# Software Verification and Validation Document

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**Abstract**

The software verification and validation process is described for the PLANETOCOSMICS code based on the CERN Geant4 toolkit. The objective is to conduct a comprehensive set of tests to verify functionality in response to user commands.

## Record of changes

| Issue | Date | Detail of changes |
|---|---|---|
| 0.1 | 28 August 2004 | First Issue to reviewers in draft form |

# Table of Contents

# 1 Introduction

## 1.1 Contractual

This document has been issued by the Physikalisches Institut of the University of Bern to ESA under contrac .

## 1.2 Purpose of the Document

This document is intended as a plan and record for the technical reviews and tests carried out on the PLANETOCOSMICS code. It shall be used to assess that the coding is of sufficient quality, contains sufficient internal documentation, responds correctly to commands provided by the user, carries out the mathematical calculations to the required accuracy, and meets the performance requirements.

## 1.3 Scope of the Software

This code is intended for use with the CERN Geant4 code for Monte-Carlo, high-energy particle transport. This code was developed with Geant4.6.2.

## 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

OO Object-Oriented

UI User Interface

UML Unified Modelling Language

UR User Requirement

URD User Requirement Document

## 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

[6] Information on AIDA can be found on http://aida.freehep.org

[7] The Anaphe web site: http://anaphe.web.cern.ch/anaphe/

[8] ESA-PSS-05-0 software engineering standards, as modified in BSSC/96/2 for small projects.

[9] 'The Unified Modeling Language User Guide', Booch G, Rumbaugh J., Jacobson I., Addison Wesley Publishing Company, 1999.

[10] 'UML Distilled', Fowler M., Scott K., 2nd –ed., Addison Wesley Publishing Company, 2000.

[11] 'Object-Oriented Analysis and Design with Applications', Booch G., 2nd –ed, Addison Wesley Publishing Company, 1994.

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[13] 'Cosmic rays at High Latitudes and Altitudes Covering Four Solar Maxima', Neher H.V. , *Jour. Geophys. Res.*, 76, 7, 1971

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### 1.6 Overview of the document

This document describes the verification and validation plan for the PLANETOCOSMICS.

## 2 Review

The purpose of the document is to test the PLANETOCOSMICS code. Things to be tested are the space cooordiante trasnformation, the magnetic field models, the atmospheric models and the geometry definition, the source particle definition, the analysis manager, the physics implemented in the code, the visualisation, and the implementation of the geomagnetic field models.

Testing will be carried out using a series of macros that can be run one after the other. These will present the PLANETOCOSMICS with all of the different inputs expected from users. The outputs can be assessed to determine the correctness of the code. Output will be either computation results in form of 1D and 2Dhistograms, or printed information on the screen, or in form of visualisation output. The test macrofiles are conatined in the verification directory of the PLANETOCSOMICS distribution under different subdirectoryie corresponding to different test categories. The directory verification/coordinate conatins macrofiles test the implementation of the space coordiante transformations for the Earth, Mars and Mercury.

The PLANETOCOSMICS code has been written by L- Desorgher who shall also carry out the tests described in this document. The document shall be updated according to the results of the Tests. The source code and documentation shall be passed to Dr Fan Lei for inspection and technical review.

# 3 Test of the space coordinate convertor

This section presents the test that have been done to check the implementation of the Space coordinate transformation for the Earth, Mars and Mercury. All the material and Geant4 macrofiles needed for these tests are conatined in the directory planetocosmics/verification/coordinate and its subdirectories.

## 3.1 1st Test for the Earth

### *3.1.1 Test description*

The test is done by typing "PLANETOCOSMICS Earth wind_test.g4mac" under the directory planetocosmics/verification/coordinate.

