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A comparison of results derived from scaling VS chirp-ionosonde ionograms with the international reference ionosphere (IRI)

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Abstract

The results derived from processing vertical-incidence ionograms obtained with the chirp-ionosonde at Irkutsk for different winter time intervals (February) and at equinox are presented. The peak height hmF2 was determined by Dudeney's formula based on ionogram parameters, including the coefficient M(3000). The algorithm is suggested for determining the coefficient M(3000) in the automatic mode using the conventional form of the transfer curve method without invoking a standard transparency called the "transfer curve". The parameters foF2 and hmF2 are compared with the international reference ionosphere (IRI-95) model. It is found that in most cases the values of the foF2 and hmF2 parameters, calculated in the IRI-95 model, are similar to the median ones. It is confirmed that for practical purposes where it is necessary to know the radio wave propagation conditions along the propagation path, the IRI model is convenient and attractive.

Keywords: Ionosphere (modeling and forecasting); IRI (empirical international reference ionosphere)

1. Introduction

Information obtained from vertical-incidence sounding (VS) ionograms with the chirp-sounder (Brynko et al., 1988) is insufficient for practical purposes of calculating propagation characteristics. Using additional algorithms for determining the basic ionospheric parameters (foE, foF2, hmF2, and ymF2), as well as the electron density profiles themselves, enhances the capabilities of the ionosonde. The question of ionogram processing where ionospheric parameters and profiles are obtained simultaneously, was addressed in a sufficiently large number of publications (McNamara et al., 1987; Berkey and Stonehocker, 1987; Reinisch et al., 1991; Altyntseva et al., 1990; Wilkinson, 1998). However, it cannot be said unambiguously that this problem is completely solved. Therefore, the semi-automatic (interactive) approach in obtaining ionospheric parameters using ionograms from the chirp-ionosonde is the most effective to date. For radio communication and radar problems, it is necessary to have the spatial distribution of electron density along the propagation path, but measurements from the VS ionosonde at a single location cannot ensure this. Therefore, ionospheric models should be invoked, which provide ionospheric profiles in sections of the path, and current data should be used in order to adapt the model to actual conditions.

Such requirements are met by the empirical international reference ionosphere (IRI) model recommended by the Union Radio Science International (URSI) for practical implementation in decametric wave propagation applications (Dudeney and Kressman, 1986; Bilitza, 1990; Bilitza and Rawer, 1990). The IRI model was tested against sufficiently large experimental material obtained in regions where modern digisondes are installed, as well as against data from standard automatic ionospheric stations (AIS) for mid-latitudes, exclusive of the data for East Siberia (Russia). Work on improving the IRI model has been

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underway all the time and a new version, the IRI-2000 model, has now been developed (Bilitza, 2001). The IRI model was used in calculating maximum usable frequencies (MUF) along the Magadan–Irkutsk path, and its validity was assessed (Chistyakova et al., 2001). For that reason, it is appropriate to employ in the IRI model of adaptation for calculating the profile by obtaining the profile parameters from VS ionograms and to use the procedure of inverting the ionogram into the profile of true heights at the stage of testing, as not all experimental ionograms are suited to calculate the $N(h)$-profiles. To achieve a reliable implementation of the IRI model in the region of East Siberia, it is necessary to make sure that here, too, the IRI model for foF2 and hmF2 gives results comparable with experimental data.

The objective of this paper is: (1) to demonstrate the capabilities of the simplified technique for calculating the hmF2 from a digitized F2-layer trace of the VS ionogram; (2) to compare the ionograms processing results for Irkutsk (lat. 52°, long. 104°) with profile parameters obtained in the IRI-95 model for the same conditions, both in the long-term prediction (LP) mode and in the adaptation mode.

