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Total electron content – A key parameter in propagation: measurement and use in ionospheric imaging

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The paper reports on a series of studies carried out within the COST 271 Action relating to the measurement and use of Total Electron Content (TEC) of the ionosphere over North West Europe. Total electron content is a very important parameter for the correction of propagation effects on applied radio systems so that it is vital to have confidence in the experimental measurements and the resultant products derived as aids for the practical user. Comparative investigations have been carried out using TEC values from several different sources. It was found that in general there was broad statistical agreement between the data sets within the known limitations of the techniques, though discrepancies were identified linked to steep ionospheric gradients at the onset of geomagnetic storm disturbance and in the vicinity of the main trough. The paper also reviews recent progress in the development of tomographic inversion techniques that use total electron content measurements to image the ionosphere as an aid to various radio systems applications.

8.1. INTRODUCTION

Total electron content is a key parameter in the mitigation of ionospheric effects on radio systems. In numerous applications involving radio links between satellites and ground, which play vital roles in the modern technology of communications, navigation and surveillance, the propagation departs from free space conditions in various ways with important consequences for the reliability and accuracy of the service. The phase advance and Doppler shift of a carrier, group retardation and time delay of a modulation, Faraday rotation of the polarisation and wedge refraction of the wave direction are all dependent in some way on the line integral of the electron density along the ray path through the ionised atmosphere, the so-called total electron content. The ability to make allowance for the effects on the propagation of the electron content and its temporal and spatial variations thus becomes an essential component in the reliable operation of the system. Indeed, adequate correction for the effect of ionospheric propagation may represent a limiting error for the accuracy of some uses of the technology. Investigations of total electron content are thus central to fulfilment of the objectives of the COST 271 Action.

Total electron content has been measured experimentally since the 1960s using a variety of different techniques. While there have been relatively few purpose-built satellites for such observations, it has often been possible to make use of radio signals from satellites launched for another primary purpose. Some early measurements involved determination of the polarisation rotation of VHF transmissions from the first-generation of geosynchronous communications satellites. Later it became possible to exploit the signals from the various satellite navigation and positioning systems, like NNSS and more recently GPS. A vast body of data and information about total electron content has been amassed over the years from numerous locations giving almost worldwide coverage. In addition, products have been developed in the form of regional and global models yielding total electron content, while more recently maps are now routinely available of the parameter on the Internet. Another recent advance has been the application of tomographic techniques to invert electron content measurements to obtain images of ionospheric electron density.

The present paper reports collectively some results from a number of separate studies carried out within the COST 271 project that have been directed towards comparative investigations of total electron content derived from various sources and the use of the parameter for ionospheric imaging. The broad aim was to demonstrate confidence in some of the basic products of the project and to identify possible areas and circumstances where further study and development are warranted.

8.2. TOTAL ELECTRON CONTENT (TEC)

Most measurements and applications of total electron content are concerned with arbitrary slant ray paths between a satellite and a ground station. However, for comparative purposes it is necessary to define the observations in a more standard way. In consequence, the convention was adopted at an early stage to apply a simple geometrical construction, usually based on an assumed thin-shell ionosphere at a fixed height, to rotate the actual slant measurement to obtain an equivalent vertical total electron content. In practice, most estimates of total electron content (usually abbreviated to TEC and measured in units where 1 TECU $\equiv 10^{16}\text{m}^{-2}$) are based on this equivalent vertical parameter.

8.2.1. GPS-TEC

Transmissions from the GPS navigation satellite system now provide the main source for most experimental measurements of TEC currently being made. The satellites are at heights of some 20 200 km, in orbits with inclination of 55° to the equatorial plane with periods of about 12 h, and so move slowly across the sky in patterns that repeat accurately from day to day in sidereal time when viewed from a given ground station. The resultant measured phase and group delays of the *L*-band signals received along the slant ray paths using segments of data from many different satellite passes can be combined in an algorithm to yield values of equivalent vertical total electron content. The diurnal variation of the equivalent vertical TEC in the vicinity of a receiving station can be estimated by means of such analysis and calibration procedures. Papers by Lunt *et al.* (1999a-d) have discussed a number of issues concerning one such process. The analysis used in the present work to estimate TEC from GPS transmissions was carried out by means of the procedure developed by Ciraolo (1993) and used by Ciraolo and Spalla (1997).

The studies described here made use of data both from GPS signals monitored in U.K. and also from other stations that form part of the IGS network throughout Europe. Values of TEC obtained from GPS observations now form the basis for most current applications of ionospheric corrections to practical radio systems and derived products like maps. It is thus important to try to understand the reliability and limits to the accuracy of such measurements. The situation is complicated further for measurements at locations in U.K. by two factors, geometrical and geophysical respectively. First, the non-polar inclination of the GPS satellite orbits means that there is incomplete sky coverage for the ray paths, particularly for ground stations at higher latitudes. Furthermore, the main trough, bounding the mid-latitude and auroral sectors is a regular feature of the nighttime ionosphere over Northern U.K. The present studies have been directed towards addressing some of the resultant issues, particularly with regard to TEC measurements and products in the vicinity of U.K., but within the wider European context of the COST 271 Action.

8.2.2. NIMS-TEC

While GPS observations give TEC values as a function of time above a given location, measurements with respect to latitude at particular times can also be made. Some satellites in 1100 km polar orbits, in what was the former NNSS constellation, now known as NIMS, provide signals for ionospheric measurements. An experimental programme using NIMS satellites has been carried out in U.K. as part of the current project to provide independent measurements of TEC determined by the differential carrier phase method. The analysis of the phase observations to obtain absolute equivalent vertical TEC was done using an extension to multiple stations of the well-established procedure described by Leitinger *et al.* (1975). Many of the results outlined here are based on these NIMS observations that yield TEC as a function of latitude at the time of the satellite pass.

8.3. ACCURACY OF TEC MEASUREMENTS

Some initial studies were carried out to investigate the limitations imposed by the equivalent vertical assumptions involved in most TEC measurements. In converting from slant to vertical electron content, the parameter that is necessary for comparison purposes, it is usual to assume a mapping function based on a thin-shell ionosphere at a chosen height. The magnitudes of the errors introduced by an inappropriate choice of height were investigated in these preliminary studies, using data from a chain of 5 stations in U.K. (Kersley *et al.*, 2002). The assumed centroid height of the ionosphere was varied between 250 km and 450 km and the consistency of the resultant latitudinal profile of the TEC investigated. It was found that for the lowest assumed mean ionospheric height of 250 km the TEC values were marginally lower in the vicinity of the stations and significant differences opened up between the records for the individual stations both to the south and the north. Conversely for an assumed ionosphere at 450 km, the TEC values were higher in absolute terms with the largest differences between the station records again at the extremities of latitude. The limitations to the accuracy of TEC measurements in any practical experimental situation can be appreciated from studies of this kind. While the 200 km range in the uncertainty of the centroid height of the ionosphere used may be over-large in general, nevertheless it was concluded from such investigations that the accuracy of the resultant equivalent vertical TEC measurements cannot be taken to be better than a few TEC units, even in the vicinity of the stations, and it could be much worse well outside the latitudinal range of the observing locations.

Additional studies, using data from pairs of stations within the set showed that to maintain accuracies of a few TECU attention must be confined to within a limited latitudinal span some 5° to 7° beyond that of the stations. It was also noted from further studies that the inversion of the data set to create a two dimensional tomographic image of electron density through which the vertical total electron content was calculated by integration is the optimal method for the estimation of the vertical TEC over the latitudinal range. Use of a tomographic image was of particular importance in regions of steep gradients, like those associated with the main trough that is often to be seen in observations over Northern U.K. It can be noted that the use of TEC observations to image the electron density by tomographic reconstruction will be discussed in more detail later in this report.

From these initial investigations it was concluded that the estimation of equivalent vertical TEC from slant measurements is likely always to be limited to an accuracy of a few TECU when a simple mapping function based on a thin-shell ionosphere is used. This inherent limitation must be kept in mind when comparisons are made of TEC measurements from different experimental techniques.

8.4. COMPARISONS OF TEC MEASUREMENTS

8.4.1. HIRAC campaign

Two studies were undertaken to compare values of TEC obtained by two completely independent techniques. The first involved observations made during a campaign of intensive measurements of TEC between 23 and 29 April 2001, which was coordinated by Dr. N. Jakowski (DRL, Germany) under the auspices of the COST 271 project and known by the acronym HIRAC. The motivation was to create a database of measurements near vernal equinox at solar maximum, a time when the TEC values would be expected to be very high. It was fortuitous that the campaign included an extended period of geomagnetic quiet followed by an impulsive storm so that the data are representative of a wide range of conditions at solar maximum.

The GPS observations used for the current work were obtained from a receiver located at Chilbolton (52.1°N) in Southern England. In addition, latitudinal plots of TEC were obtained from some 44 high-elevation passes of NIMS satellites monitored at sites in U.K. during the campaign period. These were used to determine the equivalent vertical TEC at 52.1°N at the times of the passes, for comparison with the GPS data from Chilbolton.

