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INTERNATIONAL REFERENCE IONOSPHERE – PAST, PRESENT, AND FUTURE: II. PLASMA TEMPERATURES, ION COMPOSITION AND ION DRIFT

D. Bilitza,* K. Rawer,** L. Bossy*** and T. Gulyaeva†

** NASA, GSFC, NSSDC, Code 933 / Hughes STX, Greenbelt, MD 20771, U.S.A.*
*** Albert-Ludwig-Universität, D- 7800 Freiburg, Germany*
**** Institut d'Aeronomie Spatiale, B- 1180 Bruxelles, Belgium*
† Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, 142092 Troitsk, Moscow Region, Russia

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 wish-list are (i) major improvements at high latitudes and (ii) inclusion of magnetic storm effects. This paper deals with plasma temperatures, ion composition, and ion drift; the preceding companion paper discusses the electron density.

INTRODUCTION

A short history of the IRI project and its accomplishments was given in the preceding paper and will not be repeated here. Mathematical details and formulas can be found in the IRI-90 guide-book /1/. Naturally, the focus of IRI work and studies has been more on electron density than on plasma temperatures and ion composition, because electron density is the primary parameter needed for a multitude of applications, e.g., all applications that deal with propagation of electromagnetic waves through the ionospheric plasma. In recent years, however, the number of inquiries concerning the use of IRI representations for the ionospheric plasma temperatures, the ion composition, and the ion drift have been steadily mounting. As a result the IRI group has put considerable effort in a re-evaluation of its temperature, composition and, drift models. Ray-tracing studies, for example, need information about the ion composition, and IRI has been successfully applied for this purpose by several groups. Plasma temperatures are important parameters for the assessment of ionospheric scale heights, and together with the ion composition can assist in the multi-parameter analysis of incoherent scatter spectra. The main instruments for observations of plasma temperatures and ion composition are ground-based incoherent scatter radar (ISR) and satellite and rocket in-situ probes: Langmuir Probe (LP), Retarding Potential Analyzer (RPA), and Ion Mass Spectrometer (IMS).

PLASMA TEMPERATURES

Since the early sixties, ionospheric plasma temperatures have been measured by in-situ probes (LP, RPA) and by several ISR facilities. Both data sources were used in the development of the IRI electron and ion temperature models. Reviews /2,3/ of ground and space data available for the modelling of electron and ion temperatures were presented at the 1990 IRI workshop on "Enlarged Space and Ground Data Base for Ionospheric Modelling".

Ionospheric plasma temperatures are determined by the balance of (1) energy gained from solar EUV irradiance through production of primary and secondary photoelectrons, (2) energy transferred between electrons and ions through Coulomb collisions, (3) energy lost in collisions with neutral particles, and (4) energy exchange within the electron gas and the ion gases through heat conduction. Because of the mass ratios and the effectiveness of Coulomb collisions, the heat transfer precedes from photoelectrons to ambient electron gas to ion gas to neutral gas. Thus, in general, the electron temperature T_e exceeds the ion temperature T_i, which in turn exceeds the neutral temperature T_n. Even during nighttime, in the absence of solar EUV input, this hierarchy of temperatures is often observed, because the electron gas may be heated by photoelectrons that are produced in the magnetically conjugate ionosphere and that travel along magnetic field lines from the sunlit conjugate ionosphere through the plasmasphere into the nightside ionosphere. Studying incoherent scatter data, the onset of enhanced nighttime electron temperatures could be clearly correlated to the sunrise in the conjugate ionosphere /4/. In the absence of conjugate heating, nighttime temperatures are the same for electrons, ions, and neutrals.

At low altitudes, as a result of high densities and large collision frequencies, all three gases are in thermal equilibrium with $T_n = T_i = T_e$. In IRI this equality is introduced at 120 km, which is the starting height for the IRI temperature profiles. At higher altitudes the temperature hierarchy $T_n \leq T_i \leq T_e$ is enforced in IRI. By charter, IRI is requested to use the COSPAR International Reference Atmosphere (CIRA) as its neutral temperature model. Until now, all releases of the IRI software relied on a computerized version of the CIRA-72 /5/. In 1988 and 1990 the CIRA Working Group released the next edition of this international standard atmosphere: CIRA-86 /6,7/, part of which is identical with the MSIS-86 model /8/. This update has been considered in the most recent version of the IRI-90 software (Version-No. 12), which includes the neutral temperature module of the MSIS-86 code.

