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Foreword

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This second/third/... edition cancels and replaces the first/second/... edition (), [clause(s) / subclause(s) / table(s) / figure(s) / annex(es)] of which [has / have] been technically revised.

Introduction

This standard is a magnetic field model of the Earth's magnetosphere. It is intended to calculate the magnetic induction field generated from a variety of current systems located on the boundaries and within the boundaries of the Earth's magnetosphere under a wide range of environmental conditions, quiet and disturbed, affected by Solar-Terrestrial interactions simulated by Solar activity such as Solar Flares and related phenomena which induce terrestrial magnetic disturbances such as Magnetic Storms.

Space Environment (Natural and Artificial). Model of Earth's Magnetic Field.

1 Scope

Standard is intended to calculate induction of the magnetic field in the Earth's magnetosphere. The standard establishes the parameters of magnetospheric large-scale current systems in accordance with conditions in the space environment and can be used to investigate physical processes in the Earth's magnetosphere as well as in calculations, developing, testing and estimating the results of exploitation of spacecrafts and other equipment operating in the space environment.

Calculations in terms of the magnetic field model proposed in the standard can be used to forecast radiation situation in the space, including the periods of intense magnetic disturbances (magnetic storms) when developing systems of spacecraft magnetic orientation, when forecasting the influence of magnetic disturbances on transcontinental piping and power transmission lines.

The goals of standardisation of the Earth's magnetospheric magnetic field are:

— providing the unambiguous presentation of the magnetic field in the Earth's magnetosphere;

— providing compatibility of results of interpretation and analysis of space experiments;

— providing less labour-consuming character of calculations of the magnetic field of magnetospheric currents in the space at geocentric distances of 1-6.6 Earth's radii (R_E);

— providing the most reliable calculations of all elements of the geomagnetic field in the space environment.

2 Terms and definitions

2.1

Internal magnetic field

Internal (main) magnetic field is the magnetic field produced by the sources inside the Earth's core.

2.2

External magnetic field

External (magnetospheric) magnetic field is the magnetic field produced by magnetospheric sources of magnetic field.

2.3

Magnetospheric sources of magnetic field

Magnetospheric sources of magnetic field are

— Currents flowing over the magnetopause and screening the geomagnetic dipole magnetic field.

— Currents flowing inside the Earth's magnetosphere:

  — tail current, produced by currents across the geomagnetic tail and closure currents on the magnetopause;

  — ring current, circling around the Earth and carried by trapped particles;

  — partial ring current, produced by currents flowing mostly in the pre-midnight sector of equatorial plane at the distances about of 4 R_E, field-aligned and ionospheric currents;

  — Region 1 and Region 2 field-aligned currents, produced by currents flowing along the auroral magnetic field lines and closure currents on the magnetopause and on the ionospheric surface.

— Currents flowing over the magnetopause and screening the ring current and partial ring current magnetic fields[1)].

2.4

Geomagnetic dipole tilt angle

Geomagnetic dipole tilt angle is the angle of inclination of the geomagnetic dipole to the plane orthogonal to the Earth-Sun line.

2.5

Solar-magnetospheric coordinates

Solar-magnetospheric (GSM) coordinates are the Cartesian geocentric coordinates, where X-axis is directed to the Sun, Z-axis lies in the one plane with OX axis and geomagnetic dipole and Y-axis supplements the X and Z axes to the right-hand system.

2.6

Magnetopause stand-off distance

Magnetopause stand-off distance is the geocentric distance to the subsolar point on the magnetopause.

3 General concepts and assumptions

3.1 Magnetic field induction in the Earth's magnetosphere

Vector of magnetic field induction $\vec{B}_M$ in the Earth's magnetosphere is calculated by the formula

$$\vec{B}_M = \vec{B}_1 + \vec{B}_2, \quad \text{nT}, \tag{1}$$

where $\vec{B}_1$ is the vector of induction of the internal magnetic field,

$\vec{B}_2$ is the vector of induction of the external magnetospheric magnetic field.

3.2 The internal magnetic field

1) The tail current system and Region 1 field-aligned currents include the currents flowing over the magnetopause and don't need in the screening currents.

The internal magnetic field produced by currents flowing the Earth core, $\vec{B}_1$, is presented in the form of a series of spherical harmonic functions. The expansion coefficients (IGRF model) undergo very slight changes in time. The International Association of Geomagnetism and Aeronomy (IAGA) approves these values every 5 years.