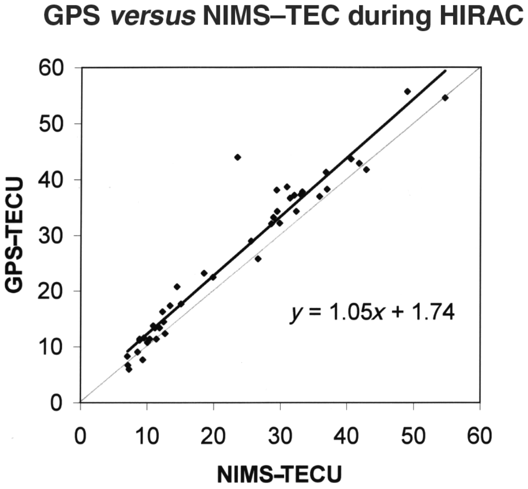


Fig. 8.1. Comparison of equivalent vertical TECs obtained using the GPS observations at Chilbolton and those for the same latitude from NIMS satellite passes during the HIRAC period. The best-fit line is plotted bold, while equality is shown by the faint line of unity slope.

A comparison of the two data sets is shown in fig. 8.1. It can be seen that the estimates of TEC from the two experimental techniques are in broad agreement, with the slope of the best-fit line close to unity. In general, the departures from agreement between individual estimates are at the level of a few TEC units, confirming the inherent limitations discussed above. It must be noted that there is a positive intercept of the best-fit line of some 1.7 TECU, indicating that the GPS measurements are inherently larger than the NIMS values. This difference can be attributed to the differing ray-path geometries in the two situations, with the NIMS measurements confined to 1100 km altitude, while those from GPS extend to some 20 000 km and encounter additional plasma on protonospheric flux tubes.

The results confirmed the measurements reported in the papers by Ciraolo and Spalla (1997) and by Lunt *et al.* (1999a-d), cited above. The former had found the GPS-TECs to be larger by some 3 TECU from analysis of a very extensive data set of NIMS-type observations in Italy. The latter workers demonstrated that GPS estimates from a station in U.K. were greater by about 2 TECU for ray paths to the south, but equivalent to the NIMS values when looking north, in keeping with current understanding of the physical mechanisms controlling the plasma on the protonospheric flux tubes. Other studies carried out here failed to reveal any additional systematic cause for the differences between the data sets. Thus it was concluded that, in general, there was broad agreement within the experimental errors between the measurements of equivalent vertical TEC over U.K. from the independent measurements made during the HIRAC period.

However, it was noted that one apparently rogue point can be seen in fig. 8.1, where the GPS estimate is almost double that of the NIMS measurement. Further investigation showed that this discrepancy arose on the afternoon of the first day of an impulsive geomagnetic storm during the collapse of the positive phase. The K_p index was generally less than 3 from 24-27 April 2001, but had three periods with values of 5 following the onset of the storm on 28 April. The diurnal plots of TEC from the GPS observations showed that the average daytime maximum was about 40 TECU during the geomagnetic quiet times, but exceeded 55 TECU on the day of the storm. These very high TECs were followed by the dramatic collapse of the ionisation, which is characteristic of such conditions, to reach a pre-dawn minimum of only 5 TECU, less than half that of earlier nights. This apparent temporal collapse in the ionisation densities and hence TEC values has consequences, not only for the longitudinal structure, but also for the latitudinal gradients in the plasma.

The dramatic changes can be appreciated from the TEC observations from the two successive NIMS passes. The first at about 16:13 UT on 28 April 2001, showed a very steep latitudinal gradient, with TEC values exceeding 57 TECU below 50°N, but less than 15 TECU at latitudes greater than 65°N. However, only one hour later the ionosphere had a very different structure. From a pass at about 17:19 UT, the TEC at 50°N was now only some 27 TECU, with less than 5 TECU being found at 65°N. It was concluded that there were very steep spatial gradients in both the meridional and zonal directions around this time, in an ionosphere that was also changing rapidly in a temporal sense. The observations contributing to the outlying point in fig. 8.1, which corresponded to the 17:19 UT pass on 28 April, can thus be placed in context. Both of the measured values were estimated from slant observations through ionospheric regions containing significant gradients. For the NIMS-TEC, the results were obtained from a single satellite as it passed, essentially following a line of longitude, in this case slightly to the west of the receiver stations with the ray paths traversing the changing ionospheric gradients. By contrast, the GPS-TEC was estimated by a complex procedure that made use of multiple satellite observations with many different, and changing, observational geometries. When steep gradients are present the ray paths from the various spacecraft may encounter rather different ionospheric conditions that will depend also on the exact form of the constellational geometry available for use at any particular time.

It was concluded that the two independent estimates that contribute to the outlying point in fig. 8.1 may be equally valid measurements, with the difference between the values being accounted for by the ionospheric conditions prevalent at the time and the particular procedures required for the derivation of the equivalent vertical TEC from the basic observations. The current study highlights the need for caution in the use of TEC values for operational applications under such circumstances. It is clear that at times of substantial spatial and temporal gradients in the ionosphere, as on the first afternoon of an impulsive geomagnetic storm, different measurement techniques may give rise to very different estimates of the equivalent vertical TEC, well beyond the accepted experimental errors of the individual results.

8.4.2. IGS site data

A later study (Kersley *et al.*, 2003) was also carried out to compare measurements of TEC made independently at sites in U.K. using different techniques. Data were selected from about 100 passes of NIMS satellites, monitored at three sites spanning U.K. latitudes, and chosen to cover a wide variety of geophysical conditions in autumn 2002, including days of geophysical disturbance. Comparisons was made with TEC measurements obtained by analysis of RINEX files from the routine GPS observations taken at the International Geodetic Survey (IGS) site in U.K., Hailsham (50.0°N, 0.3°E). Care was taken to reduce all known possible sources of error in the data for the comparison. The NIMS-TEC values were determined by vertical integration through tomographic images (fig. 8.2).

The comparative plot shows good statistical agreement between the data sets, with a variance of 0.91. The best-fit line has a slope of 0.91 and an intercept of 2.7 TECU, the latter in broad agreement with the earlier estimates of the protonospheric contribution to GPS-TEC measurements in U.K. In an examination of possible sources for the residual scatter several factors were considered.

The difference between the individual GPS and NIMS-TEC estimates is generally only a few TEC units and it must be recalled that an offset of some 2-3 TECU would be expected from the different altitude limits of the two sets of measurements. However, the difference appears to show a slight dependence on time of day. Figure 8.3 shows that cases where the TEC determined from the 1100 km altitude NIMS satellites apparently exceeds that from the 20200 km GPS satellites are concentrated in the afternoon hours, while the highest positive differences are found in the morning. The effect can

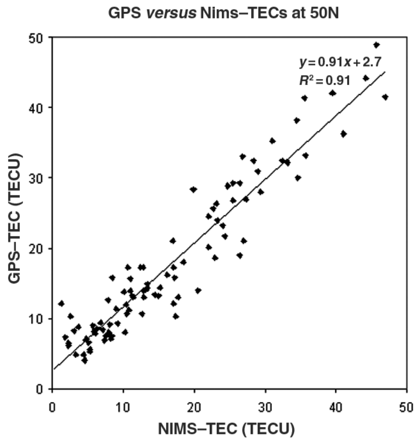


Fig. 8.2. Comparison of equivalent vertical TEC estimated from RINEX files recorded at the IGS-GPS site at Hailsham with values obtained by vertical integration through tomographic images obtained from analysis of NIMS observations at a chain of stations in U.K.

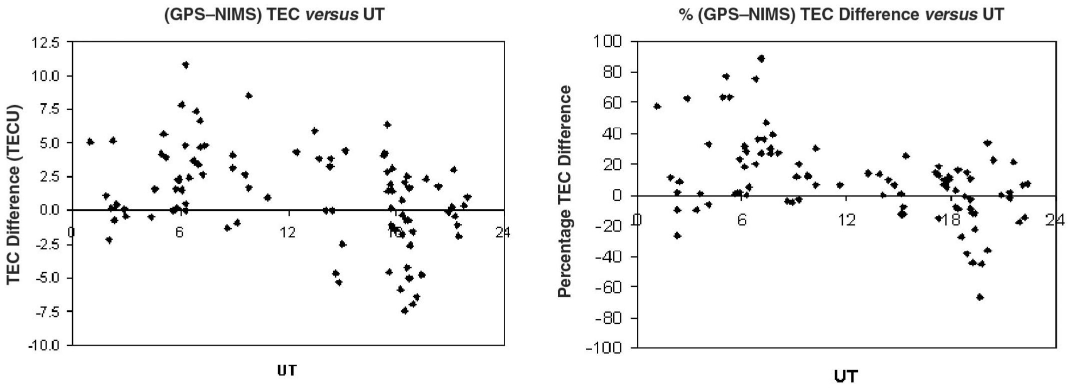
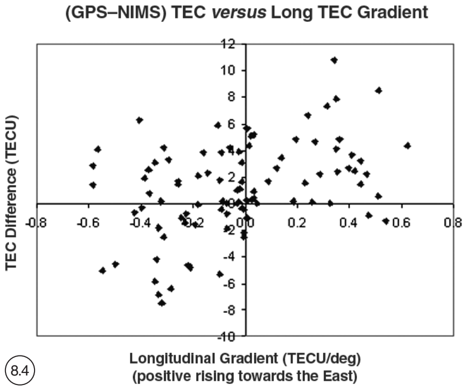


Fig. 8.3. Difference between GPS-TEC and NIMS-TEC estimates as a function of UT expressed in absolute and percentage terms.



