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THE LIMITATIONS OF USING VERTICAL CUTOFF RIGIDITIES DETERMINED FROM THE IGRF MAGNETIC FIELD MODELS FOR COMPUTING AIRCRAFT RADIATION DOSE

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ABSTRACT

Vertical cutoff rigidities derived from the International Geomagnetic Reference Fields (IGRF) are normally used to compute the radiation dose at a specific location and to organize the radiation dose measurements acquired at aircraft altitudes. This paper presents some of the usually ignored limits on the accuracy of the vertical cutoff rigidity models and describes some of the computational artifacts present in these models. It is noted that recent aircraft surveys of the radiation dose experienced along specific flight paths is sufficiently precise that the secular variation of the geomagnetic field is observable. Published by Elsevier Ltd on behalf of COSPAR.

INTRODUCTION

Geomagnetic cutoff rigidities are a quantitative measure of the shielding provided by the earth's magnetic field. More precisely, geomagnetic cutoff rigidities predict the energetic charged particle transmission through the magnetosphere to a specific location as a function of direction. The geomagnetic cutoff is often used as a coordinate that describes charged particle access at any position in the magnetic fields. Geomagnetic cutoff rigidities are used to both describe the shielding effect of the geomagnetic field and to order measurements of charged particle data or the effects of the charged particles such as radiation dose measurements. Charged particles traversing a magnetic field such as the one the earth possesses undergo a vector force that results in a curved path. Except for the special case of a dipole magnetic field there is no "solution in closed form" for the particle path. The presence of non-dipole terms and the offset of the magnetic center with respect to the geocenter greatly complicates the geomagnetic cutoff problem. Trajectories that would normally be allowed in a pure dipole magnetic field become forbidden due the presence of the solid object (the earth). The generally accepted manner for determining cutoff rigidities is by the method of tracing particle trajectories in a high order simulation model of the magnetic field (Shea et al., 1965).

The International Geomagnetic Reference Field models (Sabaka et al., 1997) generated under the auspices of IAGA (International Association of Geomagnetism and Aeronomy) are current state-of-the-art representations of the earth's internal geomagnetic field. "Precision" geomagnetic cutoff rigidities can be obtained by brute force application of massive digital computer power by tracing the orbits of cosmic ray trajectories in these models of the earth's magnetic field. Cosmic ray trajectories can be calculated at a specific direction (often the vertical for economy of computer time) for each location until there has been a reasonable sample at various rigidities and the cutoff values have been found. Figure 1 is an example of this trajectory-tracing process. High rigidity cosmic rays, (such as the trajectory labeled 1), traverse the geomagnetic field in relatively simple orbits. As the rigidity of the particle decreases the amount of geomagnetic bending increases (examine the trajectories labeled 4 and 5) and the orbits become more complicated, forming intermediate loops. When these loops intersect the solid earth, the orbits are forbidden, i.e. not accessible from interplanetary space. At still lower rigidities, there may be allowed trajectories (see trajectory 15). At still lower rigidities, all trajectories are forbidden. The complex structure of allowed and forbidden orbits form the cosmic ray penumbra. See Cooke et al. (1991) for a more detailed description of geomagnetic cutoff definitions.

A common misconception is that geomagnetic cutoffs are "sharp". The general case is that the geomagnetic cutoff is "diffuse", except for the special case of vertical geomagnetic cutoffs near the magnetic equator. There are rigidities (energies) above which all charged particles are allowed, and there are rigidities (energies) below which all charged particles are forbidden. However, in most cases, the transmission of charged particles decreases from fully allowed to totally forbidden over a discrete and often surprisingly large range of charged particle rigidities. The region between full access and totally forbidden access is called the cosmic ray penumbra (a term adapted from optics). The cosmic ray penumbra is a chaotic region of allowed and forbidden trajectories lying between the upper computed cutoff (R_U) and the lowest computed cutoff (R_L). Balloon and spacecraft precision cosmic ray instruments have experimentally observed these penumbral features. The cosmic ray penumbra and the directional effect of the geomagnetic cutoff frustrate the desire to obtain a simple useful number to quantify the geomagnetic cutoff effect. Effective geomagnetic cutoffs (R_C) are obtained by attempting to allow for the penumbra by a linear average of the allowed bands in the penumbra. These effective cutoffs in the vertical direction have limitations and Clem et al. (1997) found it was necessary to average the cutoffs in many directions in order to properly describe the cosmic ray latitude curve.
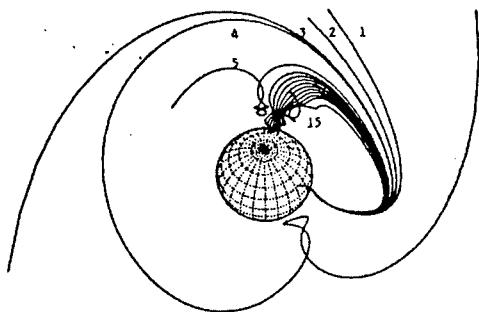

