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# International Reference Ionosphere 2000

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**Abstract.** The International Reference Ionosphere (IRI) is the international standard for the specification of ionospheric densities and temperatures. It was developed and is being improved-updated by a joint working group of the International Union of Radio Science (URSI) and the Committee on Space Research (COSPAR). A new version of IRI is scheduled for release in the year 2000. This paper describes the most important changes compared to the current version of IRI: (1) an improved representation of the electron density in the region from the F peak down to the *E* peak including a better description of the $F_1$ layer occurrence statistics and a more realistic description of the low-latitude bottomside thickness, (2) inclusion of a model for storm-time conditions, (3) inclusion of an ion drift model, (4) two new options for the electron density in the *D* region, and (5) an improved model for the topside electron temperatures. The outcome of the most recent IRI Workshops (Kühlungsborn, 1997, and Nagoya, 1998) will be reviewed, and the status of several ongoing task force activities (e.g., efforts to improve the representation of electron and ion densities in the topside ionosphere and the inclusion of a plasmaspheric extension) will be discussed. A few typical IRI applications will be highlighted in section 6.

## 1. Introduction

The International Reference Ionosphere (IRI) is a widely used standard for the specification of ionospheric parameters and is recommended for international use by the Committee On SPAce Research (COSPAR) and the International Union of Radio Science (URSI). *Szuszczewicz et al.* [1998] evaluated several models (including first-principle models) for their global Sundial/TSS-1R campaign and find IRI to be the "best of the best." At the 1999 URSI General Assembly in Toronto, Canada, the "URSI Commission G resolved that IRI be internationally recognized as the standard for the ionosphere." IRI was developed and is being improved-updated by a joint working group of URSI and COSPAR. The objectives are described in the terms of reference of the working group: (1) The task group was established to develop and improve a standard model of the ionospheric plasma parameters (electron and ion densities, temperatures, and velocities). The model should be primarily based on experimental evidence using all available ground and space data sources; theoretical considerations can be helpful in bridging data gaps and for internal consistency checks. (2) Where discrepancies exist between different data sources, the IRI team should promote critical discussion to establish the reliability of the different data bases. (3) IRI should be updated as new data become available and as old databases are fully evaluated and exploited. (4) IRI is a joint working group of COSPAR and URSI. COSPAR's prime interest is in a general description of the ionosphere as part of the terrestrial environment for the evaluation of environmental effects on spacecraft and experiments in space. URSI's prime interest is in the electron density part of IRI for defining the background ionosphere for radiowave propagation studies and applications.

The working group consists of a team of experts representing different countries, different measurement techniques, and different aspects of the modeling problem. Currently, the roster includes 43 members: M. Abdu (Brazil), J. Adeniyi (Nigeria), A. Alcayde (France), D. Anderson (USA), K. Bibl (USA), D. Bilitza (USA, Chair), P. Bradley (UK), Y. Chasovitin (Russia), A. Danilov (Russia), P. Dyson (Australia), R. Ezquer (Argentina), M. Friedrich (Austria), T. Fuller-Rowell (USA), T. Gulyaeva (Russia), S. Gupta (India), R. Hanbaba (France), X. Huang (USA), K. Igarashi (Japan), G. Ivanov-Kholodny (Russia), E. Kazimirovsky (Russia), P. Kishcha (Russia-Israel), E. Kopp (Switzerland), I. Kutiev (Bulgaria), K. Mahajan (India), A.



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Mikhailov (Russia), A. Mitra (India), M. Mosert de Gonzalez (Argentina), K. Oyama (Japan,Vice-Chair COSPAR), A. Poole (South Africa), S. Pulinets (Russia), S. Radicella (Italy-Argentina), K. Rawer (Germany), B. Reinisch (USA,Vice-Chair URSI), M. Rycroft (UK),W. Singer (Germany), J. Sojka (USA), I. Stanislavska (Poland), L. Triskova (Czech Republic), B. Ward (Australia), S. Watanabe (Japan), V. Wickwar (USA), P. Wilkinson (Australia), B. Zolesi (Italy). The main forum for the presentation and discussion of IRI shortcomings, improvements, new additions, and applications are the annual workshops. The 1997 IRI Workshop was held jointly with the European Union Cooperation in Scientific and Technical Research (COST) project 251 "Improved Quality of Service in Ionospheric Telecommunication System Planning and Operation" at the Institute for Atmospheric Science in Kühlungsborn, Germany. It focused on "New Developments in Ionospheric Modeling and Prediction" and highlighted efforts to improve the bottomside and topside electron density profile and the description of ionospheric storm effects. Selected papers from this workshop are published in *Advances in Space Research* [*Rawer and Bradley*, 1998]. During the 1998 COSPAR General Assembly in Nagoya, Japan the IRI team organized a 3-day session on "Data and Models for the Lower Ionosphere". 32 papers/posters from this session have been published in a special issue of *Advances in Space Research* [*Rawer et al.,* 2000]. This year the IRI Workshop was held at the University of Massachusetts, Lowell, from August 8 to 12. The special emphasis was on the description of ionospheric variability and on ray tracing through model ionospheres. A primary goal of the Nagoya and Lowell meetings was preparations for the IRI 2000 release of the model. Summary reports from the IRI meetings are available at http://nssdc.gsfc.nasa.gov/space/model/ionos/iri/iri_workshops.html.

As an empirical model, IRI is based on the existing data record, and the IRI working group is tasked to deduce the dominant variation patterns of ionospheric parameters from this data record. An important first step is the choice of appropriate variables for ordering the data. The coordinate system of choice is the geodetic system for low altitudes and a magnetic coordinate system higher up. The reason is the close coupling to the neutral gas (high collision frequency) in the lower ionosphere and the coupling to the magnetic field lines in the middle and topside ionosphere. The magnetic coordinate selected is the modified dip latitude (Modip) since best results were obtained with this coordinate in ionospheric mapping [*Rawer*, 1963]. For the description of diurnal variations, different parameters are used in IRI. In the *E* region the region where most of the ionization is produced and the strong solar control is best described with the solar zenith angle. In the *F* region and above, transport processes along magnetic field lines redistribute the plasma, and local time (and/or universal time (UT)) is the better parameter; a UT dependence is particularly important at high latitudes to follow the rotation of the magnetic poles.

## 2. External Drivers

### 2.1 Solar Indices and Ionospheric Indices

The 11-year periodicity in the intensity of the solar irradiance is clearly seen in long ionospheric data records. To reproduce these variations, ionospheric models rely on solar indices. Ideally this should be an index that tracks the solar cycle changes in the EUV wavelength range since this is the part of the solar spectrum that affects the ionosphere. However, such indices cannot be observed at the ground and are only available for the relatively short time periods covered by satellite EUV instruments. The solar indices used by most ionospheric modelers are the sunspot number *R* (number of dark spots on the solar disc) and the solar radio flux at 10.7 cm wavelength (*F10.7*), since both can be observed from the ground and long data records exist. Correlation studies have shown that *F10.7* is the better index for the region of strong solar control below the *F* peak and *R* is the better index for the region above, where dynamic processes compete with the solar influence. These indices exhibit an 11-year cycle similar to the EUV fluxes, but there are often considerable differences in the daily and monthly changes. Overall, it was found that the correlation between solar indices and ionospheric parameters is best for a 12-month running mean and weaker for monthly and daily averages. The IRI model utilizes the 12-month running mean of the sunspot number observed at the Zürich observatory ($Rz_{12}$). This is also the index recommended for use with the F peak parameter models of the International Radio Consultative Committee (CCIR) [1991] that were adopted by the International Telecommunication Union (ITU) and that are part of the IRI model. However, at very high solar activities ($Rz_{12}$ > 150), ionospheric densities increase much slower than $Rz_{12}$. *Balan et al.* [1994a,1994b] could show that the ionospheric *F* peak

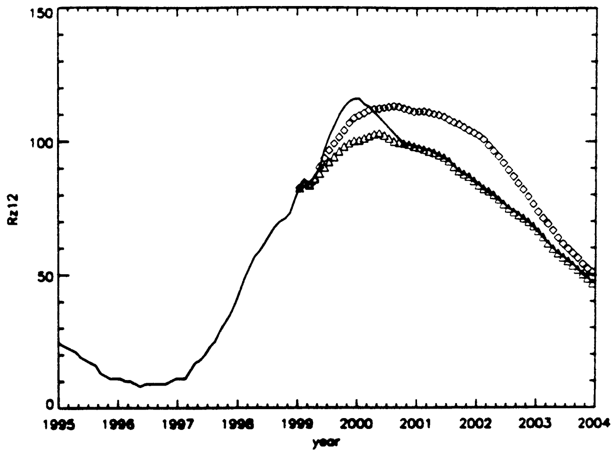


**Figure 1.** The 12-month running mean of sunspot number Rz12 as provided by the International Telecommunication Union (solid line), by the National Geophysical Data Center, National Oceanic and Atmospheric Administration (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/sunspot.predict) (diamonds), and by Marshall Space Flight Center (http://sail.msfc.nasa.gov/nse/solar.html) (triangles) in November 1999; all values after March 1999 are predicted values.

