MAGNETOCOMICS Software User Manual

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Abstract

This document provides all the necessary information to allow the user to install and operate the MAGNETOCOSMICS software. A general description of the software and of the notions needed for using the program is given, followed by a more extensive coverage of the commands available in the code. Some tutorial examples provided with the code are also described.

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0.1	3 July 2003	First issue to reviewers in draft form
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1. Introduction

1.1 Contractual

This document has been issued by the Physikalisches Institut of the University of Bern to QinetiQ under contract CU009-0000028872.

1.2 Purpose of the Document

This document is the Software User Manual (SUM) for the MAGNETOCOSMICS Geant4 application.

1.3 Scope of the Software

The MAGNETOCOSMICS software is only intended for use with the Geant4 code for Monte Carlo, high-energy particle transport.

1.4 Definitions, acronyms and abbreviations

ASCII	American Standard Code for Information Interchange
AIDA	Abstract Interface for Data Analysis
CERN	Conseil Européen pour la Recherche Nucléaire
DGRF	Definitive Geomagnetic Reference Field
ESA	European Space Agency
GEANT4	C++ toolkit for Monte Carlo simulation of high-energy, fundamental particle transport, developed by an international collaboration led by CERN.
GUI	Graphical User Interface
IAGA	International Association of Geomagnetism and Aeronomy
IGRF	International Geomagnetic Reference Field
IMF	Interplanetary Magnetic Field
OO	Object-Oriented
UI	User Interface

1.5 References

[1] The CERN Geant4 Collaboration provides a significant amount of information at the web site:

http://wwwinfo.cern.ch/asd/geant4/geant4.html
From this Web page, access can be obtained to User Documentation:

[2] User Guide for Application Developers: http://wwwinfo.cern.ch/asd/geant4/geant4_public/G4UsersDocuments/UsersGuides/ForApplicationDeveloper/html/index.html

[3] User Guide for Toolkit Developers: http://wwwinfo.cern.ch/asd/geant4/geant4_public/G4UsersDocuments/UsersGuides/ForToolkitDeveloper/html/index.html

[4] The Physics Reference manual: http://wwwinfo.cern.ch/asd/geant4/geant4_public/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/index.html

[5] The Software Reference manual provides information on the public methods to the Geant4 classes: http://geant4.kek.jp/../cgi-bin/G4GenDoc.csh?flag=1

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1.6 Overview of the document

In Section 2 of this manual a general description of the MAGNETOCOSMICS code and of some notions needed to use the program are presented. Section 3 covers the installation of MAGNETOCOSMICS and Section 4 describes the commands necessary to use it. Section 5 describes briefly different tutorial examples contained in g4macro files provided with the code.

2. General Description

The MAGNETOCOSMICS Geant4 application allows to compute the propagation of charged cosmic rays through different magnetic field models of the Earth's magnetosphere. It permits also to compute cutoff rigidities and asymptotic directions of incidence. Particle trajectories and magnetic field lines can be visualised by using one of the visualisation driver available in the Geant4 toolkit.

2.1 Space coordinate system

An important issue when simulating the propagation of cosmic rays in the Earth's magnetosphere is the transformation of the vector position and direction of a particle from one space coordinate system to another one. In MAGNETOCOSMICS the user can define the initial position and direction of a particle in the geodetic (GEOID), geographic (GEO) , geocentric equatorial inertial (GEI), geocentric solar ecliptic (GSE), geomagnetic (MAG), geocentric solar magnetospheric (GSM), and in solar magnetic (SM) coordinates [7-8]. For visualising trajectory and magnetic field lines he can select the coordinate systems : GSE, GEI, GEO, MAG, GSM, and SM.

In the geodetic coordinate system, the Earth's surface is modeled by an ellipsoid the geoid. In this system the position is defined by the geodetic altitude, latitude and longitude. The local vertical is defined by the line perpendicular to the geoid and passing trough the considered position. The distance from the position to the geoid surface along the geodetic vertical represents the altitude. The latitude is defined by the angle between the vertical and the Earth's equatorial plane. The longitude is counted eastward from the Greenwich meridian.

The coordinate systems other than the geodetic coordinate system are orthogonal, right-handed and geocentric. The Earth's center represents the center of these systems. A particle position can be defined either by a Cartesian vector or by the geocentric altitudes, latitudes and longitudes. The geocentric altitude is the distance from the position to the Earth's surface represented by a sphere of radius Re = 6371.2 *km. The latitude is defined by the angle between the vector position and the xy-plane. The longitude is measured from the xz-plane toward the y-axis.

The GEO coordinate system is fixed with the rotation of the Earth. The x-axis is the intersection of the Earth's equatorial plane and the Greenwich meridian. The z-axis is parallel to the Earth's rotation axis and the y-axis completes a right handed orthogonal set. The GEO longitude is equivalent to the GEOID longitude.

The GEI coordinate system has its x-axis pointing from the Earth toward the first point of Aries (Position of the Sun viewed from the Earth at vernal equinox). This direction is the intersection of the ecliptic plane and the Earth's equatorial plane. The z-axis is parallel to the rotation axis of the Earth and the y- axis completes the system.

The GSE coordinate system has its x-axis pointing from the Earth toward the Sun. The xy-plane coincides with the ecliptic, with the y axis pointing duskward. The z axis is parallel to the ecliptic pole.

The MAG coordinate system is oriented in function of the geomagnetic dipole. The geomagnetic dipole axis represents the z-axis of the system. The y-axis is perpendicular to the geographic poles (GEO z-axis) such that $\vec{y}_{mag} \quad \frac{\vec{z}_{GEO} \quad \vec{z}_{MAG}}{\left| z_{GEO} \quad z_{MAG} \right|}$. The x-axis completes a right-handed orthogonal set.

The x-axis of the GSM system is defined by the Earth-Sun line. The y-axis is perpendicular to the geomagnetic dipole axis so that the xz-plane contains the dipole axis. The positive z-axis is in the same direction as the northern magnetic pole. The angle between the geomagnetic dipole axis and the z-axis is called the dipole tilt angle *PS*.

The SM coordinate system has the same y-axis than the GSM system, but its z-axis is parallel to the geomagnetic dipole axis. The difference between the SM and GSM systems is a rotation about the y-axis of an angle equal to the dipole tilt angle.

In MAGNETOCOSMICS the trajectory and magnetic field lines are computed in GEO coordinates. Coordinate conversion from one system to the GEO system are used when defining particle position and directions, while conversion from GEO to another system are used for visualisation. The conversion between the different coordinate systems is performed by the SpaceCoordinateConvertor class. Due to the rotation of the Earth, the motion of the Earth around the Sun and the secular variation of the geomagnetic field, the coordinate transformation matrices change with time. For this reason when another epoch is selected by the user the transformation matrices are recomputed.

2.2 Earth's magnetosphere

The magnetic field in the Earth's magnetosphere is the sum of the geomagnetic field due to sources inside the Earth, and the external magnetospheric magnetic field resulting from currents outside the Earth in the magnetosphere and on its external boundary the magnetopause. Different models are available in MAGNETOCOMICS for the geomagnetic field and for the external magnetospheric field.

A precise model of the geomagnetic field is given by the International Geomagnetic Reference Field (IGRF) model [9-10]. In this model the geomagnetic field is considered as current free outside the Earth and is defined by the gradient of a scalar potential given by

$$V(r,\theta,\phi)=\sum_{n=1}^{n_{max}}(R_E/r)^{n+1}\sum_{m=0}^{n}(g_n^m\cos m\phi+h_n^m\sin m\phi)P_n^m(\cos\theta) \qquad (1)$$

where R_E is the Earth’s radius, r, ϕ, and θ are the spherical geographic coordinates, P_n^m is the Schmidt normalized Legendre polynomial of degree n and order m and, g_n^m and h_n^m are the Gauss spherical harmonic coefficients. The Gauss coefficients are derived from magnetic field measurements of geomagnetic stations, shiptowed magnetometers and satellites. Every five years, the International Association of Geomagnetism and Aeronomy (IAGA) issues a new set of Gauss coefficients defining the new IGRF model [9]. The precedent IGRF model becomes then a Definitive

Geomagnetic Reference Field (DGRF) . In the IGRF model, the Gauss coefficients for a given period are obtained by interpolating and extrapolating the five year DGRF/IGRF parameters. A table that contains these coefficients for the period 1900-2010 is given in the file ./igrfdata/igrf_dgrf_table.txt. The MAGNETOCOSMICS code reads this table during the initialisation phase. It is the responsabilty of the user to update this table every time IAGA published a new generation of DGRF/IGRF coefficients.

For a multitude of application a satisfactory approximation of the geomagnetic field is obtained by limiting the development in equation (1) to terms of degree 1 (n=1). It defines the Earth's centered geomagnetic dipole field that has an axis tilted with respect to the Earth's rotation axis. The momentum B_0 of the geomagnetic dipole is given by

$$B_0 \quad \sqrt{(g_1^0)^2 \quad (g_1^1)^2 \quad (h_1^1)^2} \quad (2)$$

The geocentric spherical coordinates θ_{dip} and ϕ_{dip} of the geomagnetic dipole axis are defined by

$$\cos\theta_{dip} = g_1^0 / B_0 \quad , \quad \tan\phi_{dip} = h_1^1 / g_1^1 \quad (3)$$

A better approximation of the geomagnetic field is given by translating the geomagnetic dipole from the Earth's center. The geocentric Cartesian coordinate $(x_{off}, y_{off}, z_{off})$ of the center of the eccentric geomagnetic dipole is a function of the Gauss coefficients of degree 1 and 2 that can be find in reference [10]. In MAGNETOCOSMICS the parameters of the tilted and eccentric geomagnetic dipole can be selected by the user or computed directly from the IGRF/DGRF Gauss coefficients.

