The International Reference Ionosphere – Climatological Standard for the Ionosphere

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ABSTRACT

The International Reference Ionosphere (IRI) a joint project of URSI and COSPAR is the defacto standard for a climatological specification of ionospheric parameters. IRI is based on a wide range of ground and space data and has been steadily improved since its inception in 1969 with the ever-increasing volume of ionospheric data and with better mathematical descriptions of the observed global and temporal variation patterns. The IRI model has been validated with a large amount of data including data from the most recent ionospheric satellites (KOMPSAT, ROCSAT and TIMED) and data from global network of ionosondes. Several IRI teams are working on specific aspects of the IRI modeling effort including an improved representation of the topside ionosphere with a seamless transition to the plasmasphere, a new effort to represent the global variation of F2 peak parameters using the Neural Network (NN) technique, and the inclusion of several additional parameters in IRI, e.g., spread-F probability and ionospheric variability. Annual IRI workshops are the forum for discussions of these efforts and for all science activities related to IRI as well as applications of the IRI model in engineering and education.

In this paper I will present a status report about the IRI effort with special emphasis on the presentations and results from the most recent IRI Workshops (Paris, 2004; Tortosa, 2005) and on the most important ongoing IRI activities. I will discuss the latest version of the IRI model, IRI-2006, highlighting the most recent changes and additions. Finally, the talk will review some of the applications of the IRI model with special emphasis on the use for radiowave propagation studies and communication purposes.

1.0 INTRODUCTION

The International Reference Ionosphere (IRI) project was initiated by the Committee on Space Research (COSPAR) and by the International Union of Radio Science (URSI) in the late sixties with the goal of establishing an international standard for the specification of ionospheric parameters based on all worldwide available data from ground-based as well as satellite observations. COSPAR and URSI specifically asked for an empirical data-based model to avoid the uncertainties of the evolving theoretical understanding of ionospheric processes. COSPAR's main 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. To accomplish these goals a joint COSPAR-URSI Working

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Group was established and tasked with the development of the model. The current IRI membership roster includes not only a well-rounded global distribution (see Figure 1) but also a good balance in terms of represented measurement techniques and modeling teams. The author chaired the working group from 1992 to 2002 and was than succeeded by Bodo Reinisch (University of Massachusetts Lowell) who is the currently chairing the group. Lida Triskova (Institute of Atmospheric Physics, Czech Republic) serves as URSI Vice-chair and Martin Friedrich (Graz University of Technology, Austria) as COSPAR Vice-chair.