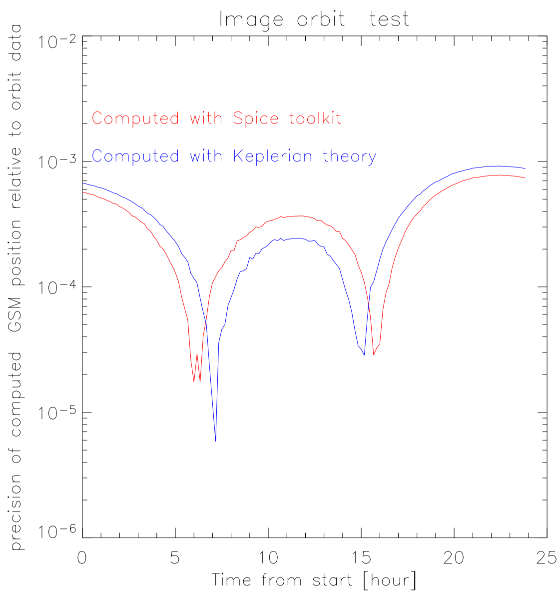
In this test PLANETOCOSMICS is used to transform the GSE coordinates of the wind spacecraft orbit on July 1st 1997 into GSM coordinates. The GSE coordinates are read from the file wind/OrbitSample.txt that has been extracted from the file wind/WI_OR_DEF_319802.txt obtained from the CDAWEB interface ( http://cdaweb.gsfc.nasa.gov/) . The computed GSM coordinates are compared with the GSM coordinates also provided in the file wind/WI_OR_DEF_319802.txt. The test is done for two cases. For the first case the Spice library is used by the coordinate convertor. In the second case our implementation of the Keplerian orbit theory in PLANETOCOSMICS is used.

### *3.1.2 Features to be tested*

- Space coordinate convertor for the Earth.

### *3.1.3 Test results*

The files *test_results_with_spice.txt* and *test_results_without_spice.txt*, are produced in the directory planetocosmics/verification/coordinate/wind. The first file corresponds to the results obatined when the Spice library is used, while the second fils corresponds to the results obtained by using our implementaion of planet orbit calculation following Kleperian theory. In the next figure we plot the realtive error in function of time between the computed GSM coordinates and the one provided in the wind orbit data file WI_OR_DEF_319802.txt. This figure is obtained by using the idl subroutine PLOT_WIND_ORBIT contained in the IDL file plot_results.pro. This figure illustrates that the difference between the computed and the published GSM coordinates in the case of the wind orbit is smaller than 0.1 %. Considering the precision achieved we conclude that the test is passed.




## 3.2 2nd Test for the Earth

### *3.2.1 Test description*

The test is done by typing "PLANETOCOSMICS Earth image_test.g4mac" under the directory planetocosmics/verification/coordinate.

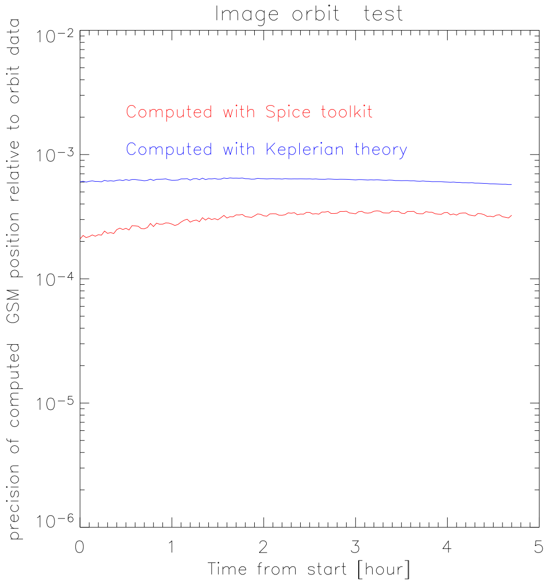
In this test PLANETOCOSMICS is used to transform the GSE coordinates of the IMAGE spacecraft orbit on May 23rd, 2005 into GSM coordinates. The GSE coordinates are read from the file image/OrbitSample.txt that has been extracted from the file "image/ IM_OR_DEF_316003.txt" obtained from the CDAWEB interface ( http://cdaweb.gsfc.nasa.gov/) . The computed GSM coordinates are compared with the GSM coordinates also provided in the file wind/IM_OR_DEF_316003.tx. The test is done for two cases. For the first cases the Spice library is used by the coordinate converor. In the second cases our implementation of the Keplerian theory in PLANETOCOSMICS is used.

### *3.2.2 Features to be tested*

- Space coordinate convertor for the Earth.

### *3.2.3 Test results*

The files *test_results_with_spice.txt* and *test_results_without_spice.txt*, are produced in the directory planetocosmics/verification/coordinate/image. The first file corresponds to the results obatined when the Spice library is used, while the second files corresponds to the results obtained by using our implemnetaion of planet orbit calulation following Kleperian theory. In the next figure we have plotted the relative error between the computed GSM coordinates and the one provided in the wind orbit data file IM_OR_DEF_316003.tx. This figure is obtained by using the idl subroutine PLOT_IMAGE_ORBIT contained in the IDL file plot_results.pro. This figure illustrates that the difference between the computed and published GSM coordinates in the case of the image orbit is smaller than 0.1 %. Considering the precision achieved we conclude that this test is passed.




