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Modelling of the electron density height profiles in the mid-latitude ionospheric *D*-region

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Abstract
A new mid-latitude *D*-region (50-105 km) model of the electron density is presented obtained on the basis of a full wave theory and by a trial-and-error inversion method. Daytime (at different solar zenith angles) absorption measurements by A3-technique made in Bulgaria yielded data with the aid of which the seasonal and diurnal courses of the $N_e(h)$-profiles were derived. Special attention is drawn to the event diurnal asymmetry, or uneven formation of the ionosphere as a function of insulation. The latter is probably connected with the influence of the diurnal fluctuations in the local temperature on the chemistry involved in the electron loss rate, as well as the diurnal variations of the main ionizing agent (NO) in the *D*-region. That is why the $N_e(h)$-profiles in the midlatitude *D*-region are modelled separately for morning and afternoon hours.

Key words *ionospheric D-region – electron density height profile – absorption measurements – full wave theory – trial-and-error method*

1. Introduction

In the present International Reference Ionosphere (IRI) the produced $N_e(h)$-profile *D*-region model differs considerably from in-situ or ground based measurements. Due to special conditions of the physics and chemistry of the lower ionosphere, this region should be considered separately from the upper ionosphere. Within the limits of *D*-region the electron density changes from several electrons up to several thousands of electron per cm^3, but it remains always lower than the neutral density. Because of this relatively dense background atmosphere many experimental methods adequate at higher altitudes often supply doubtful results.

In the present paper diurnal and seasonal courses of the $N_e(h)$-profiles in the midlatitude *D*-region are derived from multifrequency absorption measurements by A3 technique made in Bulgaria on the basis of a full wave theory by a trial-and-error inversion method.

2. Theoretical model of radio wave propagation

A full wave numerical technique for solving Maxwell's equations was developed recently by Mukhtarov (1994). His theoretical model for radiowave propagation departs slightly from the previous ones (Pitteway, 1965; Singer, 1972). The method is based on the sub-

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division of the ionosphere into homogeneous layers with sufficiently small thickness. A solution in elementary functions was derived in the homogeneous layers depending on the boundary conditions between the neighbouring layers. A condition was used that imposes a discontinuity of the electromagnetic field vector on the boundaries which was a result from applying the electrodynamic equations in an integral form to the boundaries (Tamm, 1949; Chernij, 1972). A discontinuity of the normal electric and magnetic components and a continuity of the tangential ones were obtained by using divergent Maxwell's equations. The variability of the electric permittivity from one layer to another leads to a discontinuity of the normal component of the electromagnetic field, or the partial reflections and refractions appear on the boundaries. The boundary conditions thus formulated modelled very well the mechanism of partial reflections from an ionosphere where the characteristics of the medium change with a significant height gradient, a situation typical for the lower ionosphere. In this way, the deviating absorption obtained at total reflection can also be estimated very accurately.

The calculation is started at a great height, above which the electromagnetic field is assumed to be absent (or the region responsible for the radiowave propagation is below the accepted height) and proceeds downwards. The field structure in the upper layer always allows the field constants for the adjacent lower layer to be calculated. An important feature of the program is the orthogonalization process used to maintain the independence of the solutions during a long integration (Mukhtarov, 1994).

3. $N_e(h)$-model and method for solving the inverse problem

Usually two methods of approach are used to model the $N_e(h)$-profile: i) the electron densities are given at definite altitude levels (applied usually at in-situ measurements), and ii) the $N_e(h)$-profile is produced by a chosen mathematical function (as in IRI). We decided to accept a combined approach, suitable to the measurements used in this paper. The ionospheric absorption is an integral function, depending on the whole region of the radiowave propagation, or it depends not only on the electron density at some height levels, but also on the shape of the $N_e(h)$-profile. This makes it necessary to present the $N_e(h)$-profile with a continuous function. Because at this stage it is difficult to select a function which can model the whole D-region satisfactorily well, an approach of partially functional interpolation is adopted. The $N_e(h)$-profile is generated by a limitted number of characteristic points, connected with special cubic splines, having extrema or inflections in these accepted points. In this way the whole $N_e(h)$-profile is a continuous function and also has a continuous first derivative. At given characteristic points the values of electron densities between them are determined uniquely. So, the variations of the $N_e(h)$-profile with solar zenith angle, season or solar activity can be modelled only with variations of the restricted number of points.