density is still well correlated to the solar EUV fluxes but not to $Rz$. CCIR recommends keeping $Rz_{12}$ at 150 even for the higher solar activities to artificially simulate the saturation seen in ionospheric $F$ peak densities. As an alternative option, CCIR recommends usage of the global ionospheric index $IG_{12}$ (instead of $Rz_{12}$) that was introduced by *Liu et al.* [1983]. The $IG$ index is based on $F$ peak plasma frequencies measured by 13 representative ionosonde stations and on the linear regression with solar activity taken from the CCIR model. The direct dependence on measured ionospheric parameters results in a much better representation of the saturation at high solar activities. In IRI both indices ($IG_{12}$ and $Rz_{12}$) are used: $IG_{12}$ for F peak density and $Rz_{12}$ for the $F$ peak altitude and the topside profile. Other global and regional ionospheric indices have been computed for specific time periods based on the available worldwide ionosonde data record. However, the improvement in using such indices instead of $Rz_{12}$ is generally only a few percent [e.g., *Bilitza et al.*, 1997]. In the long run, it is hoped that a solar EUV index will overcome some of these problems. The IRI team supports the Scientific Committee on Solar-Terrestrial (SCOSTEP) Thermospheric-Ionospheric GEospheric Research (TIGER) program (G. Schmidtke, Project Leader), which has the establishment of such an index as one of its goals.

Forecast of ionospheric parameters a few years into the future requires, of course, a forecast of solar indices. The uncertainties of such forecasts naturally increase with the time span for which a forecast is required, and there are also differences between the different extrapolation techniques [see *Hathaway et al.,* 1999]. Figure 1 shows the differences between three $Rz_{12}$ predictions for the upcoming solar cycle maximum.

## 2.2 Updating With Measured Parameters

The ionosphere is highly variable, and deviations from monthly medians can reach 20-40% during quiet times and even larger values during disturbed times (magnetic storms). A better specification of the ionospheric day-to-day and hour-to-hour variability especially during periods of magnetic disturbance (storms) requires updating with measured characteristic ionospheric parameters. In IRI the electron density profiles can be updated with measured peak parameters. Specifically, a user can enter measured values of the $F$ peak density or critical frequency, the $F$ peak height or the M(3000)$F_2$ propagation factor, a factor scaled from ionograms that can be used to obtain the $F_2$ peak height, the $F_1$ height and/or density/frequency, and the $E$ peak height and/or density/frequency. The electron density profile can thus be easily adopted to observed characteristic parameters. Similarly, the electron temperature profile can be updated with measured electron densities at 300-, 400-, and/or 600-km altitude employing the strong anticorrelation between the electron density and temperature. The ion and electron temperatures at low altitudes can be updated with a user-specified exospheric neutral temperature instead of the currently used CIRA-86 model [*CIRA*, 1988]. All these updates require the user to specify the input parameter at the location and time for which s/he is generating his/her IRI profile. If measurements are available for other location(s) and time(s), the user has to devise a weighting method to obtain the estimates for the location and time for which s/he wants to generate an updated IRI profile.

Several IRI teams are working on using total electron content (TEC) deduced from measurements of the Global Positioning System (GPS) satellites to update IRI. M. Hernandez and his colleagues at the Polytechnical University in Barcelona, Spain, are computing the electron content along a GPS signal path from the GPS data and from IRI and then adjusting the IRI ionospheric index until the two values match [*Bilitza et al.,* 1999]. An example is shown in Figure 2. IRI, in turn, has

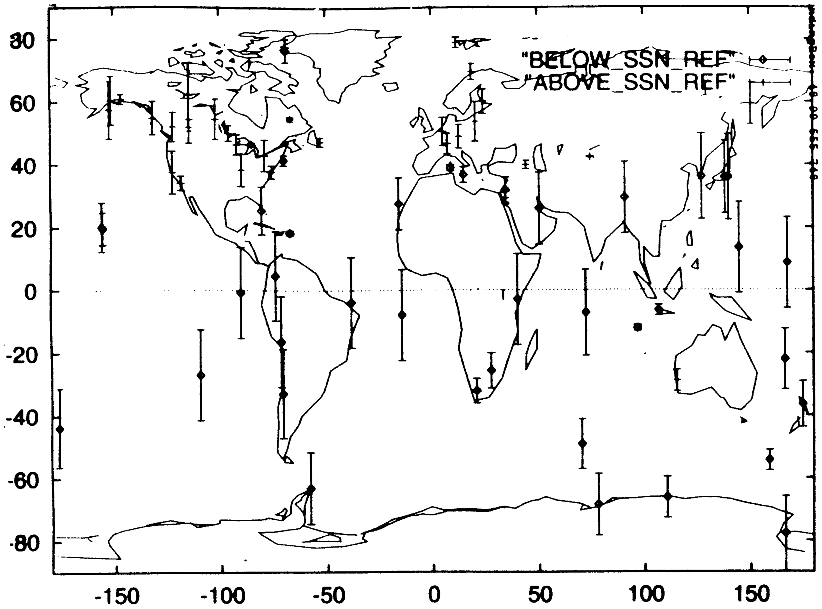


**Figure 2.** Corrected ionospheric indices deduced by adjusting IRI slant electron content along a GPS signal pass with the GPS-deduced slant TEC. Depicted is the difference between the corrected index and the base index used in IRI. Diamonds indicate a necessary reduction of the index, and plus signs indicate an increase of the index (units for differences: 1° latitude corresponds to a decrease or increase of $IG_{12}$ by 1). The hemispherical differences point to biases in IRI due to the uneven distribution of the underlying data base (the majority of data is from the Northern mid-latitudes). GM, geomagnetic dipole equator; SSN, sunspot number.

helped to improve the techniques for obtaining worldwide maps of TEC from GPS data and for interpolating within the map grid [*Komjathy et al.*, 1998].

## 3. Electron Density

IRI electron densities are normalized to the *F* peak in the upper ionosphere and to the *E* peak in the lower ionosphere, and these two parts are merged in the *E* valley region. In sections 3.1-3.5 the improvements in the different regions will be discussed.

### 3.1 *D* Region

The lowest region (*D* region) is characterized by large variability and a very small database. The only data source is rocket experiments since the region is too low for satellites and since the densities are too low for ionosondes and radars. IRI 2000 will include three options for the description of *D* region electron densities, reflecting the large uncertainties that still exist in this region. Option 1 will be the current *D* region model which was developed by *Mechtley and Bilitza* [1974; see also *Bilitza*, 1981) on the basis of a rather limited set of representative rocket data. Option 2 will be the model by *Friedrich et al.* [2000]. *Friedrich and Torkar* [1998] have compiled a database of the most reliable *D* region rocket data (~200 profiles) and experimented with different modeling approaches, always including the strong dependence on solar zenith angle and considering to various degrees dependencies on season, latitude, solar activity, and neutral density and even an extension to high latitudes [*Friedrich and Torkar*, 1995]. Their most recent modeling concept [*Friedrich et al*, 2000] combines the rocket data with the results of a theoretical model. The data are used to establish an empirical correction to the theoretical model, and *D* region profiles are then calculated for a wide range of conditions. For IRI an interpolation algorithm will be applied to obtain the density for specified zenith angle, latitude, season, and solar activity. Option3 will be the model by *Danilov et al.* [1995]. They note the large spread in *D* region densities for winter daytime conditions (almost 2 orders of magnitude). Although their rocket database is quite limited in volume, they find that the data can be grouped into four distinct classes, and they propose the following classification: (1) strong winter anomaly

(WA), (2) weak WA, (3) undisturbed conditions, and (4) stratospheric warming conditions. The largest values are found during strong WA with densities about a factor 10 larger than for undisturbed conditions. Currently, of course, we do not have an index to specify the various conditions, but it was felt that inclusion of the model could be of help for IRI users by illustrating the range of values that can be expected in this region and by indicating the possible reasons for very low or high *D* region values.

IRI efforts are continuing to exploit the long data record of ground-based absorption measurements for D region modeling [*Singer et al.*, 1984; *Mukhtarov and Pancheva*, 1995; *Nath; and Abraham*, 1996]; these are, of course, indirect measurements and involve a number of assumptions and simplification [*Serafimov et al.*, 1985]. Theoretical modeling is providing valuable insights and hints on how to improve the IRI model [*Kull et al.*, 1995] and has highlighted the importance of NO for the *D* region electron and ion densities [*Sonnemann et al.*, 1995].

### 3.2 *E* Region

The main change in the *E* region will be the inclusion of the *Mahajan et al.* [1997] model for the E valley depth and width. Their model is based on Arecibo incoherent scatter data from 1974 to 1977. In a slightly modified version it is also used in the ARTIST ionogram reduction program for digisondes [*Huang and Reinisch*, 1996]. During daytime the changes to the current IRI model are minor, but during nighttime the new model predicts a much deeper valley.