## 3.3 Test for Mercury

### *3.3.1 Test description*

The test is done by typing “PLANETOCOSMICS Mercury mariner_test.g4mac” under the directory planetocosmics/verification/coordinate.

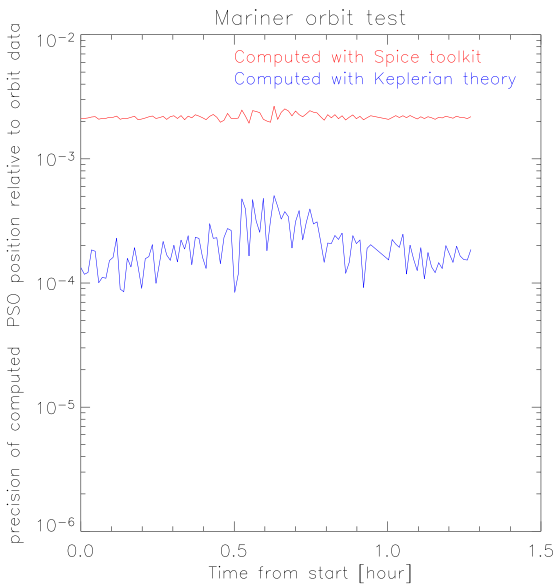
In this test PLANETOCOSMICS is used to transform the PLA coordinates of the Mariner spacecraft during its first Mercury flyby on March 29th, 1974 into PSO coordinates. The PLA coordinates are read from the file mariner/MarinerOrbit.TAB that has been extracted from the file “mariner/MAG_M1_ENC_42SEC_MO.TAB" obtained from the url . The computed PSO coordinates should be compared with the PSO coordinates also provided in the file mariner/MAG_M1_ENC_42SEC_MO.TAB. The test is done for two cases. For the first cases the Spice library is used by the coordinate convertor. In the second cases our implementation of the Keplerian theory in PLANETOCOSMICS is used.

### *3.3.2 Features to be tested*

- Space coordinate convertor for Mercury.

### 3.3.3 Test results

The files *test_results_with_spice.txt* and *test_results_without_spice.txt*, are produced in the directory planetocosmics/verification/coordinate/mariner. The first file corresponds to the results obatined when the Spice library is used, while the second files corresponds to the results obtained by using our implemnetaion of planet orbit calulation following Kleperian theory. In the next figure we have plotted the relative error between the computed PSO coordinates and the one provided in the mariner orbit data file mariner/MAG_M1_ENC_42SEC_MO.TAB. This figure is obtained by using the idl subroutine PLOT_MARINER_ORBIT contained in the IDL file plot_results.pro. This figure illustrates that the difference between the computed and published PSO coordinates in the case of the image orbit is smaller than 0.3 % for both cases . Considering the precision achieved we conclude that this test is passed.




## 3.4 Test for Mars

### 3.4.1 Test description

The test is done by typing “PLANETOCOSMICS Mars mars_odyssey_test.g4mac ” under the directory planetocosmics/verification/coordinate.

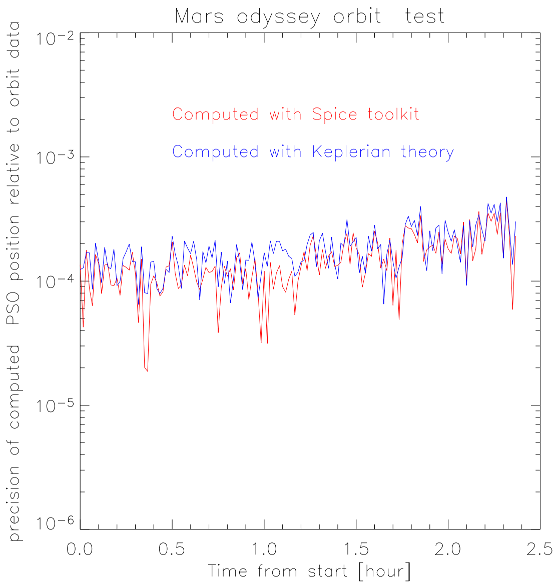
In this test PLANETOCOSMICS is used to transform the PLA coordinates of the orbit of the Mars Odyssey spacecraft on October 30th, 2001 into PSO coordinates. The PLA coordinates are read from the file mars_odyssey/orbit_sample.txt that has been extracted from the file “mars_odyssey/ODY_TRAJ_01.TAB" obtained from the url . The computed PSO coordinates should be compared with the PSO coordinates also provided in the file “mars_odyssey/ODY_TRAJ_01.TAB". The test is done for two cases. For the first cases the Spice library is used by the coordinate convertor. In the second cases our implementation of the Keplerian theory in PLANETOCOSMICS is used.