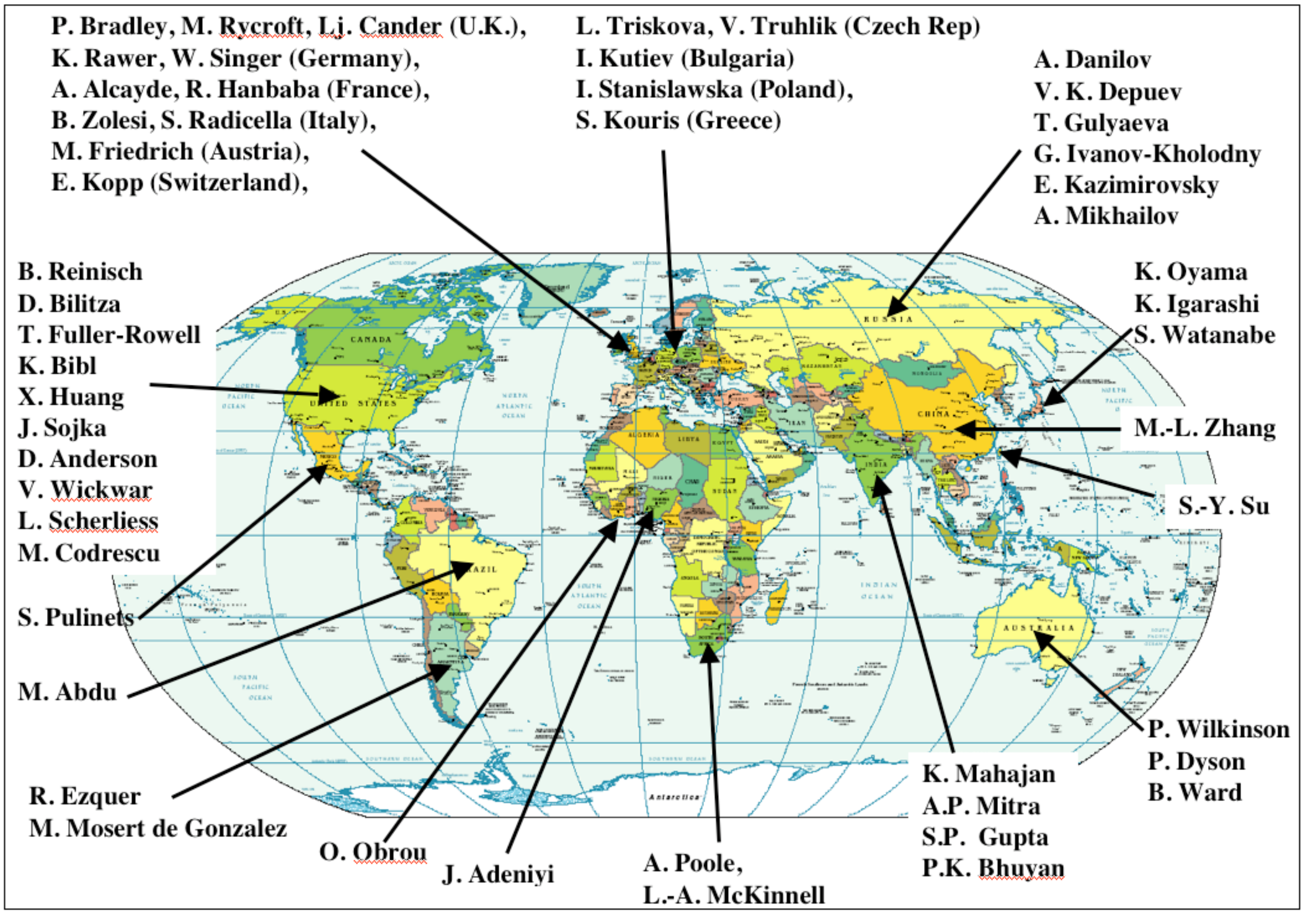

Figure 1: Global distribution of IRI Working Group members.

The model is continually updated as new data become available and this process has resulted in several major milestone editions of the model [1,2,3,4,5]. The prime venue for coordinating the model development and for initiating model improvement efforts are the annual IRI Workshops (see list and summaries at http://modelweb.gsfc.nasa.gov/ionos/iri/iri_workshops.html). The progress of the IRI project is documented in a whole series of dedicated issues of Advances in Space Research with papers from the IRI Workshops (for a list see http://modelweb.gsfc.nasa.gov/ionos/iri/asr_list.html). The 2005 Workshop was organized by the Ebro Observatory in Roquetes, Spain with a special focus on "New Satellite and Ground Data for IRI and Comparisons with Regional Models". The papers from the 2004 IRI Workshop (a session during the COSPAR General assembly in Paris, France) was recently published as Advances in Space Research, Volume 37, Number 5. The workshop series continues with an IRI-session during the COSPAR General Assembly in

Beijing, China in July 2005 on the "Solar Activity Variations of Ionospheric Parameters" and a special IRI-GPS workshop in Buenos Aires, Argentina in October 2005.

IRI describes monthly averages of the electron density, electron temperature, ion composition (O^+, H^+, N^+, He^+, O_2^+, NO^+, $Cluster^+$), ion temperature, and ion drift in the ionospheric altitude range (60 km to 1000 km). An effort is underway to also include a measure of the ionospheric variability during the month in terms of standard deviations or quartiles and deciles (see section 6.0). Prime data sources for the model development include the worldwide network of ionosondes, the few incoherent scatter radars, several compilations of rocket measurements, and satellite data from insitu and topside sounder instruments.

