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Space Environment (Natural and Artificial)– Earth's Ionosphere Model: International Reference Ionosphere and Extensions to the Plasmasphere

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Contents

Foreword

ISO (the International Organization for Standardization) is a world-wide federation of national standards organizations (ISO member bodies). The work of preparing International Standards and other ISO documents is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also are eligible to take part in the work.

When the subject in question is still under development or where for any other reason there is a future but not immediate possibility of an agreement to publish an International Standard, the technical committee or subcommittee may decide, by following the ISO procedures, that the publication of a Technical Specification would be appropriate.

In the case of the ISO standard model for Earth's ionosphere and plasmasphere a Technical Specification was recommended as an interim document to provide guidance for the user of ionospheric models while at the same time providing an opportunity for input from different organization and modeling teams. It is expected that these interactions will result in a fully integrated ionosphere-plasmasphere model that will then be submitted for registration as an ISO standard.

The drafts of International Standards and Technical Specifications approved by Technical Committees are sent to all the participant committees for consideration pending approval of the ISO Council.

This Technical Specification was prepared by Technical Committee ISO/TC 20, *Aircraft and Space Vehicles*, Subcommittee SC 14, *Space Systems and Operations*.

Introduction

This Technical Specification provides guidelines for specifying the global distribution of ionospheric electron density, electron temperature, ion temperature, ion composition, and total electron content and the extension of these parameters into the plasmasphere. The model recommended for the representation of these parameters in the ionosphere is the International Reference Ionosphere (IRI). IRI is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations formed a Working Group in the late 1960s to produce an empirical standard model of the ionosphere based on all available data sources. Several steadily improved editions of the model have been released (Rawer et al., 1978a, 1978b, 1981; Bilitza and Rawer, 1996; Bilitza et al., 1993; Bilitza, 1990, 1993, 2001). For a given location, time, and date, IRI describes the monthly averages of electron density, electron temperature, ion temperature, and the percentage of O^+, H^+, He^+, N^+, NO^+, O_2^+, and Cluster ions in the altitude range from 50 km to 1500 km. In addition IRI provides the electron content by numerically integrating over the electron density height profile within user-provided integral boundaries. IRI is a climatological model describing monthly average conditions. The major data sources for building the IRI model are the worldwide network of ionosondes, the powerful incoherent scatter radars, and the topside sounders and in situ instruments flown on several satellites and rockets. This document also presents several models that may be used to extend the IRI model to plasmasphere altitudes.

The IRI model is the de facto international standard model for the ionosphere under COSPAR and URSI patronage and is a continuously evolving model that improves as new data become available. This Technical Specification is an important initial step towards developing a common framework for an International Standard of the ionosphere and plasmasphere.

Described in this document are the scope, terms and definitions, symbols and abbreviated terms, ionospheric users, model description, model content and inputs, model availability, plasmasphere extension, and references.

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1 Scope

This Technical Specification has the objective of providing guidance to potential users for the specification of the global distribution of ionosphere densities and temperatures as well as the total content of electrons in the height interval from 50 km to 1500 km. It includes and explains several options for a plasmaspheric extension of the model, embracing the geographical area between latitudes of 80°S and 80°N and longitudes of 0°E to 360°E, for any time of day, any day of year, and various solar and magnetic activity conditions.

Technical Specification of an international model for the representation of the ionospheric and plasmaspheric plasma parameters is important to a wide spectrum of applications. Electromagnetic waves traveling through the ionized plasma at the Earth's environment experience retardation and refraction effects. A remote sensing technique relying on signals traversing the ionosphere and plasmasphere therefore needs to account for the ionosphere-plasmasphere influence in its data analysis. Applications can be found in the disciplines of altimetry, radio astronomy, satellite communication, navigation and orbit determination.

For High Frequency (HF) radio communication a good knowledge of the heights and plasma frequencies of the reflective layers of the ionosphere and the plasmasphere is critical for continuous and high quality radio reception. HF communication remains of great importance in many remote locations of the globe and for some specialized military applications. The model helps to estimate the effect of charged particles on technical devices in the Earth's environment and defines the ionosphere-plasmasphere operational environment for existing and future systems of radio communication, radio navigation, and other relevant radio technologies in the medium and high frequency ranges.

2 Terms and Definitions

2.1
ionosphere
Region of the Earth's atmosphere in the height interval from 30 to 1000 km containing partially ionized cold plasma.

2.2
plasmasphere
Torus of cold (a few eV to a few 10's eV), relatively dense (> 10 cm^{-3}) plasma of mostly H^+ in the inner magnetosphere that is trapped on the Earth's magnetic field lines and thus co-rotates with Earth.

2.3
plasmapause
Outward boundary of the plasmasphere located at 2 - 6 Earth's radii and formed by geomagnetic field lines where the plasma density drops by a factor of 10 or more across a range of L-shells of as little as 0.1.

2.4
solar activity
A series of processes occurring in the Sun's atmosphere affecting the interplanetary space and the Earth; the level of solar activity is characterized by indices.