Electron temperature

Past developments. At the onset of developing an electron temperature model the IRI group was confronted with one of the typical IRI problems. Conflicting results /9/ existed from the different measurement techniques. In-situ probes in orbits close to incoherent scatter radar facilities measured 10% to 20% higher electron temperatures than the radars. Thus, the IRI group had the difficult task of mediating between the two groups and of formulating a recommendation on which data source should be used as primary data input for the IRI development. For the first IRI tables, which were presented at the URSI General Assembly in 1972, a somewhat different venue was taken. The electron temperature profiles were based on the IRI electron density profiles and on the work done by Lejeune and Waldteufel /10,11/. Using incoherent scatter data from the French St. Santin radar facility, they had found that the simultaneously measured electron temperature (T_e), ion temperature (T_i), and electron density (N_e) are strongly interrelated. Formulas were established that describe $T_e - T_i$ in terms of N_e /10/, and T_e in terms of N_e /11/. Assuming that these relationships will also hold true in a monthly averaged sense, IRI temperatures were obtained by applying Waldteufel's $T_e(N_e)$ formula to IRI densities. Soon shortcomings of these earlier formulas were discovered in comparisons with data from other incoherent scatter radars, and improved functional descriptions were developed. Bilitza /12/ deduced a $\log N_e$ vs $T_e^{3.5}$ relationship from aeronomic theory and established correlation parameters based on four years worth of data from the radar at Millstone Hill (Massachusetts, U.S.A.). Using measurements from the radar facility at Arecibo (Puerto Rico), Mahajan /13/ derived altitude dependent correlation-parameters.

Meanwhile, the IRI group decided that it was not advisable to have one IRI parameter (here T_e) depend directly on one of the other IRI parameters (here N_e), because independent updating of IRI parameters would no longer be possible (any change in N_e would automatically change T_e as well). Instead, it was recommended to establish an independent IRI electron temperature model and then to use the strong interrelationship between N_e and T_e for an adjustment process, in which the IRI electron temperatures would be adjusted to (real-time) electron density measurements. By now, good agreement was reported /14/ between satellite (AEROS, AE-C) and ground-based measurements, most probably a result of the improved probe design and the more sophisticated incoherent scatter analysis methods in the mid-seventies. Thus, it was possible to develop a global electron temperature model /15/ for IRI-78 based on AEROS-RPA data and incoherent scatter observations of the radars at Millstone Hill, Arecibo, and Jicamarca (Peru; magnetic equator) in concurrence with the first of the group's recommendations. The second recommendation, however, could not be fulfilled in a satisfying way for the 1978 version of the model. Unsuccessful attempts were made to translate the $T_e(N_e)$ relationship into a reliable $\Delta T_e(\Delta N_e)$ correlation, i.e., to represent the deviation of actual temperature measurements from the IRI average, in terms of the deviation of simultaneously measured electron densities from the IRI density average.

IRI-78 describes the electron temperature as the sum of three terms: (1) a representation of the height-averaged variation with geomagnetic latitude deduced from the AEROS data, (2) a representation of the average height profile for all latitudes, and (3) a term introducing a valley at low geomagnetic latitudes (below ±30^o) and low altitudes (below 500 km) based on incoherent scatter data from Arecibo and Jicamarca /15/. Thus IRI-78 describes the normal, continually increasing temperature profile, as well as profiles with a peak at about 200 km and a valley above. The valley feature is seen at all latitudes but is most pronounced close to the magnetic equator. At mid-latitudes it occurs most often during high solar activity, whereas it is a permanent feature at low and equatorial latitudes. Taking into account the heat gain, loss, and conduction of the electron gas, the valley could be reproduced in theoretical calculations. Its size and depth was found to be dependent on the field line geometry and on the ratio between electron and neutral density. At low magnetic latitudes, the almost horizontal magnetic field lines inhibit vertical heat conduction, which is the cause for the deep and persistent valley found at these latitudes. IRI-78 provides two sets of model parameters, one for daytime and one for nighttime, and applies a step-type interpolation process with one-hour transition regions at sunset and sunrise.

