. The high occurrence frequency in the afternoon has, to our knowledge, not been stressed in the literature. This is, as we shall see, important because of the high latitude of the trough in this local time sector which has to be taken into account when looking for connections of the trough with other geophysical features.

As the next step, the geographic latitude and longitude of the trough were scaled from the plots and converted to an $L$ value using the International Geomagnetic Reference Field (IGRF) model of Cain *et al.* (1967). The $L$ values obtained (390 in number) were grouped according to the universal time and the value of the planetary magnetic activity index $Kp$. Three ranges of $Kp$ were used;

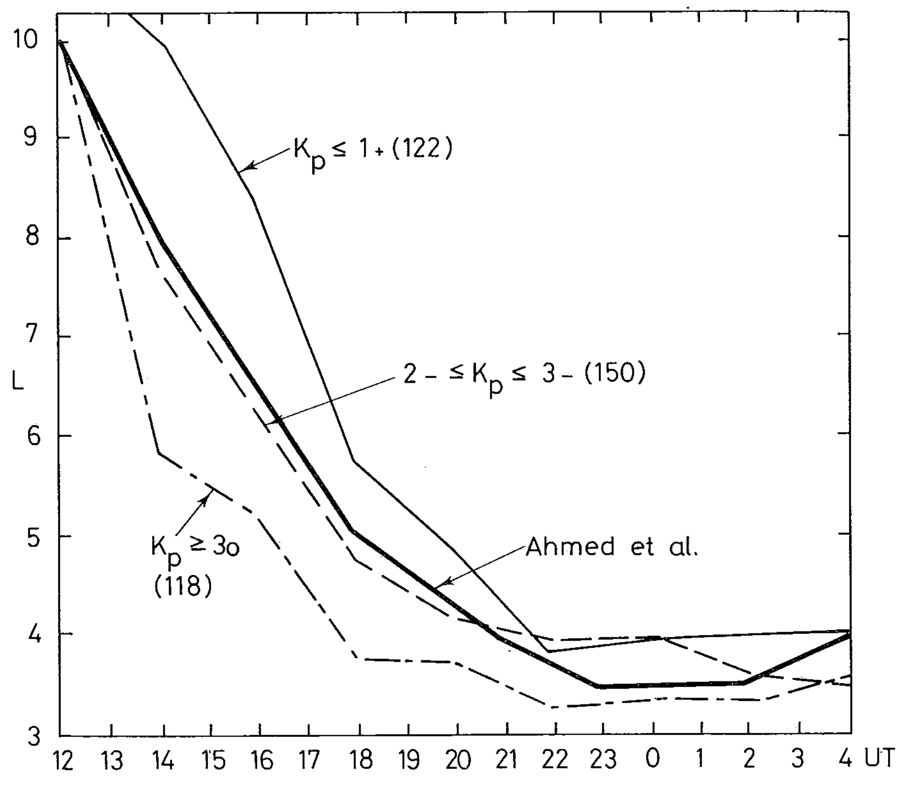


Fig. 3. Diurnal variation in the $L$ values of the trough for different degrees of geomtric activity, as indicated by the $K_p$ values (the number of measurements in parenthesis). For comparison the curve obtained by AHMED *et al.* (1979) for the average trough position in thermal positive ion and electron densities in winter below 1500 km.

their limits were chosen such that the three groups contained an approximately equal number of measured values. Finally, median values over two-hour periods were determined.

## 3. *Results*

The results are shown in Fig. 3. The forenoon hours are missing because of the poor statistics in this time interval. The following conclusions can be drawn:
1. In each *Kp* group the TEC trough appears, on the average, by day at higher *L* values than 10 and moves in the course of the afternoon rapidly to lower *L* values, reaching the *L* range between 3 and 4 at night. There is a tendency towards higher *L* values in the morning.
2. With increasing *Kp* the TEC through moves to lower latitudes at all local times.

