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Space systems — Space environment (natural and artificial) — The Earth's ionosphere model: international reference ionosphere (IRI) model and extensions to the plasmasphere

Systèmes spatiaux — Environnement spatial (naturel et artificiel) — Modèle de l'ionosphère de la Terre: modèle de l'ionosphère internationale de référence (IRI) et extensions à la plasmasphère

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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 [1)] 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 (References [18], [19], [20], [5], [6], [1], [2], [3]).

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 1 500 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 Technical Specification also presents several models that can be used to extend the IRI model to plasmasphere altitudes.

The IRI model is the *de facto* world-wide 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.

1) The homepage of the IRI project is 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 the IRI homepage. The IRI homepage also provides access to an interactive system for computing and plotting IRI parameters online and to a special PC Windows version with multiple plotting options developed at the University of Massachusetts Lowell.

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1 Scope

This Technical Specification provides 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 65 km to 1 500 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.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
ionosphere
region of the Earth's atmosphere in the height interval from approximately 50 km to approximately 1 500 km containing partially ionized cold plasma

2.2
plasmasphere
torus of cold, relatively dense ($> 10\ cm^{-3}$) plasma of mostly H^+ in the inner magnetosphere, which is trapped on the Earth's magnetic field lines and thus co-rotates with the Earth

NOTE Here, cold plasma is considered to have an energy of between a few electronvolts and a few dozen electronvolts.

2.3
plasmapause
outward boundary of the plasmasphere located at between two and six earth radii from the centre of the Earth 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

NOTE The L-shell is a parameter describing a particular set of planetary magnetic field lines, often describing the set of magnetic field lines which cross the Earth's magnetic equator at a number of Earth radii equal to the L-value, e.g. "$L = 2$" describes the set of the Earth's magnetic field lines which cross the Earth's magnetic equator two Earth radii from the centre of the Earth.

2.4
solar activity
series of processes occurring in the Sun's atmosphere which affect the interplanetary space and the Earth

NOTE The level of solar activity is characterized by indices.

2.5
ionospheric storm
storm lasting about a day, documented by depressions and/or enhancements of the ionospheric electron density during various phases of the storm

NOTE Ionospheric storms 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, as well as large-scale changes in the global neutral wind, composition and temperature.

2.6
sunspot number
R
number of sunspots and sunspot groups determined daily

2.7
R12
twelve-month-running mean monthly sunspot number

2.8
kp index
kp
planetary three-hour index of geomagnetic activity characterizing the disturbance in the Earth's magnetic field measured at ground level over three-hour universal time (UT) intervals

NOTE The index scale is uneven quasi-logarithmic and expressed in numbers from 0 to 9.

2.9
ap index
ap
three-hour UT amplitude index of geomagnetic variation linearized equivalent to kp

NOTE The index scale is linear and expressed in numbers from 1 to 400.

2.10
total electron content
TEC
integral number of electrons in a unit-area column through the ionosphere

NOTE It is expressed in units of 10^{16} electrons m^{-2} (TECU).

3 Abbreviated terms

IRI international reference ionosphere

ELF extremely low frequency

VLF very low frequency (3 kHz to 30 kHz)

LF low frequency (30 kHz to 300 kHz)

MF medium frequency (300 kHz to 3 MHz)

HF high frequency (3 MHz to 30 MHz)

VHF very high frequency (30 MHz to 300 MHz)

UHF ultra high frequency (300 MHz to 3 000 MHz)

4 General considerations

This model for the representation of the ionospheric and plasmaspheric plasma parameters is important to a wide spectrum of applications. Electromagnetic waves travelling 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 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. High frequency communication remains of great importance in many remote locations of the globe and for some specialized military applications. The model helps 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.

5 Applicability

There are a multitude of operational usages for ionospheric models, of which the most important are outlined in this clause. Operators of certain navigational satellite systems such as GPS (U.S.A.), GLONASS (Russia) and GALILEO (Europe) [2)] require ionospheric predictions to mitigate losses of navigation signal phase and/or amplitude lock, as well as to maintain accurate orbit determination for all their 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 models to provide their customers with reliable and up-to-the-minute weather information. Ionospheric models are also used in the aeronautical and space system industries and governmental agencies performing spacecraft design, surface charging, sensor interference and satellite anomaly studies.