3.3 The magnetic field of the magnetospheric currents

The magnetic field of the magnetospheric currents (external magnetic field), $\vec{B}_2$, is calculated in terms of the quantitative model of the magnetosphere.

4 Model requirements

— The model of the magnetic field of magnetospheric currents (referred to below as "model") presents the vector of induction of magnetospheric currents as a function of the solar-magnetospheric coordinates.

— The model describes a regular part of the magnetic field in the region from 1 R_E to 6.6 R_E .

— The model reflects compression of the Earth's magnetosphere in the dayside due to interaction with the solar wind, day-night asymmetry (the field on the nightside is weakened), day and season variations.

— The model takes into account geomagnetic dipole tilt angle, varying in the range from -35^o to +35^o.

4.1 The magnetospheric magnetic field sources

The standardised magnetospheric magnetic field is produced by currents on the magnetopause screening the geomagnetic dipole as well as by magnetospheric sources (ring current and tail current). The partial ring current, Region 1 and 2 field aligned current systems will be included in the future version of the standard when structure and parametrization of these current systems will be determined in more details. The present version of standard includes four magnetospheric magnetic field sources (see Section 5).

4.2 Magnetopause screening currents

Each magnetospheric source of magnetic field has its own screening currents on the magnetopause.

4.3 Parametrization

Each magnetospheric source of magnetic field depends on its own parameters.

5 Magnetic field of magnetospheric currents

Vector of induction of the magnetic field of magnetospheric currents is calculated by formula

$$\vec{B}_2 = \vec{B}_{sd}(\psi, R_1) + \vec{B}_t(\psi, R_1, R_2, \Phi_\infty) + \vec{B}_r(\psi, b_t) + \vec{B}_{sr}(\psi, R_1, b_r) + \vec{B}_{fac}(I_0) \ . \quad (2)$$

Here

— $\vec{B}_{sd}$ is the field of currents on the magnetopause screening the dipole field;

— $\vec{B}_t$ is the field of the magnetospheric tail;

— $\vec{B}_r$ is the field of the ring current;

— $\vec{B}_{sr}$ is the field of currents on the magnetopause, screening the ring current field;

— $\vec{B}_{fac}$ is the field of Region 1 field-aligned currents.

The components of the magnetic field of magnetospheric currents, $\vec{B}_{sd}$, $\vec{B}_t$, $\vec{B}_r$, $\vec{B}_{sr}$, $\vec{B}_{fac}$ are calculated separately in terms of the paraboloid model of the magnetosphere in the form of series in the Bessel functions or Legendre polynomials.

5.1 Parameters

The expansion coefficients of the components of the magnetic field of magnetospheric currents, $\vec{B}_{sd}$, $\vec{B}_t$, $\vec{B}_r$, $\vec{B}_{sr}$, $\vec{B}_{fac}$ are determined by the values of parameters of the magnetospheric current systems:

— ψ is the geomagnetic dipole tilt angle, degrees;

— $\vec{R}_1$ is the distance to the subsolar point at the magnetopause, R_E;

— $\vec{R}_2$ is the distance to the earthward edge of the magnetospheric tail current sheet, R_E;

— Φ_∞ is the magnetic flux in the tail lobes, defining the current intensity in the magnetotail, Wb;

— b_r is the intensity of the ring current magnetic field at the Earth's centre, nT;

— I_0 being for total Region 1 field-aligned currents intensity, MA.

5.2 Submodels

The instant values of the parameters of the magnetospheric current systems, ψ, $\vec{R}_1$, $\vec{R}_2$, Φ_∞, b_r, I_0 are determined using a limited set of empirical data in terms of the so-called submodels (see Annex A).

5.3 Magnetospheric dynamics

The magnetospheric dynamics is determined to be a sequence of its instant states.

6 Calculation of Induction of the Magnetic Field of the Magnetospheric Currents

The magnetospheric magnetic field calculated by paraboloid model is the solution of the magnetostatic problem inside the paraboloid of revolution.

6.1 Magnetic field of the magnetopause currents screening the geomagnetic dipole

The, $\vec{B}_{sd}$, is calculated as

$$\vec{B}_{sd} = -\nabla U_{sd},$$

where the scalar potential U_{sd} of the magnetic field of magnetopause currents is presented in spherical coordinates R, θ, φ (see Annex B.1):

$$U_{sd} = -\frac{M_E}{R_1^2}\sum_{n=1}^{\infty}\left(\frac{R}{R_1}\right)^n [d_n^{\parallel} \sin\psi P_n(\cos\theta) + d_{\perp n} \cos\psi P_n^1(\cos\theta)], \qquad (3)$$

$$P_n = (2^n n!)^{-1} \cdot (d^n (x^2 - 1)^n / dx^n), \; P_n^1(x) = \sqrt{1 - x^2} \cdot (dP_n / dx).$$

$M_E = B_0 \cdot R_E^3$ is the magnetic moment of the geomagnetic dipole, B_0 is the magnetic field at the geomagnetic equator of the Earth. The first six dimensionless coefficients $d_n^{\parallel}$ and $d_n^{\perp}$ are listed in Table 1.

