BS ISO 16457:2014

Incorporating corrigendum June 2014

BSI Standards Publication

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

...making excellence a habit.™

National foreword

This British Standard is the UK implementation of ISO 16457:2014. It supersedes DD ISO/TS 16457:2009 which is withdrawn.

The UK participation in its preparation was entrusted by Technical Committee ACE/68, Space systems and operations, to Subcommittee ACE/68/-/4, Space systems and operations - Space environment (natural and artificial).

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

ISBN 978 0 580 87078 1

ICS 07.060; 49.140

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 April 2014.

Amendments/corrigenda issued since publication

Date	Text affected
30 June 2014	Implementation of ISO corrected text 15 June 2014: Foreword updated

INTERNATIONAL STANDARD

ISO 16457

First edition
2014-04-15

Corrected version
2014-06-15

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) — Guidage sur le modèle de l'ionosphère internationale de référence (IRI) et extensions à la plasmasphère

Reference number
ISO 16457:2014(E)

COPYRIGHT PROTECTED DOCUMENT

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards 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 take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

This first edition of ISO 16457 cancels and replaces ISO/TS 16457:2009, which has been technically revised.

This corrected version of ISO 16457:2014 incorporates the following correction.

In the Foreword, the following sentence has been added regarding the revision:

This first edition of ISO 16457 cancels and replaces ISO/TS 16457:2009, which has been technically revised.

Introduction

Guided by the knowledge gained from empirical data analysis, this International Standard provides guidelines for specifying the global distribution of electron density, electron temperature, ion temperature, ion composition, and total electron content through the Earth's ionosphere and 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. The IRI Working Group consists of more than 50 international experts representing different countries and different measurement techniques and modelling communities. The group meets annually to discuss improvements and additions to the model. As a result of these activities, several steadily improved editions of the model have been released (see References [1], [2], [3], [5], [6], [18], [19], [20], and [53]).

For a given location over the globe, 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, the topside sounders, and *in situ* instruments flown on several satellites and rockets. This International Standard also presents several empirical and semi-empirical models that can be used to extend the IRI model to plasmasphere altitudes.

One advantage of the empirical approach is that it solely depends on measurements and not on the evolving theoretical understanding of the processes that determine the electron and ion densities and temperatures in the Earth's ionosphere. A physical model can help to find the best mathematical functions to represent variations of these parameters with altitude, latitude, longitude, time of day, day of year, and solar and magnetic activity.

IRI is recommended for international use by COSPAR and URSI. The IRI model is updated and improved as new data and new sub-models become available. This International Standard provides a common framework of the International Standard of the Earth's ionosphere and plasmasphere for the potential users.

---

1) The homepage of the IRI project is at http://irimodel.org/. The IRI homepage provides access to the IRI FORTRAN computer code and an interactive system for computing and plotting IRI parameters online A special PC Windows version of IRI-2001 with multiple plotting options is available from the University of Massachusetts Lowell at http://umlcar.uml.edu/IRI-2001/[16]. The IRI-Plas code including IRI extension to the plasmasphere is available at http://ftp.izmiran.ru/pub/izmiran/SPIM/.

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

1 Scope

This International Standard 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 50 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 50 km to 1 500 km containing weakly 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 co-rotates with the Earth

Note 1 to entry: 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 1 to entry: 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 1 to entry: 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 1 to entry: 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, alternatively called Ri or Rz, is a daily index of sunspot activity defined as R=k(10g+s) where s is the number of individual spots, g is the number of sunspot groups, and k is an observatory factor

2.7
R12

12-month running mean of monthly sunspot number

2.8
kp index

kp

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

Note 1 to entry: 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 equivalent to kp

Note 1 to entry: It is expressed in 1 nT to 400 nT.

2.10
total electron content

TEC

integral number of electrons in the column from a lower altitude boundary to an upper boundary

Note 1 to entry: Typically the integral is taken from the lower boundary of the ionosphere (65 km during daytime and 80 km during night time) to the plasmapause.

Note 2 to entry: It is expressed in units of 10^{16} electrons m^{-2} (TECU).

2.11
Ionosphere global index

IG

ionosphere-effective sunspot number[56] that is obtained by adjusting the CCIR maps[7] to global ionosonde measurements of the F2 plasma critical frequency foF2

2.12
IG12

12-month running mean of monthly ionosphere-effective sunspot number

3 Abbreviated terms

IRI	international reference ionosphere
ELF	extremely low frequency (less than 3 kHz)
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.