TABLE 1 **IRI Applications**

Standard for Engineering Applications	IRI is used as the standard in "Natural Orbital Environment Definition Guidelines for Use in Aerospace Vehicle Development" [6]
	IRI is the ionospheric standard in the System Engineering Hand-book of the European Cooperation for Space Standardization [7]
	IRI is the ionosphere model used in ESA/ESTEC's Space Environment Information System (SPENVIS) http://www.spenvis.oma.be/spenvis/
	IRI is under consideration to become the ISO standard for ionospheric parameters http://www.magnet.oma.be/iso/standards.html
Space Weather: Real-time ionsopheric parameters	Maps of real-time TEC for Autraliasia, North America, Europe, and Japan (IPS, Australia) http://www.ips.gov.au/Satellite/2/1
	Current Time Global NmF2, hmF2 and TEC from IRI-2001 (S.-R. Zhang, MIT) http://madrigal.haystack.mit.edu/models/IRI/index.html
	Computation of ionospheric conductivities using IRI90 and CIRA72 models at WDC Kyoto http://swdcwww.kugi.kyoto-u.ac.jp/ionocond/index.html
Visualization Tool for Education	NASA Glenn Research Center's Photovoltaic & Space Environments movie pages http://powerweb.grc.nasa.gov/pvsee/info/movies/iri90.html
	3-d electron density visualization using AVS (CRL, Tokyo, Japan) [8]
Ionospheric Correction for Remote Sensing Earth Science Satellites	Long-time data record of sea surface heights (Pathfinder Project); updating IRI with ionosonde data [9,10]
	Data analysis for future sea surface salinity missions (Aquarius, SMOS) using IRI to eliminating the ionospheric influence on the sensor signal [11]
	Processing of ERS-1 and ERS-2 data products [12]
	Work with Geosat Follow On (GFO) data [13,14]
Ionospheric parameters for Theoretical models	Comprehensive Ring current Model (CRCM) [15,16]
	Ionospheric Conductances for Rice Convection Model (RCM) [17]
	Baseline against which the predictive skills of physics-based models are compared [18]
Evaluation of Tomographic and other Techniques	Background ionosphere for testing algorithms that convert GPS measurements into global TEC maps [19]
	Background ionosphere for evaluating tomographic methods (IRI is also used for defining initial conditions) [20]
	Testing algorithm for GPS/MET occultation measurements [21]

IRI applications range across a wider user community. Some of the primary applications are listed in Table 1 together with typical usage examples. The model is recommended as ionospheric standard in a number of reference documents [6,7] and is currently undergoing registration as a Technical Specification (TS) with the International Standardization Organization (ISO).

The IRI homepage is at http://modelweb.gsfc.nasa.gov/ionos/iri.html. This paper describes the newest version of the model, IRI-2006, and also some ongoing IRI collaborations that are directed towards future improvements of the model.

