# A Direct Measurement of the Geomagnetic Cutoff for Cosmic Rays at Space Station Latitudes

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**Abstract:** We report new measurements of the vertical geomagnetic cutoff for cosmic rays with rigidities from ~500 to 1700 MV, made using data from the MAST instrument on SAMPEX. A total of ~10,000 nuclei were used to measure the latitude cutoff in nineteen separate rigidity intervals. These results show that cosmic rays and solar particles can penetrate several degrees lower in latitude than would be estimated from commonly used relations for the geomagnetic cutoff, which has implications for the radiation exposure expected on the Space Station. An excellent fit to our measured cutoffs is given by the relation $R_c = 15.062\cos^4(\Lambda) - 0.363$ GV, where $R_c$ is the geomagnetic cutoff in rigidity, and $\lambda$ is the invariant latitude. We suggest that this relation is useful over invariant latitudes from $\Lambda = 0°$ to $64°$, corresponding to rigidity cutoffs from ~0.2 to 15 GV.

## 1 Introduction

Störmer (1930) first described the behavior of cosmic rays in the Earth's dipole field. He was able to derive a relation for the geomagnetic cutoff rigidity – the minimum-rigidity particle that can reach a given latitude above the magnetic equator as a function of its direction of arrival. Most of our subsequent knowledge of the geomagnetic cutoff has resulted from studies that trace (negatively charged) particles backwards through models of the Earth's field. Such studies have produced a grid of geomagnetic cutoff rigidities distributed over the Earth's surface (e.g., Shea and Smart 1985). Smart and Shea (1994) summarized a number of useful relations to estimate the geomagnetic cutoff in a given direction at a given location and pointed out the usefulness of the McIlwain L-parameter for organizing geomagnetic cutoffs. In this paper we consider particles arriving from the vertical direction, for which the

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recommended relation is $R_{cv}$ (in GV) = $C_{sv}L^{-2}$, where the constant $C_{sv}$ gradually decreases with time as the Earth's dipole moment decreases. For the 1990 epoch, Smart and Shea (1994) recommend $C_{sv} = 14.5$ GV.

Although there have been relatively few satellite surveys of geomagnetic cutoffs, comparisons of such measurements with the particle-tracing studies generally show that the measured cutoff latitudes are several degrees lower than the theoretical cutoffs (e.g., Fanselow and Stone 1972, who studied 1.2 to 39 MeV protons). At lower latitudes, measurements of ~2 and ~5 GV oxygen nuclei by HEAO-3 also gave cutoffs 3% to 5% lower in rigidity than theoretical cutoffs (Petrou et al. 1981; Byrnak et al. 1981; Copenhagen – Saclay Collaboration 1981;). Thus, particles of a given rigidity generally have access to lower latitudes than expected (Smart and Shea 1994).

More recently, cutoff measurements carried out using solar energetic particles (SEPs) with ~1 to tens of MeV/nucleon (Leske et al. 1995; 1997; 2001; Mason et al. 1995; Boberg et al. 1995; Mazur et al. 1999) have provided detailed evidence of variations in the high-latitude cutoff with geomagnetic activity and also verified that the rigidity cutoff at a given latitude is generally less than derived from particle-tracing techniques. New calculations by Smart, Shea and Flückiger (1999) and Smart et al. (1999a, 1999b) using an improved geomagnetic field model have resulted in generally lower rigidity cutoffs than derived from earlier particle-tracing studies.

Precise knowledge of the geomagnetic cutoff has recently become more important because it affects the extent to which the Space Station is subjected to radiation hazards during large solar particle events (Siscoe et al. 1999). In this paper we present the results of direct measurements of the geomagnetic cutoff which show that at a given latitude the quiet-time geomagnetic cutoff is systematically lower than is given by the standard $R_c = C_{sv}L^{-2}$ relation given above and by the latest particle-tracing calculations. As a result, the flux of solar particles that can reach the Space Station is significantly greater than would have been expected.