There are continuing efforts toward improvements of the description of the *F* peak density *NmE* and altitude *hmE*. For *NmE* IRI utilizes the CCIR models with a few small modifications [see *Bilitza*, 1990b]. The nighttime variation was modified on the basis of incoherent scatter data from Arecibo [*Rawer and Bilitza*, 1990]. *Bradley* [1994] has used Malvern incoherent scatter data to further investigate the nighttime behavior. *Ivanov-Kholodny et al.* [1998] have developed a solar-zenith-angle dependent model for *hmE* based on Kharkov incoherent scatter data from 1978 to 1990 and proposed this as a replacement for the currently constant $hmE_{IRI}$ = 110 km. They find sharp peaks at sunrise and sunset that are ~5-10% above the daytime and nighttime values, which are, on average, at the 110-km level.

### 3.3 Bottomside and $F_1$ Region

A special Task Force Activity (TFA) at the International Center for Theoretical Physics (ICTP) in Trieste, Italy (since 1995), has been very successful in improving the bottomside electron density profile for IRI [*Radicella et al.*, 1998]. During a hands-on week in front of computers and blackboards a team of a dozen or so scientists tackles and tries to resolve a specific modeling problem. In tune with the philosophy of the ICTP (exchange of scientific knowledge between developed and developing countries) the scientists are about half from developing countries and half from developed countries. For the IRI efforts this was of special significance and benefit since modern ionogram reduction techniques could be used to obtain reliable bottomside profiles from several ionosonde stations in developing countries close to the magnetic equator. The POLAN program (J. Titheridge) and the ARTIST program (B. Reinisch and X. Huang) were used to invert the ionograms to electron density profiles. The stations from which data were used are listed in Table 1. Scientists involved in one or more of the ICTP TFAs include S. Radicella (ICTP), D. Bilitza (USA), B. Reinisch (USA), J. Adeniyi (Nigeria), M. Mosert and R. Ezquer (Argentina), S. Zhang and M. Zhang (People's Republic of China), G. Mirò and M. Hernandez (Spain), R. Hanbaba (France), R. Leitinger (Austria), G. De Franceschi, L. Ciraolo, B. Zolesi, B. Scotto, and P. Spalla (Italy), T. Gulyaeva and S. Pulinets (Russia), J. Titheridge (New Zealand), M. Morehead (UK), J. Boska and D. Buresova (Czech Republic), A. Kumluca (Turkey), B. Lazo (Cuba), O. Obrou (Ivory Coast), and K. Mahajan (India). The improvements established by the ICTP task team will

**Table 1.** List of Ionosonde Stations That Contributed Data to the ICTP TFAs

| Station | Latitude | Longitude | Modip |
|---|---|---|---|
| Lannion, France | 48.8 | 356.6 | 48.2 |
| Poitiers, France | 46.6 | 0.3 | 53.2 |
| Beograd, Yugoslavia | 44.8 | 20.5 | 52.0 |
| Poitiers, France | 46.6 | 0.3 | 53.2 |
| Beograd, Yugoslavia | 44.8 | 20.5 | 52.0 |
| Wrumchi, China | 43.8 | 87.7 | 51.9 |
| Millstone Hill, USA | 42.6 | 288.5 | 56.0 |
| Roma, Italy | 41.9 | 12.5 | 49.3 |
| Wuchang, China | 30.6 | 114.3 | 39.5 |
| Chongqing, China | 29.5 | 106.4 | 38.2 |
| Ramey, Puerto Rico | 18.5 | 292.9 | 41.8 |
| Ouagadougou, Burkina Faso | 12.4 | 358.5 | 5.7 |
| Ibadan, Nigeria | 7.4 | 356.1 | -6.6 |
| Jicamarca, Peru | -12.0 | 283.1 | -2.8 |
| Tucuman, Argentina | -26.9 | 294.6 | -21.2 |
| Buenos Aires, Argentina | -34.6 | 301.5 | -31.6 |
| San Juan, Argentina | -31.5 | 290.4 | -27.9 |
| Port Madryn, Argentina | -42.7 | 294.7 | -39.3 |
| Ushuaia, Argentina | -54.8 | 291.7 | -49.3 |

be of particular benefit for HF applications of IRI since HF propagation is affected primarily by this region of the ionosphere. The ICTP TFA effort has resulted in three major improvements for IRI 2000 (Radicella et al., 1998):

1. A better description of the occurrence statistics of the $F_1$ layer was developed in terms of solar zenith angle, solar activity, and geomagnetic latitude [*Scotto et al.*, 1997, 1998]. In addition to some of the data from Table 1 these authors also used the ionosonde data from National Geophysical Data Center's Ionospheric Digital Database on CD-ROM. The $F_1$ point is of importance since it marks a transition in ion composition from molecular ions to atomic oxygen ions and a transition from a plasma distribution determined by photochemistry (strong solar control) to a plasma dominated by dynamic processes (transport along magnetic field lines). An $F_1$ layer is seen in ionogram traces as a cusp-like feature but is difficult to identify in electron density profiles measured, for example, by an incoherent scatter radar. IRI currently uses the *DuCharme et al* [1971,1973] model that, on the basis of the long ionosonde data record, describes the $F_1$ plasma frequency, *foF1*, in terms of solar zenith angle, magnetic latitude, and solar activity ($R_{12}$, 12-month running mean of sunspot number). The model also provides a criterion for the occurrence of an $F_1$ layer by specifying the cutoff limiting solar zenith angle beyond which it cannot occur; again, this cutoff angle varies with $R_{12}$ and magnetic latitude. In IRI the conditions for the existence of an $F_1$ layer were further restricted to daytime hours and to non-winter months. *Scotto et al.* [1997, 1998] found that the IRI model described the measured *foF1* values quite well but underestimated the time span (diurnal and seasonal) for which the $F_1$ layer is observed. In developing a new model they worked with the actual probabilities (percentage of days for which an $F_1$ layer is expected) rather than with a cutoff criterion. Their model provides a much better match with the data. Ionograms often exhibit a $F_1$ ledge rather than a fully developed cusp, primarily during the time period just before the $F_1$ layer disappears. These cases are described as L condition according to the URSI standard nomenclature. Electron density profiles deduced from these two types of $F_1$ region traces are very similar. In fact, the inclusion of L condition cases provides for a smooth transition of the density profile from the time periods of $F_1$ presence to the time periods of no $F_1$ presence. Combining the cases of standard $F_1$ with those of L condition, Scotto et al. (1997) find that the probability can be described in terms of solar zenith angle only and no longer requires terms depending on R12 and/or magnetic latitude. Both formulas (with and without L condition) will be included in IRI 2000 to let the user choose the appropriate option for his/her application. Especially for wave propagation studies, it might be important to know not only the probability of an $F_1$ layer but also if it is a fully developed cusp or only a ledge.

2. A new table of values was assembled for the two parameters, $B_0$ and $B_1$ that determine the bottomside thickness and shape, respectively [*Bilitza et al.,* 2000]. Currently, IRI has two options for the thickness parameter $B_0$: (1) a set of values based on data from a few representative ionosonde stations, and (2) a formula for the half-density height $h_{0.5}$ developed by *Gulyaeva* [1987] based on mostly mid-latitude ionosonde data; $h_{0.5}$ is the altitude where the bottomside profile has dropped down to half the $F_2$ peak density. A number of studies have shown the shortcomings of both options, in particular, an underestimation of $B_0$ measurements from ionosondes and incoherent scatter radars at low and equatorial latitudes. With the database available for the ICTP effort it was possible to establish a new set of values representing a much wider range of times and locations than the current IRI $B_0$ table; most importantly, it includes values for the equatorial region that are not represented at all in the current model. Figure 3 shows the latitudinal variation of the measured and modeled $B_0$ values for day and night for a winter month (January) and a summer month (July) and for low solar activity ($R_{12}$=10) and high solar activity ($R_{12}$=100). The new model provides a significant improvement in all cases. The largest improvements are seen for the equatorial sector and for high solar activity where the new model is about a factor of 2 above the current IRI predictions. These changes will also result in a more accurate prediction of total electron content (TEC) since the bottomside contributes 20-40 % to the TEC. The shape parameter $B_1$ is set equal to 3 in IRI and is being increased in increments of 0.5 to facilitate the merging between the *E* and *F* regions. The ICTP team found a clear diurnal variation in the bottomside shape with $B_1$ varying from 1.8 during daytime to 2.6 during nighttime (see Figure 4). This reflects the difference in shape from the typical nighttime profile with a sharp drop into a deep nighttime valley compared to the gradual decrease during daytime down to first the $F_1$ layer and then a shallow *E* valley.