The inverse problem consists of finding such $N_e(h)$-profile, whose model values of absorption for a given set of circuits are closest to the measured ones. A criterion for the best approximation is the minimization of the mean square deviation. The characteristic points given here coincide with those obtained by Pakhomov and Korneeva (1988) on the grounds of the analysis of a large number of rocket measurements. From the above described inverse problem it is clear that we have to adopt some limits for the variation region of the characteristic points. We agree that IRI is a representative model for the highest D-region (there are many E-layer ionosonde measurements). That is why we accept from IRI the respective electron densities for the altitude 105 km. As regards the $N_e(h)$-profile, the ionospheric D-region is divided into two parts: lower and upper, which differ considerably with respect to physics and chemistry. The $N_e(h)$-profile in the upper D-region (80-105 km) is adopted as a monotonously increasing function, or it is very close to the classical Chapman theory. This region shows regular dependence on the solar zenith angle. An attempt was made to model the diurnal asymmetry of the $N_e(h)$-profiles observed in the ionospheric absorption. The shape of the $N_e(h)$-profile in the lower *D*-region (50-75 km) is investigated weakly and major differences exist in the known models. The IRI $N_e(h)$-profiles are extended down to 65 km and the existence of a so-called *CR*-layer is ignored, but some experimental methods demonstrated the «type-layer» around 60 km height (Thrane, 1974; Gruschwitz, 1974). We accept an $N_e(h)$-profile with a local maximum around 60 km and local minimum or inflexion around 70 km. Such a profile was also obtained by Pakhomov and Korneeva (1988) through rocket measurements in Volgograd (Russia), not far from the absorption measurements in Bulgaria.

4. Multifrequency absorption data

We use absorption data from 6 circuits (table I), as 3 of them are *LF* very obliquely incident radiopaths, which describe the lower *D*-region. The latter have continuous measurements, while the other *MF* circuits have at $\cos X \leq 0.2$. It means that data around solar culmination are absent for the upper *D*-region. So, we have daily values of absorption measurements at fixed solar zenith angles: $\cos X = 0.0$, 0.1 and 0.2. The data analysis shows that the diurnal asymmetry, especially well attending in the MF circuits, is connected not only with the inertness of the recombination processes, but also with the presence of diurnal fluctuations in the neutral atmosphere (Pancheva *et al.*, 1994). That is why the $N_e(h)$-profiles in the *D*-region are modelled separately for morning and afternoon hours.

5. Model $N_e(h)$-profiles

The present model of the electron density for the height interval 50-105 km expresses the evolution of the $N_e(h)$-profile at high solar activity (R = 100) according to the solar zenith angle and the season in the morning and afternoon hours.

Summer – During this season the inter-atmospheric relations are the weakest ones, that is why the data scatter is very low. The most important feature of the lower *D*-region is the drop in the ionospheric bottom down to 53-54 km. The influence of the electron density gradient around 60 km on the LF ionospheric absorption is responsible for the increase in the ionosphere absorption. The diurnal asymmetry is well expressed in the region 80-90 km, as the electron densities are higher in the afternoon hours (fig. 1a).

Winter – The mean bottom of the winter *D*-region is higher (more than 3-4 km) than the summer one. This essential difference explains very well not only the seasonal course of the LF very obliquely incident radiowave absorption, but also is a basic reason for the seasonal distinctions in the manifestation of the SID-effects (Mukhtarov and Pancheva, 1995). A gen-

Table I. The basic characteristics of the radiopaths used.

Transmitter	Operating frequency	Distance	Reflection point
Allouis	162 kHz	1727 km	44.4°N, 12.3°E
Oranienburg	177 kHz	1388 km	47.7°N, 18.0°E
Warsaw	225 kHz	1114 km	47.5°N, 21.4°E
Petrich	747 kHz	119 km	42.8°N, 23.3°E
Iasi	1053 kHz	600 km	44.5°E, 25.3°E
Vidin	1224 kHz	119 km	43.9°N, 23.0°E