2. Technique for analyzing experimental results

This paper presents the results of automatic as well as semi-automatic processing of VS ionograms measured with the chirp-ionosonde operated by the ISTP (Irkutsk) (Brynko et al., 1988) at 15-min intervals from November 2 to 20, 1993, March 1 to 12, 1996 and from March 4 to 12, 1997, as well as for separate days for the other months (February 1989 (days 11, 15, 18, 19, and 20), October 1989 (23, 24, and 26), February 1994 (days 15, 16, 17, and 18), and February 1996 (from 22 to 29). In November 1993 there occurred three magnetic storms that produced the disturbed days of November 4, 5, 18, and 19. In March 1997, a solar eclipse was recorded at Irkutsk (March 9 is day 67 of the year, at 0.52 UT). Programs (Brynko et al, 1988; Altyntseva et al., 1990), which envisage two versions of ionogram processing (a fully automated version, and the version involving intervention of the operator), were used to determine the parameters foE, foF1 and foF2, and h′–f traces of those layers which were present at the time of recording the height–frequency characteristic (HFC). The processing of VS ionograms taken in 1996 used a fully automatic mode, from recording to output the parameters. Of all recorded ionograms for that period, only 65% were subjected to an automatic processing. This suggests both a complexity of the information process and a need to seek methods of further improvement upon the technique of automatic determination parameters of VS ionograms.

The technique of semi-automatic (interactive) approach was predominantly used in order to exclude the error in the determination of foF2 in the automatic mode. A semi-automatic processing is carried out in two stages. The first stage involves a total digital automatic processing of the ionogram where primary VS signal processing programs identify the points on the ionogram with the maximum signal amplitude characterizing the arrival times (Grozov and Nosov, 1998). These points are displayed on a personal computer. After that, the operator singles out only those points on the ionogram, which correspond to the h′–f traces. The points of arrival times lying outside this plot are neglected. This is followed by an automatic recording of the virtual heights of separate layers in the format at uniform steps in frequency by marking off the beginning and end of the trace. For the analytical description of the HFC, the procedure provides an approximation over points characterizing the arrival times of the signal. The need to apply such an approach is dictated by the fact that, although radiation frequencies vary uniformly over the experiment, the measured HFC at separate frequencies can have gaps in virtual heights. Besides, along with the main, regular layers, various manifestations of disturbances (sporadic Es, F-spread, diffusiveness, hooks near foF2, kinks, twin-reflections, etc.) are observed. Therefore, when digitizing such complicated ionograms, it is more advantageous to use the interactive approach where the operator follows a standard technique for processing VS ionograms (Piggott and Rawer, 1978). In either case, in addition to critical frequencies and minimum virtual heights, it is necessary to determine the coefficient M(3000) which is used to determine indirectly the height of the ionization peak. To calculate the height of the peak electron density from the coefficient M(3000) we decided to use Dudeney's formula (Dudeney, 1983). The errors of calculating the height of the peak, using Dudeney's formula was estimated in McNamara et al. (1987) and Berkey and Stonehocker (1987). The substantiation for using this formula with minimum input information was presented in Dudeney (1983), and in Grozov and Kotovich (1999) we confirmed its usefulness for data where the height hmF2 was calculated by two techniques: T.L. Gulyaeva's IT-ERAN program (Gulyaeva, 1978) which is in wide use for calculating profiles (Gulyaeva et al., 1990), and Dudeney's technique (Dudeney 1983). To calculate the coefficient M(3000) requires the foF2 critical frequency and MUF for the range of 3000 km which, according to the instruction in Piggott and Rawer (1978), is determined from international standard "transfer curves" (transparencies) based on simplified Smith's method; the relevant references to publications outlining the basic principles of the method may be found in Kelso (1968).

In our algorithm, MUF (3000) is determined by a conventional form of the Smith method without such propagation curves as used in Aono (1962). According to the Breit and Tuve theorem (Breit and Tuve, 1926) about an equivalent triangle, for the range $D = 3000$ km from the effective height, the reflection angle (φ) is determined by a modified formula

$$\varphi = \text{arctg}(\sin(D/2R)/(x - \cos(D/2R))),$$

where R is the earth's radius, $x = (h' + R)/R$, and h' is the virtual height. Furthermore, it is necessary to check that the angle φ does not exceed the maximum angle for a given range: $\varphi_{\max} = \arcsin(l/x)$.

The oblique-incidence sounding frequency $f = kf_v \sec\varphi$ is deduced from this angle and the plasma frequency f_v corresponding to a given effective height h' by the secant law, taking into account the curvature of the earth and the ionosphere. The correction factor k for $D = 3000$ km is 1.117 (Wieder, 1955). The algorithm for deducing the frequency and propagation characteristics is described in Kiyanovsky (1971).

