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INTERNATIONAL REFERENCE IONOSPHERE – PAST, PRESENT, AND FUTURE: I. ELECTRON DENSITY

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ABSTRACT

In December 1990 a new IRI handbook was published by NASA's National Space Science Data Center (NSSDC) describing in detail the International Reference Ionosphere 1990. Shortly thereafter, the IRI-90 software was released on tape, diskette, and computer networks. This paper is intended as an inventory of the most important IRI activities up to 1990 and as a starting point for the next improvement cycle. It summarizes the work and studies that led to IRI-90 and provides an overview over this latest version of the model. Shortcomings and limitations are pointed out, and ways of overcoming them are discussed. Priorities are suggested for the list of work items that the IRI group has to tackle in the future. High on the wishlist are major improvements at high latitudes and inclusion of magnetic storm effects. This first paper deals with the electron density; a follow-on paper discusses plasma temperatures, ion composition, and ion drift.

INTRODUCTION

Since the joint URSI/COSPAR project for the development of the International Reference Ionosphere (IRI) begun in the late sixties, several versions of the model have been released in hard copy as well as in computer-readable form. New data input and feedback from the user community have helped the IRI group to continuously improve and elaborate upon the model from version to version. A set of tentative tables of IRI profiles was presented at the XVII General Assembly of URSI in 1972. The first widely circulated edition of the model was IRI-78 (computer program: Version No. 5), which is described in a red URSI booklet /1/ (see also /2/). It marked the transition from a model in tabular form (profiles for typical conditions) to a truly global model (using spherical harmonics). Over the following years extensive checking and validating of IRI-78 with newer ground and space data resulted in several updates of the IRI programs. Most notably, the representation of the topside electron density and of the global description of the plasma temperatures benefited from the input of satellite and incoherent scatter radar data. Finally, by the end of 1980 it was time for a new edition. IRI-80 (computer program: Version No. 7) was published in a voluminous issue /3/ of the yellow reports of the World Data Center A for Solar-Terrestrial Physics in Boulder, Colorado, U.S.A. After an improvement cycle of six years, the next milestone came with the release of IRI-86 (computer program: Version No. 9), which was the first edition to be available online through computer networks and also on diskette for use on Personal Computers (PCs). With IRI-86 came a better representation of the equatorial topside electron density profile (data base: AE-C, AEROS, Jicamarca incoherent scatter radar) and a much refined description of the global morphology of electron temperature (data base: ISIS-1, -2, AE-C, Jicamarca and Arecibo incoherent scatter radar). In November 1990 the latest edition, IRI-90 (computer program: Version No. 11), was published as a green book /4/ in the report series of the National Space Science Data Center and World Data Center A for Rockets and Satellites (NSSDC/WDC-A-R&S). It features several new options for the electron density and ion composition. Version No. 12 of the IRI computer program, which was released in November of 1991, includes the most recent COSPAR International Reference Atmosphere (CIRA) for the neutral temperature.

IRI is used for a wide range of applications in science, engineering, and education. Its ever-increasing popularity is documented by the number of citations in scientific journals (1989: 41; 1990: 57; 1991: 64) and also by the fact that it is consistently included in NSSDC's annual hit list of most frequently requested items in space science. Since 1988, IRI can also be accessed and run online on the NSSDC Online Data and Information Service (NODIS) account: To do so from a NSI-DECnet node (i) SET HOST NSSDCA, (ii) USERNAME=NODIS, and (iii) follow the prompts and menus.

This and the follow-on companion paper review the past, present and future of the IRI project. In particular the studies that led to the different editions of the model are discussed, the status of on-going IRI activities is examined, and priorities for future IRI initiatives are proposed. Details of the functional description and explanations of the formulas used in IRI can be found in the IRI-90 guide book /4/ and will not be repeated here. The focus of this paper is the electron density, all other IRI parameters (plasma temperatures, ion composition, ion drift) are the topic of the companion paper. The first part of this paper is dedicated to the global mapping of peak parameters and the second part to the representation of the density profile.