### 3.4.2 Features to be tested

- Space coordinate convertor for Mercury.

### 3.4.3 Test results

The files *test_results_with_spice.txt* and *test_results_without_spice.txt*, are produced in the directory planetocosmics/verification/coordinate/mars_odyssey. The first file corresponds to the results obatined when the Spice library is used, while the second file corresponds to the results obtained by using our implemnetaion of planet orbit calulation following Kleperian theory. In the next figure we have plotted the relative error between the computed PSO coordinates and the one provided in the Mars Odyssey orbit data file mars_odyssey/ODY_TRAJ_01.TAB. This figure is obtained by using the idl subroutine PLOT_MARS_ODYSSEY_ORBIT contained in the IDL file plot_results.pro. This figure illustrates that the difference between the computed and published PSO coordinates in the case of the image orbit is smaller than 0.1 % for both cases . Considering the precision achieved we conclude that this test is passed.




## 3.5 Test plan #2

### 3.5.1 Test items

For this test the macro file test_geometry2.g4mac is used.

All commands contained in the /PLANETOCOSMICS/GEOMETRY directory are tested. All set methods of the PLANETOCOSMICSDetectorConstruction class are tested as well as the following methods: RemoveAllDetector, AddDetectorAtDepth, AddDetectorAtAltitude, ReConstructGeometry, and ContructEuclidean geometry.

The methods ComputeAtmosphericLayers, ComputeAtmosphericLayersFromModel, and the Set method of the EarthAtmosphereModel class are tested.

The interface to the FORTRAN code MSISE90 is tested.

### 3.5.2 Features to be tested

- Construction of a flat atmosphere divided into layers

- Definition of the altitudes and the depths at which particle fluxes should be detected.

- Implementation of the MSISE90 model.

#### *3.5.3 Test deliverables*

#### *3.5.4 Test pass/fail criteria*

The PLANETOCOSMICS will be considered to pass this test if : i)the altitudes and the depths of the boundaries of the different atmospheric layers and their densities, that are printed into the log file are the ones expected; ii) the visualisation output is the one expected; iii) the normal incident geantino that is tracked through the atmosphere crosses the different boundary layers at the expected positions.

#### *3.5.5 Test*

1. Type :PLANETOCOSMICS geometry_test2.g4mac > <*your_log_file*>

2. In the log file *your_log_file* you will find the characteristic of the different layers (altitude, depth, density), as well as the result of the track of a geantino particle through the atmosphere. You can also visualised the structure of the geometry.

### 3.6 Test plan #3

#### *3.6.1 Test items*

For this test the macro file test_geometry3.g4mac is used.

All commands contained in the /PLANETOCOSMICS/GEOMETRY directory are tested. All set methods of the PLANETOCOSMICSDetectorConstruction class are tested as well as the following methods: RemoveAllDetector, AddDetectorAtDepth, AddDetectorAtAltitude, ReConstructGeometry, and ContructEuclidean geometry.

The methods ReadAtmosphereComposition, ComputeAtmosphericLayers, ComputeAtmosphericLayersFromTable of the EarthAtmosphereModel class are tested.

#### *3.6.2 Features to be tested*

- Construction of a flat atmosphere divided into layers

- Definition of the altitudes and the depths at which particle fluxes should be detected.

- Implementation of the TABLE model.

#### *3.6.3 Test deliverables*

#### *3.6.4 Test pass/fail criteria*

The PLANETOCOSMICS will be considered to pass this test if : i)the altitude and depth of the boundaries of the different atmospheric layers and their densities, that are printed into the log file are the ones expected; ii) the visualisation output is as expected; iii) the normal incident geantino that is tracked through the atmosphere crosses the different boundary layers at the expected positions.

