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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 — Environnement spatial — Rayons cosmiques et pénétration de particule énergétique solaire dans la magnétosphère: méthode de la détermination 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*, and Subcommittee SC 14, *Space systems and operations*.

Introduction

This Standard describes principal requirements for determination of the effective vertical cut-off rigidity of penetration of charged particles inward the Earth's magnetosphere. The 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. The 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 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. The 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 spacecrafts and other equipment in the near-Earth space.

The Standard is valid for calculation 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:

- 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 (ISO 16695). It can be presented by the International Geomagnetic Reference Field (IGRF) model.

2.2

International Geomagnetic Reference Field (IGRF) model

represents the geomagnetic reference field in the form of a series of spherical harmonic functions [2]. The expansion coefficients undergo very slight changes in time.

NOTE: 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 Standard.

2.3

external (magnetospheric) magnetic field

magnetic field produced by magnetospheric sources. 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 [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,….), where *e* is the value of electron charge ($1.60 \cdot 10^{-19}$ 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. The magnetic rigidity of protons and nuclei is related to the particle's energy as

$$R = \frac{A}{Z}\sqrt{E(E+2M_0)}, \quad (1)$$

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. 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. 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 center of the Earth).

2.14
index of magnetosphere disturbance – *K*
a three-hour quasi-logarithmic local index of geomagnetic activity relative to on assumed quiet-day curve for a specific recording site. The range is from zero to nine. The *K* index measures the deviation of the most disturbed horizontal component.

2.15
***Kp*-index**
a 3-hour planetary geomagnetic index of activity based on the *K* index from 13 stations distributed around the world. 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).

Some of these terms are also defined in [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 [7, 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 must 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 C1.

3.2 Models of the employed geomagnetic field

The models for the geomagnetic field must 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 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 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:

$$R(R_0, Kp, T) = \frac{R_{0H}}{\Delta(R_0, Kp, T)} \quad , \tag{2}$$

where R_{0H} is the rigidity for altitude *H*, calculated as

$$R_{0H} = R_0 \cdot \left(\frac{r_E + 450}{r_E + H} \right)^2 . \tag{3}$$

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 to 20000 km over the mean Earth radius r_E=6371.2 km.

