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Variations in the half width of the topside ionosphere according to the observations by space ionosondes ISIS 1, ISIS 2, and IK 19

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Abstract. More than 50,000 vertical profiles of the electron concentration observed on board the International Satellites for Ionospheric Studies ISIS 1 and ISIS 2 (1969–1980) and Intercosmos, satellite IK 19 (1979–1982) are analyzed to determine the half width of the topside ionosphere, Δh_{top}. The half-width parameter is determined as a residual $\Delta h_{\text{top}} = h05_{\text{top}} - h_mF2$, where the $h05_{\text{top}}$ height corresponds to a decrease in the maximum electron density in the topside ionosphere by a factor of 2 as compared with the concentration at the ionization maximum at h_mF2. An empirical model of the Δh_{top} parameter normalized to the maximum ionization height is created. The model provides Δh_{top} dependence on local time, geomagnetic latitude, and solar activity level for quiet geomagnetic conditions. The model makes it possible to determine the scale height of the topside ionosphere if it exceeds the half width by a factor of 1.3. A good agreement of the Δh_{top} empirical model with the values of this parameter calculated with the help of the Russian Standard Model of the Ionosphere (SMI) is obtained. The comparison with the International Reference Ionosphere (IRI) shows a significant overestimation of the half-width by the IRI model, where the $h05_{\text{top}} > 1000$ km height goes out the limits of the topside ionosphere at high latitudes under high solar activity. A formula to correct the electron concentration vertical profile in IRI using the empirical model of the half width of the topside ionosphere based on the data of ISIS 1, ISIS 2, and IK 19 satellites is presented. Thus the IRI version (ISO-IRI) including the plasmasphere model of SMI for the International Standardization Organization is improved. An increase of the accuracy of calculations in the ISO-IRI is demonstrated by the comparison with the EISCAT incoherent scatter data and total electron content GPS-TEC. The demo software of the ISO-IRI model with the correction method in the topside ionosphere and plasmasphere is presented at the Internet site of IZMIRAN.

1. Introduction

The International Reference Ionosphere (IRI) [*Rawer et al.*, 1978] created in the 1970s, has been improved since then in many of its parameters. The model makes it possible to determine ionospheric parameters for quiet midlatitude monthly mean conditions at any latitude and longitude as a function of the time of day, season, and solar activity level. Several generations of the IRI model have been used for forecasting of parameters of the ionized sphere of the Earth. However, in all its versions (including the recent

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one IRI 2000 [*Bilitza*, 2001]) the *Bent and Llewellyn* [1972] model of the electron density vertical profile in the topside ionosphere based on the data of the topside sounding on board the Alouette 1 and Alouette 2 satellites is used.

The comparison of IRI with the data of the satellite ionosonde on board Ionospheric Sounding Satellite (ISSb) showed that IRI considerably overestimates the electron concentration in the topside ionosphere (up to a factor of 5 at high latitudes and under high solar activity [*Iwamoto et al.,* 2002]). A need to improve the IRI-Bent model is emphasized by the problems of fitting IRI to current plasmasphere models [*Gallagher et al.*, 2000; *Webb and Essex*, 2000]. The authors of the latter models had to limit the ionospheric part of IRI by altitudes of 500–600 km to provide a continuous transition from the ionosphere to the plasmasphere, the plasmasphere models being developed independently of IRI. That is why many efforts are undertaken to improve IRI in the height region of the topside ionosphere and plasmasphere [*Bilitza,* 1985; *Bilitza and Williamson*, 2000; *Bilitza et al.,* 1998; *Gulyaeva*, 2003; *Gulyaeva et al.,* 2002; *Rawer*, 1990].

Current empirical models of the ionosphere (such as IRI, Russian Standard Model SMI [*Chasovitin et al.*, 1998], and the European Commission on Science and Technology COSTProf model [*Radicella and Leitinger,* 2001]) use the expression for the electron profile shape via the h_mF2 height and the maximum electron density N_mF2. The profile shape below the ionization maximum is in the best way characterized by the half width of the bottomside ionosphere [*Gulyaeva*, 1983] used in the IRI and SMI models. The half width is defined as the difference of the heights ($h_mF2 - h05_{\rm bot}$), where the $h05_{\rm bot}$ height below the maximum corresponds to the electron density of $0.5N_mF2$ and to a decrease of the maximum electron density in the ionosphere by a factor of 2, respectively, h_mF2 being the height of the ionization maximum.

