International Standard

ISO 17520

Second edition
2024-03

Space environment (natural and artificial) — Cosmic ray and solar energetic particle penetration inward the magnetosphere — Method of determination of the effective vertical cut-off rigidity

Systèmes spatiaux (naturel et artificiel) — Rayons cosmiques et pénétration de particule énergétique solaire dans la magnétosphère — Méthode de détermination de la rigidité de coupure verticale effective

Reference number
ISO 17520:2024(en)

Contents

Page

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 document 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).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

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

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This second edition cancels and replaces the first edition (ISO 17520:2016), which has been technically revised.

The main changes are as follows:

— basic tables for epoch 2015 and 2020 calculated using IGRF model are added.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document describes principal requirements for determination of the effective vertical cut-off rigidity of penetration of charged particles inward the Earth's magnetosphere. This model provides for calculations of cut-off rigidity in arbitrary point of the magnetosphere at given local time. The document is applicable for calculating the particle penetration by any of the component of interplanetary charged particles (galactic, solar, and anomalous) with rigidities above 0,2 GV. The model satisfying these requirements depending on geomagnetic disturbances described by the K_p-index is presented in Annex B. The main goals of the present standardization for the determination of the effective vertical geomagnetic cut-off rigidities are as follows:

— provide an unambiguous procedure for calculation of the cut-off rigidities inside of the Earth's magnetosphere reflecting dependences on geomagnetic disturbances and local time;

— provide means of estimation of the impact of charged particle fluxes in interpretation and analysis of space experiments.

Space environment (natural and artificial) — Cosmic ray and solar energetic particle penetration inward the magnetosphere — Method of determination of the effective vertical cut-off rigidity

1 Scope

This document describes the effective vertical cut-off rigidities of charged particles for near-Earth space and establishes principal requirements for their calculation based on different models of Earth's geomagnetic field.[1] The techniques are useful for determination of penetrating into the Earth's magnetosphere by charged particle fluxes, as well as for test and estimations of the impact on spacecrafts and other equipment in the near-Earth space.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
internal magnetic field
main magnetic field
magnetic field produced by the sources inside the Earth's core

Note 1 to entry: Internal magnetic field is described in ISO 16695[2].

Note 2 to entry: It can be presented by the *International Geomagnetic Reference Field (IGRF) model* (3.2).

3.2
International Geomagnetic Reference Field model
IGRF model
geomagnetic reference field in the form of a series of spherical harmonic functions

Note 1 to entry: See Reference [3].

Note 2 to entry: The expansion coefficients undergo very slight changes in time.

Note 3 to entry: The International Association of Geomagnetism and Aeronomy (IAGA) is responsible for IGRF model development and modifications and approves its coefficients every five years. The internal magnetic field is not the subject of this document.

3.3
external magnetic field
magnetic field produced by magnetospheric sources

Note 1 to entry: It can be described by different models, e.g. Tsyganenko-89[4] and more recent models presented in References [5], [6], and [7].

3.4
geomagnetic field
sum of *internal magnetic field* (3.1) and *external magnetic field* (3.3)

3.5
particle charge
Z
$+ne$, (n=1, 2, 3....), where e is the value of electron charge ($1{,}60\times10^{-19}$ C)

3.6
particle magnetic rigidity
R
value related to a particle's momentum and its charge, calculated by:

$$R = pc/Z \tag{1}$$

where

- p is the particle momentum;
- c is the speed of light;
- Z is the *particle charge* (3.5)

Note 1 to entry: The magnetic rigidity of protons and nuclei is related to the particle's energy in accordance with Formula (2).

$$R = \frac{A}{Z}\sqrt{E(E+2M_0)} \tag{2}$$

where

- E is the kinetic energy in GeV/u;
- A is the particle's mass in Dalton (atomic mass unit);
- M_0 is the rest mass of proton equal to 0,931 GeV

3.7
cut-off rigidity
location of a transition, in rigidity space, from allowed to forbidden trajectories as rigidity is decreasing

3.8
lower cut-off rigidity
R_L
rigidity value of a particle lower than which access for penetration from outside of the Earth's magnetic field is forbidden

Note 1 to entry: R_L is the calculated lowest cut-off value, i.e. the rigidity value of the lowest allowed/forbidden transition obtained in computer simulations.

