Final Technical Report on

The Development of a Dynamic Geomagnetic Cutoff Rigidity Model for the International Space Station

Grant # NAG9-1011

Account #5-2026

Submitted by

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Synopsis:

We have developed a computer model of geomagnetic vertical cutoffs applicable to the orbit of the International Space Station. This model accounts for the change in geomagnetic cutoff rigidity as a function of geomagnetic activity level. This model was delivered to NASA Johnson Space Center in July 1999 and tested on the Space Radiation Analysis Group DEC-Alpha computer system to ensure that it will properly interface with other software currently used at NASA JSC. The software was designed for ease of being upgraded as other improved models of geomagnetic cutoff as a function of magnetic activity are developed.

Introduction:

The minimum momentum a charged particle must possess to penetrate to a specified position in the earth's magnetic field is called the geomagnetic cutoff rigidity. Magnetic rigidity is momentum per unit charge and is a canonical coordinate that is independent of the charged particle mass or isotopic composition. Geomagnetic cutoff rigidities (Shea et al., 1965) quantify the geomagnetic shielding provided by the earth's magnetic field. (See Cooke et al., 1991 for contemporary definitions of geomagnetic cutoff rigidities.) The geomagnetic cutoff rigidity value uniquely describes charged particle access to a specific location in the earth's magnetic field. Accurate cutoff rigidity values permit calculation of the intensity of the galactic cosmic radiation or energetic solar particle radiation at any location on the earth or in near-earth space. Geomagnetic cutoff values can be converted to the cutoff energy of any element or specific isotope when the atomic number and atomic mass are specified.

Work performed under this grant has resulted in the development of a vertical cutoff rigidity model for space applications. For space dosimetry applications it is necessary to be able to account for every energetic charged particle having access to the space vehicle or astronaut. This improved vertical cutoff model for space applications accomplishes this by specifying the upper vertical cutoff value, the lower vertical cutoff value and the average penumbral transmission between these two values for a specific location and altitude.

This work incorporates our most recent results of calculating the vertical cutoff changes expected as a result of magnetic activity (Smart et al., 1999a,b,c). These geomagnetic vertical cutoff rigidities were derived from calculations employing the Flückiger-Kobel version of the cosmic ray trajectory program (private communication) which contains the Tsyganenko (1989) magnetospheric model as modified by Boberg et al. (1995) to accommodate additional magnetic activity levels. The basic data utilized for this effort consisted of vertical cutoff rigidity values every 5 degrees in latitude and 15 degrees in longitude for magnetic activity levels ranging from Kp = 0 to Kp = 9.

A more detailed description of the software is given in Appendix A: Description of the 5 Degree by 5-Degree Geomagnetic Interpolation Method.

Results:

We have developed computer software, written in FORTRAN 77 that will provide geomagnetic vertical cutoff rigidity values appropriate for the position of the International Space Station. The input parameters required are the space station position (geographic latitude, longitude, altitude) and the magnetic activity level specified by the Kp index. The vertical cutoff rigidity values provided include an upper vertical cutoff, a lower vertical cutoff, and the average transmission efficiency through the penumbra. The vertical cutoff rigidities for a specific spacecraft position are determined by interpolation in a series of "look up" tables (one value for each integer Kp magnetic index value between zero and 9).

When a specified magnetic activity level is given and the vertical cutoff rigidity tables for that magnetic index loaded, there is further interpolation between world grid locations. The McIlwain "L" parameter has been demonstrated to be an excellent ordering parameter for cosmic ray cutoff rigidities (Smart and Shea, 1967; Shea et al., 1985). First, the "L" parameter is used to interpolate in latitude. Then linear interpolation is used to obtain the vertical cutoff rigidity appropriate for the longitude of the International Space Station position. The "L" parameter is also an excellent parameter to interpolate in altitude in order to account for the difference between the exact orbiting altitude of the International Space Station at a specific time and the altitude of the geomagnetic cutoff calculations (i.e. 450 km above the average earth radius).