Fig. 1. Illustration of the cosmic ray trajectory tracing-process. Note the curved path in the magnetic field, which becomes increasingly complex as the rigidity is decreased (curve 1 to curve 15).
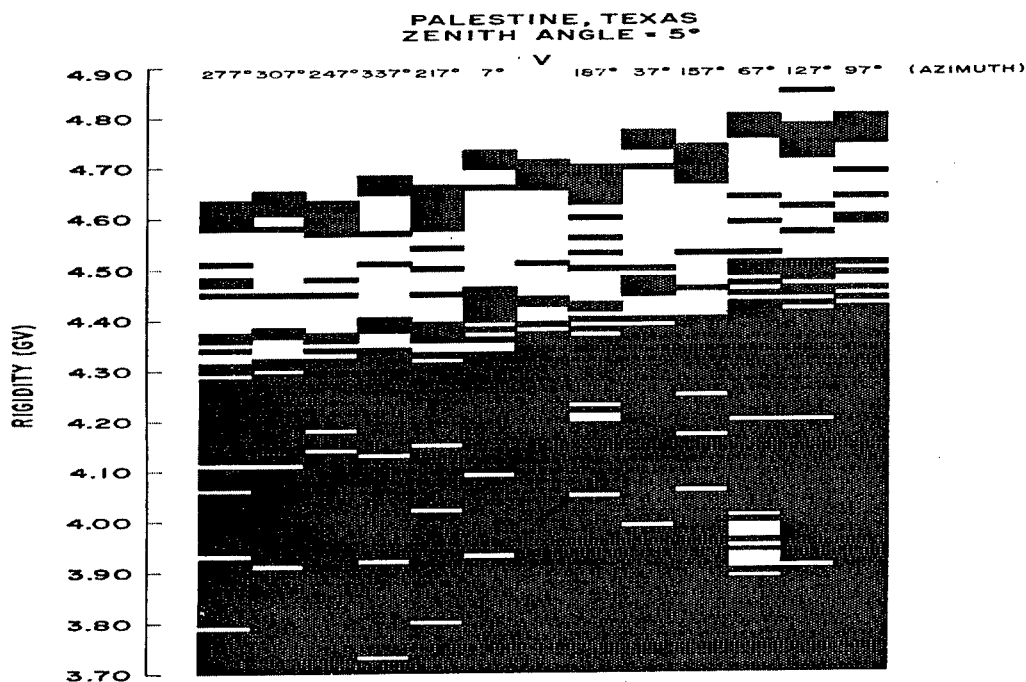

Fig. 2. Illustration of the geomagnetic cutoff transition from allowed to forbidden access. IThe black indicates forbidden and white indicates allowed. Note that the cutoff is not sharp and that as the rigidity is decreased, the transmission of cosmic rays changes from fully allowed at rigidities above the upper computed cutoff, R_U, to partly allowed in the cosmic ray penumbra, to totally forbidden at rigidities below the lowest computed cutoff, R_L.

ACCURACY OF THE CUTOFF MODELS AT LOW AND MID-LATITUDES

The accuracy of the cutoffs derived by the cosmic ray trajectory method is limited by the accuracy of the geomagnetic field model employed. A general statement is that the larger the magnitude of the cutoff, the more accurate the calculation. The cutoff values derived from cosmic ray trajectory calculations in high order simulations of the geomagnetic field at low and mid latitudes are accurate to within a "few" percent. Cosmic ray experiments have been designed purely on the basis of the cutoff rigidity calculated from the IGRF field models (Dryer and Meyer, 1975). There are very few "precision" checks of the cutoff rigidity models, i.e. absolute measurements with a precision of better than one percent. There are a number of relative accuracy checks such as reproducing the latitude effect, the east-west effect and comparison with "measured" geomagnetic cutoffs. The best available verifications of cosmic ray cutoffs show that the trajectory-derived cutoffs calculated in high order simulations of the internal geomagnetic field are about 3 % higher than the spacecraft-measured cutoffs at rigidities >2 GV during magnetically quiet times.

