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Evolution of the ionospheric mapping and modelling during the last four decades

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ABSTRACT

Since the beginning of the ionospheric discovery, ionospheric mapping and modelling has been the subject of an intense and continuous work by geophysicists and radio-users with the aim to understand better our environment and to improve diversity of applications in radio-propagation. The evolution in the last four decades of these studies, from HF system design, circuit planning and performance predictions to real-time control of the ionospheric parameters for space weather purposes and Earth satellite communications, has been reported here by a short review of the principal and accepted methods. Changes of the needed applications, from global to regional modelling and from long to short-term or even instantaneous and now-casting mapping, connected with rapid progress of the computer systems have been considered too.

Key words: Ionosphere, Modelling, Mapping, Prediction, Forecasting.

1. INTRODUCTION

The impact of solar phenomena and associated geomagnetic, magnetospheric and ionospheric activity on the near-Earth space environment is an important topic in geophysics. Terrestrial and Earth-space telecommunication systems, electric power networks, geophysical exploration, spacecraft control and scientific research campaigns are highly affected by solarterrestrial activity (e.g., Allen et al., 1989; Boteler, 1990; Gorney, 1990). Terrestrial ionosphere is a cold magnetised plasma environment enveloping the Earth which behaviour is strongly influenced both by magnetosphere above and by the neutral atmosphere below. Together with the ionospheric aeronomy, the highly variable electric current in the ionosphere and magnetosphere, connecting into currents in interplanetary space that are carried by the plasma of the solar wind, and their associated electric fields have a strong impacts on the ionospheric structure and dynamic (Richmond, 1995).

In all ionospheric modelling studies, there have been two distinct developments under way. The first focuses upon efforts to improve existing physical, empirical and semiempirical models beyond their climatological level (Sojka, 1989). The second is associated with the realtime use of data resulting from improving techniques for solarterrestrial monitoring (Cander et al., 1999). Considering the evolution of the ionospheric mapping and modelling during the last four decades in this paper, an attempt is made to answer the following three questions: (1) What maps and models are available for ionospheric long-term prediction and short-term forecasting, mainly propagation, purposes, (2) What research efforts are needed for the improvement of such maps and models, and (3) Are these maps and models still needed?

The paper presents a subjective view of past, present and future ionospheric prediction and forecasting mapping and modelling from the perspective of their evolution during the last four decades. After the introduction, long-term mapping and modelling are presented in the next section together with a brief outline of the data analysis techniques. Section 3 discusses the main results from the study of the mapping and modelling with short time horizon. Results support the view that day-to-day F region ionospheric variability is essentially altered during very disturbed conditions and therefore the consequences of those effects for short-term modelling purposes are discussed. A possible way to transform the existing global, regional and/or local maps and models to the service products and develop the new ones is discussed in section 4. It describes also developments in our ability to forecast the potentially damaging space weather events. Generally, it is concluded that the model should be time-dependent with input parameters that must be determined directly from local observations. Local, real-time observations applied to regional models are necessary. Then, by combining the physical and regional models, ionospheric prediction and forecasting will be substantially improved. Only necessary references are given to complete the paper.

2. LONG-TERM MAPPING AND MODELLING

Long-term prediction of the selected ionospheric characteristics constituted in the last decades the first and principal step for every performance prediction method of the HF radio systems. These predictions needed for radio system design, for circuit planning and frequency management were based on the analysis of long series of monthly median or mean values correlated with the level of solar activity indices. Usually geophysicists and radio- users have considered the median monthly conditions of the ionospheric characteristics as reference for the normal or quiet ionosphere. However, this is not exactly true. Firstly, because this parameter was introduced by radio users to make sure that a given value should be exceeded by the 50% of the values, at the same time in the month. Secondly, because it refers to the annual month so its geophysical meaning is rather discussible.

Anyway models for long-term prediction of the median monthly conditions have represented in the last decades an important tool not only for applied science and for radio-users, especially those frequency planners of radio broadcasting agencies, but also for geophysicists in their theoretical studies of the upper atmosphere. Median conditions are considered in many models of electron density profiles as the IRI and others (Bilitza, 1990).

The evolution of the long-term mapping and modelling has been determined by different causes as by the evolution of the computing systems, the easier opportunity to collect and exchange data and certainly by the different scientific needs and applications. The systematic collection of the regular observations of many ionospheric ground-based stations after the Second World War and especially during the next fifties years allowed Jones and Gallet (Jones and Gallet; 1960, 1965) to produce a first important method to map globally the two most important ionospheric characteristics for radio propagation: foF2 and M (3000) F2. Since then this method has been significantly improved to avoid several inconveniences due to the missing data in some geographical regions or to the inhomogeneous ionospheric observatories. It is recommended by the ITU to be used globally representing the reference method to be compared with the new ones developed for both regional and global use. Of course the evolution of the calculus systems, by large to personal computers, allows an easier application of the method. More recently, in the nineties the opportunity to have in Europe a large and dense collection of ionospheric past data led to the activity of two European actions: the PRIME (Prediction Retrospective Ionospheric Mapping over Europe) known also as the COST238 (Bradley, 1999 and references therein) and the IITS (Improved Quality in Ionospheric Telecommunication System Planning and Operation) known also as the COST251 (Hanbaba, 1999 and reference therein). These two scientific projects provided, among many other studies, a regional methods for long-term and instantaneous mapping, a web interactive data bank as well as a network to exchange real-time measurements for short-term forecasting. Then a great importance was given to the validation of the data collected and to the testing of the performances of the methods considered.

The evolution of the calculus systems has favoured also new Single Station Models (SSM), valid not only to map local areas but useful to more complex models as a part of many other mapping techniques developed in different countries in order to fill the needs of their prediction services (Stanislawska et al., 1991) and (Solé, 1998).

2.1. Global methods to map foF2 and M(3000)F2

Actually the ITU-R, International Union for Telecommunications, the name that replaced the former CCIR (International Radio Consultative Committee), provides expressions, numerical coefficients and software running on personal computer to map, in universal time (UT), the principal ionospheric characteristics used to predict the radio propagation frequencies, valid for any location at the Earth and for any month and hour of the day and solar epoch (ITU-R, 1997; ITU-BR, 1997).

Considering the complex morphology of the F2 layer over the globe, that cannot be described by an analytical function as for a Chapman layer as it is for the F1 and E layers, the numerical method adopted by ITU-R is that derived by the method developed at ITS by Jones and Gallet since 1960 (Jones and Gallet, 1960 and 1965). Figure 1 is an example showing the degree of geographical structure represented.

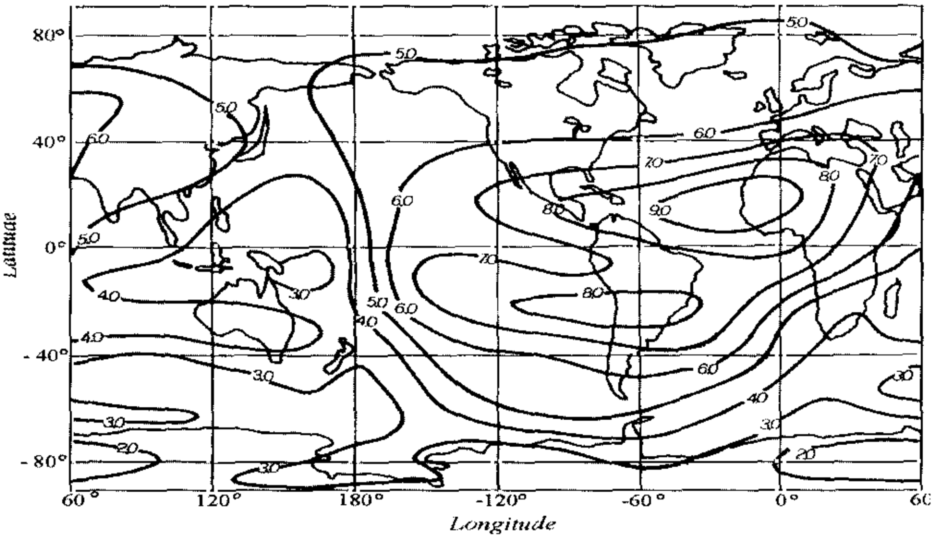


Figure 1. Numerical map of MUF(ZERO)F2. June 1983.UT=18. Values are given in MHz.

