CHANGES IN CALCULATED VERTICAL CUTOFF RIGIDITIES AT THE ALTITUDE OF THE INTERNATIONAL SPACE STATION AS A FUNCTION OF GEOMAGNETIC ACTIVITY

D.F. Smart[1], M.A. Shea[1] and E.O. Flückiger[2], A.J. Tylka[3], and P.R. Boberg[4]

[1]Air Force Research Laboratory, 29 Randolph Road, Hanscom AFB, Bedford, MA 01731, USA
[2]Physikalisches Institut, Sidlerstrasse 5, CH-3012, Bern, Switzerland
[3]Naval Research Laboratory, Code 7654, Washington, D.C., 20375, USA
[4]California Institute of Technology, 220-22 IPAC Building, Pasadena, CA, 91125, USA

Abstract

We illustrate the computed change in vertical geomagnetic cutoff at 450 km as a function of magnetic activity. Geomagnetic cutoff rigidity values were calculated employing the trajectory-tracing method utilizing the Tsyganenko magnetic field model with extensions for many magnetic activity levels. These magnetic activity levels included Kp values ranging from 0 to 5 and magnetic disturbances represented by Dst indices extending to -500 nT. The results show non-linear changes in the geomagnetic cutoff that are a function of latitude.

1 Introduction:

We have calculated world grids of vertical cutoff rigidities each 5° in latitude and 15° in longitude for a spacecraft orbiting at 450 km. We employed the Tsyganenko (1989) magnetospheric field model combined with the International Geomagnetic Reference Field (IGRF) for epoch 1995.0 (Sabaka et al., 1997). The trajectory of each particle was traced through the model magnetosphere to ascertain if the particle was allowed or forbidden from space at each location. This paper summarizes the results obtained for magnetic conditions ranging from super quiet to extremely disturbed.

2 Method:

Cosmic ray trajectory calculations were initiated in the vertical direction from a distance of 6821.2 km from the geocenter (450 km altitude above the average earth radius of 6371.2 km). The "sensible" atmosphere of the earth was considered to extend 20 km above the international reference ellipsoid, and any trajectory path that came lower than this distance was considered to be re-entrant and hence forbidden. In this work "vertical" is the direction radial from the earth center. The magnetic fields in the magnetosphere were the IGRF 1995 internal magnetic field (Sabaka et al., 1997) and the Tsyganenko (1989) magnetospheric model as combined by Flückiger and Kobel (1990). The Boberg et al. (1995) extension was used to describe the magnetospheric fields for magnetic activity levels exceeding Kp values of 5. The trajectory-tracing technique employed was developed by Kobel (1990) and utilizes the Bulirsch-Stoer numerical integration technique (Stoer and Bulirsch, 1980) to minimize the number of steps required in a charged particle trajectory computation. The magnetic fields utilized (both the IGRF and the Tsyganenko model) were defined for 1 January 1995. The geomagnetic cutoff values presented here are the average of cutoff calculations at 00, 06, 12 and 18 hours UT.

The cutoff rigidities were determined by calculating charged particle trajectories at discrete rigidity intervals starting with a rigidity value high above the highest possible cutoff and decreasing the rigidity to a value that satisfied our criteria that the lowest allowed trajectory had been calculated. As these calculations progress down through the rigidity spectrum, the results change from the easily allowed orbits to a complex structure of allowed, forbidden, and quasi-trapped orbits (loosely called penumbra) and finally to a set of rigidities where all trajectories intersect the solid earth. As a result of these trajectory calculations we determined the calculated upper cutoff rigidity (R_U) which is the rigidity value of the highest allowed/forbidden pair of adjacent cosmic ray trajectories, the calculated lowest cutoff rigidity (R_L) which is the rigidity value of the lowest allowed/forbidden pair of adjacent cosmic ray trajectories, and an "effective cutoff rigidity" (R_C) that allows for the transparency of the penumbra. (See Cooke et al., 1991, for definitions of cosmic ray cutoffs.) Rigidity intervals of 0.01 GV were used for trajectory calculations between R_U and R_L to provide a reasonable sample of the cosmic ray penumbra. The effective cutoff rigidity R_C was found by summing the allowed orbits through the penumbra (Shea et al. (1965).

3 Results and Discussion:

Smart et al. (1999a,b) give the data and some indication of the change in cutoff with magnetic activity. The cutoff contours move equatorward with increasing magnetic activity, and the 15 GV contour disappears. Also note in Figure 2 of Smart et al., 1999b, the closure of the 11 GV contour during disturbed times. The change in cutoff rigidity at the longitude of the minimum cutoff experienced by the International Space Station (ISS) orbit in the northern hemisphere is illustrated in Figure 1.

