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Improved Quality of Service in Ionospheric Telecommunication Systems Planning and Operation: COST 251 Major Achievements

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ABSTRACT

COST Action 251 (Improved Quality of Service in Ionospheric Telecommunication Systems Planning and Operation) has been a dynamic group of 122 participants from 46 organisations in 20 Nations working as a technical community towards a common goal. The main objectives were to collect additional quantities and types of ionospheric data, to generate procedures for prediction of ionospheric models over Europe and to promote their use, to extend the existing models to give system performance statistics and to develop a methodology for channel simulation. The major achievements include especially the production of databases of ionospheric measurements, the development of procedures for ionospheric and plasmaspheric modelling, mapping and forecasting and models for users for overall performance prediction of systems in Europe.

The results obtained in the frame of COST Action 251 during the period 1995-1999 are summarised with particular reference to their application for terrestrial and Earth-space ionospheric telecommunication systems planning and operation. Recommendations for future activities are presented.

Key words: Ionosphere, Modelling, Mapping, Prediction, Forecasting, Radio Waves, Radio Communications.

1. INTRODUCTION

Co-operation research on effects of the upper atmosphere on terrestrial and Earth-space communications at the European level is absolutely necessary because accurate propagation information is essential to support the design, implementation and operation of most modern terrestrial and satellite communication systems. Nowadays, communications through the upper atmosphere should meet more and more requirements, even so they seem to be excessive, unrealistic, or usefulness. Advance in performance prediction and forecasting should be achieved by bringing together groups working in two areas, namely groups with objectives radio engineering applications oriented and groups that give more emphasis on radio science. Currently, there is no structured co-ordination effort in Europe in this domain outside COST (European Cooperation in the field of Scientific and Technical Research).

In this frame, work started with COST Action 238 (Prediction and Retrospective Ionospheric Modelling over Europe - PRIME), which operated from 1991 to 1995 with objectives to develop improved models for the European area between latitudes 35-55°N and longitudes 10°W-30°E using ionospheric information taken from existing measuring equipment. Studies were conducted to the specification of the monthly median height profile of electron density up to a height of 1000 km and the mapping as a function of time-of-day, season and solar activity of the monthly median values of the Total Electron Content (TEC) and standard ionospheric characteristics. Procedures of evaluation of these quantities on an individual day were developed.

COST 251 (Improved Quality of Service in Ionospheric Telecommunication Systems Planning and Operation) was a natural succession to COST 238 without which results would not be exploited. It was built on existing COST 238 teams and appropriate new groups for the additional activities. The participants in COST 251 came mainly from public research institutes and from universities. The work was organised as a series of Work Packages, each with own sub-objective, structured within five Working Groups. All Work Packages had participants from more than two countries and have elected their own leaders. A Management Committee supervised progress.

2. GENERAL DESCRIPTION OF COST 251 AND ITS OBJECTIVES

The main objectives were to collect additional quantities and types of ionospheric data, to generate procedures for prediction of ionospheric models over Europe and to promote their use, to extend the existing models to give system performance statistics and to develop a methodology for channel simulation for HF systems in Europe. The work has been split into five main areas, allocated to five working groups: (1) models for terrestrial systems, (2) models for Earth-space systems, (3) ionospheric modelling, (4) variability and forecasting and (5) system performance and spectrum management.

According to the objectives, the principal activities were the following:

- Assembly of a data bank of vertical-incidence and oblique-path ionospheric measurements and Total Electron Content (TEC) for use in model generation and testing;
- Investigation of ionospheric propagation effects on radio systems used for navigation, geodesy and radio-astronomy;
- Studies further the development of new models for the monthly median ionospheric characteristics foF2, M(3000)F2 and TEC;
- Improvement of existing techniques for prediction of ionospheric variability parameters of interest to HF system planning and operation and

other ionospheric telecommunications systems particularly in high latitude;
- Investigation and improvement of ionospheric forecast for HF system operation;
- Studies of HF channel models, signal variability and models for overall performance prediction;
- Production of mapping functions and associated coefficients for the monthly median ionospheric characteristics foF2, M(3000)F2 and TEC;
- Production of spatial-interpolation algorithms for instantaneous values of foF2, M(3000F2) and TEC from measured data for the same epoch;
- Elaboration of forecasting algorithms for estimating values of foF2, M(3000F2) and TEC up to 24 hours ahead of the present;
- Generation of expressions for the electron-density height profile form in terms of values of foF2, M(3000F2), TEC and other available ionospheric and solar-geophysical parameters as necessary;
- Production of a methodology for channel simulation for HF systems;
- Interaction with radio users and comparison of their performance data with model results;
- Production of computer programs in accordance with the recommended procedures.

The adopted COST 251 area is rectangular in geographic coordinates for operational convenience and ease to interface to global models (Fig. 1).

In total 122 scientists and engineers from 46 Organisations in 20 Countries have been associated in the four-year of the lifetime of the Action (1995-1999). Successful Action outcome was achieved by volunteer contributions estimated by peer examination to give general agreement.

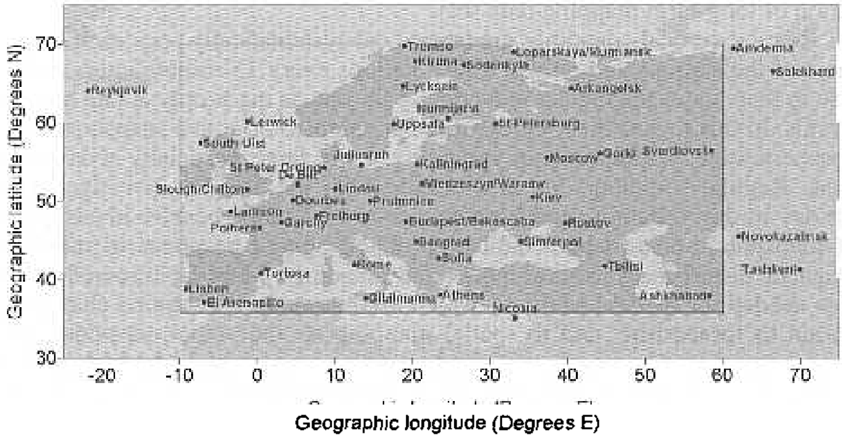

Figure 1. Map showing the COST 251 area of Europe between latitudes 35-70°N and longitudes 10°W-60°E and the locations of the 50 vertical-incidence ionosondes contributing to the data bank.

3. MEASUREMENTS AND DATABASES

The studies undertaken within COST 251 were for the most part theoretical and statistical investigations making use of ionospheric measurement data sets available from databases established under Action auspices. Many past measurements, especially those of vertical-soundings already existed and were available, though some of them needed further analysis and assembly into convenient formats for an easy use. Special efforts have been made to check the quality of the data and many participants in this Action have controlled most of the stored data. In this Section vertical- and oblique-incidence soundings, electron-density height profiles, TEC and HF spectral occupancy measurements that were carried out under Action auspices are reported and the databases established are described.

3.1. Measurements carried out under Action auspices

3.1.1. Ionospheric soundings

Within and close the COST 251 area of Europe (Fig.1) there have been about 50 ionospheric stations providing long-series of data, most of them are still in operation and maintained by Action participants. In many stations measurements performed over 4 solar cycles are now stored in the databases and made available in appropriate digitised form. Long-series data sets are very important to certain studies, particularly those undertaken which have addressed whether there have been any detectable ionospheric trends within the COST 251 area beyond those associated with solar-cycle changes, and for the generation of long-term mapping data sets.

Regular vertical-soundings are carried out systematically once each hour in most of the stations and only at a few stations every 15-minute intervals, but also in these cases the regular reduction of the data is made only at one-hour intervals. In this regard they represent under-sampled effective snapshots of ionospheric state. Within-an-hour variability can be large, especially at dawn and dusk. Regular soundings are also deficient for the detailed investigation of the day-to-day variability and from hour-to-hour. Comprehensive investigation of ionospheric disturbances indicative of ionospheric response to solar and magnetic disturbances requires more rapid soundings. More rapid soundings are also needed for spectral analyses, which involve study of temporal changes as an aid to forecasting, and to spatial mapping on individual occasions. The need is therefore for coordinated rapid-sounding measurement campaigns. Since disturbances cannot yet be forecast it was necessary to agree in advance the epochs of the campaigns. Campaigns of measurements at 5-minute intervals took place during different solar epochs. Difficulties have arisen in finding the necessary resources to analyse the large number of ionograms for these relatively lengthy data sets. However, some of them measured in Rome (Italy), Tortosa and El Arenosillo (Spain) have been analysed and have been used in statistical studies during the Action.

Oblique sounders offer the potential for data inversion to give information on midpath ionospheric conditions. The best geographical implementation of a network to monitor the ionosphere would be to have regularly spaced ionospheric sounders combining vertical and oblique transmissions between them. Unfortunately this is not possible. However, a network of such sounders exists over Europe and a number of special campaigns of oblique-sounding were performed in Belgium, Italy, Spain, Sweden and United Kingdom during the Action.

3.1.2. *Electron-density height profiles*

Bottomside electron density profiles have been obtained by inversion of vertical-incidence ionograms, using either POLAN (Titheridge, 1985) or ARTIST (Reinisch et al., 1988). Topside electron density profiles have been obtained from the COSMOS, Isis-Alouette and IK-90 satellite sounders. The main application is the validation of predicted electron-density height profiles. In this aspect it was interesting to analyse vertical- and oblique-sounding data on the same path simultaneously in order to investigate their mutual dependencies.