The main sources for the external magnetospheric magnetic field are the ring current, the Chapman-Ferraro currents on the magnetopause, the tail current sheet, and the field aligned Birkeland current systems I and II [11]. In MAGNETOCOSMICS three different models of the magnetospheric magnetic field are considered: the Tsyganenko89, Tsyganenko96, and Tsyganenko2001 models. These models are available as FORTRAN code from the url [12]. To use these models in MAGNETOCOSMICS we have build a library that contain the binary files obtained by compiling the FORTRAN Tsyganenko codes. The compiled FORTRAN code are called in MAGNETOCOSMICS by using the interface magneto_fsubroutine_def.hh. In the next paragraphs we provide a brief description of the Tsyganenko models, for a more precise definition we refer to the publications of Tsyganenko [12-17].

In all the Tsyganenko models the external magnetospheric field is influenced by the geomagnetic field that is considered as a geomagnetic dipole. The dipole tilt angle *PS* that represents the angle of the geomagnetic dipole axis with the GSM z-axis, is an important parameter of all the Tsyganenko models as it influences the shape of the magnetosheet . The magnetosheet is centered on the geomagnetic equatorial plane close to the Earth, and becomes slowly parallel to the GSM equatorial plane as it moves away form the Earth.

The Tsyganenko89 model provides seven different states of the magnetosphere corresponding to different levels of geomagnetic activity [12-13]. The *Iopt* parameter is an integer defining the different state of the magnetosphere. The correspondence between *Iopt* and the *Kp* index is given in table1. The Tsyganenko89 model has been derived from satellite measurements at distance from the Earth's lower than 70 R_E. Its domain of validity is therefore limited to this region of space.

Iopt	1	2	3	4	5	6	7
Kp	0,0+	1-,1,1+	2-,2,2+	3-,3,3+	4-,4,4+	5-,5,5+	>6-

Table 1 Correspondence between Iopt and Kp index for the Tsyganenko89 model

The Tsyganenko89 model does not provide a modeling of the continuous variation of the structure of the magnetosphere as a function of geomagnetic indices like *Dst* and of solar wind parameters. Such modeling is for example important when considering the evolution of the magnetosphere during a magnetic storm, or during the compression of the magnetosphere by an increase of the solar wind pressure. The Tsyganenko96 model introduced such a dependence [14-15]. In this model the external magnetospheric field is produced by different systems of modular currents with shape and strength depending on the dipole tilt angle *PS*, on the solar wind dynamic pressure P_{dyn},, on the *Dst* index, and on the y and z GSM components of the interplanetary magnetic field (IMF) B_y and B_z . The solar dynamic pressure is given by $P_{dyn} \quad n \ V^2$ where *n* and *V* represents the solar wind density and velocity, respectively. The contributions from the ring current, the field aligned currents and the magnetosheet currents are confined into a specific model of the magnetopause. The magnetopause is represented by a semi ellipsoid in the front, continued in the far tail ($x_{gsm} \leq -60R_E$) by a cylindrical surface. The axis of the magnetopause is parallel to the GSM equatorial plane. The size of the magnetopause decreases, when P_{dyn} increases. The strength of the ring current is a function of the *Dst* index with a correction depending on P_{dyn} to take into account the contribution of the magnetopause currents on *Dst.* The ring current is axisymetric and no partial ring current is considered. The amplitude of the magnetosheet currents depends on P_{dyn}, B_y, and B_z. Both the shape of the ring current and magnetosheet are dependent on the dipole tilt angle *PS*. The model considers also the interconnection of the IMF with the magnetospheric magnetic field. It produces a component of the field perpendicular to the magnetopause and therefore opens the magnetospheric configuration.

The Tsyganenko 2001 model is based on the same principles than the Tsyganenko96 model but brought important improvements compared to it [17]. The model is not only parametrised by *PS* , P_{dyn},, *Dst,* B_y and B_z., but also by two additional parameters, G_1 and G_2. These new parameters influenced the magnetotail components. The G_1 parameter was derived to quantify the energy transfer from the solar wind into the magnetosphere over the last hour. The parameter G_2 quantifies the strength of the sun-ward convection electric field over the last hour of observation, and controls the tailward/earthward shift of the magnetotail current system. The way to compute the G1 and G2 parameters from solar wind parameters are described in [18]. Compared to the Tsyganenko96 model, the ring current in the Tsyganenko2001 model contains not only an axisymmetric component but also a contribution from the partial ring current that formed a closed current system with the field aligned currents. The Birkeland currents vary in response to the interplanetary conditions. The magnetopause is specified by an empirical model with the size varying with the solar wind pressure as in the Tsyganenko96 model but with a shape that is no more axysymmetric and depends on the Earth's dipole title angle. The user should be aware that the Tsyganenko 2001 model is a near Earth magnetosphere model. The dependence of the model on its parameters was derived from space measurements with x_{gsm}>-15 R_E . Therefore, at a position with xgsm<-15 R_E especially in the far tail, the output of the model should be considered with caution.

2.3 Definition of the rigidity

The motion of a charged particle trough a magnetic field is described by the Lorentz equation of motion

$$d\vec{p}/dt = q\vec{v}\times\vec{B} \quad (4)$$

where $\vec{p}$, q, $\vec{V}$ and $\vec{B}$ represent the particle momentum, the particle charge, the particle velocity vector, and the magnetic field respectively. This equation of motion conserves p the magnitude of the momentum, and therefore the energy of the particle. After some transformation the equation of motion becomes

$$d\vec{I}_v/ds = \frac{q}{p}\vec{I}_v\times\vec{B} \quad (5)$$

where $\vec{I}_v$ represents the velocity direction and s is the path length along the particle trajectory. The rigidity of a particle is defined by $\frac{pc}{q}$ where c represents the velocity of light. Equation 5 shows that for the same initial position and direction, charged particles with the same rigidity and with charges of the same sign have identical trajectories. For this reason it is more convenient to characterise the trajectory of cosmic rays in function of their rigidity and not of their energy. Higher the rigidity is, smaller the bending of the particle trajectory by the magnetic field. The rigidity can be seen as as the quantification of the resistance of the particle to the bending of its trajectory by the magnetic field. The rigidity is an energy divided by a charge. In cosmic ray physics it is generally expressed in GV or MV.

2.4 Asymptotic direction of incidence, cutoff rigidity and penumbra

For the analysis of cosmic ray measurements and for space radiation environment studies its is important to quantify the lower rigidity limit above which cosmic rays can cross the Earth' magnetosphere and reach a specific position from a specific observational direction. It is also important to determine the asymptotic direction of a cosmic ray, that represents its direction before entering into the magnetosphere. The method uses to compute these informations is illustrated in Figure1, a complete description about asymptotic direction computation method and cosmic ray cutoff terminology is provided in [19] . Trajectories of cosmic rays with different rigidities, arriving at the same observing position and from the same direction of incidence are computed backward in time. The red curves labeled by 1, 2, 3 ,4 and 5 represent trajectories of positive charged particles with 20, 15, 10, 5 and 4.5 GV rigidities respectively. In this case all the trajectories are initiated in the vertical direction from the same observing position. Particles at high rigidity (trajectory 1,2,3) have small trajectory bending before escaping the Earth magnetosphere. The particle with 5 GV rigidity has a more important bending but can still escape the Earth magnetosphere. The trajectory labeled by 5 is making several complex loops before reaching another point on the Earth's surface illustrating that for this specific rigidity a cosmic ray can not reach the selected Earth's position, from the vertical direction. Such trajectory is said forbidden while trajectories of particles escaping the Earth magnetosphere are called allowed trajectories. The direction at the last position of an allowed trajectory represents the asymptotic direction of incidence of the particle corresponding to this trajectory. The black arrow on Figure 1 represents the asymptotic direction for the trajectory 3.

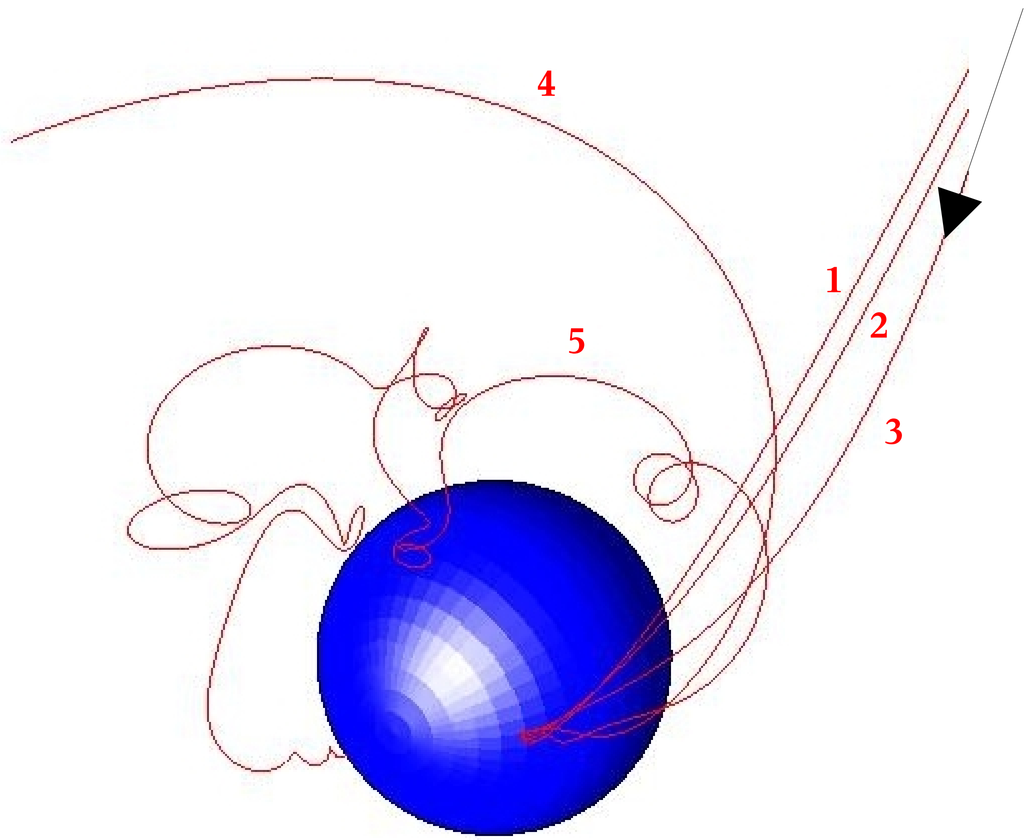

Figure 1 Illustration of the backward trajectory method used for determining if a cosmic ray with a given rigidity can reach a given position from a given direction of incidence (see text). The Earth is represented by the blue sphere. The red lines 1, 2, 3, 4 and 5, represent computed backward trajectories of positive ions with rigidity of 20, 15, 10, 5 and 4.5 GV respectively.