2.0 ELECTRON DENSITY

For the electron density recent IRI work has concentrated on the lowest (D and E-region) and on the uppermost (topside) part of the profile. The topside profile is of special importance because of its impact on the Total Electron Content (TEC), which is the prime parameter need for many ionospheric model applications. A number of studies have noted discrepancies between the IRI model and measurements especially at high latitudes and during high solar activities. A detailed description of these shortcomings and of the ongoing efforts to improve the IRI topside model was recently published [22]. At issue is an overestimation of electron densities in the upper topside (from about 500 km above the F-peak upward) that increases with altitude reaching about a factor of 3 at 1000 km above the peak (see Figure 2, left panel). The likely causes of this IRI artefact are (1) the limited data base used to develop the original IRI model, primarily Alouette 1 topside sounder data with some AE-C, and DE-2 insitu data and typical profiles from the Jicamarca incoherent scatter radar, and (2) an insufficient weighting of the low densities in the upper topside compared to F-region densities which are about an order of magnitude larger. To overcome this shortcoming two new options are introduced in IRI-2006. The first is a correction factor for the current model that was developed based on over 150,000 topside profiles from Alouette 1, 2, and ISIS 1, 2 and that depends on altitude, modified dip latitude, and local time [23]. With this correction term the IRI model represents the topside sounder data quite well as shown in the right panel of Figure 2. The resulting increasing in TEC will help to overcome differences recently noted in comparisons of IRI with TOPEX measurements [24]. The second option is the NeQuick topside model that was developed by S. Radicella and his collaborators over the last decade [25, 26,27] and is the most mature of the different proposals for the IRI topside. The NeQuick topside model uses an Epstein-layer function with a height-dependent thickness (i.e., scale height) parameter that provides a smooth transition from an atomic oxygen ionosphere to a light ion ionosphere. The model parameters were determined based on fitting this function to ISIS 1, 2 and Intercosmos 19 topside sounder profiles. Comparisons with TOPEX TEC data have shown that NeQuick provides an improvement over the present IRI TEC predictions [28]. Both new options will also provide for a smoother transition to plasmaspheric models, which in the past had problems connecting to IRI because of the high topside values [29]. A very promising new effort is the vary-Chap approach of B. Reinisch and colleagues [30] that uses the well-known Chapman formalism but instead of a constant scale-height a more realistic height-varying scale-height is assumed which results in a slightly more complex Chapman-type function. The flexibility of the vary-Chap approach also simplifies the merging of the IRI topside profile with a plasmaspheric model.

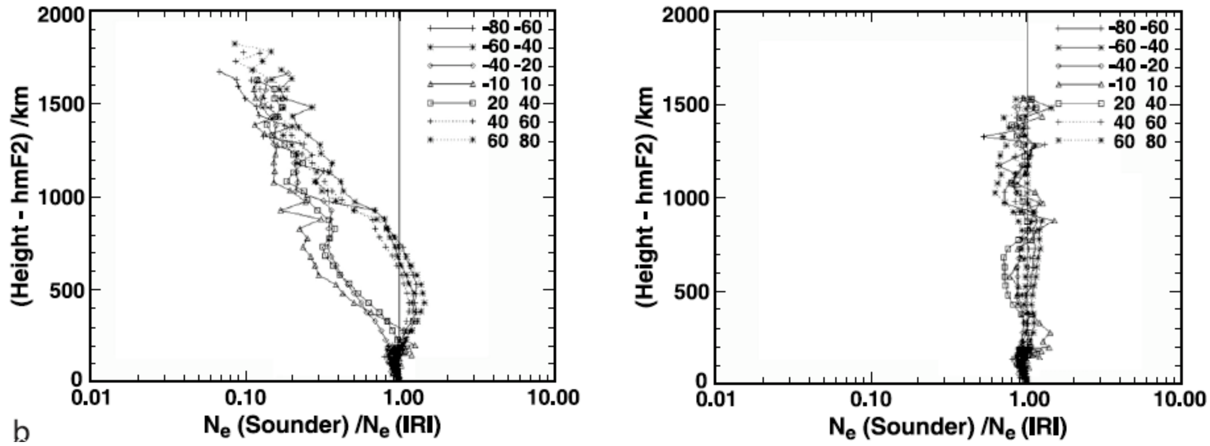

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Figure 2 Average ratio between the Alouette/ISIS sounder data and the IRI model during noon for different modified dip latitude ranges using the current IRI topside model (left) and the corrected model (right). The model and data are normalized to the F-peak density and height.

