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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

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Foreword

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

Introduction

This International Standard describes principal requirements for determination of the effective vertical cut-off rigidity of penetration of charged particles inward the Earth's magnetosphere. This International Standard establishes procedure for calculation of the effective vertical cut-off rigidities for altitude, geographical coordinates (latitude and longitude), and for conditions of geomagnetic disturbances described by the *Kp*-index, as well as for local time. The model that satisfies these requirements is described in the Annex through a series of examples. This International Standard is intended for estimation of penetration into the Earth's magnetosphere by charged particle fluxes from interplanetary space, which is important for developing and testing of influence to hardware and biological objects onboard spacecraft and orbital stations. Procedures for performing simplified calculations of rigidities are proposed.

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 International Standard describes the effective vertical cut-off rigidities of charged particles for near-Earth space and establishes principal requirements for their calculation. In Annex A, the calculation technique is verified using a typical example. This International Standard can be used to develop calculation techniques 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 spacecraft and other equipment in the near-Earth space.

This International Standard is valid 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 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;

— provide efficient calculations of the transmission functions of low-altitude orbits of spacecraft and manned space-station;

— determine impact of solar energetic particle flux on spacecraft instrumentation and astronauts using results of independent online measurement of interplanetary particle fluxes.

2 Terms and definitions

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

2.1
internal (main) magnetic field
magnetic field produced by the sources inside the Earth's core

Note 1 to entry: See ISO 16695.

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

2.2
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 [2].

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 International Standard.

2.3
external (magnetospheric) magnetic field
magnetic field produced by magnetospheric sources

Note 1 to entry: It can be described by different models, e.g. Tsyganenko-89[3] and more recent models.[4][5]

2.4
Tsyganenko-89 geomagnetic field model
model described in Reference

[SOURCE: 3]

2.5
Geomagnetic field
sum of internal and external magnetic fields

2.6
particle charge *Z*
charge Z of a particle is equal to $+ne$, ($n = 1, 2, 3,\ldots$), where e is the value of electron charge ($1{,}60 \times 10^{-19}$ C).

2.7
particle magnetic rigidity
magnetic rigidity of particle R is related to particle momentum p and its charge by:

$$R = pc/Z$$

where c is the speed of light, and Z is the charge of a particle.

Note 1 to entry: The magnetic rigidity of protons and nuclei is related to the particle's energy as

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

where E is the kinetic energy in GeV/u, A is the particle's mass in amu, and M_0 is the rest mass of proton equal to 0,931 GeV.

2.8
cut-off rigidity
location of a transition, in rigidity space, from allowed to forbidden trajectories as rigidity is decreasing

2.9
lower cut-off rigidity
R_L
access of particles of all rigidity values lower than the lower cut-off rigidity is forbidden for penetration from outside of the Earth's magnetic field

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.

2.10
main (upper) cut-off rigidity
R_U
access of particles of all rigidity values higher than the main cut-off rigidity is allowed for penetration from outside of the Earth's magnetic field

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.

2.11
penumbra
rigidity range lying between the main (upper) and the lower cut-off rigidities

2.12
effective cut-off rigidity
R_{eff}
total effect of the penumbral structure in a given direction may be represented for a number of purposes, by the "effective cut-off rigidity", a single numerical value which specifies the equivalent total accessible cosmic radiation within the penumbra in a specific direction

2.13
effective vertical cut-off rigidity
EVRC
effective cut-off rigidity value for a particle arriving to a fixed point in the vertical direction (radially to the centre of the Earth)

2.14
index of magnetosphere disturbance
K
three-hour quasi-logarithmic local index of geomagnetic activity relative to on assumed quiet-day curve for a specific recording site

Note 1 to entry: The range is from zero to nine. The *K* index measures the deviation of the most disturbed horizontal component.

2.15
***Kp*-index**
three-hour planetary geomagnetic index of activity based on the *K* index from 13 stations distributed around the world

Note 1 to entry: The *Kp*-index is originally derived at GeoForschungsZentrum in Germany. The web address should be http://www.gfzpotsdam.de/en/research/organizationalunits/departments/department-2/earthsmagnetic-field. It is also available at www.swpc.noaa.gov.

2.16
attenuation quotient
$\Delta(R_0, Kp, T)$
determines how much the vertical cut-off rigidity value in a real geomagnetic field for a given *Kp*-index, at a local time *T*, decreased relative to values calculated with the IGRF model (R_0)

Note 1 to entry: Some of these terms are also defined in Reference [6].