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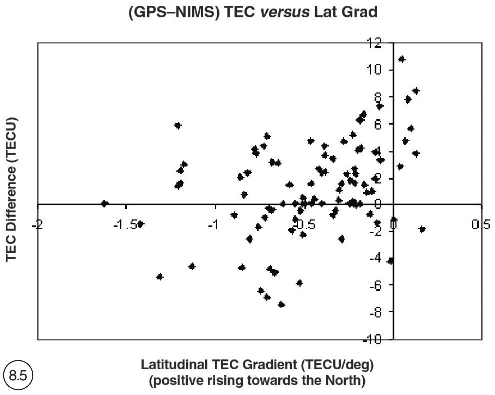


(8.5)

Fig. 8.4. Absolute difference between GPS-TEC and NIMS-TEC estimates as a function of the longitudinal TEC gradient.

Fig. 8.5. Absolute difference between GPS-TEC and NIMS-TEC estimates as a function of the latitudinal TEC gradient.

also be seen in the differences expressed as a percentage of the GPS-TEC. However, it again must be noted that protonospheric contribution introduces a bias that, while small during the day, may represent a significant fraction of the total content at night, resulting in a few very large positive percentage differences.

The predominance of positive TEC differences in the morning and negative values in the afternoon may be linked to longitudinal gradients. The plot shown in fig. 8.4 of the TEC difference *versus* the longitudinal gradient (obtained from the GPS temporal observations) shows that, allowing for the small positive mean difference between the data sets, the largest positive values occur when there is an ionospheric gradient rising to the east, while negative differences are associated with gradients increasing to the west.

Another study investigated possible effects of gradients in latitude on the difference between the two TEC data sets (Kersley *et al.*, 2003). The latitudinal gradient in the U.K. sector, determined from the NIMS observations, normally decreases to the north. Allowing for the known positive offset between the GPS and the NIMS measurements, there is some limited evidence in fig. 8.5 to suggest that less steep and even reversed mid-latitude gradients may give rise to increasing residual differences between the GPS and NIMS-TECs.

It was concluded that the TEC measurements from the two independent techniques agree well on a statistical basis within the limits of experimental observation. No seriously outlying points were found in the data sets, even through the observations encompassed times of geomagnetic disturbance. The residual scatter was generally at the level of a few TECU. There was some evidence to suggest that differences of a few TECU may be linked to gradients in the ionosphere. In particular, the GPS technique may give rise to small overestimates with respect to the NIMS value during the morning longitudinal gradient with corresponding small underestimates at the time of the afternoon decline in the ionisation. It is possible that the fixed height assumption of the thin-shell ionosphere used in the analysis procedures contributes to this effect, with the consequences being magnified for the GPS results that are obtained from much longer slant paths through the ionisation gradient. The effects of latitudinal gradients are more complex, involving not only the bias towards the south of the content on the protonospheric flux tubes, but also the incomplete coverage of the sky for the ray paths from GPS satellites, in 55° inclination orbits, when viewed from a site at U.K. latitudes. However, it must be stressed that the residual effects found here, linked to ionospheric gradients, are at the level of only a few TECU.

8.5. GPS-TEC MAPS

A product available on-line from the RAL group are the maps of TEC over Europe created from measurements made using ftp RINEX files from the network of GPS receiving stations operated for the International Geodetic Survey (IGS). Contour maps of TEC are generated after applying a Kriging gridding procedure, in which regional variable theory is used to calculate the correlation between measurements with a weighted smoothing dependent on their separations (Samardjiev *et al.*, 1993). These maps are updated at 10 min intervals to provide an indication of the changing large-scale structure of the TEC on a Europe-wide basis (Cander and Ciraolo, 2002).

At the time of the HIRAC campaign the coverage of the available IGS stations providing data was limited, nevertheless it was thought useful to try to make a first assessment of the reliability of the TEC maps by comparison with independent measurements. Once again the equivalent vertical TEC measurements from the NIMS passes were used, with values now being estimated for different latitudes (Kersley *et al.*, 2002). Selected comparative plots between the GPS-TEC from the maps at U.K. longitudes and the NIMS observations, for latitudes of 50°N, and 60°N, are shown in fig. 8.6a,b. A consistent pattern emerged from the study, with the slope of the best-fit line generally being about 0.8.

While the GPS-TEC estimates for low magnitudes exceeded those from NIMS as expected, at higher levels the values were much closer. Indeed, there was evidence to suggest that the situation may be reversed at the lower latitude of the study, in contradiction to the known physical mechanisms governing the observations. Thus, while the broad agreement between the data sets provides confirmation for the validity of the map TECs, nevertheless it is clear that there are limitations to the technique, at least in the preliminary form in which it was used at the time of the HIRAC campaign. More detailed comparisons showed that the form of the latitudinal gradient in the GPS maps was often less steep than that found by the NIMS observations. However, the general agreement was encouraging for the future development of TEC mapping techniques, particularly when it is noted that the station coverage in the vicinity of U.K. was very limited at the time of HIRAC.

In an extension to the study the form of the TEC maps during the collapse of the positive phase of the geomagnetic storm on 28 April 2001 was also investigated (Kersley *et al.*, 2002). The latitudi-

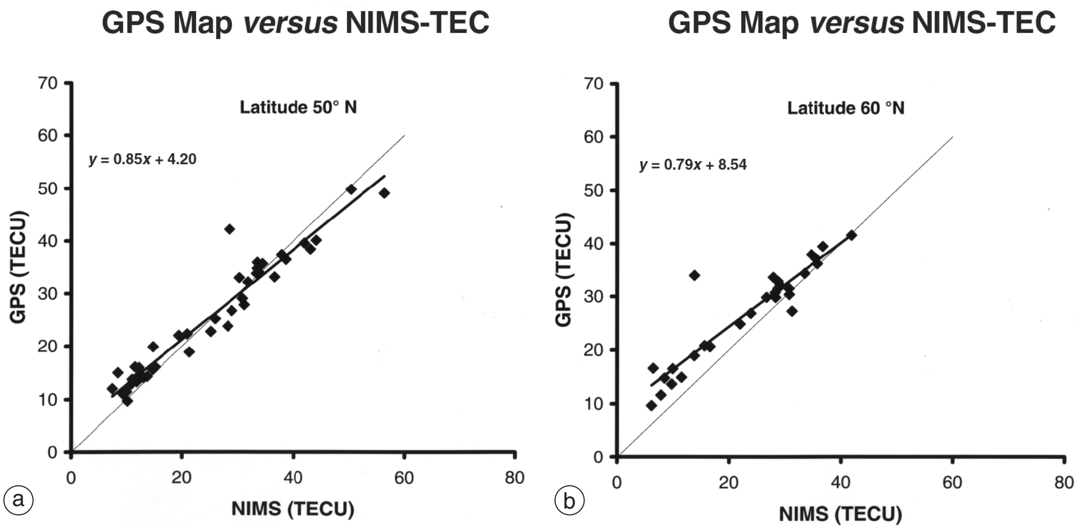


Fig. 8.6a,b. Comparison of equivalent vertical TECs from GPS maps and NIMS observations at latitudes of (a) 50°N and (b) 60°N.

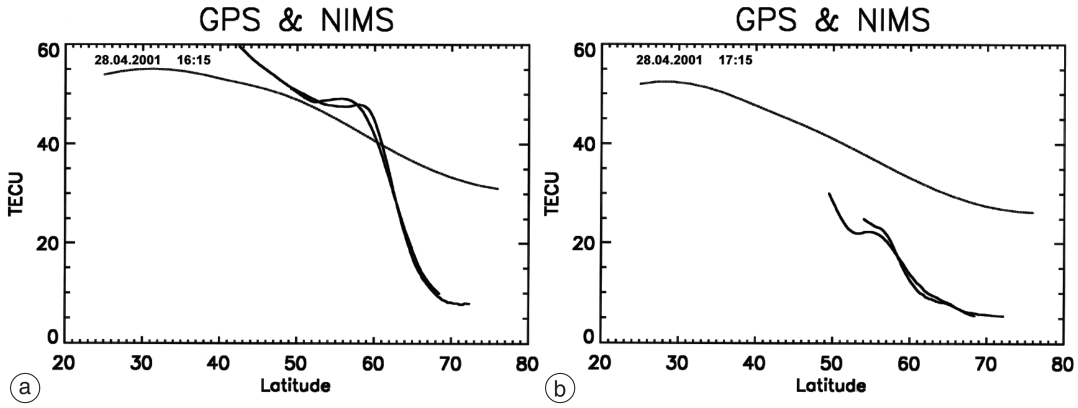


Fig. 8.7a,b. Plots of equivalent vertical TEC as a function of latitude from GPS maps (dash/dot notation) and NIMS observations at Aberystwyth and Hawick, for a satellite pass on 28 April 2001 at about (a) 16:15 UT and (b) 17:15 UT.

nal gradients in the TEC in the vicinity of U.K., for two selected times in the afternoon, are plotted as the dashed lines on fig. 8.7a,b. For comparison, the corresponding latitudinal gradients obtained from NIMS pass observations are also shown. The much shallower nature of the map gradients is confirmed, with the magnitudes of the two measurements being similar at about 60°N for the earlier time. NIMS passes at 15:05 UT and 16:15 UT (the latter is plotted here in fig. 8.7a) showed very similar strong gradients, though the maps TECs, while much less steep, were also replicated at the two times. It can also be noted that the values from the maps at about 52°N were comparable to the independent measurements from the Chilbolton receiver discussed earlier. The results at 17:15 UT (fig. 8.7b) show a similar map gradient to that found earlier, albeit with TEC magnitudes lower overall, being some 10 TECU less than the previous observations. By contrast, the NIMS-TECs are greatly reduced, as was reported in the earlier discussion. It is clear that again the GPS-based observations seem unable to yield the details of the collapse of the ionisation levels.