Present status. Based on their ISIS and AE satellite LP measurements, Brace and Theis /16/ established global models of electron temperature for different altitudes and seasons (ISIS-1: 3000 km, equinox and solstice; ISIS-2: 1400 km, equinox, winter, and summer; AE-C: 300 km and 400 km, equinox and summer). Comparing this data base with IRI-78, they found that the simple day/night distinction used in IRI-78 severely limits the model's ability to represent real data /17/. The most notable features seen in the measured diurnal temperature curves and not represented by IRI are an early morning peak, the so-called "early morning overshoot", and a much less dramatic late afternoon peak. The early morning peak, which is most pronounced at low latitudes and at low altitudes, is caused by the onset of EUV heating at sunrise while the electron density is still small. In addition it was noted that future updates of IRI should also allow for the, at times, considerable seasonal variations seen in ground and space temperature measurements.

A major step forward was done with the release of IRI-86. The electron temperature representation was now based on the models by Brace and Theis /16/, thus providing a much better description of diurnal and seasonal variation patterns. Use was also made of the compilation of AEROS-RPA data in the global model of Spenner and Plugge /18/. Electron temperature profiles were constructed by assuming piece-wise constant gradients in six regions defined by the boundary heights: 120 km, h_m, 300 km, 400 km, 600 km, 1400 km, and 3000 km; h_m is the height of the peak, if a peak and valley are present /19,20/. At these heights the temperature was determined with the help of the mission-specific models /16,18/ mentioned above. The starting temperature at 120 km was calculated with the CIRA-72 neutral temperature model /5/, and the peak parameters were obtained from Arecibo and Jicamarca radar data (see /20/).

In addition to the main temperature model, the IRI group decided to also introduce two optional models in the critical regions below 200 km and above 500 km. Chasovitin and his colleagues /21/ had established a description of the region from 100 km to 200 km based on rocket probe data and incoherent scatter measurements. In-situ probe measurements of the Interkosmos-19 satellite were used by Smilauer and Afonin /22/ to represent the global temperature variations between 500 km and 1000 km for a period of high solar activity. Unfortunately, these models are not yet available in machine readable form.

In the meantime, the $T_e(N_e)$ relationship was further explored by several research teams with the growing ground and space data base of simultaneously measured electron temperatures and densities. Brace and Theis /23/ were able to represent the temperatures measured by their AE-C LP (during daytime, below 400 km) with a simple formula depending on height and on the simultaneously measured electron density. McDonald and Williams /24/ recommended a description in terms of electron density and solar activity. Based on incoherent scatter results from the Malvern radar facility for the time period from 1972 to 1975, they established correlation parameters for various local times and seasons. Bilitza et al. /19/ combined the two approaches by introducing a solar activity dependence into the Brace and Theis model /23/ based on DE LP results. In IRI-86 this latest formula can be chosen for the determination of electron temperature at the profile fixpoint at 300 km and/or 400 km and/or 600 km. But this option is only recommended if measured electron density values are available for the selected heights.

Future improvements. The average altitudinal, diurnal, and latitudinal variations are reasonably well represented by the IRI-90 electron temperature model, which is identical with the IRI-86 model, except for some minor technical corrections and for the replacement of CIRA-72 with CIRA-86. This was proven in comparisons with incoherent scatter data /20,25/ and with satellite data /26/. The same studies have also indicated where improvement is needed. It is clear that the annual variation is not well represented with the present two class distinction (equinox and solstice). Inclusion of some type of direct dependence on solar activity seems also a necessity for future updates; at present there is only an indirect dependence through the neutral temperature model and the $T_n \leq T_e$ enforcement. This is especially important at high altitudes, where a strong increase with solar activity is observed, due to the increased heat flux from the plasmasphere. At low altitudes the electron temperature hardly changes from solar minimum to maximum, because the increase in energy gained with increasing solar activity is compensated by the similarly increased energy loss (see /26/ for a review of the observed variation patterns of ionospheric plasma temperatures with solar activity).

In the subauroral ionosphere the latitudinal variation of the electron temperature often exhibits an enhancement (peak) by a factor of two and more. It was found that this feature is closely collocated with ionospheric signatures of the plasmapause, e.g., the electron density trough /27/. The mechanisms responsible for this energy input are not yet fully resolved. A likely candidate for the plasmaspheric energy source are Coulomb collisions between ring current protons and thermal electrons. Statistical studies /27,28,29/ of the magnitude and location of this feature have now reached a state where inclusion in future editions of IRI seem reasonable.