### *3.6.5 Test*

1. Type : PLANETOCOSMICS geometry_test3.g4mac > <*your_log_file*>

2. In the log file *your_log_file* you will find the characteristic of the different layers (altitude, depth, density), as well as the result of the track of a geantino particle through the atmosphere. You can also visualised the structure of the geometry.

## 3.7 Test plan #4

### *3.7.1 Test items*

For this test the macro file test_geometry4.g4mac is used.

All commands contained in the /PLANETOCOSMICS/GEOMETRY directory are tested. All set methods of PLANETOCOSMICSDetectorConstruction class are tested as well as the following methods: RemoveAllDetector, AddDetectorAtDepth, AddDetectorAtAltitude, ReConstructGeometry, and ContructSpherical geometry.

The methods ComputeAtmosphericLayers, ComputeAtmosphericLayersFromModel, and the Set method of the EarthAtmosphereModel class are tested.

### *3.7.2 Features to be tested*

- Construction of a spherical atmosphere divided into spherical shells

- Definition of the altitudes and the depths at which particle fluxes should be detected.

- The TABLE atmospheric model.

### *3.7.3 Test deliverables*

### *3.7.4 Test pass/fail criteria*

The PLANETOCOSMICS will be considered to pass this test if : i)the altitude and depth of the boundaries of the different atmospheric layers and the density of each layers, that are printed onto the screen or in a log file are the ones expected; ii) the visualisation output is the one expected; iii) the normal incident geantino that is tracked through the atmosphere crosses the different boundary layers at the expected positions.

### *3.7.5 Test*

1. Type PLANETOCOSMICS geometry_test4.g4mac > <*your_log_file*>

2. When the run is finished you can view *your_log_file* and look the characteristic of the different layers (altitude, depth, density), as well as the result of the track of a geantino particle through the atmosphere. You can also visualised the structure of the geometry.

## 3.8 Test Plan #5

### *3.8.1 Test Items*

For this test the macro file source_test1.g4mac is used.

The different macro commands of the /ATMOCOMICS/PRIMARY directory that allow to define the primary flux of galactic proton and alpha cosmic rays are tested. The following methods of the

PLANETOCOSMICSPrimaryGeneratorAction class are tested: ModulatedDifferentialGalacticFlux, all Select... methods, ComputePrimaries.

The following macro commands of the directory /PLANETOCOSMICS/ANALYSIS are tested: OmniFluxPrimary, ZenithPrimary, AzimuthPrimary, CosZenVsEnergyPrimary, CosZenVsAzimuthPrimary, PlotHistoInFile, SaveTree, WriteTreeInASCIIFile. The methods of the class PLANETOCOSMICSAnalysisManager that allow to create 1D and 2D Histograms for registering flux of primary and that allow to save these histograms in ASCII file or in a format compliant with theAIDA3.0.0 interface are tested. The abilty to normalise these histograms to the incident flux of primary particles or per incident particle is also tested.

For this test several primaries are generated and tracked through the atmosphere without any Electromagnetic and Hadronic interaction considered.

### *3.8.2 Features to be tested*

- Definition of the primary source as a flux of galactic cosmic ray proton or alpha particles at solmax, at solmin, averaged over a typical solar cycle or with modulation parameter F defined by the user.
- Creation of 1D and 2D histograms that allow to register the flux and angular distribution of primary particles.
- Saving of all 1D and 2D histograms contained in the /PRIMARY directory of the histogram in an ASCII file or in a format supported by the user selected implementation of the AIDA3.0.0 interface, with and without normalisation.

### *3.8.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.8.4 Test pass/fail criteria*

The PLANETOCOSMICS will be considered to have passed this test if the different histograms saved in the ASCII file reproduce the expected spectrum and a cos-law for the angular distribution. It should be checked that the normalisation of the histograms is correct. The visualisation of the tracks of 100 primaries through the atmosphere should show that all primaries start at the center of the top of the atmosphere and that their track show a rotational symmetry around the z axis

### *3.8.5 Test*

1) Type : PLANETOCOSMICS source_test2.g4mac >! <*your_log_file*>
2) When the run is finished you should analyse with your analysis/plotting program the different histograms contained in the ASCII and xml files that have been produced during the run. For the different type of galactic cosmic ray source selected the track of 100 primaries can be visualised.

## 3.9 Test Plan #6

### *3.9.1 Test Items*

For this test the macro file source_test2.g4mac is used.