IRI generally describes the E-region electron density quite well, but it does not yet include the ionization enhancement at auroral latitudes due to precipitating particles. One of the new features in IRI-2006 is a Neural Network (NN) model for this auroral region that was trained with a large volume of EISCAT incoherent scatter data (~700,000 data points) and also with 115 profiles obtained from rocket borne wave propagation experiments [31]. The model describes the density variations in terms of local magnetic time, riometer absorption, local magnetic index K, solar zenith angle, and atmospheric pressure (combines variation with height and season). For the non-auroral D-region IRI offers three different options: (1) the standard model based on a small selection of representative rocket profiles, (2) the FIRI model based on a compilation of rocket data with simultaneous radio propagation and insitu measurements, (3) the Danilov model based on a compilation of Russian rocket data not included in the FIRI set, the Danilov model includes representative profiles for conditions of Winter Absorption Anomaly, and Stratospheric Warming (see [5] for details and references). Three options are offered because of the data scarcity and the large uncertainties in this region. First E and D region profiles were recently obtained with the Jicamarca incoherent scatter radar and were compared with the three IRI options [32]. Good agreement was found with the FIRI and Danilov models. It was noted that densities in the E-region bottomside are smaller than predicted by the standard IRI model and that the FIRI model provides a better representation also of this region. The FIRI model formalism, however, is such that it cannot be normalized to an E-peak and thus it is difficult to continuously merge the FIRI model into the rest of the IRI profile. Beginning with IRI-2006 FIRI will therefore be provided as a standalone electron density model for the lower ionosphere (D- and E- region).

3.0 PLASMA TEMPERATURES

Several new mission-specific plasma temperature models have been put forward at IRI meetings. These include the Hinotori T_e model at 600 km altitude and high solar activity [33], the SROSS-C2 T_e model at 500 km and low solar activity [34], the ROCSAT-1 T_i model at 600 km and high solar activity [35] (all three are low-inclination satellites covering the low-latitude ionosphere), the Akebono T_e plasmaspheric model [36], and the Millstone Hill T_e, T_i radar models [37]. The plasmaspheric model is now scheduled for inclusion in IRI-2006 as the first step towards extending IRI to plasmaspheric altitudes. The Akebono model was selected, because it is based on more than 13 years of measurements by the Thermal Electron energy Distribution (TED) instrument, far exceeding the database of other plasmaspheric models and because in general good agreement has been reported in comparisons with other data sources. Theoretical models also have relied heavily on the Akebono data to better understand plasmaspheric processes (see [36] for references).

The IRI plasma temperature models currently do not explicitly include variations with solar activity. There is an implicit dependence because of the constraint $T_n \le T_i \le T_e$ where T_n is the CIRA neutral temperature [38] that varies with solar activity. The ionospheric electron temperature indeed does show variation with solar activity but these variations are generally small compared to the significant increase observed for the electron density. This is easy to understand since both the heat gain and loss of the electron gas depends on electron density and thus both increase with solar activity compensating each other and producing only a small net change in electron temperature. Incoherent scatter studies have shown that this change can be positive or negative depending on the season, altitude, and time of day. A systematic and global description of these dependencies for IRI require a large data base and has to rely on satellite data since the ground-based T_e instrument, the incoherent scatter radar, exists only at a few locations worldwide. Such a database of satellite insitu measurements was recently assembled and first results were presented at the 2005 IRI workshop [39]. In Figure 3 T_e values from this data base are plotted versus magnetic latitude for different levels of solar activity.