Ion temperature

Gaining energy through collisions with electrons and losing energy through collisions with neutrals, the temperature of the ion gas in the ionosphere depends strongly on the temperature of the electron and neutral gas. At low altitudes T_i is virtually identical with T_n, whereas at high altitudes it is closely coupled to T_e. Observations clearly show the transition between these two regions as a sharp change in gradient. In IRI, based on incoherent scatter data, the transition height is assumed at a fixed altitude of 430 km. The global ion temperature variation at this altitude is deduced from AEROS RPA measurements /15/. Below the transition height the IRI ion temperature profile is merged with the CIRA neutral temperature model and above with the IRI electron temperature model. In both regions constant gradients are assumed, which are taken from average profiles established with incoherent scatter (St. Santin, Millstone Hill, Arecibo, Jicamarca) and AEROS RPA measurements. Diurnally, the temperature varies from a constant value during nighttime to a constant value during daytime with one-hour transition periods at sunrise and sunset /15/. This day/night pattern agrees fairly well with incoherent scatter observations.

A major shortcoming of the present approach is the fact that the T_i model at the transition height (430 km) does not include an explicit dependence on season and on solar activity. There is, of course, an implicit dependence on these parameters in the case $T_n = T_i$ (e.g., nighttime or low altitudes); in this case the IRI ion temperature follows the seasonal and solar cycle variation of the neutral temperature. Observations /25,26/ and theoretical studies /30/ have indicated that this strong coupling between the two temperatures should also be applied in cases where $T_n < T_i$, at least for altitudes below 500 km. This could be easily done in IRI by introducing a global model for the temperature difference $T_i - T_n$ at 430 km in place of the present T_i model. Another possibility would be a $T_i = f(T_e, T_n)$ formula derived from simplified theoretical considerations, e.g., from the ion heat conduction equation.

In the topside ionosphere small differences are observed among the temperatures of the O^+, the H^+ and the He^+ ion gases. Because of the mass ratio the light ions are heated more effectively by the thermal electrons, and their temperature slightly exceeds the O^+ temperature. These differences are, however, so small and there are so few measurements that no attempt was made to include two or three different ion temperatures in IRI.

Anisotropies have been observed for the ionospheric ion temperature /31/ as well as electron temperature /32/, mostly in regions where electric fields of considerable strength can occur (high latitudes). However, the data base is at present too small and too contradictory to allow statistical studies and meaningful empirical modelling. A review of theoretical and experimental work concerning temperature anisotropies was given by Demars and Schunk /33/.

ION COMPOSITION AND ION DRIFT

Ion composition

Ion composition, i.e., individual ion densities normalized to the total ion density, can be obtained from incoherent scatter radar (ISR) observations and from in-situ probe (RPA, IMS) measurements. However, problems with the instrument calibration (IMS) and with the accuracy of the data reduction algorithm (ISR,RPA) have in many cases made it difficult to deduce meaningful ion composition data. Very few studies have examined the discrepancies among results obtained for similar conditions with different measurements techniques. Gonzalez et al. /34/ find that IMS data from AE-E need to be increased by a factor of 2 to agree with RPA densities and ground-based measurements. Intercalibration among different experiments on the same satellite may help to access the large data base accumulated by the IMS instruments on the OGO and AE satellite. The status and availability of ion density and ion composition data for ionospheric modelling are discussed in a recent review paper /35/. This paper provides also a good overview of empirical models developed from these data during the last decades.

Photo-ionization and chemical reactions produce a number of different ions in the ionosphere. As is to be expected, light ions (H^+,He^+) dominate at high altitudes and heavy ions (NO^+, O_2^+, N_2^+) at low altitudes. In the intermediate region from about 200 km to 400 km, the ion gas consists mostly of O^+ ions. N^+ and N_2^+ are minor ions throughout the ionosphere; they play, however, an influential role in the chemistry of the dominant molecular ions (NO^+, O_2^+). Metallic ions (Fe^+, Mg^+, and others) of meteoric origin are a regularly observed feature in the E-region. Under certain conditions these ions can accumulate in thin layers exceeding the molecular ion densities in a phenomenon known as Sporadic-E layer. Below about 85 km cluster ions with mass numbers between 40 and 150 (e.g., $H^+[H_2O]_n$, $NO^+[H_2O]_n$) are the predominant positive ions. At these altitudes, the relatively high ambient pressure also permits formation of negative ions by a three-body attachment process involving electrons and neutrals. As a result the electron density sharply decreases below 70 km. Until now IRI modelling efforts have to a great degree focussed on the major constituents: O^+, H^+, He^+, NO^+, and O_2^+.

