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THE EFFECTS OF RECENT SECULAR VARIATIONS OF THE GEOMAGNETIC FIELD ON VERTICAL CUTOFF RIGIDITY CALCULATIONS

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Recent geomagnetic measurements have shown that changes in the geomagnetic field have deviated from the predictions of the original International Geomagnetic Reference Field (IGRF) coefficients and associated time derivatives. Accordingly, a new set of time derivatives have been determined with the suggestion that these be applied for time periods after 1975. To ascertain the effects of the changes of geomagnetic field time derivatives on cosmic ray analyses, vertical cutoff rigidities were calculated for selected locations using the IGRF 1965 field coefficients and associated time derivatives and the IGRF 1975 field coefficients and the new time derivatives making each set of calculations appropriate for a 1980 Epoch. A comparison of these two sets of calculations shows that the uncertainty in predicted magnetic fields does not appear to be a serious limiting factor in the use of calculated vertical cutoff rigidities for the analyses of cosmic radiation data.

1. INTRODUCTION

Many analyses of cosmic radiation data are dependent upon the cutoff rigidity of the locations where data are acquired. For the past fifteen years these cutoff rigidities have been determined by the computational technique of numerically tracing the orbits of cosmic rays through a mathematical model of the magnetic field. Although this technique is considered as the most reliable method of determining cutoff rigidities, it is also recognized that the cutoff rigidities determined in this manner can only be as accurate as the magnetic field description utilized in the trajectory-tracing process.

The International Geomagnetic Reference Field (IGRF) adopted by IAGA in 1969 (IAGA Commission 2 Working Group 4, 1969) is a composite of several geomagnetic field models. Although the model itself was normalized to a 1965 Epoch, the time derivatives were derived from actual field measurements through 1967. Thus, the utilization of the time derivatives for years prior to 1965 resulted in fairly representative models of the actual field as these time derivatives were determined from magnetic field measurements; however, extension of the time derivatives into the future (i.e. beyond 1968) produced a "predicted" field based upon the assumption that the time derivatives themselves were constant.

Subsequent measurements of the geomagnetic field revealed changes that were not consistent with the predictions of the original IGRF time derivatives. In general, the geomagnetic field has been changing more rapidly than was predicted in 1968 (Cain, 1975).

After consideration of the problems associated with deriving updated models and also considering the various uses of the models, the IAGA Division 1 Study Group (1976) recommended the following: that the IGRF 1965 model with its time derivatives should be used for the period 1955-1975, but that a new set of time derivatives to give a reasonable estimate of the true rate of the secular variation at Epoch 1975 should be utilized for predicting magnetic field coefficients for epochs later than 1975. Thus, a discontinuity in the IGRF specification of the geomagnetic field would occur at 1975. In this paper we have investigated if this discontinuity in the geomagnetic field specification, results in a similar discontinuity in the calculation of vertical cutoff rigidities.

2. METHOD

Vertical cutoff rigidities were calculated by the trajectory-tracing technique using two mathematical representations of the internal geomagnetic field adjusted to a 1980 Epoch as follows: (A) the IGRF coefficients for Epoch 1965 (IAGA Commission 2 Working Group 4, 1969) with their original time derivatives applied for a span of 15 years to Epoch 1980, and (B) the IGRF coefficients for Epoch 1975 (IAGA Division 1 Study Group, 1976) with the new time derivatives applied for a span of 5 years to Epoch 1980. These two representations will be called the original and adjusted time derivatives, respectively, for the remainder of this paper.

These vertical cutoff rigidities were determined by the method described by Shea et al. (1965) using 0.01 GV intervals throughout the penumbral region. These values were obtained for the following locations: (A) cosmic ray stations in the Western Hemisphere where the vertical cutoff rigidity decreases with time (Shea, 1971), and (B) selected locations on the world grid of vertical cutoff rigidities (Shea and Smart, 1975) where the vertical cutoff rigidity (1) increased, (2) decreased, or (3) remained essentially constant with respect to the 1965-1975 interval.