## 4. *Discussion*

Our result agrees rather well with the early result of LISZKA (1967) who gave the location of the TEC trough in geographic coordinates vs. local magnetic time, without grouping the material according to geomagnetic activity. It is also in agreement with the average trough positions in thermal positive ion and electron densities in winter below 1500 km, as measured by the Isis I and Injum 5 satellites by AHMED *et al.* (1979) (also shown in Fig. 3). Above 1500 km AHMED *et al.* found two troughs on the dayside, one coinciding with the trough at lower altitudes, the other being located at much lower *L* values. On the nightside the equatorward boundary of their high-altitude trough moves to continually lower latitudes with increasing altitude, and the poleward boundary becomes less marked.

The light ion trough (LIT) seems to be located at nearly constant *L* values near $L = 4$ by day and by night (TAYLOR and WALSH, 1972) whereas the trough in foF2 (JELLY and PETRIE, 1969) seems to exhibit a similar large diurnal movement in latitude as our TEC trough.

The possible connections of the trough (or better: the different troughs) with other ionospheric or magnetospheric boundaries have been the subject of considerable interest. Already MULDREW (1967) assumed that the trough in foF2 was an extension along magnetic field lines of the plasmapause. RYCROFT and THOMAS (1970) came to the same conclusion concerning the trough in local electron density at 1000 km and the plasmapause. TAYLOR (1972) noticed that the LIT and the plasmapause appear at similar *L* values and infers that the LIT is a continuation in the ionosphere of the plasmapause. He also thinks that this is quite natural because the plasmasphere is dominated by light ions. LISZKA (1967) notes the similar latitudes of the plasmapause and the TEC trough by night.

If all the different troughs are related to the plasmapause at night, they should also be related to each other. But the situation is that the different magnetospheric boundaries and their projections in the ionosphere appear in a fairly limited latitude range by night and are, consequently, more or less related. For instance, they must move (at least statistically) in the same sence with local time and changing geomagnetic activity.