The term numerical map is used to denote a function, $\Omega(\lambda, \theta, T)$ of the three variables: latitude λ, longitude θ and time T. The function $\Omega(\lambda, \theta, T)$ is obtained by fitting certain polynomial series of functions of the three variables to the basic ionospheric data. The general form of the numerical map function, $\Omega(\lambda, \theta, T)$ is the Fourier time series:

$$\Omega(\lambda,\theta,T) = \alpha_0(\lambda,\theta) + \sum_{j=1}^{H}[\alpha j(\lambda,\theta)\cos(jT) + bj(\lambda,\theta)\sin(jT)] \qquad (1)$$

where λ is the geographic latitude ($-90° < \lambda < 90°$), θ is the east geographic longitude ($0° < \theta < 360°$), T is the universal time expressed in an angle ($-180°$ $- < T < +180°$), H is the maximum number of harmonics used to represent the diurnal variation.

The Fourier coefficients, $a_j(\lambda, \theta)$, vary with the geographic co-ordinates and are represented by series of the form ($-90° < \lambda < 90°$):

$$\alpha_j(\lambda,\theta) = \sum_{k=0}^{k} U_{2j,k} G_k(\lambda,\theta), \qquad j = 0,1,2,\ldots,H \tag{2}$$

$$b_j(\lambda,\theta) = \sum_{k=0}^{k} U_{2j-1,k} G_k(\lambda,\theta), \qquad j = 1,2,\ldots,H \tag{3}$$

Therefore, a numerical map can be written more explicitly in the form

$$\begin{aligned} \Omega(\lambda,\theta,T) &= \sum_{k=0}^{k} U_{0,k} G_k + \\ &+ \sum_{j=1}^{H} \left[\cos(jT) \sum_{k=0}^{k} U_{2j,k} G_k(\lambda,\theta) + \sin(jT) \sum_{k=0}^{k} U_{2j-1,k} G(\lambda,\theta) \right] \end{aligned} \tag{4}$$

where $G_k(\lambda,\theta,T) = \sin^{q_i} X \cos \lambda^i \sin i\theta$, is the geographic co-ordinates functions. The modified magnetic dip X follows the relation

$$X = tg^{-1}\left(I / \sqrt{\cos \lambda} \right) \tag{5}$$

on the place where I is the magnetic dip. Here the integer q_i, $i = 0, 1, \ldots\, m$, denotes the highest power of $\sin X$ for the i-th-order harmonics in longitude, and m denotes the highest order of longitude.

The coefficients of numerical maps of the monthly median values of foF2 and M(3000)F2 were presented in the Report 340 of CCIR (CCIR Report n. 340, 1988). The coefficients $U_{s,k}$, which define the function, $\Omega(\lambda, \theta, T)$ of the numerical map of the given characteristic for the indicated month and level of solar activity, are given for each month of the year for foF2 and M(3000)F2 and for two levels of solar activity: R12 = 0 and R12 = 100. The R12 is the twelve-month smoothed mean of sunspot numbers and is used as solar index although other kinds of smoothed means could have been used. For every R12 different from 0 or 100 the coefficients $U_{s,k}$, may be evaluated by an interpolation of the previous values for R12 = 0 and R12 = 100 or by an extrapolation for R12 > 100. For a synthetic description of the method see Sun X. and Pan Z., 1987.

The advantage of this numerical mapping method is that when new data become available, an electronic computer can easily revise the coefficients. However, the accuracy of the global representation of the F2-layer characteristics obtained from the maps depends mostly on the geographical distribution of the ionospheric stations the data of which were used in the generation of numerical coefficients. The monthly median values of foF2 which were used to develop the global maps were obtained from over 100 vertical sounding ionospheric stations operating in different times. Figure 2 shows the map of the stations.

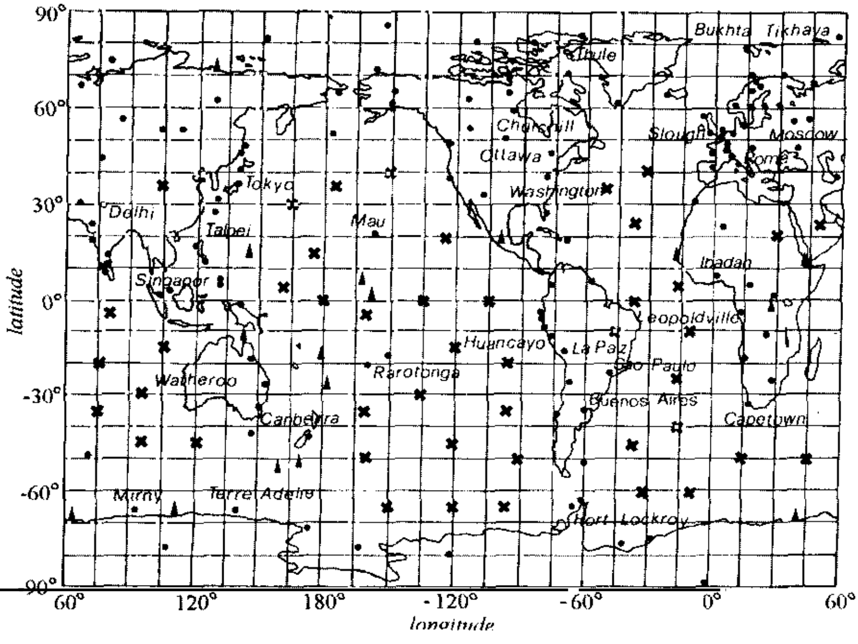


Figure 2. Map of stations, • A data, ▲ B data, × C data.

By observing these stations, it is clear that the best-generated maps of the ionospheric characteristics are at the regions for which data were available. On the other hand, the degree of accuracy of maps is quite low for those regions such as deserts or oceans for which data were not available from all sort of reasons. Jones and Gallet demonstrated successfully that the usage of a set of functions, which adequately represent the measured ionospheric data, could lead to instabilities in areas for which data are sparse or missing altogether.

To avoid these instabilities it was necessary to collect as many ionospheric data as possible, that is how, only after the IGY (July 1957 to December 1958) when the number of the stations was almost triplicate, the numerical representation of the ionospheric characteristics was possible. Figure 3 shows foF2 medians for March 1958.