Past developments. In the ionosphere above about 85 km charge neutrality exists, and therefore the electron density and the total ion density are equal and a separate description of total ion density is not needed in IRI. The important parameter is the ion composition, i.e., the individual ion densities normalized to the total ion density (= electron density). The IRI model represents the relative percentage of O^+ and O_2^+ ions and then fills up to 100% with light ions in the topside and with NO^+ ions in the bottomside. It is assumed that the light ion gas consists to 90% of H^+ ions and to 10% of He^+ ions.

Different data sources were used for the different regions. In the topside only few ion composition data were available at the time. Based on AEROS-RPA data /36/, the topside O^+ model distinguishes only two latitudinal regions (low and middle with transition at ±30°) for day and night. The situation was somewhat better for the bottomside ion composition. Danilov and Semenov /37/ had established a compilation of rocket measurements (mainly by IMS) for the altitude range 100 km to 200 km. For IRI, their representation was approximated with suitable functions describing variation with solar zenith angle for different seasons (winter, summer, equinox) and two levels of solar activity (low and high, with transition at a Covington-index of 100). The compilation did not include nighttime measurements and only very few observations at low latitudes. IRI extrapolations for these times and regions can be considered only preliminary and should be treated with care.

The most difficult modelling task is encountered at altitudes below 100 km. For several years starting in 1974, an ad-hoc working party under the chairmanship of D. Krankowsky coordinated the IRI efforts concerning "ion composition and negative ions below the 100 km level". Because of the rather limited number of rocket measurements and the conflicting results, they were, however, not able to come up with a set of final profiles or recommendations. For IRI-78 A. Danilov provided representative cluster profiles for day, night, and dawn/dusk, and these were reproduced in the red URSI booklet /38/. Ion composition observation and theory in the region below 100 km was reviewed and summarized for the IRI group by Arnold /39/ and by Kopp /40/.

Present status. Danilov and Yaichnikov /41/ largely expanded the rocket data compilation of Danilov and Semenov /37/ by adding Electron-2, -4, and S3-1 satellite data and more (high apogee) rocket observations. They used this data base to establish a description of the ion composition (O^+, H^+, He^+, NO^+, O_2^+, N^+, Cluster$^+$) in the altitude range from 75 km to 1000 km. Variations with solar zenith angle χ, latitude φ, season S, and solar activity F, were taken into account as far as possible with the existing data base: $O^+ = f(\chi,\varphi,S,F)$; NO^+, $O_2^+ = f(\chi,S,F)$; N^+, He^+, $H^+ = f(\chi,\varphi,F)$; Cluster$^+ = f(\chi,S)$. Their model was proposed for IRI and is included in IRI-90 as an alternative to the standard ion composition description.

Comparisons of the standard IRI ion composition profiles with incoherent scatter measurements /42/, with OGO-6 RPA data /43/, and with ISS-b IMS measurements /44/ have all shown that the standard IRI profile overestimates the percentage of light ions in the topside ionosphere. The Danilov-Yaichnikov model (DYM) agrees much better with the satellite data, and the IRI group recommends using this option for the topside ion composition. In the bottomside the standard IRI ion composition model is still the model of choice, because its diurnal variation agrees much better with data, than the DYM option /45/. Sridharan et al. /46/ compared results from 4 rocket flights above Thumba, India (at the magnetic equator) with IRI. The rockets were launched in the early morning and provided the NO^+/O_2^+ density ratio from 100 km to 150 km. Their ratios are, in general, larger than the IRI ratios, which are based almost exclusively on mid-latitude data. Philbrick and Bhavnani /47/ examined the S3-1 IMS data base with the intent to improve the IRI representation of the bottomside ion composition. Establishing representative ion composition profiles for different conditions, they observed that the NO^+/O_2^+ density ratio is always less than 1 below 170 km and almost constant above that height varying from 2 during summer days to 0.6 during winter nights /47,48/. They also find that the N^+ density follows the O^+ density with an almost constant ratio of about 0.015 during daytime.