Table 1 — Expansion coefficients for the scalar potential of the magnetic field of magnetopause currents

n	$d_n^{\perp}$	$d_n^{\parallel}$
1	0.6497	0.9403
2	0.2165	0.4650
3	0.0434	0.1293
4	-0.0008	-0.0148
5	-0.0049	-0.0160
6	-0.0022	-0.0225

6.2 Magnetic field of the tail current system

The magnetic field of the tail current system $\vec{B}_t$ is calculated from the equation

$$\vec{B}_t = -\nabla U_t + \vec{B}_{t_{in}} \qquad (4)$$

Where U_t is determined by the series

$$U_t = b_t R_1) \begin{cases} \sum_{k,n=1}^{\infty} (b_{nk} + c_{nk} K_n^{'}(\lambda_{nk}\alpha_0)\lambda_{nk}) \cos n\varphi \cdot J_n(\lambda_{nk}\beta) I_n(\lambda_{nk}\alpha) & \text{for} \quad \alpha < \alpha_0 \\ \beta_t \alpha_0 \ln\alpha \cdot \mathrm{sign}\left(\frac{\pi}{2} - |\varphi|\right) + & \\ \sum c_{nk} \cos n\varphi \cdot I_n^{'}(\lambda_{nk}\alpha_0)\lambda_{nk} J_n(\lambda_{nk}\beta) K_n(\lambda_{nk}\alpha) & \text{for} \quad \alpha \ge \alpha_0 \end{cases}$$

here $c_{nk} = b_{nk}\lambda_{nk} I_n(\lambda_{nk}\alpha_0)$, $\quad b_{nk} = \dfrac{2\lambda_{nk}\int_0^1\int_{-\pi}^{\pi} J_n(\lambda_{nk}\beta) f(\beta,\varphi)\cos n\varphi d\varphi d\beta}{\pi(\lambda_{nk}^2 - n^2) J_n^2(\lambda_{nk}) I_n^{'}(\lambda_{nk}\alpha_0)}$.

$$f(\beta,\varphi) = \begin{cases} \dfrac{\alpha_0}{\beta_t}\beta\cos\varphi, & \text{for } \alpha_0\beta\cos\varphi < \beta_t \\ \operatorname{sign}\left(\dfrac{\pi}{2} - |\varphi|\right), & \text{for } \alpha_0\beta\cos\varphi \ge \beta_t \end{cases},$$

where λ_{nk} are zeros of the $J' = 0$ equation, $\alpha_0 = \sqrt{1 - 2R_2 / R_1}$ is the parabolic α-coordinate of the inner edge of the tail current sheet, $\beta_t = \dfrac{d}{R_1}$, d is the half thickness of the current sheet, $b_t = \dfrac{2\Phi_\infty}{\pi R_1^2}\sqrt{R_1 /(2R_2 + R_1)}$, is a magnetic field in the tail lobe at the inner edge of the tail current sheet.

The magnetic field inside the current sheet, B_2, is calculated from the relations

$$B_{t_{in}\alpha} = b_t \frac{\alpha_0}{\alpha}\frac{\beta}{\beta_t}\frac{\cos\varphi}{\sqrt{\alpha^2 + \beta^2}}, \; B_{t_{in}\beta} = 0, \; B_{t_{in}\varphi} = 0.$$

Description of the paraboloid coordinates is presented in the Annex B.3.

6.3 Ring current magnetic field

Vector of the $\vec{B}_r$ is determined by the expressions

$$\vec{B}_r = \frac{M_R}{M_E}\cdot\begin{cases} \left(\dfrac{R}{R_{rc}}\right)^5 \cdot \vec{B}_d + 2B_0\dfrac{R_E^3}{R_2^3}\left(\dfrac{R_2^5}{R_{rc}^5} - 1\right)\vec{e}_z & \text{for } 0 \le R \le R_2 \\ \vec{B}_d & \text{for } R \ge R_2 \end{cases} \tag{5}$$

where $R_{rc} = \sqrt{0.5(R^2 + R_2^2)}$, $M_R = 0.5b_r \cdot R_2^3 /(4\sqrt{2} - 1)$ is the magnetic moment of the ring current, $\vec{B}_d$ is the magnetic field of the geomagnetic dipole, $\vec{e}_z$ being a unite vector directed oppositely to the geomagnetic dipole.