3. A better functional description of the transition region from bottomside to *E* valley was developed by *Reinisch and Huang* [2000]. The current formalism

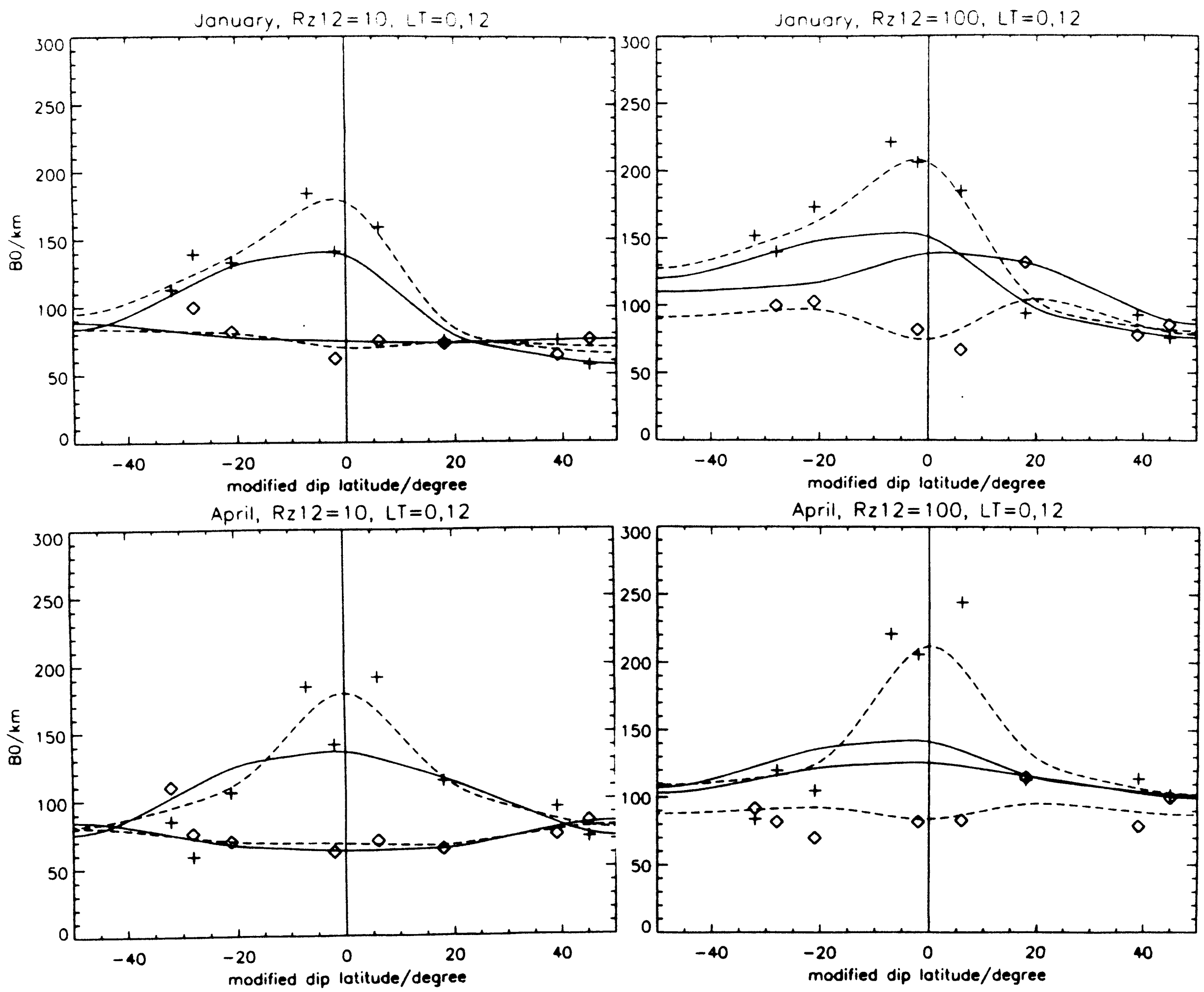


**Figure 3.** Average $B_0$ values versus modified dip latitude for local noon (plus signs) and midnight (diamonds) for different conditions (as indicated at the top of each panel). Also included are the current $B_0$ model (solid curves) and the new $B_0$ model (dashed curves). The lower curves are for midnight, and the upper curves are for noon.

could lead to discontinuities or artificial valleys under conditions when merging was particularly difficult to accomplish, because of large differences between *E* and *F* peak densities and/or small differences between the *E* and *F* peak heights. The new formalism overcomes these problems.

### 3.4 Region Above the *F* Peak

The topside and plasmasphere in IRI were the special focus of the IRI meeting held during the COSPAR General Assembly in Warsaw in July 2000. The status of IRI-related efforts for these regions were reviewed at that time, and recommendations were made for the post-IRI 2000 improvement cycle. However, even now, users can, of course, combine IRI with a plasmaspheric model of their choice. *Komjathy et al.* [1998], for example, have used IRI in conjunction with the *Gallagher et al.* [1988] plasmasphere model, which is the model currently recommended by the IRI Working Group. Other options include the model developed by *Rycroft and Jones* [1985, 1987] or the one developed by *Kimura et al.* [1996]. In all cases, satellite data are used to adjust parameters in a diffusive equilibrium type model. Gallagher et al.'s prime data source is the Dynamics Explorer 1 Retarding Ion Mass spectrometer measurements, and Kimura et al.'s prime data source is the Akebono wave data. The recommended connection altitude with the IRI topside model is the transition

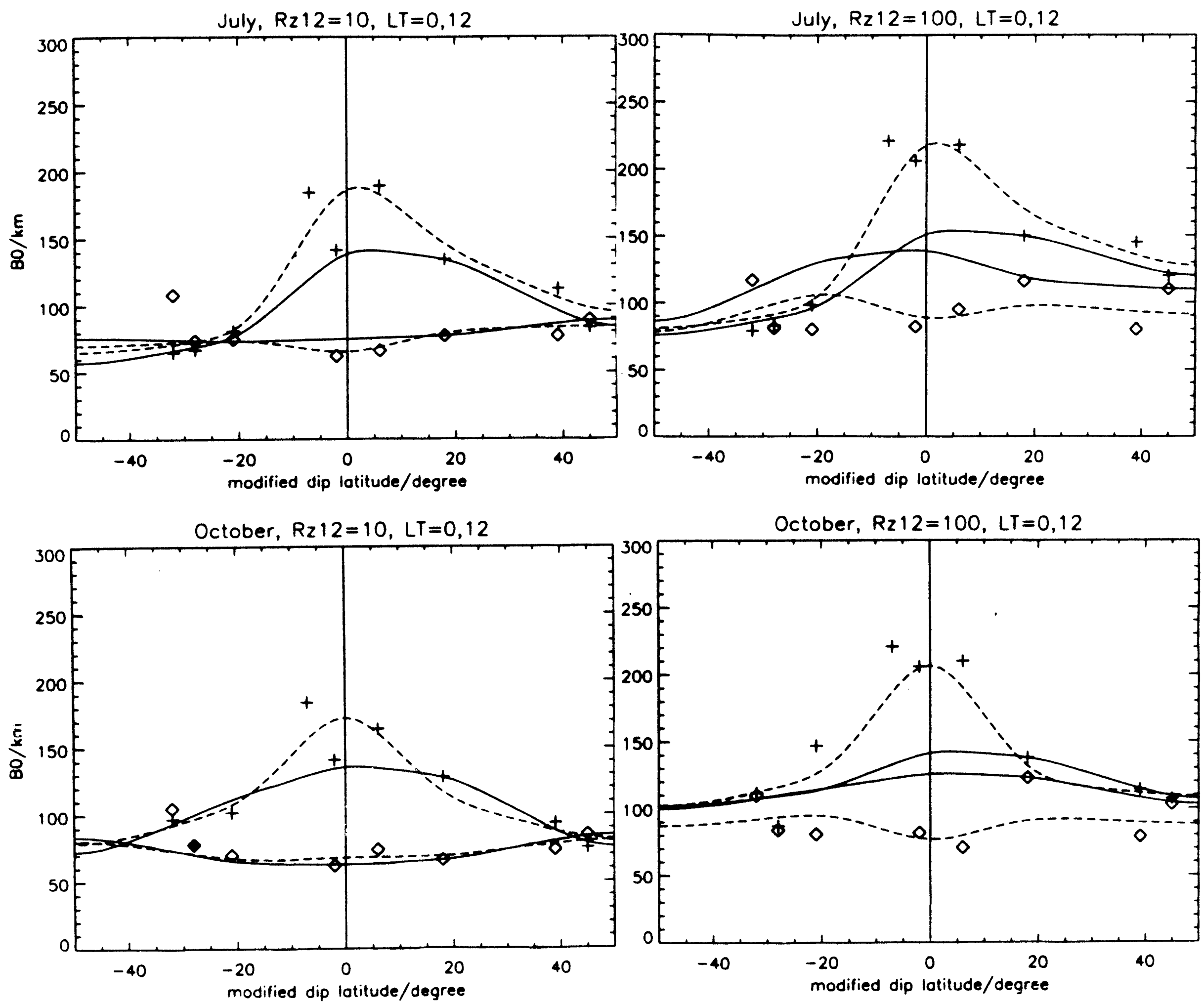


**Figure 3.** (continued)

height from $O^+$ ions to light ions (i.e., 50% $O^+$); the change in scale height simplifies the merging of the two models at this point.