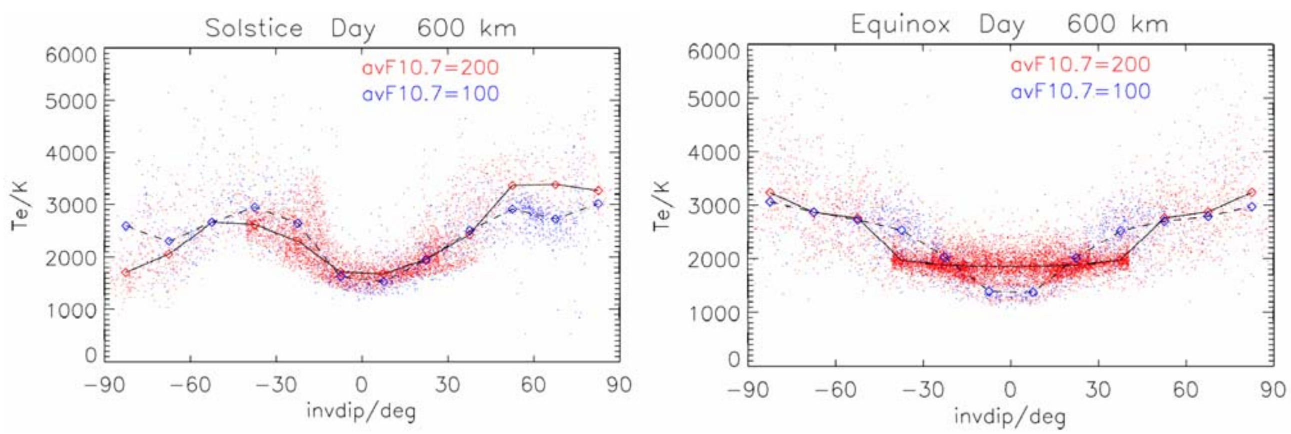

Figure 3. Electron temperature from satellite database versus dip latitude for high (red) and low (blue) solar activity and for summer solstice (left panel) and equinox (right panel); the special invdip latitude is used here which is close to the dip latitude at middle and low latitudes and close to invariant latitude at higher latitudes; the solar index is the solar radio flux at 10.7 cm wavelength.

At mid-latitudes T_e increases with solar activity in summer and decreases in winter and equinox. This is a result of the relative change of the heating and cooling terms over the solar cycle and is well reproduced by theoretical models. At low and equatorial latitudes the data show a small increase for solstice and a much larger increase for equinox. The cause of these seasonal differences is not clear yet and needs to be investigated with theoretical models.

4.0 ION COMPOSITION AND ION DRIFT

The ion composition model has traditionally been the weakest part of the IRI model because of the scarcity of well-calibrated global ion density measurements. The present IRI model is largely based on a compilation of Russian high-altitude rocket measurements [40, 41] and on a limited amount of incoherent scatter radar data. Working with the satellite insitu measurements from AE-C, -E, and Intercosmos 24 Triskova et al. [42] have developed a new model for the ion composition in the topside ionosphere. Comparisons with other satellite data (e.g., ISS-b and ISIS-2 in Figure 4) show that this new model performs much better than the old IRI model and it was therefore introduced as the new IRI ion composition model. One has, however to keep in mind that the IRI model represent ion compositions, to get absolute ion densities one has to multiply the ion composition percentages with the electron density. The accuracy of the absolute IRI ion densities therefore depends not only on the accuracy of the ion composition model but also on the electron density model (see Section 2.0).