The basic world grids of vertical cutoff rigidities every 5 degrees in latitude and 15 degrees in longitude were interpolated to a set of vertical cutoff rigidity world girds every 5 degrees in latitude and 5 degrees in longitude. The software was written employing these 5 degree by 5 degree vertical cutoff rigidity tables so when actual vertical cutoff values derived by trajectory tracing in a model magnetosphere for each 5 degrees in latitude and longitude are available, these updated data files can be incorporated into the software with minimum additional effort.

The vertical cutoff rigidity values for the upper vertical cutoff and the lower vertical cutoff are converted to proton energies for direct comparison with energetic charged particle data and for use in dose calculations.

Examples of capability of the Dynamic Geomagnetic Cutoff Rigidity Model.

We illustrate the computed change in vertical geomagnetic cutoff at 450 km as a function of magnetic activity. These non-linear changes are a function of latitude. The change in vertical cutoff rigidity at the longitude of the minimum vertical cutoff experienced by the International Space Station (ISS) orbit in the northern hemisphere is illustrated in Figure 1.

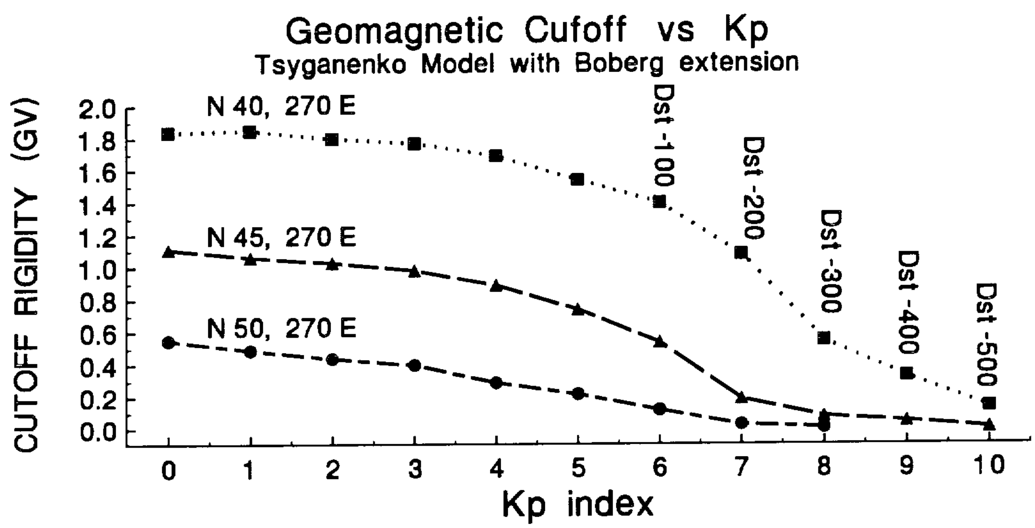

Figure 1. Illustration of the vertical cutoff reduction at various magnetic activity levels. The coordinates are the locations of the lowest vertical cutoff value experienced by the ISS orbit at the specified latitude in the Northern Hemisphere.

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 the world grids of vertical geomagnetic vertical cutoff rigidities for each magnetic activity level to determine proton vertical 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.

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 et al. (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 vertical 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 et al. (1995) extension are non-linear with the Dst increment.