Once the vertical cutoff rigidities were determined for these locations, the results were evaluated in the following manner:

TABLE 1

VERTICAL CUTOFF RIGIDITIES FOR SELECTED COSMIC RAY STATIONS IN LATIN AMERICA

		Vertical Cutoff Rigidity (GV)					
Station	Rigidity Parameter	Epoch 1955	Epoch 1965	Epoch 1970	Epoch 1975	Epoch 1980	Epoch 1980A
Mexico City	P(m)	10.06	9.57	9.51	9.44	9.35	9.33
	P(c)	9.46	9.12	8.99	8.88	8.70	8.71
	P(s)	8.95	8.77	8.67	8.57	8.47	8.46
Buenos Aires	P(m)	10.89	10.59	10.44	10.31	10.15	10.13
	P(c)	10.58	10.22	10.03	9.88	9.73	9.69
	P(s)	10.17	9.80	9.62	9.46	9.30	9.28
Ushuaia	P(m)	5.80	5.60	5.50	5.42	5.32	5.29
	P(c)	5.67	5.51	5.33	5.29	5.17	5.14
	P(s)	5.15	4.79	4.78	4.73	4.72	4.88
Chacaltaya	P(c)*	13.07	12.85	12.75	12.64	12.54	12.52
Huancayo	P(c)*	13.44	13.24	13.14	13.04	12.95	12.92

*No penumbral structure in the vertical direction for Chacaltaya or Huancayo.

(A) Does the general trend of the vertical cutoff rigidity (i.e. increase, decrease or no change) remain constant with both field representations for 1980 (i.e. using the original time derivatives and the adjusted time derivatives)?

(B) Do significant differences occur in the vertical cutoff rigidity values for the two field representations?

3. RESULTS

Table 1 presents vertical cutoff rigidities for selected Latin American locations where the vertical cutoff rigidity has been decreasing with time. All values were calculated using the IGRF Epoch 1965 field coefficients with its associated time derivatives with the exception of the last column, labeled 1980A, where the adjusted time derivatives were utilized. Table 2 presents vertical cutoff rigidities for six locations as follows: two locations each where the vertical cutoff rigidity increases, decreases, or remains essentially constant with respect to time. The parameters listed in these tables are the main cone cutoff rigidity, P(m), the effective cutoff rigidity, P(c), and the Stormer cutoff rigidity, P(s). The cutoff rigidity values were taken from Shea et al. (1976).

TABLE 2

VERTICAL CUTOFF RIGIDITIES FOR SELECTED LOCATIONS

Location/ Parameter	Cutoff Rigidity (GV) Epoch 1965	Epoch 1975	Epoch 1980	Epoch 1980A
20N, 315E				
P(m)	11.32	11.59	11.72	11.72
P(c)	10.88	11.45	11.63	11.63
P(s)	9.78	10.35	10.65	10.64
15N, 300E				
P(m)	11.08	11.29	11.40	11.41
P(c)	10.15	10.71	10.97	10.99
P(s)	9.10	9.63	9.86	9.88
25S, 135E				
P(m)	8.17	8.02	7.91	7.92
P(c)	7.93	7.71	7.61	7.67
P(s)	6.37	6.25	6.35	6.32
30S, 330E				
P(m)	10.29	10.41	10.47	10.47
P(c)	7.91	8.46	8.64	8.63
P(s)	7.49	7.83	7.97	8.06
45N, 105E				
P(m)	6.58	6.62	6.63	6.59
P(c)	6.27	6.29	6.31	6.29
P(s)	5.56	5.51	5.18	5.33
25S, 195E				
P(m)	11.69	11.65	11.63	11.76
P(c)	11.20	11.22	11.23	11.18
P(s)	10.25	10.29	10.31	10.25

4. DISCUSSION

An inspection of the values given in Tables 1 and 2 show that the general trend (increase, decrease or no change) is preserved for vertical cutoff rigidity calculations for 1980 irrespective of the utilization of the original or adjusted time derivatives in the determination of the geomagnetic field coefficients for Epoch 1980. Differences in the actual values for both the main cone and effective cutoff rigidity are of the order of 0.05 GV. (We exclude the Stormer cone cutoff rigidity in this discussion since it is the most difficult value to accurately determine by the trajectory-tracing process.) The question then arises as to whether 0.05 GV is significant in the utilization of these values in analyses of cosmic radiation data. In discussing this problem we must consider (A) the relative accuracy of the values, (B) the absolute accuracy of the values, and (C) the uncertainties in the trajectory-tracing technique.