F- AND E-PEAK MAPPING

Coordination of the international F- and E-peak mapping activities is the responsibility of special working groups of the International Union of Radio Science (URSI) and of the Consultative Committee of International Radiocommunications (CCIR), which is part of the International Telecommunication Union (ITU). CCIR's most widely known mapping publication is the "atlas of ionospheric characteristics" (Report 340 and later supplements) /5/. It contains global maps for all those ionospheric peak parameters of importance for radio wave propagation. When the IRI group began its modelling work, it decided to rely on several of these well-established CCIR parameter maps rather than pursue independent mapping solutions. Of particular interest for IRI are the CCIR models for the E- and F-peak critical frequencies foE, foF1, and foF2, and for the propagation factor M(3000)F2. From these parameters one can obtain the peak densities and height: (i) Peak densities (NmE, NmF1, NmF2) are proportional to the square of the critical frequencies, and (ii) a strong anti-correlation exists between M(3000)F2 and the F2 peak height hmF2.

From the beginning the IRI group closely followed the work done by CCIR and URSI mapping groups and, when appropriate, has urged CCIR and URSI to consider new mapping initiatives to provide more and more accurate world maps of ionospheric peak parameters. In recent years the IRI group has begun to assume a more active role in the mapping effort, recognizing that its needs, especially concerning regional mapping, are not fully served by the present level of CCIR and URSI mapping activities. Recent reviews of mapping of F2-peak parameters were prepared for the IRI group by Bilitza et al. /6/ and by Bradley /7/.

F2-peak density NmF2 and critical frequency foF2

Past developments. CCIR released its first set of numerical maps for foF2 in 1967 as CCIR Report 340 /5/. The 23,712 model coefficients listed in the report were also made available on punched cards for use on computers. Jones and Gallet /8/ developed these maps based on ionosonde data recorded at over 150 stations from 1954 to 1958. In a first step, Fourier functions up to sixth order (13 coefficients) were used to describe the monthly median diurnal variation (in Universal Time) at each station. In a second step the global morphology of each one of the 13 Fourier coefficients was represented with a special choice of geographical sine and cosine functions depending on geographic latitude and longitude and on the modified dip latitude (modip) introduced by Rawer /9/. Tests showed that modip is the best suited coordinate for the global representation of foF2, particularly in the highly structured equatorial region.

This analysis was done for each month from 1945 to 1958, thus obtaining for each coefficient (of each monthly map) five values corresponding to different solar activities. In the next step a straight line was (least-square) fitted through the five points, and coefficient values were calculated for two levels of solar activity (R_{12}= 0, 100 – R_{12} being the 12-month-smoothed mean value of the Zurich monthly sunspot number). For other levels of solar activity the CCIR Report 340 /5/ recommends linear interpolation up to R_{12}= 150. Above this level saturation is observed in a lot of cases, and CCIR suggests using an effective sunspot number of 150 if R_{12} is greater than 150. Even though the CCIR-67 maps were regarded as provisional at the time, they are to this day still the most widely applied foF2 model.

In 1971 the "Supplement N°1 To Report 340" /5/ was released introducing a revised set of coefficients for foF2 that was produced by Jones and Obitts /10/. Different from the 3-dimensional CCIR-67 functions, their 5-dimensional model functions include also annual variations (Fourier series) and solar cycle variations (second degree polynomial). Thus their approach resulted in a considerable reduction of coefficients and introduced more smoothing of the original data base. Both models, however, were built with the exact same data base and therefore do not differ much in terms of forecast capability. Most users decided to stay with the original CCIR-67 maps rather than to develop new computer programs for the implementation of the CCIR-71 set. In the "Supplement N° 3 To Report 340" /5/, which was released in 1980, CCIR recommends using the CCIR-67 maps for long-term predictions and the CCIR-71 maps for short-term forecast.