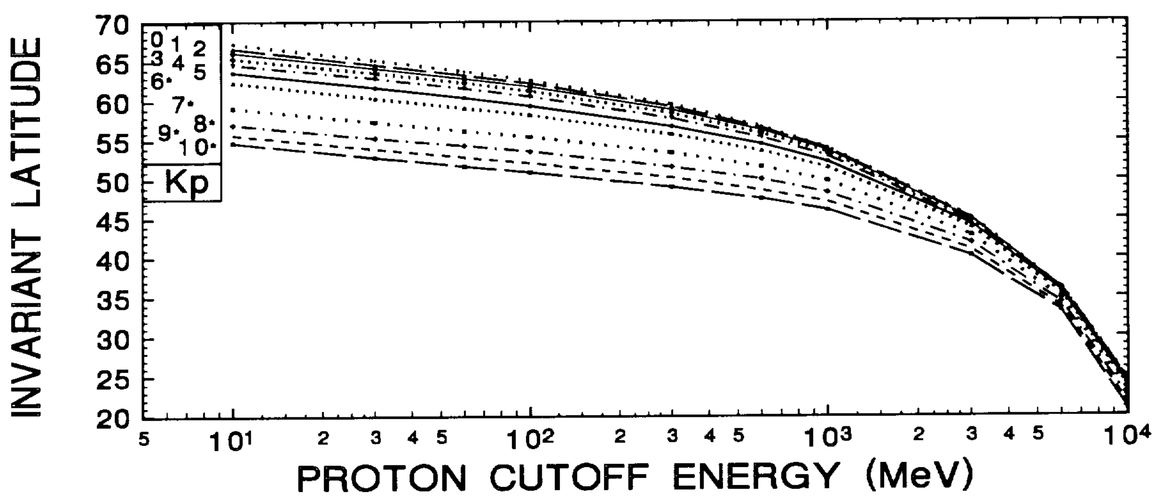

Figure 2. Calculated changes in the effective vertical cutoff energy for protons at 450 km altitude as a function of magnetic activity

Comparison with SAMPEX measured cutoffs

Smart and Shea (1967, 1994) found that the cutoff rigidity change with radial distance is proportional to L^{-2}. We fitted the vertical 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 vertical cutoff values appropriate for the altitude of the SAMPEX spacecraft (~ 600 Km). From these interpolations we determined the invariant latitude corresponding to the cutoffs of the energy ranges observed by the SAMPEX particle detectors for each observed Kp value from day 304 to day 312 of 1992 (30 October to 7 November) to compare our values with those measured by SAMPEX (Mason et al., 1995; Leske et al., 1997). Our simulation of the invariant latitude of the 29-64 MeV proton vertical 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 vertical 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 are also times when magnetic storm activity indicated by the hourly 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.

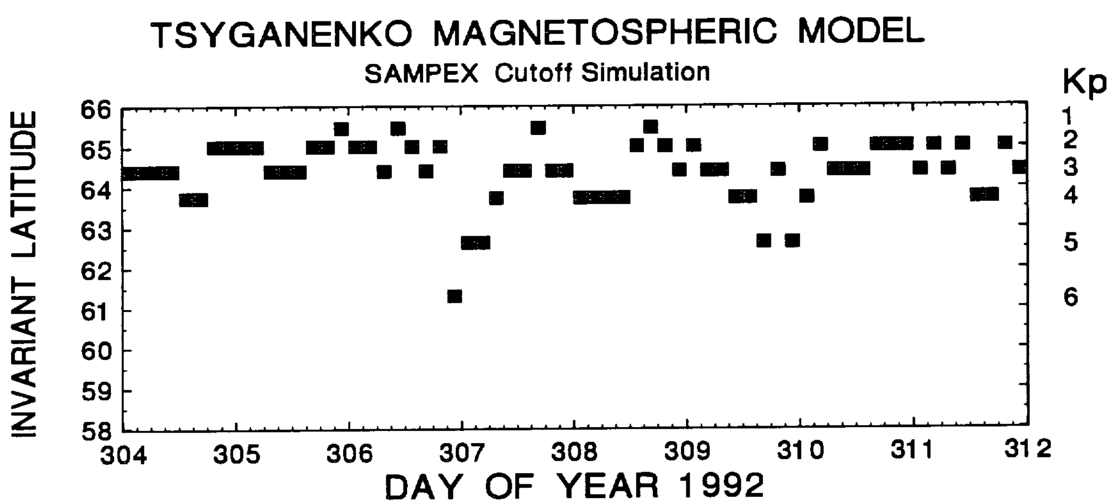

Figure 3. Simulation of the proton vertical cutoff energy variation as a function of the Kp index for the time period of 31 October to 7 November, 1992.

Appendix A is a description of the 5-degree by 5-degree geomagnetic interpolation method. This software was delivered to NASA Johnson Space Center in July 1999 and tested on the Space Radiation Analysis Group DEC-Alpha computer system to ensure that it would properly interface with other software currently used at NASA JSC.

