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A method for operative calculation of charged particle penetration into the LEO

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Abstract

We develop a simple method for calculating the effective vertical cutoff rigidity of charged particles, taking into account the *Kp*-index and the local time, on the basis of generalization of the results of extensive trajectory calculations for trial particles moving in the geomagnetic field. The vertical cutoff rigidities, calculated by the Tsyganenko-89 model, are presented as an International Geomagnetic Reference Field (IGRF) model calculated and thereafter corrected in accordance with the geomagnetic disturbance and local time conditions. The fits from the proposed method agree with the results of cutoff rigidity measurements carried out by satellites. The method is intended for applications using cutoff calculations, such as evaluating particle penetration of spatial boundaries, calculating magnetospheric transmissions for low-orbital spacecrafts flights and interpreting the results of orbital experiments.

Keywords: Earth magnetosphere; Cutoff rigidity; Calculation algorithms

1. Introduction

The effective cutoff rigidity (ECR) is a parameter that characterizes a given point of near-Earth space in terms of the ability of a cosmic ray with a known magnetic rigidity to reach this point from outer space. These particles, along with those trapped in the Earth's radiation belt, comprise the radiation environment onboard low-orbital spacecrafts. In addition, the geomagnetic cutoff effect allows the energy spectra and charge of solar energetic particles (SEPs) to be studied. In practice, a vertical ECR, which represents the most important case (Nymmik, 1991b), is usually applied (EVCR). The ECR calculations are ordinarily based on a numerical integration of charged particle motion equations using a model of the Earth's magnetosphere (Smart et al., 2000). Until now, EVCR values have been calculated using this technique for the points of the global neutron monitor network (Shea and Smart, 2001), for the world geographic grid at a 20-km altitude and for typical satellite or manned station orbit altitudes (Shea and Smart, 1983; Smart and Shea, 1997). Besides its altitude dependence, the value of ECR is also a function of both the geomagnetic disturbance level (Smart et al., 1999a,b) and the local time (Smart et al., 1969). Although the possibilities for direct trajectory ECR calculation continually grow due to the increasing power of computers, most practical tasks, such as evaluating the position of the penetration boundaries in space and calculating magnetospheric transmission, require simpler and less resource-consuming techniques. In this work, we propose such a technique based on the generalization of trajectory computation results for a multidimensional grid of parameters that is intended to replace the numerical trajectory integration method for EVCR calculation.

2. Overview of the method's structure

In this work, we have adopted the rigidity attenuation formalism (Nymmik 1991a,b; Nymmik et al., 2007) that an earlier version has already successfully applied (Tylka

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et al., 1997). As it was shown in Nymmik (1991a), the attenuation quotient's depends rather on the rigidity value than on a point's geographical position, at least for rigidities above tenths of GV. Hence, we can essentially simplify the approach for calculating world cutoff grids. Our method uses three steps to calculate EVCR for any given near-Earth space location, *Kp*-index and local time *LT*:

(1) An geographic grid (for latitude λ_i and longitude φ_i) of EVCR is calculated according to the IGRF model of interior geomagnetic field sources on a spherical surface at altitude $H_0 = 450$ km above the mean Earth radius ($r_E = 6471.2$ km) – basic table $R_{IGRF}(H_o, \lambda_i, \varphi_i)$ (Table 1, presented for modern IGRF epoch 2005).

(2) A non-linear interpolation procedure, combined with the following well-known formula:

$$R_{IGRF}(\lambda, \varphi, H) = R_{IGRF}(\lambda, \varphi, H_0)((r_E + H_o)/(r_E + H))^2 \quad (1)$$

allows us to calculate the IGRF EVCR value $R_{IGRF}(\lambda, \varphi, H)$ for a point with given spatial coordinates (latitude λ, longitude φ and altitude H) from table $R_{IGRF}(\lambda_i, \varphi, H_0)$. For the altitude range 270–900 km, Eq. (1) is correct with the accuracy better than 1%.

(3) The functional dependence of $\Delta(R_{IGRF}, Kp, LT)$ on its parameters, where Δ is the cutoff rigidity attenuation quotient describing relative changes in the value of IGRF EVCR due to the effects of a geomagnetic disturbance (*Kp*-index) and local time (*LT*). According to the proposed method, for a point with coordinates H, λ and φ we can state

$$R_{TSYG}(R_{IGRF}, Kp, LT) = R_{IGRF}/\Delta(R_{IGRF'}, Kp, LT) \quad (2)$$

where R_{TSYG} is the EVCR value, calculated using a superposition of the IGRF and Tsyganenko-89 (Tsyganenko, 1989) models, *Kp* is the geomagnetic disturbance index and *LT* is the local time. The algorithm for obtaining $\Delta(R_{IGRF}, Kp, LT)$ is presented below in Eqs. (3)–(6). We sought an approximation of the form

$$\Delta(R_{IGRF}, Kp, LT) = 1 + 0.001 \exp\left(aR^b_{IGRF} - 1\right) \quad (3)$$

where *a* and *b* (and *c*, see below) are parameters dependent upon both *Kp* and *LT*. Data relating these parameters were fitted by equations

Table 1
Basic R_{IGRF} data for epoch 2005 (altitude 450 km).

Latitude	Geographic east longitude											
	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