It was concluded that, at the time of the HIRAC campaign, the TEC maps gave a general indication of the magnitude of the equivalent vertical TEC likely to be encountered in the vicinity of U.K. However, the gradients present in the ionosphere did not appear to be very well represented in the maps and, in particular, the steep spatial and temporally changing gradients driven by geomagnetic storm process were not followed. However, it was stressed that the coverage of the data from the IGS stations was somewhat restricted during HIRAC and, in addition, the mapping techniques used were at a very early stage of development. The positive nature of the present results encouraged further development, together with subsequent assessment by means of independent comparison following the methods used here, though such analysis has not been possible under the present project for a variety of reasons.

8.6. TEC IN THE VICINITY OF THE MAIN TROUGH

An important aspect of the project has been an ongoing programme of experimental observations directed towards obtaining definitive information on TEC variations in the vicinity of the main ionospheric trough in the U.K. sector (Kersley *et al.*, 2004). The main trough represents a significant feature of the ionosphere in the sub-auroral region. It forms at the interface between the high-latitude regime, where the dynamics of the plasma are in the control of processes driven by space-weather interactions, and the mid-latitudes where production by solar EUV radiation is a key factor. The trough forms in the magnetic post-noon sector near the boundary between the sunwards convection of flux tubes at high latitudes and the co-rotating flow of the mid-latitude plasma. As local time progresses during the night it moves to lower latitudes, so that in the sector of the ionosphere over north-west Europe it represents the dominant large-scale structure.

The trough and the associated gradients present particular problems for ionospheric models, developed for use in the mitigation against propagation effects on practical radio systems, because of the dynamic and variable nature of the feature. Many models simply ignore the trough, but even for those where the structure is included, 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 and with the results being used to try to characterise different aspects of behaviour. While some understanding has been gained of aspects of the fundamental responses to 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.

The present project was aimed at providing data from experimental measurements in a consistent and reliable form that could be used for the validation of ionospheric models applicable to the western European sector. The approach was to characterise the trough location and shape in terms of a set of closely defined parameters, building up a database of values from the observations. The parameters were chosen and defined so that it would be possible to obtain estimates of their values in any given situation directly from a model, hence enabling direct comparison with the actual experimental measurements.

The basic experimental measurements were of TEC, obtained from NIMS transmissions monitored at three ground stations spanning U.K. latitudes, Aberystwyth, Hawick and Reay. Observations for the complete year from September 2002 to August 2003 have been analysed, with vertical TEC as a function of latitude being obtained by integration tomographic images. Parameters characterising the location and shape of the trough were estimated from the observations resulting in a database of more than 600 examples of trough form and behaviour.

A detailed analysis demonstrated that some of the parameters underwent systematic variations with local time and/or levels of geomagnetic disturbance. Many previous studies had concentrated essen-

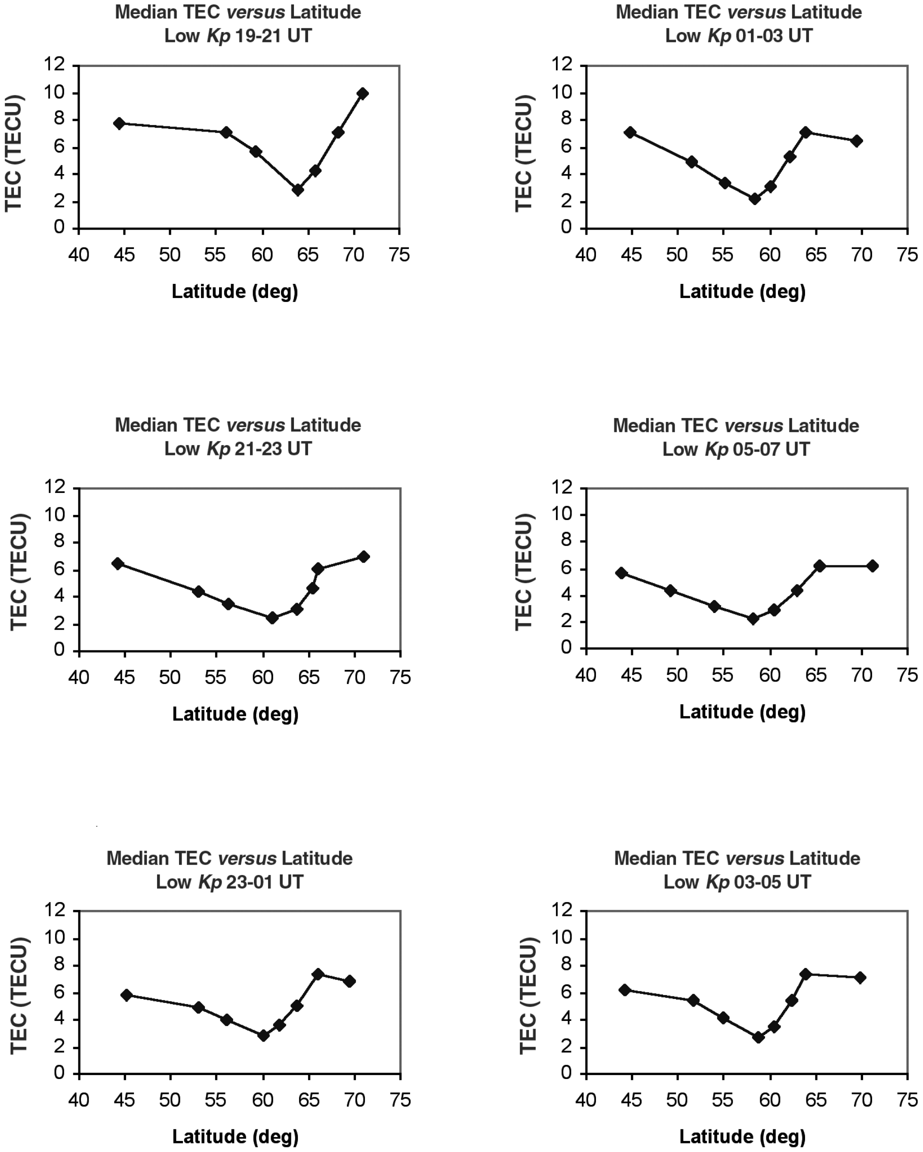
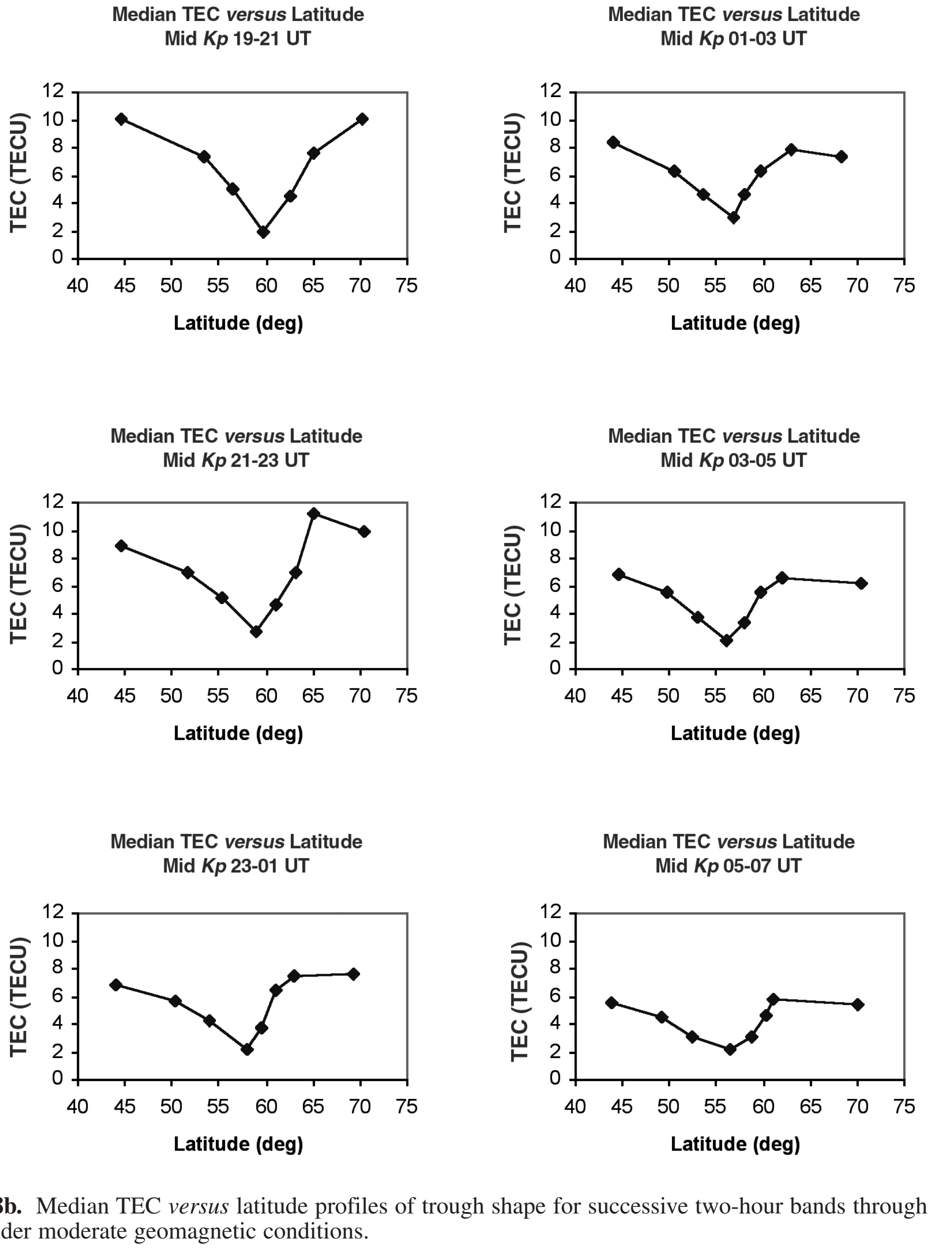