Accuracy of the Geomagnetic Cutoff at 400 KM

The most rigorous determinations of the accuracy of the cutoff rigidity calculations was done as a result of the French-Danish cosmic ray experiment on the HEAO-3 satellite. This instrument, on a spinning spacecraft, could record the energy, charge and direction of every cosmic ray heavy nuclei observed in its approximately one square meter collecting area. A trajectory calculation was made for each of the high-energy heavy nuclei recorded by this instrument and these calculations were compared with the experimental measurements. The objective was to use the sharp edge of the penumbral structure for isotope separation. This procedure was successful at all rigidities above about 5 GV. As a by-product, these results can be used as an absolute check of the accuracy of the cosmic ray cutoffs obtained by the trajectory-tracing procedure. Within the experimental accuracy of the instrument, all the predictions regarding cosmic ray access to an orbiting spacecraft were verified by this experiment. This set of calculations and measurements also match the prediction of Störmer (1955) theory. Comparison of the experimental and computed cutoffs in the 5 GV range from the analysis of 1885 oxygen nuclei indicates the calculated cutoffs were about 3% high. Figure 3 illustrates the differences between the predicted cutoff (solid line) and the actual observations (dashed line).
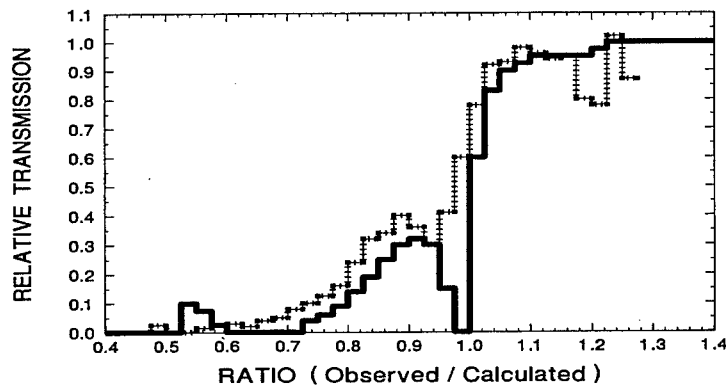

Fig. 3. Comparison between the predicted (by the trajectory-tracing procedure) and observed transition from allowed to forbidden transmission in the 5 GV geomagnetic cutoff region. The heavy solid line indicates the average predicted theoretical cutoff transition and the dashed line indicates the average observed cutoff transition. (The Copenhagen - Saclay Collaboration for HEAO, 1981).

THE EFFECT OF THE PENUMBRA ON THE EFFECTIVE VERTICAL CUTOFF RIGIDITY

The desire to have a simple number for the cutoff rigidity resulted in the development of the concept of the effective geomagnetic cutoff (Shea et al., 1965). This widely used concept is based on the premise that sampling the rigidity interval of the probable geomagnetic cutoff region at 0.01 GV intervals provides a useful sample from which a cutoff value can be determined. In this process is it implicitly assumed that the sample in the vertical direction is also indicative of the particle access in other directions different from the vertical direction. The

allowed rigidities in the penumbra are summed and subtracted from the upper cutoff value (R_U) and called the effective cutoff (R_C). The result is a linear sum of the particle transmission through the penumbra, which ignores the effect of the cosmic ray (or solar particle) spectral parameters. Unfortunately the cosmic ray penumbra does not have a simple structure. It may best be described as chaotic, and we have been unsuccessful in finding parameters that describe its detailed behavior. A reasonable ordering of the penumbral width can be obtained by plotting as a function of magnetic latitude. We have used the invariant latitude, (often utilized in space physics because it inherently accounts for the non-dipole terms in the geomagnetic field) derived from the McIlwain (1961) "L" parameter. Figure 4 shows the penumbral width plotted as a function of the invariant latitude. Experience has shown that the maximum penumbral width occurs when the cutoff is in the 6 to 9 GV range.
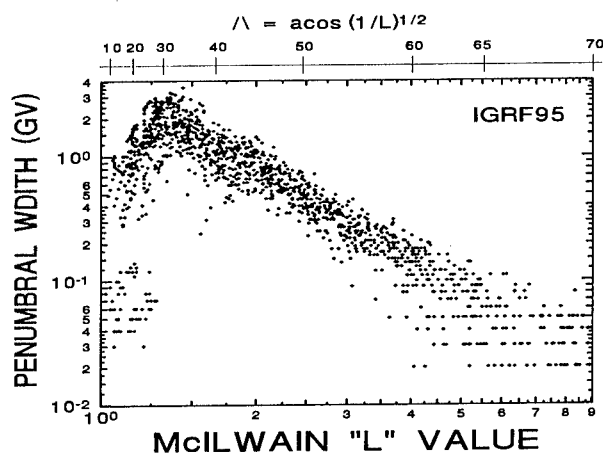

