IONOSPHERIC MODELS INCLUDING THE AURORAL ENVIRONMENT

Lj.R. Cander[1], R. Leitinger[2] and M.F. Levy[2]

[1]CLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, Great Britain
[2] Institut fur Meteorologie und Geophysik, Universitat Graz, Halbarthgasse 1, A-8010 Graz, Austria

ABSTRACT

Modelling of the ionospheric-plasmaspheric electron-density height profile N(h), as well as other parameters like the ion composition or electron and ion temperatures, over the whole altitude range for all geographical positions, time spans, and geophysical conditions is an essential part of ionospheric physics and a critical element in the development of practical schemes for ionospheric space weather applications. This paper attempts to review recent progress in electron-density profile modelling. The various types of models available are described, and their applicability to space weather forecasting is assessed.

Keywords: ionosphere,electron density, auroral region

1. INTRODUCTION

In view of the importance of ionospheric effects on radiowave propagation and satellite hardware, models for ionospheric specification and forecasting should be a crucial component of any space weather program. A case in point is the provision of time delay corrections for Global Positioning System applications. Since a multitude of different ionospheric models is readily available it is important to note that: (i) all-purpose models do not exist; (ii) all ionospheric models need input data; (iii) the decision which model to use depends on the aims and the needs of the model users, on available resources, on available input data.

Ionospheric modelling programmes have been conducted by a variety of international and national organizations on: (i) global government level (e.g., ITU); (ii) regional level with government support (e.g., COST Telecom); (iii) scientific union and committee level (e.g., URSI and COSPAR) as well as national levels (e.g., IEEE). There are ionospheric models available to the scientific community as well as models with restricted access.

Between ionospheric models there can be large differences in accuracy, in temporal and spatial resolution, in required computer resources (CPU time, memory, size of the code) and in adaptability and user friendliness. It is also important to distinguish between models with provide electron density height profiles only and models which allow the calculation of electron density along arbitrarily chosen ray paths. Some models provide continuity in electron density only, others provide continuity in all spatial first derivatives too, others are fully analytical (in general at the expense of accuracy and resolution).

Finally the prospective user should learn to distinguish carefully between models which aim at representing average conditions, the most widely used average being the monthly median, and models with real-time applications. Some models which are labelled as “average models” can be modified to give indication on disturbed conditions and/or updating with observed values. The latter possibility allows their use in real-time mode.

We outline the three main categories of models, namely theoretical models based on physics and chemistry, parametric models which simplify the theoretical models in terms of a small number of parameters, and empirical models based on observations.

We describe in more detail one class of 3D empirical models, namely those which join together “maps” of profile anchor points and other profile parameters. These “profilers” allow the replacement of mapped values by observed values without changing the mathematical formulation of the profile itself. The maps provide profile anchor points as functions of the geographic coordinates. If the profile formulation itself is independent of latitude and longitude the models can be used as global and as regional ones depending on the type of anchor points and parameters maps used.

2. THEORETICAL MODELS

Theoretical models attempt to solve a set of first principles equations for the ionospheric plasma, starting from the continuity, energy, and momentum equations for electrons and ions (Schunk, 1988; Anderson, 1993). The most advanced models have been developed at:

(i) Utah State University - Time Dependent Ionospheric Model (TDIM) by Schunk et al. (1986). A detailed review of observation model comparisons is given by Sojka (1989);
(ii) University College London and Sheffield University - Coupled Thermosphere-Ionosphere Model (CTIM) by Fuller-Rowell et al. (1987) and Quegan et al. (1982);

(iii) National Center for Atmospheric Research - NCAR Thermosphere-Ionosphere Global Circulation Model (TIGCM) by Roble et al (1988);
(iv) University of Alabama - Field Line Interhemispheric Plasma Model (FLIP) by Torre et al. (1990) and Richards et al. (1994a, b); and
(v) Phillips Laboratory - Global Theoretical Ionospheric Model (GTIM) by Anderson (1973), Moffett (1979) and Decker et al. (1994).