Fig. 8.8a. Median TEC *versus* latitude profiles of trough shape for successive two-hour bands throughout the night under quiet geomagnetic conditions.

tially on the location of the trough minimum. However, the present work has highlighted other aspects, including the sensitivity of the gradient in TEC equatorwards of the minimum in the afternoon and evening to geomagnetic disturbance (Kersley *et al*., 2004). It was found that median values of most of the fundamental parameters in the database, for both TEC and latitude, in two-hour bands throughout



Median TEC *versus* Latitude
Mid *Kp* 19-21 UT

Median TEC *versus* Latitude
Mid *Kp* 01-03 UT

Median TEC *versus* Latitude
Mid *Kp* 21-23 UT

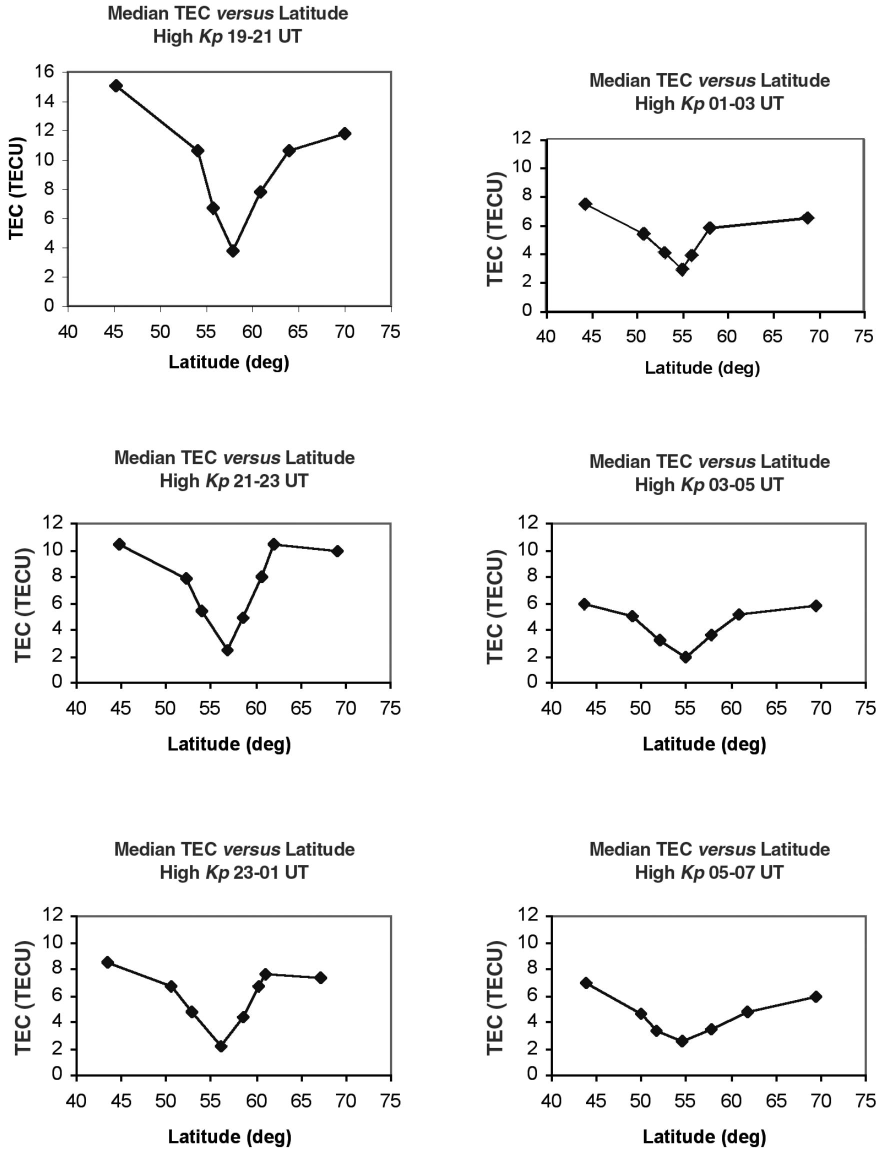
Median TEC *versus* Latitude
Mid *Kp* 03-05 UT

Median TEC *versus* Latitude
Mid *Kp* 23-01 UT

Median TEC *versus* Latitude
Mid *Kp* 05-07 UT

Fig. 8.8b. Median TEC *versus* latitude profiles of trough shape for successive two-hour bands throughout the night under moderate geomagnetic conditions.

the night within three ranges of geomagnetic activity, showed stable and consistent variations. In consequence, plots of TEC *versus* latitude were produced to represent how the location, structure and latitudinal shape of the trough varied with time for three different bands of *Kp*. The results are presented in figs. 8.8a-c for low, medium and high *Kp* levels respectively. The plots provide a reliable and con-



Median TEC *versus* Latitude
High *Kp* 19-21 UT

Median TEC *versus* Latitude
High *Kp* 01-03 UT

Median TEC *versus* Latitude
High *Kp* 21-23 UT

Median TEC *versus* Latitude
High *Kp* 03-05 UT

Median TEC *versus* Latitude
High *Kp* 23-01 UT

Median TEC *versus* Latitude
High *Kp* 05-07 UT

Fig. 8.8c. Median TEC *versus* latitude profiles of trough shape for successive two-hour bands throughout the night under disturbed geomagnetic conditions.

sistent dataset with which to test the validity of ionospheric models in the trough region and it is believed that, within the defined criteria, these TEC *versus* latitude profiles represent the best available description of trough form and behaviour in the north-west European sector.

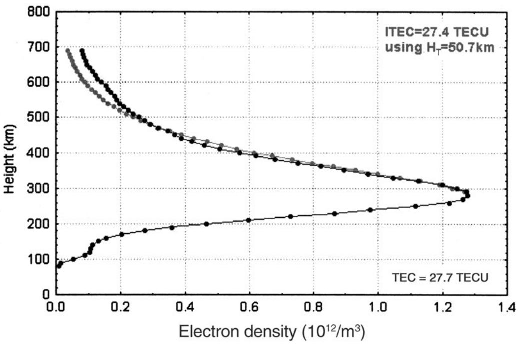
8.7. THE ITEC PARAMETER

In general, TEC is obtained experimentally from slant measurements between a satellite and ground. However, Reinisch and Huang (2001) proposed a new technique to estimate the TEC of the ionosphere up to 1000 km from ground-based digisonde ionograms. Since ionograms only contain direct information about the vertical electron density profile up to the peak of the *F*2-layer, the proposed method approximated the profile above the peak to an a-Chapman function with constant scale height (H_T), derived from the bottomside shape at the peak. A new parameter ITEC was defined to represent the content obtained by integration through the resultant profile. A study was undertaken within COST 271 to try to assess the potential of the ITEC parameter as a proxy for the total electron content (Belehaki and Kersley, 2003).

A data set of some 4000 height profiles of ionospheric electron density up to 700 km was used. These had been measured by a prototype Incoherent Scatter Radar (ISR), which was operated at the mid-latitude site of Malvern (52.1°N, 2.3°W) in U.K. for several years around 1970. Each bottomside electron density profile was extrapolated to the topside using the Reinisch and Huang (2001) method and the ITEC parameter estimated from the integral of the reconstructed electron density with height up to 700 km. In addition, the actual total electron content (TEC_{700}) was estimated from the integral of the observed electron density up to the same height. A representative example of the resultant profiles is presented here in fig. 8.9.

The scale height at the peak of the *F*2-layer for this specific case was found to be 50.7 km, a value then used for the scale height in the topside ionosphere. The difference between ITEC and TEC_{700}

8.9



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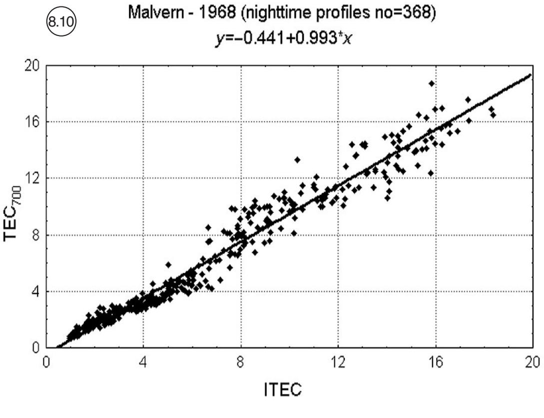

Fig. 8.9. Comparison of the Malvern radar profile (dark line) taken on 18 February 1970 at 14:57 UT, with the profile (grey line) extrapolated according to the Reinisch and Huang (2001) method.

Fig. 8.10. Comparison between the ITEC and TEC_{700} parameters calculated using the electron density profiles measured by the Malvern radar during nighttime in 1968.

for this example was found to be only ~1%, though it can be seen that differences in profile shape below and above some 500 km act to cancel each other in the integration.