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DESCRIPTION OF THE 5 DEGREE BY 5 DEGREE GEOMAGNETIC CUTOFF INTERPOLATION METHOD

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July 1999

PROLOG

Our basic geomagnetic cutoff rigidity calculations for 450 km altitude have been completed only for a relatively course grid of 5 degrees in latitude and 15 degrees in longitude. These values have been determined using the trajectory-tracing technique in the Tsyganenko magnetospheric model for magnetic activity levels ranging from "super-quiet" (Kp = 0) to extraordinarily disturbed conditions (Kp = 9+ which is, in this process, Kp = 10). The net result is that there are 11 unique data files giving vertical cutoff rigidities expected for every level of magnetic activity quantified by integer Kp values from 0 to 10. Each of these 11 data files contain averages of vertical cutoff rigidity values calculated by the trajectory-tracing method for four different Universal Times: 0000, 0600, 1200, and 1800 hours UT.

These 5-degree by 15-degree world grids of calculated vertical cutoff rigidities are a first approximation for determining cutoff rigidities for the International Space Station (ISS) orbit. We believe that a smaller grid size, 5 degrees in latitude and 5 degrees in longitude, would be better suited to predicting geomagnetic cutoff rigidities at spacecraft altitudes. However, this effort is beyond the scope of the current grant. (We estimate that completing the 5-degree by 5-degree world grid of vertical cutoff rigidities for the different magnetic conditions via the trajectory-tracing method requires state-of-the-art very fast processors for about 1000 processor hours.

Because of the computer work involved to determine the cutoff values for the basic grid, the scope of this specific grant was to produce an interpolation process (utilizing the previously calculated vertical cutoff rigidity values) that would generate interpolated cutoff rigidities appropriate for the ISS as a function of geomagnetic activity.

In anticipation that vertical cutoff rigidity values for a smaller world grid (5 degrees in latitude and 5 degrees in longitude) will eventually be available, we have prepared cutoff interpolation software for this smaller grid size (utilizing interpolated cutoff rigidity values for those grid points for which actual vertical cutoff rigidity values are not available.)

This specific software is called Subroutine LINT5X5 (FLATD, FLOND, ALTKM, PTV, RLP, RUP, RCP). The current data files that this software requires have been generated using the basic "L" interpolation procedure from the 5 x 15 degree world grid of vertical cutoff rigidity values calculated for an altitude of 450 km. The purpose of installing a 5 x 5 degree geomagnetic cutoff interpolation procedure at this point in time is to avoid later software changes when finer grid values become available. Updates to the vertical cutoff rigidity values can be accomplished by merely changing input data files, and will not require significant software modifications.

The software described below is intended to be "operational" software that will run quickly and efficiently, capable of providing real-time vertical cutoff rigidity values to the JSC SRAG group. The data files prepared for this 5 degree by 5 degree interpolation procedure contain pre-computed McIlwain "L" values to avoid having to calculate these parameters each time one of these data files is loaded.

As noted previously, there are 11 data files (5 by 5 degree world grids of vertical cutoff rigidity values) associated with this software. There is one data file corresponding to each integer magnetic activity level ranging from a Kp magnetic index of zero to extremely disturbed magnetic activity identified as Kp = 10. These 11 files are specifically identified in the description of subroutine SETUP5.

When this software is incorporated into other JSC SRAG software programs, some provision must be made for automatically checking for a change in the Kp value and if this occurs, to load in the file of world grid cutoff rigidity values corresponding to this magnetic activity level.

We have, for demonstration proposes, a test program based on the last two days of the STS28 orbit. This program reads the spacecraft ephemeris data file, obtains the date and time from this file, checks for a Kp index for the specified time, and automatically loads the world grid geomagnetic cutoff rigidity values (from one of the 11 files) corresponding to the given magnetic activity level.

Program LINT450J

This specific program is for testing purposes only. Its primary purpose is to test and evaluate the 5-degree by 5-degree vertical cutoff rigidity interpolation software. The key subroutines are

Subroutine SETUP5 (KPIDX)
and
Subroutine LINT5X5 (FLATD, FLOND, ALTKM, PTV, RLP, RUP, RCP)

These subroutines are required for the final operational version of the software that will provide geomagnetic vertical cutoff rigidity values for the International Space Station.

When program LINT450J is initiated, it will ask for an on-line entry of a Kp value. Error checking insures that the manual entry is an integer between 0 and 10. (If an unacceptable value is entered, the diagnostic 'Bad typing, try again' is printed and the software waits for another value.)