3.9
upper cut-off rigidity
main cut-off rigidity
R_U
rigidity value of a particle higher than which access for penetration from outside of the Earth's magnetic field is allowed

Note 1 to entry: R_U is the rigidity value of the calculated upper cut-off value, i.e. the rigidity value of the highest allowed/forbidden transition obtained in computer simulations.

3.10
penumbra
rigidity range lying between the *lower cut-off rigidity* (3.8) and the *upper cut-off rigidity* (3.9)

3.11
effective cut-off rigidity
R_{eff}
numerical value which specifies the equivalent total accessible cosmic radiation within the *penumbra* (3.10) in a specific direction

3.12
effective vertical cut-off rigidity
EVRC
effective cut-off rigidity (3.11) for a particle arriving to a fixed point in the vertical direction (radially to the centre of the Earth)

Note 1 to entry: The total effect of the *penumbra* (3.10) structure in a given direction may be represented, for a number of purposes, by the effective cut-off rigidity.

3.13
K_p-index
three-hour quasi-logarithmic index of geomagnetic activity based on data of from 13 stations distributed around the world

Note 1 to entry: The K_p-index is originally derived at GeoForschungsZentrum in Germany (http://www.gfzpotsdam.de/en/research/organizationalunits/departments/department-2/earthsmagnetic-field). It is also available at www.swpc.noaa.gov.

Note 2 to entry: The range is from zero to nine.

4 General concepts and assumptions

4.1 Determination of effective vertical cut-off rigidity

The geomagnetic cut-off rigidities are determined by tracing particle trajectories in the geomagnetic field. For a more detailed description of the method see Annex A and References [8], [9], and [10]. The method determines the trajectory of negatively charged particles emitted from the given coordinate point in the vertical direction in an effort to estimate whether the particle escapes the magnetosphere. As a result of tests of particles with different rigidities, it is possible to determine upper and lower cut-off rigidities for given magnetospheric conditions. From these data, the effective value of the vertical cut-off rigidity can be determined.

The calculation technique should be detailed enough to determine the effective cut-off values with an accuracy better than 2 %. Results of application of this type of calculation technique to IGRF model for a given set of initial points are presented in Tables B.1 to B.4.

4.2 Models of the employed geomagnetic field

The models for the geomagnetic field should reflect the changes of the internal magnetic field (IGRF model for each five-year period) as well as changes of the external magnetic field caused by current flowing in the magnetosphere and on its surface. All models available (Tsyganenko or other extensions[4],[5],[6],[7]) may be used.

4.3 Effective vertical cut-off rigidity databases (libraries)

In addition to direct computation of cut-off rigidities, the world grids of calculated values of vertical cut-off rigidities can be used to evaluate the radiation conditions for different spacecraft and manned station orbits. Sometimes, that kind of database is calculated for many different levels of magnetosphere disturbances and different local (or universal) time groups. These databases are put together a “library”[9],[11]. That kind of “library,” together with the associated cut-off rigidity interpolation software, provides a tool for general use in space physics applications.

4.4 Method for effective vertical cut-off data generalization

In these libraries, the effective vertical cut-off rigidity world grids are tabulated versus the discounted magnetosphere disturbance levels and local (or universal) time. Spacecraft and manned station orbits are variable, which means that the disturbance levels are not integers, but are subdivided. The same is true for the local (or universal) time. Therefore, it is not convenient to tabulate the detailed library needed to store all this data. The sheer size of the tabulation can make it unusable. However, the content of the library can be generalized in the form of a unique world grid of effective vertical cut-off rigidities calculated with the IGRF model for altitude H_0=450 km, and a set of analytic equations describing the EVCR values as a function of IGRF rigidity values, altitude, magnetosphere disturbance, and local time. A working example of the simplest model describing magnetosphere disturbances via the sole parameter, namely the K_p-index, is presented in Annex B.

5 Model requirements

5.1 General

The model for determination of the effective vertical cut-off (referred to below as "model") presents the effective vertical rigidity cut-off calculation.

The model determines an effective vertical cut-off at the altitudes from 250 km to 20 000 km over the mean Earth radius r_E=6 371,2 km.

5.2 Parameterization

The cut-off rigidities depend on the following parameters: geographic latitude (λ) and longitude (φ), altitude (H) over the Earth radius, the geomagnetic disturbance, and local time T.