The IRI topside model is an analytical representation of the *Bent et al.* [1972] model, which in its original version is given in graphical form. The Bent model is based on data from ionosondes, and on satellite topside sounder (Alouette 1) and in situ (Ariel 3) measurements. The characteristic parameters are described in terms of the $F_2$ peak plasma frequency *foF2*, the geomagnetic latitude, and the monthly solar radio flux at 10.7-cm wavelength. The same independent variables are used also in IRI to describe the variation of the topside scale heights deduced from the Bent model (the method and formulas are described by *Rawer et al.* [1978] and by *Bilitza* [1990b]). The Bent model consists of a graphical representations of the profile parameters versus solar activity for different latitude regimes and different ranges if *foF2* values. *Rawer et al.* [1978] noted the irregular behavior and discontinuities of the Bent model at the class boundaries. Their analytic representation provides a more reasonable smooth transition across the class boundaries in latitude and *foF2*. Comparisons with a large number of *TEC* data [*McNamara and Wilkinson*, 1983; *McNamara*, 1984, 1985[ have shown good agreement of the Bent and IRI models with mid-latitude data but large discrepancies close to the magnetic equator. The model predictions were almost a factor of 2 below the measurements during high solar activity. This was partly corrected in IRI with the help of incoherent scatter radar data and with AEROS, AE-C, and DE-2 satellite data [*Bilitza,* 1985]. However, the need for

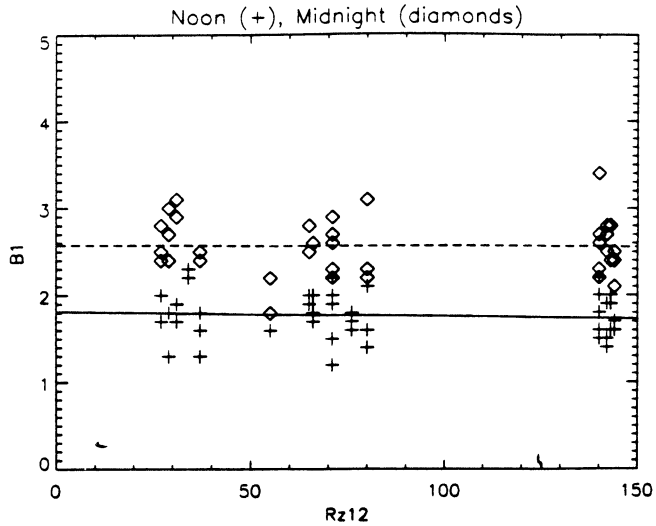


**Figure 4.** Average $B_1$ values from several ionosonde stations versus $Rz_{12}$ for noon (plus signs) and for midnight (diamonds). Also shown is the least squares fitted linear representation of the day values (solid line) and the night values (dashed line).

further improvements of the IRI topside model was illustrated by *Ezquer et al.* [1998] in a study that used *TEC* and *foF2* measurements for 1982 (high solar activity) from Tucuman, Argentina, a station close to the southern crest of the equator anomaly. They found that IRI still underestimated the daytime data although the margin is not considerably closer than in the McNamara studies. Similar results were reported for crest locations in Brazil [*Batista et al.,* 1994] and in China and India [*Iyer et al.,* 1996]. One has, of course, to keep in mind that in terms of modeling, the crest region is one of the most difficult regions of the ionosphere. The model has to follow the development from a single peak at the dip equator in the early morning to well-developed peaks on both sides of the equator in the afternoon and from the camel-back signature at *F* region altitudes to a single peak at the dip equator at altitudes above the equatorial plasma fountain. There is also a considerable day-to-day variability in the location and magnitude of the crests [e.g., *Bilitza et al.,* 1996]. Averaging over all these variations will smear out the moving narrow peaks to a broad peak with a lower maximum value.

*Bilitza et al.* [1998] and *Bilitza and Williamson* [2000] are using Alouette and ISIS topside sounder data to improve the current IRI topside profile. Only a small amount of this data had been used in the development of the Bent model. The longer data record covers a wider range in solar activity and therefore should help to overcome the problems at high solar activities. *Leitinger* [1998] is using a diffusive equilibrium description of $O^+$ and $H^+$ ions along magnetic field lines. His model is based on three characteristic parameters: the oxygen scale height, its gradient and the $O^+/H^+$ transition height. For these parameters he recommends the global models deduced by *Titheridge* (1976a, 1976b) from Alouette 1 electron density profiles. There is also now a considerable amount of topside sounder data becoming available from the Russian Intercosmos 19 and other topside sounder satellite missions as analyzed by S. Pulinets and his colleagues at IZMIRAN. A merging of these data sets and modeling approaches should lead to a reliable new topside model for the post-2000 version of IRI.

### 3.5. *F* Peak

The major changes for the *F* peak density in IRI 2000 will be a description of the ionospheric effects of magnetic storms. Developing an algorithm for the updating of IRI parameters during storm-time conditions has long been a high priority of the IRI team. First efforts were made and are being continued at IZMIRAN in Moscow, Russia [*Kishcha,* 1995, 1997]. *Fuller-Rowell et al.* [1999, 2000] have now used the long data record from ionosonde measurements to establish a first-order model for the description of ionospheric storm effects. Their model captures the most obvious, long-lived, coherent feature of the ionospheric response to a geomagnetic storm, which is the deep ion depletion ("negative phase") that typically develops in the summer hemisphere during the driven phase of a storm and persists well into the recovery phase. The model also includes the well-established diurnal differences in the storm response: Midlatitude stations show a minimum in the ratio of disturbed to quiet *NmF2* in the morning hours and a maximum around 1800 LT; this is a result of the compositional changes in response to the diurnally varying winds (upwelling/downwelling of molecular ions). The index applied is the integral over the auroral power index over the previous 30 hours with a weighting function deduced from physically based modeling. This model will be included in IRI 2000. It needs, of course, to be pointed out that individual storms may show large deviations from the average behavior described by the updating algorithm. A more accurate description of individual storms requires some form of updating with measured ionospheric parameters as described in section 2.2.

Inclusion of auroral features is an important future goal of the IRI team. IRI recommends use of the Feldstein ovals as parameterized by *Holzworth and Meng* [1975] in conjunction with the corrected geomagnetic coordinates (CGM) of *Gustafsson et al.* [1992]. Other representations of the auroral oval have also been used with IRI [e.g., *Szuszczewicz et al.*, 1993]. Several trough models have been proposed [*Brace,* 1990; *Karpachev et al.*, 1996; *Werner and Proelss,* 1997] and need to be consolidated into one standard model. *Sojka et al.* [1991] made first steps toward translating the UT and interplanetary magnetic field $B_y$ dependence of the ionospheric polar hole into an empirical model.

## 4. Plasma Temperatures, Ion Composition, and Drift

### 4.1. Electron and Ion Temperature

As a major improvement the IRI electron temperature model will now incorporate the height-specific models developed by *Truhlik et al.* [2000] and *Triskova et al.* [1996] based on data from three Intercosmos satellites. This will help to overcome shortcomings of the current IRI model in the description of the diurnal variation in the topside and help to overcome seasonal and solar cycle limitations of the earlier used database. The most notable changes will be found in the upper topside, where the present model was limited to a simple day-night transition and did not reproduce the early morning and afternoon peaks seen in the satellite data. At the lower boundary (at 100 km) the IRI temperatures are forced to agree with the neutral temperature as given by the COSPAR International Reference Atmosphere [*CIRA*, 1988]. A newer CIRA model will be incorporated if and when it becomes available. Data from a number of Japanese satellites are been used for the evaluation of the IRI model [*Oyama et al.*, 1996] and for its extension to plasmaspheric altitudes [*Oyama and Abe,* 1995].

### 4.2. Ion Composition

No changes are planned for the IRI ion composition model, but a few efforts are worth mentioning at this point. *Hoegy and Grebowsky* [1994] and *Grebowsky and Hoegy* [1995] have established a large database of in situ ion density measurements from a number of satellites covering the 1960s and 1970s. This database should help to overcome the shortcomings of the IRI ion composition model noted by *Hoegy and Grebowsky* [1994] and *Grebowsky et al.* [1998], although calibration issues may not always allow the deduction of reliable ion composition data from the ion density measurements.

The IRI describes the percentage of $O^+$ and $O_2^+$ ions and then fills up to 100% (total ion density equals electron density) with light ions ($H^+$, $N^+$, and $He^+$) in the topside and with NO+ and Cluster ions in the region below the F peak. The primary source is Russian rocket and satellite data compiled by *Danilov and Semenov* [1978], *Danilov and Yaichnikov* [1985], and *Danilov and Smirnova* [1995]. The composition is described in terms of latitude, solar zenith angle, season, and solar activity. Limitations of the current IRI ion composition model can be explained by the limited database on which the model is based: e.g., there were no data available for nighttime and for high solar activity. A review of empirical ion composition models was given by *Bilitza* [1990a].