## 2 Approach

Galactic cosmic rays are stripped of their orbital electrons during passage through $\sim 5$ to $10$ g/cm$^2$ of interstellar material, and therefore have an ionic charge state (Q) equal to their nuclear charge (Z). We determine the rigidity (R) of individual particles by specifying Z, their mass (M) and their kinetic energy per nucleon in MeV/nucleon (E), and using the relation

$$R \text{ (in MV)} = (M/Ze)[E^2 + 2mE]^{1/2}. \quad (1)$$

Here R is the rigidity in MV, e is the electron charge, and m is the equivalent of an atomic mass unit in MeV.

The Mass Spectrometer Telescope (MAST) on SAMPEX measures the elemental and isotopic composition of solar, magnetospheric, and cosmic ray nuclei with ~20 to 200 MeV/nucleon in low-Earth orbit. The nuclear charge, mass, and kinetic energy of particles that stop in the telescope is determined using the conventional $\Delta$E-E technique (Cook et al. 1993). The rms mass resolution varies from ~0.1 amu for $Z = 6$ to ~0.3 to 0.4 amu for $Z = 26$, while the energy resolution is ~0.1%. The resulting uncertainty in particle rigidity is ~1%.

SAMPEX was launched on July 3, 1992 into a polar orbit with 82° inclination, with an average altitude of ~600 km. It is known that geomagnetic cutoffs are well organized by the McIlwain L parameter (e.g., Selesnick et al. 1995). From the SAMPEX orbital elements the L-shell where each particle was measured was identified using the 1990 IGRF magnetic field model. It is convenient to organize the geomagnetic cutoffs using the invariant latitude ($\Lambda$), defined by $L = \cos^{-2}(\Lambda)$ (Roederer, 1970). During this study SAMPEX was oriented towards the zenith while at latitudes above ~45°, ideal for measuring the vertical cutoff. Although MAST has a 50°-opening angle, averages of the estimated azimuthal variations in the cutoff over the MAST opening angle differ from the vertical cutoff by only a few tenths of a per cent. In order to eliminate SEPs, which are not generally fully stripped (e.g., Leske et al. 1995), we accepted for analysis only time periods when the daily-average flux of ~8 to 15 MeV/nucleon He was <4 x 10$^{-4}$ per cm$^2$sr-sec.

To avoid contamination by singly-charged anomalous cosmic rays (ACRs), we excluded B and C nuclei with <50 MeV/nucleon, N with <60 MeV/nucleon, O with <90 MeV/nucleon, and F and Ne with <65 MeV/nucleon. Recently discovered low-energy enhancements in Mg, Si, and S, which may consist of singly-charged ions (e.g., Reames 1999, Cummings et al. 1999) contribute less than 0.1% of the nuclei in the energy interval covered by MAST.

During geomagnetic storms the cutoff at high latitudes is often variable and temporarily lowered by a significant amount (e.g., Leske et al. 2001). We therefore eliminated periods within ±12 hours of times when the geomagnetic index Dst was less than –100 nT. The mean value of Dst for the remaining periods was –17 nT. The final cutoff measurements were not sensitive to this Dst cut.
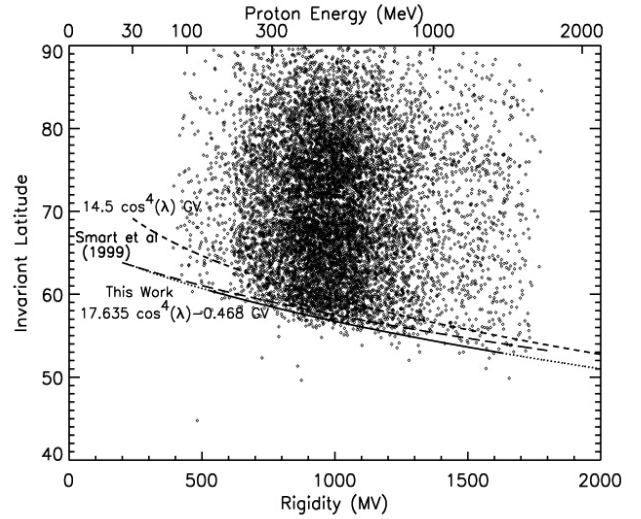


Figure 1: A plot of the measured invariant latitude versus rigidity for all accepted nuclei. The relation $R_c = 14.5\cos^4\Lambda_c$ GV is shown for comparison. Note that the actual cutoff is uniformly lower than is given by this relation. Also shown is a curve derived from calculations by Smart et al. (1999) that are discussed below.