Annex A
(informative)

Effective vertical cut-off determination procedure

A.1 Main prepositions for cut-off rigidity calculation

— The effective vertical cut-off rigidity calculation for each (λ_i,φ_i) node of a geographic map is performed by numerical integration of a sampling of charged particle trajectories with opposite charge, ejected in the local radial direction with the given rigidity.

— The atmospheric boundary is assumed to be at an altitude of 20 km over the International Reference Ellipsoid (WGS-84).[12] Particle trajectories falling inside this region during the tracing were considered as forbidden.

— Particles achieved the distance of 15 r_E from Earth's centre were considered to escape the magnetosphere. Such trajectories were considered as allowed.

— Integrating along a particle's trajectory provided accurate calculations that can be checked using Tables B.1 to B.4.

A.2 Method for effective cut-off calculation

As a result of the cut-off calculation, the penumbra structure is obtained with concomitant values of R_L and R_U, the upper and lower cut-off rigidities, respectively. The EVCR quantity required for the model, R_{eff}, that characterizes the "transparency" of the penumbra, was calculated according to the standard technique [13]:

$$R_{eff} = R_L + n\,\delta R \quad \text{(A.1)}$$

where

n is the number of points in the interval between R_L and R_U, for which the arrival trajectories are forbidden, as a result of tracing;

δR is an integration step.

Annex B
(informative)

Method for effective vertical cut-off data generalization for different conditions

B.1 General

The effective vertical cut-off data are presented in basic tables calculated for a 5-year period, using the IGRF model. A system of analytical equations allows further calculation for any geomagnetic disturbance level, any time period and any altitude from 250 km to 20 000 km.

B.2 The basic tables for IGRF

Table B.1 — Basic data of R_0 for the 2005 epoch (altitude is 450 km)

λ, °	φ, °											
	0	30	60	90	120	150	180	210	240	270	300	330
85	0,004	0,004	0,007	0,007	0,010	0,010	0,010	0,013	0,000	0,013	0,007	0,007
80	0,004	0,004	0,025	0,031	0,016	0,004	0,007	0,010	0,010	0,007	0,004	0,004
75	0,109	0,154	0,178	0,196	0,178	0,127	0,004	0,007	0,007	0,004	0,004	0,004
70	0,316	0,373	0,421	0,454	0,469	0,352	0,169	0,004	0,004	0,004	0,079	0,079
65	0,666	0,741	0,810	0,888	0,951	0,756	0,408	0,144	0,018	0,075	0,282	0,282
60	0,990	1,203	1,330	1,426	1,579	1,705	1,408	0,846	0,356	0,174	0,264	0,615
55	2,018	2,165	2,357	2,588	2,711	2,339	1,460	0,713	0,389	0,560	1,166	2,018
50	3,150	3,351	3,615	3,933	4,101	3,540	2,379	1,262	0,743	1,028	2,010	3,150
45	4,223	4,472	4,733	5,084	5,471	5,630	4,739	3,527	2,059	1,285	1,717	3,356
40	6,043	6,244	6,697	7,381	7,850	8,057	6,640	4,768	3,124	1,987	2,641	4,669
35	8,234	8,237	9,098	9,497	9,944	9,635	8,114	6,628	4,387	2,932	3,787	7,063
30	9,766	10,174	10,981	11,663	12,086	11,432	9,955	8,356	5,818	3,789	5,136	9,046
25	11,197	11,779	12,586	13,420	13,324	12,535	11,377	10,057	7,927	5,236	7,006	10,270
20	12,117	12,873	13,678	14,356	14,125	13,209	12,108	11,052	9,153	6,440	8,664	11,208
15	12,634	13,348	14,254	14,950	14,638	13,681	12,673	11,758	10,284	7,683	10,188	11,770
10	12,682	13,480	14,497	15,217	14,875	13,954	13,078	12,280	11,122	9,535	10,840	11,950
5	12,427	13,291	14,413	15,157	14,836	14,017	13,306	12,625	11,731	10,510	11,152	11,851
0	11,908	12,802	14,017	14,770	14,518	13,849	13,339	12,781	12,052	11,113	11,248	11,536
–5	11,140	12,067	13,330	14,062	13,903	13,417	13,147	12,745	12,154	11,335	11,167	11,029
–10	10,231	11,131	12,379	13,027	12,976	12,679	12,691	12,508	12,070	11,356	10,936	10,354
–15	9,111	9,921	10,956	11,500	11,194	11,353	11,935	12,061	11,824	11,188	10,527	9,561
–20	7,718	8,352	9,051	9,381	9,186	9,156	10,374	11,388	11,412	10,890	10,050	8,544
–25	6,337	6,934	7,255	6,634	6,619	7,312	8,392	9,742	10,843	10,450	9,328	7,417
–30	5,262	5,413	5,058	4,635	4,593	5,079	6,682	7,678	10,090	9,829	8,533	6,334
–35	4,246	3,949	3,706	3,100	3,004	3,625	4,798	6,802	8,396	9,134	7,684	5,602
–40	3,436	3,088	2,539	1,933	1,867	2,317	3,541	4,780	6,997	8,234	6,706	4,915
–45	2,777	2,272	1,714	1,165	1,000	1,336	2,275	3,659	5,264	7,218	6,086	3,983
–50	2,229	1,673	1,100	0,611	0,488	0,722	1,424	2,508	3,960	5,440	4,854	3,222
–55	1,718	1,199	0,686	0,294	0,188	0,326	0,806	1,682	2,843	3,924	3,687	2,570
–60	1,297	0,828	0,405	0,111	0,006	0,111	0,405	1,038	1,939	2,851	2,854	1,990
–65	0,948	0,546	0,222	0,000	0,006	0,006	0,195	0,600	1,257	1,866	1,980	1,464
–70	0,640	0,352	0,100	0,004	0,004	0,007	0,046	0,328	0,757	1,163	1,268	0,985
–75	0,415	0,205	0,022	0,004	0,004	0,004	0,004	0,169	0,424	0,664	0,754	0,622
–80	0,229	0,109	0,000	0,004	0,004	0,004	0,004	0,064	0,223	0,347	0,389	0,341
–85	0,106	0,037	0,000	0,004	0,004	0,004	0,004	0,022	0,088	0,139	0,175	0,151