In the long term it is planned to replace the current model with a description based on the characteristic transition heights. These are the changeover heights from O+ ions to light ions in the topside and to molecular ions in the bottomside ($F_1$ region) and then, further down, the changeover to cluster ions (*D* region). Efforts are under way to develop global models for these heights based on satellite data [*Triskova et al.*, 1998; *Kutiev et al.*, 1994]. *Truhlik et al.* [1997] note the importance of including magnetic storm effects. They find an increase in the upper transition height with increasing magnetic activity. *Lathuillere and Pibaret* [1992] illustrate the storm effects on the lower transition height at auroral latitudes with EISCAT incoherent scatter data. *Zhang et al.* [1996] compared the results of their theoretical model calculations with empirical models for the lower transition height.

### 4.3. Ion Drift

Efforts to include an ion drift model in IRI were spearheaded by E. Kazimirovsky and his colleagues at SibIZMIRAN in the mid-1980s [*Kazimirovsky and Zhovty,* 1984; *Kazimirovsky et al.*, 1985]. With data deduced by ground-based radio methods D1 and D3 (spaced receivers) they developed a model fir the horizontal ion drift at *E* region and *F* region heights [*Kazimirovsky et al.*, 1990]. The model is based on data from 23 stations in the Northern Hemisphere obtained between 1957 and 1970. The zonal and meridional drift components are provided as functions of geomagnetic latitude and local time for different seasons and solar activity periods. Noting the considerable amount of ion drift data available from incoherent scatter radar stations and also from satellite in situ measurements, the IRI team has put high priority on including in IRI an ion drift model based on all the different data sources. As a first step, IRI 2000 will include the equatorial *F* region vertical drift model developed by *Scherliess and Fejer* [1999] based on radar and satellite data. Their model depends on local time, longitude, season, and solar activity and describes well the characteristic diurnal features (maximum around noon and post-sunset pre-reversal spike) and their longitudinal, seasonal, and solar cycle differences. Inclusion of this model in IRI should be of help in the pursuit of a better understanding of the processes that shape the equatorial ionosphere and of the representation of this critical region in IRI. The pre-reversal peak in equatorial vertical drift results in a similar peak in the *F* peak height (*hmF2*). This feature is currently not reproduced in the *M3000*-based IRI *hmF2* model. A correlation with the new ion drift model may help to overcome this shortcoming.

A number of researchers have modeled the ion drift data from specific incoherent scatter radar. The model of *Blanc and Amayenc* [1979] represents the St. Santin data from 1973 to 1975. *Richmond et al.* [1980] established a global model (excluding high latitudes) based on data from Millstone Hill, St. Santin, Arecibo and Jicamarca. *Zhang et al.* [2000] have described the ion drift variations over the Japanese MU radar based on data from 1986 to 1997. These models will help the IRI team on the road to a global ion drift model for IRI based on all available data sources.

## 5. Future Projects

A special task force working on models for the occurrence statistics of equatorial irregularities (e.g., spread *F*) is headed by M. Abdu (Brazil). First results were reported by *Abdu et al.* [1998, 2000]. They used data from Brazilian and Argentinian stations to study diurnal, seasonal, and solar cycle trends of spread-*F* occurrence. Regional model for the Indian and Chinese subcontinent were presented by *Saksena* [1996] and *Jiao and Wu* [1996], respectively.

Occurrence statistics for sporadic *E* are also of interest especially for VHF propagation studies and applications. The IRI team is interested in a revitalization of these modeling work and setting up a special task group. Regional Sporadic E models were presented at earlier IRI workshops [*Jiao and Wu,* 1996; *Grubor,* 1991].

The variability (deviation from the monthly mean) is an important parameter for many space-weather-related applications, because an operator quite often not only needs the most likely value for a specific ionospheric parameter but also a measure of how far the actual value can stray from the median prediction. *Gulyaeva et al.* [1998] have studied the variability of *foF2* and *Mosert de Gonzalez and Radicella* [1995] have investigated the changes in variability with altitude. A functional description of the standard deviation for a regional TEC model was recently presented by *Gulyaeva et al.* [1998]. Developing models for the variability of ionospheric parameters will be a primary focus of future IRI Task Force Activities at the ICTP in Trieste, Italy.

## 6. Applications and Availability

IRI has been used for a wide range of applications. To name just a few, *Huang et al.* [1996] used IRI as initial guess in their tomography method to facilitate reconstruction of ionosphere images. *Miller et al.* [1990] have derived neutral winds from the IRI F peak height. *Bilitza et al.* [1995] have applied IRI for obtaining ionospheric corrections for satellite altimeter measurements of sea surface heights. IRI has been also used as background ionosphere for testing various GPS data analysis and data reduction algorithms [e.g., *Coster et al.,* 1990]. IRI usage for HF propagation assessment was reviewed by *Bradley* [1991].

IRI is used as the standard in a number of publications including the "Natural Orbital Environment Definition Guidelines for Use in Aerospace Vehicle Development" [*NASA*, 1994] and the "System Engineering – Space Environment" handbook of the European Cooperation for Space Standardization [*ECSS*, 1997]. A proposal is currently pending to the International Standardization Organization (ISO) to make IRI the ISO standard for the ionosphere.

The IRI home page is at http://nssdc.gsfc.nasa.gov/space/model/ionos/iri.html. It includes information about the IRI Working Group members, the IRI Workshops (including summaries), and the IRI Newsletter and electronic mailer. The IRI Newsletter is being distributed from ISAS (K. Oyama, editor). The software can be retrieved via anonymous ftp from nssdc.gsfc.nasa.gov in directory pub/models/ionospheric/iri/iri95; an iri2000 directory will be created as soon as the new code is released. The IRI Web pages and ftp site register a total of ~4000 accesses per month. Software and internet-related developments include a Web interface (Java) that allows computation and plotting of IRI parameters and a Windows NT version with similar capabilities. The Java system was developed by N. Papitashvili at the National Space Science Data Center and is available on the web at http://nssdc.gsfc.nasa.gov/space/model/models/iri.html. It lets the user calculate and plot IRI parameters versus height, latitude, longitude, time, month, year, or solar activity. The Windows NT version developed by X. Huang (UML) provides similar capabilities and, in addition, also an option for contour plots.

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## References

Abdu, M., J. Sobral, I. Batista, V. Rios, and C. Medina, Equatorial spread-F occurrence statistics in the American longitudes: Diurnal, seasonal and solar cycle variations, *Adv. Space Res., 22*(6), 851-834, 1998.

Abdu, M., J. Sobral, and I. Batista, Equatorial spread F statistics in the American longitudes: Some problems relevant to ESF description in the IRI scheme, *Adv. Space Res.*, *25*(1), 113-124, 2000.

Balan, N., G. Bailey, B. Jenkins, P. Rao, and R. Moffett, Variations of ionospheric ionization and related solar fluxes during an intense solar cycle, *J. Geophys. Res.*, *99*, 2243-2253, 1994a.

Balan, N., G. Bailey, and R. Moffett, Modeling studies of ionospheric variations during an intense solar cycle, *J. Geophys. Res.*, *99*, 17,467-17,475, 1994b.

Batista, I., J. de Souza, M. Abdu, and E. de Paula, Total electron content at low latitudes and its comparison with the IRI90, *Adv. Space Res.*, *14*(12), 87-90, 1994.

Bent, R., S. Llewellyn, and M. Walloch, Description and evaluation of the Bent ionospheric model, *AD 753081*, Nat. Tech. Inf. Serv., Springfield, Va., 1972.

Bilitza, D., Electron density in the *D*-region as given by the IRI, in *International Reference Ionosphere – IRI 79*, edited by V. Lincoln, R. Conkright, and K. Rawer, *Rep. UAG-82*, pp. 7-10, World Data Cent. A for Sol.-Terr. Phys., Boulder, Co., Nov. 1981.

Bilitza, D., Electron density in the equatorial topside, *Adv. Space Res.*, *5*(10), 15-19, 1985.

Bilitza, D., Empirical modeling of the ion composition in the middle and topside ionosphere, *Adv. Space Res.*, *10*(11), 47-56, 1990a.

Bilitza, D., *International Reference Ionosphere: IRI-90*, http://nssdc.gsfc.nasa.gov, Nat. Space Sci. Data Cent., *Rep. 90-22*, Greenbelt, Md, 1990b.

Bilitza, D. and R. Williamson, Towards a better representation of the IRI topside based on ISIS and Alouette data, *Adv. Space Res.*, *25*(1), 149-152, 2000.

Bilitza, D., C. Koblinsky, B. Beckley, S. Zia, and R. Williamson, Using IRI for the computation of ionospheric corrections for altimeter data analysis, *Adv. Space Res.*, *15*(2), 113-120, 1995.

Bilitza, D., C. Koblinsky, S. Zia, R. Williamson, and B. Beckley, The equator anomaly region as seen by the TOPEX/Poseidon satellite, *Adv. Space Res.*, *18*(6), 23-32, 1996.

Bilitza, D., S. Bhardwaj, and C. Koblinsky, Improved IRI prediction for the Geosat time period, *Adv. Space Res.* *20*(9), 1755-1760, 1997.