After receiving an acceptable entry, the software calls for the subroutine SETUP5 (KPIDX), where the integer variable KPIDX is the Kp value entered via the keyboard.

What we are doing, for this particular test, is to compare the L-interpolated cutoff values for a 5-degree by 5-degree world grid with cutoff values that have been calculated by the trajectory-tracing method. We have calculated these vertical cutoff rigidity values by the trajectory-tracing method every 5 degrees in latitude and 5 degrees in longitude for one set of conditions: magnetic activity index of Kp = 2 (at 0000 UT on 1 January 1995) using the Tsyganenko magnetospheric model. A detailed comparison of the calculated vs. the interpolated values allows a quantification of the utility of employing a 5 degree in latitude and 15 degree in longitude world grid of cutoff rigidity values for International Space Station purposes.

For this test, the software reads a data set of latitudes, longitudes and altitudes from unit 3. (The current tape3 is the set of world grid calculations made with the Tsyganenko magnetospheric model for a magnetic activity index of Kp = 2 as described in the previous paragraph.) For each latitude, longitude and altitude entry read, the software calls subroutine LINT5X5 (FLATD, FLOND, ALTKM, PTV, RLP, RUP, RCP) which returns values for the average penumbral transparency (PTV), the upper cutoff (Ru), the lower cutoff (Rl), and the effective cutoff (Rc).

The interpolated geomagnetic cutoff rigidity values (RLP, RUP, and RCP, in units of GV) calculated by subroutine LINT5X5 are written on tape7. This output unit also contains the calculated geomagnetic cutoff rigidity values read in (from tape3), the interpolated geomagnetic cutoff rigidity values for the specified latitude, longitude and altitude, and the difference between the calculated effective cutoff rigidity and the interpolated effective cutoff rigidity.

The interpolated geomagnetic cutoff rigidity values RLP, RUP, and RCP are also converted to proton kinetic energy since energy is the unit normally used in dose calculations. This is accomplished through the subroutine AZRGEG. First the cutoff rigidity values are converted from units of GV to MV. (1 GV = 1000 MV. Subroutine AZRGEG is designed to accept rigidity in units of MV and return energy in units of MeV.) Each of the geomagnetic cutoff rigidity quantities (RLP, RUP, and RCP) is converted to proton cutoff energies (EPNRL, EPNRU, and EPNRC). The variable names are intended to convey the quantity energy per nucleon for the proton lower cutoff value, the proton upper cutoff value, and the proton effective cutoff value.

The interpolated geomagnetic cutoff proton energy values (EPNRU, EPNRL, and EPNRC, in units of MeV) are written on tape8.

Subroutine SETUP5 (KPIDX)

This subroutine sets up the cutoff rigidity arrays. The argument KPIDX determines which set of cutoff rigidity data is entered into the arrays.

Input arguments

KPIDX	Integer value that corresponds to the Kp magnetic activity index

Return Arguments
none

Labeled Common arguments:

Block name:	SETRCL
/SETRCL/	RUG(37,75), RLG(37,75), RCG(37,75), FLG(37,75), VKRU(37,75), VKRL(37,75), VKRC(37,75), PWV(37,75)

RUG(37,75)	Array of pre-computed upper vertical cutoff rigidity values for 450 km.
RLG(37,75)	Array of pre-computed lower vertical cutoff rigidity values for 450 km.
RCG(37,75)	Array of pre-computed effective vertical cutoff rigidity values for 450 km.
FLG(37,75)	Array of pre-computed McIlwain "L" values for 450 km.
VKRU(37,75)	Array of Ru constants for the cutoff equation for each grid location
VKRL(37,75)	Array of Rl constants for the cutoff equation for each grid location
VKRC(37,75)	Array of Rc constants for the cutoff equation for each grid location
PWV(37,75)	Array of penumbral widths (zero in this version)

Dimensioned Variables
none

Data files:
There are 11 data files associated with this subroutine.
Depending on the variable KPIDX, a specific data file is loaded.

kp000av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 0.
kp100av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 1.
kp200av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 2.
kp300av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 3.
kp400av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 4.
kp500av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 5.
kp5d1av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 6*.
kp5d2av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 7*.
kp5d3av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 8*.

kp5d4av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 9*.

kp5d5av.dat	Pre-computed 5x5 world grid (five degrees in both latitude and longitude) of cutoff rigidity values for the magnetic activity level of Kp = 9+*

NOTE: The pre-computed grid values utilize actual computed vertical cutoff values for the 5 degree in latitude and 15 degree in longitude grid points, and L-interpolated vertical cutoff values for the remaining locations.