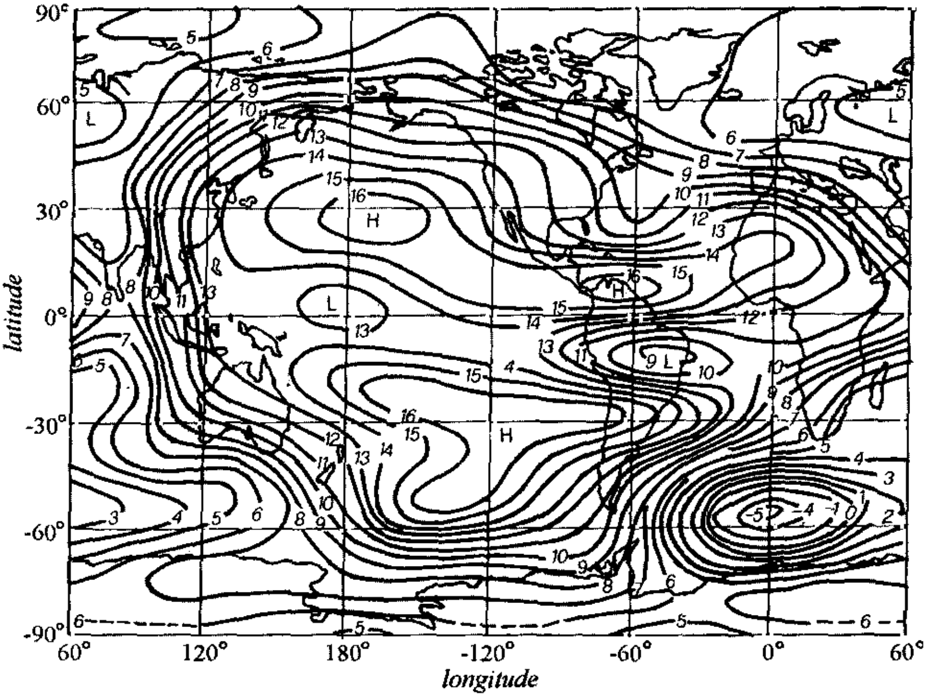


Figure 3. Map of monthly medians foF2, March 1958, UT=00.

The problem was partially solved by Jones and Gallet (Jones and Gallet, 1965) by adding, to the observed median monthly data coming from real vertical sounding stations, referred to as points A, the data evaluated and coming from two sets of virtual points referred to as points B and C (Fig. 2). The data coming from the points B were obtained by a prediction using a correlation of the available data at the same station. They used a method (Crow and Zacharison, 1960) that applied an interpolation of the ionospheric characteristic by a polynom of the first or second order *vs.* an index of the solar activity. Obviously data coming from the points A and B were available only for land base regions. Whereas the C data, used as reference points, were obtained by an interpolation of the ionospheric characteristic considered as a variable of only one co-ordinate, i.e. the latitude. The diurnal variation of the characteristics at the B and C points has been represented by Fourier series. That is how, as a whole, the data distribution from A, B and C points contributed to determine the numerical coefficients. Although, this method with its following improvements gave good results especially from the ionospheric predictors point of view, the maps of foF2 still lack the required precision.

A very important improvement was proposed by Rush et al. (Rush et al., 1983; 1984) in order to solve this problem. They decided to employ a theoretical model of the ionosphere to generate values of foF2 in all mid-latitude regions including those locations where observations are not available. The values determined by means of the theoretical model were added to the ones drawn from the observations, thus contributing to generate the numerical coefficients, which produce global maps of the F2-layer critical frequency for a specific month. The results of this method show that the description of the global behaviour of the foF2 is consistent with the structure of the mid-latitude F2-layer and agrees with other observations such as topside soundings. Rush et al. used the time-dependent ion continuity equation described by Anderson (Anderson, 1973a; 1973b) to calculate the theoretical values of foF2 .

If the ion density N_i is equal to the electron density N_e, the values obtained by the solution of the ion continuity equation can be used to determine directly foF2 as follows:

$$N_e = 1.24 \cdot 10^4 (foF2)^2 \tag{6}$$

where N_e is expressed in electron/cm^3 and foF2 in MHz. Considering that the continuity equation is given by

$$\frac{\delta N_i}{\delta t} + \nabla \cdot (N_i \bar{V}_i) = P_i - L_i, \tag{7}$$

where P_i the ion production rate, L_i the loss rate and V_i is the transport velocity. The transport of the ionospheric plasma is due principally to diffusion and neutral winds along the lines of the geomagnetic field and to electromagnetic drift perpendicular to the field lines. Models of the neutral composition are then used to obtain parameters such as neutral temperature, production, loss and diffusion rates, neutral winds and geomagnetic field, all of them necessary for the solution of the ion continuity equation.

The effects of neutral winds and their correlation with the geomagnetic field are very important for the solution of the continuity equation. The values of meridional and zonal winds are inferred following the method described by Rush et al. by fitting calculated values of foF2 using the continuity equation and comparing them with the available and observed data. The southern wind component was adjusted in order to obtain an agreement between observed and calculated data. The same operation was repeated for another location placed at the same magnetic latitude but with a different declination. Using the same southern wind the zonal wind component was adjusted so that the calculated values of foF2 should agree with the observed data.

The numerical coefficients, representing the global variation of foF2, developed by Rush et al. and that are consistent with physical processes that govern the F-region, were put into the same format as those of CCIR and Jones et al. (Jones et al, 1969). These new coefficients derived from observed data of the world-wide network of vertical incidence ionosonde stations (A data) were then used to predicted data (B data) and theoretical data points (D data) obtained from the time continuity equation at mid and high-latitudes.

Various comparisons between the diurnal behaviour of the foF2 obtained by new coefficients, and that obtained by the old CCIR coefficients demonstrate that new method gives better results. This is particularly true in regions for which observed data are available (Matuura, 1983).

A further improvement in ionospheric mapping has then provided by Fox and McNamara (Fox and McNamara, 1988). They developed a method which merged the features of the Australian Ionospheric Prediction Service IPS maps and the maps obtained with the Jones and Gallet method modified and implemented by Rush et al. Examining the advantages and limitations of the existing ITS and IPS mapping methods they stated that the maps are hand-drawn and as such they cannot be easily revised and are subjective, although, when hand drawing, it is possible to take into account the importance of some points or some physical insights. On the other hand, IPS maps are drawn on an extended bank of data and based on the ionospheric index T that gives regression lines of foF2 vs T with a better correlation than other indexes, (Turner, 1968; Wilkinson, 1982). Regarding moreover the improved ITS maps, Fox and McNamara object to decision taken by Rush et al. to use data from only two selected years, one at a level of solar activity and the other at a lower level. For the New World maps of foF2 they have applied a linear regression analysis of the monthly median values against the solar index T thus obtaining the values of foF2 at $T = 0$ and $T=100$.

They provided additional data in order to fill the gaps existing in the world distribution prior to the mapping, by using the ITS foF2 coefficients computed by Rush et al. valid for mid-latitude. As it is well known, the maps obtained by using the observed median data and the ITS maps as inputs failed to show any equatorial anomaly. For low-and high-latitude regions, the data base was supplemented by means of a procedure known as «refilling» which derives from IPS maps to which an interpolation on geomagnetic co-ordinates at a given modified dip latitude is applied.

A modified Jones and Gallet method was applied to the mentioned data in order to produce the global maps. Two important modifications have been introduced to the mentioned Jones and Gallett method. The first one is that with the new method the data from all the years are used to obtain maps at $T = 0$ and $T = 100$ by an easier interpolation or extrapolation. The second difference concerns the choice of the basic functions used in mapping. In fact a good description of the behaviour of foF2 global distribution, outside the equatorial region, was given by means of lower-order functions than those used by Jones and Gallet, whereas, within the equatorial region, the behaviour is well described by using high-order functions. These considerations are applied by means two kinds of functions, of which the first one is used globally and the second only below the same cut-off latitude. Finally new set of updated coefficients have been calculated using also data theoretically calculated over the oceans by Rush et al in 1989.