In general backward trajectories are computed for several rigidities spanning a large range of values with a constant rigidity interval ΔR (usually 0.01 GV). Results of such a computation are illustrated in Figure2. In this plot a filter value of 0 and 1 are associated to rigidity corresponding to forbidden and allowed trajectories respectively. Three distinct regions are observed. A high rigidity region where all trajectories are allowed, a low rigidity region where all trajectories are forbidden and an intermediate region called the penumbra where penumbral bands of allowed trajectories are separated by band of forbidden ones.

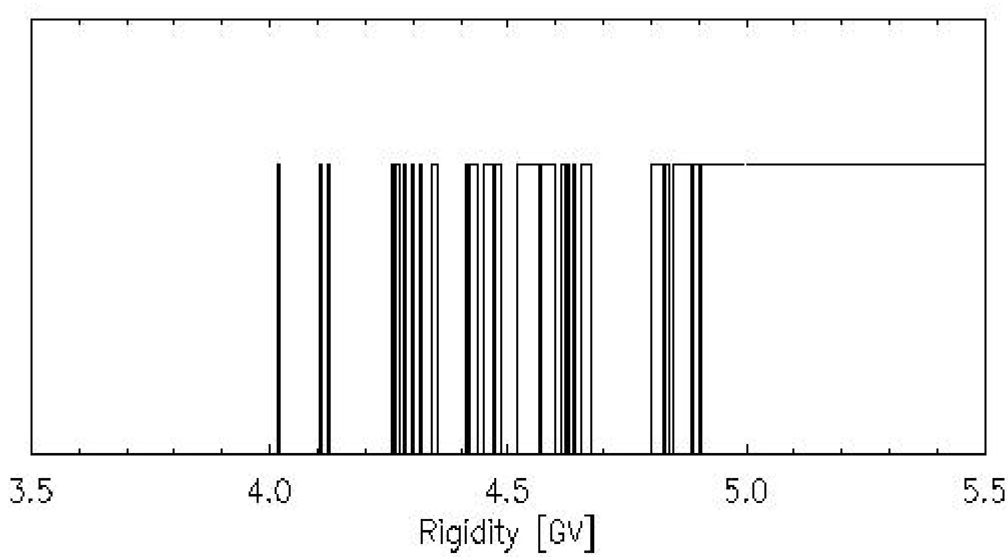

Figure 2 Typical results of backward trajectory calculation for computing cutoff rigidity.

The rigidity of the last allowed computed trajectory before the first forbidden one is called the upper cutoff rigidity R_U. The rigidity of the last allowed trajectory, below which all trajectories are forbidden is called the lower cut-off rigidity R_L. An effective cutoff rigidity R_C characterising the structure of the penumbra is defined by

$$R_C = R_U - n_{allowed}\,\Delta R \qquad (6)$$

where $n_{allowed}$ represents the number of allowed trajectories encountered in the penumbra.

2.5 Integration method

For computing the trajectory of a charged particle trough a magnetic field, the Lorentz equation of motion (Equation (4)) is integrated numerically. For tracing the magnetic field lines an additional differential equation, that defines the motion parallel to the magnetic field, is also considered.

In the Geant4 toolkit, the trajectory or track of a particle is divided in tracking steps. For non linear motion trough fields these tracking steps are divided in smaller steps called chord. The equation of motion is integrated over these chords. After the integration of a chord it is checked if the particle did not cross a boundary between two different regions of the geometry. If this is the case the intersection with a boundary is determined and the tracking step is stopped at this boundary. To avoid the non-detection of boundaries an upper limit is given to the length of chord. This limits is defined by the parameter *MaxChord* and can be changed according to the application.

For the numerical integration, the chord is divided into small integration steps. The motion of the particle over a small integration step is done by a G4Stepper object.

Different type of G4Stepper objects are available corresponding to different integration algorithms. In MAGNETOCOSMICS the user can choose between the following stepper methods: Euler implicit, Euler explicit, 3rd order RungeKutta , 4th order RungeKutta, and KashKarper. For more information on these algorithms we refer to the Numerical recipes and to the Geant4 documentation[3,20]. After each integration step an estimate of the numerical relative error is computed, if this error is bigger than the maximum accepted relative error ξ, a smaller integration step is chosen and the integration restart from precedent step. When the relative error is significantly smaller than ξ, the step size is increased.

In MAGNETOCOSMICS we have implemented an additional integration algorithm based on the Bulirsh Stoer method [6] . In this method an integration step consist into the integration of the independent variable $y(x)$ over an interval $[x,x+H]$ where the step H is much larger that for a RungeKutta method. Several integrations over $[x,x+H]$ are performed by using a low order RungeKutta method (usually the modified midpoint method) with a step $h=H/n$ where n is an integer that increase from one integration to another one. The idea of the Bulirsh Stoer method is to consider that the results of the numerical integration $y(x+H)$ is an analytical function of $h=H/n$, $f(h)$ and that the exact solution is given by $y(x+H) =f(0)$. When enough points of the function $f(h)$ are calculated, the best approximation of $y(x+H)$ is obtained by an extrapolation of $f(h)$ to $h=0$. This method provides also a good estimate of the integration error over H and allows to adapt H during the integration according to the maximum allowed relative error ξ. According to the author of the Numerical recipes this method is considered to be more precise and more rapid than the RungeKutta methods for integrating smooth function.

The step H should be taken large enough to benefit fully from the Bulirsh-Stoer method. However in the general trajectory integration algorithm of Geant4 this H corresponds to a chord step and should not be too large for efficient detection of boundaries (see above). To be still able to select H large enough and therefore profit from the Bulirsh-Stoer algorithm we were forced to design our own tracking and detecting boundary algorithm. This algorithm an the implementation of the Bulirsh-Stoer method in Geant4 will be described in another documentation.

3. Installation and compilation

The MAGNETOCOSMICS software is installed as a Geant4 application. For this reason before compiling the code the user should install the Geant4 toolkit [1-4]. If the user wants to avoid the Geant4 installation and the MAGNETOCOSMICS compilation, he can directly download the static/executable version of the MAGNETOCOMICS from the MAGNETOCOSMICS official web site (cosray.unibe.ch/~laurent/magnetocosmics). The files needed to compile and install MAGNETOCOMICS are in the GNU tar file magnetocosmics.tar.gz. From the directory where you want to install the source code of magnetocosmics, you should type "*tar –xvzf tarfilepath/magnetocosmics.tar.gz*" where *tarfilepath* defines the path where is the file magnetocosmics.tar.gz. It creates in the current directory the directory ./magnetocosmics. In this directory you should find the MAGNETOCOSMICS.cc main file, the GNUmakefile for compiling the code, the file configure_and_build.sh, the READEME file, and the directories magnetocosmics/bin, magnetocosmics/src, magnetocosmics/include, magnetocosmics/examples, magnetocosmics/fortran and magnetocosmics/igrfdata. The include files and source files of the code are contained in the directories magnetocosmics/include and magnetocomics/src respectively. The magnetocosmics/ examples directory contains different Geant4 macro files corresponding to different examples. The magnetocosmics/fortran directory contains the Tsyganenko fortran codes slightly modified to be used with MAGNETOCOSMICS, and the magnetocosmics/igrfdata directory contains the igrf_dgrf_table.txt that defines the Gauss coefficient for the IGRF model for the period 1900-2010.

Providing that all external libraries and packages have been correctly installed, the MAGNETOCOSMICS code is compiled by doing the following :

1. From the directory where MAGNETOCOSMICS is installed type "./configure_and_build.sh" .

2. Add the command "source MAGNETOCOSMICS_dir/setupMAGNETOCOSMICS.sh(csh)" into the bash (tcl) shell startup file (most probably $HOME/.bashrc) where MAGNETOCOSMICS_dir should be replaced by the directory where MAGNETOCOSMICS is installed.

4. Execution and commands

The code is executed by typing MAGNETOCOSMICS <[*macrofile*]>. If you do not provide an argument you will use MAGNETOCOSMICS in normal G4 interactive mode. When providing an argument, the corresponding macro file is executed in batch mode. You can interact with MAGNETOCOSMICS by using standard Geant4 UI commands and the additional commands provided in the directory /MAGCOS. In the following sections we describe these commands.

For visualisation purpose if you are using the VRML2 driver you will probably not bee able to look at the *wrl file produced by MAGNETOCOMICS due to a scaling problem. To solve this problem we have written the bash script scale_vrmlfile.sh provided with the code that allows to transform a VRML2 file produced by MAGNETOCOSMICS into another VRML2 file that can be view without problems. To perform this transformation you should type the command "scale_vrmlfile.sh *file1 file2"* where *file1* is the name of the VRML2 file produced by MAGNETOCOSMICS and *file2* is the output file that you will look at with your vrml viewer.

4.1 Command directory /MAGCOS/BFIELD

By using the commands of this directory the user select the geomagnetic field model and the external magnetospheric field model. He also fixes the value of the different input parameters (geomagnetic indices, solar wind parameters, geodipole axis,....) of the selected models.

The models available for the geomagnetic field are the geomagnetic dipole (DIPOLE) or the IGRF model. The geomagnetic dipole is defined by the dipole moment B_0, the dipole axis in GEO coordinates and the dipole shift in GEO coordinates. The user can define separately each of these parameters or set them according to the IGRF Gauss coefficients of order 1 and 2. The maximum degree n_{max} of the IGRF model in equation 1 can also be set by the user, its default and maximal value is 13. Note that the maximum degree 13 is only available for the 9 and 10 th generation of IGRF that corresponds to the epoch a 2000-2010, for the epoch 1990-2000 the maximal degree is 10 and terms of higher degree will not be considered.