A plot of the measured latitude versus rigidity for particles satisfying the above cuts is shown in Fig. 1, where the cosmic-ray cutoff is clearly defined down to rigidities as low as ~500 MV. These data were used to measure the minimum latitude to which cosmic rays with a given rigidity could penetrate. Latitude distributions were plotted for 19 rigidity intervals, taking into account the exposure time in each latitude bin (example in Fig. 2). The cutoff latitude ($\Lambda_c$) at a given rigidity was defined to be the latitude at which the number of events per degree dropped to 50% of the average level at latitudes >60°.
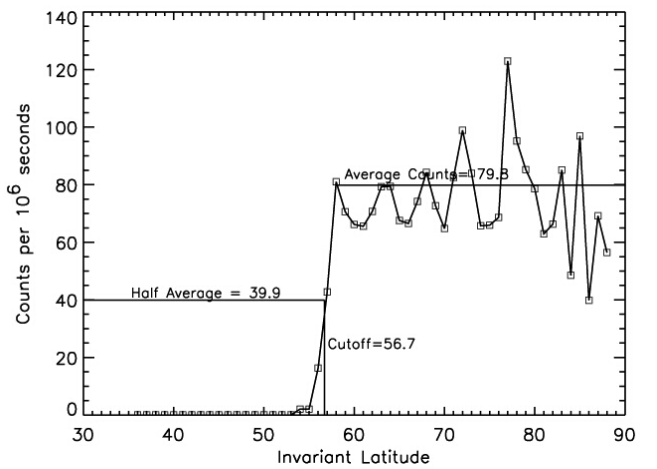


Figure 2: An example of the method for determining the cutoff latitude for a given rigidity interval. In each case the mean number of events per 10$^6$ seconds was determined (averaged over latitudes ≥60°). The cutoff latitude was defined to be that latitude where the event rate dropped to 50% of the mean value above 60°.
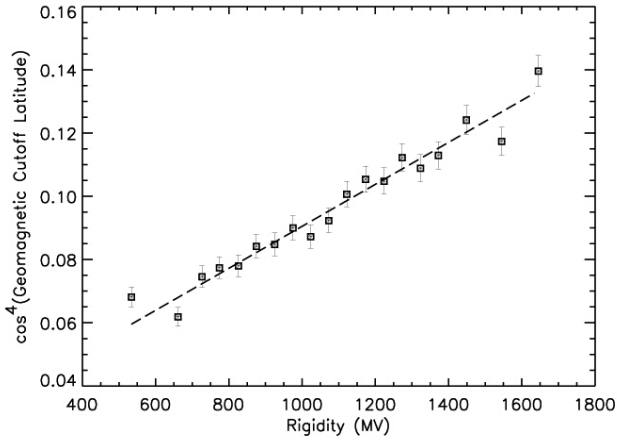
Figure 3: Measured values of $\cos^4\Lambda_c$ plotted versus rigidity are well fit by the relation $R_c = 15.062\cos^4\Lambda_c - 0.363$ GV.

In Fig. 3 we plot the quantity $\cos^4\Lambda_c$ as a function of rigidity, as suggested by earlier work. From a least squares fit we find $\cos^4\Lambda_c = (6.639 \times 10^{-5})R_c + 0.0241$ (where $R_c$ is in GV), which can be inverted to give

$$R_c = 15.062\cos^4\Lambda_c - 0.363 \text{ GV}, \qquad (2)$$

or equivalently, $R_c = 15.062L^{-2} - 0.363$ GV.