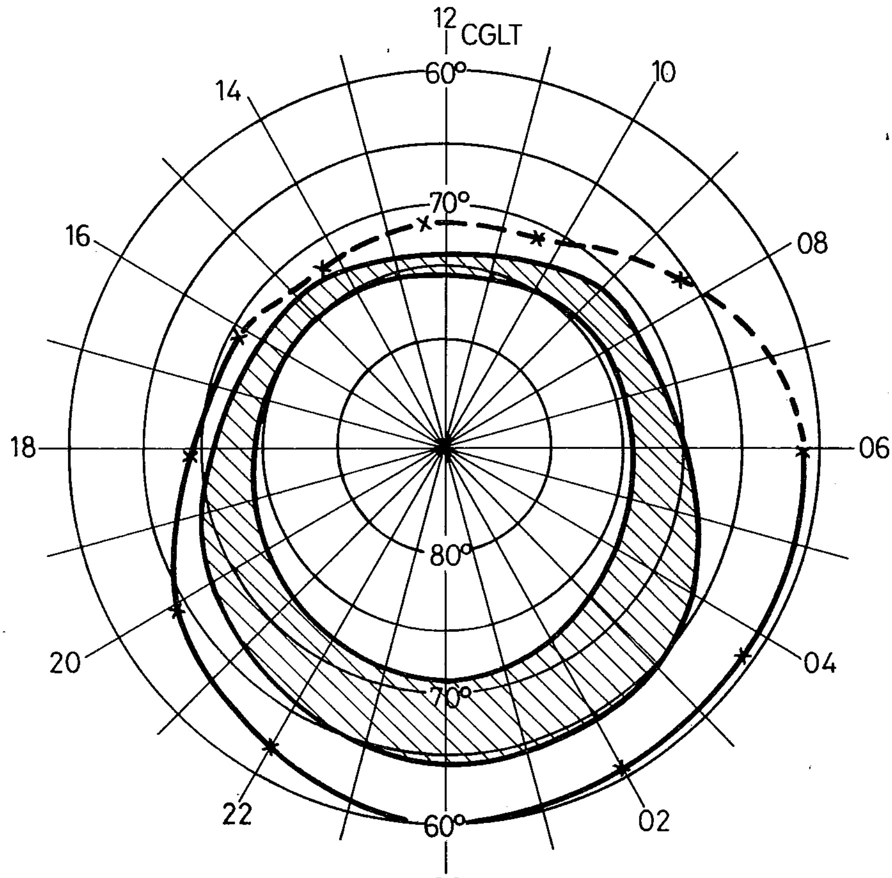


Fig. 4. The statistical auroral oval of FELDSTEIN and STARKOV (1967) for relatively quiet geomagnetic conditions ($Q$ = 3) in relation to TEC trough for $Kp \leqslant 1+$. Corrected geomagnetic latitude and corrected geomagnetic local time have been used as coordinates.

The situation is clearer in the day sector where the different boundaries are more separated, and it seems more profitable to look for possible relationships between the different troughs and boundaries there.

The low $L$ values of the LIT seem to speak for the close relationship between it and the plasmapause (TAYLOR and WALSH, 1972). The low-latitude trough in ion density at high altitudes, found by AHMED *et al.* (1979), seems also to be connected with the plasmapause. On the other hand, the high $L$ values of the troughs in foF2 and TEC and of the high-latitude ion density troughs by day seem to suggest a relation with the magnetospheric cusp (cleft) (AHMED *et al.*, 1979), the troughs being located at the equatorward edge of the cusp.

In Fig. 4 we present evidence for a possible association of the TEC trough with the low-latitude boundary of the statistical auroral oval (FELDSTEIN and STARKOV, 1967) during relatively quiet geomagnetic conditions. The trough seems to be located a few degrees equatorwards of the oval boundary, and the distance seems to increase with local time. Similar results were obtained for more disturbed conditions. This result is, of course, not contradictory to those presented above because the auroral oval is known to be located near the cusp region by day and poleward of the plasmapause by night.

Summing up, the troughs in foF2, TEC and low-altitude local ion density seem to coincide and to be connected with the cusp by day and (at least loosely) with the plasmapause at night. At great altitudes the ion density seems to have a more complicated behaviour: It exhibits troughs connected with the plasmapause and the cusp by day and a broad trough by night.

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## APPENDIX

Our method for obtaining the total electron content of the ionosphere is an integral method: The number of electrons per unit area between the satellite and the receiving station is measured. It is clear that the variation of the TEC with time (as the satellite moves) depends on the actual three-dimensional electron density distribution. The conversion to a vertical TEC, in turn, depends on the altitude of the sub-ionospheric point chosen. Here we present the results of a model study on the possible amount of error involved in determining the latitude of TEC trough from the TEC vs. latitude plots.

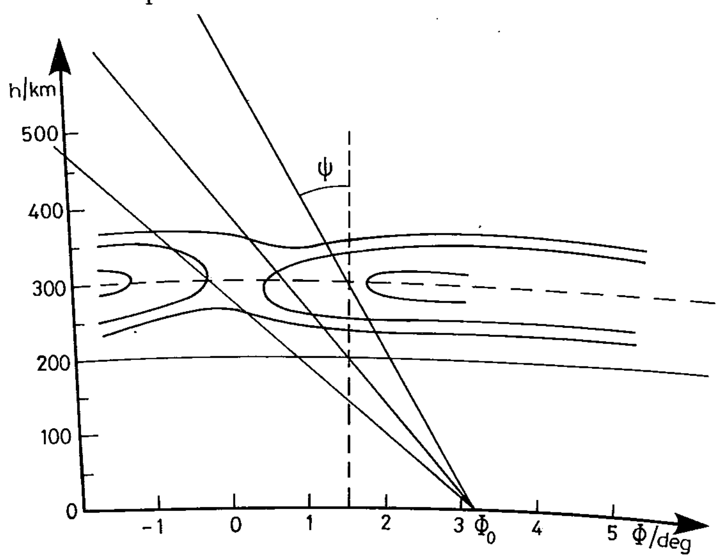


Fig. 5. Schematic presentation of the method used for checking the accuracy of determining the latitude of the TEC trough. For explanations see the text.