Radio signals, transmitted by modern communication and navigation systems can be heavily disturbed by space weather hazards. Thus, severe temporal and spatial changes of the electron density in the ionosphere and plasmasphere can significantly degrade the signal quality of various radio systems which even can lead to a complete loss of the signal. Model-based products providing specific space weather information, in particular now- and forecast of the ionospheric state, serve for improvement of the accuracy and reliability of impacted communication and navigation systems.

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. 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.

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 (USA), GLONASS (Russia), BeiDou (China), 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 its satellites. Users of global navigation satellite systems need precise ionospheric models to increase the accuracy and to reduce the precise positioning convergence time.[57][58] 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 support their customers with reliable and up to the minute space weather information. Ionospheric models are also used in the aeronautical and space system industries

---

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

and by governmental agencies performing spacecraft design studies. Here the models help to estimate surface charging, sensor interference, and satellite anomaly conditions.

Users also apply ionospheric models to mitigate problems with HF communications, HF direction finding, radar clutter, and disruption to ELF/VLF communications with underwater vehicles. 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 might 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 International Standard might be also applied for ray-path calculations to assess the performance of a particular ground-based or space-borne systems. Monthly medians of ionospheric 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 first version of the IRI model, IRI-1979, and its mathematical build-up is described in References [18], [19], and [20]. The most detailed description of the model and the mathematical formulas and methods used is given in a 155-page report about IRI-1990.[2] The next significant updates of the model were introduced with IRI-1995[5] and IRI-2000.[3] The core of the version of IRI proposed for this International Standard, IRI-2007, is described in detail in References [53] and [54].

IRI-related research efforts and applications of the IRI model are presented and discussed during annual IRI workshops3), with each workshop focusing on a specific modelling topic. Papers from these workshops have been published in dedicated issues of the journal Advances in Space Research3). Recent reviews of IRI and other ionospheric models can be found in References [4], [51], [52], and [54].

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:

- International Telecommunication Union ITU-R (former CCIR) model for the F2 layer critical frequency foF2 (directly related 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]; IRI recommends use of the CCIR model above continental areas and recommends use of the URSI model[55] above ocean areas, because the URSI model produces better results than the CCIR model in these areas; Instead of the CCIR-recommended sunspot number IRI uses the global ionosphere index IG[56] because it gives better results especially at high solar activities,
- COSPAR International Reference Atmosphere (CIRA) model[14] for the neutral temperature,
- STORM model for storm-time updating of the F2 layer peak density[9], and
- International Geomagnetic Reference Field (IGRF) model of the International Association of Geomagnetism and Aeronomy (IAGA) for the magnetic coordinates (http://www.ngdc.noaa.gov/IAGA/vmod/).

The IRI model requires the following indices as input parameters:

- R12, the 12-month running mean of sunspot number R;
- IG12, the 12-month running mean of global ionosphere index IG;

---

3) Information about past and future workshops can be found on the IRI homepage (http://irimodel.org), which also provides access to the final report from each workshop and to a bibliography of IRI-related papers and issues of Advances in Space Research.

— ap, the 3-hourly planetary magnetic indices for the prior 33 h.

These indices can either be found automatically from the indices files that are included with the IRI software package and that are 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 include indices prediction for two years ahead. For ap, the index values start from January 1960[4].

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 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 plasmasphere extension of the IRI model.

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 and extends it 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 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]

8.5 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 profiles at an altitude of topside half peak density (400 km to 600 km for electron density and 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

---

4) For ap, the index values currently lag a few months behind, because of the problems in obtaining and predicting this index.

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

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

7) IZMIRAN: Institute of Terrestrial Magnetism, Ionosphere and Radio Waves Propagation, Russian Academy of Sciences.

using ISIS-1, ISIS-2, and IK-19[8] satellite inputs.[12] The plasmasphere model depends on solar activity and magnetic activity (kp-index)[9].

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 (given here as standard deviation divided by monthly median in %):

- 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 night time;
- 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°).

---

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 http://ftp.izmiran.ru/pub/izmiran/SPIM/.

Annex A
(informative)

Brief introduction to ionosphere and plasmasphere physics

The ionosphere and plasmasphere are conductive, ionized regions of the Earth's atmosphere consisting of free electrons and ions. The ionosphere and plasmasphere are embedded within the Earth's magnetic field and thus are constrained by interactions of the ionized particles with the magnetic field. The ionization levels in this near-Earth space plasma are controlled by solar extreme ultraviolet (EUV) radiation and particle precipitation. The dynamics of the neutral atmosphere plays a significant role in causing movement of the ionized particles by collisions with neutral atoms and molecules from the surrounding thermosphere. The ionosphere extends in altitude from about 65 km to about 1 500 km and exhibits significant variations with local time, altitude, latitude, longitude, solar cycle, season, and geomagnetic activity. At middle and low latitudes, the ionosphere is contained within a region of closed field lines, whereas at high latitudes the geomagnetic field can reconnect with the interplanetary magnetic field and thus open the ionosphere to the driving force of the solar wind.