In a statistical comparison between the two parameters good agreement was found, especially at night (Belehaki and Kersley, 2003). Figure 8.10 gives a representative example of such a comparison for profiles measured during nighttime in 1968, a year close to solar maximum. The slope of the best-fit line is very close to unity and the intercept negligibly small. Corresponding results for daytime observations showed reasonable statistical agreement, but with a wider scatter of the data points. An earlier study by Belehaki and Jakowski (2002) had already noted that the ITEC parameter was subject larger fluctuations during the day than at night. The topside ionosphere undergoes a composition change at some height, where the O^+ dominance lower down gives way to the essentially hydrogen-based plasma of the protonosphere. While the transition height has wide variations it is generally higher during daytime. Further analysis showed that the differences between the observed and assumed profiles found in fig. 8.9 were more representative of nighttime conditions, with differences in one sense immediately above the peak essentially compensating for those of opposite sign higher up in the integrated ITEC measurement up to 700 km.

The results from the study were encouraging. While some two thirds of the electrons generally reside in the topside, nevertheless the investigation indicated that information obtained from an ionosonde probing the bottomside mid-latitude ionosphere may be of use in obtaining a first-order estimate of total electron content of the whole profile to 700 km, particularly at night. An ongoing study is underway to try to understand the details underlying the correspondence and the limitations to the applicability of the assumption of a constant scale height for the topside profile and the validity of the ITEC parameter.

8.8. COMPARISONS WITH NEQUICK TEC

The studies reported to date have been concerned with experimental measurements of TEC. However, an ultimate aim of such investigations is to support the development of models that can be used for the mitigation of propagation effects on practical radio systems. One of the most important aspects of the COST 271 Action and its predecessors has been the ongoing development by the groups at Graz and Trieste of a family of ionospheric models (Hochegger *et al.*, 2000; Radicella and Leitinger, 2001).

NeQuick, is a quick-run model that is particularly tailored for transionospheric propagation applications. It has been used by the ESA-EGNOS project for assessment analysis and is being proposed for single-frequency operation in the European Galileo project. It has been adopted by Recommendation P531-6 of the International Telecommunication Union-Radiocommunication sector (ITU-R) as a suitable method for TEC modelling. The basic input parameters of the model are geographic coordinates, epoch, solar activity index and values of $foF2$ and $M(3000)F2$, while the output is electron density as a function of height, geographic coordinates and epoch in universal or local time. The model is continuous in all spatial first derivatives, a condition that is necessary in applications like ray tracing and location finding. In addition, it allows the calculation of electron density along arbitrarily chosen ray paths and vertical or slant TEC, including the case of satellite-to-satellite links. The topside of NeQuick is an approximation to a height-aligned diffusive equilibrium. Other members of the family of models developed at Trieste and Graz provide more sophisticated approaches. For example, COSTprof uses a height-aligned O^+-H^+ diffusive equilibrium, NeUoG-plas has a magnetic field aligned plasmasphere above 2000 km and is especially tuned to satellite-to-satellite applications. All three members of the model family can be modulated to allow for smaller-scale static or dynamic structures like the main trough, travelling ionospheric disturbances and other types of depletions and enhancements (Leitinger *et al.*, 2002).

A version of the NeQuick model was made available to the COST 271 community for evaluation purposes in mid-2003. A brief study was undertaken to assess the applicability of the model to the U.K. sector by comparing the TEC predicted with actual experimental measurements. While the input drivers for the model are limited to location, month, time and monthly average solar flux, the experimental data set was that from the autumn of 2002 used for the investigations described earlier, covering a wide range of geomagnetic conditions (Kersley *et al.*, 2003).

The TEC estimated by the NeQuick model up to 20000 km showed good statistical agreement with the experimental values from the GPS observations at the Hailsham site (fig. 8.11). The variance was 0.81 and the best-fit line gradient 0.72, though an intercept of 8.3 TECU indicated that there may be a small positive bias to the model estimates. However, given that the model is essentially representative of monthly conditions with no account taken of geomagnetic disturbance, while the actual observations covered a wide range of activity, the broad agreement is encouraging.

The study was extended to compare the model output TEC up to 1000 km with the experimental measurements from the NIMS observations covering the latitude range of U.K. The results, replicated in fig. 8.12a,b, showed that for a latitude of 50°N the correlation coefficient was 0.75, with a gradient of 0.64. The intercept of 7.3 TECU was in broad agreement with the conclusion from the study with the GPS results that there may be a small positive offset of a few TECU in the NeQuick model estimates. However, the slope of less than unity appears to indicate that the model may underestimate the TEC at the higher levels observed.

The comparison between the model output and the NIMS measurements for 60°N latitude (fig. 8.12b) showed a greater scatter than that for the lower latitude, particularly for the smaller TEC values at night. The correlation coefficient was now only 0.48 and the best fit gradient 0.62. However, the increased scatter was consistent with a location in northern U.K. that is in the vicinity of the main trough on most nights. The problems of accurate modelling of the ionosphere in the trough region have already been noted. The intercept of 8.9 TECU was again broadly consistent with those found from the comparisons at lower latitude.

It was concluded from this limited study that within the limitations imposed by changing geomagnetic activity the model output showed similar trends to the experimental measurements. A broad correspondence was demonstrated, particularly in the results for 50°N, though it was clear from the spread of the data points that the performance was degraded in the vicinity of the trough further north.

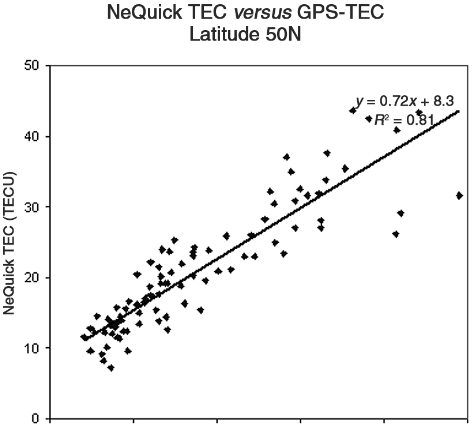

Fig. 8.11. Comparison of TEC up to 20000 km estimated by the NeQuick model with experimental measurements obtained from GPS observations at Hailsham in U.K.

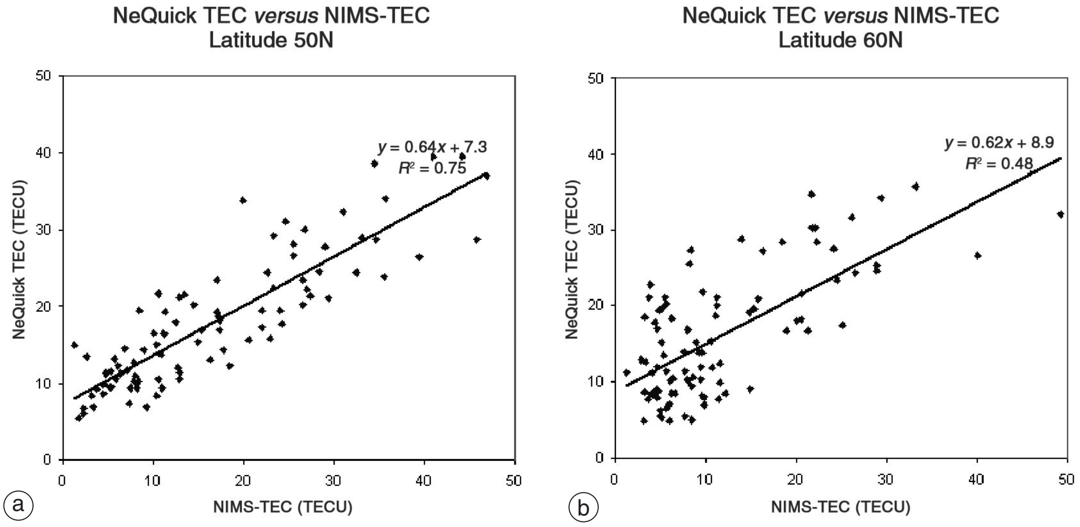

Fig. 8.12. Comparison of TEC up to 1000 km estimated by the NeQuick model with experimental measurements obtained from observations of NIMS satellites in U.K. for latitudes of (a) 50°N and (b) 60°N.

While there were indications from the intercept of the best-fit lines that the model values may have a small positive bias of a few TECU, the gradients were indicative of a tendency to underestimate the higher levels of TEC.

8.9. RADIO TOMOGRAPHIC IMAGING

One of the recent advances in the use of total electron content measurements has been the development of techniques for tomographic imaging of the ionised atmosphere. In a wider sense, the application of tomographic reconstruction techniques has been one of the scientific achievements of the final decades of the twentieth century. While the mathematical basis of the method was formulated early in the century, the advances in computing technology in the 1960s gave practical realization to the use of tomography as an imaging tool. The technique is now hailed primarily for transforming medical diagnostics, but it has also given rise to significant progress in many other fields, including several areas of geophysics.