Because of the irregular distribution of ionosonde stations and the total absence of data above the oceans, it is not surprising that errors were detected in comparisons of the CCIR maps with ground and space data /11,12/. When Jones and Gallet /8/ originally developed their foF2 numerical maps, they had to introduce so-called screen points to stabilize their analysis method. At these phantom stations, located mostly in the ocean regions, artificial values were obtained by averaging over the real data from stations with similar modip but different longitudes. A much better way of determining foF2 at the screen points was chosen by Rush and his colleagues at the Institute for Telecommunication Sciences (ITS) in the early eighties /13,14/. They filled the ocean data gaps at mid-latitudes with theoretically determined foF2 values. Neutral wind amplitudes needed for this calculation were inferred from the comparison of theoretical and measured foF2 above the continents. Rush et al. /13,14/ decided to build their ITS maps with a rather limited data base, using only about 2,400 station-months compared to the about 10,000 station-months used for CCIR-67. Only two years of data were considered in their analysis, one for low and one for high solar activity. The maps thus relyied on only two values for the determination of the solar activity variation of each coefficient rather than 5 as in the case of the CCIR-67 maps. Discrepancies were found in comparisons with the topside sounder data of the Japanese ISS-b satellite /15,16/; ISS-b operated during a period of very high solar activity (1979-1980).

The next step toward better foF2 maps came from work done at the Australian Ionospheric Prediction Service (IPS). Fox and McNamara /17/ combined the theoretical ITS values over the oceans with a very large data base of ionosonde recordings (over 45,000 station-months) and then applied their own type of harmonic analysis. Their method allows for differing numbers of harmonic terms depending on magnetic latitude. By using more terms than older maps (CCIR, ITS) in the equatorial region and less at mid-latitudes, better agreement was reached with the global foF2 maps obtained by the ISS-b satellite. Other differences to the Jones-Gallet method include: (i) Rather than mapping Fourier coefficients, Fox and McNamara mapped the hourly values; (ii) rather than using modip and geographic longitude, they used modip and geomagnetic longitude; and (iii) their final maps are provided for T = 0, and 100, where T is the ionospheric T-index /18/ traditionally used for ionospheric forecasting at IPS.

Present status. Meanwhile, at the General Assembly in 1984 URSI acknowledged the need for a renewed international mapping effort and established the Working Group G.5 'to make improvements in the present CCIR maps'. Under the chairmanship of K. Davies, the ITS and IPS groups combined their efforts and came up with a new set of coefficients in 1988 /19,20/. In creating these maps, it was decided to stay within the mathematical framework of the earlier CCIR and ITS models but at the same time to make use of the extensive data base synthesized in the IPS maps. Thus, the URSI-88 numerical maps were obtained by applying the Jones-Gallet method to foF2 maps established with the IPS model. As expected, comparisons with ISS-b topside sounder maps showed the URSI-88 maps to be more accurate than the CCIR-67 maps over the oceans. But at the same time some accuracy was lost over continental areas. It is easily understood that the better representation of the ionization structure over the oceans came at the expense of a slightly less accurate model in other areas of the globe, because the set of model functions remained unchanged. Even though the URSI-88 maps are not yet adopted by CCIR, the IRI group decided to use these maps for its 1990 edition. CCIR-67, however, was kept as a second choice, because of the possible preference of certain user groups. As in the past, foF2 (or NmF2) can be also a user-provided input parameter.

Future improvements. Progress in global foF2 mapping may come from applying more sophisticated numerical analysis procedures to the unevenly distributed data base. It seems clear that the equatorial and auroral regions need more harmonic terms than the mid-latitudes, as the work by Fox and McNamara /17/ has shown. This can, of course, only succeed if the ionospheric data base continues to be enlarged, particularly at low and equatorial magnetic latitudes. Unfortunately, ionosonde stations are largely accumulated in the European and North American sectors, and only few are near the magnetic equator. Help may also come from the topside sounder measurements made by the Japanese ISS-b and OZOHRA satellites and the Russian IK-19 satellite. Regrettably, there are no new topside sounder missions planned at this time.

A better representation of the solar activity variations of foF2 is also of great importance. In the CCIR "Supplement N°3 To Report 340" /5/ it was noted that the level of solar activity at which foF2 appears to be saturated is a function of location, time of day, and season, but no recommendation was made to replace the constant saturation level of R_{12}= 150 used in the CCIR-67 model. One possible solution is the use of one of the ionospheric indices IF2, IG, or T instead of solar sunspot number. These indices are obtained from a linear regression analysis of solar sunspot numbers and foF2 values measured at selected sites. For IF2 the regression lines were obtained from past monthly noon data (1942-1957) recorded at 13 selected ionosonde stations /21/. IG was designed specifically for use with the CCIR-67 maps. It uses the same 13 locations as IF2, but its regression lines were determined from the CCIR-67 maps /22/. Different from IF2 and IG, the Australian T-index /18/ is based on foF2 data for all hours from 30 stations; regression lines are obtained in a fashion similar to IF2. Not surprisingly, these ionospheric indices have shown much better correlation with foF2 than any of the solar indices, but their availability and consistency depend on the continuous operations of the selected ionosondes. CCIR prepares a monthly circular of IF2 and IG values (monthly and 12-month-running mean). At its recent meeting the IRI group decided to allow use of IG in addition to the presently used solar sunspot number in future editions of the model.