3.1.3. *Total Electron Content*

Total Electron Content (TEC) data have been derived in DLR/DFD Fernerkundungsstation Neustrelitz (Germany) from GPS measurements carried out at stations of the European GPS Tracking Network of the International GPS Service (Jakowski et al., 1998a). Assuming a single layer approximation for the ionosphere, slant TEC data were then mapped to a vertical at the pierce point of the ray path with the «ionospheric shell» fixed at 400 km height. Within the COST Action GPS measurements over 4 years (1995-1998) were collected, analysed and transformed to the COST 251 data format.

3.1.4. *HF spectral occupancy*

HF spectral occupancy was measured with four automatic systems as part of a joint United Kingdom/Swedish experiment (Gott et al., 1996). These systems were located at Baldock (United Kingdom), at Linköping and Kiruna (Sweden) and at Munich (Germany) and provide effective measurement of spectral occupancy over Northern Europe. Also, there was a fifth measurement system at Cobbett Hill, near Farnborough (United Kingdom). The measure of occupancy used is defined as congestion, which is the probability that the output signal of a bandpass filter of given bandwidth, randomly placed within a given ITU frequency allocation, exceeds a given threshold level.

3.2. Databases established under Action auspices

3.2.1. The COST 251 data bank

The COST 251 data bank based at the Abdus Salam International Centre for Theoretical Physics, Trieste (Italy) is operational since April 1997 from Web home page: http://www.cost251.ictp.trieste.it/. The COST 251 database provides monthly-median and daily hourly values of up to 14 ionospheric characteristics measured at about 50 stations located in the European COST 251 region and the immediate surrounding geographic area, for the years 1944-1997. This data bank contains also a number of electron-density profiles, as well as TEC and ionospheric absorption data. Participants in COST 251 have made tests on the quality of the data, and a number of errors in the original data have been corrected. Recognising that the database has applicability for other scientific investigations beyond the lifetime of COST 251 it was decided to include up to 14 ionospheric characteristics although not all of these have been used to date.

The database of vertical-incidence ionospheric soundings has been made available on CD-ROM by the Rutherford Appleton Laboratory (United Kingdom), including a modern Windows-based interface, the IIWG DATA package developed by the Geophysical Institute of Sofia (Bulgaria).

3.2.2. The Ionospheric Despatch Centre in Europe

The Ionospheric Despatch Centre in Europe (IDCE) has been established as an initiative of COST Action 251 (Stanislawska et al., 1999a). It is operated since January 1997 in Heliogeophysical Prediction Service Laboratory of the Space Research Centre of PAS (Regional Warning Centre of the International Space Environment Service, ISES) in Warsaw (Poland).

IDCE allows convenient access to some recent ionospheric data from vertical-incidence sounders located mainly in Europe. Data for the current month are presented from the beginning of the month up to last measurements available. IDCE offers the catalogues of disturbed and quiet days, the list of disturbed periods of few hours duration, data on sudden ionospheric disturbances as well as solar, magnetic and other ionospheric information, predictions and forecasting. IDCE provides also values of the MF2 indices (Mikhailov, 1999). On the basis of the most recent data a presentation of the instantaneous maps of foF2 for Europe for is made available. Data are available from Web page: http:\\www.cbk.waw.pl\rwc\idce.html and on ftp.cbk.waw.pl.

4. IONOSPHERIC AND PLASMASPHERIC PREDICTION

4.1. The COST 251 model for the monthly median ionospheric characteristics foF2, M(3000)F2 and TEC

4.1.1. Model for the monthly median ionospheric characteristic foF2

The COST 251 model for the monthly median foF2, known as MQMF2R, is based on Single Station Models (SSM) and the multiquadric method for spatial approximation.

Most of the ionosondes in the COST 251 area have more than one solar cycle period of observations, enabling the creation of foF2 monthly median models, called SSM's, for the location of these ionosondes. The ionospheric index MF2 was used to derive the foF2regressions on solar activity for each ionosonde station. A set of coefficients for 12 months and 24 UT moments for each ionosonde were generated with a non-linear (cubic polynomial) dependence on MF2 index.

The choice of a method for spatial interpolation was a crucial point. The multiquadric method (Hardy, 1971) used for mapping in topography may be successfully applied to global as well as to regional ionospheric mapping as was shown by Teryokhin and Mikhailov (1992). This method draws a surface strictly over given set of points in distinction from other methods adopted for ionospheric mapping. All points inside the COST 251 area as well as in the buffer zone were used for drawing the surface. Thus this approach always provides a smooth interfacing to the ITU-R (1997) model outside the COST 251 area. The method is numerically stable and does not require additional «screen points» for numerical stability in data-sparse regions. A buffer zone of 45 points around the COST 251 area was used to interface the COST 251 maps to the global ITU-R maps (Fig. 2). It should be noted that the model MQMF2R is based on the MF2 index that is available only for the past. A conversion procedure from R_{12} to MF2 is adopted in the model MQMF2R.

4.1.2. Model for the monthly median ionospheric characteristic M(3000)F2

The COST 251 model for the monthly median M(3000)F2, known as UNDIV, uses SSM's, making no distinction between solar cycles, no distinction between rising and falling parts of the cycles and no accounting for hysteresis effects.

Since for constant local time no appreciable systematic dependence of M(3000)F2 on geographic longitude was found over the COST 238 area the original UNDIV approach was to use linear regressions with geographic latitude. Tests demonstrated that this approach was not good enough for the much wider COST 251 area (Leitinger, 1998a). The use of magnetic latitude (dip latitude and modified dip) instead of geographic latitude brought slight impro-

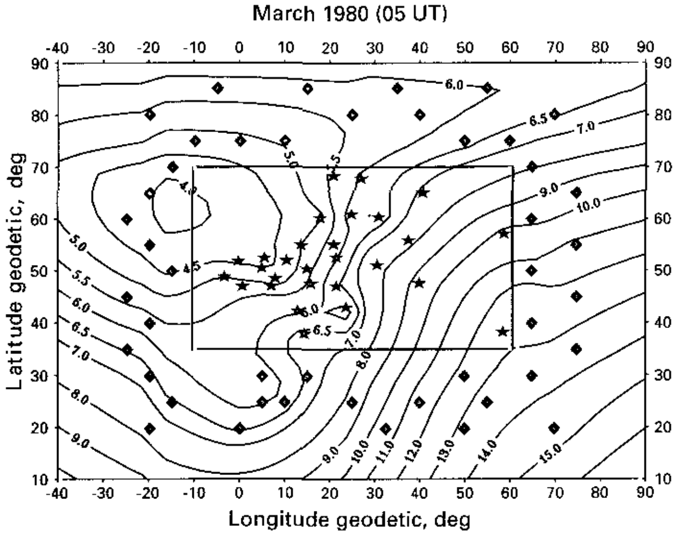

Figure 2. Example of COST 251 to ITU-R foF2 maps interfacing. The COST 251 area, ground-based ionosondes (★) and buffer zone points (◆) are shown.

vements only. Therefore geographic latitude was maintained and a linear dependence on geographic longitude was added. For constant local time (LT) and month of the year bi-linear regressions in latitude and longitude were adopted.

The monthly medians of M(3000)F2 were taken from the COST 251 database and prepared in the following way: (i) for each COST 251 station not reserved for testing, for each month and for each hour UT linear regressions for the R_{12} dependence of M(3000)F2 were constructed, (ii) level values of monthly medians from the regressions were calculated for two R_{12} levels (R_{12}=35 and R_{12}=135), (iii) by means of Fourier interpolation the diurnal variation of the level values were transformed from UT dependence to LT dependence and (iv) for several different selections of stations bilinear regressions were calculated for each R_{12} level, for each month and for each hour LT.

The buffer zone procedure adopted in COST 238 was used. This buffer zone has a width of 5 degrees in latitude and longitude, half of the buffer zone being inside the COST 251 area, half of it outside. This means that with the buffer zone interpolation the «unadulterated» COST 251 area is restricted to between latitudes 37.5-67.5°N and longitudes 7.5°W- 57.5°E. It should be mentioned that the buffer zone solution is an analytical one and therefore continuous in the map value and in all its derivatives.

The M(3000)F2 maps from UNDIV show a smooth behaviour without small scale structures which would be unrealistic for a monthly median map. Figure 3 displays examples as contour lines over the entire COST 251 area.

4.1.3. Model for TEC

The COST 251 model for TEC, known as COSTTEC, is based on monthly and hourly medians of electron content derived from the Differential Doppler effect on the signals of the polar orbiting NNSS satellites for three solar activity interval. The medians were gained for the latitudes 45, 50, 55 and 60°N from latitudinal profiles of electron content. For each of these latitudes a set of 1212 Fourier coefficients was produced by transforming the bi-hourly and monthly medians. The Fourier sets were cut down to 55 coefficients (time independent value, diurnal, semi-diurnal, annual, semi-annual components and combinations). Since the latitude dependence