A number of authors have reviewed the application of computerised reconstruction to radio tomographic imaging of the ionised atmosphere. Early developments in the field are documented in special issues of the journals *International Journal of Imaging Systems and Technology* (1994) and *Annales Geophysicae* (1996), while in further reviews Leitinger (1996, 1999) discussed the theoretical basis and the limitations of the ionospheric application. More recently, ionospheric tomography, including descriptions of a number of theoretical formulations, has been the subject of a book by Kunitsyn and Tereshchenko (2003). In addition, Pryse (2003) has reviewed experimental results from the application of radio tomography to ionospheric imaging, concentrating in the main on use of the method in investigations directed towards understanding of the underlying geophysics. Another comprehensive review within the context of the COST 271 Action (Kersley, 2004) focussed on aspects of the use of tomographic imaging as an aid to practical radio science applications. Material included in that review will be outlined here in summary only.

The radio tomographic method involves measurement of the slant electron content, the line integral of the electron density, along ray paths from a satellite to a chain of ground stations approximately aligned with the satellite orbital track. Inversion of the data set in a reconstruction algorithm yields a pixelised image in two dimensions of the spatial distribution of the electron density throughout the region of the ray-path intersections. While many groups worldwide have been involved in the development of radio tomographic imaging and the technique has now been used in many situations, the results presented here of relevance to the COST 271 Action are concerned in the main with investigations of the potential usefulness of the method to applications related to practical radio systems. The experimental programme involved reception of the phase coherent signals from satellites in the NIMS system, in polar orbits at about 1100 km altitude, monitored at a chain of receiving locations aligned essentially in longitude, but separated in latitude. The observations have been made for the most part at locations instrumented by the UWA group in U.K. and Scandinavia. The former sites have been used for studies of structures in the mid-latitude and sub-auroral regions, including the main trough, while the measurements at high latitude have been concerned with investigations of signatures of space-weather processes in the auroral and polar ionospheres.

The development work carried out in recent years has demonstrated that radio tomography has now matured into a powerful experimental technique capable of providing images of large-scale spatial structures in a wide area of the ionosphere from a limited number of ground stations. The spatial nature of the observations is complementary to those from many other types of experimental measurements of the ionosphere. The limitations to the method were thoroughly investigated and well understood from early simulation studies. These result primarily from the limited-angle geometry of the satellite-to-ground observations so that there is incomplete information in the raw measurements about the vertical profile. However, even at an early stage of the development, algorithms were formulated capable of reproducing ionospheric layers at different heights throughout the image (Fremouw *et al.*, 1993). An additional limitation is that the temporal coverage is dependent on the number and orbits of the available satellites with appropriate beacon transmitters. The possible relevance of radio tomographic techniques to a number of areas of practical radio systems is outlined below. A comprehensive account of the most important results has been given in the recent review (Kersley, 2004), while further details can be found in the reference cited therein.

8.9.1. Tomography and ionosondes

The ionosonde remains the basic experimental tool used to monitor the state of the ionised atmosphere for radio systems applications. Significant advances have been made in the development of the instrument in recent decades, not just in the electronic hardware and digital processing of the sounding signals, but also in inversion software that can yield electron density *versus* height profiles below the layer peak in near-real-time. However, ionosondes can only provide measurements for specific locations at discrete times. The spatial imaging capability of the radio tomography technique forms a natural complement to the ionosonde for routine monitoring, with synergies of mutual benefit to both methods. The addition of information about the horizontal structure of the ionosphere from tomographic imaging can be used to place the point measurements from the sounder in their wider spatial context, while inclusion of input from an ionosonde in the reconstruction algorithm can be used to mitigate the limited capability of the tomographic technique to determine heights. A case study was discussed by Kersley *et al.* (1997) that demonstrated the complementary nature of the measurements by the two techniques, which involved observations in the main trough region over Europe at a time of extreme geomagnetic disturbance. Measurements by ionosondes have also been used to improve the representation of the vertical profile in tomographic reconstructions. Discussion of the role of ionosonde input in reconstruction algorithms, used as complementary information to the TEC observations, can be found in papers by Raymund *et al.* (1993) and Heaton *et al.* (1995). The former was also the first to include verification of the resultant image of electron density using independent results from the EISCAT incoherent scatter radar.

8.9.2. Tomography and the validation of ionospheric models

A powerful potential application of radio tomographic imaging is in the validation of ionospheric models. Dabas and Kersley (2003) discussed comparisons between tomographic images over U.K. and corresponding output from three different ionospheric models: the International Reference Ionosphere (IRI-95) (Bilitza *et al.*, 1993), the Parameterised Ionospheric Model (PIM) (Daniell *et al.*, 1995) and the European regional model developed during the COST 238 action (Bradley, 1999). The experimental results from observations at a tomographic chain of stations in U.K. in an example presented showed an ionosphere with a clear trough and also a mid-latitude nighttime enhancement to the south. The output from the IRI-95 model for the same geophysical conditions failed to replicate either feature, while that from PIM did show a trough, but with no localized enhancement to the south. The results from the COST 238 model did appear to show a trough, though because this particular model was designed specifically to cover the European region below 55°N latitude, with default matching to the IRI model above that latitude, it was concluded that the feature found was likely to be an artefact of this process.

While the work outlined above involved the testing of models that had been developed specifically for radio-systems applications, tomographic images have also been used to assess the ability of a physical model of the coupled ionosphere/thermosphere system to replicate conditions in the high-latitude ionosphere. Experimental observations from a chain of satellite stations in the Scandinavian sector were used to provide ‘ground truth’ information for comparison with output from the Sheffield University Coupled Thermosphere Ionosphere Plasmasphere (SUCTIP) model in a study reported by Idenden *et al.* (1998). A subsequent investigation by Balthazor *et al.* (2002) compared the locations of the trough minimum, determined experimentally from tomographic images made under quiet geomagnetic conditions, with those predicted by the model. It was found that the model tended consistently to place the trough at slightly lower latitudes than those identified experimentally from the tomographic observations.

8.9.3. Tomography and the mapping of ionospheric parameters

Maps of ionospheric parameters, on a regional or global basis, provide another tool used to correct for propagation effects in practical radio systems. Dabas and Kersley (2003) also investigated the potential use of tomographic images in such mapping. They demonstrated that improvements could be achieved to the reliability of maps of the *F*2-layer critical frequency and peak electron density over Europe by incorporating information from experimental tomography into the mapping process. In essence, the electron densities at the layer peak, determined from the image and containing information about latitudinal structures, were mapped in longitude, with zonal gradients from the model being used to create a revised map that was more realistic of the actual conditions. Verification of the improvement afforded by the use of tomographic observations in the mapping procedure was obtained by comparing the mapped values with actual measurements of *foF*2 from the network of ionosondes throughout Europe. Figure 8.13 shows the results of such comparison for the PIM model. It can be seen that inclusion of tomographic input with the PIM model improved the correlation coefficient between the mapped *NmF*2 and actual ionosonde measurements to 0.92, while a smaller coefficient of 0.83 was found when the PIM model was used alone.

8.9.4. Tomography and oblique ionograms

The possible role of radio tomography as an aid to oblique ionospheric sounding was investigated by Heaton *et al.* (2001). A network of oblique sounders was established in U.K. during an experimental campaign, covering the region spanned by a chain of tomographic receivers. The results demonstrat-

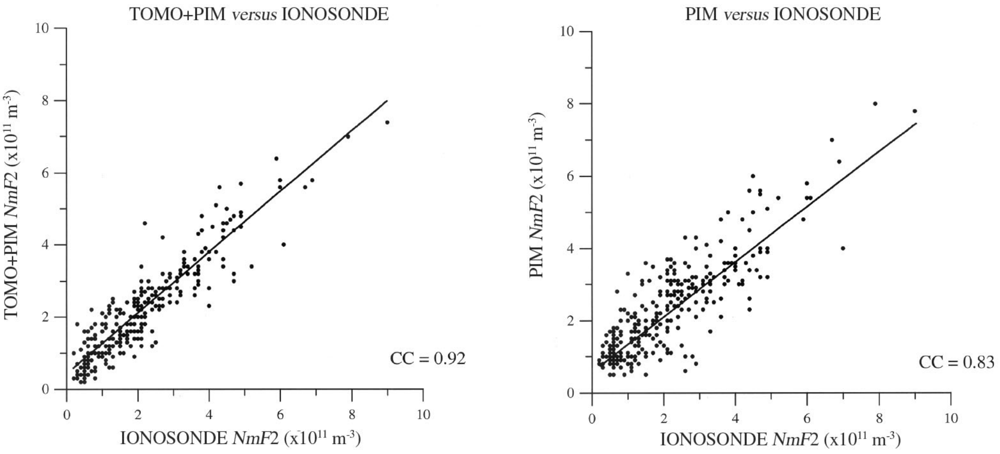

Fig. 8.13. Correlation of *NmF*2 from tomography plus PIM maps (*left* panel) and PIM alone maps (*right* panel) with corresponding values from ionosondes (from Dabas and Kersley, 2003, reproduced by permission of the American Geophysical Union).

ed that the maximum density at the mid-point of the oblique path estimated by inversion of the oblique ionogram was in reasonable agreement with the density at the corresponding height and latitude in the tomographic image. It was concluded from the study that images of path conditions from the tomographic technique could have a role to play in assessing the applicability of the assumption of spherical symmetry in the reduction of oblique incidence ionograms.

8.9.5. Tomography and HF ray tracing

The observations from the oblique incidence sounder network in U.K. were also used in a study of the potential of radio tomography as an aid to the ray tracing of HF propagation paths (Rogers *et al.* (2001). The study investigated the effects of various types of input information that can be used to constrain the vertical electron density structure in the tomographic reconstructions. It was found that the use of a fine height resolution and incorporation of input from one vertical ionosonde in the reconstruction process made significant improvements to the overall reliability of the tomographic image. As expected, *E*-layer propagation was better defined using a climatological model than by the tomographic method. However, the use of tomographic images reduced the RMS error in the determination of the *F*2-layer Maximum Useable Frequency (MUF), yielding significantly smaller errors than those obtained from three independent ionospheric models (FAIM, PIM and IRI-95).