Plasma flowing upwards from the oxygen-dominated topside ionosphere remains constrained by Earth's field lines of force co-rotating with the Earth and comprises the hydrogen-dominated plasmasphere extended up to a few earth radii.[25][26] The O^+/H^+ transition height where the ion gas consists of an equal percentage of both ions is often taken as the boundary between the ionosphere and plasmasphere. These two regions of the upper atmosphere are strongly coupled through diffusion and resonant charge exchange reactions between O^+ and H^+. At quiet conditions, H^+ in the plasmasphere typically diffuses down to the topside ionosphere at night and undergoes resonant charge exchange reactions with atomic oxygen to produce O^+ (downward flux). The O^+ produced in this way can make a significant contribution to the maintenance of the night time ionosphere, and works in combination with the meridional component of the neutral wind. The depleted night time plasmasphere can be refilled during the day through the reverse process; that is, the O^+ ions flow up from the ionosphere, exchange charges with the neutral hydrogen atoms to produce protons, and the protons are then stored in the plasmasphere (upward flux). During geomagnetically disturbed conditions, the plasmaspheric plasma can be eroded by the enhanced magnetospheric electric fields, and consequently, the flux becomes upward both during the day and night, due to the reduced plasmaspheric pressure, to refill the empty plasmaspheric flux tubes. While the low-latitude flux tubes refill relatively quickly due to their small volumes, most of the mid-latitude flux tubes are always in a partially depleted state, since the average time between consecutive geomagnetic storms is not long enough for the upflowing ionospheric flux to completely refill the flux tubes.

Terrestrial HF communications rely entirely on reflections from the ionized layers in the upper atmosphere, but the ionosphere acts also as a hindrance because it distorts Earth-space and spacecraft-to-spacecraft links. Although empirical models of the ionosphere are now accessible via electronic networking, most of them are far from reliable in predicting the average ionospheric conditions, not to mention their limitations in forecasting the ionospheric "space weather". In particular, a reliable and standard ionosphere-plasmasphere model is required for calibration of trans-ionospheric signals of the high altitude Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) satellites at 20 200 km above the Earth. On the other hand, Global Navigation Satellite System (GNSS) are also benefiting ionospheric modelling because they provide measurements of total electron content (TEC) between ground receiver and satellite transmitter if the system operates on two or more frequencies. This is the case because TEC can be deduced from the difference in delay at the different frequencies.

Due to the high temporal and spatial variability of the space plasma surrounding the Earth and due to the requirements of its specification for the design and operation of space vehicles, remote sensing, reliable communication and navigation, modelling of the ionosphere and plasmasphere is an important research focus within the worldwide space science communities. Among these efforts, the International Reference Ionosphere (IRI) plays an outstanding part and is widely used by space agencies and scientists and engineers worldwide. It is recommended for international use by the Committee on Space Research (COSPAR) and the international Union of Radio Science (URSI).

Annex B
(informative)

Physical models

Physical models typically use a numerical iterative scheme to solve the Boltzmann equations for the ionospheric gas including the continuity, energy, and momentum formulae.[53] They are solved along field-lines of the Earth magnetic field where the field is represented either by a simple tilted dipole or a multipole model like the International Geomagnetic Reference Field (IGRF). The equations are either solved self-consistently along a full flux tube or the plasmaspheric flux is provided as a top boundary condition. The effects of the geomagnetic field on the transport of the ionospheric plasma are introduced by the magnetic dip (I) and declination (D) angles from the (IGRF).

The ionosphere is strongly coupled with the neutral atmosphere, chemically as well as dynamically. In addition to the effects of the neutral wind, the neutral atmosphere significantly affects the ionospheric plasma density distribution through neutral composition and temperature. The neutral composition is a crucial factor not only for the production and loss of the plasma, but also for the diffusion of the ionospheric plasma through the neutral atmosphere. The neutral temperature effect on the ionosphere usually comes from the changes of the neutral densities caused by the neutral temperature change. Below the F-region peak, chemical equilibrium prevails and the plasma density profile is largely controlled by the neutral composition through the production and loss. As altitude increases, plasma diffusion becomes important and well above the F-region peak, the plasma density profile is primarily determined by diffusion. However, the diffusion of the plasma through the neutral atmosphere strongly depends on the neutral densities, mainly the O density in the topside ionosphere, via collisions between the plasma and the neutrals.