Expressions for $\vec{B}_d$ and $\vec{e}_z$ in the solar-magnetospheric coordinates are presented in Annex B.4.

6.4 Magnetic field of the magnetopause currents screening the ring current

The magnetic field of the magnetopause currents screening the ring current $\vec{B}_{sr}$ is calculated from the equation

$$\vec{B}_{sr} = -\nabla U_{sr},$$

where the scalar potential U_{sr} of the magnetic field of magnetospheric currents presented in spherical coordinates R, θ, φ (see Annex B.2) reads

$$U_{sr} = -\frac{M_R}{M_1^2} \sum_{n=1}^{\infty} \left(\frac{R}{R_1} \right)^n [d_n^{\parallel} \sin \psi P_n(\cos\theta) + d_n^{\perp} \cos \psi P_n^1(\cos\theta)]. \quad (6)$$

Coefficients $d_n^{\parallel}$ and $d_n^{\perp}$ are listed in Table 1.

6.5 Magnetic field of field-aligned currents

The magnetic field of field-aligned currents $\vec{B}_{fac}$ is calculated from the equation

$$\vec{B}_{fac} = \mathrm{curl} \vec{A}_{fac}$$

where the vector potential $\vec{A}_{fac}$ of the magnetic field of field-aligned currents is presented in spherical coordinates R, θ, φ with polar axis directed opposite the Earth's dipole (see Annex B.2):

$$\vec{A}_{fac} = \frac{\mu_0 I_0 \sin\varphi}{2(1+\cos\theta_m)} \begin{cases} \dfrac{\tan(\theta/2)}{\tan(\theta_m/2)} & \text{for } \ 0 \le \theta \le \theta_m \\ \dfrac{\sin\theta_m}{\sin\theta} & \text{for } \ \theta_m \le \theta \le \pi - \theta_m \\ \dfrac{\cot(\theta/2)}{\tan(\theta_m/2)} & \text{for } \ \pi - \theta_m \le \theta \le \pi \ . \end{cases}$$

θ_m - is polar cap radius in radians:

$$\sin^2 \theta_m = 3.9 \cdot \Phi_{\infty}[\mathrm{MWb}] / |B_0[\mathrm{nT}]| .$$

Annex A
(normative)

Submodels

A.1 Submodels: Calculation of the Main Parameters of Magnetospheric Current Systems

In the paraboloid model of the magnetosphere the values of parameters of the magnetospheric current systems are calculated using submodels. The submodels represent empirical relations or auxiliary models to relate parameters of the magnetospheric current systems to the measured data. Submodels are not the standardisation objects.

A.1.1 The tilt angle of geomagnetic dipole

The tilt angle of geomagnetic dipole, ψ, is calculated by the formula

$$\sin\psi = -\sin\beta\cos\alpha_1 + \cos\beta\sin\alpha_1\cos\varphi_m, \qquad (7)$$

where

— $\alpha_1 = 11.43^0$ is the angle between the Earth's axis and the geomagnetic dipole moment,

— β is the Sun's deflection ($\sin\beta = \sin\alpha_2\cos\varphi_{se}$),

— $\alpha_2 = 23.5^0$ is the angle between the Earth's axis and the normal to the ecliptic plane,

— φ_{se} = 0.9856263(172 – I_{day}) is angle between Earth-Sun line and the projection of the Earth's axis at the ecliptic plane,

— I_{day} is the number of the day in a year,

— $\varphi_m = UT \cdot 15^0 - 69.76^0$ is the angle between the midnight geographic meridian plane and northern magnetic pole meridian plane,

— UT is the universal time in hours.

A.1.2 The distance from the Earth to the subsolar point on the magnetopause

The distance from the Earth to the subsolar point on the magnetopause, R_1, is calculated from the balance between the solar wind dynamic pressure and the magnetic pressure in the magnetosphere

$$2kP = B_{0m}^2 / 2\mu_0 .$$

Here k is the coefficient describing "a degree of elasticity" of solar wind particle interaction with the magnetopause (k =1 when elastic reflection is assumed and k =0.5 fir a case of inelastic reflection assumed), P is the solar wind dynamic pressure, B_{0m} being the value of the magnetospheric magnetic field at the magnetopause. Using the data on solar wind velocity *v* and proton concentration *n* one can obtain

$$R_1 = 100/(nv^2)^{1/6} \quad (8)$$

(where R_1 is determined in R_E; *n*, in cm^{-3}; and *v*, in km/s).