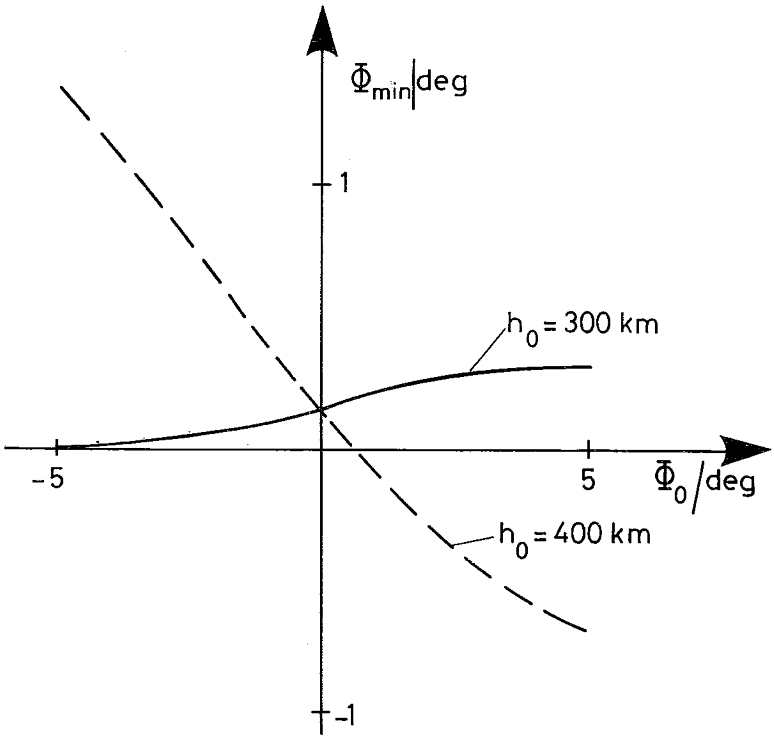


Fig. 6. The error in the latitude of the TEC trough vs. latitude of the receiving station $\Phi_0$ for two subionospheric altitudes $h_0$ (300 and 400 km).

The latitudinal cross-section of the electron density model used in this study is shown schematically in Fig. 5. The model was chosen such that its electron density maximum lies at an altitude of about 300 km and that the TEC-values obtained were of the right magnitude (about $5 \cdot 10^{16}\,m^{-2}$). The latitude of the trough minimum was set at $\Phi = 0°$, the latitude of the receiving station ($\Phi_0$) was varied. The changing position of the satellite corresponds to different slanting lines. The determination of the subionospheric point (and its latitude) for the altitude of 300 km is shown in one case.

TEC was calculated numerically for this model using, in addition to the correct subionospheric altitude 300 km, also the altitude 400 km and moving the receiving station in latitude. From these calculated TEC vs. latitude plots the latitudes of the minima were determined; they are shown in Fig. 6 for both altitudes as a function of $\Phi_0$.

We see that $\Phi_{min}$ (or the error because the correct value was $0°$) remains well below one degree if the subionospheric altitude is chosen correctly and the receiving station is less than five degrees away from trough minimum. Even for an subionospheric altitude 100 km too high the error remains smaller than one degree in the range $-4° < \Phi_0 < +5°$. Of course, the result depends in detail on the model chosen but be believe that the obtained magnitude of the error is typical.

In conclusion we think that if always the nearest station is used for determining the latitude of the trough (as we have done), the latitude is typically less than one degree in error.