2.5
ionospheric storm
Ionospheric storms last about a day and are documented by depressions and/or enhancements of the ionospheric electron density during various phases of the storm. They are the ultimate result of solar flares or coronal mass ejections which produce large variations in the particle and electromagnetic radiation that hit Earth's magnetosphere and ionosphere and produce large-scale changes in the global neutral wind, composition, and temperature.

3 Symbols and abbreviated terms

km 1 kilometer is 1×10^3 meters
eV electron volt
L L-shell
Rz Zürich Sunspot Number is the number of sunspots and sunspot groups determined daily
R12 12-months-running mean monthly Zürich Sunspot Number
kp Planetary 3-hour index of geomagnetic activity characterizing the disturbance in the Earth's magnetic field over 3-hours UT interval; the index scale is uneven quasi-logarithmic and expressed in numbers from 0 to 9
ap Three-hours UT amplitude index of geomagnetic variation equivalent to kp and expressed in 1 to 400 nT
Ne Number of free electrons per one cubic meter, m^{-3}
hmF2 peak height in the ionosphere, km
NmF2 electron density at the peak height in the ionosphere, m^{-3}
TEC Total electron content, i.e., the integral number of electrons in the column from 65 km to the plasmapause in units of electrons m^{-2}
τ slab thickness or the equivalent thickness of ionosphere/plasmasphere defined by ratio of TEC/NmF2, km
kHz kilo Hertz (1 kHz is 1×10^3 cycles per second)
Φ' Corrected geomagnetic latitude calculated using the higher spherical harmonic expansion terms of geomagnetic field alongside with dipoles
VLF Very Low Frequencies from 30 kHz to 3 kHz
LF Low Frequencies from 300 kHz to 30 kHz
MF Medium Frequencies from 3 MHz to 300 kHz
HF High Frequencies from 30 MHz to 3 MHz
VHF Very High Frequencies from 300 MHz to 30 MHz
UHF Ultra High Frequencies from 3000 MHz to 300 MHz

4 Ionospheric Users

There is a multitude of operational usages for ionospheric models. A few of the most important groups are listed in this chapter. Operators of navigational satellite systems such as GPS (USA), GLONASS (Russia), Galileo (Europe) require ionospheric predictions to mitigate losses of navigation signal phase and/or amplitude lock as well as to maintain accurate orbit determination for all its satellites. Radio and television operators using MF, HF, VHF, UHF satellite or ground stations require ionospheric parameters for efficient communications and for reducing interferences. Space weather forecasters have a great need for accurate ionospheric model to support their customers with reliable and up to the minute weather information. Aeronautical and space system industries and Governmental agencies performing spacecraft design, surface charging, sensor interference, and satellite anomaly studies are users.

Military users apply the models to mitigate problems with HF communications, HF direction finding, over-the-horizon (OTH) radar clutter, targeting errors, disruption to ELF/VLF communications with submarines, and reduced detectability of missile launches. Insurance companies estimating the cost of protecting human health in space and satellites are ionospheric users. Scientists using remote sensing measurement techniques in astronomy, biology, geology, geophysics, and seismology require parameter estimates for compensating the effects of the ionosphere on their observations. An ionospheric model may be also used to evaluate tomographic, radio occultation, and other similar techniques by providing the ground-truth background model for test runs. Amateur radio operators as well as students and teachers in space research and applications also use ionosphere parameters.

Users may apply this Technical Specification for ray-path calculations to assess the performance of particular ground-based and space-borne systems. Specifically, long-term monthly median parameters are useful for HF circuit and service planning while maps for individual days and hours aid frequency management and retrospective studies.

5 Model Description

The IRI model and its mathematical build-up was first described in a special URSI report (Rawer et al., 1978a) and a later version was described in a 250-page report published by the World Data Center A for Solar-Terrestrial Physics (Rawer et al., 1981). The core of the latest version of IRI is described in detail in a 155-page WDC/NSSDC report (Bilitza, 1990) and also in a 40-page article by Bilitza and Rawer (1993) in the book “The Upper Atmosphere”. Both documents include ample graphical representations of IRI parameters for typical conditions. The WDC/NSSDC report is available as a PDF document from the IRI homepage (http://iri.gsfc.nasa.gov). Bilitza (2001) described the IRI updates that led to the 2001 version of the model.

The IRI-related research efforts and applications of the IRI model are presented and discussed during annual IRI Workshops with each workshop focusing on a specific modeling topic. Information about past and future workshops can be found on the IRI homepage, which also provides access to a final report from each workshop. The refereed papers presented at these workshops have been published in several dedicated issues of Advances in Space Research. A bibliography of IRI-related issues of Advances in Space Research can be found at the IRI homepage. Papers from the 2003 and 2004 IRI Workshops were published as Volume 34, Number 9 and Volume 37, Number 5, respectively.

A recent review of IRI and other ionospheric models can be found in the 1999-2002 Review of Radio Science published by the International Union of Radio Science (URSI) (Bilitza, 2002).