Table B.2 — Basic data of R_0 for the 2010 epoch (altitude is 450 km)

λ, °	φ, °											
	0	30	60	90	120	150	180	210	240	270	300	330
85	0,004	0,004	0,007	0,007	0,010	0,010	0,010	0,013	0,000	0,013	0,007	0,007
80	0,004	0,004	0,004	0,024	0,030	0,016	0,004	0,007	0,010	0,010	0,007	0,004
75	0,039	0,106	0,150	0,174	0,191	0,174	0,124	0,004	0,007	0,007	0,004	0,004
70	0,215	0,308	0,364	0,411	0,443	0,458	0,343	0,165	0,004	0,004	0,004	0,077
65	0,476	0,653	0,726	0,794	0,871	0,932	0,741	0,400	0,141	0,018	0,074	0,276
60	0,971	1,179	1,304	1,398	1,548	1,672	1,380	0,829	0,349	0,171	0,259	0,603
55	1,746	1,959	2,059	2,255	2,480	2,692	2,330	1,386	0,745	0,429	0,571	1,139
50	2,841	3,080	3,227	3,539	3,828	4,045	3,458	2,361	1,266	0,739	1,035	2,071
45	4,249	4,453	4,595	4,994	5,249	5,521	4,639	3,091	2,025	1,289	1,758	3,415
40	5,916	6,128	6,492	7,138	7,742	7,914	6,522	4,698	3,517	2,048	2,684	4,687
35	8,228	8,349	9,111	9,414	9,837	9,585	8,017	6,461	4,288	2,933	3,899	7,087
30	9,717	10,068	10,951	11,503	11,953	11,381	9,877	8,267	5,713	3,791	5,268	9,002
25	11,192	11,743	12,495	13,355	13,265	12,483	11,319	9,925	7,782	5,218	7,211	10,328
20	12,104	12,854	13,646	14,318	14,077	13,165	12,052	10,964	8,995	6,231	8,892	11,201
15	12,633	13,345	14,247	14,929	14,588	13,636	12,613	11,675	10,130	7,720	10,246	11,761
10	12,684	13,486	14,508	15,209	14,828	13,896	13,014	12,202	10,992	9,467	10,849	11,941
5	12,413	13,295	14,448	15,159	14,799	13,957	13,245	12,526	11,622	10,429	11,139	11,821
0	11,881	12,814	14,067	14,778	14,478	13,786	13,265	12,693	11,953	11,039	11,209	11,490
–5	11,110	12,082	13,385	14,087	13,866	13,347	13,075	12,663	12,052	11,241	11,109	10,938
–10	10,158	11,139	12,423	13,045	12,944	12,608	12,586	12,423	11,972	11,221	10,829	10,247
–15	9,001	9,905	11,030	11,461	11,132	11,242	11,846	11,981	11,721	11,070	10,408	9,434
–20	7,543	8,329	9,053	9,363	9,122	9,044	10,269	11,300	11,319	10,778	9,885	8,328
–25	6,343	6,867	7,210	6,623	6,563	7,219	8,369	9,648	10,740	10,278	9,174	7,282
–30	5,165	5,378	5,013	4,617	4,485	5,002	6,562	7,606	9,988	9,725	8,350	6,154
–35	4,259	3,952	3,641	3,070	2,944	3,601	4,778	6,705	8,480	8,983	7,464	5,492
–40	3,414	3,071	2,543	1,892	1,756	2,341	3,464	4,657	6,977	8,087	6,455	4,780
–45	2,682	2,220	1,663	1,109	0,992	1,338	2,264	3,589	5,382	7,089	5,908	3,837
–50	2,113	1,623	1,061	0,622	0,521	0,724	1,380	2,447	3,920	5,312	4,666	3,114
–55	1,684	1,175	0,673	0,288	0,184	0,320	0,790	1,649	2,787	3,847	3,615	2,520
-60	1,297	0,828	0,405	0,111	0,006	0,111	0,405	1,038	1,939	2,851	2,854	1,990
–65	0,929	0,535	0,218	0,001	0,006	0,006	0,191	0,588	1,232	1,829	1,941	1,435
–70	0,627	0,345	0,098	0,004	0,004	0,007	0,045	0,322	0,742	1,163	1,268	0,985
–75	0,403	0,199	0,021	0,004	0,004	0,004	0,004	0,164	0,412	0,645	0,732	0,604
–80	0,223	0,106	0,001	0,004	0,004	0,004	0,004	0,062	0,217	0,337	0,378	0,331
–85	0,103	0,036	0,001	0,004	0,004	0,004	0,004	0,021	0,085	0,135	0,170	0,147