The uncertainties on the $\Lambda_c$ values have been estimated in several ways. Based on the uncertainty in the plateau value and the slope of the distribution in the region of the cutoff we find a typical uncertainty of 0.1° to 0.2°. By considering the nineteen points in Fig. 4 as 17 sequences of three adjacent values, and assuming that $\cos^4\Lambda_c$ varies linearly with rigidity over an interval of ~100 MV, we find that the rms uncertainty on the points is 0.39°. We therefore assume that all points have equal statistical uncertainties of 0.4°. A least-squares fit to the data in Fig. 3 then gives a reduced chi-square of 1.4.

## 3    Comparison with Previous Studies

Fanselow and Stone (1972) measured 1.2 to 39 MeV protons in several rigidity intervals and found that the cutoff varied with local time. Fig. 4 shows our new measurements and their values for local midnight. The extrapolation of our cutoff relation agrees quite well with their results. Fig. 4 also includes SAMPEX measurements of the cutoff using SEP H and He nuclei. Note that the cutoffs from SEPs differ somewhat from each other, presumably because the measurements were generally made during disturbed geomagnetic conditions (see, e.g., Leske et al. 1995, 2001). However, the extrapolation of our relation to lower rigidities is consistent with the ensemble of the SEP results.

Smart and Shea (1994) summarized a number of useful representations of the geomagnetic cutoff. Figure 4 includes the relation $R_c = 14.5$ GV/$L^2$, which they recommended for the vertical cosmic ray cutoff. We find that cosmic rays of a

given rigidity can penetrate several degrees lower in latitude than is predicted by this well-known relation. Equivalently, our results show that at a given geomagnetic latitude it is possible to observe cosmic rays with rigidities ~200 to 300 MV lower than expected from this relation.
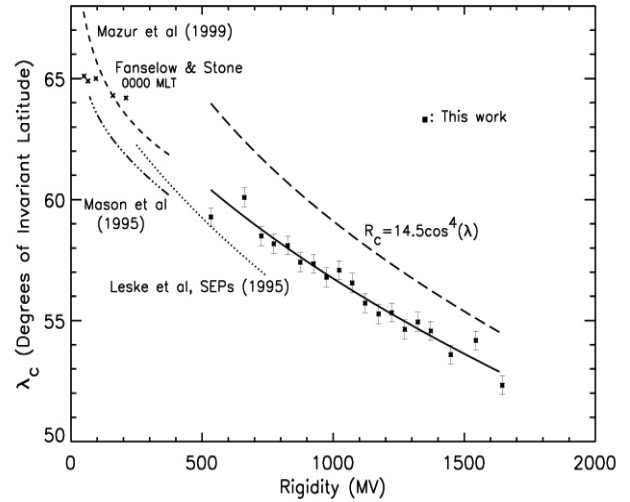


Figure 4: Comparison of the quiet-time geomagnetic cutoff determined here with average cutoffs determined using SAMPEX data during solar energetic particle events in 1992 and 1997 by Leske et al. (1995), Mason et al. (1995) and Mazur et al. (1999). Also shown are OGO-4 measurements at local midnight (Fanselow and Stone 1972). In SEP events the geomagnetic cutoff often varies due to associated geomagnetic activity. Note that the quiet-time cutoff reported here is significantly less than that given by the well-known relation, $R_c = 14.5L^{-2}$ GV
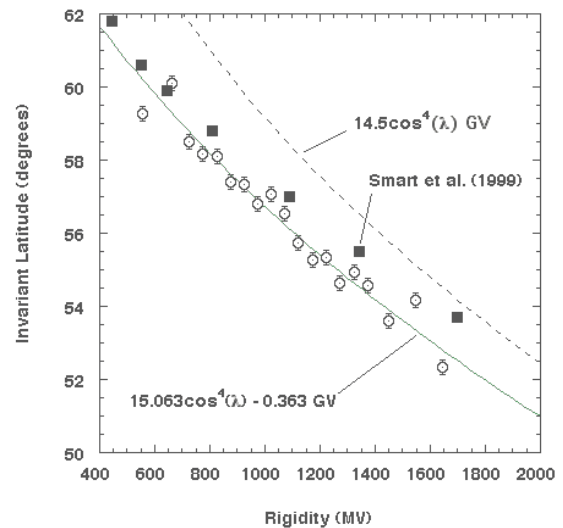