A.1.3 The distance to the earthward edge of the geomagnetic tail current sheet

The distance to the earthward edge of the geomagnetic tail current sheet, R_2, is calculated by the formula

$$R_2 = 1/\cos^2 \varphi_k, \quad (9)$$

where R_2 is expressed in R_E, and φ_k is the latitude of the equatorward boundary of the auroral oval at midnight.

A.1.4 Magnetic flux through the magnetotail lobes

Magnetic flux through the magnetotail lobes, Φ_∞, is calculated by the formula

$$\Phi_\infty = \Phi_0 + \Phi_s \quad (10)$$

where Φ_0 is the magnetic flux in the magnetotail during quiet periods, Φ_s being the time-dependent magnetic flux in the lobes associated with intensification of the magnetotail current system during disturbances

$$\Phi_0 = 3.7 \cdot 10^8 Wb$$

$$\Phi_s = -AL \frac{\pi R_1^2}{14} \sqrt{\frac{2R_2}{R_1} + 1}, \quad (11)$$

where *AL* is the auroral index of geomagntic activity.

A.1.5 The ring current magnetic field at the Earth's centre

The ring current intensity is characterised by the value of ring current magnetic field at the Earth's centre, which is calculated by the Dessler-Parker-Scopke relation

$$b_r = -\frac{2}{3} B_0 \frac{\varepsilon_r}{\varepsilon_d}, \quad (12)$$

where ε_r is the total energy of ring current particles, $\varepsilon_d = \frac{1}{3} B_0 M_E$ is the geomagnetic dipole energy.

A.1.6 The total Region 1 field-aligned current

The total Region 1 field-aligned current intensity is calculated by the formula

$$I_0 = 2\sqrt{\frac{v}{400}} \cdot \left(\frac{5}{n}\right)^{1/8} \cdot \begin{cases} 0.327744 & \text{for } \; b_z > -1.6nT \\ -1.017 \cdot \dfrac{b_z}{5} & \text{for } \; b_z \le -1.6nT \end{cases} \tag{13}$$

where b_z is IMF north-south component, nT, solar wind velocity *v* and proton concentration *n* are the same as in A.1.2.

Annex B
(informative)

B.1 Spherical coordinates (1)

Spherical coordinates R, θ, φ with the polar axis plotted along the Sun-Earth axis are determined by the expressions

$$x / R_1 = R\cos\theta$$

$$y / R_1 = R\sin\theta\sin\varphi \qquad (14)$$

$$z / R_1 = R\sin\theta\cos\varphi$$

where x, y, z are the solar-magnetospheric (GSM) coordinates, θ is the polar angle plotted from x axis, φ being the azimuths angle plotted counterclockwise from z axis.

B.2 Spherical coordinates (2)

Spherical coordinates R, θ, φ with the polar axis plotted opposite the Earth dipole moment are determined by the expressions

$$x / R_1 = R\sin\theta\cos\varphi$$

$$y / R_1 = R\sin\theta\sin\varphi \qquad (15)$$

$$z / R_1 = R\cos\theta$$

where x, y, z are the solar-magnetic (SM) coordinates, θ is the polar angle plotted from z axis, φ being the azimuths angle plotted counterclockwise from x axis.

B.3 Parabolic coordinates

Parabolic coordinates α, β, φ with the polar axis plotted along the Sun-Earth axis are determined by the expressions

$$2x / R_1 = \beta^2 - \alpha^2 + 1$$

$$y / R_1 = \alpha\beta\sin\varphi \qquad (16)$$

$$x / R_1 = \alpha\beta\cos\varphi$$

where x, y, z are the GSM coordinates, φ being the azimuths angle plotted counterclockwise from z axis. In the magnetospheric paraboloid model the magnetopause is the $\beta = 1$ surface.

B.4 Magnetic Field of Geomagnetic Dipole

$\vec{B}_d$ and $e_{z_{sm}}$ in the solar-magnetospheric coordinates are described by the expressions

$$\vec{B}_d = -\nabla V_d$$

$$V_d = \left(\frac{R_e}{R}\right)^3 B_0 \cdot (z\cos\psi - x\sin\psi) \qquad (17)$$

$$\vec{e}_z = (-\sin\psi;\ 0;\ \cos\psi).$$

