Aberystwyth University

Parameterization of the main ionospheric trough in the European sector
Pryse, Sian; Kersley, Leonard; Malan, D.; Bishop, G. J.

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S. E. Pryse,[1] L. Kersley,[1] D. Malan,[1] and G. J. Bishop[2]

[1] Measurements of total electron content, obtained by monitoring satellite transmissions at stations in the United Kingdom during a period of 12 months, have been used to characterize the structure and dynamics of the main ionospheric trough in terms of a set of defined parameters. The primary aim of the investigation was to represent the position and shape of the trough in such a way that the experimental observations can be used for direct comparison and validation of ionospheric models.

1. Introduction

[2] The ionospheric trough has been studied for several decades using many different techniques [*Tulunay and Sayers*, 1971; *Moffett and Quegan*, 1983; *Rodger et al.*, 1992]. Attempts have been made to infer the statistical dependencies of the latitudinal position of the trough on local time and geomagnetic activity from experimental data sets [e.g., *Rycroft and Burnell*, 1970; *Kohnlein and Raitt*, 1977; *Halcrow and Nisbet*, 1977; *Dudeney et al.*, 1983]. However, the resultant equations have had only limited application because of the wide day-to-day variability in the location and form of the feature. More recently, the radio tomography technique has been shown to be particularly adept at imaging the large-scale horizontal spatial structure of the trough [*Pryse et al.*, 1993; *Kersley et al.*, 1997; *Dabas and Kersley*, 2003; *Pryse*, 2003], a success that has been exploited here in the characterization of the form of the structure by means of a number of carefully defined parameters.

[3] In the northwestern European sector, the main trough is the dominant large-scale structure in the evening and nighttime ionosphere. It forms at the interface between the midlatitude ionosphere and the auroral region as a result of complex interplay between different geophysical processes. The variability in the occurrence and structure of the trough means that it is not yet possible to represent the feature accurately in the empir-

ical or parameterized models that are used to correct for propagation effects on practical radio systems.

[4] The current study aims to obtain definitive information on the form and dynamics of the trough from observations made during a radio tomography experiment in the United Kingdom. The intention was to obtain experimental data on the trough location and its gradients, which could be represented in terms of a parameter set that would then be available for direct comparison with corresponding output from ionospheric models. The trough and the associated gradients present particular problems for models developed for use in the mitigation of propagation effects on radio systems because of the dynamic and variable nature of the feature. Some models simply ignore the trough (e.g., International Reference Ionosphere), but even for those where the structure is included (e.g., parameterised ionospheric model (PIM)), locating the depletion in the wrong place or having the incorrect form may represent a worse description of the actual ionosphere than complete omission. There have been many attempts to investigate the trough over several decades using various types of experimental observations, with the results being used to try to characterize different aspects of behavior. While some understanding has been gained of aspects of the responses to the different geophysical influences that play roles in controlling the mechanisms responsible for the location and form of the feature, definitive information necessary for the testing of models has been lacking.

2. Experiment

[5] An experiment, designed to obtain routine tomographic images of the ionospheric electron density in the vicinity of the United Kingdom, was carried out with

[1]Institute of Mathematical and Physical Sciences, University of Wales, Aberystwyth, UK.
[2]Air Force Research Laboratory, Space Vehicles Directorate, Hanscom Air Force Base, Massachusetts, USA.
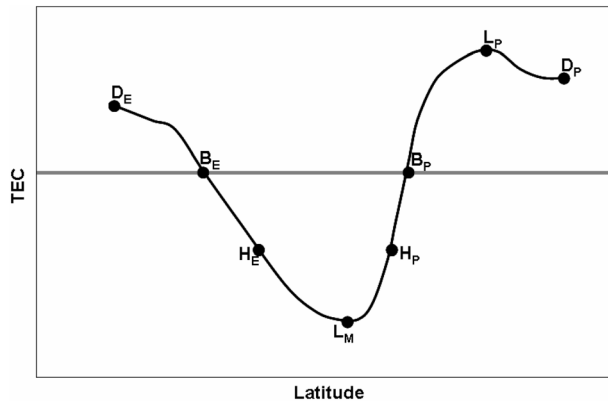
Figure 1. Schematic diagram of total electron content as a function of latitude based on actual observations, illustrating the parameters defined to characterize the location and shape of the trough.

three automated receiving systems, monitoring radio transmissions from satellites in the Navy Ionospheric Monitoring System (NIMS) constellation, deployed at Aberystwyth (52.42°N, 4.06°W), Hawick (55.42°N, 2.80°W), and Reay (58.57°N, 3.76°W). Observations from individual satellite passes were processed using standard, well-documented techniques to yield images of electron density in the height versus latitude plane. Vertical integration through the image was then used to obtain the vertical total electron content as a function of latitude for each satellite pass. Preliminary studies had demonstrated that integration through tomographic images in this way yielded more reliable estimates of the form of the latitudinal structures in the vertical total electron content than values of equivalent vertical electron content obtained by conventional processing based on assumptions of a thin-shell ionosphere at some chosen fixed height. Earlier work on the development of radio tomography had also shown that reliable images can be obtained for a range of latitudes well beyond the span of the stations. However, it must be noted that there is an inevitable element of self-selection in the data, with the trough in general only coming into view of the monitoring sites from the north during the afternoon.