In recent years the IRI group has begun to explore more actively solutions to certain aspects of the mapping problem. Topics of particular interest are high-latitude mapping and foF2 updating during magnetic storms. Even though IRI at present is a non-auroral, quiet-time model, Schunk and Szuszczewicz /23/ pointed out that in its monthly-averaged format the IRI/CCIR compares well, even at high latitudes, with the monthly-averaged foF2 maps that were produced from ISS-b measurements. They also found good agreement with the ionosonde data collected during their global-scale SUNDIAL campaigns, even for stations assumed to be in the nighttime trough /24/. Regional mapping may help to further improve IRI at high latitudes. Two such methods have in particular gained the interest of the IRI group, and first results have been reported at IRI meetings. Dvinskikh /25/ proposed the use of so-called Empirical Orthogonal Functions (EOF), which are obtained as the eigenfunctions of the autocorrelation matrix of a data field. Using EOFs, Bossy et al. /26/ produced a regional foF2 model for invariant latitudes greater than 50°. Their numerical maps are based on foF2 values obtained from aeronomical simulations with the Utah State University (USU) model. EOFs have also proven to be a more efficient way for the representation of global maps both in terms of computation time and space requirements /27/. The second method is based on the use of fractional Legendre functions, the so-called Spherical Cap Harmonics (SCH) /28/. SCHs have been applied for regional mapping of foF2 in Europe. At auroral and polar latitudes plasma convection is clearly affected by the direction of the Interplanetary Magnetic Field (IMF) /29/. Therefore, different sets of regional maps have to be established for different IMF directions. Sojka et al. /30/ used the USU aeronomical model to investigate the IMF dependence of an often observed plasma depletion, the so-called polar hole.

Of great interest to the IRI group are the continuing efforts to describe the effects of magnetic disturbed conditions on foF2. Wrenn /31,32/ devised an integrated geomagnetic activity index to describe the ratio of the storm-time foF2 to its quiet-time reference.

It is hoped that future updates of the IRI model will also include occurrence statistics for Spread-F, a disturbance often seen at equatorial and auroral latitudes. A possible candidate for this purpose are the Spread-F maps established by Maruyama and Matuura /33/ based on ISS-b topside sounder data.

F2 peak height hmF2 and propagation factor M(3000)F2

Past developments. Information about F-layer heights is of great importance for radiowave propagation studies and forecast, but real heights are difficult to obtain from ionograms. Therefore a propagation factor M(3000)F2 was devised that can be derived graphically directly from logarithmic ionograms. M(3000)F2 is defined as the ratio MUF/foF2, where MUF is the maximum usable frequency that refracted in the ionosphere can be received at a distance of 3000 km. This factor has been routinely scaled from ionograms at many stations worldwide. Numerical maps were established from this data base in the same way as described above for foF2. Published in CCIR's Atlas of Ionospheric Characteristics /5/, these maps use Fourier terms up to 4th order (9 coefficients) and 49 of the geophysical functions. Thus, 441 coefficients are needed per month and solar activity level. No updates have been produced since the original CCIR maps were released in 1967.