Future improvements. The IMS instruments flown on the AE-B, OGO-6, ISIS-2, AE-C, Taiyo, AE-D, AE-E, and ISS-b satellites have produced a wealth of information about the ionospheric ion composition, which has not yet been tapped for IRI. Attempts to compile and represent at least part of this data resource have unfortunately so far focussed on absolute ion densities, rather than ion composition /49,50/.

Recently, a different modelling approach was suggested /45/ that makes use of the ion transition heights. Transition heights are the boundaries between the regions dominated by different ion species: <light ions> H_T <atomic oxygen> h_t <molecular ions> h_c <cluster ions>. Thus H_T is the height at which the ion gas consists to equal parts of light ions and of atomic oxygen ions. In the new approach these characteristic heights are used as anchor points for the construction of the ion composition profiles. These heights provide important clues about the underlying chemical and dynamical processes in the ionospheric ion gas. The upper and lower transition heights (H_T, h_t) have been studied extensively with rocket, satellite, and incoherent scatter radar data (see /36,45/ for references). Global descriptions have been developed for these parameters based on satellite data from Alouette 1 /51/, Taiyo /52/, and OGO-6 /53/, based on rocket data /54/, and based on incoherent scatter data /55/. Thus, incorporation of these models into IRI would represent an indirect way of tapping the large data base mentioned above.

Improvements should be also considered for the light ion ratio, which at present is held at a constant value of $He^+/H^+ = 1/9$ in IRI. ISS-b IMS measurements /44/ and DE-2 RPA measurements /56/ have shown that He^+ can become the dominant ion above 900 km in the nighttime ionosphere. This indicates that there is a need to replace the constant ratio in IRI with a variable ratio depending on time and latitude or with an independent model for the percentage of He^+ ions.

Ion drift

Bulk movement (drift) of ions in the ionosphere is the result of forcing by thermospheric winds and at high latitudes by solar wind induced magnetospheric (convection) electric field. At mid-latitudes ionization is driven upward along magnetic field lines by the equatorward wind at night and downward by the poleward wind during the day. This wind effect competes with field-aligned diffusion and photochemical processes, and the net effect determines the distribution of ionization along a magnetic flux tube. At the magnetic equator tidal winds induce an electric field that drives ionization upward across field lines in a process that is described as "fountain effect", and that leads to the well-known equatorial anomaly of electron density.

Early drift measurements were obtained by recording the drift pattern of ionospheric irregularities with ground-based receivers. Using different sounding frequencies the drift in the different ionospheric layers could be observed. Another ground-based method uses the ionized trail of meteors as tracer for the ion drift. These methods are mostly geared toward measuring the horizontal component of the drift vector. Since the seventies ion drifts have been almost continually monitored with the powerful incoherent scatter radars. This technique provides the drift component in the direction of the radar beam. Only multistatic or steerable radar facilities can measure all three components of the drift vector. Based on radar data from Millstone Hill, St. Santin, Arecibo and Jicamarca, Richmond et al. /57/ developed an empirical model of the F-region ion drift (and electric field) at middle and low latitudes. More recently, ion drifts have also been measured by satellite in-situ instruments.

Ion drift is a relatively recent addition to the list of parameters for which IRI intends to provide standard representations. Therefore, the coordination of modelling efforts is still in an early stage. E. Kazimirovsky has been in charge of this sub-task since its beginning and has presented several progress reports /58,59/. Together with his colleagues at the Siberian Institute of terrestrial Magnetism, Ionosphere, and Radio Propagation (SibIZMIR), he has developed models for the horizontal E- and F-region drifts based on data obtained with the spaced receiver technique. Data from 23 stations in the Northern Hemisphere were used covering the time period from 1957 to 1970. These models are described in the IRI-90 document /1/, which in addition lists a PASCAL computer program developed by the model authors.

Improvements of the IRI ion drift model can be expected from comparisons with incoherent scatter data and in-situ measurements. Very useful in this context is the summary of seasonal averages of the equatorial F-region drift presented by Fejer et al. /60/ based on Jicamarca radar data from 1968 to 1988. Consideration should also be given to the anticorrelation that has been observed between the drift components parallel to and perpendicular to the geomagnetic field /61/. At high latitudes the IRI effort could benefit from the models of the ion convection pattern /62,63/ established with the help of satellite data.

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