3. Trough Parameters

[6] The approach to the characterization was to represent the position and shape of troughs seen in the vertical total electron content (TEC) versus latitude plots from the experimental observations by a set of parameters. The parameters were defined in such a way that they could be estimated both from the experimental measurements and from output of ionospheric models. The

parameters were chosen so that both the location of the trough and the form of the latitudinal gradients could be characterized. In general, the parameters formed pairs in the resultant data set, one component giving the geographic latitude of the defined feature, with the second giving the value of the vertical TEC at the location. Sufficient information was thus retained to allow latitudinal gradients in the TEC to be estimated in the vicinity of the trough. Since some earlier studies have ordered trough behavior in magnetic coordinates, it should be noted that subtraction of some 2° from the geographic latitudes used here gives the approximate magnetic latitude in this sector.

[7] The defined parameters chosen to characterize the trough are illustrated in Figure 1. The schematic diagram is drawn to be representative of the basic form of the troughs that are found in the observations to dominate this region and have been studied here. It can be noted that very occasionally, more complex structures are found in the experimental data, though these have been omitted from the analysis. Current models have problems in replicating the basic features of the trough, so that additional structure would represent an unnecessary complication at this stage.

[8] The location and TEC at the trough minimum (L_M) was identified from each plot. The limits of the usable data range (D_E and D_P) and corresponding TEC values were recorded for each pass, with the subscripts E and P referring to the equatorward and poleward extremes, respectively. The specification of these latitudinal limits and the corresponding TEC measurements are of fundamental importance to the entire concept of the parameterization used here. Knowledge of this information will make it possible for future workers to apply identical processing to model output and so obtain averages and hence estimates of parameters that are directly compatible with the experimental results given in this paper. The average TEC was calculated for the entire range of the data between the extreme limits and was used to define the locations of two "breakpoints" on the equatorward (B_E) and poleward (B_P) sides of the trough minimum, where the TEC again crossed the average level, enabling an estimate to be made of the trough width. Two additional points (H_E and H_P) were identified, defined at latitudes that were halfway between the minimum and the equivalent breakpoint. In this way, information was retained that enabled details of the gradients in four segments in the vicinity of the trough minimum to be obtained. The locations and TEC values were also noted at the first subsidiary maximum on either side of the trough minimum, if these were present. It was hoped that these might provide information on possible midlatitude nighttime enhancements and boundary blobs surmounting the poleward wall, respectively. However, in practice it was found that the wave-like signatures of the traveling

ionospheric disturbances (TIDs) that characterize the winter ionosphere at midlatitudes and which, for geometrical reasons are most marked in the TEC on ray paths to the south [*Pryse et al.*, 1995], were a complicating factor, so that the information on the equatorial maxima were of little value. However, data on the poleward maximum (L_P) have been of use to identify the occurrence of boundary blobs and to define the limit of the poleward gradient of the trough wall. Additional information relating to TEC gradients at the latitudinal extremes, which were recorded in the initial processing but were found to be of little value in subsequent analysis because of the effects of TIDs, were later excluded from the database of the parameters analyzed.

4. Data Analysis

[9] Observations from more than 2800 high-elevation satellite passes were monitored at the UK stations in the year between September 2002 and August 2003. While there were a few gaps of short duration at individual sites, the data set is believed to be representative of ionospheric conditions over the United Kingdom for a complete 12-month period. Software analysis procedures were used to identify passes where troughs were observed and to obtain estimates of the parameters. A criterion was established to record information only where the depth of the trough minimum was at least 20% below the average TEC for the satellite pass, so that well-defined measurements of clearly identified troughs were used to create the database. Parameters were estimated from some 618 satellite passes, and these formed the data set used in the study.