For the external magnetospheric magnetic field model the user can choose between no field (NOFIELD) or one of the Tsyganenko models (TSY89, TSY96 and TSY2001). He can define separately the *Iopt*, P_{dyn} , *Dst*, B_y, B_z, G_1 and G_2 parameters of these models. To each Tsyganenko model a specific magnetopause model is associated. When no external field are considered the magnetopause is defined by a 25 R_E spherical surface centered on the Earth. When a particle is outside the magnetopause the trajectory computation is stopped.

The parameters of the magnetospheric models are time dependent. The time at which the magnetic field is calculated is defined by a time t after a given date of reference $date_{ref}$. The user can fix both t and $date_{ref}$. Every time a new $date_{ref}$ parameter or a new time t are selected by the user the IGRF Gauss coefficients corresponding to the new selected time are recomputed, as well as the coordinate transformation matrices. The geomagnetic dipole momentum B_0, and axis are also recomputed according to this new IGRF parameters by using equations 2 and 3, while the shift of the geomagnetic dipole is set to (0,0,0) .

For the Tsyganenko96 and 2001 models it is possible to define the dependence of *Pdyn*, *Dst*, B_y, B_z, G_1 and G_2 on time trough an ASCII file. The format of this file is as follow:

	Year	Month	Day	hour	minute	second	
	nlines						
time	Pdyn	Dst	By	Bz	G1	G2	
	....	....	......	.....	.....	....	.....

The first line defines the date of reference $date_{ref}$. The second line defines the number of times at which the parameters are given in the rest of the file. Each of the following lines define the values of *Pdyn*, *Dst*, B_y, B_z, G_1 and G_2 at different times given in second after $date_{ref,}$. The solar wind pressure *Pdyn* is given in nanopascals (nPa), the *Dst* index, B_y, and B_z components of IMF are given in nT wile the parameters G_1 and G_2 are dimensionless. The time should be given chronologically. The values of the Tsyganenko parameters and their corresponding times are stored into vectors. When the user select a given time t for computing the magnetic field, the *Pdyn*, *Dst*, B_y, B_z, G_1 and G_2 parameters values are interpolated/extrapolated from these vectors. If the vectors are empty the values of the Tsyganenko parameters are static values that can be defined by the *SetPdyn, SetDst, SetBy, SetBz, SetG1 and SetG2* commands.

4.1.1 /MAGCOS/BFIELD/SetTimeOfB

Format: /MAGCOS/BFIELD/SetTimeOfB *time unit*

Arguments: Double *time*
G4String *unit.*

Function: Defines the time after the reference date, at which the magnetic field is computed.

Default: 0.

Errors: An error is flagged if the units are not time units defined in the unit table.

4.1.2 /MAGCOS/BFIELD/SetStartDate

Format: /MAGCOS/BFIELD/SetSartDate < *year month day [hour min sec]*>

Arguments: Int *year, month, day, hour, min* and *sec*

Function: Set the reference date in universal time.

Default: 2000 1 1 0 0 0

Errors: An error is flagged if *month, day, hour, min,* and *sec* are not integral values in the ranges [1-12], [1-31], [0-23], [0-59], and [0-59] respectively.

4.1.3 /MAGCOS/BFIELD/SetNmaxForIGRF

Format: /MAGCOS/BFIELD/SetNmaxForIGRF <n_{max}>

Arguments: Integer n_{max}

Function: Set the maximum degree n_{max} for the IGRF model (see Equation 1).

Default: 13

Errors: An error is flagged if n_{max} is not an integral value in the range [1-13].

4.1.4 /MAGCOS/BFIELD/SetGeomagneticFieldModel

Format: /MAGCOS/BFIELD/SetGeomagneticFieldModel <*Model*>

Arguments: G4String *Model*

Function: Set the geomagnetic field model .

Candidates: DIPOLE, IGRF, NOFIELD.

Default: IGRF

4.1.5 /MAGCOS/BFIELD/SetExternalFieldModel

Format: /MAGCOS/BFIELD/SetExternalFieldModel<*Model*>

Arguments: G4String *Model*

Function: Set the external magnetospheric magnetic field model .

Candidates: NOFIELD, TSY89, TSY96 and TSY2001.

Default: NOFIELD

4.1.6 /MAGCOS/BFIELD/SetDipoleB0

Format: /MAGCOS/SetDipoleB0 <B_0 *unit*>

Arguments: Double B_0
G4string *unit.*

Function: Set the geomagnetic dipole momentum B_0.

Default: By default B_0 is derived from the IGRF Gauss coefficients.

Errors: An error is flagged if *unit* is not one of the following units: nT, T, kG, G, nanotesla, tesla, kilogauss, gauss.

4.1.7 /MAGCOS/BFIELD/SetDipoleTiltAngle

Format: /MAGCOS/BFIELD/SetDipoleTiltAngle <*ps angle_unit*>

Arguments: Double *ps*
G4String *angle_unit.*

Function: Sets the tilt angle of the geomagnetic dipole.

Default: By default the tilt angle is deduced from the IGRF Gauss coefficients.

Errors: An error is flagged if *angle_unit* is not one of the following units: degree, deg, rad or radian.

4.1.8 /MAGCOS/BFIELD/SetDipoleAxis

Format: /MAGCOS/BFIELD/SetDipoleAxis < θ Φ *angle_unit*>

Arguments: Double θ Φ
String *angle_unit.*

Function: Defines the direction of the geomagnetic dipole axis in GEO spherical coordinates.

Default: By default the direction of the dipole axis is computed from IGRF Gauss coefficients.

Errors: An error is flagged if *angle_unit* is not one of the following units: degree, deg, rad or radian.

4.1.9 /MAGCOS/BFIELD/SetDipoleCenter

Format: /MAGCOS/BFIELD/SetDipoleCenter < C_x, C_y, C_z, *length_unit* >

Arguments: Double C_x, C_y, C_z
String *length_unit*

Function: Sets the the center of the geomagnetic dipole in GEO coordinates.

Default: Set to (0,0,0).

Errors: An error is flagged if *length_unit* is not one of the unit of length contained in the unit table.

4.1.10 /MAGCOS/BFIELD/SetConsiderDipoleShift

Format: /MAGCOS/BFIELD/SetConsiderDipoleShift <*aBool*>

Arguments: Bool *aBool*.

Function: If *aBool* is true the geomagnetic dipole with the center shifted from the Earth center is used in the Tsyganenko models. It means that the external magnetspheric magnetic field is also shifted to the geomagnetic dipole center. If *aBool* is false the geomagnetic dipole centered on the Earth's center is used in Tsyganenko models.

4.1.11 /MAGCOS/BFIELD/SetNonShiftedGeodipoleFromIGRF

Format: /MAGCOS/BFIELD/SetNonShiftedGeodipoleFromIGRF

Arguments: None

Function: The geomagnetic dipole momentum, axis and tilt angle are deduced from IGRF Gauss coefficients of degree 1 by using the equations 2 and 3. The center of the geomagnetic dipole is placed on the Earth's center.

4.1.12 /MAGCOS/BFIELD/SetShiftedGeodipoleFromIGRF

Format: /MAGCOS/BFIELD/SetShiftedGeodipoleFromIGRF

Arguments: None

Function: The geomagnetic dipole momentum, axis and tilt angle are deduced from the IGRF Gauss coefficients of degree 1 by using the equations 2 and 3. The GEO coordinates of the center of the geomagnetic dipole are computed from IGRF coefficients of degree 1 and 2 [].

4.1.13 /MAGCOS/BFIELD/SetIopt

Format: /MAGCOS/BFIELD <*Iopt*>

Arguments: Int Iopt.

Function: Sets the Iopt parameter for the Tsyganenko 89 model. The correspondence between Iopt and Kp is given in table 1.

Default: Iopt =1

Errors: An error is flagged if Iopt ≤ 0 or ≥ 8.

4.1.14 /MAGCOS/BFIELD/SetPdyn

Format: /MAGCOS/BFIELD <P_{dyn}>

Arguments: Double P_{dyn} .

Function: Set the solar wind dynamic pressure in nPa. This parameter is used by the Tsyganenko 96 and 2001 models.

Default: 2.

Error: An error is flagged if $P_{dyn} \leq 0$

4.1.15 /MAGCOS/BFIELD/SetDst

Format: /MAGCOS/BFIELD/SetDst <*Dst bfield_unit*>

Arguments: Double *Dst*
G4string *bfield_unit*.

Function: Set the *Dst* index used in the Tsyganenko96 and 2001 models.

Default: 0. nT

Errors: An error is flagged if *bfield_unit* is anything else than nanotesla, tesla, gauss, kilogauss, nT, T, G or kG.

4.1.16 /MAGCOS/BFIELD/SetImfBy

Format: /MAGCOS/BFIELD/SetImfBy <B_y *bfield_unit*>

Arguments: Double B_y
G4String *bfield_unit*.

Function: Sets the GSM y component of the

Errors: An error is flagged if *bfield_unit* is anything else than nanotesla, tesla, guauss, kilogauss, nT, T, G or kG.

4.1.17 /MAGCOS/BFIELD/SetImfBz

Format: /MAGCOS/BFIELD/SetImfBz <B_z *bfield_unit*>

Arguments: Double B_z
G4String *bfield_unit*.

Function: Sets the GSM z component of the interplanetary magnetic field. It represents an input parameter of the Tsyganenko96 and 2001 models.

Default: 1 nT.

Errors: An error is flagged if *bfield_unit* is anything else than nanotesla, tesla, guauss, kilogauss, nT, T, G or kG.

4.1.18 /MAGCOS/BFIELD/SetG1

Format: /MAGCOS/BFIELD/SetImfBy <G_1 >

Arguments: Double G_1

Function: Sets the G_1 parameter used in the Tsyganenko 2001 model.

Default: 1.