Fig. 4.   The vertical cutoff penumbral width as a function of the "L" parameter. The invariant latitude is indicated the scale at the top of the figure.
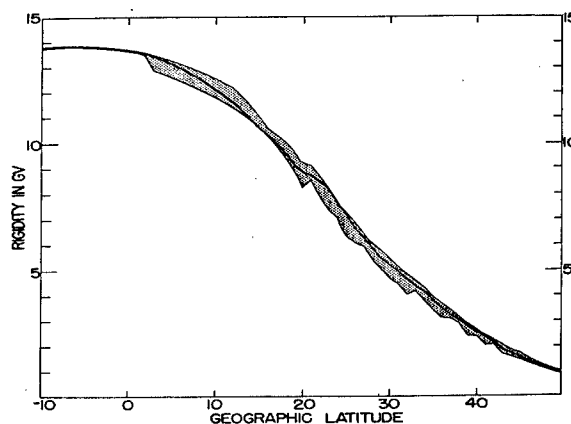

Fig. 5. Vertical cutoff rigidities determined at one-degree latitude intervals along the 260° E meridian. The shaded area illustrates the width of the penumbra. R_U is at the top, R_L at the bottom. R_C is the solid line.
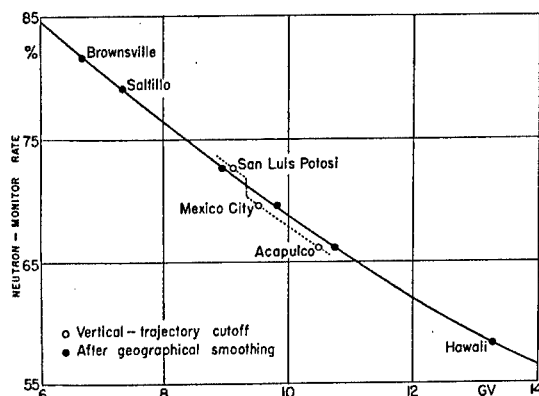

Fig. 6.   Illustration of the systematic discrepancy at about 9 GV between neutron monitor counting rate and the expected smooth latitude curve (solid line). The dotted line represents the computed effective vertical cutoff.   This effect is due to discontinuities in the penumbral structure. From Carmichael et al., (1969).

Fig. 7.   Illustration of the "Caribbean Trouble Spot". These cutoff variations in the 6 to 9 GV region are the result of the offset of the geomagnetic field from the geocenter. Some of the trajectories from this region mirror in the South Atlantic where at other longitudes similar trajectories would intersect the earth.   From Carmichael et al., (1969).

An illustration of the penumbral effects on the effective vertical cutoff rigidity is shown in Figure 5. This is the result of computing the cutoff rigidities at one-degree intervals along the 260° E meridian in North America. Examination of this figure shows that there is significant deviation from an idealized smooth curve, especially in
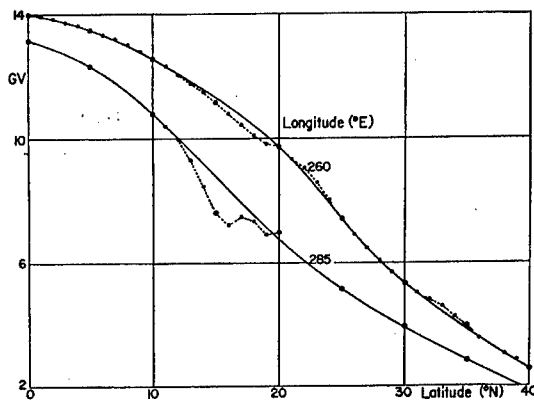
the lower cutoff values that are uneven. Note that the penumbral width has significant and abrupt variations as the rigidity changes along this longitude.