The half width of the topside ionosphere is defined similar as an increment of height from h_mF2 to the $h05_{\rm top}$ level above the ionization maximum where the electron density is equal to $0.5N_mF2$:

$$\Delta h_{\rm top} = h05_{\rm top} h_mF2 \tag{1}$$

The half-width parameter is proportional to the scale height of the topside ionosphere, $H_{\rm top}$, indicating the height interval for $1/e$ decay of electron concentration. For example, for the Chapman α layer [*Chapman*, 1931] the scale height is determined by

$$H_{\rm top} = 1.3236\Delta h_{\rm top} \tag{2}$$

The formula of the Chapman α layer with a constant scale height above the ionization maximum is used for the extrapolation of the $N_e(h)$ profile toward the topside ionosphere to produce the total electron content Ionosphere Total Electron Content (ITEC) from ionograms [*Huang and Reinisch*, 2001]. The empirical model of the half width of the topside ionosphere may be used to model the scale height (taking into account the proportionality of equation (2) of the two parameters) in various solar and geophysical conditions to increase the accuracy of ITEC calculations from the ground-based ionosonde network. Moreover, it makes it possible to improve considerably the IRI electron density profile shape of the topside ionosphere as described below.

2. Modeling of the Topside Ionosphere Half Width on the Basis of Experimental Data

The topside sounding data from the International Satellites for Ionospheric Studies, ISIS 1 (1969–1971, the orbit altitude was 500–3500 km), ISIS 2 (1971–1980, the orbit altitude was 1400 km) [*Bilitza et al.,* 2003] and Intercosmos 19 satellite (1979–1982, the orbit altitude was 500–1000 km) are used as the database in the present study. These data cover more than a complete cycle of solar activity, including the whole range of diurnal, seasonal, and spatial variations in the vertical profile of the electron density $N_e(h)$ above the $F2$-layer maximum up to the satellite orbit. Most of these profiles do not include the $F2$ peak being terminated at the extreme observed plasma frequency $f_{\max}$. To compensate for that shortcoming, the lowest profile point has been extrapolated toward the F region peak with increment of frequency and height assumed so that the critical frequency $f_oF2 = 1.05 f_{\max}$ and the peak height $h_mF2 = h(f_{\max}) - 30$ km [*Kishcha and Kochenova,* 1996]. For further analysis more than 50,000 $N_e(h)$ profiles under quiet geomagnetic conditions (index $Kp < 3$) have been selected. The half width (1) was determined from the $N_e(h)$ profile at $N_e = 0.5N_mF2$. To create the empirical model mean values of the half width $\Delta h_{\rm top}$ normalized to the h_mF2 height were calculated:

$$\mathrm{Rat} = \Delta h_{\rm top}/h_mF2 \tag{3}$$

Ratio of equation (3) was determined for the specified ranges of spatial and temporal variations under quiet magnetic conditions according to the following scheme: (1) four levels of solar activity averaged over 81 days (three solar rotations) of sunspot number R_z during the solar minimum ($0 < R_z < 25$), moderate solar activity ($25 < R_z < 75$), high solar activity ($75 < R_z < 125$), and solar maximum ($R_z > 125$); (2) four intervals of local time hours, LT, for each level of solar activity: night (0000<LT<0200, 2200<LT<2400), dawn (0400<LT<0800), daytime (1000<LT<1400), dusk (1600<LT<2000); and (3) eight ranges of the geomagnetic dip latitude from the equator to the pole (a symmetry of the Southern and Northern Hemispheres is assumed; the latitude intervals are taken partly overlapping to make each sampling more representative). The number of data points for the sampling boxes is given in Table 1. When the number of observations has been insufficient (e.g., less than 20 profiles), the interpolation/extrapolation has been applied for the equation (3) ratio.