Bilitza, D., C. Koblinsky, R. Williamson, and S. Bhardwaj, Improving the topside electron density model for IRI, *Adv. Space Res.*, *22*(6), 777- 792, 1998.

Bilitza, D., M. Hernandez-Pajares, J. Juan, and J. Sanz, Comparison between IRI and GPS-IGS derived electron content during 1991-97, *Phys. Chem. Earth, Part C*, *24*(4), 311-319, 1999.

Bilitza, D., S. Radicella, B. Reinisch, J. Adeniyi, M. Mosert de Gonzalez, S. Zhang, and O. Obrou, New $B_0$ and $B_1$ models for IRI, *Adv. Space Res.*, *25*(1), 89-96, 2000.

Blanc, M., and P. Amayenc, Seasonal variations of the ionospheric $E \times B$ drifts above Saint-Santin on quiet days, *J. Geophys. Res.*, *84*, 2691-2704, 1979.

Brace, L., Solar cycle variations in *F*-region $T_e$ in the vicinity of the mid-latitude trough based on AE-C and DE-2 measurements at solar maximum, *Adv. Space Res.*, *10*(11), 83-88, 1990.

Bradley, P., Use of electron density profiles in HF propagation assessment, *Adv. Space Res.*, *11*(10), 117-134, 1991.

Bradley, P., Improved representation of the night and twilight E-region critical frequency, *Adv. Space Res.*, *14*(12), 71-74, 1994.

CCIR (International Radio Consultative Committee), Atlas of ionospheric characteristics, *Rep. 340-6*, Int. Telecommun. Union, Geneva, 1991.

CIRA 1986, Part I: Thermosphere Model, D. Rees (ed.), *Adv. Space Res.*, *8*(5-6), 1988.

Coster, A., M. Buonsanto, E. Gaposchkin, D. Tetenbaum, and L. Thornton, Ionospheric and tropospheric path delay obtained from GPS integrated phase, incoherent scatter and refractometer data and from IRI-86, *Adv. Space Res.*, *10*(8), 105-108, 1990.

Danilov, A., and V. Semenov, Relative ion composition model at mid-latitudes, *J. Atmos. Terr. Phys.*, *40*, 1093-1102, 1978.

Danilov, A., and N. Smirnova, Improving the 75 to 300 km ion composition model of the IRI, *Adv. Space Res.*, *15*(2), 171-178, 1995.

Danilov, A., and A. Yaichnikov, A new model of the ion composition at 75km to 1000km for IRI, *Adv. Space Res.*, *5*(7), 75-79, 1985.

Danilov, A., A. Rodevich, and N. Smirnova, Problems with incorporating a new D-region model into the IRI, *Adv. Space Res., 15*(2), 165-169, 1995.

DuCharme, E, L. Petrie, and R. Eyfrig, A method for predicting the F1-layer critical frequency, *Radio Sci., 6*, 369-378, 1971.

DuCharme, E, L. Petrie, and R. Eyfrig, A method for predicting the F1-layer critical frequency based on Zurich smoothed sunspot number, *Radio Sci., 8*, 837-839, 1973.

ECSS (European Cooperation for Space Standardization, System engineering: Space environment, handbook, Noordwijk, Netherlands, 1997.

Ezquer,R., C. Jadur, and M. Mosert de Gonzalez, IRI-95 TEC predictions for the South American peak of the equatorial anomaly, *Adv. Space Res., 22*(6), 811-814, 1998.

Fejer, B., E. de Paula, R. Heelis, and W. Hanson, Global equatorial ionospheric vertical plasma drifts measured by the AE-E satellites, *J. Geophys. Res., 100*, 5769-5776, 1995.

Friedrich, M., and K. Torkar, Typical behaviour of the high latitude lower ionosphere, *Adv. Space Res., 16*(1), 73-81, 1995.

Friedrich, M., and K. Torkar, Empirical D-region modelling, a progress report, *Adv. Space Res., 22*(6), 757-766, 1998.

Friedrich, M., R. Pilgram, and K. Torkar, A novel concept for empirical D-region modelling, *Adv. Space Res.*, in press, 2000.

Fuller-Rowell, T., M. Codrescu, E. Araujo-Pradere, and I. Kutiev, Progress in developing a strom-time ionospheric correction model, *Adv. Space Res., 22*(6), 821-827, 1999.

Fuller-Rowell, T., E. Araujo-Pradere, and M. Codrescu, An empirical ionospheric storm-time correction model, *Adv. Space Res., 25*(1), 139-148, 2000.

Gallgher, D.L., P.D. Craven, and R.H. Comfort, An empirical model of the Earth's plasmasphere, *Adv. Space Res., 8(8)*, 15-24, 1988.

Grebowsky, J., and W. Hoegy, High latitude ion composition, *Adv. Space Res., 16(1)*, 95-104, 1995.

Grebowsky, J., R. Erlandson, J. Sojka, and D. Bilitza, Comparison of measured high latitude *F*-region ion composition climatological variability with models, *Adv. Space Res., 22(6)*, 885-894, 1998.

Grubor, D., A method of including sporadic *E* in the ionospheric $N_e(h)$ models, *Adv. Space Res., 11(10)*, 113-116, 1991.

Gulyaeva, T., Progress in ionospheric informatics based on electron density profile analysis of ionograms, *Adv. Space Res., 7(6)*, 39-48, 1987.

Gulyaeva, T., S. Aggarwal, K. Mahajan, and S. Shastri, Variability of *foF2* at low and middle latitudes, *Adv. Space Res., 22(6)*, 847-850, 1998.

Gustafsson, G., N. Papitashvili, and V. Papitashvili, A revised corrected geomagnetic coordinate system for Epochs 1985 and 1990, *J. Atmos. Terr. Phys., 54*, 1609-1631, 1992.

Hathaway, D., R. Wilson, and E. Reichmann, A synthesis of solar cycle prediction techniques, *J. Geophys. Res., 104*, 22,375-22,388, 1999.

Hoegy, W., and J. Grebowsky, Comparison of ion composition from the Goddard Comprehensive Ionosphere Database with the IRI, *Adv. Space Res., 14(12)*, 121-124, 1994.

Holzworth, R., and C. Meng, Mathematical representation of the auroral oval, *Geophys. Res. Lett., 2*, 337-380, 1975.

Huang, X., and B. Reinisch, Vertical electron density profiles from the digisonde network, *Adv. Space Res., 18(6)*, 121-129, 1996.

Huang, C., C. Liu, H. Yeh, W. Tsai, C. Wang, K. Yeh, K. Lin, and H. Tsai, IRI model application in low latitude ionospheric tomography, *Adv. Space Res., 18(6)*, 237-240, 1996.

Ivanov-Kholodny, G., P. Kishcha, and T. Zhivolup, A mid-latitude *E*-layer peak height model, *Adv. Space Res., 22(6)*, 767-770, 1998.

Iyer, K., H. Joshi, R. Jivrajani, and P. Aravindakshan, Comparative study of TEC near the crest of the equatorial anomaly with IRI model for solar minimum and solar maximum, *Adv. Space Res., 18(6)*, 233-236, 1996.

Jiao, P., and J. Wu, Ionospheric models and data for the Chinese subcontinent, *Adv. Space Res., 18(6)*, 191-200, 1996.

Karpachev, A., M. Deminov, and V. Afonin, Model of the mid-latitude ionospheric trough on the base of COSMOS-900 and Intercomsmos-19 satellite data, *Adv. Space Res., 18(6)*, 221-230, 1996.

Kazimirovsky, E., and E. Zhovty, A plan for compilation of experimental data on drifts for IRI, *Adv. Space Res., 4(1)*, 149-151, 1984.

Kazimirovsky, E., E. Zhovty, and M. Chernigovskaya, Modelling of ionospheric ion drifts in view of IRI, *Adv. Space Res., 5(7)*, 95-96 and 109-112, 1985.

Kazimirovsky, E., E. Zhovty, and M. Chernigovskaya, Models for horizontal *E*- and *F*-region drifts, in International Reference Ionosphere 1990, *Rep. 90-22*, pp. 41-42, Nat. Space Sci. Data Cent., Greenbelt, Md., 1990.

Kimura, I., A. Hikuma, Y. Kasahara, and H. Oya, Electron density distribution in the plasmasphere in conjunction with the IRI model deduced from Akebono wave data, *Adv. Space Res., 18(6)*, 279-288, 1996.

Kishcha, P., Indices and updating procedures for modelling of ionospheric disturbances, *Adv. Space Res., 16(1)*, 55-64, 1995.

Kishcha, P., Short-term prediction of ionospheric peak parameters and TEC by the updated IRI model, *Adv. Space Res., 20(9)*, 1733-1740, 1997.

Komjathy, A., R. Langley, and D. Bilitza, Ingesting GPS-derived TEC data in to the IRI for single frequency radar altimeter ionospheric delay corrections, *Adv. Space Res., 22(6)*, 793-801, 1998.

Kopp, E., A global model of positive and negative ions in the lower ionosphere, *Adv. Space Res., 25(1)*, 173-182, 2000.