This deviation from an idealized latitude curve has been noted ever since precision cosmic ray measurements have been organized by the calculated effective vertical cutoff rigidity. Carmichael et al. (1969) first published this effect (see Figure 6) when attempting to order his careful land-based latitude survey (attempting 0.1 percent statistical precision in all his cosmic ray neutron monitor data). We are not aware of any cosmic ray data acquired on aircraft that has the statistical precision to show this effect. However, the penumbral effect has been noted by modern cosmic ray latitude surveys conducted by cosmic ray neutron monitors on ocean voyages to the Antarctic (see Clem et al., 1997). There is a longitude dependence effect in the penumbral structure with resulting additional discontinuities in the effective geomagnetic cutoff rigidity. These penumbral discontinuities are largest in the Caribbean area where the "mirror point" of the cosmic ray trajectories occurs in the southern hemisphere where the relative offset of the effective magnetic dipole center is at it's maximum distance, and some trajectories that would normally re-enter at other longitudes, have an additional "bounce" in their orbit and become allowed. The result is a wider penumbra and a lower cutoff rigidity in this area (see Figure 7).

THE EFFECT OF SECULAR CHANGES IN THE GEOMAGNETIC FIELD

The magnetic field of the earth is changing rapidly on a geological time scale. What is generally not appreciated is that the changes are sufficiently large that they can be observed in decadal time scales with existing cosmic ray monitoring equipment. This effect for the Huancayo, Peru cosmic ray neutron monitor was first predicted by Shea (1971) and then confirmed by Cooper and Simpson (1979). The magnitude of the effect on aircraft measurements was not appreciated until König and Stoker (1981) showed that data acquired by an airborne cosmic latitude survey from Johannesburg, South Africa to New York, NY, USA in 1976 could not be satisfactorily ordered using geomagnetic vertical cutoff rigidities calculated using an IGRF epoch 1965 magnetic field model (IAGA, 1969). As shown in Figure 8 we found that it was necessary to interpolate to the month of the flight in order to generate a satisfactory ordering of the data with the computed geomagnetic cutoff rigidity. Further investigations by Shea and Smart (1990) found that this was the region of the world where the most rapid changes in the vertical cutoff rigidities were occurring (a phenomena familiar to geomagnetic specialists but relatively unappreciated in other disciplines). Shea and Smart (1990) found that the maximum change in the South Atlantic was a decrease of ½ percent a year and in the North Atlantic, the maximum rate of change was an increase of about 1 percent per year. Figure 9 illustrates the rate of changes in vertical geomagnetic cutoff due to the secular change in the geomagnetic field.

An unprecedented amount of radiation dose data at aircraft altitudes is being collected as a result of the Commission of European Communities Directive (1996). The state-of the-art instrumentation and cross-calibrations required to meet this directive have resulted in superb data on the radiation exposure due to cosmic radiation. Analysis of these data allows a comparison between the observations and the calculated values from the various radiation dose codes, (see, for example, Sáez et al. 2002). The latest version of the US aircraft radiation dose code CARI-6 (Friedberg et al., 1999) uses an epoch 1995 geomagnetic cutoff rigidity model and also can compensate for the geomagnetic evolution by extrapolation to a specific month for earlier epochs. By contrast the European aircraft radiation dose code EPCARD (Schraube, et al., 1999, 2000) uses an epoch 1990 geomagnetic cutoff rigidity model (Smart and Shea, 1997). It is our opinion that some of the differences noted are the result of the two different epochs of the geomagnetic field utilized for the geomagnetic cutoff rigidity models in these aircraft radiation dose codes.