The following macro commands of /ATMOCOMICS/PRIMARY directory are tested: SetCutoffRigidityValue,ConsiderCutoff and ReadCutoffVsDirection. The following methods of the

PLANETOCOSMICSPrimaryGeneratorAction class are tested: ComputePrimaries, GeneratePrimaries, SetCutoffRigidity, SetConsiderCutoff, SetCutoffType, ReadCutOffVsDirection, ComputeCutoff, ComputeMaximumAndMinimumCutoff.

The following macro commands of the directory /PLANETOCOSMICS/ANALYSIS are tested: OmniFluxPrimary, ZenithPrimary, AzimuthPrimary, CosZenVsEnergyPrimary, CosZenVsAzimuthPrimary, PlotHistoInFile, SaveTree, WriteTreeInASCIIFile. The methods of the class PLANETOCOSMICSAnalysisManager that allow to create 1D and 2D Histograms for registering flux of primary and that allow to save these histograms in ASCII or in a format compliant with theAIDA3.0.0 interface are tested. The ability to normalise these histograms to the incident flux of primary particles or per incident particle is also tested.

For this test several primaries are generated and tracked through the atmosphere without taking in to account any Electromagnetic and Hadronic interaction.

### *3.9.2 Features to be tested*

- Definition of a constant cut-off rigidity for the spectrum
- Definition of cut-off rigidities in function of the direction of incidence.
- Test that the normalisation of the histograms is correct for the case where the cut-off rigidity is function of the direction of incidence.

### *3.9.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.9.4 Test pass/fail criteria*

The PLANETOCOSMICS will be considered to have passed this test if the different histograms saved in the ASCII file reproduce the expected spectrum and angular distribution. At high energy above the maximum cutoff rigidity the spectrum should be equivalent to the corresponding energy spectrum generated with the source_test1.g4mac file where no cut-off rigidity is considered. The azimuth angle distribution should show a east-west asymmetry.

### *3.9.5 Test*

1. Type : PLANETOCOSMICS source_test2.g4mac >! <*your_log_file*>
2. When the run is finished you can look at and plot with your analysis/plotting program the different histograms contained in the ASCII and xml files that have been produce during the run.

## 3.10 Test plan #7

### *3.10.1 Test Items*

For this test the macro file source_test3.g4mac is used. The user spectrum that will be generated during this test are defined in the ASCII file dir_diff_spectrum.txt, omnidir_diff_spectrum.txt, omnidir_int_spectrum.txt, dir_int_spectrum.txt.

The macro command /PLANETOCOSMICS/PRIMARY/ReadPrimaryFlux is tested. The following methods of the PLANETOCOSMICSPrimaryGeneratorAction are tested: ReadUserSpectrum ComputePrimaries, GeneratePrimaries.

### 3.10.2 Features to be tested

- Generation of user defined omnidirectional differential, directional differential, omnidirectional integral and directional integral fluxes of primary particle.

- Normalisation of the primary histograms for user defined spectrum.

### 3.10.3 Test deliverables

The test deliverables shall be a completed Test Table (see ).

### 3.10.4 Test pass/fail criteria

If the histograms generated during this test correspond to the user defined spectrum.

### 3.10.5 Test

1) If needed the dir_diff_spectrum.txt, omnidir_diff_spectrum.txt, omnidir_int_spectrum.txt, dir_int_spectrum.txt files can be modified to define your spectra.

2) Type PLANETOCOSMICS source_test3.g4mac

3) The normalised 1D spectrum histogram contained in the ASCII and xml file generated during the test should be equivalent to the spectrum defined in the dir_diff_spectrum.txt, omnidir_diff_spectrum.txt, omnidir_int_spectrum.txt, dir_int_spectrum.txt.

## 3.11 Test Plan #8

### 3.11.1 Test Items

For this test the macro file source_test4.g4mac is used. The command / PLANETOCOSMICS/PRIMARYSetPosition is tested. The method SetPosition of the PLANETOCOSMICSPrimaryGeneratorAction.hh is tested.

### 3.11.2 Features to be tested

- Definition of the altitude of the start position of the primary source in the case of a flat geometry.

### 3.11.3 Test deliverables

The test deliverables shall be a completed test table.

### 3.11.4 Test pass/fail criteria

The PLANETOCOSMICS is considered to have passed the test if the track of the primary particle printed on the screen and its visualisation output correspond to a primary particles starting at the defined altitude.