A physical model requires several input parameters, including the neutral densities and temperature, neutral wind, and plasma temperatures. For these inputs, empirical or self-consistent models are adopted. In assimilative mode of operation, up to six free model parameters should be adjusted to measurements within physically reasonable ranges, and this cannot be reached straightforward under certain conditions.

Utah State University has been developing the Global Assimilation of Ionospheric Measurements (GAIM) models that specify and forecast the state of the ionosphere. There are two models: the Gauss Markov (GAIM-GM) and Full Physics (GAIM-FP) models [27, 29, 59, 60, 61, 62, and 63]. GAIM-GM uses a physics-based ionosphere model and a Kalman filter as a basis for assimilating a diverse set of measurements. The physics-based model is the Ionosphere Forecast Model (IFM), which is global, covers altitudes from 90 to 1 400 km, and takes account of five ion species (NO^+, O_2^+, N_2^+, O^+, H^+). However, the main output of the model is a 3-D electron density distribution. GAIM-FP uses a physics-based model of the ionosphere-plasmasphere system and an ensemble Kalman filter as a basis for assimilating the measurements. The physics-based model is the Ionosphere Plasmasphere Model (IPM), which is global, covers the ionosphere and plasmasphere from 90 to 30 000 km, and takes account of six ion species (NO^+, O_2^+, N_2^+, O^+, H^+, He^+). The primary output of GAIM-FP is a 3-D plasma density distribution. However, the model also provides the self-consistent drivers of the ionosphere-plasmasphere system (e.g. neutral winds and composition and electric fields).

The University of Southern California (USC) and the Jet Propulsion Laboratory (JPL) physics model[28][30][31] is derived from the Sheffield University Plasmasphere Ionosphere Model (SUPIM).[32] In physical models, such as SUPIM, the time-dependent equations of continuity, momentum (ignoring the time variation and inertial terms in the momentum equation), and energy balance are solved along eccentric-dipole magnetic field lines for the densities, field-aligned fluxes, and temperatures of the ions and the electrons. Its application relies on accurate estimates of the solar EUV, E × B drift, neutral wind, and neutral densities. The ion momentum equation is further broken into a field-parallel and field perpendicular component. The velocity component perpendicular to the magnetic field is considered to be due entirely to E × B drift and is an input driver. The parallel component of velocity also has input drivers due to neutral winds and electron and ion temperatures. Thus in the USC/JPL system, the only state variable solved for is the O^+ density; the rest are input drivers to the system.

The Coupled Thermosphere Ionosphere Model (CTIM)[33] was developed by coupling a self-consistent thermosphere physical model with the Sheffield University high latitude ionosphere model.[64] As with many of the theoretical model, the global atmosphere is divided into a series of elements in geographic latitude, longitude, and pressure (or altitude). Each grid point rotates with Earth to define a non-inertial frame of reference in an Earth-centred coordinate system. The magnetospheric input is provided by statistical models of auroral precipitation[34] and electric fields.[35], [65] Both inputs are keyed to a hemispheric power index (PI), based on the TIROS/NOAA auroral particle measurements or use solar wind density and magnetic field measurements. A recent upgrade of this model included a self-consistent plasmasphere and low latitude ionosphere models [32]in the Coupled Thermosphere-Ionosphere-Plasmasphere model (CTIP).[36] The effects of E × B drift at lower latitudes are incorporated by the inclusion of low-latitude physical electric field dynamo model[66]. The new ionosphere-plasmasphere component of CTIP solves the coupled equations of continuity, momentum, and energy to calculate the densities, field-aligned velocities, and temperatures of the ions O^+ and H^+ and the electrons, along a total of 800 independent flux-tubes arranged in magnetic longitude and L value (20 longitudes and 40 L values).

The Field Line Interhemispheric Plasma (FLIP) model[37][67] is a first-principles, one-dimensional, time-dependent, chemical, and physical model of the ionosphere and plasmasphere. It couples the local ionosphere to the overlying plasmasphere and conjugate ionosphere by solving the ion continuity and momentum, ion and electron energy, and photoelectron equations along entire magnetic flux tubes. The interhemispheric solutions yield densities and fluxes of H^+, O^+, He^+, and N^+ as well as the electron and ion temperatures. The neutral densities, temperature, and wind are supplied by the empirical NRLMSISE-00[38] and HWM[39] models. During quiet times, the error in the inputs for the solar EUV flux, MSIS neutral parameters, reaction rates, and cross sections are typically about 20 %. During magnetic storms, uncertainties can be much larger. The set of nonlinear, second-order, partial differential equations for continuity, momentum, and energy is transformed into finite difference equations and solved by a Newton-Raphson iterative scheme. The current FLIP model is primarily a mid-latitude model but it can include convection electric fields, which are important at equatorial and auroral latitudes.