STOKER LATITUDE SURVEY
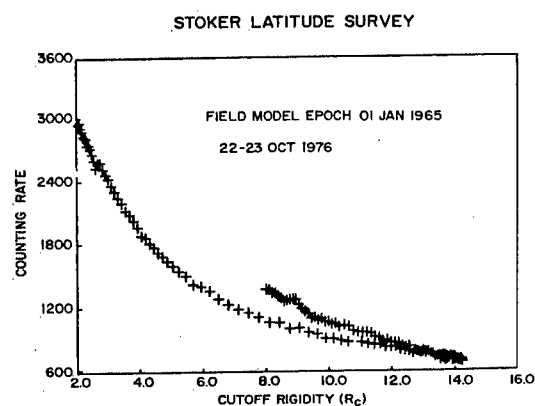

STOKER LATITUDE SURVEY

Fig. 8a. The airborne cosmic latitude survey in 1976 from Johannesburg to New York is not properly organized using Epoch 1965 cutoff rigidities.
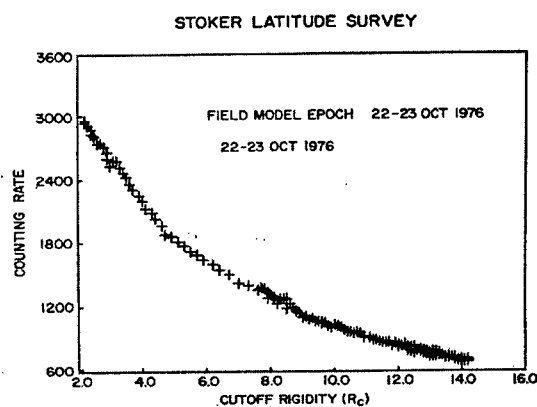
Fig. 8b. The airborne cosmic latitude survey in 1976 from Johannesburg to New York is properly ordered using Epoch 1976 cutoff rigidities.

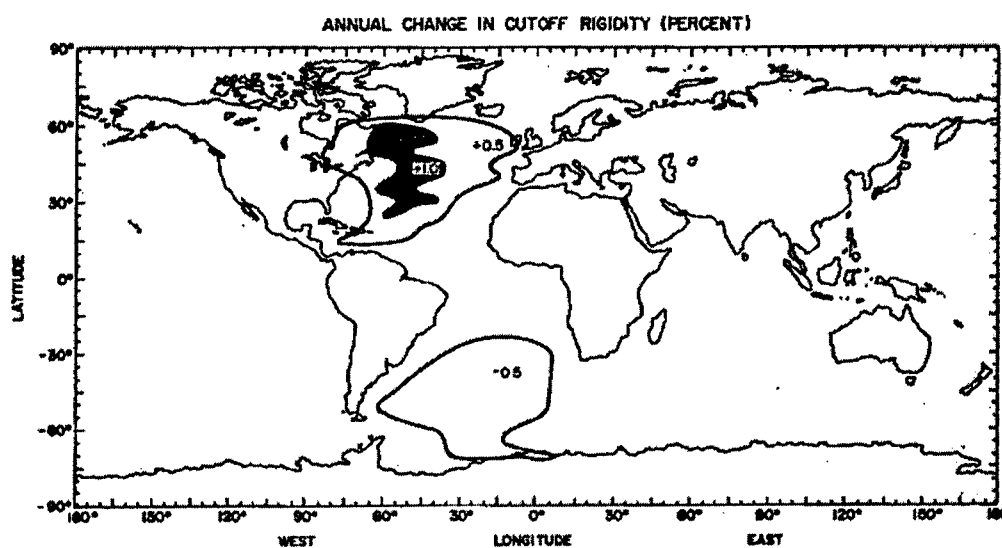ANNUAL CHANGE IN CUTOFF RIGIDITY (PERCENT)

Fig. 9. Illustration of the annual percent change in the vertical cutoff rigidity due to the secular change in the geomagnetic field. This change is not uniform throughout the world, and is largest in the North Atlantic (increasing geomagnetic cutoff rigidities) and the South Atlantic (decreasing geomagnetic cutoff rigidities).

USING VERTICAL CUTOFF RIGIDITES TO ESTIMATE THE CUTOFF IN NON-VERTICAL DIRECTIONS

The work doing cosmic ray trajectory calculations in model geomagnetic fields has verified the physics on which Störmer theory is based. As previously stated, the trajectory calculations done for the HEAO-3 cosmic ray experiments were verified within the ~2 percent experimental accuracy of the instrumentation. We have extensively used the vertical cutoff rigidity calculations to estimate the geomagnetic cutoff in other directions. Repeated checks of these angular extrapolations by actual trajectory calculations has verified the utility of this method (keeping in mind the penumbral effects).