3 General concepts and assumptions

3.1 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 [7] and [8]. 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 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 data for a given set of initial points are presented in Table C.1.

3.2 Models of the employed geomagnetic field

The models for the geomagnetic field should reflect the changes of the internal field (IGRF model for each five-year period), as well as changes of the external (magnetosphere) magnetic field caused by current flowing in the magnetosphere and on its surface. This International Standard allows the use of all of present day models (Tsyganenko or other extensions).

3.3 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 in a "library".[9] That kind of "library", together with the associated cut-off rigidity interpolation software, provides a tool for general use in space physics applications.

3.4 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 would 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 magnetosphere 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.

The changes of the value of EVCR due to magnetosphere disturbance (the *Kp*-index) and local time (T) are considered in the given technique as corrections whose values are described by the attenuation quotient Δ[10][11] as:

$$R\left(R_0, Kp, T\right) = \frac{R_{0H}}{\Delta\left(R_0, Kp, T\right)} \qquad (1)$$

where $R_{0\mathrm{H}}$ is the rigidity for altitude H, calculated as

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

Here, R_0 is the effective vertical cut-off rigidity for an altitude of 450 km calculated for the IGRF field. r_E=6371,2 km is the Earth's radius and H is the altitude (km). A working example of the models for the attenuation quotient Δ is presented in Annex B.

4 Model requirements

4.1 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 = 6371,2 km.

4.2 Parameterization

The cut-off rigidities depend on the following parameters: geographic latitude (λ) and longitude (φ), altitude (H) over the Earth radius, the *Kp*-index of 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 not considered.

— Particles at distance of 15 r_E from Earth's centre were considered to penetrate the atmosphere.

— Integrating along a particle's trajectory provided accurate calculations that can be checked using Table C.1.

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 thresholds of the cut-off rigidity, respectively. The EVCR quantity required for the model, R_{eff}, that characterizes the "transparency" of the penumbra, was calculated according to the standard technique:

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

where n is the number of points in the interval between R_L and R_U, for which the arrival directions are forbidden, as a result of tracing, and δR is an integration step.

Annex B
(informative)

Presentation of the results

The results of calculations for each (λ_i, φ_i) node of a geographic map for different magnetosphere conditions (described by *Kp* indices, different Dst values etc., universal or local time data) complete the different tables of vertical cut-off rigidities. The set of tables (lists) form the library, the number of pages of which corresponds to the number of rigidities versus the magnetosphere conditions (see, for example, Reference [9]). The model also contains the associated cut-off rigidity interpolation software for general use for every intermediate magnetosphere condition, every arbitrary (λ_i, φ_i) combination and any altitude, different from calculated 450 km.

Annex C
(informative)

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

C.1 General

The effective vertical cut-off data are presented in one table calculated for a five-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.

C.2 Basic tables for IGRF

Table C.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	0,004	0,025	0,031	0,016	0,004	0,007	0,010	0,010	0,007	0,004
75	0,040	0,109	0,154	0,178	0,196	0,178	0,127	0,004	0,007	0,007	0,004	0,004
70	0,220	0,316	0,373	0,421	0,454	0,469	0,352	0,169	0,004	0,004	0,004	0,079
65	0,486	0,666	0,741	0,810	0,888	0,951	0,756	0,408	0,144	0,018	0,075	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	1,778	2,018	2,165	2,357	2,588	2,711	2,339	1,460	0,713	0,389	0,560	1,166
50	2,808	3,150	3,351	3,615	3,933	4,101	3,540	2,379	1,262	0,743	1,028	2,010
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 C.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	1,272	0,812	0,397	0,109	0,006	0,109	0,397	1,018	1,901	2,795	2,798	1,951
-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

C.3 System of analytical equations

$\Delta(R_0, Kp, T)$ is the attenuation quotient[10][11], 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 *Kp*-index) and local time (T). It should be noted that the value $\Delta' = \Delta - 1$ is the attenuation factor, offered in Reference [13] and used in Reference [11] for the same EVCR change. According to the proposed method, for the spatial point with coordinates H, λ and φ, one can write:

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

where R_{eff} is the effective vertical cut-off value calculated using superposition of IGRF and Tsyganenko-89 model[10][11], Kp and T (geomagnetic disturbance level and local time at this point).

Values of R_0 for arbitrary coordinate points λ_i, φ_i are calculated by an interpolation using the basic tables for IGRF (Table C.1 or Table C.2). A procedure of this interpolation is not the subject of this International Standard. The dependence of R on H is described by Formula (2).