8.9.6. Tomography and HF direction finding

Warrington *et al.* (2002) presented observations from an HF direction-finding experiment, on a link between Uppsala in Sweden and Leicester in U.K., where the propagation path was aligned approximately along the orientation of the main ionospheric trough. Examples were found on many nights of significant deviations from the great-circle path, with consequent increased times of flight and doppler frequency shifts. In a particular case studied the azimuth of the received signals shows a sudden transition from the great-circle direction, followed by a smooth rotation and reversal over a period of several hours before returning to the original direction. In a subsequent study, reported in Kersley *et al.* (2004), images of electron density from the U.K. tomography chain from a succession of satellite passes, revealed a trough with a steep poleward wall that advanced equatorwards during the early part of the night before receding again northwards. The anomalous propagation found in the results from the HF experiment could be explained in terms of reflection by the enhanced densities seen in the tomographic images polewards of the trough minimum.

8.9.7. Tomography and space weather

Many of the processes that can have adverse effects on the performance of radio systems are of particular significance during times when disturbed space weather impacts on the terrestrial environment. Radio tomographic imaging of ionospheric structures found at high latitudes has been shown to provide insight into space-weather processes. The convergence of the geomagnetic field close to the Earth results in flux tubes containing very different plasma populations, which are characteristic of widely separate regions of space, being brought into close spatial proximity in the dayside cusp ionosphere. In consequence, structures in the ionospheric plasma represent signatures of physical processes that are operating far out in space. Tomographic imaging of such spatial features has demonstrated that they contain footprints of important mechanisms in solar-terrestrial coupling. Several papers have addressed such issues, including two that illustrate the signatures in the dayside cusp ionosphere of the reconnection processes that link the Interplanetary Magnetic Field (IMF) carried by the solar wind to the geomagnetic field. Walker *et al.* (1998) used radio tomography to image features resulting from reconnection near the equatorial plane when the IMF was southwards, while Pryse *et al.* (1999) discussed structures linked to lobe reconnection under northwards IMF.

8.10. 4D IMAGING

The radio tomographic imaging reported above uses signals from satellites in low-Earth orbit, which when received at a chain of stations provide the electron content data from the intersecting ray paths for the inversion process. A recent development has been the extension of the underlying principles of the

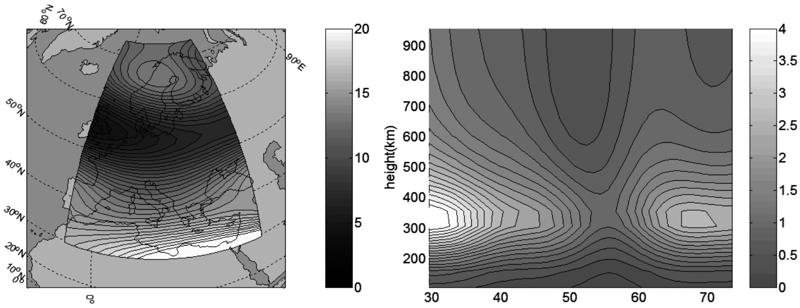

Fig. 8.14. (*Left* panel) Frame from a movie of vertical TEC (in TECU) over Europe obtained from the inversion of GPS data recorded about 22 UT on 12 August 2000; (*right* panel) corresponding plot of electron concentration ($\times 10^{11} m^{-3}$) at 15°E longitude.

method to GPS satellites. Simultaneous measurements are made by a single receiver along the slowly varying ray paths from several GPS satellites. While the ionosphere can be taken to be stationary during the period of a few minutes of data acquisition from a LEO satellite, this assumption is no longer valid for GPS. However, a method has been developed that allows for inversion of the greatly increased quantity and angular coverage of measurements from GPS signals monitored at a widely distributed network of receiving sites. The MIDAS (Multi-Instrument Analysis Technique) inversion method has been described in detail by Mitchell and Spencer (2003). In summary, the technique uses measurements of slant electron content obtained from dual-frequency differential phase observations of GPS satellites at a network of receivers to produce hour-long movies of the electron concentration, in what is essentially a 4D inversion. The inversion uses a linear, least-squared approach, with the algorithm incorporating *a priori* information about the evolution of the electron concentration during a specified period of time. An example of output from the method is shown in fig. 8.14. The left panel gives the vertical TEC over much of Europe, estimated by vertical integration of the electron concentration in the image of one particular frame. A longitudinally extended depletion, corresponding to the main trough, can be seen over the U.K. and Northern Europe at this time. The right panel shows the corresponding height *versus* latitude plot of the electron concentration along the 15°E longitude. It can be seen that the location of the trough minimum was well to the south at about 55°N, consistent with the significant geophysical disturbance on the day in question.

8.11. CONCLUSIONS

Total electron content is a key parameter for the mitigation of ionospheric effects on practical radio systems. The paper has reviewed recent progress in studies carried out within the COST 271 Action on the estimation of TEC and the use of such measurements in ionospheric imaging. Results have been outlined from a number of investigations directed towards the validation of observations and estimates by different techniques with a view to demonstrating consistency and hence confidence in the products. Most of the work has been concerned with the ionosphere over north-west Europe where the main trough represents a significant feature on many nights.

The term total electron content is often used to refer to the equivalent vertical TEC obtained from slant ray path measurements between a satellite and ground using a geometrical conversion based on an assumed thin-shell ionosphere at given height. Studies demonstrated that the choice of centroid height is critical to such measurements, leading to the conclusion that the accuracy of such equivalent vertical TEC estimates can never be relied on to better than a few TEC units. Integration through tomographic images was found to yield marginally more consistent values of vertical TEC, particularly in regions of steep ionospheric gradients like the vicinity of the main trough.

Comparisons were made between TEC values estimated from NIMS observations with those obtained from GPS satellites, both in dedicated monitoring and use of routine data from IGS sites. The results demonstrated a broad consistency between the measurements within the known limits, allowing for the contribution from the protonosphere on the much longer GPS ray paths. However, a significant departure was noted and attributed to differences in observational geometry through steep gradients linked to the collapse of the ionisation on the first afternoon of an impulsive storm. Inability accurately to replicate such gradients was also noted as a limitation to the current state of development of maps of TEC over Europe available for applications purposes. In another study, the regular gradients associated with the morning rise and evening fall in ionisation and also the normal latitudinal structure during daytime were shown to be linked to discrepancies in TEC estimates at the level of a few TECU. It is clear from this series of investigations that in general the GPS and NIMS techniques yield consistent values, though further study is needed of the circumstances leading to potentially serious errors at times of severe geomagnetic disturbance when localised gradients associated with storm enhanced density structures are found over north-west Europe.

A brief study was made of the ITEC parameter using historic ionospheric profile data from an incoherent scatter radar operated in U.K. It was found that there was reasonable agreement between the actual TEC and that estimated by the ITEC method up to 700 km for nighttime measurements, but poorer agreement by day. There were indications that the assumption of a constant scale height resulted in differences in the profile that were in a particular sense immediately above the peak, but which cancelled with opposite errors higher up in the integrated estimate. However, the study indicted that application of the ITEC method to ionosonde data had the potential to provide first order information about the TEC magnitude.

In another limited investigation comparison was made between actual measurements of TEC in the U.K. sector and estimates from the NeQuick model. Reasonable correspondence was found at 50°N in the essentially mid-latitude ionosphere. However, the agreement between model and experiment was less good at 60°N, in a region where the main trough is a dominant feature of the ionosphere on many nights.

A systematic programme of experimental observations was carried out in U.K. as part of the project to determine the latitudinal structure of the TEC and its variations in the vicinity of the trough. The approach was to characterise the form of the trough in terms of a set of defined parameters that could be replicated in a model for comparative purposes. Median values of the parameters from measurements made over a complete year have been use to create plots of TEC *versus* latitude for different times throughout the night within three bands of geomagnetic disturbance. This data set is now available as an output from COST 271 for the testing of models in the trough region.

An important application of total electron content measurements, which has been developed in recent years, has been radio tomographic imaging of ionospheric electron density. The paper reviewed progress in the use of the technique, particularly in relation to applications as an aid to practical radio systems. The potential roles of radio tomographic observations as complementary to ionosondes, validating both empirical and physical ionospheric models and improving the mapping of structures in the regional ionosphere, were discussed. Additional results were also described, involving possible uses of the technique to aid oblique sounding and HF ray tracing and direction finding, together with applications a high latitudes in mapping signatures in the ionosphere of space weather processes.

A recent extension of radio tomographic inversion to use data from a network of GPS observing stations to create moving images of the ionosphere in three spatial dimensions and time was described briefly, with an example frame being shown from the European sector.

The various studies outlined here, carried out under the broad remit of the measurement and use of total electron content, have demonstrated a broad consistency between results from the different types of measurement, within the known limitations. However, further work is needed in key areas, particularly in relation to the reliability of both measurements and resultant products at times of steep gradients in the mid-latitude ionosphere during the onset phase of geomagnetic storms. In addition, the ability of models to replicate conditions in the vicinity of the main trough also needs investigation, though the present project has been able to provide a data set that is now available for validation.

ACKNOWLEDGEMENTS

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