As described in the previous paragraphs, driver inputs shall be obtained from empirical models including the following: thermospheric densities from the NRLMSISE-00 model,[38] neutral winds from the Horizontal Wind Model,[39] solar EUV,[40] electric fields ([35][41][42][43][65]), and electron energy precipitation flux.[34] The interested reader can refer to Reference [30] and references therein. In the 2003 model validation experiment, only vertical drift at the geomagnetic equator was simulated and estimated, while all the other inputs were held at their empirical values. The vertical drift was parameterized by nine coefficients at different local times.

The Open Geospace General Circulation Model (OpenGGCM) is a global model of the magnetosphere-ionosphere system. It solves the magneto-hydrodynamic (MHD) equations in the outer magnetosphere and couples via field aligned current (FAC), electric potential, and electron precipitation to an ionosphere potential solver and the Coupled Thermosphere Ionosphere Model (CTIM).[44] This code coupling enables studies of the global energy budget of the magnetosphere-ionosphere-thermosphere system. The CTIPe model is a nonlinear, coupled thermosphere-ionosphere-plasmasphere physically based numerical code that includes a self-consistent electrodynamics scheme for the computation of dynamo electric fields. The model consists of four distinct components which run concurrently and are fully coupled. Included are a global thermosphere, a high-latitude ionosphere, a mid and low-latitude ionosphere/plasmasphere, and an electrodynamical calculation of the global dynamo electric field.[45]

The Thermospheric General Circulation Model (TGCM) of the National Center for Atmospheric Research (NCAR) was extended to include a self-consistent aeronomic scheme of the thermosphere and ionosphere.[46] The model now calculates total temperature, instead of perturbation temperature about some specified global mean, global distributions of N(2D), N(S), and NO, and a global ionosphere with distributions of O^+, NO^+, O_2^+, $N^{\bullet+}$, N^+, electron density, and ion temperature as well as the usual fields of winds, temperature, and major composition. Mutual couplings between the thermospheric neutral gas and ionospheric plasma occur at each model time step and at each point of the geographic grid. Steady-state results for this first Eulerian model of the ionosphere are presented for solar minimum equinox conditions. The calculated thermosphere and ionosphere global structure agrees reasonably well with the structure of these regions obtained from empirical models. This suggests that the major physical and chemical processes that describe the large-scale structure of the thermosphere and ionosphere have been identified and a self-consistent aeronomic scheme, based on first principles, can be used to calculate thermospheric and ionospheric structure considering only external sources. Global empirical atmospheric models, such as the mass spectrometer/incoherent scatter models (e.g. Reference [38]), were used to specify atmospheric properties for ionospheric model. Equations describing the ionosphere and thermosphere are both solved on the TGCM geographic grid. Ion drift for the ionospheric calculation is obtained from the empirical model[47] for low and mid-latitudes and the empirical model[48] for high latitudes. Consideration of displaced geomagnetic and geographic poles is included. Results for solar minimum equinox conditions are presented that show good agreement with MSIS-86.[38] The self-consistent model requires only specifications of external sources as solar EUV and UV fluxes, aurora particle precipitation, ionospheric convection pattern, and the amplitudes and phases of semi-diurnal tides from the lower atmosphere.

The models of the ionospheric plasma density distribution and TEC depend on a number of upper atmospheric and ionospheric parameters, such as the neutral density, neutral wind, neutral and plasma temperatures, plasmaspheric flux, and ion-neutral collision frequencies. In the numerical modelling of the ionosphere, these parameters are generally often only roughly known and can cause significant uncertainties in the model results.[49] The physical models are also tested for implementation in the ionosphere tomography though a numerical model is often derived to give a close approximation to the full theoretical calculations under all conditions.[50] The physical model can be used to determine the qualitative relationship, but we do not have to rely on the physical model to provide the quantitative dependence for operational use.[9] The physical models can match empirical models in accuracy provided accurate drivers are available, but their true value comes when combined with data in an optimal way (data assimilative scenario).