4.1.19 /MAGCOS/BFIELD/SetG2

Format: /MAGCOS/BFIELD/SetImfBy <G_2 >

Arguments: Double G_2.

Function: Sets the G_2 parameter used in the Tsyganenko 2001 model.

Default: 0.

4.1.20 /MAGCOS/BFIELD/ReadTSYParametersVsTime

Format: /MAGCOS/BFIELD/ReadTSYParametersVsTime <*file_name*>

Arguments: G4String file_name

Function: Read an ASCII file that defines the time variation of the parameters P_{dyn}, Dst, B_y, B_z, G_1 and G_2 used in the Tsyganenko 96 and 2001 models. The format of the file is described in section 3.1.

4.1.21 /MAGCOS/BFIELD/PrintTSYParameters

Format: /MAGCOS/BFIELD/PrintTSYParameters

Arguments: None

Function: Prints the actual values of the parameters P_{dyn}, Dst, B_y, B_z, G_1 and G_2 used in the Tsyganenko 89, 96 and 2001 models.

4.2 Command directory /MAGCOS/SOURCE

The commands in this directory are complementary to the /gps commands and allow to define the start position and start direction in different space coordinate systems (GEO, GEOID, SM, GSM and MAG). One command allows also to define the rigidity of a particle. By using the command *SetDirectionFromPitchAngle* it is possible to fix the pitch angle of a particle at its start position The pitch angle represents the angle between the direction of the particle and the magnetic field.

4.2.1 /MAGCOS/SOURCE/SetPositionVector

Format: /MAGCOS/SOURCE/SetPositionVector <*coorsys X Y Z unit*>

Arguments: G4String *coorsys*, *unit*
Double *X, Y,Z* .

Function: Set the Cartesian coordinate of the start position in the coordinate system define by *coorsys*.

Error: An error is flagged if *coorsys* is anything else than: GEO, SM, MAG, GEI, GSE or GSM.

4.2.2 /MAGCOS/SOURCE/SetPosition

Format: /MAGCOS/SOURCE/SetPosition
<*coorsys altitude length_unit latitude longitude angle_unit*>

Arguments: G4String *coorsys*, *length_unit*, *angle_unit*
G4double *altitude, latitude, longitude*

Function: Define the start position by its altitude, latitude and longitude in the space coordinate system defined by *coorsys*.

Error: An error is flagged if coorsys is anything else than: GEO, GEOID, SM, MAG, GEI, GSE or GSM.

4.2.3 /MAGCOS/SOURCE/SetPositionOnDipoleMagneticShell

Format: /MAGCOS/SOURCE/SetPositionOnDipoleMagneticShell
<*coorsys* L_{val} *lat long angle_unit*>

Arguments: G4String *coorsys, angle_unit,*
G4double L_{val} *latitude, longitude*

Function: The start position is placed on the $L=L_{val}$ shell of the geomagnetic dipole, at magnetic shell latitude *lat* and at longitude *long*. The longitude is given in the coordinate system defined by *coorsys* that should be either MAG or SM.

Error: An error is flagged if *coorsys* is anything else than SM or MAG, and if $L_{val} \leq 0$.

4.2.4 /MAGCOS/SOURCE/SetDirectionVector

Format: /MAGCOS/SOURCE/SetDirectionVector <*coorsys X Y Z* >

Arguments: G4String *coorsys*
G4double *X, Y,Z* .

Function: Define the start direction of a particle in the system of coordinate defined by *coorsys*. The vector (*X*,*Y*,*Z*) does not need to be normalised.

Error: An error is flagged if *coorsys* is anything else than GEO, SM, MAG, GEI, GSE, or GSM.

4.2.5 /MAGCOS/SOURCE/SetDirection

Format: /MAGCOS/SOURCE/SetDirection
<*coorsys zen azim angle_unit*>

Arguments: G4String *coorsys*, *angle_unit*
G4double *zen*, *azim*

Function: The start or incoming (for backward tracking) direction of a particle is set antiparallel to a direction of observation defined by the zenith angle *zen*, and the azimuth angle *azim*, given in the coordinate system defined by *coorsys.* As the vertical direction (zenith = 0.) depends on the position, this command should be invoked after the definition of the position.

Error: An error is flagged if coorsys is anything else than GEO, GEOID, SM, MAG, GEI, GSE or GSM.

4.2.6 /MAGCOS/SOURCE/SetDirectionFromPitchAngle

Format: /MAGCOS/SOURCE/SetDirectionFromPitchAngle
< *pitch_angle phi angle_unit*>

Arguments: G4double *pitch_angle, phi*
String *angle_unit*

Function: The start direction of the primary particle is defined by the *pitch_angle* and the angle *phi.* We consider a local coordinate system centered on the particle position. The z-axis is parallel to the magnetic field at the primary position. The x- axis is chosen such that the x-z plane contains the vector position, and the y-axis completes a right handed system. In this system the *pitch_angle* and the parameter *phi* represents respectively the spherical coordinates theta and phi of the direction.

Error: An error is flagged if *angle_unit* is anything else than degree, deg, rad, radian, mrad, and milliradian.

4.2.7 /MAGCOS/SOURCE/SetRigidity

Format: /MAGCOS/SOURCE/SetRigidity *r rigidity_unit*

Arguments: Double *r*
String *rigidity_unit*

Function: Set the rigidity of the primary particle.

Error: An error is flagged if *rigidity_unit* is anything else than GV, V, kV, MV gigavolt, volt, kilovolt, or megavolt.

4.2.8 /MAGCOS/SOURCE/verbose

Format: /MAGCOS/SOURCE/verbose *n*

Arguments: G4int *n*

Function: For testing purpose if *n*>0 the particle name, rigidity, energy, GEO position and GEO direction of each generated primary are printed. If *n*>1 the position and direction are also printed in GSM, GEI, GSE, MAG and SM coordinates, as well as the geodetic altitude, latitude and longitude.

4.2.9 /MAGCOS/SOURCE/BfieldAtPrimaryPosition

Format: /MAGCOS/SOURCE/BfieldAtPrimaryPosition

Arguments: none

Function: Print the components of the magnetic field in the coordinate system GEO, GEI,GSE, GSM,MAG, and SM .

4.3 Command directory /MAGCOS/INTEGRATION

The commands in this directory allow to select between the different integration methods available in the application and to set the different integration parameters i.e. the relative precision, the crossing precision, the maximum size of a chord for the integration method available in G4 and the maximum step length for the Bulirsh-Stoer method. Another parameter that influence the integration is the maximum step length of a tracking step (see section 2.5). This maximum step length can be defined by using the command /MAGCOS/USERLIMIT/SetMaxStepLength (see 4.6.1).

4.3.1 /MAGCOS/INTEGRATION/SetPrecision

Format: /MAGCOS/INTEGRATION/SetPrecision <*epsilon*>

Arguments: G4double *epsilon*

Function: Set the relative precision for the numerical integration of the equation of motion

Default: 10^{-6}

Eroor: An error is flagged if *epsilon* < 1e-8 or >1e-3

4.3.2 /MAGCOS/INTEGRATION/SetG4MaxStep

Format: /MAGCOS/INTEGRATION/SetG4MaxStep <$chord_{max}$ *length_unit*>

Arguments: G4double $chord_{max}$
G4String *length_unit*

Function: Set the maximum length of a a chord in the numerical integration algorithm used in the Geant4 toolkit.

Default: 10^{-2} Re

Error: An error is flagged if *length_unit* is not one of the unit of length contained in the unit table.

4.3.3 /MAGCOS/INTEGRATION/SetBSMaxStep

Format: /MAGCOS/INTEGRATION/SetBSMaxStep <H_{max} *length_unit*>

Arguments: G4double H_{max}
G4String *length_unit*

Function: Set an upper limit to the step H used in the Bulirsh-Stoer integration method (see section 2.5).

Default: 0.5 Re

Error: An error is flagged if *length_unit* is not one of the unit of length contained in the unit table.

4.3.4 /MAGCOS/INTEGRATION/SetDeltaCrossing

Format: /MAGCOS/INTEGRATION/SetDeltaIntersection
<delta_intersection length_unit>

Arguments: G4double *delta_intersection*
G4String *unit*

Function: Defines the precision for detection of a crossing boundary.

Default : 10^{-3} Re

4.3.5 */MAGCOS/INTEGRATION/SetDefaultIntegrationParameters*

Format: /MAGCOS/INTEGRATION/SetDefaultIntegrationParameter

Arguments: None

Function: Reset the integration parameters to their default values.

4.3.6 */MAGCOS/INTEGRATION/SelectBulirshStoerMethod*

Format: /MAGCOS/INTEGRATION/SelectBulirshStoerMethod

Arguments: None

Function: Select the Bulirsh-Stoer method for the numerical integration of the equation of motion

4.3.7 */MAGCOS/INTEGRATION/SelectG4IntegrationMethod*

Format: /MAGCOS/INTEGRATION/SelectG4IntegrationMethod

Arguments: None

Function: Select the numerical integration method available in Geant4.

4.3.8 */MAGCOS/INTEGRATION/SetStepperModel*

Format: /MAGCOS/INTEGRATION/SetStepperModel *stepper*

Arguments: String *stepper*

Function: Select the stepper model that should be used used in the numerical integration algorithm available in Geant4 (section 2.5).

Candidates: ExplicitEuler, ImplicitEuler, SimpleRunge, ClassicalRK4, CashKarpRKF45, RKG3_Stepper

4.4 Command directory /MAGCOS/SCENARIO

In this directory the user can execute one of the following application scenarios:

- Trace a magnetic field line

- Trace a particle trajectory forward and backward in time

- Compute asymptotic directions of incidence, rigidity filter and cutoff rigidities for a given observational position and direction

- Compute the main, Störmer and effective cutoff rigidities R_m, R_s and R_c in function of latitude and longitude, at the same altitude and for the same direction of observation.

- Compute R_U, R_L and R_C in function of dipole magnetic latitude and longitude, at the same dipole L value and for a given direction of observation

- Compute R_U, R_L and R_C in function of direction of observations given in azimuth and zenith angle for the same position.