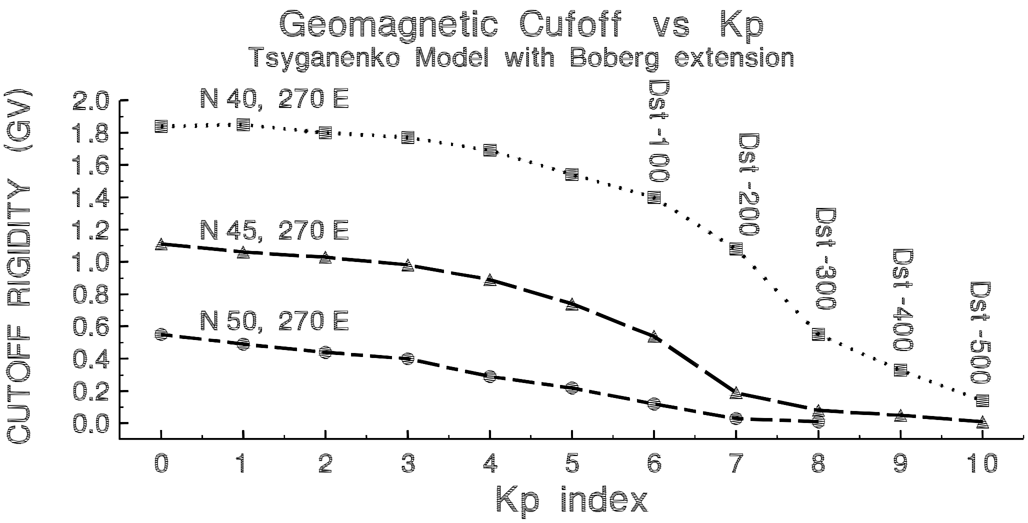

Figure 1. Illustration of the cutoff reduction at various magnetic activity levels. The coordinates are the locations of the lowest cutoff value experienced by the ISS orbit at the specified latitude in the Northern Hemisphere.

Rigidity is not the most convenient unit for use in comparing with energetic particle data since most energetic particle measurements are in units of energy. For comparison purposes, we have selected the invariant latitude calculated from the internal geomagnetic field as a common parameter. We interpolated through our world grids of vertical geomagnetic cutoff rigidities for each magnetic activity level to determine proton cutoff energy contours as a function of invariant latitude and obtained an average invariant latitude for each energy. These results are presented in Figure 2. While these results are the global average, we note a systematic trend that the invariant latitude of a mid- or high latitude cutoff is about one degree higher than the average in the Atlantic region and about one degree lower than the average in the Pacific region.

The Tsyganenko (1989) magnetospheric field model describes the magnetospheric field topologies for the Kp magnetic indices from 0 to 5. We have utilized the Boberg (1995) extension to include the probable effect of additional ring currents during severe magnetic storm conditions. For convenience we have labeled these as Kp 6 through 10 for Dst increments of -100 nT. The curves in Figure 2 indicate an almost linear relation between the proton cutoff energy with latitude in the range from about 10 MeV to a few hundred MeV. We note that the change of proton energy with Kp is relatively uniform over the range of the original Tsyganenko (1989) model, but the cutoff changes introduced by the Boberg (1995) extension is non-linear with the Dst increment.

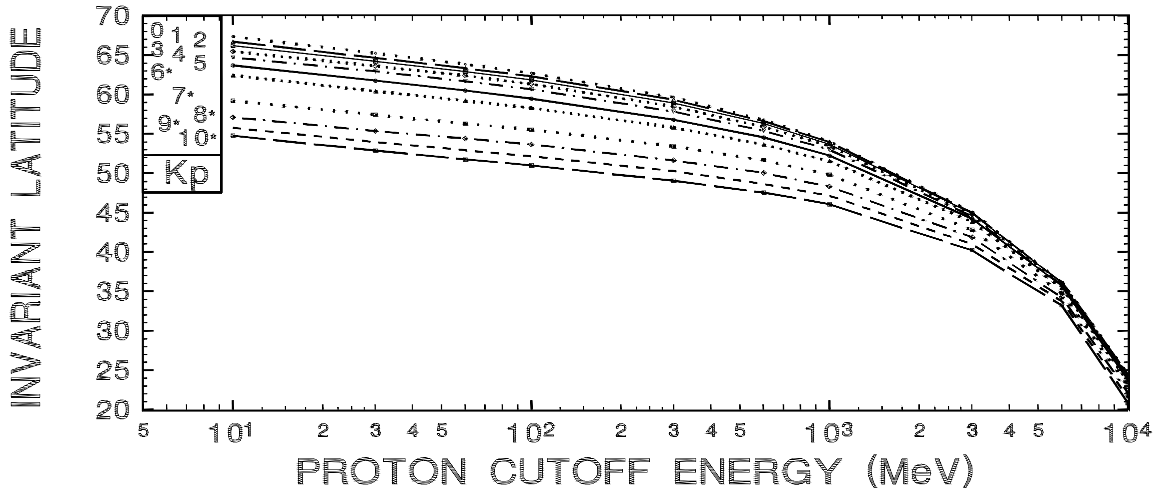

Figure 2. Calculated changes in the effective vertical cutoff energy for protons at 450 km altitude as a function of magnetic activity