Thus, the corresponding pairs of virtual heights h' and reflection frequencies f_v of one ionogram trace identified as the F2-layer of the ordinary component are used to determine the oblique-incidence sounding frequencies, and it is the highest frequency which determines the MUF(3000). The coefficient M(3000) can then be determined as MUF(3000)/foF2.

The accuracy of calculating the parameter M(3000) is determined both by errors of deducing the foF2 critical frequency for any approach and by the accuracy of calculating MUF(3000) by the "transfer curve" method. Therefore, for digitizing h'–f traces it is necessary to carefully monitor the correctness of the inclusion of the digitized HFC in the observed h'–f traces. In doing this, it should be borne in mind that errors introduced by approximating traces when filling the set of heights will give rise to errors in determining the coefficient M(3000) and, hence, the height of the peak hmF2 as well.

It should be noted that an important element of the chirp-ionosonde with regard to the reliability of obtaining data on the signal delay (in terms of the virtual height) is the provision of a reliable referencing to the standard time meter and a correct placing of the initial mark for measuring the virtual height. For that reason, this study is devoted not only to discussing the results derived from processing the ionograms by the above technique for obtaining hmF2 using a simplified algorithm but also to explaining the factors that sometimes lead to substantial differences of these heights from those given by the IRI model.

In the long-term prediction mode, calculations of the profile node parameters as well as calculations of the profile itself were based on using the international IRI-95 model with URSI coefficients. Diurnal foF2 and hmF2 variations were calculated; based on the parameters obtained from experimental data at the processing stage. The height hmF2 was determined from the coefficient M(3000) in accordance with Dudeney's technique. Our choice of this straightforward formula was dictated by the promptness and minimum input information. The parameters determined from VS ionograms were used to calculate the model $N(h)$-profile, which was compared with the profile calculated from the ionogram by T.L. Gulyaeva's technique.

3. Discussion of results

An analysis of the data covering the period of observation has shown that at the time of the March 9, 1997 eclipse (day 67), from 00.00 to 02.00 UT, the anticipated, considerable decrease in electron density in the F-layer peak was observed. The solar eclipse response to the ionosphere in the experiment under consideration is described in sufficient detail in Grozov and Kotovich (1999). In November 1993, the ionospheric response to magnetic disturbances was also observed, which were characterized by significant deviations from the mean suggesting that the foF2 has a wave character in its day to day behavior. If it is assumed that the model describes average undisturbed periods, then the experimental median must not differ very strongly from model values. Therefore, model values must—to some extent—substitute the median. This is mentioned in publications on testing results of comparisons of experimental data obtained in regions not covering Russia's East Siberia. The IRI model, as a median model, is also compared with models in which disturbances are taken into account (Fuller-Rowell et al., 2000). Such an extensive use of a median model as the reference for quiet conditions indicates that the complex developed is reliable, although the height in the complex is also calculated by an approximate formula from the coefficient M(3000), but Bilitza's rather than Dudeney's.

Thus, the IRI model can be advantageously used in such applications as radio communication and radar where it is necessary to know predicted oblique-incidence sounding frequencies for different paths including those for which Irkutsk is a transmitting or receiving center. In this connection, we carried out an additional comparison of the height of the peak electron density and foF2 critical frequencies obtained by processing the VS ionograms from the chirp-ionosonde (Irkutsk, Russia) with LP data in the IRI-95 model by adapting to a current monthly index of solar activity. Since the model is a median one, the comparison involved calculations of the median foF2 and hmF2 using ionogram parameters from the chirp-ionosonde for the relevant interval observed, supplemented by data from the AIS where available. Unfortunately, regular observations at the AIS at Irkutsk were suspended in 1997 while observations with the chirp-ionosonde are carried out on an irregular basis. The height of the peak was determined from median critical frequencies foE and foF2, and from the coefficient M(3000). As an example, Fig. 1a presents the experimental median foF2 (solid line with points) and the values of foF2 calculated in the IRI-95 model (solid line—from CCIR coefficients, dashed line—from URSI) for the season of November 1993 with $F_{10.7}$ equal to 93.8; Fig. 1b—also for March 1997 with $F_{10.7}$ equal to 73.9. In the former case the monthly median is given, and in the latter case the median was calculated from 9 days of observation.