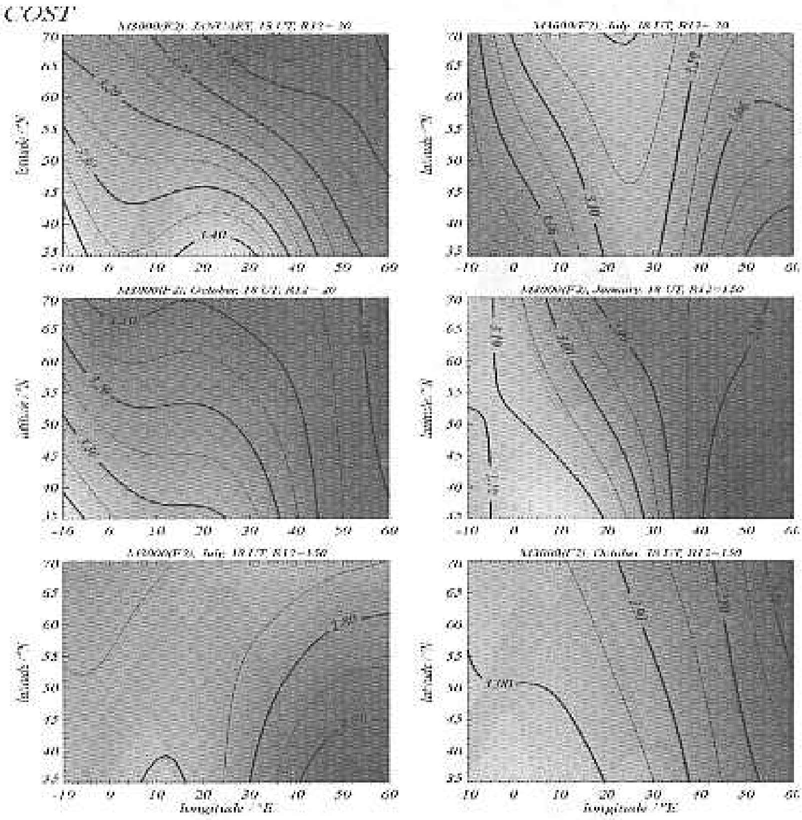

Figure 3. Regional map of the ionospheric characteristic M(3000)F2 for 1800 h UT, as obtained from the COST 251 recommended mapping procedure. The shading indicates maxima (lightest grey) and minima (darkest grey). Season and solar activity from left to right and from top to bottom: low solar activity (R_{12} = 20) for January, July and October and high solar activity (R_{12} = 150) for January, July and October.

turned out to be nearly linear, regression lines were fitted to the Fourier coefficients leading to two sets of 55 Fourier terms (values for the latitude 52.5°N and values for the latitudinal gradients) for each of the two levels of solar activity.

Because no electron content data exist (or were made available) from the longitude region East of 20°E it was necessary to transfer experience with the longitude dependence of peak electron density to electron content. This was achieved by introducing the equivalent slab thickness, the ratio electron content divided by peak density, (Leitinger and Hochegger, 1999). Technically the longitude dependence was derived from the UNDIV 251 foF2 map and formulated with two more sets of Fourier coefficients.

Figure 4 displays examples of the annual and diurnal variation of TEC for two locations and two level of solar activity.

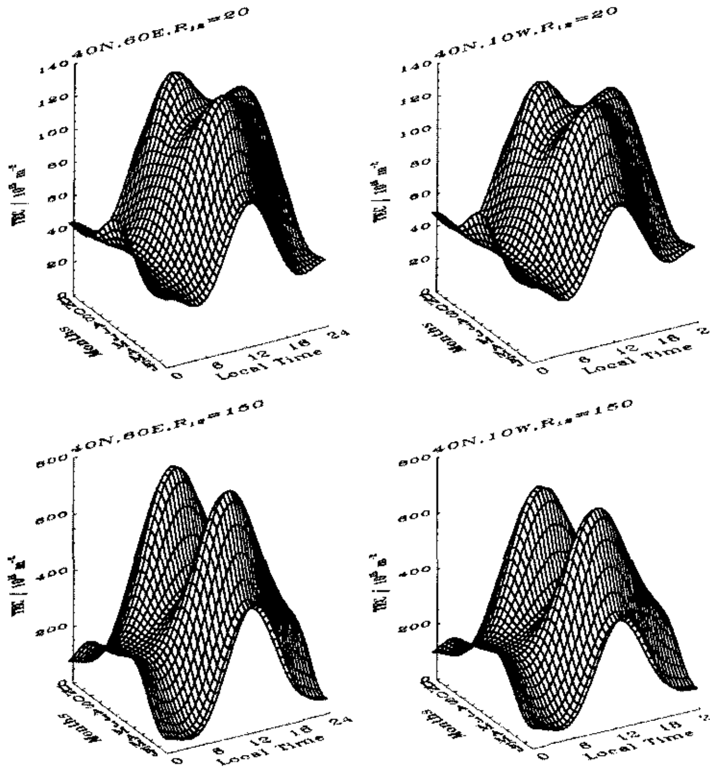

Figure 4. Annual and diurnal variation obtained from COSTTEC for latitude 40°N; top: low solar activity (R_{12}=20); bottom: high solar activity (R_{12}=150); left: longitude 60°E; right: longitude 10°W.

4.2. The COST 251 model for the electron-density height profile

The COST 251 recommended model COSTPROF for the electron-density height profile consists of two parts:

1. A bottomside model for the height region below the F2-layer peak based on the ionospheric characteristics foE, foF1, foF2 and M(3000)F2 and on rocket soundings.
2. A topside model for the height region above the F2-layer peak based on O^+-H^+ diffusive equilibrum with built-in maps for three parameters: the oxygen scale height at the F2-layer peak, its height gradient and the O^+-H^+ transition height.

The model is continuous in all spatial first derivatives, a necessity in applications e.g. ray tracing and location finding.

4.2.1. Bottomside model for the height region below the F2-layer peak

The model for the E, F1 and F2 regions is a modified «Di Giovanni-Radicella» (DGR) model (Radicella and Zhang, 1995). Regional or global map or measured values are adopted as input for the ionospheric characteristics foE, foF1, foF2 and M(3000)F2. The model uses five semi-Epstein layers (Bossy, 1987). Two semi-Epstein are used for the E-layer (top and bottom), two for the F1-layer (also top and bottom) and one for the bottom of the F2-layer. The maximum of the E-layer is fixed at 120 km altitude, the height of the F1-layer is modelled and the height of the F2-layer peak is derived from M(3000)F2 and the ratio foF2/foE.

The D region model covering the 55-85 km height range was produced by the University of Rostock, Germany, (Singer et al., 1995) and has been interfaced with the DGR model. The formulation is based on rocket sounding data and comparison with radio wave propagation data and uses data files for atmospheric pressure derived from the CIRA-86 model.

To combine the D-region model with the DGR model of the E-F region, the models were linked by a connecting region between 85 and 95 km to secure a transition without discontinuities in electron density and its first derivative.

4.2.2. Topside model for the height region above the F2-layer peak

The topside ionosphere formulation, for the height region above the F2-layer peak up to 2000 km, uses three physical parameters, namely the oxygen scale height at the F2-layer peak, its height gradient, and the $O^+ - H^+$ transition height. These three parameters are modelled according to solar activity, season, local time and modified dip latitude (Leitinger et al., 1995).

Diffusive equilibrium does not give a maximum but a decrease of electron density with increasing height. A Chapman's layer expression is adopted to force a peak of the electron density profile. At the peak electron density it is assumed that the electron density scale height is approximately the plasma scale height for atomic oxygen ions. This scale height increases with height together with the transition in ion composition from atomic oxygen to atomic hydrogen ions. The transition height is the height where the densities of the two ions are equal.

The oxygen scale height was found by fitting Chapman layers to theoretical models in the surroundings of the electron density peak (Titheridge, 1993). The temperature of neutral gas was taken from MSIS86 (Hedin, 1987), the temperatures of ions and electrons were calculated from simplified heat conduction equations (Titheridge, 1993), calibrated with observed data (Titheridge, 1976a,b) and by comparison with the results of more accurate but much more complicated calculations.

The height gradient of the oxygen scale height was derived from an analysis of observed data and of the heat flow equations (Leitinger 1998b). COSTPROF uses a scale height, which increases linearly with height from the F2-layer peak to a ceiling height h_c. Above h_c a constant scale height is taken for electron density.

The $O^+ - H^+$ transition height is obtained in COSTPROF from a diffusive equilibrium formulation.

4.3. The COST 251 method for instantaneous values of foF2, M(3000F2) and TEC

Almost all approaches for obtaining instantaneous maps of foF2, M(3000F2) and TEC may give significant errors especially in data-sparse regions, or even on some occasions can lead to numerical instability of the mapping procedure. The accuracy of an ionospheric map depends on its the ability to describe the different phenomena in the ionosphere. Unfortunately, the number of measurement locations is generally insufficient for the production of fully accurate maps, even over a restricted geographical region, and use must be made of artificial screen-point values to constrain the mapping contours in remote areas. Furthermore higher latitudes are significantly influenced by the mid-latitude trough phenomena during nighttime (see Section 4.5.12).

4.3.1. Method for instantaneous values of foF2, M(3000F2)

The COST 251 method for instantaneous values of foF2 and M(3000)F2, known as PLES (Poland PL, Spain ES), combines monthly median maps of ionospheric characteristics and a set of screen points-measurements using two interpolation methods modified this purpose: Kriging and «fitting».

The basis of Kriging (Matheron, 1971) is to apply weighted interpolation among adjacent data points using variogram, i.e. function which illustrates the differentiation of the value of a parameter depending on the distance between the different measurements. Weighting factors are given to the measurements in order to assure the most accurate estimation of the unknown parameter. A scaling factor is introduced in the Kriging interpolation technique.

Fitting (Rush and Edwards, 1976) uses a set of weighting functions, which are a measure of the statistical dependence of foF2 between points on a sphere.

The ionospheric characteristics at two close points change in time in a very similar way. The correlation decreases with the distance between the observation points and the variogram is found to be anisotropic i.e. the variogram is different in distinct azimuths. The correlation radius, which is the distance between two points for which the correlation of the ionospheric characteristic changes by 0.5, is adopted to parameterise this propriety. In some methods the full correlation function, called weighting function, is used (Rush and Edward, 1976). One of the disadvantages of the method is the fact that the resultant function does not pass through the input point values. For COST 251 applications, Juchnikowski and Zbyszynski (1992) modified the Rush-Edwards interpolation method to obtain more desirable results.

It is well known that the weak point of every mapping procedure is generally the number and/or the distribution of measurement locations, which may be insufficient for the production of fully accurate maps, even over a restricted geographical region. It may not allow describing gradients properly. To constrain results to physically realistic figures, deviations from monthly median predicted values are modelled. It has been demonstrated that this technique smoothes out many discontinuities (Stanislawska and Juchnikowski, 1997). Three or four data points allow constructing a map with acceptable precision.