- Compute R_U, R_L and R_C in function of time at the same position and direction of observation

When computing asymptotic directions, particle trajectories are integrated backward in time from a user defined position and direction of incidence, at different rigidities values defined in a decreasing vector that can be defined by using the commands from the directory MAGCOS/RIGIDITYVECTOR. The output of such computation is contained in an ASCII table structured as below:

Rigidity	Filter	Asympt. Lat.	Asympt. Long.	Position Xgeo	Ygeo	Zgeo
20.00	1	69.33	95.90	-0.53	8.81	24.42
19.99	1	69.33	95.90	-0.53	8.81	24.42
19.98	1	69.32	95.89	-0.53	8.81	24.42
19.97	1	69.32	95.89	-0.53	8.82	24.42
19.96	1	69.31	95.89	-0.53	8.82	24.42
19.95	1	69.31	95.89	-0.53	8.82	24.42
19.94	1	69.30	95.88	-0.52	8.82	24.42
19.93	1	69.30	95.88	-0.52	8.82	24.42
....	...	... ...	... ...	...		
0.12	1	-21.60	153.18	-8.09	24.02	0.69
0.11	1	-22.27	163.95	-9.37	23.19	-0.57
0.10	1	-18.22	-177.20	-12.60	21.62	-2.42
0.09	1	6.89	-135.51	-21.13	13.15	-3.17
0.08	-1	-33.09	-121.42	-11.85	-6.06	-4.89
0.07	-1	10.88	-15.62	-8.91	-5.70	-6.46
0.06	-1	-15.26	-39.38	-14.54	-0.57	-3.36
0.05	-1	81.43	47.38	-5.08	2.21	-4.17
0.04	-1	79.62	-38.08	-8.89	7.04	-2.77
0.03	-1	-20.47	-72.00	-5.23	9.00	-3.31
0.02	-1	-28.69	-74.79	-2.59	9.97	-3.22
0.01	0	62.48	-99.77	-0.10	0.48	-0.87
Rl 0.09	Rc 0.09	Ru 0.09				

The first column represents the rigidity of the particle in GV. In the second column a filter value is set to -1, 0 or 1 if the backward trajectory has reached a user defined maximal trajectory length, has penetrated in the Earth's atmosphere or has reached the magnetopause, respectively. The maximum length of the trajectory can be defined by the command /MAGCOS/USERLIMIT/SetMaxTrajectoryLength. In the third and fourth columns the asymptotic direction is given by the asymptotic latitude and longitudes. It defines the direction of the trajectory when it crosses the magnetopause. For trajectories that do not cross the magnetopause it represents their direction at the last position of the trajectory. The GEO coordinates of the last position of the backward trajectories are given in the last columns. The R_U, R_L and R_C cut-off rigidities deduced from the computation results are written on the last line.

For the scenario where the cutoff rigidities R_U, R_L and R_C are computed in function of position, direction of incidence, or time, two methods can be selected to compute these rigidities. In the first method backward trajectories are computed for the same rigidity vector used for computing asymptotic directions. The R_m, R_s, and R_c cutoff rigidities are determined by considering the forbidden and allowed trajectory regions as explained in section 2.4 . It is necessary that the rigidity vector covers at least all the penumbra region. Moreover over the penumbra the values in the rigidity vector should decrease monotically by a constant interval ΔR. In standard rigidity cutoff computation programs ΔR is generally set to 0.01 GV.

In the second method the rigidity vector is not used and the penumbra region is detected automatically. The Störmer cutoff in the geomagnetic dipole R_{sdip} at the considered position and direction of incidence is computed from the formula

$$R_{sdip} = \frac{B_0 \, R_E \, c \cos^4 \lambda}{r^2 \left(1 + \sqrt{1 - \cos^3 \lambda \cos \epsilon \sin \zeta}\right)^2} \quad (7)$$

where B_0, c, r, λ, ε, and ζ, is the momentum of the geomagnetic dipole, c is the velocity of light, r is the distance from the Earth' dipole center in Re, λ is the geomagnetic latitude, ε is the azimuth angle measured clockwise from the geomagnetic east direction, and ζ is the angle from the local magnetic zenith direction[19].

The algorithm looks for a 1 GV wide rigidity region above R_{sdip}, for which all the trajectories computed at a rigidity interval of 0.01 GV are allowed. It is considered that this region is above the penumbra. Then from the lower limit of this region by decreasing step by step the rigidity by 0.01 GV, backward trajectories are computed. This process is stopped when the trajectories in the last covered 1. GV wide rigidity region are all forbidden. The last rigidity above the first encountered rigidity with a forbidden trajectory represents the upper cut-off rigidity R_U. The rigidity of the last encountered allowed trajectory represents the cut-off rigidity R_L. The effective cutoff is given by $R_C = R_U - n_{allowed} \cdot 0.01 \, GV$ where $n_{allowed}$ represents the number of allowed trajectories encountered in the penumbra. The automatic detection of the penumbra is used as default in the code. For selecting the other method you should use the command

"/MAGCOS/SCENARIO/AutomaticDetectionOfPenumbra false".

The results of the computation of R_U, R_L and R_C in function of the position, the direction of incidence, or the time are contained in ASCII tables.

4.4.1 /MAGCOS/SCENARIO/TraceBline

Format: /MAGCOS/SCENARIO/TraceBline

Arguments: None

Function: Trace a magnetic field line passing trough the primary position defined by using /gps or /MAGCOS/SOURCE commands

4.4.2 /MAGCOS/SCENARIO/TraceParticleTrajectory

Format: /MAGCOS/SCENARIO/TraceParticleTrajectory

Arguments: None

Function: Traces the trajectory of a charged particle trough the Earth's magnetosphere. The type, start position, start direction and energy of the particle is defined by using the UI commands from the directories /gps and/or /MAGCOS/SOURCE

4.4.3 /MAGCOS/SCENARIO/ReverseParticleTrajectory

Format: /MAGCOS/SCENARIO/ReverseParticleTrajectory

Arguments: None

Function: Traces the trajectory of a charged particle backward in time trough the Earth's magnetosphere. The type, arrival position, arrival direction and energy of the particle is defined by using the UI commands from the command directories /gps and /MAGCOS/SOURCE .

4.4.4 /MAGCOS/SCENARIO/ComputeAsymptoticDirections

Format: /MAGCOS/SCENARIO/ComputeAsymptoticDirections <*file_name*>

Arguments: G4String *file_name*

Function: Compute the asymptotic directions, rigidity filter values and cutoff rigidities for given observing position, and direction of incidence and for a selected type of particle. The different rigidities at which particle trajectory are computed are defined in a rigidity vector defined by using the UI commands from the /MAGCOS/RIGIDITYVECTOR command directory. Observing position and direction of incidence are defined by using UI commands from the /gps and /MAGCOS/SOURCE directories. The asymptotic directions and rigidity filter values in function of rigidities as well as cutoff rigidities are stored in the ASCII file *file_name*.

4.4.5 /MAGCOS/SCENARIO/RCutoffVsPosition

Format: /MAGCOS/SCENARIO/RCutoffVsPosition <*coorsys altitude length_unit* lat_0 d_{lat} n_{lat} $long_0$ d_{long} n_{long} *zen azim angle_unit* *output_file*>

Arguments: G4String *coorsys*, *length_unit*, *angle_unit*, *output_file*.
G4double *altitude*, lat_0, d_{lat}, $long_0$, d_{long} , *zen*, *azim*
G4int n_{lat}, n_{long}

Function: Computes the cutoff rigidities in function of latitude and longitude, at a given observing altitude, and for a given observing direction of incidence defined by the zenith and azimuth angle. The string coorsys defines the space coordinate system in which position and direction are expressed. The following latitudes lat_i and longitudes $long_i$ are considered:

$$lat_i = lat_0 + i \cdot d_{lat} \qquad i = 0\text{dotsaxis}\, n_{lat} - 1$$
$$long_j = long_0 + j \cdot d_{long} \qquad j = 0\text{dotsaxis}\, n_{long} - 1$$

The results are printed in the file *output_file.*

Error: An error is flagged if coorsys is not one of the following string:
GSM, MAG, SM, GEO, GEOID, GEI, GSE.

4.4.6 /MAGCOS/SCENARIO/RCutoffVsPositionOnLshell

Format: /MAGCOS/SCENARIO/RCutoffVsPositionOnLShell
<*coorsys* L_{val} lat_0 d_{lat} n_{lat} $long_0$ d_{long} n_{long} *zenith* *azimuth angle_unit* *output_file*>

Arguments: G4String *coorsys, angle_unit, output_file*.
G4double L_{val}, lat_0, d_{lat}, $long_0$, d_{long}, *zenith, azimuth*
G4int n_{lat}, n_{long}

Function: Compute the cutoff rigidities at different positions on the same magnetic dipole shell with $L=L_{val}$, and for a given direction of observation defined by the *zenith* and *azimuth* angles. The string *coorsys* defines the space coordinate system in which position and direction are expressed. As we are defining position on magnetic shell *coorsys* should be either SM or MAG. Positions on the L shell are defined by their magnetic latitude lat_i and longitude $long_j$ where

$$lat_i = lat_0 + i \cdot d_{lat} \qquad i = 0\text{dotsaxis}\, n_{lat} - 1$$
$$long_j = long_0 + j \cdot d_{long} \qquad j = 0\text{dotsaxis}\, n_{long} - 1$$

The results are saved in the ASCII file *output_file*.

Error: An error is flagged if *coorsys* is not MAG or SM.