The choice of the three parameters indicated above is not incidental. It corresponds to the driving parameters of

Table 1. Number of Topside Electron Density Profiles at Sampling Boxes Used for the Analysis of the Topside Half Width of the Ionosphere at Four Levels of Solar Activity, Four Local Time Periods, and Eight Ranges of Dip Latitude

Sunspot Number	LT, hours	Dip $0° \pm 15°$	$20° \pm 10°$	$30° \pm 10°$	$40° \pm 10°$	$50° \pm 10°$	$60° \pm 10°$	$70° \pm 10°$	$80° \pm 10°$
0	00 ± 2	0	30	71	184	175	98	102	98
	06 ± 2	0	24	54	146	250	267	212	105
[0 : 25]	12 ± 2	0	7	16	91	156	187	203	115
	18 ± 2	4	74	105	255	303	301	393	293
50	00 ± 2	161	310	528	912	1099	1129	1439	1375
	06 ± 2	173	274	380	593	906	1081	1721	1554
[25 : 75]	12 ± 2	116	305	596	1138	1548	1827	2440	1874
	18 ± 2	346	743	1777	3261	4231	4424	5923	5473
100	00 ± 2	840	773	859	476	336	323	520	586
	06 ± 2	1566	1371	1096	680	645	778	998	772
[75 : 125]	12 ± 2	1683	1428	1275	919	782	806	1135	1022
	18 ± 2	3454	3952	4777	3386	3034	3218	3593	2736
150	00 ± 2	0	0	7	66	213	289	149	14
	06 ± 2	0	2	5	12	22	32	29	12
[> 125]	12 ± 2	139	94	118	91	87	62	36	17
	18 ± 2	6	23	56	153	440	538	253	29

the Bent's model: geomagnetic latitude, solar radio emission flux $F_{10.7}$ at 10.7 cm (proportional to the sunspot number R_z), critical frequency f_oF2, and the maximum height h_mF2, two latter parameters depend on local time. Other dependencies of the half width of the topside ionosphere on solar and geophysical conditions are implied by variations of the h_mF2 parameter of equation (3).

Figures 1a, 1b, 1c, and 1d show the half width of the topside ionosphere normalized to the peak height value according to observations on board the ISIS 1, ISIS 2, and IK 19 satellites and also the results of calculations using the IRI and SMI models. The results for IRI differ considerably from those for SMI and the data of ISIS and IK 19. In particular, under high solar activity ($R_z = 150$) at high dip latitudes (70–90°) the $h05_{\text{top}}$ height (where half decay of the peak electron density occurs) goes outside the topside ionosphere in IRI (exceeds 1000 km) and the ratio of equation (3) goes out of the frames of Figure 1a. The IRI values for the half width are overestimated also at high solar activity $R_z = 100$ in the polar zone (Figure 1b). In the vicinity of the equator, IRI also provides overestimated results as compared with the data of SMI, ISIS, and IK 19, though the shortcomings of the Bent's model near the equator were partly improved by *Bilitza* [1985]. The SMI model provides a better agreement of the relation (3) with the data of ISIS and IK 19 than the IRI model, the fact being most evident at high latitudes under high solar activity. This is explained by the use of the topside ionosphere model by *Benkova et al.* [1984] in SMI based on the IK 19 data.

The results of the analysis of observations on board ISIS 1, ISIS 2, and IK 19 provide an empirical model of the variations of half width in the topside ionosphere normalized to the ionization peak height. It depends on four driving parameters (sunspot number R_z, absolute value of geomagnetic latitude $|\Phi|$, local time LT, and the peak height h_mF2) and contains 200 mesh point values which make it possible to apply a linear interpolation of the ratio (3) for any intermediate solar and geophysical conditions. Relevant FORTRAN subroutine TOPH05 providing $h05_{\text{top}}$ height is incorporated in ISO-IRI software (IRI version for the International Standardization Organization) (available at ftp site of IZMIRAN ftp://ftp.izmiran.rssi.ru/pub/izmiran/SPIM/).

Figure 1 shows that at all levels of solar activity an increase of the ratio of the half width to the ionization maximum height is observed within the limits 0.3–0.8 from low to high geomagnetic latitudes. The half-width values at the dawn hours are prevailing. These results allow us to undertake a correction of the IRI model in the way described below.