Shimazaki /34/ showed that propagation theory predicts a strong anti-correlation between M(3000)F2 and hmF2. In a second step he fitted his theoretically obtained formula to experimental data, but his empirical formulas are based on peak heights (hpF2) deduced from ionograms with simplified assumptions about the density profile in the middle ionosphere (parabolic bottomside, no E-layer). It was found that the Shimazaki formula overestimated peak heights obtained with a more elaborate real-height analysis of ionograms. To take account of the ionization in the E-layer, Bradley and Dudeney /32/ modified the original Shimazaki formula by introducing an additional term depending on the ratio foF2/foE, where foE is the critical frequency of the E-peak. A few years later, Dudeney /33/ was able to come up with a considerably improved hmF2-M(300)F2 formula, based on a more detailed consideration of the density profile in the region from E- to F-peak. Up to this point all studies were based on hmF2 values deduced from ionograms through some type of real-height analysis of the ionogram trace. This procedure needs a priori information about the ionization (i) below the ionogram starting point and (ii) in the valley that is often found above the E-layer. Depending on the assumptions made, the calculated hmF2 may vary by several tens of km /37/. More reliable measurements of hmF2 are obtainable with the incoherent scatter technique. Bilitza et al. /38/ used these data to verify the hmF2-M(3000)F2 correlation. They found that they had to introduce additional dependences on solar activity and on magnetic dip latitude into the relationship to represent hmF2 data of the incoherent radar facilities in Millstone Hill (Massachusetts, U.S.A.), Arecibo (Puerto Rico), and Jicamarca (Peru).

Present status and future improvements. Since 1979, IRI applies the formula by Bilitza et al. /38/ to represent the global hmF2 with the help of the CCIR-M(3000)F2 maps. Comparisons with newer measurements have been in general favorable /39,40/ and have encouraged researchers to use IRI-hmF2 values for the calculation of ionization fluxes /41/ and neutral winds /42/ in the F-region. During nighttime, IRI values were found to be somewhat higher than incoherent scatter and ionosonde measurements /39,40/. The post-sunset uplift of the F-layer observed close to the magnetic equator is not well represented by any of the M(3000)F2-based models. There is a general agreement that remedy of these shortcomings cannot come from further correcting the M(3000)F2-based models. Direct global mapping of hmF2 is the most reasonable next step. Attempts have been made to describe hmF2 with relatively simple descriptive models /43,44/ using only a small number of terms and coefficients. It is clear, however, that this simplified description cannot reproduce the global structure to the same detail as representations in spherical harmonics. One of the descriptive models /43/ was recently improved by Anderson et al. /45/, who introduced a sixth-order Fourier correction into the Chiu-model to better approximate hmF2 values obtained with their Semi-empirical Low-latitude Ionospheric Model (SLIM). On the topic of hmF2 mapping, close cooperation exists with the Working Group on Ionospheric Informatics (WGII, Chair: B. Reinisch) of URSI's Commission G, which was formed in 1987; the former URSI mapping group was merged with this group in 1990.

F1-peak density NmF1, critical frequency foF1, and height hmF1

During daytime ionograms often exhibit a characteristic F1 point, clearly identified by a cusp-like trace structure similar to those for the E- and F2-peaks. Inverted into electron density profiles, the F1 feature translates into a small gradient discontinuity. This feature is sometimes difficult to recognize in electron density profiles measured directly by, for example, incoherent scatter radars. The strong dependence of F1 parameters on solar zenith angle proves that this region is predominantly under solar control, different from the highly variable F2-region, where plasma transport mechanisms play an important role.

The standard empirical model for foF1 (and the correlated NmF1) was developed by DuCharme, Petrie, and Eyfrig /46/ in the early seventies. Based on data from 39 ionosonde stations for more than a solar cycle (1954-1966), their model describes foF1 variations with solar zenith angle, geomagnetic latitude and solar sunspot number (12-month-running mean). In addition, the model also provides a limiting solar zenith angle as function of geomagnetic latitude and solar sunspot number. For zenith angles above the limiting value, the model assumes that a distinct F1-layer is not present. This global foF1 model was used in IRI from the very beginning. CCIR included it in later supplements of the Atlas of Ionospheric Characteristics /5/. Following a recommendation by one of the model authors (Eyfrig) and discussions in the IRI group, it was decided to replace geomagnetic latitude with magnetic dip latitude in the IRI version of the foF1 model. F1 occurrence was further restricted in IRI by the outright omission of this feature in winter and during nighttime.

The height of the F1 point (hmF1) is found as the height at which the bottomside IRI profile reaches the model density NmF1. Thus, it is important to note that hmF1 depends on the choice of the bottomside thickness parameter B_0 for which IRI-90 offers two choices, as described later in this article. It was found that the older one of these options (B_0 Table) produces a diurnal variation of hmF1 synchronous with hmF2, whereas the newer one (Gulyaeva's model) results in solar zenith dependent hmF1 values /47/.