6 Model content and inputs

The IRI model uses a modular approach combining sub-models for the different parameters in different altitude regimes. Examples of such sub-models are:

(i) COSPAR International Reference Atmosphere (CIRA) model (Hedin, 1991) for the neutral temperature
(ii) International Telecommunication Union ITU-R (former CCIR) model for the F2 layer critical frequency foF2 (directly correlated with the F2 peak electron density NmF2) and for the propagation factor M(3000)F2 (inversely correlated wit the peak height hmF2) (CCIR, 1990)
(iii) International Reference Geomagnetic Field (IGRF) Model of the International Association of Geomagnetism and Aeronomy (IAGA) for the magnetic coordinates (http://www.ngdc.noaa.gov/IAGA/vmod/)
(iv) STORM model for storm-time updating of the F2 layer peak density developed by Fuller-Rowell et al. (2001)

The IRI model requires the following indices as input parameters:
(1) 12-month running mean of sunspot number R12
(2) 12-month running mean of global ionospheric index IG
(3) 3-hourly planetary magnetic ap indices for the prior 39 hours

These indices can either be found automatically from an indices file that is included with the IRI software package and that is updated quarterly, or the user can provide his/her own input values for these indices. For R12 and IG12 the indices file starts from January 1958 and includes indices prediction for two years ahead. For ap the index values start from January 1960 and currently lack a few month behind because of the problems in obtaining this index.

In addition model users have the options to use measured peak parameters to update the IRI profile, including the F2, F1, and E layer critical frequencies (or electron densities), the F2 peak height (or M(3000)F2 propagation factor), and the E peak height. In this way real-time IRI predictions can be obtained if the real-time peak parameters are available.

The total electron content TEC is obtained by numerical integration from the model's lower boundary (65 km during daytime and 80 km during nighttime) to the user-specified upper boundary.

7 Computer code availability

The homepage of the IRI project is at http://iri.gsfc.nasa.gov/.

The IRI program is provided as a FORTRAN computer code for use on UNIX, VAX, and PC-Windows systems. The code can be downloaded from ftp://nssdcftp.gsfc.nasa.gov/models/ionospheric/iri/iri2007/. A special PC Windows version with multiple plotting options is available form the University of Massachusetts Lowell at http://umlcar.uml.edu/IRI-2001/ (Huang et al., 2001). An interactive system for computing and plotting IRI parameters is accessible at http://omniweb.gsfc.nasa.gov/vitmo/iri_vitmo.html.

8 Plasmasphere Extension of the IRI Model

Several models have been proposed as plasmasphere extension of the IRI model and are listed here.

8.1 Global Core Plasma Model
The GCPM-2000 of Gallagher et al. (2000) is an empirical description of thermal plasma densities in the plasmasphere, plasmapause, magnetospheric trough, and polar cap. GCPM-2000 uses the kp index and is coupled to IRI in the transition region 500-600 km. A FORTRAN code implementation that includes all except the polar cap is available from dennis.gallagher@msfc.nasa.gov.

8.2 Global Plasmasphere Ionosphere Density model
The semi-empirical GPID model of Webb and Essex (2000, 2004) includes IRI below 500-600 km, extended with theoretical plasmasphere electron density description along the field lines. Authors report on drawbacks of merging of the IRI with the plasmasphere part of GPID. Model source GPID code written in commercial MATLAB software is not currently available for release.

8.3 IZMIRAN plasmasphere model
The IZMIRAN model (Chasovitin et al., 1998; Gulyaeva et al., 2002, Gulyaeva and Titheridge, 2006) is an empirical model based on whistler and satellite observations. It presents global vertical analytical profiles of electron density and temperature smoothly fitted to IRI electron density profile at 1000 km (400 km for Te) altitude and extended towards the plasmapause (up to 36,000 km). For the smooth fitting of the two models, the shape of the IRI topside electron density profile is improved using ISIS 1, ISIS 2, and IK19 satellite inputs (Gulyaeva, 2003). The plasmasphere model depends on solar activity and magnetic activity (kp-index). Source code for this IRI ionosphere-plasmasphere version is available from the IZMIRAN web site ftp://ftp.izmiran.ru/pub/izmiran/SPIM/.

8.4 IMAGE/RPI plasmasphere model
The IMAGE/RPI plasmasphere model of Huang et al. (2004) is based on Radio Plasma Imager (RPI) (Reinisch et al., 2000) measurements of the electron density distribution along magnetic field lines. A plasmaspheric model is evolving for up to about 4 R_E. The depletion and refilling of the plasmasphere during and after magnetic storms is described (Reinisch et al., 2004). A power profile model as function of magnetic activity was developed from RPI observations for the polar cap region (Nsumei et al., 2003).

9 Accuracy of the Model

The IRI model has been built to represent the monthly average behavior of space plasma. Efforts are underway to also include a quantitative description of the monthly variability in IRI. As variability measure, either the relative standard deviation or upper/lower quartiles and deciles will be used.

The accuracy of the IRI electron density model is typically

- 50-80 % at heights from 65 km to 95 km
- 5-15 % at heights from 100 km to 200 km during daytime
- 15-30 % at heights from 100 km to 200 km during nighttime
- 15-25 % at heights from 200 km to 1000 km at low and middle dip latitudes (< 60°)
- 50-80 % at heights from 200 km to 1000 km at high dip latitudes (> 60°)

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