Fig. 2 shows the diurnal variations in foF2 critical frequencies for the days of observation obtained by a semi-automatic processing (solid line). Dashed lines in the

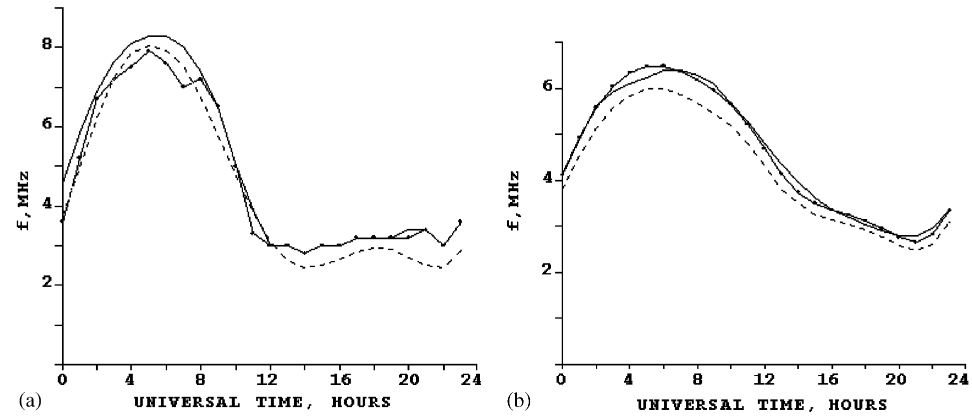

Fig. 1. Diurnal variations of the median of critical frequencies: (a) for November 1993 and (b) for March 1997 (solid line with dots—experiment, solid line—IRI model (CCIR coefficients), dashed line—IRI model (URSI coefficients).

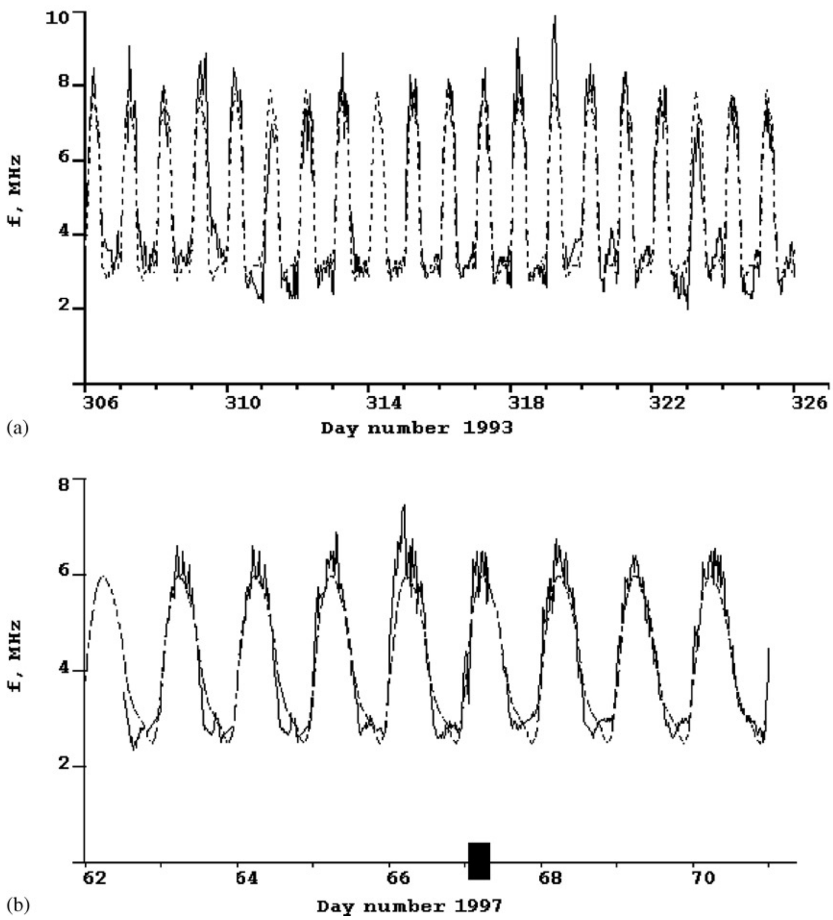

Fig. 2. Diurnal variations of foF2 critical frequencies: (a) November 1993 and (b) March 1997 (solid line—experiment, dashed line—IRI model (URSI coefficients). In Fig. 3b the square shows the eclipse time.