Theoretical ionospheric models have proved their capabilities in reproducing selected sets of non-auroral observations. All these models are essentially confined to modern day supercomputers because of their complexity. The main disadvantage of using theoretical models for prediction and forecasting is the large amount of computer time needed. In addition, an extensive preparation of inputs is needed to obtain meaningful results (Sojka, 1989). For most ionospheric weather applications this would be a significant limitation.

2. PARAMETRIC MODELS

Parametric models simplify the theoretical models by expressing them in terms of solar-terrestrial parameters and geographical locations, giving a realistic representation of the ionospheric spatial and temporal structure using a limited number of numerical coefficients. Some of the best models available at present are:

(i) SLIM - Low latitude model, based on theoretically obtained grid values for electron density profiles normalized to the F2-peak and then represented by modified Chapman function (Anderson et al., 1987);
(ii) FAIM - Low- and mid-latitude model, which uses the formalism of the Chiu model with coefficients fitted to the SLIM model profiles (Anderson et al., 1989);
(iii) ICED - Global with improved performance in the high latitude, controlled by the sunspot number (SSN) and geomagnetic Q index and conceived to allow for real-time updates of the input parameters from a number of sensors (Tascione et al., 1988); and
(iv) PIM - Global, generated as an amalgam of a number of other models by useing either the foF2 CCIR coefficients for normalisation of the electron density profiles or coefficients produced by the TDIM (Daniell et al., 1993a and 1993b).

It is important to emphasise that parametric models allow realistic ionospheric models to be adjusted in real-time and to provide an accurate specification of the instantaneous ionosphere and then to be incorporated in three-dimensional ray tracing programs for HF propagation purposes (Reilly et al., 1991). However, it is clear that parametric models based on theoretical considerations are suitable only for well-specified geophysical problems.

3. STATISTICAL EMPIRICAL MODELS

Empirical models attempt to extract systematic ionospheric variation from past data records. Hence they describe average conditions of the non-auroral, non-disturbed ionosphere. Based on measurements, empirical models are realistic in providing electron density profiles in those areas suficiently covered by observations. Recently an excellent review of empirical models of the electron density was presented by Bilitza (1992). The list and description of the empirical models which are currently available is given in Table 1.

Table 1a. Empirical Models of Ionospheric Electron Density

Models with ITU Peak Bottomside only	Characteristics
Bradley and Dudeney (1973), ionosonde data	Parabolic and linear segments, no F1, no valley, no D region
Dudeney(1978), ionosonde data	Improved functional description, no valley, no D region
IONCAP Model 1983 (Teters et al., 1983), ionosonde data	Parabolic and linear segments, valley of constant density, exponential tail below E parabola
Top and Bottomside	
Bent ionospheric model (Llewellyn and Bent, 1973; Bent et al., 1976), satellite, ionosonde	Three exponential topside segments, bottomside bi-parabola
International Reference Ionosphere-IRI (Bilitza, 1990), ionosonde, incoherent scatter, rocket, satellite	Analytical description of Bent’s topside, E valley, D region

Most empirical models evolve in time as the arrival of new measurements allows improvements of the coefficients.

Table 1b. Empirical Models of Ionospheric Electron Density

Models without ITU Peak	Characteristics
Chiu ionospheric model	Three superposed Elias-Chapman layers

(Ching and Chiu, 1973; Chiu, 1975), ionosonde data	(E,F1,F2), phenomenological description of peak parameters
Kohnlein (1978), rocket, ionosonde, topside sounder, in situ data	One Elias-Chapman layer with parameterised scale height, phenomenological description of peak parameters
Di Giovanni and Radicella - DGR (Di Giovanni et al., 1992), ionosonde data	Analytical model based on routine ionogram scaling

Introduction of real-time ionospheric values at certain altitudes can improve the prediction accuracy of the empirical models at all altitudes. For example, the IRI model has an option for using real-time F peak density and altitude instead of the ITU mapped values.