Kull, A., E. Kopp, G. Brasseur, and C. Granier, Ions and electrons in the mesosphere: A model for the quiet *D*-region, *Adv. Space Res., 15(2)*, 183-188, 1995.

Kutiev, I., S. Tankov, and P. Marinov, Analytical expression of the $O^+$-$H^+$ ion transition surface for use in IRI, *Adv. Space Res., 14(12)*, 135-138, 1994.

Lathuillere, C., and B. Pibaret, A statistical model of ion composition in the auroral lower *F* region, *Adv. Space Res., 12(6)*, 147-156, 1992.

Leitinger, R., A magnetic field aligned approach to model the topside $F_2$ layer, *Adv. Space Res., 22(6)*, 789-792, 1998.

Liu, R., P. Smith, and J. King, A new solar index which leads to improved *foF2* predictions using the CCIR atlas, *Telecommun. J., 50*, 408-414, 1983.

Mahajan, K., N. Sehti, and V. Pandey, The diurnal variation of E-F valley parameters from incoherent scatter measurements at Arecibo, *Adv. Space Res., 20(9)*, 1781-1784, 1997.

McNamara, L., Prediction of total electron content using the IRI, *Adv. Space Res., 4(1)*, 25-50, 1984.

McNamara, L., The use of total electron content measurements to validate empirical models of the ionosphere, *Adv. Space Res., 5(7)*, 81-90, 1985.

McNamara, L., and P. Wilkinson, Prediction of total electron content using the International Reference Ionosphere, *J. Atmos. Terr. Phys., 45*, 169-174, 1983.

Mechtley, E., and D. Bilitza, Models of *D*-region electron concentration, *Rep. IPW-WB1*, Inst. für phys. Weltraumforsch., Freiburg, Germany, 1974.

Miller, K., A. Hedin, P. Wilkinson, D. Torr, and P. Richards, Neutral winds derived from IRI parameters and from the HWM87 wind model for the Sundial campaign of September 1986, *Adv. Space Res., 10(8)*, 99-102, 1990.

Mosert de Gonzalez, M., and S. Radicella, Study of ionospheric variability at fixed heights using data from South America, *Adv. Space Res., 15(2)*, 61-65, 1995.

Mukhtarov, P. and D. Pancheva, Model of the electron density height profile in the lowest *D*-region (50 to 75 km), *Adv. Space Res., 15*(2), 179-182, 1995.

NASA, Natural orbital environment definition for use in aerospace vehicle development, *NASA Tech Memo., NASA-TM-4527*, 1994.

Nath, N., and S. Abraham, A test for the solar cycle variability of ionospheric radio wave absorption by A1 technique, Adv. *Adv. Space Res., 18*(6), 319-322, 1996.

Oyama, K., and T. Abe, Morphology of electron temperature in the high latitude plasmasphere, *Adv. Space Res., 16(1)*, 85-94, 1995.

Oyama, K., S. Watanabe, Y. Su, T. Takahashi, and K. Hirao, Season, local time, and longitudinal variations of electron temperature at the height of ~600 km in the low latitude region, *Adv. Space Res., 18*(6), 269-278, 1996.

Radicella, S., D. Bilitza, B. Reinisch, J. Adeniyi, M. Mosert Gonzalez, B. Zolesi, M. Zhang, and S. Zhang, IRI task force activity at ICTP: proposed improvements for the IRI region below the peak, *Adv. Space Res., 22*(6), 731-739, 1998.

Rawer, K., Propagation of decameter waves (h.f. band), in *Meteorological and Astronomical Influences on Radio Wave Propagation*, edited by B. Landmark, pp. 221-250, Macmillan, Indianapolis, Indiana, 1963.

Rawer, K., and D. Bilitza, International Reference Ionosphere – plasma densities: Status 1988, *Adv. Space Res., 10*(8), 5-14, 1990.

Rawer, K., and P. Bradley (Eds.), IRI 1997 Symposium: New Developments in Ionospheric Modeling and Prediction, *Adv. Space Res., 22(6)*, 723-915, 1998.

Rawer, K., D. Bilitza, S. Ramakrishnan, and M. Sheikh, Intentions and buildup of the International Reference Ionosphere, in *Operational Modeling of the Aerospace Propagation Environment, AGARD Conf. Proc. 238*, 6.1 – 6.10, 1978.

Rawer, K., D. Bilitza, K. Oyama, and W. Singer (Eds.), Lower Ionosphere Measurements and Models, *Adv. Space Res., 25*(1), 1-226, 2000.

Reinisch, B. and X. Huang, Redefining the IRI $F_1$ Layer profile, *Adv. Space Res., 25*(1), 81-88, 1999.

Richmond, A., et al., an empirical model of quiet-day ionospheric electric fileds at middle and low latitudes, *J. Geophys. Res., 85*, 4658-4664, 1980.

Rycroft, M., and I. Jones, Modeling the plasmasphere for the IRI, *Adv. Space Res., 5*(10), 21-27, 1985.

Rycroft, M., and I. Jones, A suggested model for the IRI plasmaspheric distribution, *Adv. Space Res., 7*(6), 13-22, 1987.

Saksena, R., Occurrence statistics for spread-*F* over the Indian subcontinent, *Adv. Space Res., 18*(6), 99-102, 1996.

Scherliess, L., and B. Fejer, Radar and satellite global equatorial *F* region vertical drift model, *J. Geophys. Res., 104*, 6829-6842, 1999.

Scotto, C., M. Mosert de Gonzalez, S. Radicella, and B. Zolesi, On the prediction of the $F_1$ ledge occurrence and critical frequency, *Adv. Space Res., 20(9)*, 1773-1776, 1997.

Scotto, C., S. Radicella, and B. Zolesi, An improved probability function to predict the $F_1$ layer occurrence and L condition, *Radio Sci.*, *33*, 1763-1765, 1998.

Serafimov, K., M. Serafimova, Y. Ramanamurty, and K. Rawer, A note on the use of absorption measurements for improving the IRI electron density distribution in the lower ionosphere, *Adv. Space Res.*, *5(10)*, 99-102, 1985.

Singer, W., J. Bremer, and J. Taubenheim, Improvement of the solar-cycle variation of IRI lower ionosphere models by means of radio wave propagation data, *Adv. Space Res.*, *4(1)*, 79-88, 1984.

Sojka, J., R. Schunk, W. Hoegy, and J. Grebowsky, Model and observation comparison of the UT and IMF $B_y$ dependence of the ionospheric polar hole, *Adv. Space Res.*, *11(10)*, 39-42, 1991.

Sonnemann, G., A. Ebel, C. Kremp, B. Fichtelmann, and U. Berger, The global NO distribution computed on the basis of a dynamic *D*-region model and implications on the winter anomaly of the *D*-layer, *Adv. Space Res.*, *16(1)*, 133-136, 1995.

Szuszczewicz et al., Measurements and empirical model comparison of F-region characteristics and auroral boundaries during the solstitial Sundial campaign of 1987, *Ann. Geophysicae*, *11*, 601-613, 1993.

Szuszczewicz, E., et al., The first real-time worldwide ionospheric predicitions network: An advance in support of spaceborne experimentation, on-line model validation, and space weather, *Geophys. Res. Lett.*, *25*, 449-452, 1998.

Titheridge, J., Ion transition heights from topside electron density profiles, *Planet. Space Sci.*, *24*, 229-245, 1976a.

Titheridge, J., Plasma temperatures from Alouette 1 electron density profiles, *Planet. Space Sci.*, *24*, 247-259, 1976b.

Triskova, L., J. Smilauer, V. Truhlik, and V. Afonin, On the low latitude topside models: II electron temperature, *Adv. Space Res.*, *18(6)*, 213-216, 1996.

Triskova, L., V. Truhlik, J. Smilauer, and Y. Shultchishin, Comparison of $O^+/H^+$ and $O^+/(H^+ + He^+)$ transition levels, *Adv. Space Res.*, *22(6)*, 895-898, 1998.

Truhlik, V., J. Smilauer, L. Troskova, Y. Shultchishin, and N. Smirnova, Manifestation of ionospheric storms in the upper transition height, *Adv. Space Res.*, *20(9)*, 1709-1712, 1997.

Truhlik, V., L. Triskova, J. Smilauer and V. Afonin, Global empirical model of electron temperatures in the outer ionosphere for period of high solar activity based on data of three Intercosmaos satellites, *Adv. Space Res.*, *25(1)*, 163-172, 2000.

Werner, S., and G. Proelss, The position of the ionospheric trough as a function of local time and magnetic activity, *Adv. Space Res.*, *20*(9), 1717-1722, 1997.

Zhang, S., M. Zhangm S. Radicella, X. Huang, D. Bilitza, A comparison of the lower transition height obtained with a theoretical model and wit IRI, *Adv. Space Res.*, *18*(6), 165-173, 1996.

Zhang, S., W. Oliver, and S. Fukao, MU radar ion drift model, *Adv. Space Res.*, in press, 2000.

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