3. Correction of the Topside Ionosphere Model by the Half-Width Parameter

The analytical description of the model of the topside ionosphere vertical profile in IRI [*Bent and Llewellin*, 1972; *Rawer et al.*, 1978] for the altitudes $h_mF2 \le h \le 1000$ km was presented by *Rawer et al.* [1981]:

$$N_e(h) = N_mF2 \exp(-Z) \tag{4}$$

We introduce a multiplier q in equation (4):

$$Z = q \times Y \tag{5}$$

where

$$Y = \frac{1000 - h_mF2}{700} \left\{ \frac{\beta\eta \ln[1 + \exp((X - 394.5)/\beta)]}{1 + \exp[(-94.5 - \delta)/\beta]} \right.$$

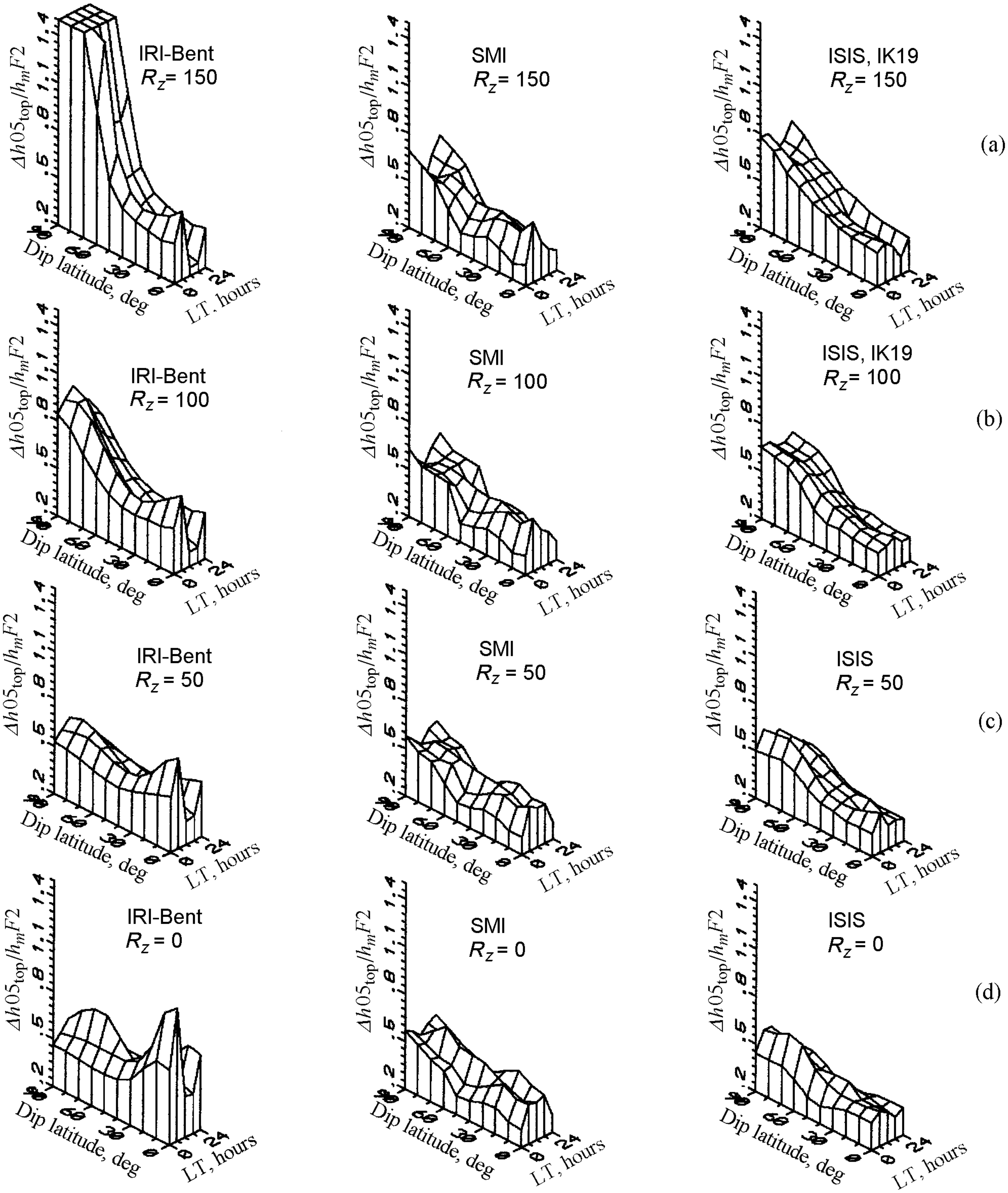

Figure 1. Comparison of the IRI-Bent and SMI empirical models to the model of the ratio of the topside ionosphere half width to the ionization maximum altitude according to the data of the ISIS 1, ISIS 2 and IK 19 satellites depending on the geomagnetic (dip) latitude and local time (Figures 1a, 1b, 1c, and 1d correspond to four solar activity levels).

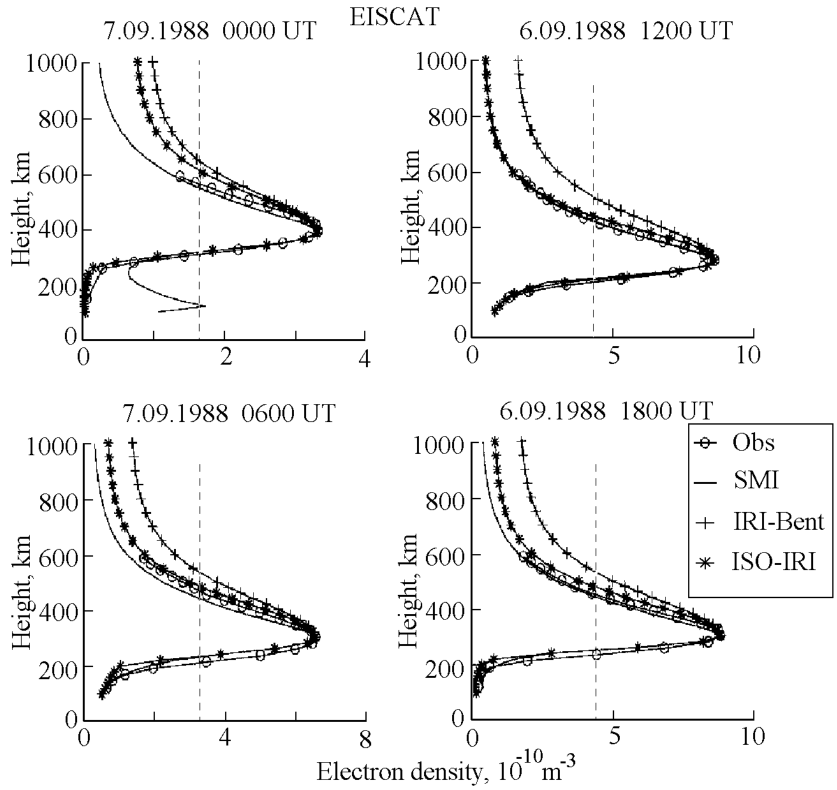

Figure 2. The electron density profiles in the high-latitude ionosphere (night, dawn, daytime, dusk) according to the EISCAT incoherent scatter data and the calculations using three models: IRI-Bent, SMI, and ISO-IRI corrected by the ISIS 1, ISIS 2, and IK 19 data.