4.4.7 /MAGCOS/SCENARIO/RCutoffVsDirection

Format: /MAGCOS/SCENARIO/RCutoffVsDirection
<*coorsys* zen_0 d_{zen} n_{zen} $azim_0$ d_{azim} n_{azim} *output_file*>

Arguments: G4String *coorsys, output_file*.
G4double zen_0, d_{zen}, $azim_0$, d_{dazim}
G4int n_{zen}, n_{azim}

Function: Compute the cutoff rigidities for different directions of incidence, at the same observing position. The string *coorsys* defines the space coordinate system in which directions are expressed. The position of observation should have been defined previously by UI commands from /gps or /MAGCOS/SOURCE commands. The directions of incidence are defined by their zenith angle zen_i and azimuth angle $azim_j$ where

$$\begin{aligned} zen_i &= zen_0 + i \cdot d_{zen} & \quad i &= 0\text{dotsaxis}\, n_{zen} - 1 \\ azim_j &= azim_0 + j \cdot d_{azim} & \quad j &= 0\text{dotsaxis}\, n_{azim} - 1 \end{aligned}$$

The results are saved in the ASCII file *output_file*.

Error: An error is flagged if *coorsys* is not MAG,SM, GEOID, GEO, or GSM.

4.4.8 /MAGCOS/SCENARIO/RCutoffVsTime

Format: /MAGCOS/SCENARIO/RCutoffVsTime
< t_0 d_t n_t *time_unit output_file*>

Arguments: G4String *time_unit output_file*.
G4double t_0, d_t
G4int n_t

Function: Compute the cutoff rigidities for the same direction and position of observation but at different time t_i where

$$t_i \quad t_0 \quad i \; d_t \quad i \quad 0 \cdots n_t \quad 1$$

The observing position and direction of incidence should have been defined previously by UI commands from /MAGCOS/SOURCE directory. The results are saved in the ASCII file output_file.

Error: An error is flagged if *time_unit* is anything else than hour, minute or second.

4.4.9 /MAGCOS/SCENARIO/AutomaticDetectionOfPenumbra

Format: /MAGCOS/SCENARIO/AutomaticDetectionOfPenumbra *abool*

Argument: bool *abool*

Function: If *abool* is true the penumbra is detected automatically when computing the cutoff rigidities Vs position, direction of incidence, or time (see section 4.4).

4.5 Command directory /MAGCOS/RIGIDITYVECTOR

For computing cutoff rigidities and asymptotic direction of incidence, particles trajectories are computed backward in time for different rigidities values contained in a rigidity vector decreasing monotically (see section 2.4). A default rigidity vector is available. The user can also choose to define this vector by adding subvector to an existing vector. Before defining a new rigidity vector the user should reset the precedent one.

4.5.1 /MAGCOS/RIGIDITYVECTOR/Reset

Format: /MAGCOS/RIGIDITYVECTOR/Reset

Arguments: none

Function : Reset the rigidity vector

4.5.2 /MAGCOS/RIGIDITYVECTOR/SetDefault

Format: /MAGCOS/RIGIDITYVECTOR/SetDefault

Arguments: none

Function: Set the rigidity vector to the default vector.

4.5.3 /MAGCOS/RIGIDITYVECTOR/AddValues

Format: /MAGCOS/RIGIDITYVECTOR/AddValues <rig_0 d_{rig} n_{rig}>

Arguments: G4double rig_0, d_{rig}
G4int n_{rig}

Function: Add the vector [rig_0,..., $rig_0+i\ .d_{rig}$, ..., $rig_0 + (n-1)\ .d_{rig}$] to the rigidity vector.

Error: As the vector should be decreasing, an error is flagged if $d_{rig} \geq 0$, and if rig_0 is not smaller than the last defined value of the rigidity vector.

4.6 Command directory /MAGCOS/USERLIMIT

The commands in this directory set the user limit parameters *MaxStepLength, MaxTrajectoryLength*, and *MaxTrajectoryTime.* The tracking of a trajectory will be stopped when the length of the trajectory is > *MaxTrajectoryLength* or when the global time needed by a particle to reach the last trajectory position is > *MaxTrajectoryTime.* In Geant4 particle trajectories or tracks are divided in tracking steps. For charged particle in a magnetic field, the Lorentz equation of motion is integrated over a track step. A track step is therefore divided in smaller integration steps. Integration steps and tracking steps are therefore not the same. The maximum length of a tracking step *MaxStepLength* is set by the command *SetMaxStepLength.* The maximum length of integration step is set by commands form the directory /MAGCOS/INTEGRATION.For visualisation purpose, the trajectory is divided by straight lines representing the different tracking step. For this reason to obtain a rather smooth drawing of a particle trajectory you should select *MaxStepLength<.1Re.* Too small steps length limit the length of integration step and decrease the computing performance. Therefore if you are not considering visualisation you should select *MaxStepLength>1.Re.*

4.6.1 /MAGCOS/USERLIMIT/SetMaxStepLength

Format: /MAGCOS/USERLIMIT/SetMaxStepLength <*max_step length_unit*>

Arguments: G4double *max_step*
String length_unit

Function: Set an upper limit to the length of the tracking step.

4.6.2 /MAGCOS/USERLIMIT/SetMaxTrajectoryLength

Format: /MAGCOS/USERLIMIT/SetMaxTrajectoryLength
<*max_length length_unit*>

Arguments: G4double *max_length*
String length_unit

Function: Set an upper limit for the length of a particle trajectory, and a magnetic field line.

4.6.3 /MAGCOS/USERLIMIT/SetMaxTrajectoryTime

Format: /MAGCOS/USERLIMIT/SetMaxTrajectoryLength
< t_{max} *time_unit*>

Arguments: G4double t_{max}
String *time_unit*

Function: Set an upper limit for the particle trajectory time.

4.6.4 /MAGCOS/USERLIMIT/SetStopAltitude

Format: /MAGCOS/USERLIMIT/SetMaxStop
< alt_{stop} *length_unit*>

Arguments: G4double alt_{stop}
String *length_unit*

Function: Set the altitude below which the trajectory of a particle will be stopped. It represents the top of the atmosphere. By default it is set to 20 km.

4.7 Command directory /MAGCOS/DRAW

The commands in this directory allow the user to control the visualisation of trajectories and magnetic field lines. If the flag DrawTrajectory is set to true, particle trajectories and magnetic field lines computed during application scenario 1-4, are stored in the vector of curves. A drawing color is associated to each of this curve. At any time this color can be select by the user with the command /MAGCOS/DRAW/SetColour. If the flag *DrawPoints* is set to true the different step positions of the trajectory are stored in a vector of step points. When plotted these points are represented by full circle of size *PointSize*, and with the same color than for its corresponding trajectory. By selecting small enough tracking step (see /MAGCOS/USERLIMIT) and large enough point size you are able to obtain bold lines for plotting trajectory under some visualisation driver. The user can also select the coordinate system of reference for visualising. He can choose between the systems GEO, GEI, GSE, MAG, SM and GSM. The trajectory and step point vectors are plotted by invoking the command /MAGCOS/DRAW/Draw. By invoking the command /MAGCOS/DRAW/Reset, all the stored trajectories and step points are removed from their vectors.

4.7.1 /MAGCOS/DRAW/SetColour.

Format: /MAGCOS/DRAW/SetColour. <*red green blue*>

Arguments: G4double *red, green, blue*

Function: Defines the color for drawing trajectories and magnetic field lines. The color is defined by a RGB code.

Default: (1,0,0) corresponding to red.

Errors: The values of the color index should be in the range [0.,1]. If greater they are fixed to 1, if smaller they are fixed to 0.

4.7.2 /MAGCOS/DRAW/SetCoordinateSystem

Format: /MAGCOS/DRAW/SetCoordinateSystem <*coorsys*>

Arguments: G4String *coorsys*

Function: Define the coordinate system of reference for drawing trajectories and magnetic field lines.

Default: GEO

Errors: An error is flagged if the coordinate system selected is not one of the following: GEO, MAG, GSM, GEI, GSE, SM

4.7.3 /MAGCOS/DRAW/DrawTrajectory

Format: /MAGCOS/DrawTrajectory < *aBool*>

Arguments: G4bool *aBool*

Function: If *aBool is* true the next particle trajectories and magnetic field lines computed during scenario 1-4 are added to the vector of curves. This vector is visualised at any time by the command /MAGCOS/DRAW/Show.

4.7.4 /MAGCOS/DRAW/DrawPoints

Format: /MAGCOS/DrawPoints < *aBool*>

Arguments: G4bool *aBool*

Function: If *aBool* is true the step points of particle trajectories and magnetic field lines computed during scenario 1-4 are added to the step position vector. This vector is visualised at any time by the command MAGCOS/DRAW/Show.

4.7.5 /MAGCOS/DRAW/SetPointSize

Format: /MAGCOS/DRAW/SetPointSize

Arguments: G4double *size*

Function: Set the size of the circle used for visualising the step points of the next computed particle trajectory.

Default: 1

4.7.6 /MAGCOS/DRAW/Show

Format: /MAGCOS/DRAW/Show

Arguments: None

Function: Visualise all the trajectories and points contained in the trajectory vector and in the step point vector respectively. The Earth is also drawn in blue.

4.7.7 /MAGCOS/DRAW/Reset

Format: /MAGCOS/DRAW/Reset

Arguments: None

Function: Empty the vectors of trajectories and step points representing particle trajectories and magnetic field lines that were registered to be plotted later on.

5. Examples

In the magnetocosmics directory different g4mac files are provided as tutorial examples. These files contain many comments that should guide the user during its learning phase of MAGNETOCOSMICS that we wish him funny, interesting and easy . We describe the files briefly in this section.

The file Bline.g4mac illustrates how to trace and visualise magnetic field lines. The magnetic field model is given by the geomagnetic dipole shifted from the Earth center + the Tsyganenko89 magnetospheric magnetic field model. Visualisation results obtained with the DAWNFILE driver are plotted in Figure 3. The GSM coordinate system was selected as the referential system for the visualisation. The magnetic field lines in the morning side are plotted in red together with their step points. Magnetic field lines in the night side are plotted in green without their stepping points. The Earth is represented in blue.

The file CosmicTrajectory.g4mac illustrates how to trace and visualise cosmic rays trajectory backward in time. Visualisation results obtained with the DAWNFILE driver are plotted in Figure 4. The reverse time trajectory of a 5 GV proton arriving vertically at the top of the atmosphere above a given Earth position is traced for different magnetic field models. The blue and green trajectories are obtained when considering a dipole shifted from the Earth center as the geomagnetic field, without external magnetospheric magnetic field and with the Tsyganenko89 model respectively. The yellow and red curves are obtained when considering the IGRF model as the geomagnetic field, without external magnetospheric magnetic field and with the Tsyganenko89 model respectively.