[10] It is well known that the behavior of the trough is very dependent on geophysical conditions and in particular on geomagnetic activity. In consequence for the analysis, the data were divided into three groups, forming three approximately balanced data sets, corresponding to low, medium, and high Kp, respectively. Values up to 2+ were classified as low Kp, giving 178 data records. However, it should be noted that the criterion of a trough depth of at least 20% probably eliminated many cases of shallow troughs found under quiet geomagnetic conditions. The mid-Kp range was defined between 3− and 4−, yielding some 266 records of trough parameters, and the disturbed conditions, with Kp between 4 and 7+, gave 174 trough entries. It should be noted that it can now be recognized that the 3-hour Kp index is perhaps not a particularly good parameter for the ordering of the influence of geomagnetic activity on a dynamic feature like the trough. However, many of the earlier studies and indeed current ionospheric models use Kp as a driver input, so it has been retained for the present work. Furthermore, there is no readily available and acceptably proven index that could serve as an alternative to char-

a   **Median Latitude of Trough Minimum vs UT**

b   **Minimum TEC in Trough vs UT Hourly Medians**
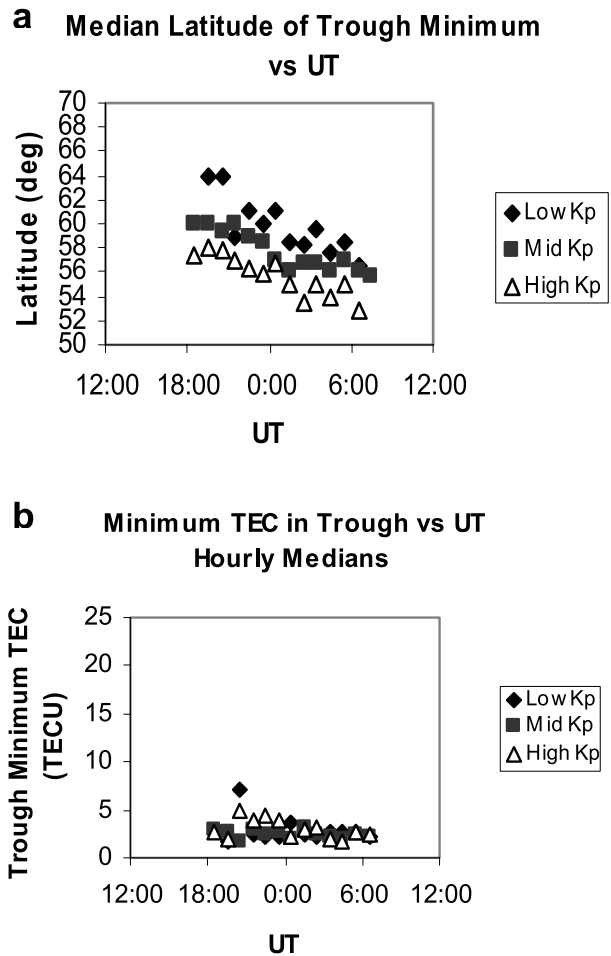
Figure 2. Hourly (a) median latitude of the trough minimum and (b) total electron content in the trough minimum as a function of time for the three ranges of geomagnetic activity.

acterize the sensitivities of the physical processes involved in trough formation to changing geophysical conditions. It must also be recognized that the upper grouping represents a wide range of disturbed conditions and trough behavior. However, since the range has been specified over which medians have been calculated, here it will be possible to make direct comparison with model output. It can also be noted for the record that the monthly average solar radio flux index showed a declining trend from 178 to 113 units during the time of the experimental observations.

5. Sample Results

[11] A number of sample results are presented to illustrate the main features of the behavior of the trough
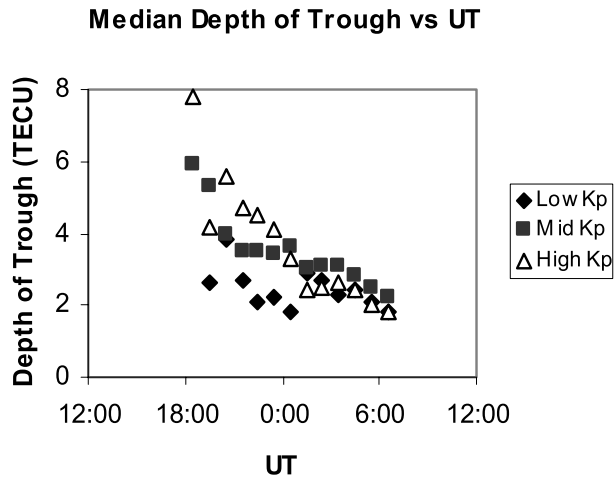
Figure 3. Hourly median values of the depth of the trough in total electron content units (TECU) as a function of time for the three ranges of geomagnetic activity.

established from the database. These take the form of hourly median values plotted as a function of time throughout the night (LT and UT are approximately equivalent in this longitude sector) for each of the three defined divisions of geomagnetic activity. It should be noted that while relatively few troughs were identified in the summer months, no seasonal variations of significance in the location or form could be established from the data.