2.2. Regional methods to map foF2 and M(3000)F2

The study and the application of regional mapping techniques, both for instantaneous or real-time prediction as well for median conditions, emerge from the need to improve their performances. It is possible by use the available or a more dense network of ionospheric stations and, in a restricted area, by simplifying the difficulties. On the other hand, it is not completely obvious that a regional technique should always give better results than the global methods. In fact an incorrect application of the data bank or simply the use of non validated measurements of a poor network of ionospheric stations may emphasise «virtual» local variations, very far from the real behaviour. The study and development of global methods were performed in the past due to the wide application of the ionospheric mapping to long distance HF radio links. It is instead relatively recent the trend to generate regional methods in order to obtain better results when these are interfaced with other geophysical models both for telecommunications as for geophysical modelling.

The purpose to propose an organic study of different regional models to apply in the European area was an important task of the four years European projects COST 238 PRIME (1991-1995) and the COST251 IITS (1995-1999). Then it was just during these two projects life times that many regional models and mapping methods were developed, examined and tested in their application to the European area and finally compared with the performances of the most used ITU-R global method.

Some of these models as SIRM (Zolesi et al., 1993; 1996), PASHA (De Franceschi et al., 1994), MQMF2 (Mikhailov et al. 1990; Mikhailov and Mikhailov, 1993) and EOF (Dvinskikh, N, I and N.Y. Naiedova, 1991) were initiated before the PRIME project commencement and were improved later on using the updated PRIME data bank. Other models as KGRID, LINLAT, ILCNN, SWILM, ISIRM, SAILT, MQMF2R and UNDIV were generated in the contest of these two European actions PRIME and IITS (Zolesi and Cander, 1998). The potential of these techniques were shown to different mid-latitude regional areas such as on North East and South East America and on North East Asia and South Australia by Zolesi et al. (1996) in case of the SIRM model, and on Eastern China by Wang et al. (1997) in case of the adopted PRIME model. It is important to note that firstly during the PRIME action and then later during IITS action a testing procedure was developed and applied by an impartial testing team to verify and rank the performances of the different methods, including the global ITU-R. This work was performed by using the improved and valid data bank (Levy et al., 1998). Important consideration was given also to the buffer zone between the global and regional models in an attempt to avoid large gradients especially at high latitudes where a complex behaviour of the ionospheric conditions exists (Leitinger, 1993; Hanbaba, 1999).

In the COST 251 project the best mapping methods appeared to be the MQF2R for the foF2 and the UNDIV for the M(3000)F2) (Bradley, 1999 and references therein). They performed much better than the global of ITU-R and still better than the other models proposed in COST actions. However, all the differences, expressed as standard deviation of the errors in terms of MHz, were rather small especially from the point of view of predictors of the monthly median conditions.

MQMF2R (Multiquadric Method of spatial interpolation based on foF2 vs MF2 Regression) is an improved version of MQMF2, a long-term prediction method first developed for world wide median mapping (Mikhailov and Mikhailov, 1993; Mikhailov et al., 1990) and then applied to the European region to model foF2 and M(3000)F2 ionospheric characteristics (Mikhailov and Teryokhin, 1992). Data bank used in MQMF2R for foF2 consists of a set of numerical coefficients calculated over a range of ionospheric stations, as for a single station model, inside the regional area and in the buffer zone, by a foF2 polynomial regression vs solar activity index MF2. The MQMF2 method is based on the multiquadric (MQ) algorithm of spatial interpolation (Teryokhin and Mikhailov, 1992) for which a selected ionospheric characteristic is represented by:

$$f = \sum_{i=1}^{n} C_i \left[1 - \mathrm{sen}\,\theta \cos\theta_i \cos(\varphi - \varphi_i) - \cos\theta \cos\theta_i\right]^{\frac{1}{2}} + b \qquad (8)$$

with

$$\sum_{i=1}^{n} C_i = 0 \qquad (9)$$

where θ is the geographic colatitude, φ is the geographic longitude and Ci are a set of numerical coefficients and b a constant. This method draws a surface strictly over given set of points in distinction from other methods adopted for ionospheric mapping. The whole data bank inside regional area as well as in the

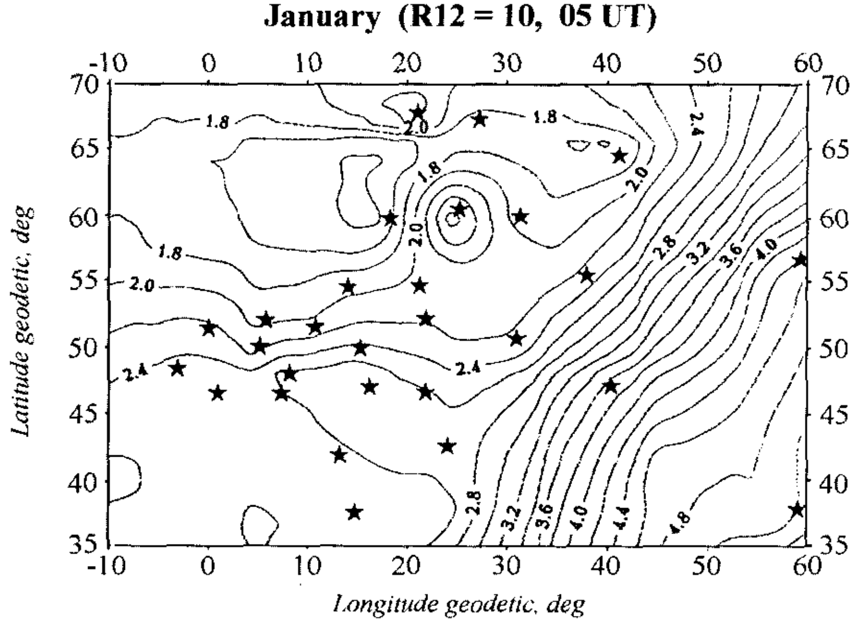


Figure 4. Example of MQMF2R map, for foF2, over the COST 251 region, in winter and solar minimum (R12=10) conditions. (★) Are the COST251 area ground-based ionosondes.

buffer zone was used for drawing the surface so this approach always provides a smooth interfacing to the ITU-R global model outside the regional area. The MF2 monthly ionospheric index (Mikhailov et al., 1990; Mikhailov and Mikhailov, 1995) has been produced for the past epochs. Predicted MF2 index can be calculated so long as there are available 10 ionospheric stations at least with foF2 noon values to which a regression analysis may be applied using the McNish Lincoln procedure. A conversion procedure from R12 to MF2 is adopted in the model MQMF2R. An example of a regional map obtained with MQMF2R procedure is given in Figure 4.

MQMF2R is a mapping method that belongs, as ITU-R, PASHA, KGRID and others, to those procedures that were generated for world-wide mapping and then adjusted to be applied in restricted regions. Other models as the SIRM, ISIRM, the many Single station Models and the UNDIV were instead devised to be valid only in a restrict area whatever it may be their simple or complex application.

The UNDIV model was the long term mapping procedure, first recommended by the COST238 PRIME for use in the European regional area, both for foF2 and M(3000)F2 ionospheric median conditions, and then adopted, after tests in comparison with other developed methods, also by the COST251 only for M(3000)F2. According to the Kouris and Bradley results, (Kouris et al., 1994; Bradley et al., 1994) the solar cycle dependence of M(3000)F2 has been conveniently quantified for each station, month and hour by reference values within the low and high epoch bands for R12 = 35 and R12 = 135, making no distinction between solar cycles, no distinction between rising and falling parts of the cycles and no accounting for hysteresis effects.