* The data for Kp = 6, 7, 8, 9, and 9+ are approximations obtained by adding an external Dst disturbance in addition to the Kp values.

Operation:
When this subroutine is called, the variables in the labeled common block that are cutoff rigidity values or "L" values are loaded with a value of -1.0. The variables loaded with -1's are:

RUG(37,75), RLG(37,75), RCG(37,75), FLG(37,75), PWV(37,75)

(In all further processing, a value of -1.0 indicates missing data.)

Depending on the value of KPIDX, a specific data file of cutoff rigidities is opened to be read. The data file must contain (on each line) a latitude, longitude, zenith, azimuth, altitude, "L" value, upper cutoff rigidity, lower cutoff rigidity, penumbral width, and effective cutoff rigidity. As each "line" is read, the latitude and longitude are converted to grid indices and then the cutoff data and "L" value are loaded into the appropriate data array. The data file is read until an End-of-File indicator is found. Then, a data checking sequence is initiated.

In the operational version of this software, the diagnostic output is normally turned off in order to increase the operational speed. To obtain diagnostics, the program must be re-compiled with the specific diagnostic print turned on. The control variables for the diagnostic printouts are the integer variables:

idg22, idg23, idg24, idg25, idg26, idg27, idg28, idg29,
idg30, idg31, idg32, and idg33. These values are normally set to zero.

Data checking:

(1). When a world grid cutoff rigidity file is loaded, every grid point is checked for a cutoff value. If any values are missing, then a one-line diagnostic is written instructing the operator to check the "missing.dat file" for the grid location values that are missing. (If this error message occurs, the data file should be corrected immediately!) The software will continue and fill in any missing grid values by interpolation.

(2). There must be a McIlwain "L" value at every grid point. These values should be in the data file loaded; however, if a value is missing it will be computed by a call to the initial B and L subroutine INVAR. The diagnostic file is 't22setl'. (unit 22 open statement)

(3). At high polar latitudes, the cutoff values can be artificially "jagged" because the 0.01 GV sampling intervals can be large compared with the cutoff value. (The allowed-forbidden criteria of the trajectory-tracing technique is beyond the scope of this report, but jagged contours can result in any region of the world, but particularly in the polar regions.) Cutoff values below 0.1 GV are fitted by the "L" parameter and smoothed values obtained. A separate output file can be obtained for each fit.

Upper cutoff values (Ru) can be on file 't23rufit'. (unit 23 open statement)
Lower cutoff values (Rl) can be on file 't24rlfit'. (unit 24 open statement)
Effective cutoff values (Rc) can be on file 't25rcfit'. (unit 25 open statement)

The original cutoff values in the data file are replaced by the fitted values for cutoffs below 0.1 GV. A separate output file can be obtained for each set of cutoff rigidities replaced.

Upper cutoff replacement (Ru) on file 't26rufit'. (unit 26 open statement).
Lower cutoff replacement (Rl) on file 't27rlfit'. (unit 27 open statement).
Effective cutoff replacement (Rc) on file 't28rcfit'. (unit 28 open statement).

The interpolation technique presumes a uniform grid at 5-degree intervals. The polar points, 90 degrees latitude both north and south are special cases. To preserve a uniform grid, pseudo 5-degree longitude intervals are constructed at north 90 and south 90. These pseudo longitudes all contain the same value. The values written in these pseudo longitudes are on file "t29plr'. (unit 29 open statement)

Another special case is the inconvenient fact that the magnetic field routine will "blow up" at 90 degrees. This is circumvented by substituting a latitude of 89.98 for 90 degrees in magnetic field calculations.