Recent compilations of ionospheric and atmospheric models, including statistical and physical models were published by STEP,[51] AIAA,[52] and NOVA.[54]

Bibliography

[1] Bilitza D. International Reference Ionosphere - A Review. In: *Solar-Terrestrial Predictions - IV*, (Hruska J., Shea M.A., Smart D.F., Heckman G. eds.)., **Vol. 3**, 1993, pp. 313–37.

[2] Bilitza D. *International Reference Ionosphere 1990*, 155 pages, National Space Science Data Center, NSSDC/WDC-A-R&S 90-22, Greenbelt, Maryland, November 1990 Available at: http://irimodel.org

[3] Bilitza D. International Reference Ionosphere 2000. *Radio Sci.* 2001, **36** (2) pp. 261–275

[4] Bilitza D. Ionospheric Models for Radio Propagation Studies. In: *Review of Radio Science 1999-2002, 625 - 679*. Oxford University Press, Oxford, 2002

[5] Bilitza D., & Rawer K. International Reference Ionosphere, pp735-772, in: *The Upper Atmosphere - Data Analysis and Interpretation*, W. Dieminger, G. Hartmann and R. Leitinger (eds.), Springer-Verlag Berlin Heidelberg, 1996

[6] Bilitza D., Rawer K., Bossy L., Gulyaeva T.L. International Reference Ionosphere - past, present, and future: I. Electron density. *Adv. Space Res.* 1993, **13** (3) pp. 3–13

[7] CCIR Atlas of Ionospheric Characteristics. Comité Consultatif International des Radiocommunications Rept. 340, Geneva, 1990

[8] Chasovitin Yu.K., Gulyaeva T.L., Deminov M.G., Ivanova S.E. Russian Standard Model of Ionosphere (SMI). In *COST251TD(98)005*, RAL, UK, 161-172, 1998

[9] Araujo-Pradere E.A., Fuller-Rowell T.J., Codrescu M.V. STORM: An empirical storm-time ionospheric correction model, 1, Model description. *Radio Sci.* 2002, **37** (5) p. 1070. DOI: doi:10.1029/2001RS002467

[10] Gallagher D.L., Craven P.D., Comfort R.H. Global Core Plasma Model. *J. Geophys. Res.* 2000, **105** (A8) pp. 18819–18833

[11] Gulyaeva T.L., Huang X., Reinisch B.W. The ionosphere-plasmasphere model software for ISO. *Acta Geodaetica et Geophysica Hungarica*. 2002, **37** (2-3) pp. 143–152

[12] Gulyaeva T.L. Variation in the half width of the topside ionosphere according to the observations by space ionosondes ISIS 1, ISIS 2, and IK 19. *Intern. J. Geomagn. and Aeronomy*. 2003, **4** (3) pp. 201–207

[13] Gulyaeva T.L. and J.E. Titheridge Advanced specification of electron density and temperature in the IRI ionosphere-plasmasphere model. *Adv. Space Res.* 2006, **38** (11) pp. 2587–2595. DOI: doi:10.1016/j.asr.2005.08.045

[14] Hedin A.E. Extension of the MSIS Thermospheric Model into the Middle and Lower Atmosphere. *J. Geophys. Res.* 1991, **96** p. 1159

[15] Huang X., Reinisch B.W., Song P., Nsumei P., Green J.L. D. L. and Gallagher, Developing an empirical density model of the plasmasphere using IMAGE/RPI observations. *Adv. Space Res.* 2004, **33** (6) pp. 829–832

[16] Huang X., Reinisch B.W., Bilitza D. IRI in Windows Environment. *Adv. Space Res.* 2001, **27** (1) pp. 127–131

[17] Nsumei P.A., Huang X., Reinisch B.W., Song P., Vasyliunas V.M., Green J.L. et al. Electron Density Distribution Over the Northern Polar Region Deduced from IMAGE/RPI Sounding. *J. Geophys. Res.* 2003, **108** p. A2

[18] Rawer K., Bilitza D., Ramakrishnan S. *International Reference Ionosphere, International Union of Radio Science*. URSI, Brussels, Belgium, 1978

[19] Rawer K., Bilitza D., Ramakrishnan S. Goals and status of the International Reference Ionosphere. *Rev. Geophys.* 1978, **16** pp. 177–181

[20] Rawer K., Lincoln J.V., Conkright R.O. eds. *International Reference Ionosphere – IRI 79. Rept. UAG-82, WDC-A for STP*. NOAA, Boulder: 1981

[21] Reinisch B.W., Haines D.M., Bibl K., Cheney G., Galkin I.A., Huang X. et al. The Radio Plasma Imager investigation on the IMAGE spacecraft. *Space Sci. Rev.* 2000, **91** pp. 319–359