Considering that in the European region the use of geomagnetic co-ordinates or the modified magnetic dip gave not important improvements, due to a weak geomagnetic control in comparison with very high latitude or extended regions, the simple geographical co-ordinates were adopted in all PRIME and IITS studies. Then assuming that in the same area no first order longitude effect may be taken into account only a linear dependence on geographical latitude was adopted, added to a linear dependence on geographic longitude; that is for a constant local time (LT) and month of the year a bi-linear regressions in latitude and longitude. Using the monthly medians of M(3000)F2 taken from the database, linear regressions for the R12 dependence of M(3000)F2 were constructed for each month and for each hour UT of each station, not reserved for testing. Then level values of monthly medians were calculated, from the regressions, for the two R12 levels of solar activity and transformed from UT to LT dependence applying a Fourier interpolation of the diurnal variation. Finally, for several different selections of stations bilinear regressions were calculated for each R12 level, for each month and for each LT hour. In Figure 5 the regional map of the ionospheric characteristic M(3000)F2 for 1800 UT, as obtained from UNDIV model, the COST 251 recommended mapping procedure, is shown.

2.3. Single Station Models

In the past mapping techniques based on single station models were the typical home made mapping methods produced in many ionospheric prediction services both for long-term and short-term predictions (Hanbaba, 1988; Stanislaswka et al.,1991; Moraitis et al., 1991; Cander et al., 1993; Vasiljevic et al., 1995). These models were very important not only for local or medium distance telecommunications purposes because of their accuracy, but also because of their ability to be interfaced with other geophysical models such as electron density profiles models or total electron content determination. The models are obviously based on the accurate study of the behaviour of one station characterised by a long history of observations (Dominici and Zolesi, 1987) so they may be considered the extreme limit of a regional model. In the last decade Single Station Models (SSMs) have been widely used in several other applications as to fill data gaps in active stations or to produce new screen points for mapping ionospheric characteristics (Mikhailov and Mikhailov, 1993, Bradley, 1999). The largest number of these models applied a polynomial or even a li-

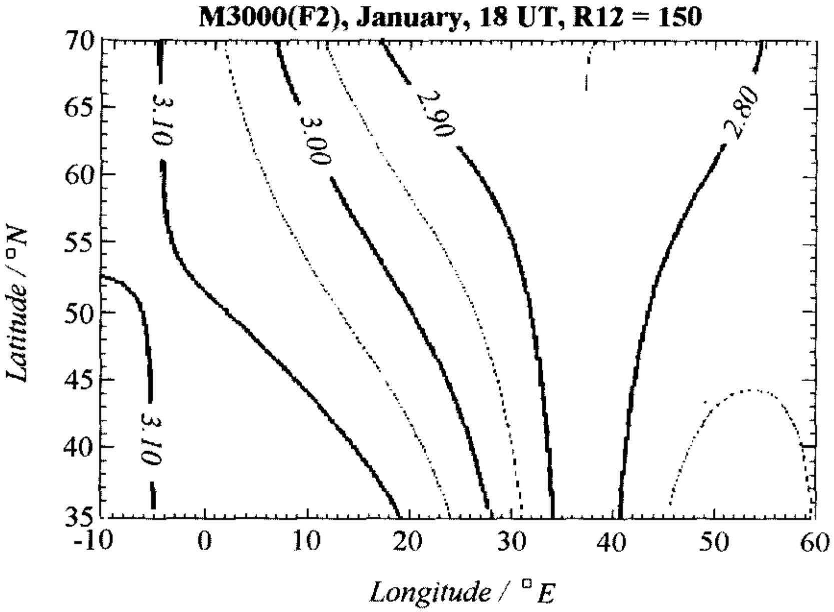

M3000(F2), January, 18 UT, R12 = 150

Figure 5. The regional map of the ionospheric characteristic M(3000)F2 for 1800 h UT, as obtained from UNDIV model, the COST 251 recommended mapping procedure.

near regression of the monthly median values vs the solar activity or vs a more or less complex ionospheric index, for every hour and for every month of the year. As for examples the polynomial regression given by Xenos et al. (Xenos et al., 1996):

$$\mathrm{foF2} = a_o + a_1\, S + a_2\, S^2 \tag{10}$$

where S is an ionospheric index. More recently the polynomial regression is given by Solé (Solé , 1998) as follows:

$$\mathrm{foF2} = a + bT + dAP + eAP^2 \tag{11}$$

where the Australian T index and the geomagnetic index Ap have been used.

2.4. Modelling of other ionospheric layers: foF1, foE and foEs

F1 and E ionospheric layers are well known as Chapman layers. This means that their spatial and temporal behaviour may be modelled by an analytical expression as function of the solar zenith angle cos(. In the past many local models were produced by national prediction services, valid in the vicinity of the ionospheric station, as it was for the F2 layer by SSMs (Dominici and Zolesi, 1987; Davies, 1990). The most used expression to predict median values of foF1 was given by Du Charme et al. first in 1971. Then, after a more accurate statistics, by the same author in 1973 using data from 1954 to 1966 and from 1967 to 1969 (Du Charme et al., 1971; 1973). The method adopted by IRI (Bilitza, 1990) consisted in a series of expressions containing the solar zenith angle cos χ and the solar activity smoothed index R12 dependence:

$$\mathrm{foF1} = fs\cos^{n}\chi \tag{12}$$

$$fs = f_0(f_{100} - f_0)\,\mathrm{R12}/100 \qquad f_0 = 4.35 + 0.068\,|\varphi| - 0.00012\varphi^2 \qquad f_{100} = 5.348 + 0.011\,|\varphi| + 0.00023\,\varphi^2 \tag{13}$$

$$n = 0.093 + 0.0046\,|\varphi| - 0.000054\,\varphi^2 + 0.0003\,\mathrm{R12} \tag{14}$$

and providing also the critical solar zenith angle (for the occurrence probability of the F1 feature. The F1 layer may exist only when the solar zenith angle is smaller than a given χ_s. Recently the Du Charme formulas have been tested again during some IRI Task Force meetings for the F1 layer held at ICTP in Trieste in 1996 and 1996 (Radicella et al., 1997; 1998) on a more extended data bank that in the original studies confirming the same results. An improvement to this formula was given so performing a probability function to predict the F1 layer occurrence including L conditions, (Scotto et al., 1997; 1998).

The representation of foE adopted by IRI was given by Kouris and Muggleton in 1973 (Kouris and Muggleton, 1973a; Kouris, 1981; Davies, 1990) and then recommended by ITU-R (Kouris and Muggleton, 1973b). It is a complex analytical expression depending on solar zenith angle χ, on the 12 months running mean of the solar 10.7 cm radio flux, on season and on geodetic latitude. The model is very accurate except for the sunrise and sunset when the solar zenith angle is large or proxy to 90 degrees. Several different improvements have been introduced especially for the night hour conditions by Wakay in 1971, by Leftin in 1976 and by Rawer and Bilitza (Wakay, 1971; Leftin, 1976; Bilitza, 1990). More recently a model to describe the night hourly variations has been proposed by Bradley (1993) and adopted in the PRIME COST 238 project.