The basis of the interpolation technique is the fact that the McIlwain "L" parameter can be utilized in the cutoff equation for the cosine squared of the magnetic latitude. The equation

$R = \text{Constant}/L^2$ where, for this discussion we use the following:

$R = V_{(k)}/ L^2$

is presumed to exist at every gird location. The data file loaded in supplies the cutoff value and the "L" value. The software solves this equation for the constant V(k) at every grid point. A specific value for $V_{(kRu)}$, $V_{(kRl)}$, and $V_{(kRc)}$, is computed at each grid location in order to allow for the higher order variations in the earth's magnetic field. These $V_{(k)}$ values can be written to files for diagnostic checking. Tabular listing of the key values (i.e. the cutoff value, the "L" value, and the $V_{(k)}$ value) can be written to tables. These tables are organized so there will be one-quarter hemisphere per page, when printed on paper at 15 characters per inch.

The upper cutoff (Ru) table can be on file 't30rutbl'. (unit 30 open statement).
The lower cutoff (Rl) table can be on file 't31rutbl'. (unit 31 open statement).
The effective cutoff (Rc) table can be on file 't32rctbl'. (unit 32 open statement).

There is provision for a future diagnostic table of penumbral widths. The penumbral width is the difference between the upper computed cutoff (Ru) and the lower computed cutoff (Rl).

The penumbral width table can be on file 't33pwtbl'. (unit 33 open statement).

Subroutine LINT5X5 (FLATD, FLOND, ALTKM, PTV, RLP, RUP, RCP)

This is the "workhorse" subroutine to obtain a geomagnetic vertical cutoff value.

Input arguments

FLATD	Geographic latitude in degrees of the spacecraft position. (North is positive: 0 = equator)
FLOND	Geographic longitude in degrees of the spacecraft position. (Positive is East of Greenwich)
ALTKM	Attitude in kilometers above the earth's surface of the spacecraft position.

Return Arguments

PTV	Average transmission between RUP and RLP at the spacecraft position.
RLP	Geomagnetic vertical cutoff rigidity (in GV) at the spacecraft position. Lowest value.
RUP	Geomagnetic vertical cutoff rigidity (in GV) at the spacecraft position. Highest value.
RCP	Geomagnetic vertical cutoff rigidity (in GV) at the spacecraft position. Effective value.

Labeled Common arguments:

Block name: SETRCL

/SETRCL/ RUG(37,75), RLG(37,75), RCG(37,75), FLG(37,75), VKRU(37,75), VKRL(37,75), VKRC(37,75), PWV(37,75)

RUG(37,75)	Array of pre-computed upper vertical cutoff rigidity values
RLG(37,75)	Array of pre-computed lower vertical cutoff rigidity values
RCG(37,75)	Array of pre-computed effective vertical cutoff rigidity values
FLG(37,75)	Array of pre-computed McIlwain "L" values
VKRU(37,75)	Array of Ru constants for cutoff equation for each grid location
VKRL(37,75)	Array of Rl constants for cutoff equation for each grid location
VKRC(37,75)	Array of Rc constants for cutoff equation for each grid location
PWV(37,75)	Array of penumbral widths (zero in this version)

Block name: DIAGC

/DIAGC/ LTS(37), LNS(75)

LTS(37)	Array of latitude values every 5 degrees (+90 to -90)
LNS(75)	Array of longitude values every 5 degrees (-5 to 365)

Dimensioned Variables

PVTVDAT(16) Array of average penumbral transmission at each GV

Data files: none

Operation:

The initial calculations are performed for an altitude of 450 km, after which an interpolation to the spacecraft altitude is applied.

When the subroutine is called (with the coordinates and altitude of a specific spacecraft location) the latitude and longitude are converted to the correct geographic grid "box" on the 5-degree by 5-degree world grid "map". For each of the four corners of the grid "box" there are pre-computed constants for the cutoff equation in terms of the McIlwain "L" coordinate.

The basis of the interpolation technique is the fact that the McIlwain "L" parameter can be utilized in the cutoff equation for the cosine squared of the magnetic latitude. The constants for the equation

$R = \text{Constant}/L^2$ where, for this discussion we use the following:

$R = V_{(k)}/L^2$

were calculated in subroutine SETUP5 for every grid location and stored in the appropriate $V_{(k)}$ arrays. The data file loaded in by subroutine SETUP5, supplied the cutoff value and the "L" value for each grid point at 450-km altitude. The orientation of the specified latitude and longitude position of the spacecraft within the grid box is then determined. The McIlwain "L" coordinate of the spacecraft latitude and longitude is computed for 450 km (the altitude of the pre-computed values at the corners of the box). A cutoff value at 450 km at each corner of the box is present in the cutoff data arrays.