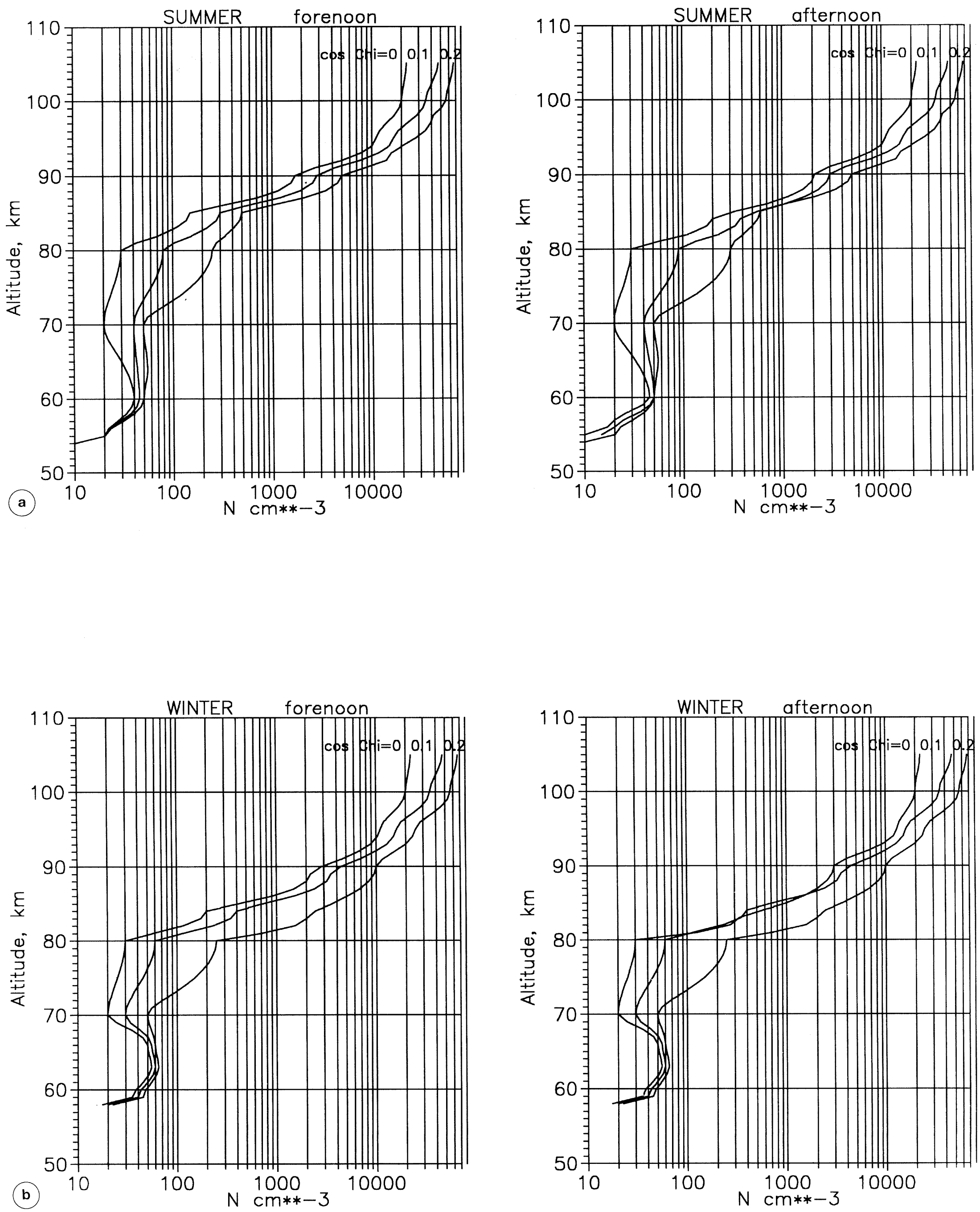

Fig. 1a,b. a) Summer $N_e(h)$-profiles at different solar zenith angles, separately for forenoon and afternoon (R = 100); b) winter $N_e(h)$-profiles.