The file ProtonOnMagneticShell.g4mac allows to trace and visualise the gyrating, bouncing and drifting motion of a 10 MeV proton on a geomagnetic shell. The visualisation results obtained with the DAWNFILE driver are plotted in figure5.

The file AsymptoticDirection.g4mac allows to compute asymptotic direction for cosmic ray for a given observing position and direction of incidence. The file CutoffRigidityVsPosition.g4mac allows to compute cutoff rigidities at different position for a vertical direction of incidence.

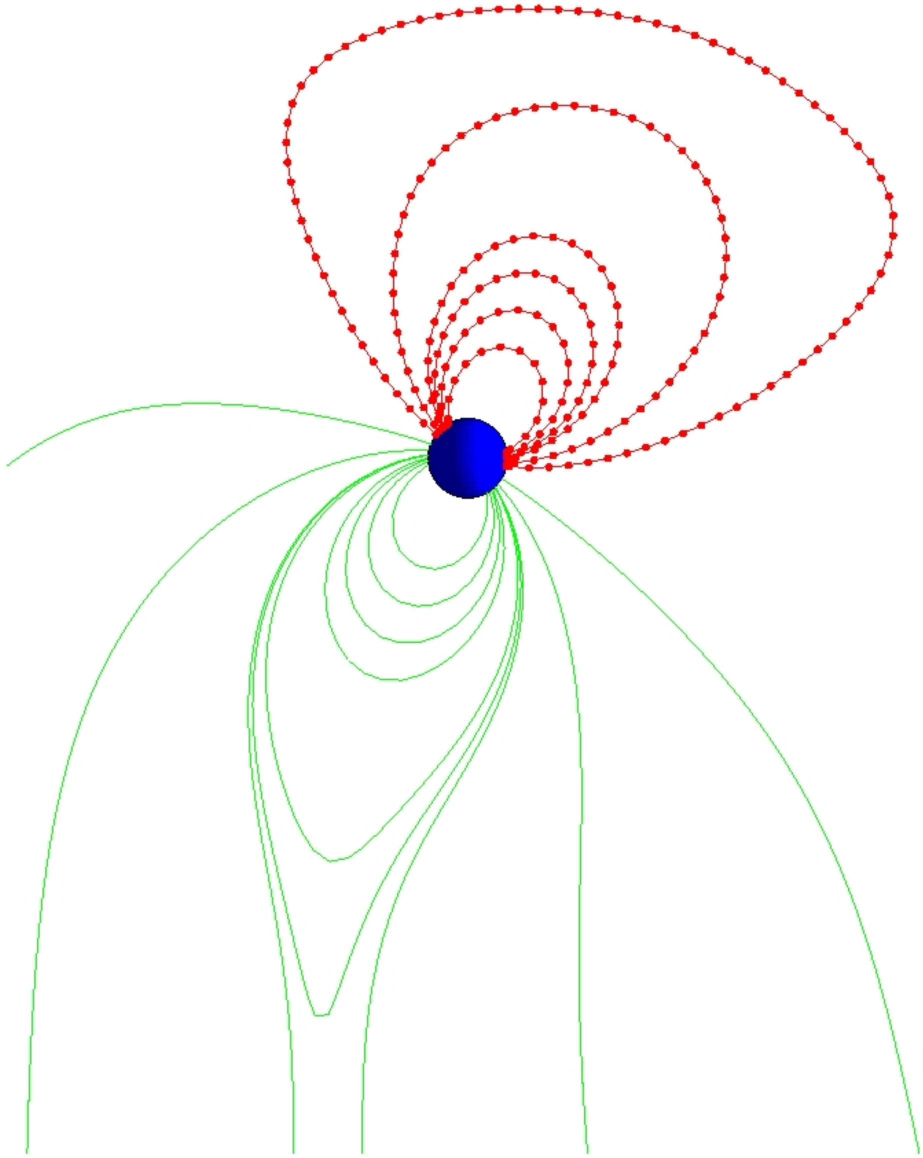

Figure 3 Visualisation of magnetic field line with MAGNETOCOMICS by using the DAWNFILE visualisation driver

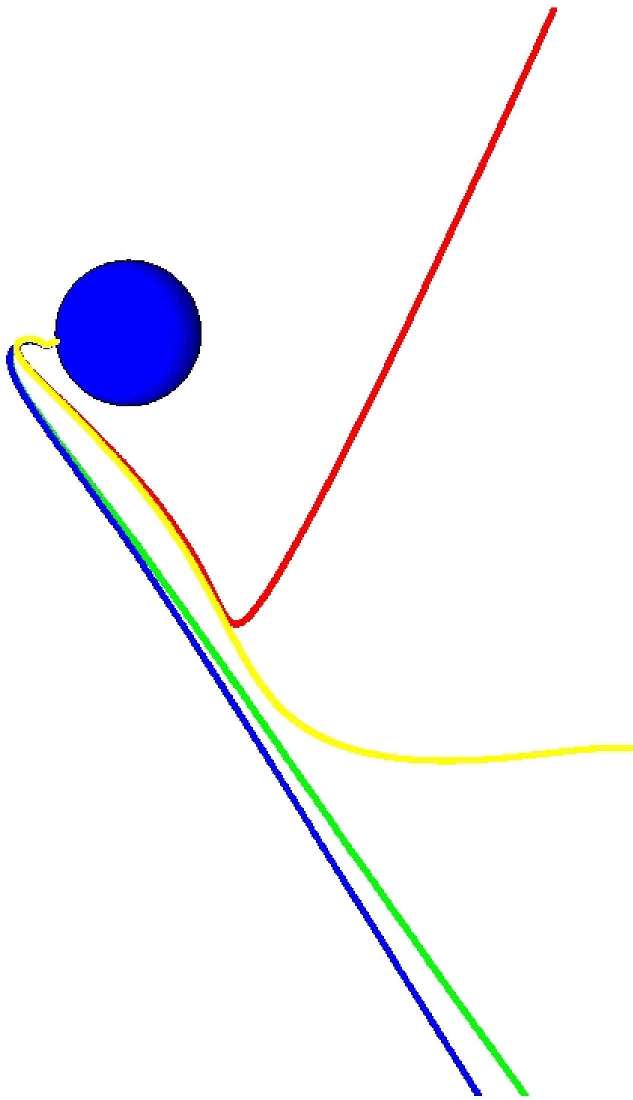

Figure 4 Visualisation of the trajectory of 5GV proton computed backward in time for different model of the magnetosphere. This was obtained with MAGNETOCOMICS by running the macro file CosmicTrajectory.g4mac and by using the DAWNFILE visualisation driver.

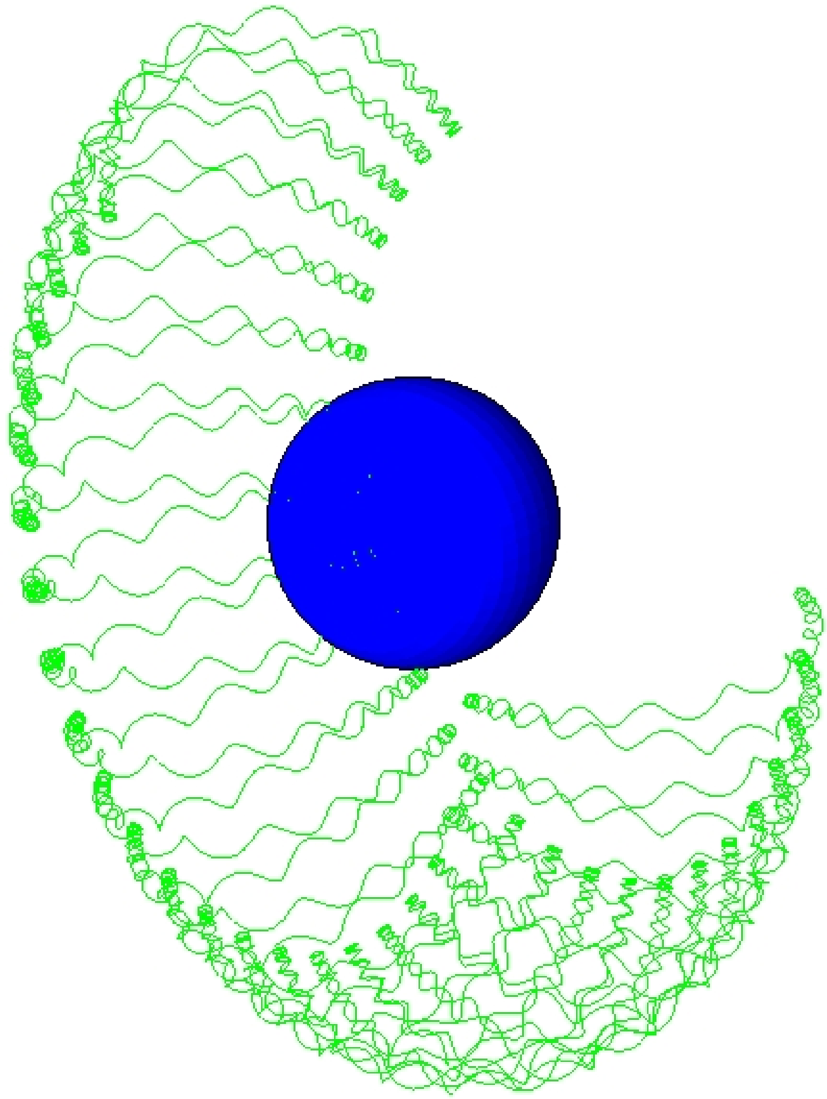

Figure 5 Motion of a 10 MeV proton on a geomagnetic shell during 50 s. This was obtained by executing the ProtonOnMagneticShell.g4mac file under MAGNETOCOSMICS . The DAWNFILE driver was used for this visualisation .