[12] Figure 2a shows the equatorward movement of the trough throughout the night under each *Kp* banding, results that are in broad agreement with those found in many earlier studies. It can be seen from Figure 2b that the median TEC values in the trough minimum are generally very consistent at about 2 to 3 TECU (1 TECU = 10^{16} el m^{-2}) regardless of time or *Kp* level, apart from a few slightly higher values before midnight under the most disturbed conditions. The depth of the trough, defined as the difference between the TEC average and that at the trough minimum, shows only a small dependence on time throughout the night at low *Kp* (Figure 3), though it must be recalled that the selection criteria used here excluded shallow troughs. However, it can be seen that at the higher levels of geomagnetic activity, the depth decreases with time, particularly in the evening sector. It is interesting to note that after midnight, the median values for all three ranges of Kp tend to group together, in contrast to the situation at earlier times. This temporal difference in behavior may be a reflection of the fundamental physical processes responsible for the formation of the trough. Before magnetic
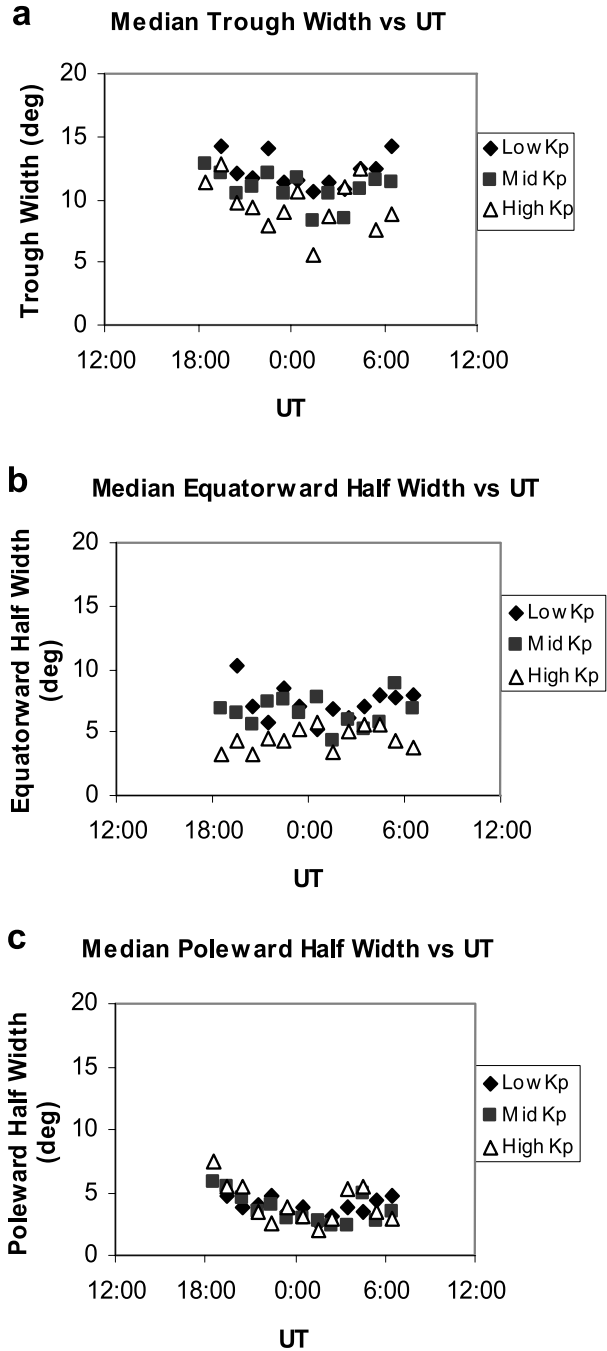

Figure 4. Hourly median values of the latitudinal (a) width of the trough, (b) half width of the trough on the equatorward side of the minimum, and (c) half width of the trough on the poleward side of the minimum as a function of time for the three ranges of geomagnetic activity.
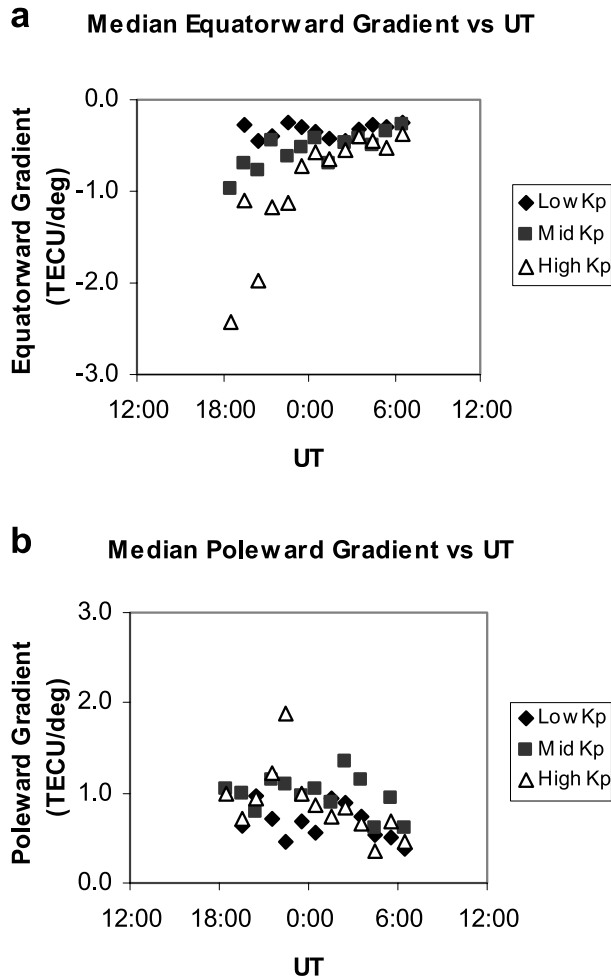
a