Relative Accuracy. For analyses where the cosmic radiation intensity observations at one location are compared with those at other locations, the vertical cutoff rigidity calculated for 1980 using either set of time derivatives would be adequate provided consistency was maintained.

Absolute Accuracy. We know of no experimental measurements at the present time capable of determining a 0.05 GV difference in vertical cutoff rigidity. In utilizing vertical cutoff rigidity as an analysis parameter, we must remember that this is the cutoff value in one specific direction (i.e. radial vertical) often accepted as a value typifying the location. Absolute differences of 0.05 GV would be a second order effect when compared against the above simplifying assumption. If the vertical value is extrapolated (perhaps by the application of Stormer theory) to other azimuth and zenith angles, then the absolute differences of 0.05 GV are probably smaller than the uncertainties introduced by the extrapolation process.

Computational Technique. The problems in the computational technique can be separated into two parts - the increment of rigidity used in the determination of the vertical cutoff rigidities, and the size of the step length used in the trajectory-tracing process.

Most vertical cutoff rigidities calculated by the trajectory-tracing procedure have utilized 0.01 GV rigidity intervals, particularly in the penumbral regions. (See Shea et al., 1965 and Shea and Smart, 1974, for a discussion of the effects of interval size.) Even using a standard interval of 0.01 GV can result in slight differences in the calculation of an allowed or a forbidden orbit in the penumbral region when utilizing two different computers simply because of the manner in which each computer operates, such as the number of significant figures carried, etc. However, even though minor differences in the determination of allowed and forbidden orbits in the penumbra might be calculated, the gross features in the penumbra are preserved. This same effect is true of the trajectories calculated for this paper. Figure 1 illustrates the penumbral structure for particles vertically incident at 15^{o}N, 300^{o}E for Epochs 1965, 1975 and the two sets of coefficients utilized for Epoch 1980. Although the effective vertical cutoff rigidity increases with time at this location (See Table 2), the gross characteristics of the penumbral structure are preserved.

The original trajectory-tracing program of McCracken et al. (1962) utilized a library of step sizes in the numerical integration technique that were deliberately made small in an attempt to minimize the error accumulation in the Runge-Kutta iteration process. In an effort to make the computer program more efficient and less time consuming, the standard McCracken library of step sizes was replaced by a variable step size that was about 1/50 of the distance a particle with a specific rigidity traveled during one gyration (Shea et al., 1976). Although this necessitated the recalculation of the step length for each Runge-Kutta iteration, the trajectory calculations could be performed with considerably greater speed without loss of appreciable accuracy. Minor differences between the two programs that occurred, primarily in the penumbral region, were attributable to the slightly different orbits calculated for two identical particles.

An example of the differences that may occur in the utilization of different step sizes in the trajectory-tracing process is given in Figure 2 which illustrates the penumbral structure for particles vertically incident at 45^{o}S, 240^{o}E as calculated using four different step sizes in tracing the particle trajectories through the IGRF (Epoch 1965) geomagnetic field model. Although minor differences in the fine line structure can be ascertained, the gross features are similar. These minor differences result in the determination of effective vertical cutoff rigidities that differ by 0.06 GV - approximately the same differences that are found in the vertical cutoff