4. EXAMPLE INTERNATIONAL REFERENCE IONOSPHERE (IRI).

This model has been produced, is maintained and updated by the IRI Working Group which is a joint enterprise of URSI (the International Radio Science Union) and COSPAR (the Comittee of Space Research). The bottomside of the IRI profile has been revised several times. The topside which is related to the Bent model only once. There is no doubt that the IRI is a good model for the region from the ground to the peak of the F layer but the topside needs improvements. Typical space weather applications use transionospheric propagation of radio waves. For such applications the IRI should be used with great care: some topside profiles (e.g., for high solar activity, nighttime, Northern higher mid latitudes) are wrong in the sense that they decrease much too slowly. Cases can be found with negative scale height profiles (exponential increase of electron density above the peak of the F layer). The official limiting height of the IRI is 1000 km. Continuation above this height is an extra-polation. This might lead to problems in transionospheric propagation studies which are sensitive to the electron density profile or to electron content above 1000 km. The Reference Ionosphere provides continuous values of electron density but continuity in spatial first derivatives is not guaranteed.

5. MODELLING THE AURORAL ENVIRONMENT

The high-latitude ionosphere provides a window to the outer magnetosphere, since electric fields, electric currents and energetic charged particle populations in magnetosphere readily project along magnetic-field lines down to the ionosphere, where they are more easily measured. The aurora is probably the best known feature of the high-latitude ionosphere. Although modelling of the high-latitude ionosphere has improved in recent years, most of the modelling attempts are only case studies (e.g. Sojka and Schunk, 1988). The main difficulty is that magnetospheric processes and solar inputs have an important effect on the morphology of the high-latitude ionosphere, and that the observational databases are still too sparse to enable the development of an empirical model which has adequate parameters to describe the dependence on the various ionospheric drivers. Also, even with the most extreme simplifying assumptions, the high-latitude ionosphere cannot be treated analytically.

A few statistical models of certain high-latitude ionosphere regions have been produced by combining measurements from different satellite missions with partial success. As an oversimplified high latitude morphology is present in empirical models of Chiu (1975) and IRI (Bilitza, 1990), they are not practical at this time. Ruch et al. (1982) developed a simplified model of the high latitude ionosphere for telecommunications applications. The model is based upon the modification of the median ionospheric structure given by ITU-R, using formulations that characterise specific features of the high-latitude ionosphere. These include the auroral oval, the F2 region trough, F region irregularities, the auroral E region and its irregularities and auroral absorption.

To date, the alternative is to develop a numerical model that includes the physical processes of the high latitude regions. This had been done with the Time Dependent Ionospheric Model (TDIM) and has been proven to be successful at the climatological level (Sojka and Schunk, 1997). The simulation associated with this climatological study used the equivalent of 300 Cray XMP CPU hours. In order for a successful weather model of the high-latitude ionosphere to be developed, progress is needed on a storm input model. Even then models will only be as good as their weather drivers.

6. COSTPROF MODEL

The COSTPROF electron density height profile model has recently been adopted by the COST 251 Action "Improved Quality of Service in Ionospheric Telecommunication Systems Planning and Operations". This model is a member of a family of models with different complexity levels and intended uses:

- Nequick (quick run, simplified topside formulation);
– COSTPROF (topside formulation fully developed);
- NeUoG-plas (magnetic field aligned plasmasphere).

These models are empirical, but suitable for real-time applications. All three models are continuous in all spatial derivatives and are directly applicable to electron density calculation along arbitrary ray paths. The models are "profilers" in the sense that they can use ionosonde parameters from various sources as "anchor point" values for the profile (the full set consists of the critical frequencies foE, foF1, foF2 and the propagation parameter M3000(F2). The models are global ones but used with regional maps of ionosonde parameters they become regional models. The models allow the input of the properties of the F layer peak (height and electron density) instead of input of a full set of "anchor point" values.

Nequick and COSTPROF consist of two parts:

(1) The bottomside is a modification of the Di Giovanni - Radicella (DGR) model;
(2) The topside of Nequick is a semi-Epstein layer. The scale height increases linearly with height but a gradual limiting avoids unrealistically large values. COSTPROF uses O^+–H^+ equilibrium with a Chapman layer. Three parameters are modelled: the oxygen scale height at the F layer peak, its height gradient and the O^+–H^+ transition height.