4 Comparison with SAMPEX data:

Smart and Shea (1967, 1994) found that the cutoff rigidity change with radial distance is proportional to L^{-2}. We fitted the cutoff values at 450 km to the McIlwain L parameter (calculated for the IGRF internal field) at each world grid location and interpolated as a function of L for altitude and latitude, and linearly in longitude to derive cutoff values appropriate for 600 km altitude. From these interpolations we determined the invariant latitude of the Sampex cutoff energies for each observed Kp value from day 304 to day 312 of 1992 (30 October to 7 November) to compare with the Sampex cutoffs published by Leske et al. (1997). Our simulation of the invariant latitude of the 29-64 MeV proton cutoff is shown in Figure 3. When we compare the values in this figure with those derived by Leske et al. (1997) we find a general systematic trend that our calculated proton cutoff energies are about 1.5 degrees higher (poleward in latitude) than the values published by Leske et al. (1997). However, there is one time period on 1 November (day 306) when the Dst values are exceptionally quiet (prior to the arrival of the interplanetary shock at 2147 UT and the resultant magnetic storm), when there is an exceptional agreement between our simulated and the Sampex derived proton cutoff latitudes. There is also a time on 3 November (day 308) when magnetic storm activity indicated by the Dst index is not reproduced in the Kp magnetic index. Note that the 3-hour averaging interval of the Kp index was designed to 'damp out' the higher frequency magnetic storm variations (Berthelier, 1993). There is also no corresponding major cutoff depression following the sudden commencement (SC) at 1312 UT on 4 November (day 309), apparently because the variation in the Dst index is not reproduced in the Kp magnetic index. Leske et al. (1997) found the hourly Dst index was a good indicator of the temporal behavior of the observed cutoff variations.

5 Systematic Differences Between Computed and "Measured" Cutoffs:

Measured cutoffs are often determined by a procedure such as finding when the instrument counting rate during a solar particle event has dropped to a value of 1/e of the polar counting rate. If we used an exponential in rigidity (such as $J = J_o \exp(R/R_o)$ to describe the particle flux spectrum, then this "measured" latitude of the cutoff will always be R_o MV equatorward of the latitude of the "computed" cutoff rigidity. This is for an instrument with a reasonably compact differential energy window of response. For an integral response above a specified energy threshold, the R_o displacement may be larger because of counting events such as stars induced in the detector by particles during high energy solar proton events.

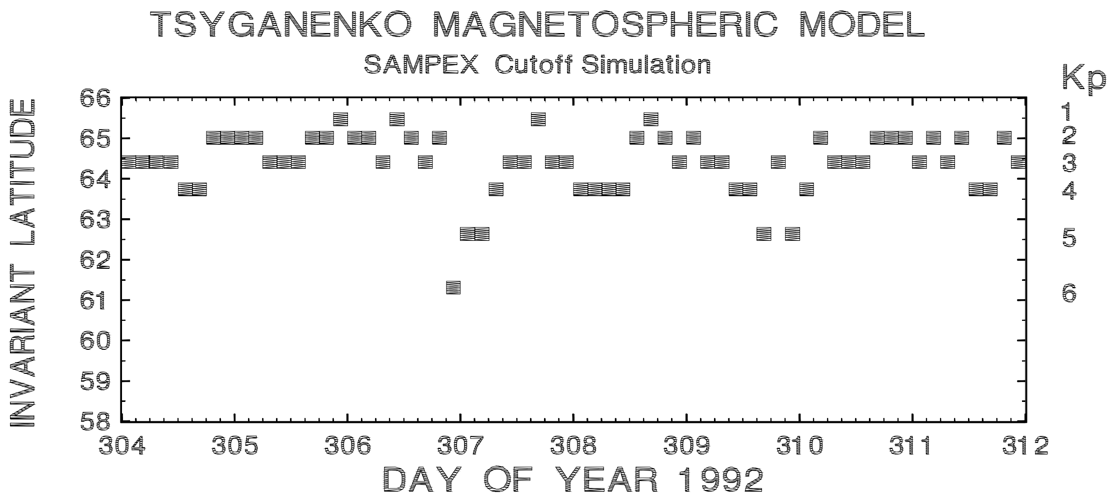

Figure 3. Simulation of the proton cutoff energy variation as a function of the Kp index for the time period of 31 October to 7 November, 1992.

6 Conclusions:

Cutoff rigidity values derived from the Tsyganenko magnetic field model combined with the IGRF for various magnetic conditions ranging from quiet to very disturbed show non linear changes in geomagnetic cutoff that are a function of latitude. We note that the change of proton cutoff energy with Kp is relatively uniform over the range of the original Tsyganenko (1989) model (Kp 0 to 5), but the cutoff changes introduced by the Boberg (1995) extension is non-linear with Dst increments. These results are intended to be a basic reference for charged particle access to the International Space Station.

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