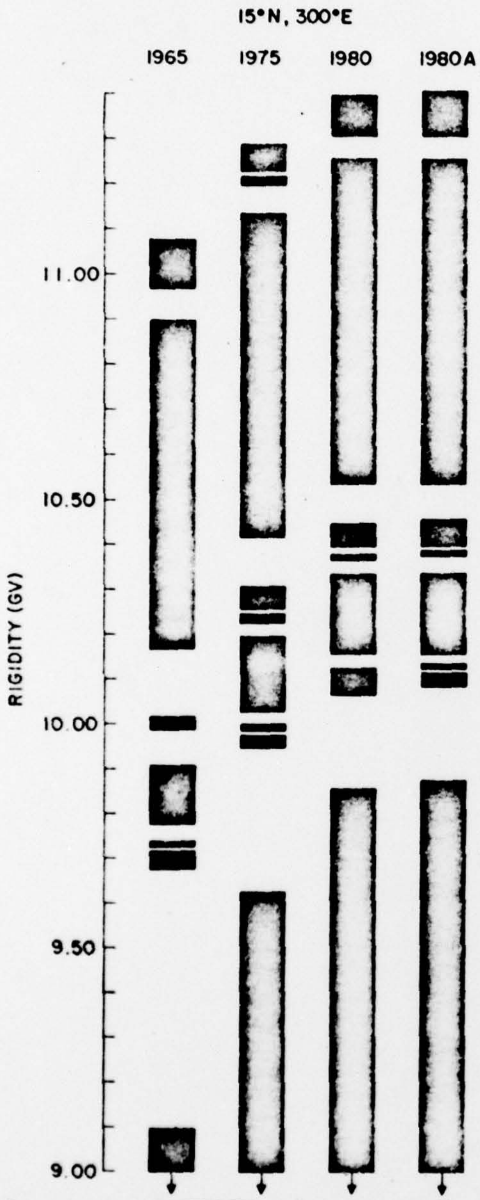

Figure 1. Penumbral structure for particles vertically incident at 15°N, 300°E for Epochs 1965, 1975, and the two sets of coefficients utilized for Epoch 1980. The column labeled 1980A indicates Epoch 1980 utilizing the adjusted time derivatives. White indicates allowed rigidities and black indicates forbidden rigidities.

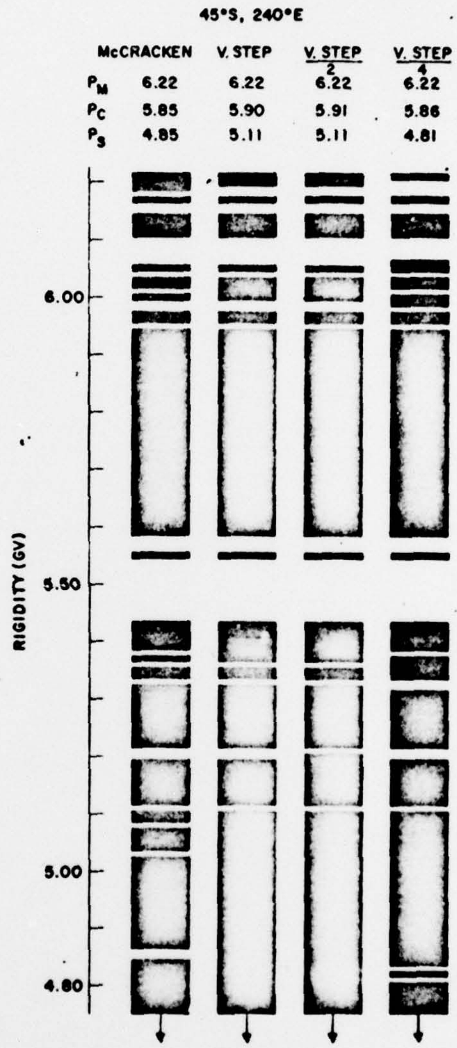

Figure 2. Penumbral structure for particles vertically incident at 45°S, 240°E, as calculated using four different step sizes: the original McCracken step size, the new variable step size (v. step), and the variable step size divided by 2 (v. step/2) and divided by 4 (v. step/4). The main cone cutoff rigidity is given by P_m, the effective cutoff rigidity by P_c, and the Stormer cutoff rigidity by P_s. White indicates allowed rigidities and black indicates forbidden rigidities.

rigidity calculations determined utilizing the two sets of coefficients for a 1980 Epoch of the geomagnetic field.

5. *CONCLUSIONS*

From the results presented in this paper we conclude that the utilization of the adjusted time derivatives with the 1975 IGRF coefficients does not result in a discontinuity in the calculation of vertical cutoff rigidities. The cutoff rigidity differences we calculate utilizing the original time derivatives for the IGRF (Epoch 1965) field coefficients and the adjusted time derivatives for the IGRF (Epoch 1975) field coefficients are approximately 0.05 GV - the same order of uncertainty that is present in the computational technique itself. We, therefore, recommend that the new adjusted time derivatives with the 1975 Epoch of the geomagnetic field be utilized in determining cutoff rigidity values for the interval 1976-1980.

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coefficients and the new time derivatives making each set of calculations appropriate for a 1980 Epoch. A comparison of these two sets of calculations shows that the uncertainty in predicted magnetic fields does not appear to be a serious limiting factor in the use of calculated vertical cutoff rigidities for the analyses of cosmic radiation data.