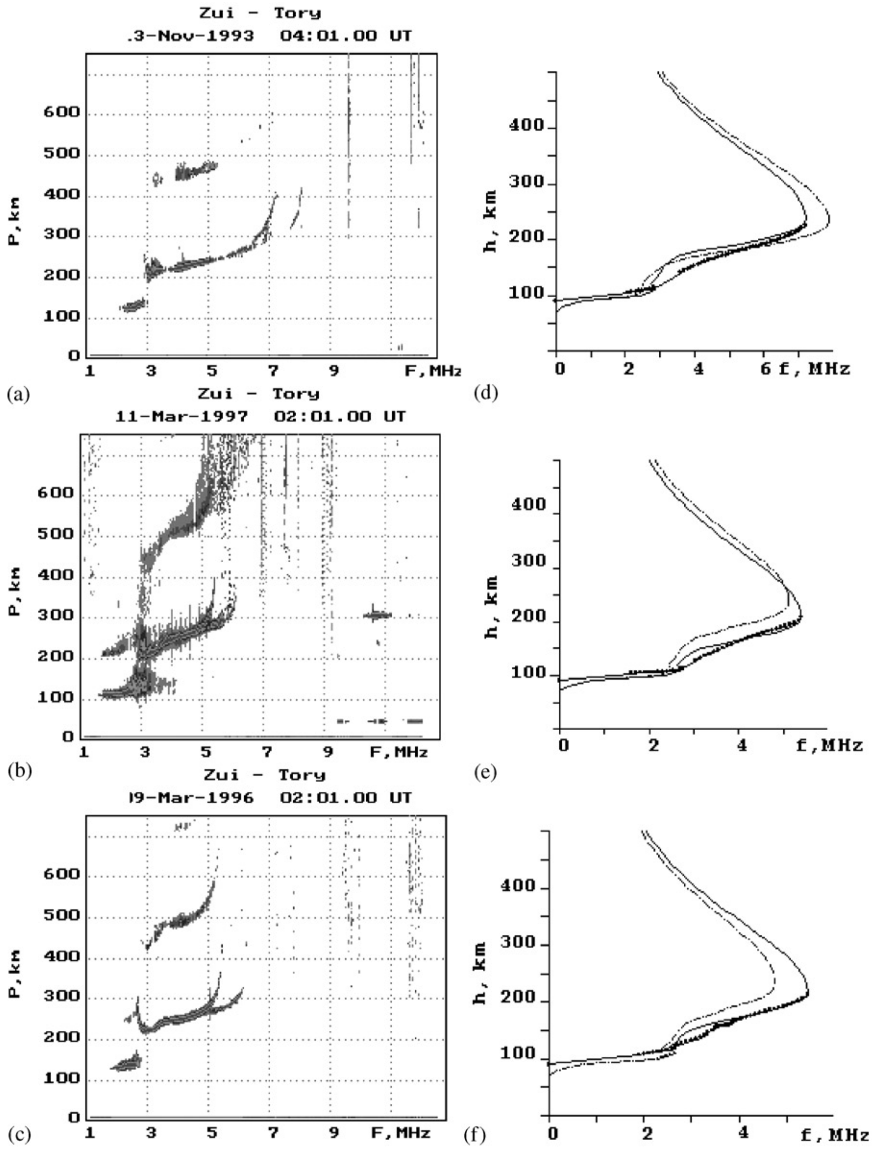

Fig. 3. Experimental h'–f traces (3a–c) and $N(h)$-profiles (3d–f); dashed line—predicted profile in terms of the IRI model in the LP mode, solid line with dots—profiles calculated from ionograms by T.L. Gulyaeva's technique; solid line—$N(h)$ obtained in terms of the IRI-95 model adapted to actual foF2 and using the calculated hmF2 from the coefficient M(3000).