Median Equatorward Gradient vs UT

b

Median Poleward Gradient vs UT

Figure 5. Hourly median values of the (a) equatorward and (b) poleward TEC gradient (in TECU/deg) for the three *Kp* ranges.

midnight, the trough is often found in the vicinity of the slowly moving counterstreaming flows at the equatorward edge of the dusk cell of the high-latitude convection pattern, though enhanced loss in fast ion motion does play a role at times of high geomagnetic activity. However, after the Harang discontinuity, the troughs are likely to be fossils from earlier times convecting in the eastward flows into the dawn sector. The latitudinal width of the trough, defined from the separation of the breakpoints, is illustrated in Figure 4a. The scatter in the points is large, but there is some evidence from the median values to suggest that there is a narrowing of the trough with time in the evening hours, particularly at the highest level of geomagnetic activity.

[13] A study was also undertaken to investigate whether any possible variations in the width of the trough were associated with changes either equatorward or poleward of the minimum. Half widths were estimated from the latitudinal differences between the trough minimum and the respective breakpoints on the equatorward and poleward gradients. While individual points were very spread, there is evidence from the medians to suggest a narrower equatorward half width of the trough at the highest *Kp* levels (Figure 4b). The corresponding plot for the half width between the latitude of the trough minimum and that of the poleward breakpoint is shown in Figure 4c. Here, a trend demonstrating a narrowing half width during the evening, followed by a possible small increase before dawn, is replicated closely at all levels of geomagnetic activity. Somewhat unexpectedly, it appears that the marked and variable changes to trough structure are thus associated primarily with processes on the equatorward side of the minimum.

[14] The latitudinal gradients in the TEC were determined for the equatorward and poleward walls of the trough for the three levels of geomagnetic activity. The gradients were calculated from the differences in TEC and latitude between the trough minimum and the equatorward and poleward breakpoints, respectively, and so represent smoothed estimates. The temporal changes in the median gradients of the equatorward wall are shown in Figure 5a. While little change can be seen in the gradient under quiet geomagnetic conditions, the slope in the early evening is steeper when *Kp* is moderate and markedly so at the highest levels of geomagnetic disturbance. Additionally in the latter case, there is a marked reduction in the slope with time so that after midnight, the dependence on geomagnetic activity is much less pronounced. The corresponding plot for the latitudinal gradient between the trough minimum and the poleward breakpoint is shown in Figure 5b. The scatter in this case was large, and there is little evidence of regular behavior apart from possibly at the highest *Kp*, where the gradient of the poleward wall shows a tendency to decrease throughout the night. The median values seem to be marginally higher for the midrange of *Kp* values.

[15] Another feature identified was the maximum poleward of the trough minimum, although a peak is not always present. This structure, sometimes known as the boundary blob, surmounts the gradient of the poleward wall. It was found that a maximum could be identified in just under two thirds of the images. The percentage occurrence showed no marked dependence on *Kp*, being 62%, 64%, and 65% for the low, middle, and high levels, respectively. The latitude of the boundary blob is shown as a function of time in Figure 6. The median values demonstrate an equatorward trend throughout the night, particularly for the two higher *Kp*
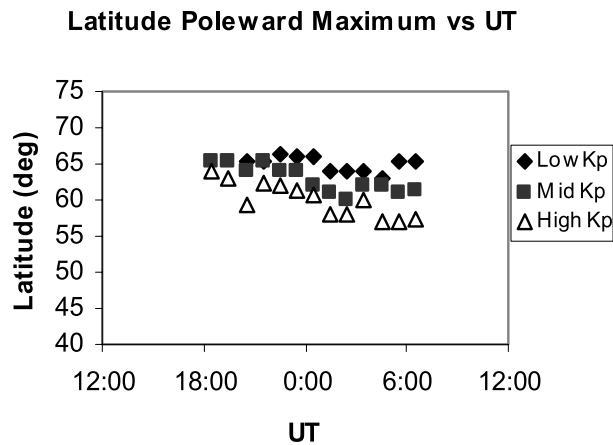
Latitude Poleward Maximum vs UT

Figure 6. Hourly median values of the latitude of the boundary blob as a function of time for the three ranges of geomagnetic activity.

bands, though less pronounced than that found for the trough minimum.