E-peak density NmE, critical frequency foE, and height hmE

Compared to the F2-region, the E-region is well behaved, exhibiting a strong solar control and relatively small day-to-day data scatter. Descriptive models using only a small number of coefficients have shown excellent results and have been favored over the coefficient-intensive mapping with spherical harmonics. Systematic analysis of the large data base of ionosonde foE measurements led Kouris and Muggleton /48,49/ to the model currently used in IRI and CCIR. Based on data from 55 ionosonde stations for the time period from 1944 to 1973, the model /49/ describes foE in terms of solar zenith angle, geographic latitude, monthly mean 10.7 cm solar radio flux (F10.7M), and a seasonal parameter (solar zenith angle at noon). A solar activity dependent minimum value is enforced based on a study of nighttime results by Wakai /50/. In IRI the nighttime variation was improved with the help of Arecibo incoherent scatter observations /51/.

E-peak heights measured by ionosondes and by rocket experiments show only a small variation with solar zenith angle (day/night amplitude of less than 10 km). At present this small change is ignored in IRI, which assumes a constant value of 105 km. Introduction of one of the solar zenith angle dependent formulas would make this part of the IRI profile more consistent with the D-region below and the F1-region above, which both move upward during nighttime.

Close to the E-peak a very thin and patchy Sporadic-E layer appears irregularly, whose peak density can exceed the normal E- and F-peak densities. Sporadic-E can strongly disturb radiowave propagation, and it would be therefore desirable to have some type of global occurrence statistics for this feature. Models have been established for individual ionosonde stations /52,53/. Global-scale representation is made difficult by insufficient knowledge about the extent of Sporadic-E patches and by the non-existence of a truly global data set. Mapping procedures based on the data from a few stations, as they were done for CCIR (see Report 340-3 /5/), cannot overcome these difficulties.

ELECTRON DENSITY PROFILE

In IRI the topside and bottomside F-region is normalized to the F2-peak density and height, whereas the bottomside E-region and the E-valley region are normalized to the E-peak density and height. Both profile parts are merged parabolically in the region between the the F1 point and the top of the E-valley. Under certain unfavorable conditions the merging cannot be accomplished, and in this case the profile gap is closed by linear interpolation. This can disrupt the latitudinal variation of IRI electron density, by causing small, artificial discontinuities.

Topside ionosphere and plasmasphere

The topside ionosphere is the region from above the F2 peak to roughly 1000 km and the plasmasphere is the region above the topside out to the plasmapause. Plasmaspheric electron densities have been obtained indirectly from trans-plasmaspheric VLF measurements (Whistler) and from highly sensitive in-situ instruments. Topside electron densities have been observed with incoherent scatter radars, satellite topside sounders, and in-situ experiments.

Past developments. By the early seventies the highly successful Alouette satellites had accumulated a large data base of global topside soundings so that empirical modelling of the topside could be seriously considered. The first major effort was undertaken by Bent and his colleagues /54,55/ using more than 50,000 Alouette 1 topside soundings covering the time period 1962 to 1966 (low to medium solar activity). For high solar activity they relied on Ariel 3 in-situ measurements for 1967 and 1968, which were combined with F2-peak densities obtained from ground-based ionosondes. Their model is given in graphical form providing plots of the linear variation of their model parameters with daily solar 10.7 cm radio flux (F10.7) for four foF2 classes (2, 5, 8, 11 MHz) and three ranges in geomagnetic latitude (0° to ±30°, ±30° to ±60°, ±60° to ±90°).

In the very first version of IRI, topside profiles were based on incoherent scatter data from Malvern (U.K.) and Arecibo (Puerto Rico). The thickness of the upper F-layer was chosen in such a way that the total electron content (TEC) calculated for the IRI profile agreed with TEC measurements. However, the determination of the thickness parameter should really be based on the so-called slab thickness, which is the TEC value normalized with the simultaneously measured F2-peak density. Unfortunately, very little information is available about the global variation of slab thickness. Eventually, the IRI group decided to drop the TEC coupling, which failed to produce reasonable thickness parameters in a number of cases. For IRI-78 /1/ Ramakrishnan and Rawer developed an analytical description of the data base contained in Bent's model. An important result of this newer model is a smoothly varying scale height, which is more acceptable than the very irregular scale height behavior obtained with the original Bent model.