Our preferred method for using Störmer (1955) theory to extrapolate from the vertical cutoff rigidity to the cutoff at other azimuth and zenith angles is to normalize to the cutoff value in the vertical direction with equation (1). In this application it is important to use an appropriate magnetic latitude. Simple dipole geomagnetic latitude is not sufficient. We often use the invariant latitude derived from the McIlwain (1961) "L" parameter. An alternate coordinate system we have found very useful is the corrected geomagnetic coordinate system, originally

derived by Gustafsson (1969) and later updated by Gustafsson et al. (1992). A current update of the software for corrected geomagnetic coordinates is available from the Solar-Terrestrial section of the US National Geophysical Data Center (WDC-A):

$$R_\alpha = 4R_v / \{[\ 1 + (1 - \sin\varepsilon\ \sin\varphi\ \cos^3\lambda)^{\frac{1}{2}}]^2\ \}. \tag{1}$$

In this equation R_α is the cutoff rigidity in a specific angular direction, R_v is the vertical cutoff rigidity, λ is the magnetic latitude, ε is the angle from the zenith direction, and φ is the azimuthal angle measured clockwise from magnetic north. The angular geomagnetic cutoffs are lowest from the magnetic west and maximum from the magnetic east.

CHANGES IN GEOMAGNETIC CUTOFF DUE TO MAGNETIC STORMS

Due to the interaction of the magnetic field imbedded in the solar wind and the geomagnetic field, a phenomena known as the geomagnetic storm perturbs the earth's magnetic field. These transient perturbations are most severe in the earth's polar regions. The most noted effect of these magnetic storms are high-frequency radio communication problems and the resulting magnetic compass direction variations that sometimes cause navigation difficulties. Less known is the geomagnetic cutoff reduction. Again, these geomagnetic cutoff reduction effects are most severe in the earth's polar regions where the magnetospheric effects are most pronounced. When considering this effect with respect to aircraft cosmic radiation exposure it is important to note that the atmospheric mass above the aircraft (~250 to 300 grams at standard commercial flight altitudes; ~100 grams at Concorde flight altitudes) provides sufficient shielding so that the radiation dose due to cosmic radiation is primarily generated by charged particle with energies >1 GeV. As noted by Smart and Shea, (2003) the most often occurring magnetic storm (those having Kp magnetic activity indices of 5 or less) have only a small cutoff reduction in the GeV energy range as shown in Table 1.

Table 1. Percent differences in cutoff rigidity having a magnitude >1 GV due to magnetic activity in the North Atlantic - American air corridors at specific geographic coordinates. (Western hemisphere longitude are designated as negative in this table.) The differences shown are the result of a comparison of the cutoff rigidities computed for a quiet geomagnetic field (magnetic activity index of Kp = 0) compared to the cutoff rigidities computed for a moderately disturbed (magnetic activity index of Kp = 4) geomagnetic field.

W. Lon	-90	-85	-80	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0
Lat																			
50									-26	-23	-18	-16	-14	-13	-12	-10	-7	-6	-5
45	-21	-23	-23	-24	-23	-20	-17	-13	-12	-9	-8	-7	-8	-6	-6	-5	-5	-4	-4
40	-12	-13	-14	-13	-14	-11	-9	-7	-5	-5	-3	-4	-3	-3	-3	-3	-3	-2	-2
35	-5	-7	-8	-8	-8	-6	-5	-3	-3	-2	-3	-3	-3	-2	-2	-1	-1	-1	-1
30	-3	-4	-4	-4	-4	-4	-4	-3	-2	-1	0	-1	-1	-1	-1	0	-1	-1	-1
25	-1	-1	-2	-2	-2	-2	-2	-2	-1	-1	-1	-1	0	0	0	0	0	0	-1
20	-1	-1	-2	-1	-1	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0
15	0	-1	-1	-2	-2	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0
10	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	-1	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0

SUMMARY

Vertical cutoff rigidities derived from the International Geomagnetic Reference Fields are used to compute the radiation dose at aircraft altitudes. In general the geomagnetic cutoff values obtained from cosmic ray trajectory calculations in these precision geomagnetic field models are accurate to a few percent. The effective vertical cutoff values obtained by a linear sum of the allowed trajectories in the cosmic ray penumbra have discontinuities because the width of the cosmic ray penumbra and the transparency of the penumbra is discontinuous, partially in the 6 to 9 GV region. The rate of change of the secular changes in the geomagnetic field is sufficiently rapid that on a decade

scale, differences in the cosmic ray exposure and hence the radiation dose due to cosmic rays is measurable. These changes are most rapid in the North and South Atlantic region. Recent aircraft surveys of the radiation dose along specific flight paths can detect the effects of these secular variations in the geomagnetic field.

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