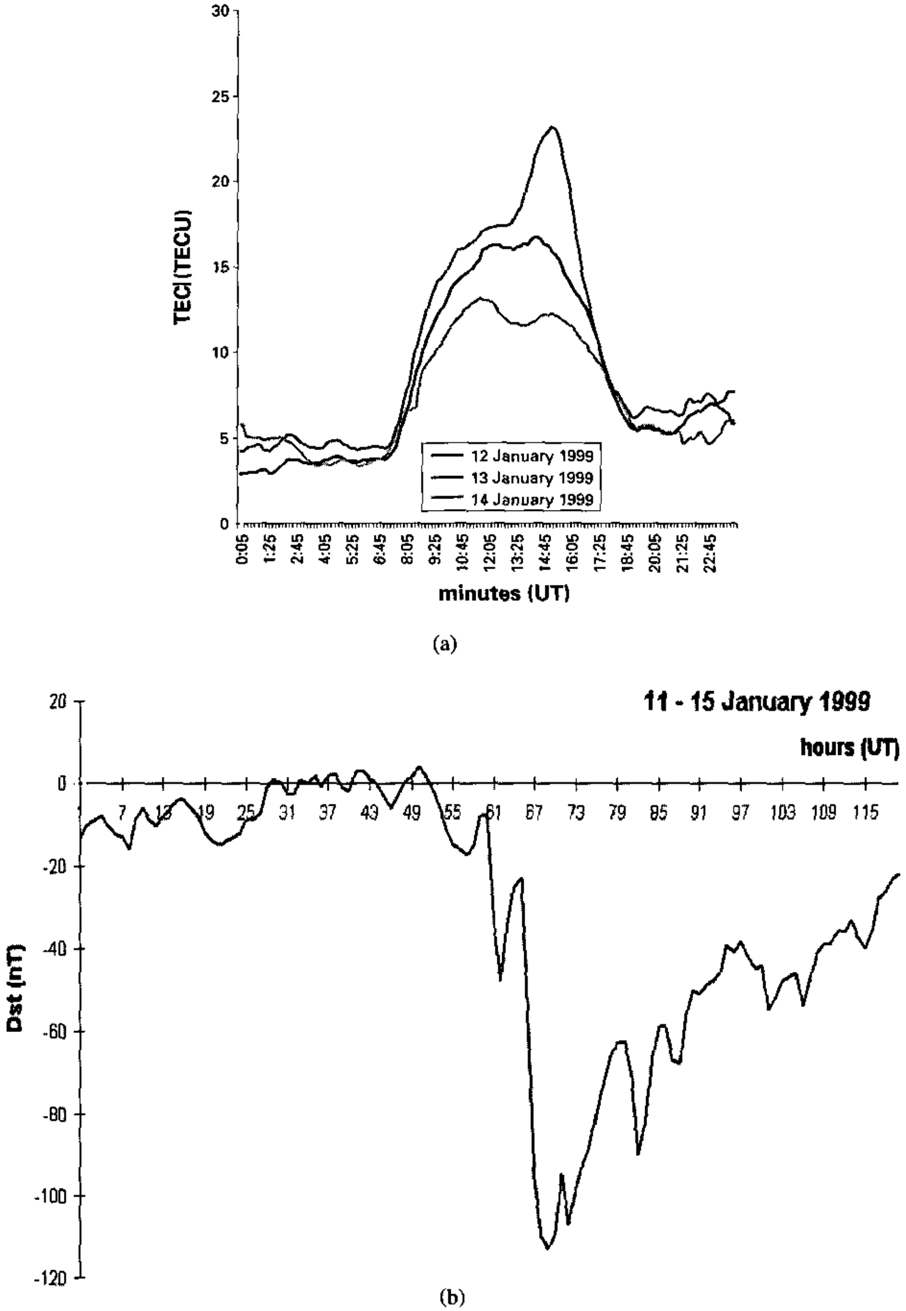
Jones and Gallett's mapping procedure has been also applied to perform predictions over the globe for the median conditions of the sporadic E layer critical frequency, foEs, of by Leftin et al. in 1968 using a set of separate numerical coefficients for the minimum and maximum solar activity (Leftin et al., 1968). Unfortunately, due to the uncertain determination of this parameter and to the difficult predictable occurrence of this layer joined to the poor data bank, the method still does not give good performance over the entire globe. Slight better results have been obtained mapping the percentage of occurrence when the foEs exceeds a given value (Smith, 1978).

3. SHORT-TERM IONOSPHERIC FORECASTING

In the last four decades, the HF radio operators often needed to plan frequencies a few hours in advance, which required a short-term forecasting of the ionospheric characteristics like foF2 and M(3000)F2. Ideally, this could have been done using a global numerical model of the coupled thermosphere/ionosphere, but in practice, the necessary input data were not available and the running times were prohibitive. A simpler solution consisted in using empirical methods to forecast the behaviour of ionospheric few hours ahead at a given location. Currently one possibility could be to use an artificial neural network (Cander, 1998a), which has the advantage of taking into account the non-linear ionospheric phenomena.

A characteristic of the terrestrial ionosphere during solar-terrestrial active as well as most of the quiet periods is the great degree of variability. Shortterm ionospheric modelling is usually defined as a quantitative indication of the ionospheric characteristic variations up to twentyfour hours ahead. The main problems associated with the short-term forecasting models and/or algorithms are those of specifying the dramatic effects in the ionospheric regions produced by geomagnetic storms. The ionospheric storms result from the input of solar wind energy captured by the Earth's magnetosphere, released and dissipated into the auroral ionosphere which set up a complex morphology of temperature, winds, electric fields and composition changes (Prölss, 1995). An example of the Total Electron Content (TEC) storm variations is given in Figure 6 together with associated Dst variations.

Ionospheric storms continue from a few hours to several days. These lead to significant changes in the plasma parameters during which time the band of available frequencies for radio waves propagating by ionospheric reflection is reduced while other effects can be particularly damaging to both satellite and ground-based systems. Question arises how circumstances under which these phenomena are repeatable can be specified precisely and forecast successfully. During the years various studies have been made showing that an adequate understanding of the variability of electron density as well as electric currents and real-time data access may eventually produce the successful forecasting of short-term ionospheric changes (FullerRowell, 1996). First step along that line is instantaneous mapping of the ionospheric characteristics.



(a)

(b)

Figure 6. TEC (a) and Dst (b) variations during the January 1999 storm.

3.1. Ionospheric instantaneous mapping

Ionospheric instantaneous mapping is a technique that, using a set of simultaneous observations integrated by calculated values, is able to generate a map of the required characteristics at a single moment of time in a restricted region or even globally. Although the instantaneous mapping may be considered as a now-casting technique, it is important, from the geophysical point of view, for retrospective analyses where the median conditions are too rough to detect local or temporal correlation and disturbances.

Instantaneous mapping methods, developed in the last few years, consist of the numerical functions that try to smooth the observed values measured at a limited numbers of ionospheric stations and the additional screen points values where there are no measurements (Bradley, 1996). Due to an easier application of these methods to a region most of these techniques have been presented and developed inside the COST activities (Bradley, 1999; Hanbaba, 1999 and references therein). Therefore, it is important to mention the method adopted by the COST251 that was submitted to a complete test procedure. The COST 251 method for instantaneous values of foF2 and M(3000)F2, known as PLES (Stanislawska and Juchnikowski, 1998), combines monthly median maps of ionospheric characteristics and a set of screen points-measurements using two interpolation methods modified for this purpose: Kriging and «fitting» (Hanbaba,1999).

Kriging is a technique, (Oliver and Webster, 1990), that applies weighted interpolation among adjacent data points using variogram, i.e. a function that illustrates the differentiation of the value of a parameter depending on the distance between the different measurements. Fitting uses a set of weighting functions, which are a measure of the statistical dependence of foF2 and M(3000) F2 between points on a sphere, (Hanbaba,1999).