Table B.3 — Basic data of R_0 for the 2015 epoch (altitude is 450 km)

λ, °	φ, °											
	0	30	60	90	120	150	180	210	240	270	300	330
85	0,052	0,052	0,052	0,004	0,004	0,004	0,004	0,004	0,004	0,052	0,052	0,052
80	0,052	0,068	0,052	0,004	0,004	0,004	0,004	0,004	0,004	0,052	0,052	0,052
75	0,087	0,119	0,134	0,148	0,172	0,163	0,087	0,004	0,004	0,004	0,004	0,075
70	0,239	0,310	0,364	0,405	0,427	0,452	0,341	0,174	0,004	0,004	0,075	0,130
65	0,529	0,652	0,711	0,773	0,838	0,909	0,741	0,429	0,195	0,011	0,168	0,310
60	1,027	1,178	1,253	1,358	1,478	1,612	1,328	0,822	0,389	0,218	0,333	0,668
55	1,780	1,925	2,059	2,191	2,470	2,616	2,264	1,459	0,735	0,433	0,631	1,262
50	2,820	3,038	3,134	3,353	3,755	4,022	3,444	2,308	1,266	0,808	1,176	2,179
45	4,248	4,423	4,564	4,892	5,277	5,432	4,657	3,476	2,024	1,350	1,915	3,486
40	6,088	6,088	6,351	6,997	7,532	7,755	6,463	4,667	3,049	2,069	2,872	4,801
35	8,217	8,287	8,962	9,363	9,646	9,524	8,027	6,452	4,279	2,956	4,095	7,310
30	9,808	10,118	10,770	11,363	11,773	11,301	9,837	8,247	5,654	3,862	5,521	9,063
25	11,252	11,723	12,444	13,255	13,195	12,453	11,279	9,865	7,692	5,268	7,594	10,399
20	12,144	12,844	13,606	14,237	14,027	13,135	12,012	10,856	8,566	5,942	9,154	11,291
15	12,653	13,335	14,217	14,879	14,568	13,616	12,573	11,566	9,990	7,665	10,408	11,851
10	12,684	13,476	14,498	15,189	14,828	13,896	12,974	12,087	10,872	8,969	10,918	11,961
5	12,403	13,295	14,448	15,169	14,809	13,957	13,195	12,445	11,481	10,389	11,149	11,811
0	11,851	12,814	14,087	14,818	14,508	13,786	13,225	12,623	11,852	11,000	11,179	11,440
−5	11,051	12,082	13,425	14,147	13,907	13,471	13,035	12,593	11,943	11,151	11,038	10,869
−10	10,079	11,159	12,483	13,135	12,994	12,793	12,593	12,373	11,881	11,130	10,738	10,136
−15	8,941	9,915	11,090	11,721	11,292	11,281	11,816	11,931	11,640	10,940	10,287	9,323
−20	7,541	8,359	9,093	9,634	9,373	9,084	10,259	11,269	11,239	10,639	9,735	7,706
−25	6,141	6,856	7,301	6,805	6,746	7,269	8,458	9,648	10,659	10,157	9,043	7,060
−30	5,064	5,390	5,044	4,686	4,668	5,084	6,582	8,429	9,916	9,565	8,120	5,940
−35	4,105	3,951	3,621	3,122	3,020	3,642	4,677	6,633	8,410	8,882	7,069	5,179
−40	3,249	3,019	2,565	1,938	1,891	2,288	3,495	4,687	6,847	7,957	6,285	4,576
−45	2,663	2,233	1,692	1,179	1,060	1,363	2,263	3,599	5,186	6,916	5,814	3,662
−50	2,103	1,646	1,112	0,640	0,531	0,728	1,422	2,438	3,870	5,125	4,391	3,019
−55	1,669	1,165	0,696	0,326	0,223	0,358	0,807	1,680	2,839	3,754	3,427	2,447
−60	1,264	0,820	0,408	0,103	0,004	0,097	0,460	1,047	1,894	2,683	2,660	1,823
−65	0,922	0,531	0,225	0,004	0,006	0,006	0,211	0,620	1,252	1,802	1,881	1,377
−70	0,638	0,348	0,123	0,004	0,004	0,004	0,004	0,318	0,745	1,138	1,205	0,952
−75	0,427	0,205	0,097	0,004	0,004	0,004	0,004	0,187	0,421	0,644	0,713	0,614
−80	0,233	0,134	0,068	0,004	0,004	0,004	0,004	0,119	0,233	0,345	0,389	0,369
−85	0,134	0,092	0,069	0,004	0,004	0,004	0,004	0,081	0,126	0,160	0,170	0,172

Table B.4 — Basic data of R_0 for the 2020 epoch (altitude is 450 km)