[22] Reinisch B.W., Huang X., Song P., Green J.L., Fung S.F., Vasyliunas V.M., Gallagher D.L., Sandel B.R. Plasmaspheric mass loss and refilling as a result of a magnetic storm, *J. Geophys. Res.*, 109, A1, A01202, 1-11, 2004

[23] Webb P.A., & Essex E.A. An ionosphere-plasmasphere global electron density model. *Phys. Chem Earth (C)*. 2000, **25** (4) pp. 301–306

[24] Webb P.A., & Essex E.A. A dynamic global model of the plasmasphere. *J. Atmos. Sol. Terr. Phys.* 2004, **66** (12) pp. 1057–1073. DOI: doi:10.1016/j.jastp.2004.04.001

[25] Carpenter D.L., & Park C.G. On what ionospheric workers should know about the plasmapause – plasmasphere. *Rev. Geophys. Space Phys.* 1973, **11** pp. 133–154

[26] Kotova G.A. The Earth's Plasmasphere: current state of research. *Geomagn. Aeron.* 2007, **47** (4) pp. 1–16

[27] Scherliess L., Schunk R.W., Sojka J.J., Thompson D.C. Development of a physics-based reduced state Kalman filter for the ionosphere. *Radio Sci.* 2004, **39**RS1S04. DOI: doi:10.1029/2002RS002797

[28] Wang C., Hajj G., Pi X., Rosen I.G., Wilson B. Development of the Global Assimilative Ionospheric Model. *Radio Sci.* 2004, **39**. DOI: doi:10.1029/2002RS002854

[29] Schunk R.W., & Nagy A.F. *Ionosphere: Physics*. Plasma Physics, and Chemistry, Cambridge, New York, 2000, pp. 333–5.

[30] Pi X., Wang C., Hajj G.A., Rosen G., Wilson B.D., Bailey G.J. Estimation of ExB drift using a global assimilative ionospheric model: An observation system simulation experiment. *J. Geophys. Res.* 2003, **108** (A2) p. 1075. DOI: doi:10.1029/2001JA009235

[31] Hajj G.A., Wilson B.D., Wang C., Pi X., Rosen I.G. Data assimilation of ground GPS total electron content into a physics-based ionospheric model by use of the Kalman filter. *Radio Sci.* 2004, **39**RS1S05. DOI: doi:10.1029/2002RS002859

[32] Bailey G.J., Balan N., Su Y.Z. The Sheffield University plasmasphere ionosphere model—A review. *J. Atmos. Sol. Terr. Phys.* 1997, **59** pp. 1541–1552

[33] Fuller-Rowell T.J., Rees D., Quegan S., Moffett R.J., Codrescu M.V., Millward G.H. In: *STEP Handbook of Ionospheric Models*. (Schunk R.W. ed.). Utah State Univ, 1996

[34] Fuller-Rowell T.J., & Evans D.S. Height-integrated Pedersen and Hall conductivity patterns inferred from the TIROS-NOAA satellite data. *J. Geophys. Res.* 1987, **92** pp. 7606–7618

[35] Foster J.C., Holt J.M., Musgrove R.G., Evans D.S. *Geophys. Res. Lett.* 1986, **13** pp. 656–659

[36] Millward G.H., Moffett R.J., Quegan S., Fuller-Rowell T.J. A Coupled Thermosphere Ionosphere-Plasmasphere Model, CTIP. In: *STEP Handbook of Ionospheric Models*, (Schunk R.W. ed.). Utah State University, 1996

[37] Richards P.G. The Field Line Interhemispheric Plasma Model. In: *Solar-Terrestrial Energy Program: Handbook of Ionospheric Models*, (Schunk R.W. ed.). 1996, pp. 207.

[38] Hedin A.E. Extension of the MSIS thermosphere model into the middle and lower atmosphere. *J. Geophys. Res.* 1991, **96** pp. 1159–1172

[39] Hedin A.E. et al. Empirical wind model for the upper, middle and lower atmosphere. *J. Atmos. Terr. Phys.* 1996, **58** pp. 1421–1447

[40] Tobiska W.K. Revised solar extreme ultraviolet flux model. *J. Atmos. Terr. Phys.* 1991, **53** pp. 1005–1018

[41] Fejer B.G. Low latitude electrodynamic plasma drifts: A review. *J. Atmos. Terr. Phys.* 1991, **53** pp. 677–693

[42] Heppner J.P., & Maynard N.C. Empirical high-latitude electric field models. *J. Geophys. Res.* 1987, **92** pp. 4467–4489