Present status. The next improvement of the IRI topside was triggered by the results of a study by McNamara /56/, who compared TEC values calculated with the IRI and Bent models with a large set of TEC measurements. For mid-latitudes, he found in general good agreement with IRI being the slightly better performing model. Close to the magnetic equator, however, a factor of two discrepancy was found for daytime conditions during high solar activity. Both models predict TEC too low, with Bent producing somewhat higher values than IRI. At least partly, this is a result of Bent's /54/ original sampling procedure. For the highly structured equatorial region, he only allows for one sampling bin (30°S to 30° N geomagnetic latitude). Comparisons with incoherent scatter data from close to the magnetic equator (Jicamarca, Peru) and with AEROS and AE-C in-situ measurements showed that the IRI formula had to be corrected at low latitudes /57/. Starting with IRI-86, such a correction was included in the topside model.

Future improvements. Buonsanto /58/ compared IRI with a large set of profiles from the incoherent scatter radar at Millstone Hill. He finds that IRI overestimates the electron density in the upper topside. Similar discrepancies at mid-latitudes were found with Interkosmos-19 topside sounder data /59/. Close to the magnetic equator, on the other hand, electron densities measured by DE-2 at 700 km are considerably higher than the IRI predictions /61/. From these studies it is clear that the upper part of the topside profile has to be revised in future editions of IRI. Rawer /60/ pointed out that this should be done with a field-aligned height coordinate rather than vertical height because plasma transport processes in the topside are forced to proceed along magnetic field lines.

A plasmaspheric extension of IRI was developed by Rycroft and Jones /65/ based on a diffusive equilibrium model. Electron density, temperature, and ion composition are given as function of distance along field line. All parameter functions are thighed to the corresponding IRI topside profiles at 650 km altitude. The model density in the equatorial plane varies with L^{-3} in accordance with ISEE-1 measurements and Whistler results at the Siple ground station /65/. Implementation in IRI can be accomplished after a field-aligned coordinate system is included in the IRI code. Shortcomings of the present model are that (i) it does not include the sharp drop in density at the plasmapause (at $L \approx 3 - 4$) and (ii) it does not consider interhemispheric plasma fluxes. As a result different values are obtained at the equator when starting from the northern and southern ends of the same field line. The DE-1 satellite has assembled a large data base of plasmaspheric in-situ measurements, which only now is starting to be tapped for empirical modelling /62/.

Middle ionosphere (E- to F2-peak)

The middle ionosphere is the region extending from the E-peak upward to the F2-peak. Characteristic features are a F1 ledge, which is often observed during daytime, and a valley above the E-peak, which is always present at night, and at mid-latitudes also often during daytime. Incoherent scatter radar and ionosonde measurements are the primary data sources for the middle ionosphere. Profile heights deduced from ionograms, however, may be in error by several percent because their deduction depends on the assumptions made about the ionization in the E-valley region and below the ionogram starting point /37/. The hardware and software aspects of ionogram real-height analysis was one of the major topics discussed at an IRI-sponsored workshop in Novgorod (C.I.S) in 1987 /63/. Improvements may come from comparative studies using incoherent scatter and ionosonde results /64/. These studies were initiated in conjunction with the URSI Working Group on Ionospheric Informatics (WGII).

Past developments. Only at a few stations was real-height analysis of ionograms done on a routine basis. The IRI group decided to base its F-region bottomside model on profiles obtained at Lindau (F.R.G.), Mexico City (Mexico), and Huancayo (Peru). For the latter two so-called composite profiles /65/ were used, which represent monthly averaged ionograms. After normalizing these profiles to the F2-peak density and height, and to the bottomside thickness B_0, a suitable mathematical description was established by Ramakrishnan /66/. B_0 values obtained from these profiles were averaged for two latitude classes (low, middle), two levels of solar activity (low, high), day/night, and the four seasons. Major disadvantages of this approach are the limited latitudinal and diurnal discrimination.