NeUoG-plas is identical with COSTPROF from the ground to 2000 km where a third model region is superposed: a magnetic field aligned plasmasphere with H^+ diffusive equilibrium in magnetic flux tubes. The decrease of the accelaration of gravity and the widening of the flux tubes with height are taken into account. The use of equivalent dipole poles ensures that the field lines peak above the magnetic dip equator used in model regions 1 and 2 (the ITU-R equator). Since continuity across the magnetic tip equator is a necessity, electron density and profile scale height are recovered on both ends of the field lines and a gradual inter-hemispheric compensation leads to the model values in the plasmasphere. The model also contains a plasmapause.

Work is ongoing on simplified versions of COSTPROF which might be more directly relevant to the forecasting of total electron content, which is crucial in positioning applications.

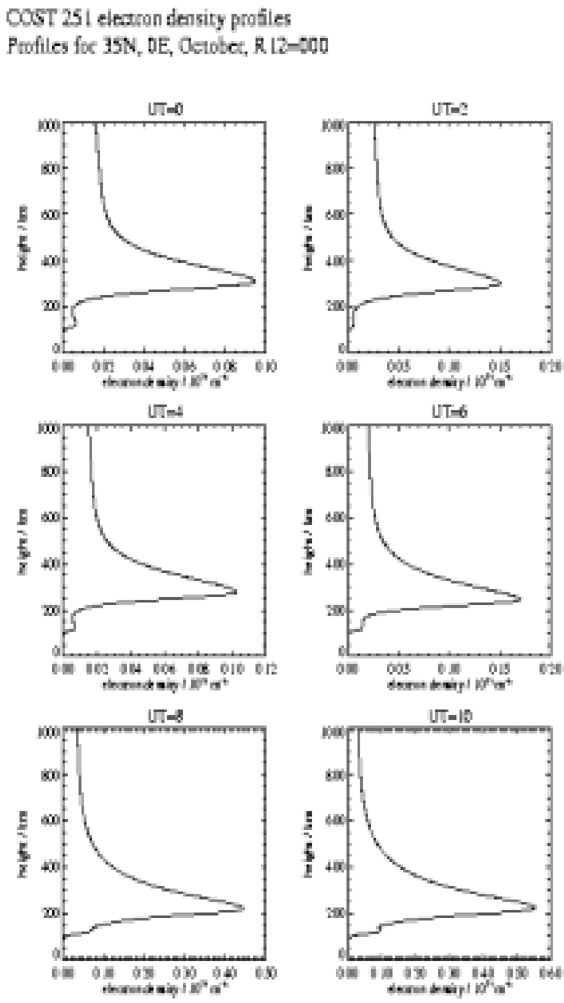

Figure 1. *COSTPROF Electron density height profile.*

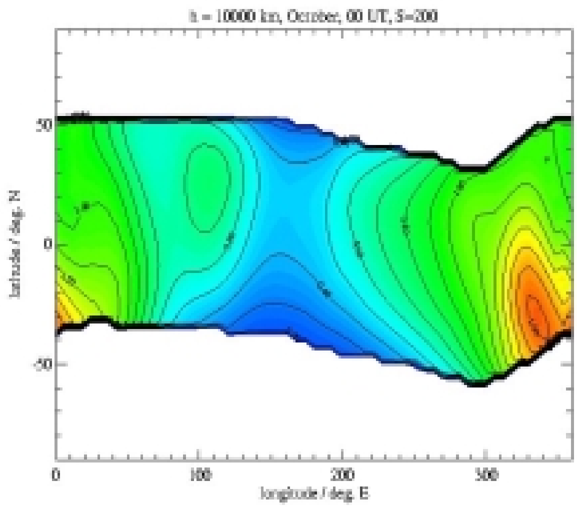

Figure 2. *NeUoG-plas Map of electron density at constant height.*

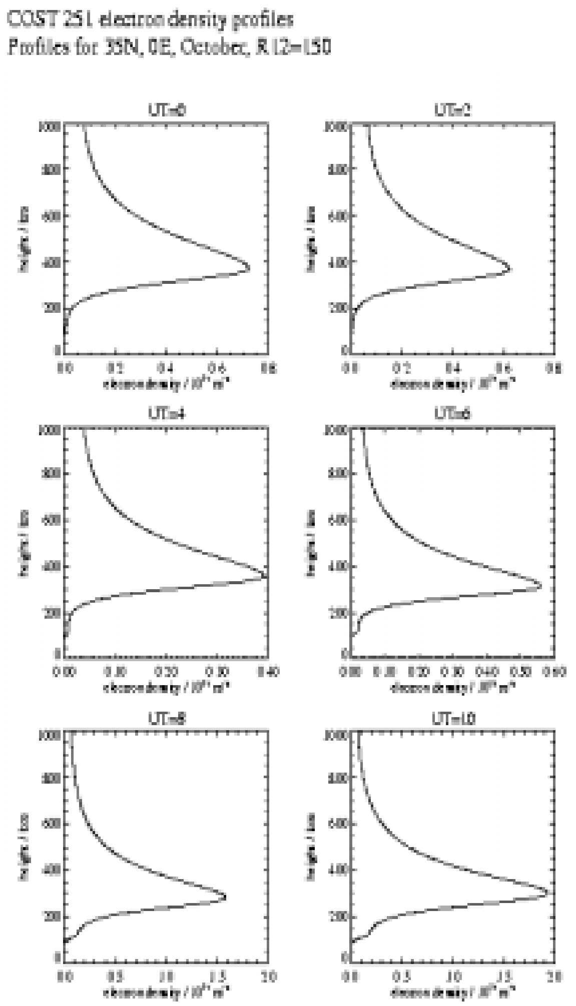