λ, °	φ, °											
	0	30	60	90	120	150	180	210	240	270	300	330
85	0,052	0,051	0,050	0,004	0,004	0,004	0,004	0,004	0,050	0,051	0,052	0,052
80	0,068	0,068	0,052	0,004	0,004	0,004	0,004	0,004	0,004	0,052	0,052	0,052
75	0,081	0,101	0,115	0,134	0,153	0,147	0,081	0,004	0,004	0,052	0,052	0,068
70	0,259	0,341	0,362	0,378	0,421	0,427	0,369	0,195	0,004	0,052	0,068	0,125
65	0,531	0,627	0,679	0,726	0,821	0,919	0,745	0,433	0,195	0,102	0,147	0,333
60	1,014	1,175	1,227	1,292	1,409	1,600	1,328	0,848	0,396	0,239	0,355	0,702
55	1,792	1,926	2,004	2,158	2,395	2,542	2,232	1,456	0,749	0,464	0,661	1,288
50	2,809	3,009	3,050	3,290	3,630	3,982	3,415	2,297	1,278	0,846	1,214	2,276
45	4,300	4,361	4,484	4,740	5,155	5,359	4,627	3,432	2,037	1,424	1,982	3,579
40	6,058	5,957	6,220	6,795	7,593	7,753	6,463	4,617	3,080	2,126	2,999	4,932
35	8,184	8,126	8,820	9,330	9,586	9,454	8,007	6,421	4,227	3,020	4,239	7,491
30	9,567	10,058	10,680	11,242	11,753	11,321	9,817	8,147	5,603	3,943	5,885	9,154
25	11,272	11,713	12,394	13,210	13,170	12,448	11,224	9,825	7,552	5,329	7,785	10,480
20	12,174	12,849	13,611	14,221	14,011	13,130	11,956	10,783	8,604	5,941	9,484	11,351
15	12,669	13,340	14,242	14,884	14,563	13,601	12,528	11,486	9,860	7,705	10,484	11,876
10	12,688	13,501	14,543	15,214	14,823	13,872	12,929	12,037	10,762	9,487	10,963	11,967
5	12,398	13,320	14,513	15,214	14,813	13,932	13,150	12,388	11,421	10,389	11,154	11,786
0	11,836	12,849	14,162	14,874	14,523	13,761	13,180	12,548	11,741	10,941	11,164	11,395
–5	11,031	12,117	13,501	14,212	13,942	13,317	12,989	12,528	11,871	11,071	10,993	10,799
–10	10,068	11,184	12,568	13,220	13,040	12,578	12,534	12,308	11,796	11,059	10,618	10,016
–15	8,950	9,965	11,200	11,762	11,382	11,262	11,785	11,876	11,555	10,859	10,197	9,152
–20	7,432	8,409	9,204	9,729	9,404	9,064	10,229	11,224	11,142	10,508	9,585	8,006
–25	6,119	6,978	7,360	7,027	6,856	7,229	8,208	9,667	10,589	10,036	8,821	6,888
–30	5,014	5,419	5,155	4,819	4,696	4,983	6,562	8,536	9,848	9,444	8,028	5,728
–35	4,064	3,952	3,704	3,197	3,156	3,632	4,667	6,673	8,459	8,701	6,867	5,086
–40	3,310	3,091	2,565	1,983	1,914	2,340	3,485	4,637	6,805	7,766	6,093	4,423
–45	2,558	2,224	1,760	1,238	1,110	1,431	2,297	3,589	5,114	6,775	5,612	3,549
–50	2,113	1,622	1,114	0,685	0,580	0,785	1,457	2,491	3,910	4,942	4,258	2,947