Figure 5: Comparison of the geomagnetic cutoff determined by SAMPEX with the results of new cutoff estimates by Smart et al. (1999) using particle trajectory tracing techniques in an improved magnetic field model. The points shown are for protons with 100, 150, 200, 300, 500, 700, and 1000 MeV and were interpolated from their Fig. 2 for Kp $\approx$ 2.3.

Smart, Shea and Flückiger (1999) and Smart et al. (1999a, 1999b) recently presented new estimates of the geomagnetic cutoff based on particle-trajectory tracing in magnetic field model that combined a Tsyganenko (1989) magnetospheric field model with the International Geomagnetic Reference Field for epoch 1995.0. They determined the cutoff over a grid of geographic points for several values of the geomagnetic index Kp. The average value of Kp during our study was 2.3. Smart et al. (1999b) provide a summary of cutoff latitudes as a function of rigidity for Kp values from 1 to 10 (see their Figure 2). In Fig. 5 we compare their calculated cutoffs (for Kp = 2.3) with our measured values, and with our best-fit cutoff relation. Although their estimates agree much better with our measurements than does the standard relation, there remains an average difference of ~0.7° between their calculated cutoffs and our best-fit relation.

Our results indicate that the cutoff grid in Smart, Shea and Flückiger (1999) systematically overestimates the quiet-time cutoff for invariant latitudes from 52° to 60° by 8% to 14%. In spite of these differences, these new calculations are significantly improved over earlier studies that employed less-sophisticated magnetic field models.

## 4 Implications for the Space Station

The International Space Station (ISS), in low-Earth orbit with an inclination of ~55°, has access to invariant latitudes up to ~66°. Although much of the radiation dose equivalent experienced by ISS astronauts is due to galactic cosmic rays and trapped radiation , the largest SEP events can contribute a significant radiation dose from high-energy protons and He (Siscoe et al. 2000). As an illustration, we use the proton spectrum measured by the GOES spacecraft during the large ("Bastille Day") SEP event of 14 July, 2000. For >100 MeV protons we find that the fluence reaching the ISS during this event would be ~4 times as great with the new cutoff relation as with the standard relation. Previous studies have concluded that the ISS is not subjected to significant fluxes of solar protons with <30 MeV during quiet geomagnetic conditions (e.g., Figure 1.5 in Siscoe et al. 2000). However, using our relation 30 MeV protons can be observed down to $\Lambda \approx 63°$ during geomagnetically-quiet periods. We find that the orbit-averaged intensity of >30 MeV solar protons is ~20 times greater with our relation [Eq. (2)] than with the older relation $R_c = 14.5L^{-2}$ GV.

## 5 Summary

The measured quiet-time geomagnetic cutoff from 0.5 to 1.7 GV is well represented by the relation $R_c = (15.062L^{-2} - 0.363)$ GV. At a given invariant latitude the geomagnetic cutoff given by this relation is anywhere from 200 to 300 MV lower than is given by the commonly-used relation $R_c = 14.5$ GV/$L^2$. It is also somewhat lower than given by recent calculations using improved geomagnetic field models. The new relation also appears to provide good

estimates of the cutoff well outside the range over which it is measured.

Use of our improved geomagnetic cutoff relation leads to significantly larger estimates of the radiation exposure of the ISS due to SEPs than are obtained with commonly-used relations for the cutoff. Recent particle-tracing techniques based on improved models of the geomagnetic field (Smart, Shea, and Flückiger 1999) appear to be in better agreement with the results presented here than are previously used relations, but the theoretical cutoffs still overestimate the rigidity cutoff at a given latitude.

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