[43] Scherliess L., & Fejer B.G. Radar and satellite global equatorial F region vertical drift model. *J. Geophys. Res.* 1999, **104** pp. 6829–6842

[44] Raeder J., Larson D., Li W., Kepko E.L., Fuller-Rowell T. Open GGCM Simulations for the THEMIS Mission. *Space Sci. Rev.* 2008, **141** (1-4) pp. 535–555

[45] Fedrizzi M., Fuller-Rowell T.J., Codrescu M.V. Global Joule heating index derived from thermospheric density physics-based modeling and observations. *Space Weather*. 2012, **10**S03001. DOI: doi:10.1029/2011SW000724

[46] Roble R.G., Ridley E.C., Richmond A.D. A Coupled Thermosphere/Ionosphere general circulation model. *Geophys. Res. Lett.* 1988, **15** (12) pp. 1325–1328

[47] Richmond A.D., Blanc M., Emery B.A., Wand L.H., Fejer B.G., Woodman R.F. et al. An Empirical Model of Quiet-Day Ionospheric Electric Fields at Middle and Low Latitudes. *J. Geophys. Res.* 1980, **85** (A9) pp. 4658–4664. DOI: doi:10.1029/JA085iA09p04658

[48] Heelis R.A., Lowell J.K., Spiro R.W. A Model of the High-Latitude Ionospheric Convection Pattern. *J. Geophys. Res.* 1982, **87** (A8) pp. 6339–6345. DOI: doi:10.1029/JA087iA08p06339

[49] Jee G., Schunk R.W., Scherliess L. On the sensitivity of total electron content (TEC) to upper atmospheric / ionospheric parameters. *J. Atmos. Terr. Phys.* 2005, **67** (11) pp. 1040–1052

[50] Bust G.S., & Mitchell C.N. History, current state, and future directions of ionospheric imaging. *Rev. Geophys.* 2008, **46**RG1003. DOI: doi:10.1029/2006RG000212

[51] Shunk R.W. ed. *Solar-Terrestrial Energy Program, STEP Handbook of Ionospheric Models*. Utah State University, 1996

[52] AIAA. *Guide to Reference and Standard Ionosphere Models, ANSI/AIAA G-034-1998*. American Institute of Aeronautics and Astronautics, Reston, Virginia, 1998

[53] Bilitza D., & Reinisch B.W. International Reference Ionosphere 2007: Improvements and new parameters. *Adv. Space Res.* 2008, **42** (4) pp. 599–609. DOI: doi:10.1016/j.asr.2007.07.048

[54] Gulyaeva T., & Bilitza D. Towards an ISO Standard Earth Ionosphere and Plasmasphere Model. In: *New Developments in the Standard Model*, (Larsen R.J. ed.). NOVA, Hauppauge, New York, 2012, pp. 1–39.

Available at https://www.novapublishers.com/catalog/product_info.php?products_id=35812 [Available at]

[55] Rush C., Fox M., Bilitza D., Davies K., McNamara L., Stewart F. and M. PoKempner. Ionospheric Mapping – An Update of foF2 Coefficients. *Telecommunication Journal*. 1989, **56** pp. 179–182

[56] Liu R.Y., Smith P.A., King J.W. A New Solar Index Which Leads to Improved foF2 Predictions Using the CCIR Atlas. *Telecommunication Journal*. 1983, **50** (8) pp. 408–414

[57] Allain D.J., & Mitchell C.N. Ionospheric delay corrections for single-frequency GPS receivers over Europe using tomographic mapping. *GPS Solut.* 2008. DOI: doi:10.1007/s10291-008-0107-y

[58] Juan J.M., Hernández-Pajares M., Sanz J., Ramos-Bosch P., Aragón-Àngel A., Orús R. et al. Enhanced Precise Point Positioning for GNSS Users. *IEEE Trans. Geosci. Rem. Sens.* 2012. DOI: doi:10.1109/TGRS.2012.2189888

ICS 07.060;49.140

Price based on 15 pages

This page deliberately left blank

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email bsmusales@bsigroup.com.

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Copyright

All the data, software and documentation set out in all British Standards and other BSI publications are the property of and copyrighted by BSI, or some person or entity that owns copyright in the information used (such as the international standardization bodies) and has formally licensed such information to BSI for commercial publication and use. Except as permitted under the Copyright, Designs and Patents Act 1988 no extract may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, photocopying, recording or otherwise – without prior written permission from BSI. Details and advice can be obtained from the Copyright & Licensing Department.

Useful Contacts:

Customer Services
Tel: +44 845 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 845 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK

...making excellence a habit.™