$$+\zeta\frac{100\ln[1+\exp((X-300)/100)]}{1+\exp(-\delta/100)}-X+300-\delta\Bigg\}$$

$$X=(h-h_mF2)/(1000-h_mF2)\times 700+300-\delta$$

The expressions for X and Y as well as all corresponding coefficients β, δ, η, and ζ are given by *Rawer at al.* [1981] as functions of geomagnetic latitude, solar radio emission flux, and $F2$-layer critical frequency.

Taking into account that $q = 1$ for the initial IRI-Bent expression, we obtain a correcting factor $q \neq 1$ from equation (4) and (5), installing $N_e = 0.5N_mF2$ and $h = h05_{\text{top}}$ determined from the empirical model based on the ISIS and IK 19 data:

$$q = 0.69315/Y(h05_{\text{top}}) \qquad (6)$$

As a result, the topside ionosphere vertical profile passes through an additional correction point $N_e(h05_{\text{top}})$ and its shape in the topside ionosphere changes due to the allowance for the q factor based on the ISIS/IK 19 model. Relevant update of IRI subprograms for the topside ionosphere profile with its extrapolation according to the SMI plasmasphere model up to the plasmapause heights (up to 35,000 km) is made included into the ISO-IRI software package in the project of the standard of the ionosphere and plasmasphere of the Earth of the International Organization on Standardization (ISO) [*Gulyaeva*, 2003; *Gulyaeva et al.,* 2002].