6. Median Trough TEC Profiles

[16] A primary aim of the project was to obtain a definitive characterization of the trough from the experimental data in a form that could be compared directly with corresponding output from ionospheric models. In fulfillment of this objective, median values of both TEC and latitude were determined for the fundamental parameters of the database, for 2-hour bands throughout the night within each of the three ranges of geomagnetic activity. It was found that most of the parameters showed stable and consistent variations. In consequence, it was decided to use these values to produce plots of TEC versus latitude to represent how the location and latitudinal structure of the trough varied with time for the different bands of Kp. The results are presented in Figures 7a–7c, with the values being tabulated in Tables 1a, 1b, and 1c, to be available directly for use in the validation of models. The individual points are for median TEC against median latitude plotted for the trough minimum, both breakpoints, both halfway points between the minimum and the corresponding breakpoint, and the equatorward and poleward data limits. Most of the plots also mark the median position of the first maximum poleward of the trough minimum, that is, the boundary blob.

[17] It is important to address the accuracy of the data points quoted here. The values have been estimated as medians to reduce the effects of extreme outliers, and it is neither practical nor particularly meaningful to include, for example, interquartile ranges on the plots.

However, estimates have been made of the typical accuracies of the results by considering the errors associated with the corresponding averages for samples taken from the data set. It was found that in general, the standard error of the mean for a typical point was about 0.5° in latitude and marginally less than 0.5 TECU in total electron content. In consequence, confidence can be placed in the details of the form of the plots shown here and in the corresponding numerical values presented in Tables 1a, 1b, and 1c.

6.1. Low *Kp*

[18] It can be seen from Figure 7a that for low Kp, the trough is broad and shallow with a poleward wall that is generally steeper than the equatorward gradient and which culminates in a maximum. The notch-like trough at the earliest times, with a minimum at about 64°N, transforms to have a concave shape to the poleward wall and a reasonably linear equatorward gradient throughout the night. The minimum progresses down to 58°N before dawn, after which the trough is filled in by solar-produced ionization building up from midlatitudes.

6.2. Mid-*Kp*

[19] It can be seen from Figure 7b that the trough retains a notch-like shape throughout much of the night for the midrange of Kp. The gradient of the equatorward wall becomes less steep at later times, as the ionization at the midlatitudes decreases during the night. The poleward wall is steeper than that on the equatorward side of the minimum and is usually surmounted by a boundary blob maximum. While the trough minimum is still only at about 56°N at the latest times, the poleward gradient is much steeper than was found for the quiet geomagnetic conditions, though the overall TEC levels are broadly similar.