Figure 3. *COSTPROF Electron density height profile.*

Figures 1-4 show a variety of results on electron density profile modelling which can be obtained with the most recent COSTPROF model.

7. CONCLUSIONS

This review has focused on models of the electron-density height profile. Global numerical models have the potential to provide better understanding of high-latitude effects. Further research is needed to increase their ability to assimilate measured data and improve their computer performance.

Although there is a limit to the accuracy with which any empirical model may represent the instantaneous ionosphere, this approach is probably the most practical for ionospheric weather applications. Auroral effects can be taken into account with an empirical trough model. Of course empirical models rely on good quality real-time data, for example from a network of ionosondes.

When real-time data are not available, statistical empirical models giving average values of ionospheric characteristics and their natural variabilities provide a useful fall-back option.

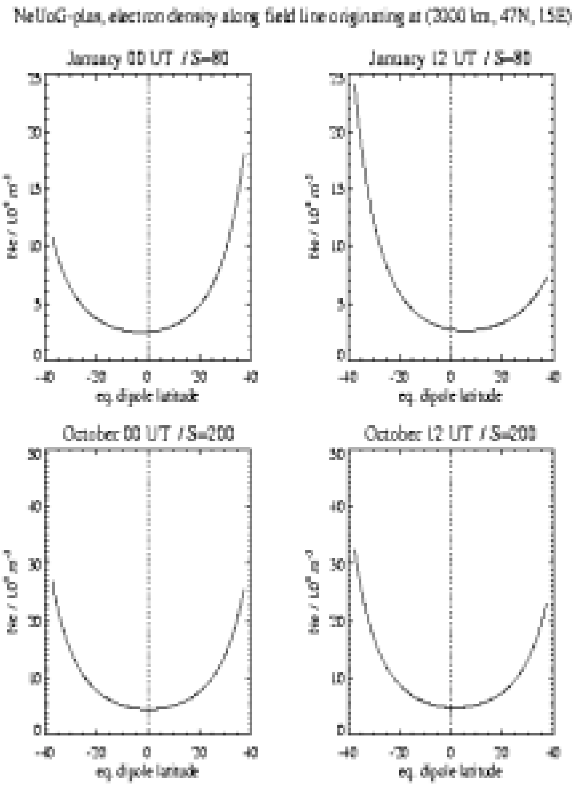

Figure 4. *Electron density along magnetic field line.*

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