We then determine the cutoff value of the spacecraft latitude and longitude at 450 km as follows:

(1) Using the L value of the spacecraft latitude and longitude (at 450 km) and the constants for the above cutoff equation at each "box corner", we determine a cutoff value at the latitude of the spacecraft along the left and right side of the "box". For the left side of the "box", the constant for the upper left grid location is applied with the spacecraft L value to obtain the first trial left cutoff rigidity. Next the constant for the bottom left grid location is applied with the spacecraft L value to obtain the second trial left cutoff rigidity. Then these two values are averaged to obtain a "left side" cutoff rigidity. This process is repeated for the right side of the box.

(2) We then find the interpolated cutoff value at the spacecraft longitude using linear interpolation between the cutoff values obtained for the left side and the right side of the "box" at the spacecraft L coordinate at 450 km. The above two steps are applied to obtain the appropriate Rl, Ru, and Rc values for the spacecraft coordinates at 450-km altitude. A value for $V_{(k)}$ is specifically computed for the spacecraft coordinate (latitude and longitude) in the "box" using the cutoff rigidity values calculated above and the "L" value in the box. A value is obtained for $V_{(kRu)}$, $V_{(kRl)}$, and $V_{(kRc)}$.

Next we obtain the cutoff rigidities at the spacecraft altitude.

If the spacecraft altitude is not at 450 km, then the McIlwain "L" coordinate is computed at the spacecraft position and altitude and "L" interpolation is used to extrapolate from the values at 450 km altitude to the spacecraft altitude. The previously computed values of $V_{(k)}$ for the spacecraft latitude and longitude are used with the "L" coordinate of the spacecraft latitude, longitude and altitude to compute the cutoff values Ru(p), Rl(p), and Rc(p) where the final character (p) implies the actual spacecraft position (i.e. latitude, longitude and altitude).

The penumbral transparency (average transmission between the upper cutoff value and the lower cutoff value) is found by a lookup in the PVTVDAT array based on an index that is the magnitude of the average cutoff rigidity in GV.

Subroutine AZRGEG (NA, NZ, PAMU, RIGIN, EPN, BETA)

This is a subroutine for rigidity to energy conversion and vise-versa

Input arguments:

NA	integer atomic number
NZ	integer atomic charge
PAMU	physical mass unit of element (or isotope)

Utility arguments

RIGIN	Rigidity in MV
EPN	Energy per nucleon in MeV

Return Arguments

BETA	particle speed as a fraction of light speed (v/c)

Labeled Common arguments: none

Dimensioned Variables none

Data files: none

Operation:
When the subroutine is called it can do either a rigidity-to-energy conversion or an energy-to-rigidity conversion. If the variable RIGIN is positive, then the conversion is rigidity-to-energy and the output energy is in the variable EPN. If the variable RIGIN is initially set to zero or a negative value, then the conversion is energy-to-rigidity. The value RIGIN is replaced with the appropriate rigidity value for the energy specified in the variable EPN. The subroutine will work for any element or isotope. It is necessary to specify the atomic number (1 for protons), the atomic charge (1 for protons) and the atomic mass in physical mass units (1.0081451 for protons). (For the International Space Station cutoff rigidity interpolation process we only utilize the proton rigidity-to-energy conversion.) The RIGIN must be in the rigidity unit MV. The EPN (energy per nucleon) will be in MeV.

When called with the proper arguments, the software first tests the value of the variable RIGIN to determine which conversion to perform. The total kinetic energy of the particle is computed. The next step is to compute the relativistic gamma. (The relativistic gamma factor is a "natural unit" used in high-energy physics that is the ratio of the particle kinetic energy to rest mass energy.) From the relativistic gamma factor, either energy or rigidity can be computed. The particle speed BETA can also be computed from the relativistic gamma factor. The particle speed BETA is returned as an argument since it is useful in many conversions such as differential flux in terms of energy or rigidity.