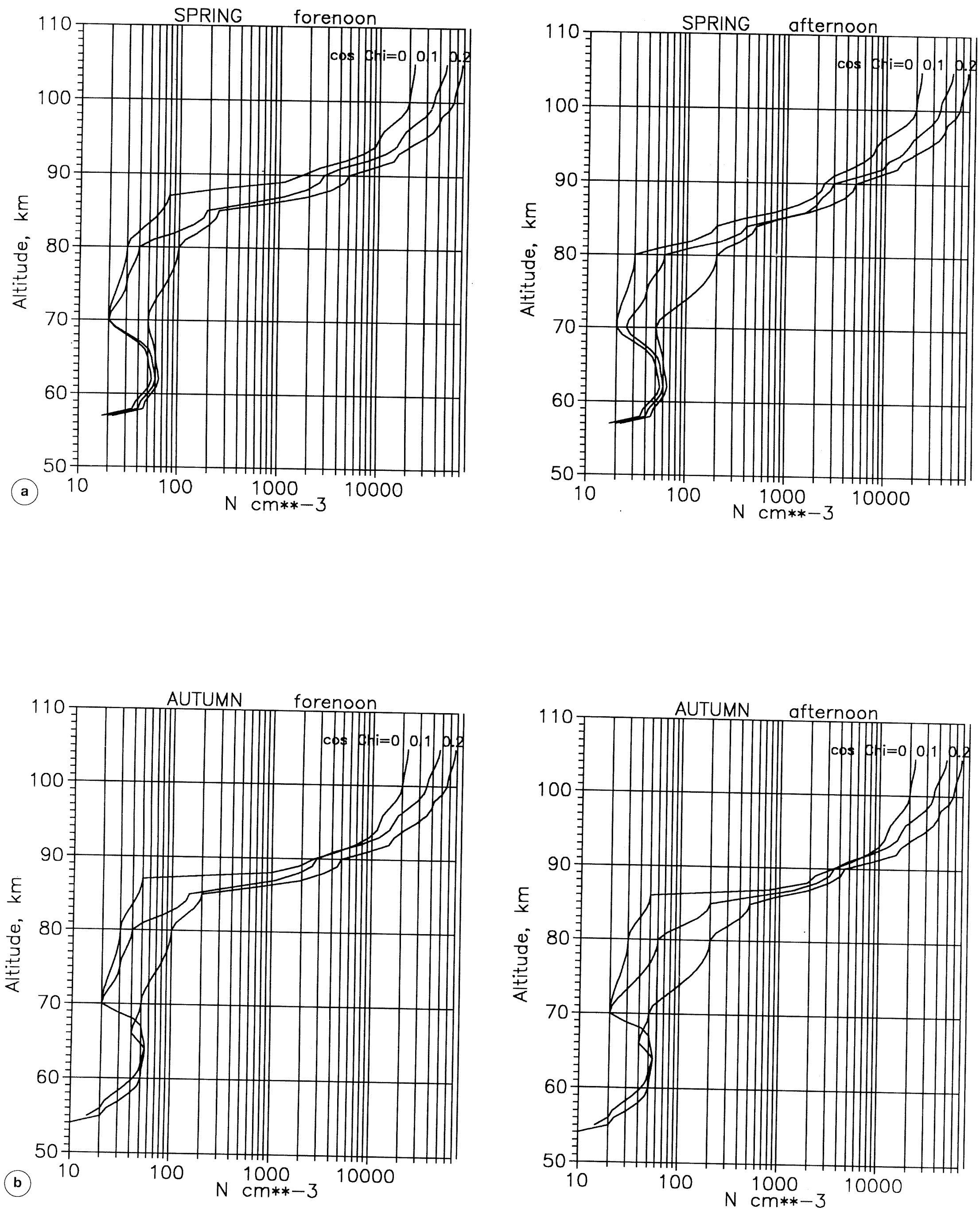

Fig. 2a,b. a) Spring $N_e(h)$-profiles; b) autumn $N_e(h)$-profiles.

eral increase in the electron density is visible above altitude 80 km. The diurnal asymmetry is insignificant during winter, but the electron density at sunset is higher than at sunrise (fig. 1b).

Spring – There is a difference in the time scales for the lower and upper *D*-region transition. The lower *D*-region adjusts itself to spring conditions comparatively slowly, as the essential changes of the LF ionospheric absorption are visible during May. That is why the spring model of the lower *D*-region is similar to the winter one, with slightly lower ionospheric bottom. The asymmetry between sunrise and sunset electron densities in the altitude range 70-85 km is very obvious, as the latter are significantly higher (fig. 2a).

Autumn – Again the time scales for transition are different for lower and upper *D*-region. The transition of the lower *D*-region occurs very sharply during the second half of October (so-called «October-effect»). The reconstruction of the upper *D*-region started at the end of August and its basic feature is connected with a very strong decrease in the electron density in the altitude range 70-85 km during sunrise and sunset (fig. 2b).

The basic seasonal and diurnal variations of the $N_e(h)$-profile in the altitude range 50-105 km are similar to those described by Singer *et al.*, (1994) and Friedrich and Torkar (1992), but two main peculiarities are introduced in the present paper: i) the existence of the so-called «type-layer» with maximum around 60 km height (known also as *CR*-layer), and ii) the obtained lower values of the electron density in the altitude interval 70-80 km. Independently of the fact that some authors discard the attendance of the *CR*-layer we note that there are measurements showing its existence (Mechtly and Smith, 1968; Thrane, 1974; Gruschwitz, 1974; Mambo *et al.*, 1983; Pakhomov and Korneeva, 1988). Nor is the second peculiarity connected with the lower values of the electron density in the 70-80 km height range a unique result. Similar values are derived by *in-situ* measurements presented by Mechtly and Smith (1968, 1970).

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