3.2. STIF technique

An operational short-term ionospheric forecasting (STIF) tool for the European region based on continuous monitoring of the ionosphere is available on the World Wide Web for interactive use: http://www.rcru.rl.ac.uk/iono/STIF.htm (Levy et al., 1999). A network of about 20 ionosondes in Europe provides the basic inputs, measurements of foF2 and M(3000)F2, for the region of interest (10° W – 90° E, 30° – 70° N). Data are currently updated every 24 hours. An auto-correlation procedure was developed for the short-term forecasting of ionospheric characteristics (Muhtarov and Kutiev, 1999; Kutiev et al., 1999) and applied to produce forecast values of foF2, MUF(3000)F2 and TEC at integer hours UT up to 72 hours ahead at each vertical incidence station where sufficient measurements are available.

All maps are drawn using the Kriging interpolation technique. The grid resolution is 2.5 degrees in latitude and 5 degrees in longitude. Following Stanislawska et al. (1996) an anisotropy factor of 2.1, which gives greater weight to variations along the longitudinal axis, was introduced. Contour maps of forecast values and of the most recently available measurements are produced which are updated daily at fixed times. In addition to these passive maps, a facility has been provided enabling a user to interactively produce a map of Operational FOT (optimum working frequency), again for up to 72 hours ahead, for specified location. Examples of forecast and measurement maps of foF2 are given in Figure 7. Examples of forecast values of TEC and values of TEC calculated from modelled values are given in Figure 8. No crosses are indicated in Figure 8, as TEC is not directly measured.

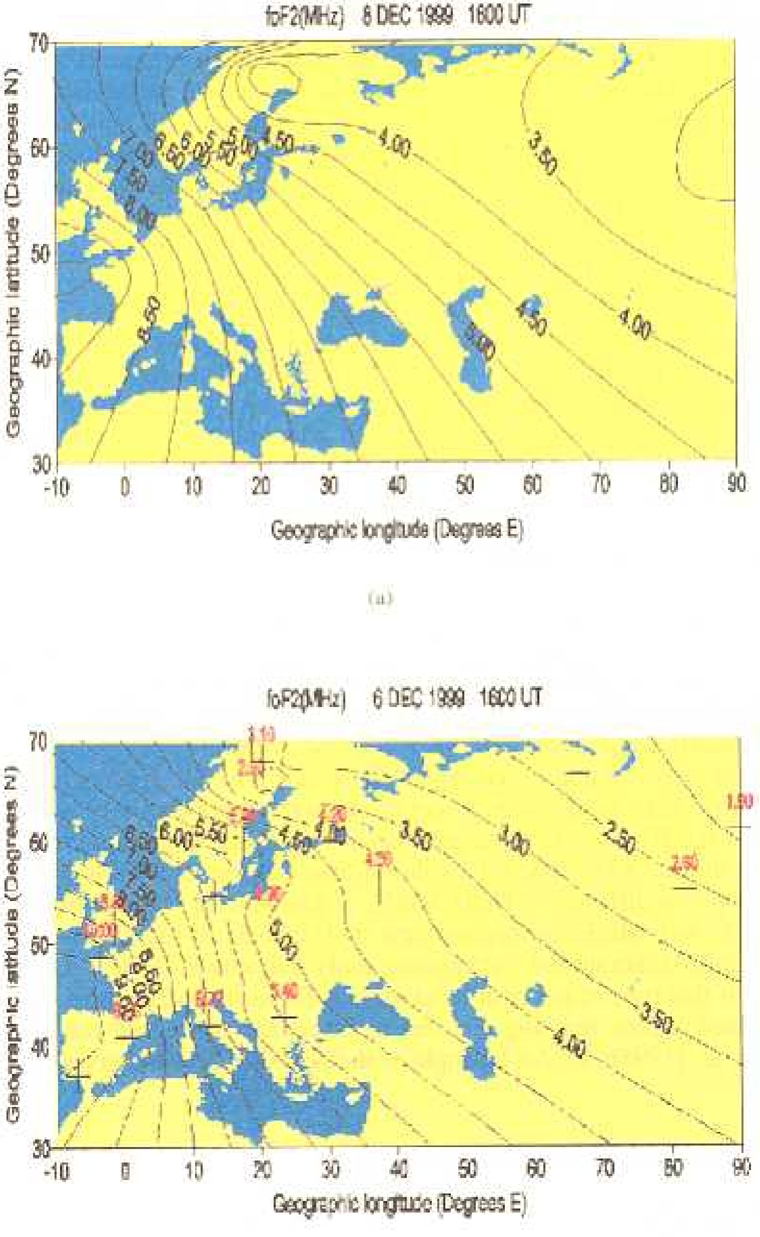
The TEC profiler is a modified Di Giovanni - Radicella (DGR) model (Radicella and Zhang, 1995) that uses 5 semi-Epstein layers and the ionospheric characteristics foE, foF1, foF2 and MUF3000(F2) as inputs. TEC maps are calculated with the last two characteristics given by STIF and simplified models for foF1 and foE. The profiler has been adapted from the NeQuick model (ICTP and University of Graz) developed with ESA-ESTEC support.

3.3. Neural networks techniques

Successful attempts to build different artificial neural networks models for ionospheric long-term prediction and short-term forecasting have been made by a number of groups within and outside of the COST 251 project (Altinay et al., 1997; Poole and McKinnell, 1998; Cander et al., 1998b, c; Lamming and Cander, 1999; Wintoft and Cander, 1999). NNARX - Neural network based auto-regressive model with additional inputs (X) is one possible approach that use the hybrid time-delay multi-layer percepton neural network with only critical frequency of the F2 layer as input parameter to produce one output foF2 value at hour t+1. Inputs (X) include foF2 value at time t, seven days mean MfoF2 values and appropriate differences Delta MfoF2 at particularly selected hours (t, t-1, t-23, t-47) as well MfoF2 at forecast time (t+1) calculated using only the learning set of data to generate the background daily variations of foF2. Detailed description of this type of the neural network as far as its architecture, first and second hidden layers, learning and test data sets are concerned can be found in Cander et al. (1998b, c). An example of the NNARX result is given in Figure 9.

3.4. Ionospheric storm forecasting

Although there is special interest in advance storm warnings for major storms (Richmond, 1996), less is known about defining the ionospheric forecasting models during great solar-terrestrial events. Case studies and theoretical results prove that any algorithm for shortterm ionospheric forecasts during storms should consist at least three parts: (1) Geomagnetic activity forecasting,



(a)

(b)

Figure 7. Maps derived from 24 hours ahead forecast values of foF2 (a) and measured (b) values of foF2.