Comparisons with measurements have shown that the accuracy achieved by both methods is almost the same. Nevertheless the modified Kriging algorithm is better for foF2 (method PLES2), while fitting is better for M(3000)F2 (PLES5). So that both methods have been combined (PLES2 for foF2 and PLES5 for M(3000)F2) to produce the COST 251 instantaneoüs mapping model for ionospheric characteristics.

4.3.2. Method for instantaneous values of TEC

Instantaneous values of TEC maps are gained by using the COST 251 electron-density height profile in its «instantaneous» mode and numerical integration along vertical or slant rays.

4.4. The COST 251 forecasting procedure

The COST 251 forecasting procedure is based on the auto-correlation procedure CORLPREV developed by Muhtarov and Kutiev (1999) in the framework of the Action. A network of 23 vertical-incidence ionosondes provides the basic inputs. Mapping is possible for the area extending from 10° W to 90°E and from 30° to 70°N, which includes the COST 251 region. Data are currently updated every 24 hours on weekdays.

The difficulty is that good statistical estimates of the autocorrelation function require very long observation periods. This is impractical since the underlying physical processes are not stationary over long periods of time. In order to avoid this, a predetermined shape with a finite number of parameters is imposed to the autocorrelation function. These parameters are chosen in such a way that diurnal variations and medium-term decorrelation of the ionospheric characteristic of interest are well represented. A time period of 20 days is used for the calculation of the empirical autocorrelation function. Tests at a variety of locations have demonstrated that the autocorrelation method performs substantially better than using regularly updated monthly median values. It is clear that this method will break down at the onset of ionospheric storms, as it cannot have prior warning of disturbances. However it has turned out to be surprisingly robust in disturbed conditions. The autocorrelation method is applied to produce forecast values of foF2 and the F2-layer basic MUF for a 3000 km range (MUF(3000)F2) at integer hours UT up to 4 days ahead at each vertical-incidence station when sufficient measurements are available. This is necessary to ensure a forecast for up to 24 hours ahead is always available, despite weekend's difficulties. Values from the past 60 days are used to construct an autoregressive filter.

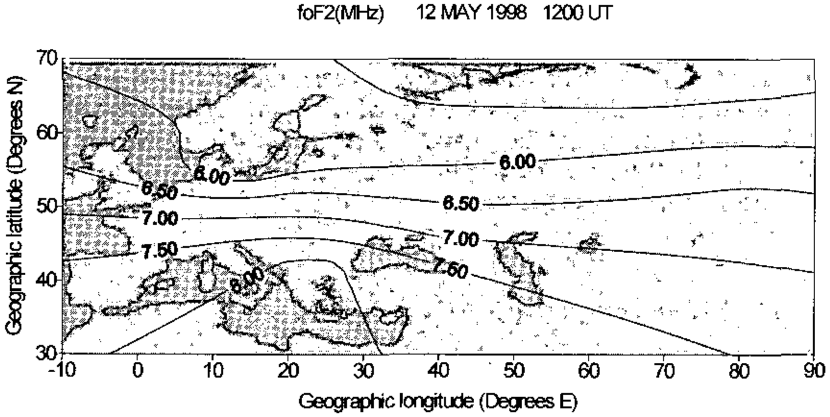

Figure 5. Map derived from 24 hours ahead forecast of foF2 for 12 May 1998 at 1200 h UT.

Forecasts maps of foF2 and MUF(3000)F2 are drawn using a commercial package with a Kriging option, which is particularly suitable for contouring sparse data (Fig 5). An operational forecasting tool is available on the World Wide Web for interactive use (http://www.rcru.rl.ac.uk/iono/maps.htm). CORL-PREV software is available at Space Research Centre, Warsaw (Poland), from anonymous ftp://haydn.cbk.waw.pl (see Section 8).

4.5. Other studies and models

Within this line of activities studies were conducted first of all on the development of models relevant to ionospheric telecommunication applications for the COST 251 area. In this Section these models are briefly described and the main achievements of different studies are reported.

4.5.1. Monthly median ionospheric characteristics foF2 and M(3000)F2

4.5.1.1. Ionospheric Single Station Models

As it is generally accepted, ionospheric Single Station Models (SSM's) give the most accurate representation of the modelled ionospheric parameters in the immediate vicinity of an ionospheric station. For this reason SSM's can be used in several applications, as, for instance, filling data gaps, either retrospective data gaps of active stations with long enough series of measurements, or to extend the series of values of closed stations, while a secular variation is not foreseen. Another important use is to produce screen points for mapping ionospheric characteristics. The work has been done as follows: i) to produce new SSM's, ii) to compare them with the previously produced models during the COST 238 project and iii) to use them in ionospheric mapping.

Two new foF2 models were produced. Xenos et al. (1996) use a quadratic regression between monthly hourly median values of foF2 and the Aristotelian University ionospheric S-index. Solé (1998) model introduces a geomagnetic dependence. This model is based on a statistical second degree multiregression between foF2, the monthly ionospheric T index and the monthly geomagnetic index Ap.

These models and the ITU-R model have been compared with the models produced in the COST 238 project and tested with data from 22 ionospheric stations that cover the whole COST 251 area (Alberca et al., 1998). As expected, the SSM's give better results than global models. The best results are produced by Solé's model and the model of Mikhailov and Mikhailov produced during COST 238 (Bradley, 1995). The results of both models are very close, but those of Solé's model are the best. A prediction of the Ap magnetic index may be needed to make use of this model. To achieve this, a neural network procedure was introduced in the model, obtaining the index with an error of

25%. Furthermore, Solé et al. (1999) have drawn attention to the fact that the dependence of the Ap index on the results of the model is not high. It is found that a 30% error in the Ap index affects the final result of foF2 in only 0.1 MHz in average. With this Ap index prediction program, Solé's model can be adopted to predict foF2. Consequently, the model of Solé is the SSM of foF2 recommended by COST Action 251.

Besides the foF2 SSM's, three M(3000)F2 SSM's have been produced. Mikhailov et al. (1996) model use a second degree relationship between M(3000)F2 and R_{12}. Solé (1998) utilises the same algorithm for M(3000)F2 that the one for foF2. Xenos and Alberca (1999) use neural network technique for M(3000)F2. Most of the values are predicted with less than 5% error.

4.5.1.2. ISIRM (Improved Simplified Ionospheric Regional Model)

ISIRM is a regional model of the ionospheric characteristics foF2 and M(3000)F2, evolved by SIRM (Simplified Ionospheric Regional Model) (Zolesi et al., 1996) and applied to a more extended area taking into account the consequences of high latitude region. The model is based on the Fourier analysis of the monthly median values of the ionospheric parameters measured at the stations in the European and near East regions and collected under the COST 251 project. The first step of the procedure is the linear regression analysis of the monthly median values of a given ionospheric characteristic against the solar activity index R_{12}. The second step is a Fourier analysis of the data for two fixed values of $R_{12} = 0$ and $R_{12} = 100$. In order to better reproduce the monthly behaviour the Fourier analyses were performed month by month instead of along the two virtual years of the two solar epochs.

The improved SIRM model is still a very simple procedure, not only for its easy mathematical formulation and for the reduced number of numerical coefficients, but above all for the short software program that can be easily used and linked with other software procedures.

4.5.1.3. ILCNN (Ionosphere Local Copy by Neural Network)

ILCNN is a neural network procedure designed to model and predict the monthly median foF2 and M(3000)F2 over the COST 251 area (Lamming and Cander, 1999). A multi-layer perceptron trained with back-propagation is adopted. The number of hidden units is 16 and 9 on first and second hidden layers, respectively. It is well known that the knowledge of a neural network is contained in its weight. These weights are on each input of all hidden units and all output units. The aim of the back-propagation algorithm is to find the weights. To implement the ILCNN model, only the architecture of the neural network, the weight coefficients, sigmoid function and normalised functions are needed.

4.5.1.4. MQMF2

The MQMF2 method for the monthly median foF2 and M(3000)F2 uses the same SSM and interpolation procedure as in the method MQMF2R described in Section 4.1.1 but the solar activity index in MQMF2 method is MF2 instead of R_{12}.

4.5.1.5. PLES1 and PLES2 (Poland *PL* Spain *ES*)

PLES1 and PLES2 are the implementation for monthly median modelling of the approach described in Section 4.3.1. These methods involve the generation of SSM achieved by Solé's procedure (Solé, 1998). The model requires the monthly averaged Ap and T indices as input for SSM's calculations. The values created by SSM's are interpolated for the whole COST 251 area with the modified Kriging technique (PLES2) or with fitting (PLES1). Different responses to geomagnetic disturbances can be taken into account with the inclusion of the Ap index. This index can be successfully used for retrospective modelling when Ap index is known. However for long-term prediction the difficulty of sufficient accuracy in its predictability nowadays should be noted.

4.5.1.6. SWILM (Space-Weighted Ionospheric Local Model)

SWILM is a technique for modelling the foF2 monthly median, which uses past data series and the R_{12} index. Two sets of coefficients are calculated by linear relations between foF2 and R_{12} for 20 stations in the COST 251 area, for each month and for each hour. From the two set of coefficients and from given values of the input parameter R_{12}, the foF2 monthly medians are calculated for the period 1957-1996, for each station of the database, for each month and for each hour. The 20 stations are then assembled in different sectors depending on the latitude distance from the location where predicted values of foF2 have to be calculated. Each sector has a width of 5 degrees in latitude. The predicted foF2 values are finally based on the values of foF2 coming from different sectors, opportunely weighted on the spatial scale.