Military users apply ionospheric 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 make use of ionospheric models. 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.

This Technical Specification may be applied 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.

6 Model description

The IRI model and its mathematical build-up was first described in Reference [18], and a later version was described in Reference [20]. The core of the latest version of IRI is described in detail in References [2] and [5], both of which include ample graphical representations of IRI parameters for typical conditions. The IRI updates that led to the 2001 version of the model are described in Reference [3].

2) GPS: Global Positioning System; GLONASS: Global Orbiting Navigation Satellite System; GALILEO: European Global Satellite Navigation System.

The IRI-related research efforts and applications of the IRI model are presented and discussed during annual IRI workshops 3), with each workshop focusing on a specific modelling topic. A recent review of IRI and other ionospheric models can be found in Reference [4].

7 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:

a) COSPAR international reference atmosphere (CIRA) model [14] for the neutral temperature;

b) International Telecommunication Union ITU-R (former CCIR) model for the F2 layer critical frequency foF2 (directly correlated with the F2 peak electron density, in m^{-3}) and for the propagation factor M(3000)F2 (inversely correlated with the peak height, in km) [7];

c) 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/);

d) STORM model for storm-time updating of the F2 layer peak density [9].

The IRI model requires the following indices as input parameters:

— 12-month running mean of sunspot number R12;

— 12-month running mean of global ionospheric index IG;

— 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 4).

In addition, model users have the option 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 night time) to the user-specified upper boundary.

8 Plasmasphere extension of the IRI model

8.1 General

The models described in 8.2 to 8.5 have been proposed as a plasmasphere extension of the IRI model.

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3) Information about past and future workshops can be found on the IRI homepage (http://IRI.gsfc.nasa.gov), 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* is accessible from the IRI homepage.

4) For ap, the index values currently lack a few months prior to 1960 because of the problems in obtaining this index.

8.2 Global Core Plasma Model (GCPM)

GCPM-2000 [10] 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 km to 600 km 5).

8.3 Global Plasmasphere Ionosphere Density (GPID) model

The semi-empirical GPID model [23], [24] includes IRI below 500 km to 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 6).

8.4 IZMIRAN plasmasphere model

The IZMIRAN 7) model [8], [11], [13] 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 an altitude of 1 000 km (400 km for electron temperature) 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 8) satellite inputs [12]. The plasmasphere model depends on solar activity and magnetic activity (kp-index) 9).

8.5 IMAGE/RPI plasmasphere model

The IMAGE/RPI plasmasphere model [15] is based on radio plasma imager (RPI) [21] measurements of the electron density distribution along magnetic field lines. A plasmaspheric model is evolving for up to about four earth radii. The depletion and refilling of the plasmasphere during and after magnetic storms is described in Reference [22]. A power profile model as function of magnetic activity was developed from RPI observations for the polar cap region [17].

9 Accuracy of the model

The IRI model has been built to represent the monthly average behaviour 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 % to 80 % at heights from 65 km to 95 km;

— 5 % to 15 % at heights from 100 km to 200 km during daytime;

— 15 % to 30 % at heights from 100 km to 200 km during nighttime;

— 15 % to 25 % at heights from 200 km to 1 000 km at low and middle dip latitudes (< 60°);

— 50 % to 80 % at heights from 200 km to 1 000 km at high dip latitudes (> 60°).

5) A FORTRAN code implementation of GCPM that includes all except the polar cap is available from dennis.gallagher@msfc.nasa.gov.

6) The GPID model source code was written using commercial MATLAB software, but is not currently available for release.

7) IZMIRAN: Institute of Earth magnetism, ionosphere and radiowaves propagation.

8) ISIS: International Satellites for Ionospheric Studies; IK-19: Intercosmos-19 satellite.

9) Source code for this IRI ionosphere-plasmasphere version is available from the IZMIRAN web site ftp://ftp.izmiran.rssi.ru/pub/izmiran/SPIM/.

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