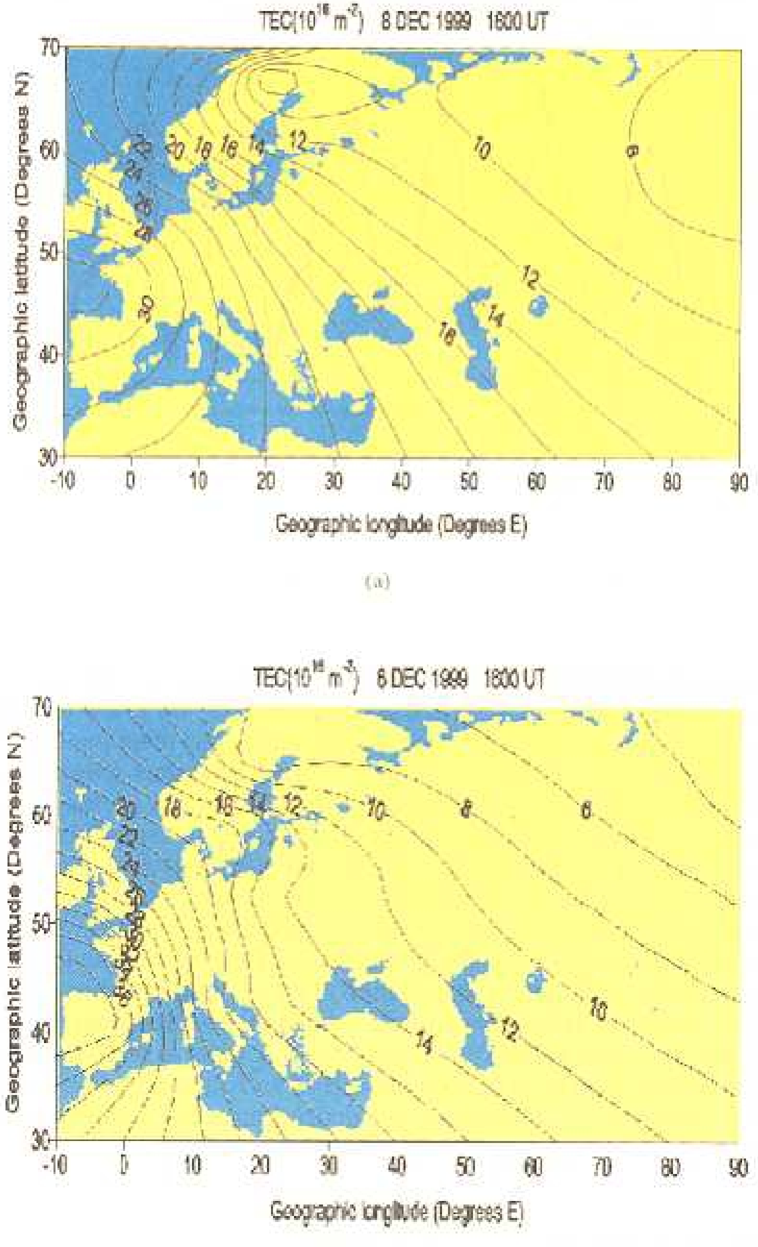


Figure 8. Map derived from 24 hours ahead forecast values of TEC (a) and values of TEC calculated from modelled values (b).

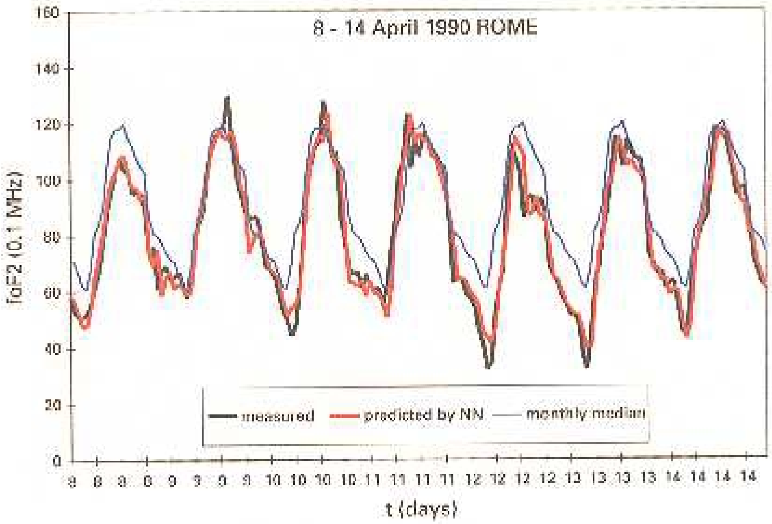


Figure 9. foF2 values measured and predicted one our ahead by neural networks during the period 8-14 April 1990 at Rome ionospheric stations together with their monthly median values.

(2) Forecasting ionospheric storms, and (3) Modelling ionospheric parameters for a storm period (Cander, 1993). Work is in progress on a new technique development for storm-time forecasting and instantaneous mapping over Europe, based on analytical presentation of the mapped quantities (Muhtarov et al., 2000). In this technique diurnal and seasonal variations of the ionospheric foF2 and M (3000) F2 characteristics are represented by a modified version of the regional model ISIRM adjusted to the past measured data. An autoregressive extrapolation of the data from the past month enables the 15-day-ahead forecast of the quiet ionospheric distribution to be performed. In addition, the short-term variations due to geomagnetic activity are defined as a plane surface superimposed on the quiet distribution. This correction is obtained by two plane characteristics as functions of the geomagnetic three-hour Kp index. In this way the 24-hour forecast can be obtain during quiet as well as disturbed ionospheric conditions. The corresponding EIFM software provides variety of options to perform the short-term forecast depending on availability of the measured ionospheric data and predicted Kp values.

4. DISCUSSION AND CONCLUSIONS

A common method used in long-term prediction and shortterm forecasting of ionospheric characteristics is extrapolation/interpolation of the ionospheric characteristic itself or of an index derived from this ionospheric characteristic based on a timeseries of past observations and the assumption that the previous epoch trend will be maintained for at least the near future. This is particularly important having in mind that fully realistic simulation using a coupled magnetosphereionospherethermosphere global model is not yet readily available. In spite of a lot of studies concerned the morphology, physical mechanisms and predictability of ionospheric variations for geomagnetically quiet and disturbed conditions outside (Wilkinson, 1995) and within COST 238 and 251 Actions (Bradley, Hanbaba and Zolesi, this issue), there are still a lot of things to be done in areas of ionospheric mapping and modelling. They mostly concerned world-wide or regional aspects of complex phenomenon such as low and high latitude ionospheres, regions without enough measurements and large stormtime variations. Realistic simulations of the ionosphere, particularly throughout the periods of intense geomagnetic activity, require detailed timedependent descriptions of energy, ionisation and momentum sources for the thermosphere and ionosphere. Since some of the inputs are poorly represented in current models thus limiting seriously the ability to predict the events illustrated by means of the simple example described in the previous sections.

For these purposes, there are two effective ways to use current data and knowledge from different sources. Firstly, develop methods for forecasting daily geomagnetic activity indices which sum the effects of multiple geophysical current systems driven by separate physical processes such as AE (auroral latitudes), Ap (mid latitudes) and Dst (low latitudes). In addition, it is essential to improve indices describing the local state of solar and geomagnetic activity. Secondly, an online system for monitoring all kinds of geophysical activities should be developed. This would provide information on uptodate conditions of solarterrestrial interactions. Up to now, a large quantity of ionospheric data obtained in the European area have been collected and analysed with the aim of constructing the patterns of ionospheric storm that are most appropriate for a particular location. More internationally co-operative work on other data sources is required, particularly these concerning the storm precursors.

Rapid advances in computer technology have opened a number of possibilities in expert systems, image pattern recognition, realtime data access, and data base systems. Allowing for advances in computing environments and networking more effective use can be made of current ionospheric data and knowledge by employing artificial intelligence methodologies and neural network computation techniques to solarterrestrial past and on-line data (Cander and Wintoft, 1999). Currently a way to address this problem is by developing a ionospheric specification or nowcasting models as operational tools. This is planning to be done under the auspices of the next four years COST 271 action on «Effects of the upper atmosphere on terrestrial and Earth-space communications» due to begin in early months of 2000. Action will partly focus upon efforts to map and model the ionospheric space weather conditions over Europe in the near-real–time bases and to forecast them few hours ahead.

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