figure also show the values of foF2 calculated in the IRI-95 model for the middle of the month for monthly mean $F_{10.7}$ indices. In Fig. 2b, the time of solar eclipse is shown by a square. As an example, Fig. 3 presents the profiles for the time when the predicted critical frequency differs only slightly from the experimentally observed frequency. Fig. 3 a–c presents the ionograms taken by the chirp-ionosonde: the solid line shows the digitized traces of the E- and F-layers. Fig. 3d–f shows the $N(h)$-profiles corresponding to ionograms 3 a–c: dashed line shows the predicted profile in the IRI model in the LP mode for given indices of solar activity; the solid line with points shows the profiles calculated from ionograms following T.L. Gulyaeva's technique; the solid line corresponds to $N(h)$ obtained in the IRI-95 model by adapting to the actual foF2 and to the hmF2 calculated from the coefficient M(3000). In this case the coefficient M(3000), deduced from a standard international propagation curve, is 3.4 for ionogram 3a, 3.64 for 3b, and 3.5 for 3c. For the same ionograms, according to the technique of a modified method of the "transfer curve" proposed in this paper, M(3000) is 3.41, 3.63 and 3.52 in the first, second and third variants, respectively. These

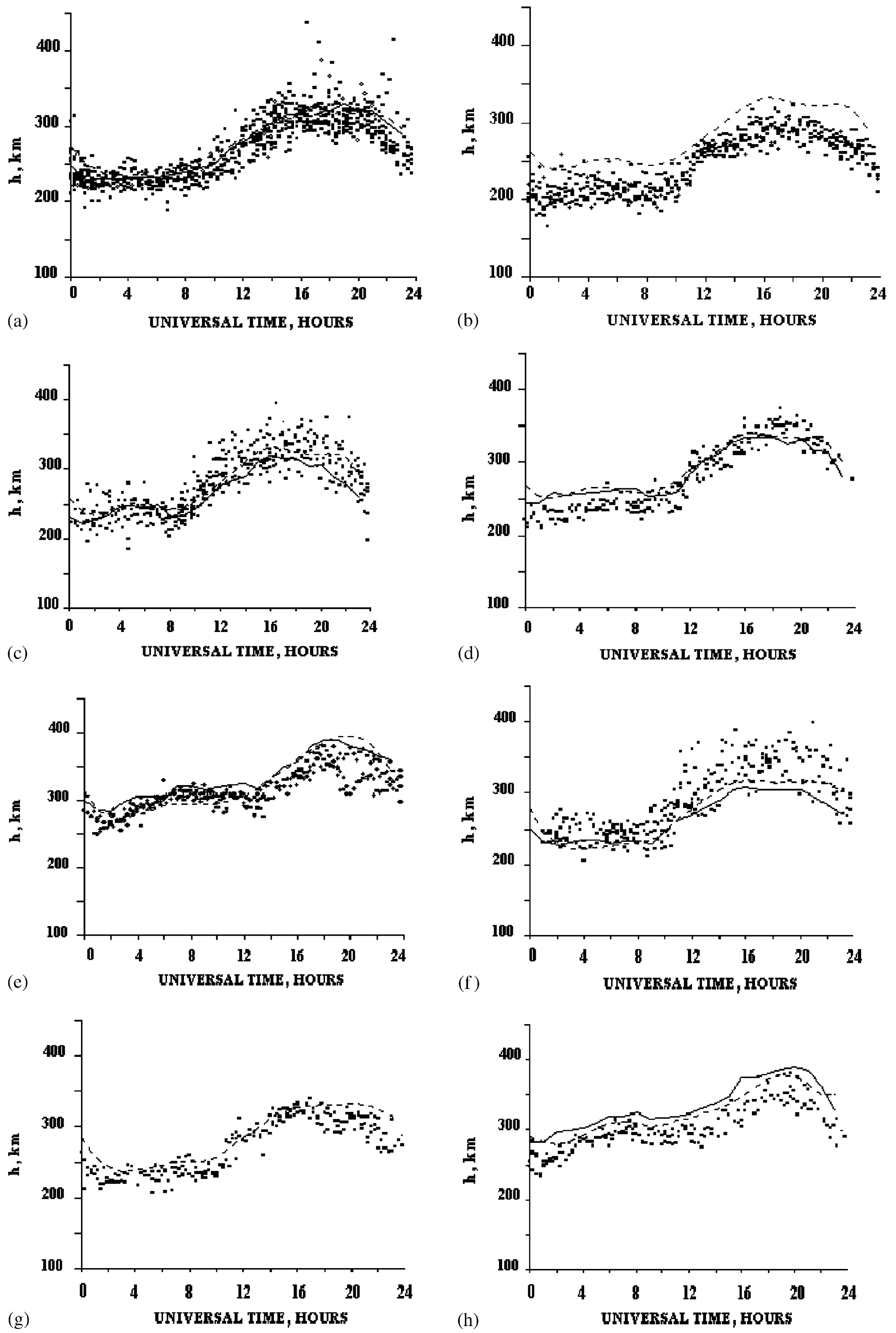

Fig. 4. Diurnal variations height of the peak electron density hmF2: (a) for November 1993 ($F_{10.7} = 93.8$), (b) for March 1997 ($F_{10.7} = 73.9$), (c) for March 1996 ($F_{10.7} = 70$), (d) March 1994 ($F_{10.7} = 89.5$), (e) February 1989 ($F_{10.7} = 217$), (f) February 1996 ($F_{10.7} = 69.8$), (g) February 1994 ($F_{10.7} = 97.2$), and (h) October 1989 ($F_{10.7} = 217$) (solid line—hmF2 calculated from experimental median foE, foF2 and M(3000), dashed line—hmF2 predicted of IRI model, dots—hmF2 calculated by the Dudeney method from chirp-ionosonde ionograms).

values of M(3000) and the parameters foE and foF2 taken from ionograms were used to calculate (by the Dudeney formula) the heights of the ionization peaks (240, 209 and 220) which are similar to the values of hmF2 obtained from the profile in accordance with the ITERAN program (228, 208, and 213).

Fig. 4a for November and Fig. 4b for March 1997 (for 9 days) present the diurnal variations of the calculated hmF2: the solid line corresponds to the height calculated from the median foE and foF2 and from M(3000), and the dashed line refers to the model. The November median was obtained from the data for the entire month by taking account of the AIS measurements as well, and the March 1997 median was deduced for 9 days of observation with the chirp-ionosonde only. Points in