4.5.1.7. UNDIV

The UNDIV method for modelling the foF2 monthly median use the same procedure as described in Section 4.1.2 for M(3000)F2. A parabolic regression for the R_{12} dependence of foF2 is adopted. Three level values of monthly medians were calculated from the regressions for three R_{12} levels (35, 85 and

135). The results are 12 x 24 x 3 level values per station for foF2. Bilinear regressions for each R_{12} level, for each month and for each hour (LT) are derived.

4.5.1.8. SAILT

SAILT is an empirical model of foF2 for the 35(-70° latitude belt during quiet and disturbed conditions (Eliseyev and Besprozvannaya, 1998). The model is based on a statistical analysis of multiyear observation at the vertical-incidence sounding network. The level of the noon foF2 is approximated by product of two functions. The foF2 for other hours are related to the noon value by a simple dependence:

$$foF2 = K_i \cdot foF2_{12}$$

The values are obtained by interpolation between tables of coefficients.

4.5.2. Models for Total Electron Content

The regional TEC model NTCM (Neustrelitz TEC Model), produced at DLR/DFD Fernerkundungsstation Neustrelitz (Germany) from GPS measurements, has been improved and updated (Jakowski, 1998, 1999). Two versions of the model were developed and applied to map construction.

NTCM 1 The algorithm includes fundamental ionospheric variations and solar activity dependence. The coefficients of the model are based on TEC-Faraday rotation data obtained at the European stations Neustrelitz (Germany), Graz (Austria) and Florence (Italy) during the years 1976-82.

NTCM 2 This version compared with NTCM 1 includes additionally a geomagnetic latitude dependence term. The coefficients are taken from GPS derived TEC maps over Europe obtained from February 1995 until January 1996.

An evaluation has been made of the global *rms* error, given by:

$$\sigma = \left(\frac{1}{N} \sum_{i=1}^{N} (p_i - m_i)^2 \right)^{1/2}$$

where N is the total number of samples, is the value predicted by the model for sample i and is the measured value for sample i. The *rms* error of NTCM 2 was less than 1 x10^{16}m^{-2} for 1995 (Jakowski et al., 1998b). It is clear that this model provides high accurate TEC data over the COST 251 area for low solar activity condition.

4.5.3. *Methods for instantaneous values of foF2, M(3000)F2 and TEC*

4.5.3.1. MQMF2-IM

The method MQMF2-IM for foF2 and M(3000)F2 instantaneous mapping uses the following: (i) SSM's for foF2 and M(3000)F2, (ii) screen points inside the area, (iii) effective hourly MF2$_{eff}$ and R$_{12eff}$ indexes, (iv) buffer zone, (v) main ionospheric trough model and (vi) multiquadric method for spatial approximation.

The ionospheric index MF2 is used to find the foF2 relationship with solar activity. However for modelling M(3000)F2 the index R$_{12}$ is adopted as it provides better regression accuracy.

SSM model may be used to produce foF2 and/or M(3000)F2 screen point value if the nearest available current observation is located further than 10(in longitude and 5(in latitude. In the areas with sparse ionosondes additional screen points are introduced with the ITU-R model.

A buffer zone of 45 points is defined as a constraint to avoid unrealistic behaviour of foF2 and M(3000)F2 along the boundary of the area. Local MF2$_{loc}$ indices are derived for each ionosonde location from the observed foF2 values to draw a MF2 surface over the area with the multiquadric method for spatial approximation. MF2$_{eff}$ values for the buffer zone points are deduced from the regression of MF2$_{12}$ versus R$_{12}$. This is possible with a minimum of 3 observed values of foF2. If this condition is not met, the MF2$_{eff}$ for previous hours (or monthly median value) may be used. In the same way, an effective index R$_{12eff}$ is adopted as the input to the M(3000)F2 SSM's and for the buffer zone to calculate foF2 and M(3000)F2 using the ITU-R model. This index R$_{12eff}$ is deduced from the minimisation of the standard deviation for the calculated foF2 with respect to the observed ones over the whole area in question for all integers UT. Effective R$_{12eff}$ index is used as input to the ITU-R model in the buffer zone.

The main ionospheric trough model based on COSMOS-900 and InterCOSMOS-19 satellite observations developed in IZMIRAN, Russia (Annakuliev et al., 1997) is introduced in the model optionally (Mikhailov et al., 1998).

4.5.3.2. PLES3 and PLES6 (Poland *PL* Spain *ES*)

PLES3 and PLES6 are two other versions of the recommended COST 251 instantaneous mapping method described in Section 4.3.1. In those methods the mid-latitude trough model is introduced, as well as SSM's, developed by Solé (1998), which supplemented the monthly median model. The trough model supplies additional screen-points for map construction. The model of the mid-latitude trough, described in Section 4.5.12, has been included in PLES3 only, where the interpolation procedure is the modified Kriging. PLES6 make use of SSM's and fitting.

4.5.3.3. SAIM

The objective was to develop a method which can provides maps of foF2 even in situations when foF2 observations are available only from 1-3 ionosondes (Eliseyev and Besprozvannaya, 1998). An effective level of solar activity is evaluated by the analysis of the noon data from the previous days. Real time ionospheric data are then introduced. As a replacement of the Kp-index, an effective Kp value is estimated from the experimental data in order that the predicted foF2 value is equal to the observed one at the ionospheric station. The trough position and the effective Kp are given by monitoring the equator-ward diffuse auroral boundary.

4.5.4. Instantaneous model for electron-density height profile

A neural network scheme was proposed by Stanislawska et al. (1999b) for the generation of an instantaneous model for electron-density height profile. Instead of a direct prediction of this profile it was proposed to predict the ionogram which is unambiguously connected with the profile.

The model derives from a feed-forward multi-layer structure. A predetermined profile formula is established to describe past profiles obtained at the location of interest. The training process uses eleven points on the trace of a set of previously recorded typical ionograms. The final profile formula is developed step-by-step by an iterative process. The neural network is used as a universal approximate connecting the profiles with five characteristics parameters of the ionogram. The same parameters are then used as inputs when the training process ends up with a profile formula that is best fitted to the set of training profiles.

4.5.5. Forecasting procedures

Within the framework of this COST 251 activity there are a number of forecasting procedures relevant to ionospheric telecommunication applications. A major thrust of the work has been the application and development of non-linear techniques to improve ionospheric forecasting capabilities.

The DERA (United Kingdom) Ionospheric Forecasting Service neural network model can provide predictions of the hourly variation of foF2 from 1 to 24 hours ahead. However, the operational package of the model has been designed in such a way that it would be a simple matter to incorporate predictive models for additional geophysical parameters into the same framework.

A neural network based stand-alone model with intrinsic inputs has been developed by Tulunay et al. (1999) to forecast foF2 one hour in advance. In this research, the feedforward multilayer perceptron neural network was preferred as architecture. Standard back-propagation algorithm was adopted.

A method for foF2 prediction from 1 to 24 hours ahead has been produced at the Atmospheric Sounding Station «El Arenosillo» (Spain) by Mikhailov et al. (1999). This method is based on a multi-regression of deviation of hourly foF2 from running median with the previous observations and Ap index. Special procedures have been developed by Marin et al. (1999) to predict foF2 during severe storm periods with lead times larger than 3 hours. The method comprises the basic version of the method to be used during quiet time and moderately disturbed conditions with switching to a special mode to predict during strongly disturbed periods.

Finally, the COST 251 forecasting procedure for estimating values of foF2 and M(3000)F2 has been extended to include forecasts of TEC over Europe (Cander et al., 1999).

4.5.6. Merit of ionospheric indices

Research in this field was carried out with the double aim of characterising both the relationships between indices and also seasonal changes. Separate cubic polynomial relationships have been derived between R_{12} and MF2 indices for each month of the year and for the up-going and down-coming half solar cycles, but adopted figures are those for both half cycles combined. A simplified linear relationship in terms of R_{12} has been proposed for use with these past MF2 for input to mapping codes which are specified in terms of R_{12}, since in some cases the alternative use of the cubic relations would result in inconsistencies and would not be possible. Small systematic seasonal changes in MF2 have been detected but such features are absent in the cases of R_{12} and T indices. The reasons for these effects are currently not clear, but are believed to be related to the fact that MF2 is given entirely from Northern hemisphere measurements, whereas T is based on measurement data for both hemispheres. This aspect is subject to further review, but it is suggested these seasonal changes are not important since they are compensated in the way the foF2 regression relationships are determined.

As far as indices for use in short-term ionospheric predictions were concerned, three separate investigations concerning can be reported: (i) Perrone and De Franceschi (1998) have reviewed the most common solar, ionospheric and geomagnetic indices with particular reference to their application for radiocommunication predictions purposes, (ii) Bencze et al. (1998) have undertaken studies to derive a daily MF2 index which is perturbed from the monthly value by an exponential function which depends on neutral density change due to geomagnetic activity as characterised by the Kp index and (iii) Muhtarov and Kutiev (1998a) have developed a similar type of index as the basis of a new short-term prediction method in which regular monthly median variations of a given ionospheric characteristic are corrected by a factor which depends linearly on the associated auto-correlation function expressed in terms of Kp.

4.5.7. Long-term trends of ionospheric change

Studies in the area dealt with long-term trends observations of different ionospheric parameters (Bencze et al., 1998; Bremer, 1998, 1999a,b; Danilov and Mikhailov, 1998; Lastovicka, 1997). Here mainly ionosonde data have been analysed considering the following two main problems: a) Are there marked trends in the ionosphere which could be important for the ionospheric HF propagation and its prediction? b) Are there trends which are connected with anthropogenically caused atmospheric influences (e.g. greenhouse effect)? In the frame of the COST 251 project the first problem is more important whereas the second problem is a general scientific and also political question. For the investigation of the second problem also some additional ionospheric and atmospheric parameters have been analysed.