6.3. High *Kp*

[20] The median plots for the highest Kp band shown in Figure 7c have enhanced TEC levels on both sides of the minimum in early evening and lower values at the higher latitudes later in the night. These features reflect the influences of complex, storm-induced processes. It has been known for several decades that thermospheric winds, driven by energy input to the auroral zone, can carry the lighter monatomic oxygen associated with ionization production processes equatorward during the early positive phase. The molecular rich species, which control the loss mechanisms, may be left behind at high latitudes initially but can dominate later to create the negative phase of the disturbance. In addition to these composition effects, it has been shown more recently that mechanisms linked to the contraction of the plasmasphere in the early stages of a magnetic disturbance can cause large localized storm-enhanced densities
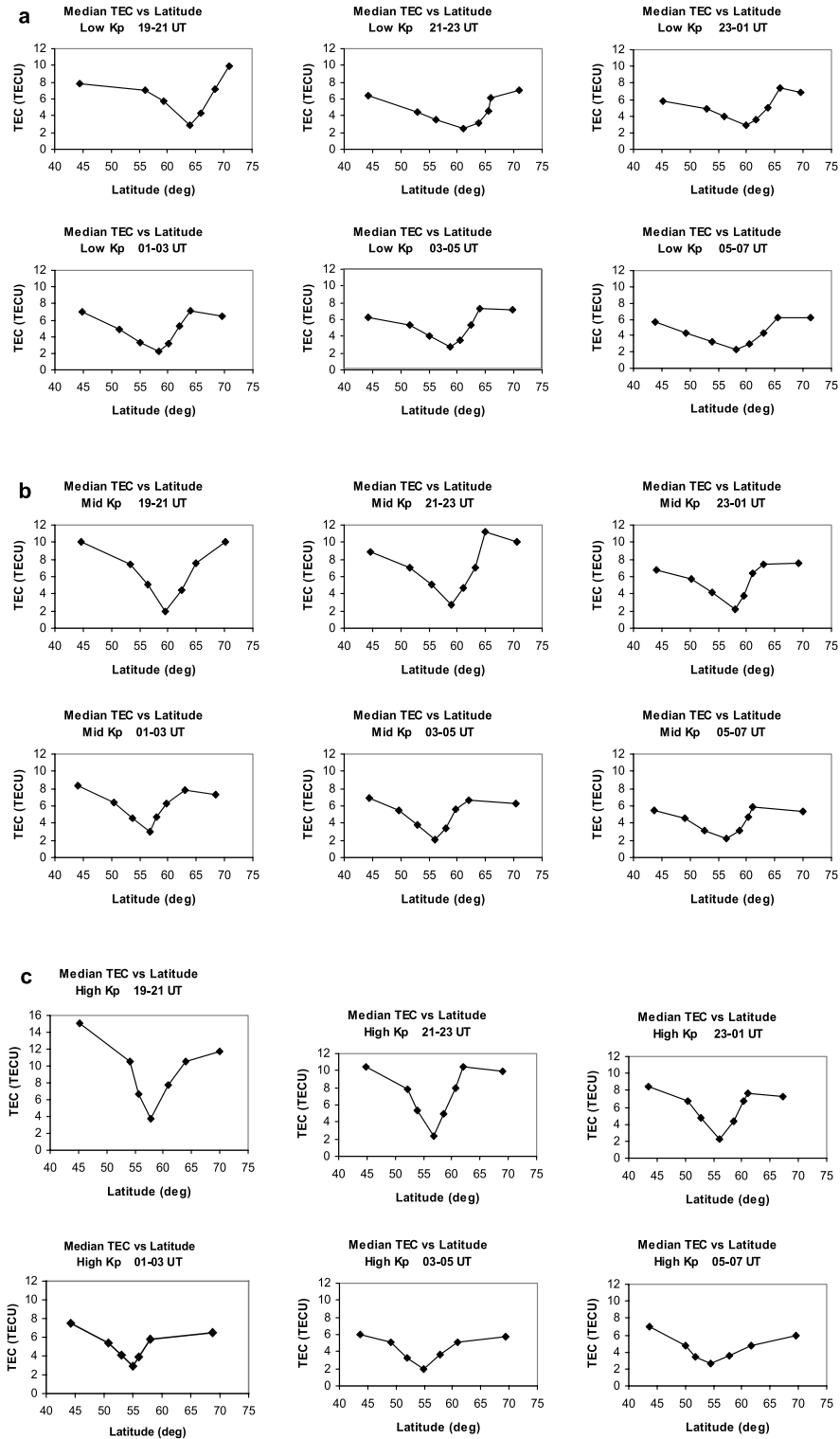
Figure 7. Median TEC versus median latitude of the trough parameters for (a) low *Kp*, (b) mid-*Kp*, and (c) high *Kp*.

Table 1a. Median Values of the Latitude and TEC for Each of the Defined Trough Parameters, in 2-Hour Periods Throughout the Night Between 1900 and 0700 UT, for Low Kp[a]

	1900−2100 UT		2100−2300 UT		2300−0100 UT		0100−0300 UT		0300−0500 UT		0500−0700 UT	
	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC
Eq Lim D_E	44.4	7.8	44.3	6.4	45.3	5.8	44.8	7.1	44.3	6.3	43.9	5.7
Eq Brpt B_E	56.0	7.1	53.0	4.4	53.0	4.9	51.5	4.9	51.6	5.4	49.3	4.4
Eq Hlf H_E	59.4	5.7	56.3	3.5	56.0	4.0	55.1	3.4	55.0	4.1	53.9	3.2
Tr Min L_M	64.0	2.9	61.0	2.5	60.0	2.9	58.4	2.3	58.8	2.7	58.3	2.3
Pol Hlf H_P	65.9	4.3	63.8	3.1	61.8	3.6	60.1	3.2	60.5	3.5	60.5	2.9
Pol Brpt B_P	68.4	7.2	65.5	4.6	63.8	5.0	62.1	5.3	62.4	5.4	63.0	4.4
Pol Max L_P			66.0	6.1	66.0	7.4	64.0	7.1	64.0	7.3	65.5	6.2
Pol Lim D_P	71.0	10.0	71.0	7.0	69.5	6.9	69.5	6.5	69.8	7.2	71.3	6.3

[a]Latitude (Lat) is given in degrees north, and TEC is given in TECU. Eq is equatorward, Lim is limit, Brpt is breakpoint, Tr is trough, Pol is poleward, Hlf is half, and Max is maximum.

(SEDs) with very steep gradients in the midlatitude ionosphere. It can also be seen from the plots that the gradients on both sides of the minimum are similar at earlier times, but on the equatorward side they are generally steeper later in the night. No boundary blob can be identified on the shallow poleward wall after 0100 UT.

7. Conclusions

[21] Analysis has been carried out on an extensive database to characterize the structure and behavior of the main ionospheric trough in the northwestern European sector. Vertical TEC values as a function of latitude were determined by integration through tomographic images of electron density, with the location and shape of the trough being determined in terms of a number of defined parameters. The analysis has investigated the temporal variations in the parameters and some derived quantities for different levels of geomagnetic activity.