Fig. 4 show the values of the height calculated from chirp-ionosonde ionograms using the coefficient M(3000). Open circles in Fig. 4a represent the hmF2 for the disturbed day of November 18. An analysis of raw and processed material showed that while the electron density at a maximum of the profile is determined exactly from the VS data on the F2-layer critical frequency, the height of the peak is determined approximately by indirect methods from the digitized $h'–f$ trace of the F2-layer (from the virtual height h' and from the plasma frequency f). Furthermore, it was found that the VS ionograms recorded in March 1997 involved a systematic error in the determination of the initial mark of time reading. This introduced an error into the measurement of the virtual height ($\Delta h' \approx 20$ km) and, hence, of the parameter M(3000). It is for that reason that the height of the ionization peak deduced from the VS ionogram for that period is substantially lower than the hmF2 predicted in the IRI model.

Furthermore, our analysis used the processed data for March 1996 ($F_{10.7} = 70$) when the observing interval also corresponded to the beginning of the month, as in the March 1997 experiment. Fig. 4c presents the results on hmF2 for March 1996. It is evident from the figure that the heights calculated from M(3000) using ionograms for the concerned period are in agreement with the model. Computational results on hmF2 for the other periods used in the analysis are presented in Fig. 4d–h; for comparison, the solid line in this figure shows the heights calculated from the median foE, foF2 and M(3000) of the AIS data.

4. Conclusion

In this paper we have demonstrated, that in the region under consideration the model describes satisfactorily the peak electron density distribution, which confirms the results obtained by other authors for mid-latitudes. It has been established that during the periods under consideration the critical frequencies, calculated in terms of the IRI-95 model are in good agreement in their diurnal variation with experimentally observed frequencies using the chirp-sounder (6% error for median averages). In spite of the fact that the height of the peak from the ionogram was determined by approximate methods, the error in calculating the height of the peak electron density corresponds to that provided by long-term predictions of ionospheric parameters and does not exceed 15–20%. It was confirmed that for practical applications, where it is necessary to know the radio wave propagation conditions along the propagation path, the IRI model is convenient and attractive.

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