It has been shown that the detected ionospheric trends are relatively small compared with the solar and geomagnetic influences. Therefore, during the next years it is not necessary to take into account their influences on the ionospheric HF radio propagation. Nevertheless this effect has to be carefully monitored in the future. Especially it should be noticed that the scientific problem of a possible increasing atmospheric greenhouse effect requires further investigations. Mainly in the F2 region the results of the trend analyses are partly controversial and cannot be explained by the greenhouse effect.

4.5.8. Assessment of trans-ionospheric propagation

Research in this area was part of the issues concerning investigation of ionospheric propagation effects on radio systems used for navigation, geodesy and radio-astronomy. Propagation effects due to background ionization (retardation, dispersion, plane-of-polarisation rotation and absorption) and due to irregularities (scintillation) were analysed and prediction techniques produced.

Attention primarily focussed on day-to-day variability. Due to complex solar-terrestrial relationships ionospheric parameters such as the peak electron density and TEC show a rather high day-to-day variability due to a strong competition of various processes. Variability studies for TEC have been carried out, especially on the basis of the high resolution Faraday data that were gained between 1978 and 1989 at Florence (Italy). It turned out that equivalent slab thickness can be used to transfer the variability information for foF2 in the following way: a) calculate peak electron density from foF2 and b) multiply peak electron density with model values of slab thickness and use the result to assess variability of vertical electron content. This scheme is proposed for the future because it is not possible to replace the high resolution Faraday data by GPS-TEC.

The second topic on which attention was focused was the study of storms. During storms TEC data indicate large deviations from the mean behaviour up to 200% (Jakowski and Schlueter, 1999). The statistical study has revealed significant differences in the temporal development between Summer and Winter storms. To study the ionospheric variability in terms of TEC, a *rms* analysis has been carried out referring to a mean diurnal TEC variation. The absolute *rms* values range from about 1- $4x10^{16}m^{-2}$, whereas the highest values appear at lower latitudes probably due to the higher absolute level of TEC at day-times. The percentage deviations range from about 20% at lower latitudes up to 60% in auroral latitudes. No significant longitudinal effect appears. Using global or regional permanent operating GPS ground station networks (e.g. that from IGS) it is suggested that the derived TEC maps may be used to study large scale structures in electron density and their movement during ionospheric perturbations. Thus, both individual storm characteristics of the geomagnetic/ionospheric storms as well as common features derived from statistical studies can be analysed.

The generation of TEC maps allows also the computation of *rms* maps over the European area. The application of such maps to find out areas of particular variability was considered. GPS based TEC monitoring can effectively be used to study large scale ionospheric perturbations.

4.5.9. Prediction of the F1 layer occurrence and «L condition»

The critical frequency foF1 predicted by the Du Charme formula (Du Charme et al., 1973) assumes limits for the presence of the layer as a function of the solar zenith angle and of the solar activity given by the R_{12} index. In the study undertaken in the frame of COST 251, a probability function to evaluate the occurrence of the F1 layer and «L condition» (cases where electron density profiles on the ionograms traces show a ledge rather than a remarkable cusp, so no critical frequency can be assigned to the layer) was proposed to replace the limits mentioned above (Scotto, 1999).

4.5.10. Ionospheric variability

A lot of efforts has been devoted to the establishment of statistics of the relative deviations of foF2 and M(3000)F2 from a reference level over the European region (Kouris et al., 1998; Muhtarov et al., 1999). The relative contributions of quasi-periodic oscillations from 2 to 35 days to the variability of foF2 at middle Northern latitudes in Europe have been investigated (Altadill, 1996; Lastovicka and Mlch, 1996; Altadill and Lastovicka, 1996; Altadill et al., 1998; Apostolov et al., 1998; Solé et al., 1999). The results suggest that there is a clear seasonal variation with maximum in Summer solstice and minimum in Winter one. The contributions are modulated by the solar cycle and simultaneously influenced by the long-term geomagnetic activity variations. The existence and development of the quasi-2-day oscillations in the plasma frequency variations of the F-region at Northern middle latitudes has been confirmed using a methodology that allows to do such study at fixed heights. Ionospheric quasi-periodic variability caused by gravity and planetary waves has been analysed (Lastovicka, 1999). Effects on the F-region of three types of waves, which come from below and affect the ionosphere, were considered. These waves are planetary waves (periods of days), tides (periods of 24, 12, sometimes 8 hours) and gravity waves (a few minutes to a few hours – partly coming from auroral ionosphere/thermosphere, partly coming from below).

The annual and latitudinal variations of spread F have been studied at mid-latitudes (Bencze and Märcz, 1998, 1999; Bencze and Poor, 1999). The spread F occurrence frequency has been determined. This occurrence indicates an annual variation with a maximum in the Winter months and a minimum in the Summer months like the annual variation of the occurrence at high latitudes. However, the amplitude of the annual variation of the occurrence is smaller in years of maximum solar activity than in years of minimum solar activity. It was shown that the occurrence frequency of spread F decreases with increasing geomagnetic activity, which is opposite to the situation at high latitudes. The observed latitudinal extension of the irregularities varies between ~350 km and ~1100 km.

In addition characteristics changes have been established of electron density profile in response to gravity wave upward propagation. Gravity waves propagating through the ionosphere cause a cyclic variation of the vertical electron density profile. This signature has been observed in a number of single site ionogram sequences taken at 5 minute and 15 minute intervals by Moorhead and Radicella (1998). The wavelength of the gravity waves was 600 to 2000 km. The temporal variation observed at the sounder location was translated into a spatial model of the gravity wave. Some parameters of the channel scattering function have been deduced.

4.5.11. Disturbance effects

The activities carried with this area refer to the investigation of disturbance effects on the behaviour of ionospheric parameters (Bradley et al., 1997; Bremer, 1996; Bremer et al., 1996; Davis et al., 1997; Fuller-Rowell et al., 1998; Gordienko and Kaliev, 1998; Lastovicka, 1996; Tulunay, 1996). The reaction of the middle latitude ionosphere to geomagnetic storms has been modelled empirically by Fourier decomposition (Kutiev et al., 1998; Muhtarov and Kutiev, 1998b) and an algorithm based on linear prediction filters has been developed to forecast foF2 changes related to strong geomagnetic storms (Vasilievic and Cander, 1997). The post storm effects in the D region ionisation that influences ionospheric propagated radio waves has been studied with promising results.

Special consideration has been given to high latitude disturbance effects. Direct correlation studies between geomagnetic indices and ionospheric parameters gave in the past poor results till to the introduction by Wrenn (1987) of a simple way of treating a selected magnetic index by means of a time series accumulation of the index itself. In the frame of COST Action 251, a similar analysis has been carried out but related to the high latitude stations Europe (Perrone and De Franceschi, 1999). Methods were explored to evaluate the correlation degree separately for each month of the year and for the up-going and down-coming half solar cycle. It was demonstrated especially that the correlation degree shows a clear seasonal dependence, being maximum during Summer. A better correlation was found during the rising phase of the solar cycle.

The effects of strong meteorological events on the F-region ionosphere have been studied. It seems to be developed best at heights near 200 km but affects the whole F2 region up to its maximum. It is believed to be transferred upwards by gravity waves of tropospheric origin. This gravity wave activity was found to increase remarkably after the Mt. Pinatubo volcanic eruption in the long-period range (1.5-3 hours) and to increase with increasing solar activity in the 11-year solar cycle (Lastovicka et al., 1998).

Lastly mention should be made of investigations of geomagnetic storm effects on the F1-layer.

4.5.12. Trough modelling

The main or mid-latitude trough is the main ionospheric structure at mid- and sub-auroral latitudes during nighttime. There have been a variety of techniques to observe the trough, including ionosondes, incoherent scatter and TEC, as well as satellite-borne experiments. Unfortunately the ionosonde network is not dense enough and nighttime ionograms from trough-region latitudes often suffer from disturbances. Topside sounders are a possible source of information about trough shape, but the latitudinal resolution is insufficient to define the trough morphology. Direct use of the latitude dependence of vertical TEC has provided case studies for the steepness of the walls of the trough, its width and statistical data for these parameters, but with comparatively large error margins. Relationships between the latitudinal position of the trough and local time and geomagnetic activity indices have been generated. However despite the long history of theoretical work, our knowledge is not far-reaching. Nevertheless it is very important to have reliable information on the shape of the trough in electron density at the F-layer peak for terrestrial and transionospheric telecommunications applications.

A new approach to modelling the trough has been demonstrated. This method is based on a tomographic image of the ionosphere over United Kingdom that is extrapolated to other longitudes across the European sector (Fig. 6). Initial results from the mapping were shown to compare well with observations from ionosondes located between 12 to 30(East of the tomography receiver chain (Mitchell et al., 1997). In a separate study a seasonal variation has been revealed in the latitudinal position of the trough, showing the trough to be further south during the winter than the summer (Mitchell et al., 1999a,b).