–55	1,678	1,189	0,670	0,333	0,228	0,376	0,832	1,677	2,745	3,703	3,331	2,362
–60	1,238	0,818	0,408	0,103	0,004	0,110	0,467	1,008	1,848	2,620	2,532	1,783
–65	0,892	0,561	0,239	0,052	0,004	0,004	0,068	0,620	1,250	1,578	1,618	1,385
–70	0,600	0,355	0,115	0,052	0,004	0,004	0,004	0,369	0,745	1,096	1,177	0,934
–75	0,404	0,218	0,081	0,052	0,004	0,004	0,004	0,218	0,421	0,632	0,700	0,578
–80	0,259	0,134	0,052	0,004	0,004	0,004	0,004	0,119	0,259	0,550	0,387	0,326
–85	0,126	0,103	0,068	0,068	0,004	0,004	0,004	0,004	0,081	0,165	0,153	0,157

B.3 The system of analytical equations

$\Delta(R_0, K_p, T)$ is the attenuation quotient,[10] which describes relative changes of the IGRF effective vertical cut-off value due to the effects of geomagnetic disturbance (its level is expressed by the K_p-index) and local time (T). According to the proposed method, for the spatial point with coordinates H, λ and φ one can write:

$$R_{eff}(R_0, K_p, T) = \frac{R_0}{\Delta(R_0, K_p, T)} \quad \text{(B.1)}$$

where

R_{eff} is the effective vertical cut-off value calculated using superposition of IGRF and Tsyganenko-89 models[10];

R_0 is the effective vertical cut-off value calculated using IGRF model;

K_p is the index of geomagnetic disturbance level;

T is local time at this point.

Values of R_0 for arbitrary coordinate point λ,φ are calculated by an interpolation using the basic tables for IGRF (Tables B.1 to B.4). A procedure of this interpolation is not the subject of this document. The dependence of R_0 on H is described by Formula (B.2).

$$R_{0H} = R_0 \cdot \left(\frac{r_E + 450}{r_E + H} \right)^2 \quad \text{(B.2)}$$

where

R_0 is the effective vertical cut-off rigidity for an altitude of 450 km calculated for the IGRF field;

r_E=6 371,2 km is the mean Earth's radius;

H is the altitude (km).

The algorithm for obtaining $\Delta(R_0, K_p, T)$ is presented in Formulae (B.3) to (B.6):

$$\Delta(R_0, K_p, T) = 1 + 0{,}001 \cdot \exp(a \cdot R_0^b - 1) \quad \text{(B.3)}$$

For the lowest R_0 values, the additional top limit c for the attenuation quotient was introduced to satisfy Formula (B.5) throughout a wide range of calculated effective vertical cut-off values and parameters K_p, T and H.