[22] The sample plots presented here confirm the well-established equatorward movement of the trough throughout the night and with increased geomagnetic activity. The TEC values in the trough minimum are generally consistent at about 2 to 3 TECU, while the depth of the trough is much more dependent on Kp in the evening hours than after midnight. The half width equatorward of the minimum shows much greater variability than that on the poleward side, reflecting a steep latitudinal equatorward gradient in the early evening during disturbed geomagnetic conditions.

[23] The main results reported here relate to the primary aim of the study to yield definitive information from experimental observations in a form compatible with model output. The location and shape of the trough have been characterized in terms of a set of closely

Table 1b. Median Values of the Latitude and TEC for Each of the Defined Trough Parameters, in 2-Hour Periods Throughout the Night Between 1900 and 0700 UT, for the Midrange of Kp Levels[a]

	1900−2100 UT		2100−2300 UT		2300−0100 UT		0100−0300 UT		0300−0500 UT		0500−0700 UT	
	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC
Eq Lim D_E	44.6	10.1	44.6	8.9	44.0	6.8	44.0	8.4	44.5	6.9	43.8	5.5
Eq Brpt B_E	53.4	7.4	51.6	7.0	50.3	5.7	50.5	6.4	49.8	5.5	49.1	4.6
Eq Hlf H_E	56.5	5.1	55.4	5.1	54.0	4.2	53.7	4.6	53.0	3.8	52.5	3.1
Tr Min L_M	59.6	2.0	59.0	2.8	58.0	2.2	56.8	3.0	56.0	2.1	56.5	2.3
Pol Hlf H_P	62.5	4.5	61.0	4.7	59.5	3.8	58.0	4.7	58.0	3.4	58.8	3.2
Pol Brpt B_P	65.0	7.6	63.1	7.0	61.0	6.4	59.8	6.3	59.8	5.6	60.3	4.7
Pol Max L_P			65.0	11.2	63.0	7.5	63.0	7.9	62.0	6.6	61.0	5.9
Pol Lim D_P	70.3	10.1	70.5	10.0	69.3	7.6	68.4	7.3	70.4	6.2	70.0	5.4

[a]Latitude (Lat) is given in degrees north, and TEC is given in TECU. Eq is equatorward, Lim is limit, Brpt is breakpoint, Tr is trough, Pol is poleward, Hlf is half, and Max is maximum.

Table 1c. Median Values of the Latitude and TEC for Each of the Defined Trough Parameters, in 2-Hour Periods Throughout the Night Between 1900 and 0700 UT, for the Highest Range of Kp[a]

	1900−2100 UT		2100−2300 UT		2300−0100 UT		0100−0300 UT		0300−0500 UT		0500−0700 UT	
	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC	Lat	TEC
Eq Lim D_E	45.3	15.1	44.9	10.5	43.5	8.5	44.3	7.5	43.6	6.0	43.8	7.0
Eq Brpt B_E	54.1	10.6	52.3	7.9	50.5	6.7	50.8	5.4	49.0	5.1	50.0	4.7
Eq Hlf H_E	55.8	6.7	54.0	5.4	52.8	4.8	53.0	4.1	52.0	3.3	51.8	3.4
Tr Min L_M	57.9	3.8	56.8	2.4	56.0	2.2	55.0	2.9	54.9	2.0	54.5	2.6
Pol Hlf H_P	60.9	7.8	58.5	4.9	58.5	4.4	56.0	3.9	57.9	3.6	57.8	3.5
Pol Brpt B_P	64.0	10.6	60.6	8.0	60.3	6.7	58.0	5.8	60.9	5.2	61.8	4.8
Pol Max L_P			62.0	10.5	61.0	7.6	58.1	5.9				
Pol Lim D_P	70.0	11.8	69.0	10.0	67.3	7.3	68.8	6.5	69.4	5.8	69.5	5.9

[a]Latitude (Lat) is given in degrees north, and TEC is given in TECU. Eq is equatorward, Lim is limit, Brpt is breakpoint, Tr is trough, Pol is poleward, Hlf is half, and Max is maximum.

defined parameters, median values of which have been presented as plots giving the latitudinal structure and temporal development of the trough throughout the night within three bands of geomagnetic activity. Tabular values of the median parameters have also been given so that these are available for the validation and testing of other ionospheric models, in addition to those planned in the original conception of the work. It is believed that this data set of trough parameters represents the most comprehensive experimental description determined to date of the position and form of the main ionospheric trough in the European sector.

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G. J. Bishop, Air Force Research Laboratory, Space Vehicles Directorate, 29 Randolph Road, Hanscom AFB, MA 01731-3010, USA.

L. Kersley, D. Malan, and S. E. Pryse, Institute of Mathematical and Physical Sciences, University of Wales, Aberystwyth SY23 3BZ, UK. (sep@aber.ac.uk)