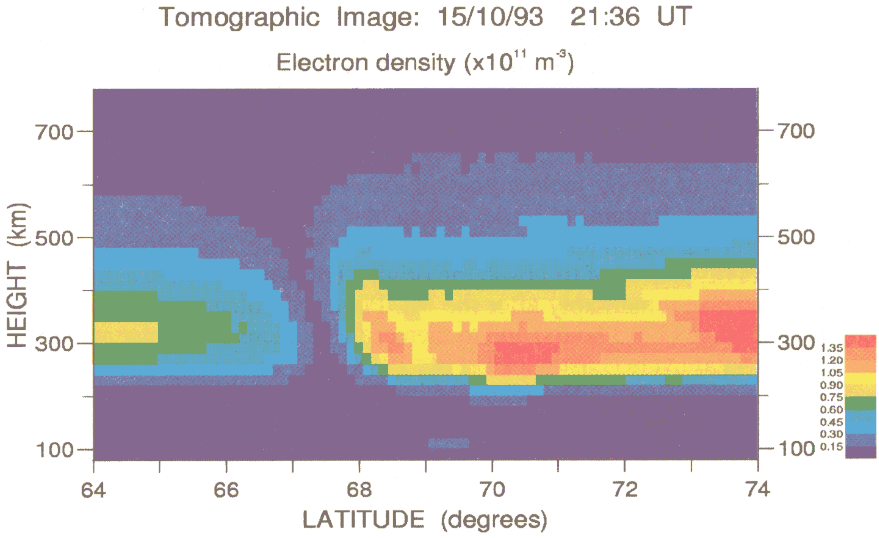

Figure 6. Model of electron density over Europe using the tomographic image from a satellite pass.

The basis for the COST 251 trough model is a combination of a small-scale trough model with a large-scale background model for electron density:

$$N_e(h, \varphi, \lambda) = M_L(h, \varphi, \lambda) \cdot T(h, \varphi, \lambda)$$

where N_e : electron density; M_L : large-scale model; T : trough model; h : height; φ : latitude; λ : longitude. A Gaussian depression could serve as one of the simplest possibilities for T. An investigation was carried out in order to evaluate the position of the trough minimum in invariant geomagnetic coordinates on the basis of a large database from the DE2 satellite (Stanislawska et al., 1999c). The shape of the trough is defined by the simplification of the mid-latitude ionospheric trough model based on European foF2 values derived from analysis of Magion-3 HF radio spectrometer data (Bradley et al., 1998). An example of instantaneous map of foF2 generated by the PLES3 procedure with this trough model during an intense magnetic storm is presented in Fig. 7. Following comparison with other models, it was demonstrated that this model is well suited for telecommunications applications (Tulunay et al., 1998).

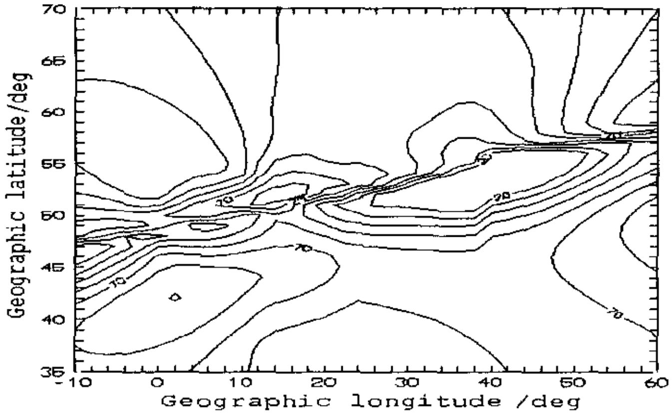

Figure 7. Example of instantaneous map of foF2 (x10/MHz) for 10 May 1992 at 2200 h UT generated by the PLES3 procedure with the new mid-latitude trough model and five measurements.

4.6. Comparison procedures and results

The overall accuracy of different foF2, M(3000)F2 and electron density profile models developed during the project needs to be assessed. In order to obtain comparable results, the same data set and the same procedure was applied when making comparisons between measurements and the results of the models. Tests were carried out independently in Bulgaria, Italy and the United Kingdom, with identical results.

Thirteen vertical-incidence ionosonde stations were selected for testing, giving good spatial sampling of the COST 251 area. For long-term mapping, monthly medians were used, while for instantaneous mappings, hourly data from the 15th day of each month were used. Quality checks on the testing databases resulted in the elimination of most of the unreliable data. For long-term mapping, months with gaps of total length greater than 15 days, or single gap of length greater than 10 days, or extreme values exceeding 20% of the total number of valid values for that month were eliminated. Hours with number of valid values less than 5 were also eliminated. For instantaneous mapping, extreme values were eliminated. A threshold probability of 0.99 was used to define the extreme values for each station.

The testing database for electron-density height profile included topside profiles obtained from COSMOS and ISIS-Alouette topside sounders and bottomside profiles from five stations in Italy, Poland, Spain and United Kingdom, obtained by inversion of vertical-incidence ionograms using POLAN (Titheridge, 1985) and ARTIST (Reinisch et al., 1988). An overall *rms* error was computed for each profile, and these were then averaged over the whole database. For bottomside profiles, it was decided to focus on the F2-layer in view of uncertainties in the inverted profiles in the D- and F1-layer.

4.6.1. Long-term mapping of monthly median foF2 and M(3000)F2

The models were ranked according to the global *rms* error. In addition, auxiliary tests were carried out to ensure a good merge with the ITU-R global mappings. The modellers were asked to supply 24 maps, in the form of a latitude-longitude grid of results (resolution 2.5(for latitude, 5(for longitude) for the COST 251 area, for a selection of months and hours. Maps were required for 0000, 0600, 1200 and 1800 h UT for the selected months. A gradient check was carried out at the borders of the maps.

Most models improve on the current ITU-R model. The gradient checks were a crucial part of the testing procedure. A number of models did not pass that test, some with very serious problems, some with minor problems only. For foF2, in retrospective mode, MQMF2 is the only model that satisfies the gradient checks and has *rms* error less than 0.5 MHz. The next best model which satisfies the gradient check is PLES1. Of the models with R_{12} input only and satisfying the gradient checks, MQMF2R has the best *rms* error. For M(3000)F2, UNDIV is the model with the best *rms* error. It also satisfies the gradient checks and R_{12} input requirements. MQMF2 is a close second.

4.6.2. Instantaneous mapping of foF2 and M(3000)F2

Again the models were ranked according to *rms* error. For foF2 mapping, the Kriging algorithms in the methods PLES2 and PLES3 perform better than the fitting algorithms in the methods PLES5 and PLES6 and give excellent results while for M(3000)F2 mapping fitting algorithms in the method PLES5 provide the best accuracy. For both characteristics the performance of MQMF2 is excellent too and has comparable accuracy. The use of the trough model in PLES3 does bring a small improvement, but requires additional input data.

4.6.3. Electron-density height profile

Comparisons have been made between the profiles obtained from COST-PROF and IRI models and measured topside and bottomside electron-density height profiles.

The COSTPROF model gives a substantial improvement over the IRI model for topside profiles on the testing database. The performance of the COSTPROF and IRI model is similar on the bottomside profiles tested here, with both models giving a very small *rms* error. However it should be noted that the IRI has some serious shortcomings in its formulation for the upper F region. One of the problems appears in higher latitudes at high solar activity. The profiles tend to acquire unrealistically large profile scale heights. Even negative scale heights appear (exponential increase of electron density with height above the F2-layer peak). COSTPROF remains realistic under all conditions, both with global (ITU-R) and regional (COST 251) input parameters.

6. METHODOLOGY FOR CHANNEL SIMULATION FOR HF SYSTEMS

The primary objective was to define a functional channel simulator architecture for HF systems in Europe. There are clear shortcomings in the Watterson model (Watterson et al., 1970) which is widely used as a basis of existing simulators, not least being the limited data on which the model was originally based. Also, the Watterson model inherently describes narrowband (approximately 3 kHz bandwidth) channels, whereas future simulators should be compatible with a range of system bandwidths up to at least 1 MHz, corresponding to a time resolution of 1 microsecond.

A new basic structure for the realisation of a channel simulator on general purpose DSP-boards has been produced (Van der Perre, 1997; Van der Perre et al., 1997). The functional elements of the simulator are specified in such a way that a complete range of channel types, appropriate for HF transmission system testing up to bandwidths of at least 1 MHz, can be implemented. In addition, a Watterson model may be simulated, if required. Consideration was given to the applicability of a replay-type simulator in the COST 251 context. In general, it was felt that this did not provide an appropriate basis of flexibility for the range of applications envisaged. However, for unpredictable events such as high latitude disturbances, it would be possible to incorporate replay segments into the overall time profile of the simulator test program.

7. MODELS FOR USERS FOR OVERALL PERFORMANCE PREDICTION

7.1. General propagation modelling

Research activity concerning general propagation modelling was oriented above all towards producing simulation tools for overall performance prediction. Numerical methods for the modelling of HF radio wave propagation in the real ionosphere has been developed (Gherm et al., 1998a). The term «real ionosphere» is understood to describe a medium with three dimensional slowly-varying electromagnetic properties of the background and time dependent inhomogeneities as well as deterministic and random inhomogeneities, including extra bending of rays, multi-ray effects and diffraction effects. These methods are based on the complex phase method for wave propagation in a slowly varying media with local inhomogeneities embedded.

Special attention has been given to the problem of the HF fluctuating channel characterisation in the case of frequencies close and above the MUF. This particular situation of a skip field is described by a specifically developed wave field integral representation in terms of diffracting component waves (Gherm et al., 1998b, 1999). In addition the technique has been developed for modelling large-scale ionospheric structures with the horizontal gradients of the ionospheric electron density. Research activities on propagation modelling involved also the construction of a computer code to take into account the movement of the main ionospheric trough.

7.2. F2-layer basic MUF variability

In the highly congested HF band the signal quality generally increases as the frequency approaches the MUF. HF propagation predictions procedures such as that of Recommendation ITU-R P.533 (ITU-R, 1995) can provide guidance on the expected performance of circuits. These procedures are based on average behaviour of the ionosphere and should not be expected to give information beyond their statistical capabilities. It should be noted that generally operators and frequency managers tend to select frequencies, which are anywhere from 65 to 90% of the predicted MUF. If models should provide a better prediction of the distribution of the daily MUF's around the monthly median MUF, then it might be possible successful operation at frequencies closer to the predicted MUF. This would be very advantageous for spectrum occupancy since it would widen the available bands for use, especially during periods of low solar activity. Furthermore the evaluation of the MUF variability may facilitate improved frequency sharing in HF terrestrial systems.