4. Approbation of the Corrected ISO-IRI Model

Figure 2 shows the comparison of three model calculations of the electron concentration $N_e(h)$ with the results of observations by the European incoherent scatter facility EISCAT at Tromsö (the geodetic coordinates 69.6°N, 19.2°E, the geomagnetic latitude 66.9°N) in the equinox period (6–7 September 1988) under high solar activity ($R_z = 110$) and quiet geomagnetic conditions.

The calculations by the SMI, IRI-Bent, and ISO-IRI (after the correction of the topside ionosphere half width) were performed fitting the parameters of the F region peak (N_mF2 and h_mF2) from the EISCAT observations. One can see that the SMI and improved ISO-IRI models describe well the shape of the vertical profile in the topside ionosphere. In all cases the initial IRI-Bent model gives overestimated width of the plasma layer in the topside ionosphere as compared with observations and other model calculations improved according to the results of the ISO-IRI correction.

Observations of the GPS navigational satellites from the orbit of 20,000 km to the Earth's surface provide the data

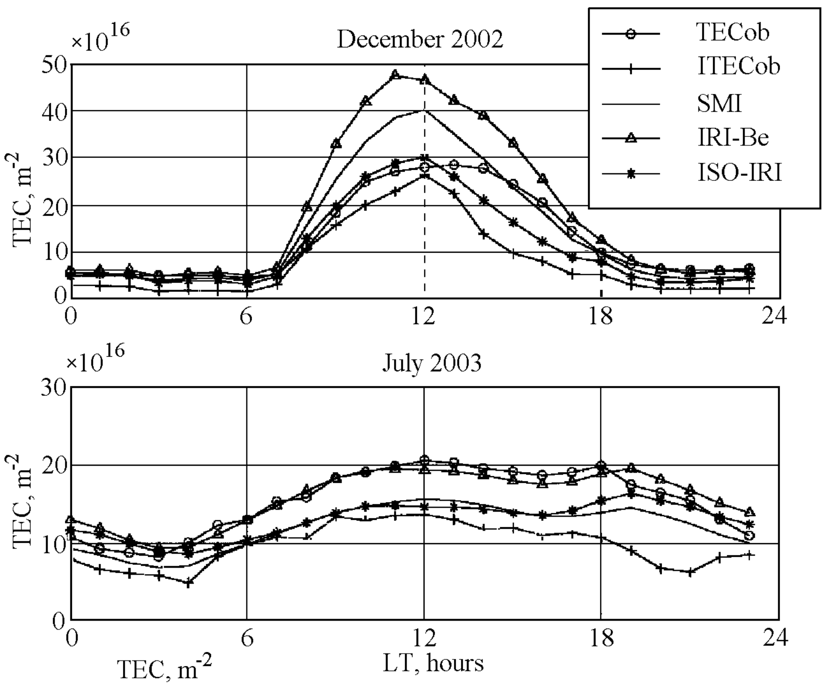

Figure 3. Comparison of the model calculations with the diurnal variations of the total electron content according to the observations of the GPS-TEC navigation satellite signals and to the ionospheric electron content ITEC estimated from the data of ground-based ionosondes at middle latitudes.