### 3.11.5 Test

1) Type : PLANETOCOSMICS source_test4.g4mac

2) By looking at the tracking information printed on the screen and by looking at the visualisation output you should check if the start altitude of the primary particles is the one expected.

## 3.12 Test Plan #9

### *3.12.1 Test Items*

For this test the macro file source_test5.g4mac is used. The command /PLANETOCOSMICS/PRIMARYSetPosition is tested. The method SetPosition of the PLANETOCOSMICSPrimaryGeneratorAction.hh is tested.

### *3.12.2 Features to be tested*

- Definition of altitude, longitude and latitude in GEO or GEODETIC coordinates of the start position of the primary source in the case of the spherical geometry.

- Test if the system of reference used to generate the angular distribution is oriented with the Z axis anti-parallel to the vector defining the position of the source.

### *3.12.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.12.4 Test pass/fail criteria*

The PLANETOCOSMICS will be considered to have passed this test if the zenith angle and azimuth angle histograms saved in the ASCII and xml file generated during the run correspond to a cos-law angular distribution. The visualisation of the tracks of 100 primaries through the atmosphere should show that all primaries start at the position defined by the user and that their track show a rotational symmetry around the vertical direction.

### *3.12.5 Test*

1) Type : PLANETOCOSMICS source_test5.g4mac.

2) By using a analysis:plotting packages you can look at the histograms contained in the ASCII and xml files generated during the run. By looking at the visualisation output you should check if the start altitude of the primary particle is the one expected.

## 3.13 Test Plan #10

### *3.13.1 Test Items*

For this test the macro file trajectory_vis_test.g4mac is used. The commands AddParticleToBeDrawn and RemoveParticleToBeDrawn of the /PLANETOCOSMICS/DRAWING directory are tested. The methods AddParticleToBeDrawn, RemoveParticleToBeDrawn and EventAction of the PLANETOCOSMICSEventAction are tested.

### *3.13.2 Features to be tested*

- Drawing of particle tracks in cosmic ray shower with colours depending of the particle types and defined by the user.

### *3.13.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.13.4 Test pass/fail criteria*

The test is passed if for the visualisation of the first simulated cosmic ray shower the tracks of protons, e-, e+, neutron, gamma, mu- and mu+ are drawn in red, green, green, blue, white, yellow, and yellow respectively, and if in the visualisation of the second simulated atmospheric shower the neutrons tracks are not drawn.

### *3.13.5 Test*

1) Type : PLANETOCOSMICS trajectory_vis_test.g4mac

2) By visualising the two simulated cosmic ray shower you should check if the particle tracks are drawn with the good colours.

## 3.14 Test Plan #11

### *3.14.1 Test Items*

For this test the macrofile bfield_test1.g4mac is used.

All the commands of the /PLANETOCOSMICS/BFIELD directory are tested. The ATMOCOSGeomagneticField class is tested.

### *3.14.2 Features to be tested*

- The definition and use of the geomagnetic field in the case of the flat geometry.
- The orientation of the magnetic field in the local coordinate system

### *3.14.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.14.4 Test pass/fail criteria*

The test is passed if the component of the magnetic field components for the different selected models and at the different selected positions are correct and if in the visualisation output of the magnetic field lines are correctly oriented in the local coordinate system. Field lines from the CONST field model set to the IGRF field at a given position should coincide with the line tangent to the IGRF field line passing through this position.

### *3.14.5 Test*

1. Type : PLANETOCOSMICS bfield_test1.g4mac > log_file
2. Look at the the magnetic field component for the selected positions and selected models in the log file. Visualise the drawing of magnetic field lines.

## 3.15 Test Plan #12

### *3.15.1 Test Items*

For this test the macrofile bfield_test2.g4mac is used.

All the commands of the /PLANETOCOSMICS/BFIELD directory are tested. The ATMOCOSGeomagneticField class is tested.

### 3.15.2 Features to be tested

- The definition and use of the geomagnetic field in the case of the spherical geometry.

### 3.15.3 Test deliverables

The test deliverables shall be a completed Test Sheet.

### 3.15.4 Test pass/fail criteria

The test is passed if the components of the magnetic field printed on the screen for the different selected models and at the different selected positions are correct and if in the visualisation output the drawing of magnetic field lines is correct. Field line from the CONST field model set to the IGRF field at a given position should coincide with the line tangent to the IGRF field line passing through this position.