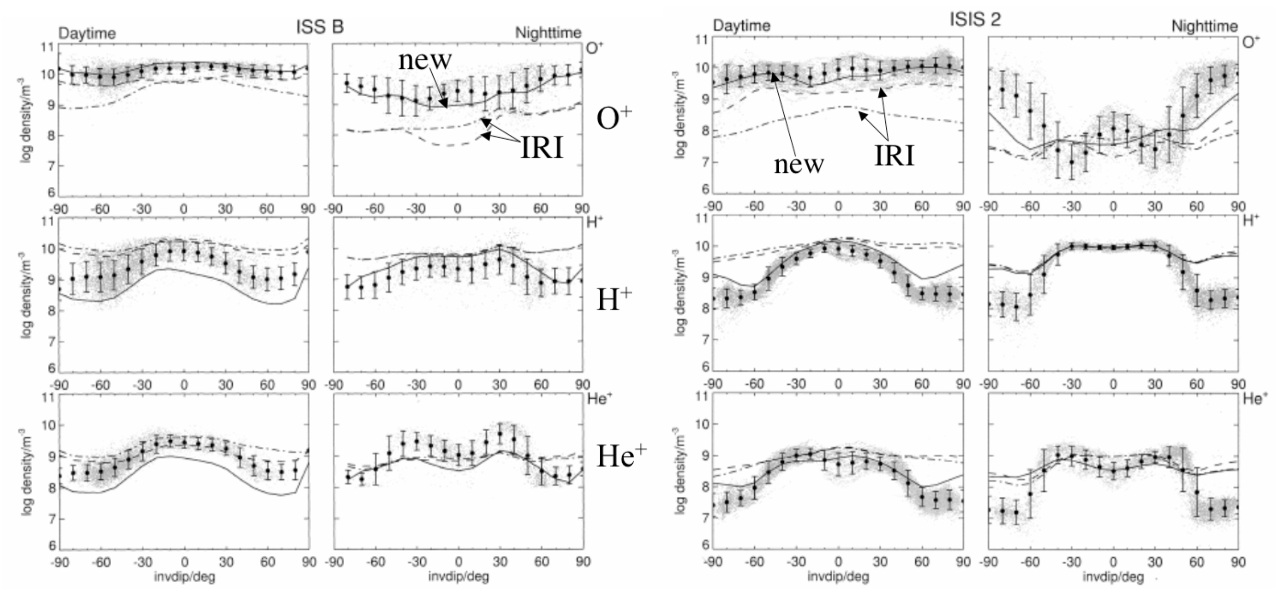

Figure 4. Daytime and nighttime latitudinal profiles of O^+, H^+, and He^+ densities during equinox as measured by ISS-b (•) at 1000 km (left panel) and as predicted by the new IRI model (solid line) and by the earlier IRI standard (dashed line) and Danilov-Yaichnikov option (dash-dot line). The right panel shows a similar comparison for ISIS-2 at 1400 km also at equinox.

The IRI team is also encouraging model efforts that focus on the upper and lower transition heights since these are the characteristic height parameters of the ion composition profile. The lower height marks the point of 50% O^+ and 50% molecular ions, whereas the upper height is determined by 50% O^+ 50% light ions. The newly available Alouette and ISIS topside sounder profiles have triggered a number of studies and modelling attempts regarding the upper transition height [43, 44].

With IRI-2001 for the first time a model for the vertical equatorial *F* ion drift [45] was introduced into the IRI model. This model based on radar and satellite data 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 variation patterns. IRI-2006 will now also include the storm-time drift model that was developed by the same authors [46]. Inclusion of these models in IRI is important because of the critical role the vertical ion drift plays in shaping the fountain of ionization that produces the characteristic Equator Anomaly (EA). 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 ion drift model may help to overcome this shortcoming.

5.0 OTHER CHANGES

The IRI-2006 version will for the first time include a model for the occurrence probability of spread-F. This will be a regional model for the Brazilian longitude sector based on the work of Abdu et. [47] with Brazilian ionosonde data. The model describes the variations of the probability with latitude, local time, day of year, and solar activity. Efforts are underway to combine Brazilian and Indian models for a global representation of spread-F occurrence.

The magnetic field model in IRI was updated to the latest generation (10) of the International Geomagnetic Reference Field (IGRF). IGRF is used to compute magnetic field coordinates including dipole coordinates as well as magnetic latitude, dip latitude, modified dip latitude, and invariant latitude. For all coordinates the long-term (secular) change of the magnetic field is taken into account.

6.0 SUMMARY

This paper presents the latest version of the widely used International Reference Ionosphere (IRI) model describing the various improvements and additions to the model. The long list of IRI application (see Table 1) underlines the importance of this international effort. Several ongoing IRI activities are directed towards future improvements of the IRI model, most importantly a new approach to modelling the topside and plasmaspheric electron density and work towards the inclusion of solar activity variations for plasmas temperatures in IRI. IRI is a truly international project with contributions from all parts of the globe. This wide range of activities has made IRI the international standard for ionospheric parameters and a registration process with the International Standardization Organization (ISO) is currently underway.

The IRI Fortran software can be obtained from the solar-terrestrial models archive of NASA's Space Physics Data Facility (ftp://nssdcftp.gsfc.nasa.gov/models/ionospheric/iri/iri2006/fortran_code/). A web interface for computing and plotting IRI values is available at http://modelweb.gsfc.nasa.gov/models/iri.html.

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