The variability of the basic MUF (i.e. the highest frequency by which a radio wave can propagate between given terminals, on a specified occasion, by ionospheric refraction only) with path length has been investigated by Bradley et al. (1998). It has been found that the upper decile deviation from the median usually increases slightly with distance whilst the lower decile deviation falls, but changes are relatively small. One of the key aspects treated was the establishment of bounds for the relative magnitudes of the day-to-day variations in foF2 and M(3000)F2 on quiet and disturbed days and how these change with season, location and solar activity (Fotiadis and Kouris, 1998). The day-to-day variation of the basic MUF have been compared with those of foF2 and M(3000)F2 (Kouris et al., 1999). Tables of values for both the ratio of the upper and lower decile values to the median basic F2-MUF have been provided. The F2-layer basic MUF variability may be evaluated for the COST 251 area from these new reference figures, which are slightly different from those given in CCIR (1980).

7.3. Statistical characterisation of HF channel

The statistical characterisation of the behaviour of the transmission channel was an important topic of research. Since ionosphere varies with time, space and frequency in many scales, this task was not a trivial activity. Different approaches to describe the scattering function were studied (Gherm and Zernov, 1998; Zernov et al., 1999) and methods to statistically analyse and characterise the variations of the HF channel response have been developed (Arikan and Erol, 1998; Arikan, 1999).

Since most of the widely available data sets consist of vertical- or oblique-incidence sounding data, characterisation parameters can be extracted from such data sets utilising only the amplitude information of received single tone signals. By the proposed methodology, robust estimates to time varying mean and variance of the channel response is obtained. For this purpose, sliding window statistics of the available data is used. In applying the sliding window statistics, the window size is chosen as long as possible to provide better estimates and still short enough to capture the underlying time variation of the channel response. Based on the estimated variance of obtained results, detailed justification on the proper window size is given. In order to obtain more reliable estimates, the data is median filtered prior to statistical analysis. This new statistical analysis approach is applied to available data obtained from measurement campaigns. The results of the statistical analysis confirmed the expectations on the physical behaviour of the ionospheric channel. It was found that the midlatitude single frequency channel is slowly time varying and locally stationary in a sliding window of 22 seconds. It was confirmed that during early morning hours and night hours, the channel is considerably more stable for communication purposes compared to day and early evening hours.

When considering the establishment of efficient and reliable communication links through the ionospheric channel, scattering function and other channel coherence functions are usually computed and examined. Two major alternatives were considered for the numerical computation of these functions. In the first method, this is achieved through the estimation of the autocorrelation of channel impulse utilising the transmitted and received signals from controlled experiment response (Arikan and Arikan, 1997). In the second suggested method, estimation of the HF channel impulse response is the first step and the scattering function is computed utilising the channel response (Arikan, 1998, 1999).

After assessing the efficiency, performance, computational complexity and cost of these methods in estimating the HF channel response, it is concluded that Kalman Filter estimator with proper adaptation provides the best estimate. Thus a methodology was developed to estimate time varying, fading, multipath HF channel response numerically through an adaptive Kalman Filter based channel estimator utilising the data from controlled experiments (Arikan, 1998, 1999). Major advantage of adaptive Kalman Filter based channel estimator is that it can efficiently track the variations in the channel response. Thus the physical model of the channel can be incorporated into the estimator. This capability does not exist in other methods. Adaptation of the Kalman Filter to the variations in the channel response has been implemented at various levels and scales especially at the initialisation and parameter adaptation. Based on simulations of HF channels under good, moderate and poor ionospheric states and for Signal to Noise Ratios (SNR) from 10 to 40 dB, it has been observed that adaptive Kalman Filter converges faster for lowest error not only for good and moderate conditions and high SNRs but also for poor ionospheric state and low SNRs. Thus the suggested adaptation significantly improves the performance of the standard Kalman Filter estimator.

7.4. Modelling of HF spectral occupancy

Measurements of HF spectral occupancy allowed the development of (i) low- and high-angle occupancy over Northern Europe and (ii) variation of occupancy with azimuth (Economou et al., 1998; Pantjiaros et al., 1998).

The logit model, with the appropriate model index function y_k, forms the Laycock-Gott model for estimated congestion Q_k for ITU frequency allocation k (Pantjiaros et al., 1997). The index function y_k of the parameters on which occupancy depends is determined by statistical analysis of the experimental data. For each receiving site, estimates of y_k are determined for each of the 95 ITU frequency allocations, and the variation of these 95 index functions with frequency is then modelled, to give a single model index function applying to the entire HF spectrum. By developing the same form of model for each site, and comparing the coefficients of the parameters of these models, a single model for four sites is derived by attributing differences in measured congestion values to differences in the locations of the receiving sites. The fitting procedure attempts to model the systematic component of the data, whilst allowing for the random component. This gives a model which is better able to predict future values of occupancy, and which may be developed readily by the inclusion of additional measurements.

7.5. Real Time Frequency Management

Developments in the availability of flexible and rapidly-controllable equipment, in broad band antennas and in the regulatory environment now permit the economic possibility of adaptive HF systems to provide high performance using real time frequency management. Studies within this COST Action have been concerned with aspects of the control algorithms, models and diagnostic measurement methods to enhance the frequency management function.

There is now an increasing need to provide high data rate communication and the overall utilisation of the spectrum will be enhanced by consideration of adaptivity in the modulation waveforms and data rates in response to the characteristics of the channel transfer function.

The topics considered during the COST Action relevant to this subject were the following.

1. The effective use of ionospheric sounding with very low powers has been introduced, thus minimising the interference caused by the necessary diagnostic measurements
2. The probabilistic modelling of interference was undertaken. This work may be used within the frequency selection algorithm.
3. Techniques for the measurement of the scattering function, based on the spreading of signal delay and Doppler or on a fractal measurement of the function, have been developed and should lead to statistical models.
4. Short-term forecasting (hours ahead) and very short-term forecasting (minutes ahead) has been considered. In particular, methods of data fusion and a neuronal approach were considered which enable estimates of interference to be made.

8. THE COST 251 COMPUTER PROGRAMS

Seven computer programs (Table 1) have been prepared to provide predictions in accordance with the recommended procedures (Stanislawska et al., 1998). The calculation related either to results for different times at a single chosen place, or as maps over a specified area at a single time. Locations and maps may be anywhere in the world, with interface as appropriate to the ITU-R global maps of ionospheric characteristics and to the IRI electron-density height profile model. The computer programs are available from anonymous *ftp://haydn.cbk.waw.pl.*

Table 1: *List of programs and output parameters available from anonymous ftp://haydn.cbk.waw.pl.*

Program name	*Author/Organisation/ Country*	*Ionospheric characteristic*	*Prediction*
MQMF2R	A. Mikhailov, Institute of Applied Geophysics, Russia	foF2	Long-term mapping
UNDIV	R. Leitinger, University of Graz, Austria	M(3000)F2	Long-term mapping
PLES2	I. Stanislawska, Space Research Centre, Poland	foF2	Instantaneous mapping
PLES5	I. Stanislawska, Space Research Centre, Poland	M(3000)F2	Instantaneous mapping
COSTPROF	R. Leitinger, University of Graz, Austria	electron-density height profile	Long-term mapping and instantaneous mapping
COSTTEC	R. Leitinger, University of Graz, Austria	TEC	Long-term mapping
CORLPRED	I. Kutiev, Geophysical Institute, Bulgaria	foF2	Short-term forecasting

9. CONCLUDING REMARKS AND FUTURE ACTIVITIES

COST 251 has undertaken and completed a large variety of tasks. The primary objective of the project was to recommend improved procedures to improve quality of ionospheric telecommunication systems planning and operation in Europe. Major advances have been obtained in ionospheric and plasmaspheric modelling and system performance prediction under normal and disturbed conditions. The results obtained during the Action can be applied directly to operational use. The Final Report, based on material provided by 34 contributing authors within this Action, is edited by Hanbaba (1999) and published by the Space Research Centre, Warsaw, Poland. It is anticipated to announce that the new procedures will meet users requirements and will be adopted for a long time.

Co-operation within COST has provided efficiency and informality of the co-operation with other scientists beyond the political and administrative confines of Europe. Participants gave emphasis on specific themes following their own expertise and interest but with an application oriented goal. It should be noted that COST insures a cross fertilisation of ideas and working together in a larger group to provide faster progress on a greater number of fronts than one country could manage alone. It was recognised that the COST framework is the only framework to develop this research independently of economical interests. Only the scientific interest and the potential future applications were the key factors. The added value in carrying out research under the COST framework is first of all the establishment of new networks. The collaboration established during COST 251 permitted the establishment of viable combined teams with sufficient size and resources and enlarged the collaboration between institutes in European Countries, stimulating research in many of them.

Taking into account the new horizons of Earth-space systems development including that interests Europe a more careful definition of the upper atmosphere structure and variability particularly in its topside region is needed. Such definition is an important basis for a COST Action oriented towards the evaluation of the upper atmosphere effects on the advanced Earth-space communications systems including navigational systems and LEO and MEO satellites constellations. Consistent with this, a four-year follow-on Action «Effects of the upper atmosphere on terrestrial and Earth-space communications» has been proposed with the following objectives: (i) to perform studies to influence the technical development and the implementation of new communication services, (ii) to develop methods and algorithms to predict and to minimize the effects of ionospheric perturbations and variations on communications, (iii) to collect additional and new ionospheric and plasmaspheric data for now-casting and forecasting purposes and (iv) to stimulate further co-operation in the domain of ionospheric and plasmaspheric prediction and forecasting for terrestrial and Earth-space communications, including interactive repercussions on the corresponding standards in this field, taking into account users present and future need.

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