Present status and future improvements. IRI-90 includes a new option for the calculation of B_0, which overcomes some of the shortcomings of the earlier description. In the new approach B_0 is calculated /47/ from the formula that Gulyaeva /67/ developed for the ratio between the half-density point $h_{0.5}$ and hmF2; $h_{0.5}$ is the height where the bottomside profile reaches half the F2-peak density ($N_e(h_{0.5}) = 0.5$ Nmf2). Investigating a large amount of profiles obtained from ionograms, Gulyaeva found that she could describe this ratio as function of solar zenith angle and season. Her formula was also confirmed with incoherent scatter data /68/. Discrepancies occur in the presence of a strong F1-layer /68,69/.

Quite frequently, a valley can be observed in the region above the E-peak. During nighttime densities within the valley can drop down to a factor of 5 and more below the E-peak density. During daytime the valley appears most consistently at mid-latitudes. In IRI, valley parameters were established from incoherent scatter results (Malvern, St. Santin, Arecibo) for daytime and from a compilation of Japanese rocket observations /70/ during nighttime. For the nighttime profile two conflicting compilations were available at the time. Soboleva's /71/ data predicted a much deeper valley than the Japanese data. Comparing both with Schumann resonances, Booker gave a strong vote in favor of the Japanese rocket measurements. Results from aeronomical calculations agree fairly well with the IRI parameters /72/.

Since first initiated by Booker /73/ in 1977, the IRI group has been working on a scheme to represent the electron density profile in analytical form. This would greatly enhance the value of IRI for radiowave propagation studies, which often encounter difficulties because of slope discontinuities. Based on the Epstein function proposed by Booker /73/, Rawer developed the LAY-formalism to represent the layered structure of the density profile /74/. As a special option, IRI-90 offers an analytical representation of the density profile in the middle ionosphere based on the LAY-formalism. Using four LAY-function, this method applies a least-square fitting procedure to obtain the four LAY-amplitudes from a number of point and gradient constraints (e.g. E-, F1- peaks, valley top and base) /74/. This approach needs an explicit description for the height of the F1-peak, hmF1. At present IRI uses a solar zenith angle dependent formula. Radicella and Gonzalez /75/ described ionosonde hmF1 data with a formula depending on F1-peak density and dip latitude. A preliminary set of height and scale parameters for the LAY-approach was established by trial and error for a wide range of ionospheric conditions /47/. In choosing this option, one should be aware of the fact that on rare occasions the combination of constraints and pre-set parameters can result in unreasonable profile structures. Fine tuning of the parameter set and additional point constraints may help to overcome this shortcomings.

Lower ionosphere (D-region)

Past developments and present status. The electron density in the lower ionosphere can be determined with ground-based and rocket radiowave propagation experiments and with rocket in-situ measurements. A major problem in this region, as far as empirical modelling is concerned, are the large discrepancies found between results obtained with different techniques, in particular at nighttime. To resolve some of the issues of this conflict and to establish general guidelines for IRI work, a special symposium was held in Konstanz, F.R.G., in 1973 /76/. It was stated that in-situ measurements, when combined with radio propagation measurements between ground and rocket, should be used as primary data input. Following these recommendations, Mechtly and Bilitza /77/ established a compilation of acceptable rocket profiles. In all cases a characteristic point could be identified at which the profile showed a sharp change in gradient. During nighttime this 'inflection' point was observed at about 88 km and during day at about 80 km. Making use of all rocket measurements, the density at this point was represented as a function of solar activity and solar zenith angle /78/. Comparisons with radiowave propagation data have resulted in several, sometimes conflicting proposals for changes of the IRI D-region profile /79,80,81,82/. Since, however, these are all indirectly deduced profiles based on certain assumptions about the collision frequencies, additional experimental evidence is needed before IRI can be changed with confidence /83/.

Future improvements. An effort is under way to represent the density profile in the lower ionosphere with the analytical LAY-formalism /84/ that is already applied in the middle ionosphere. As data base for this modelling activity, two sets of experimental data are under consideration: (1) Friedrich's /85/ compilation of about 100 profiles obtained by Faraday technique between ground and rockets; (2) Singer's /86/ set of profiles depending on season and solar zenith angle obtained from terrestrial radiowave propagation data measured at several frequencies.

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