on the total electron content (TEC) useful for testing of ionosphere-plasmasphere models. Figure 3 shows the diurnal behavior of the monthly median according to the GPS-TEC data at middle latitudes (Hailsham, 50.9°N, 0.3°E, $\Phi = 53.4$°N; and Matera, 40.6°N, 16.7°E, $\Phi = 40.3$°N) for December (Figure 3, top) and June (Figure 3, bottom) 2002. Figure 3 shows also the medians of the total electron content ITEC [*Huang and Reinisch*, 2001] derived from the ionograms obtained in the nearest points of Fairford (51.7°N, −1.8°E, $\Phi = 54.6$°N) and San Vito (40.7°N, 17.9°E, $\Phi = 40.5$°N). The ITEC parameter is systematically lower than GPS-TEC because the former includes the electron content up to a height of 1000 km without taking into account the plasmasphere contribution seen in the GPS-TEC data [*Belehaki and Jakowski*, 2002]. Model calculations of TEC were performed for monthly mean conditions introducing median parameters of the F region maximum (N_mF2 and h_mF2) taken from ionosonde observations. The comparison of the results of the TEC calculations using SMI, IRI-Bent, and ISO-IRI models shows that the correction of the ISO-IRI model leads to a significant improve of the IRI-Bent results initially overestimated by a factor of up to 2 as compared with the observations in winter conditions under high solar activity ($R_z = 110$). The results of the TEC calculations using the SMI model overestimated in both examples have lower accuracy than the results based on the ISIS/IK 19 model.

The latitudinal variations in the total electron content TEC in the ionosphere and plasmasphere of the Earth according to the initial IRI-Bent model, the ISO-IRI model corrected by the ISIS/IK 19 data, and the SMI model are shown in Figure 4. They are compared with the latitudinal variations in the observed values of the total electron content in April 2002 at a latitude of 30°E derived from the interpolation maps of the observed GPS-TEC data [*Stanislawska et al.,* 2002]. One can see that the correction by the topside ionosphere parameter in the ISO-IRI model improves considerably the results of the IRI-Bent model. Taking into account that the N_mF2 and h_mF2 parameters were taken in this case from the *CCIR* [1986] map used in the IRI and SMI models, one may state that a good agreement with observational data is achieved.

5. Conclusions

Using the data of the ionosondes on board the ISIS 1, ISIS 2, and IK 19 satellites, an empirical model of the topside ionosphere half width $\Delta h_{\rm top}$ normalized to the ionization maximum height is created. The model provides $\Delta h_{\rm top}$ dependence on local time, geomagnetic latitude, and solar activity for quiet geomagnetic conditions. The model provides an additional point for specification of the electron density profile in the International Reference Ionosphere Model. Its correction is realized in the software of the ISO-IRI ionosphere-plasmasphere model proposed as a standard of the International Standardization Organization (ISO). The approbation of the modelling results, using the independent data of EISCAT incoherent scatter and the GPS-TEC nav-

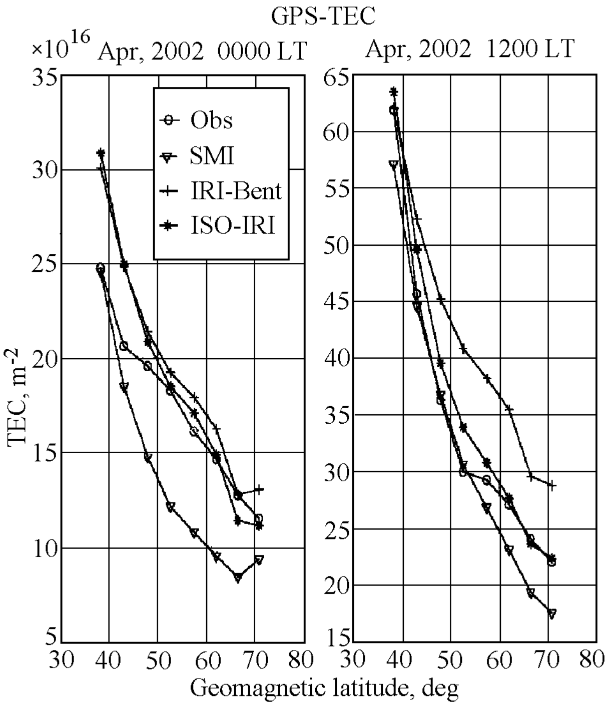

Figure 4. Comparison of the model calculations with the latitudinal behavior of the total electron content at a longitude of 30°E according to the observations of the GPS-TEC navigation satellite signals at the network of European observatories.

igation satellite signals, demonstrates the advantages of the proposed method as compared with the initial IRI model. The calculations using the Russian Standard Model give the results comparable to the ISIS 1, ISIS 2, and IK 19 results.

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