### 3.15.5 Test

3. Type : PLANETOCOSMICS bfield_test2.g4mac > log_file
4. Look at the the magnetic field component for the selected positions and selected models in the logfile. Visualise the drawing of magnetic field lines.

## 3.16 Test Plan #13

### 3.16.1 Test Items

For this test the macrofile bfield_test3.g4mac is used.

The commands of the /ATMOCSOMICS/BFIELD and /PLANETOCOSMICS/INTEGRATION are tested. The class GeomagneticField is tested.

### 3.16.2 Features to be tested

- Tracking of charged particle in the geomagnetic field in the case of the flat geometry.

### 3.16.3 Test deliverables

The test deliverables shall be a completed Test Sheet.

### 3.16.4 Test pass/fail criteria

The test is passed if the the visualisation outputs are the one expected for the motion of an e- in the selected magnetic field.

### 3.16.5 Test

1. Type : PLANETOCOSMICS bfield_test3.g4mac
2. At the end of the simulation you can view the particle trajectories in the visualisation output.

## 3.17 Test Plan #14

### 3.17.1 Test Items

For this test the macrofile bfield_test4.g4mac is used.

The command of the /ATMOCSOMICS/BFIELD and /PLANETOCOSMICS/INTEGRATION are tested. The class GeomagneticField is tested.

### *3.17.2 Features to be tested*

- Tracking of charged particle in the geomagnetic field in the case of the spherical geometry.

### *3.17.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.17.4 Test pass/fail criteria*

The test is passed if the the visualisation outputs are the one expected for the motion of an 1 GeV proton in the Geomagnetic field.

### *3.17.5 Test*

1. Type : PLANETOCOSMICS bfield_test4.g4mac

2. At the end of the simulation you can view the particle trajectory in the visualisation output.

## 3.18 Test Plan #15

### *3.18.1 Test Items*

For this test the macrofile detection_flux_test1.g4mac is used.

Except the command for defining energy deposited histograms all  the commands of the / PLANETOCOSMICS/ANALYSIS directory are tested. The classes ATMOCOSAnalysisManager, ATMOCOSFluxHit, ATMOCOSPrimaryHit and ATMOCOSSteppingAction are tested.

### *3.18.2 Features to be tested*

- Detection of particle flux in the case of flat geometry at user selected altitudes and/or depths that coincide with boundary layers.
- Creation of particle flux histograms
- Saving, addition and normalisation of histogram tree
- Security save

### *3.18.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.18.4 Test pass/fail criteria*

In a first run a downward flux of galactic proton with a cosinus law for the angular distribution and with the start position set in the middle of the atmosphere is tracked through the rest of the atmosphere. In a second run a mono-directional normal upward flux of proton with the same spectrum and start position than in the first run is tracked through the atmosphere. In both cases only the transportation process is considered (the  EM and hadronic physics are neglected). For each run the spectrum and angular distribution of protons are detected at the different user-defined altitudes into 1D and 2D histograms. The results are saved in xml files and ASCII files without normalisation, with normalisation per primary particle and with normalisation to the primary flux. Registered results are read and add to the permanent tree histogram. Results from different runs are added together. At the end an additional run allow to test the repeated security save of the simulation results during a run after a user defined number of events. The test is passed if : i)for the first run the downward proton flux histograms obtained at altitudes below the start position are equivalent to the primary flux histograms, ii) for the second run the upward proton flux histograms obtained at altitudes above the start position are equivalent to the primary flux histograms, iii) the normalised results are the one expected, iv) the saving and addition of histogram trees produce the expected results, v) the security save is working correctly.

#### *3.18.5 Test*

1. Type : PLANETOCOSMICS detection_flux_test1.g4mac
2. At the end of the simulation you can analysis, plot and compare with your favourite analysis/plotting tool the histograms contains in the different ASCCI and xml file produce during the test.

### 3.19 Test Plan #16

#### *3.19.1 Test Items*

For this test the macrofile detection_flux_test2.g4mac is used.

The classes ATMOCOSAnalysisManager, ATMOCOSFluxHit, ATMOCOSPrimaryHit and ATMOCOSSteppingAction are tested.

#### *3.19.2 Features to be tested*

- Detection of particle flux in the case of spherical geometry at user selected altitudes and/or depths.

#### *3.19.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

#### *3.19.4 Test pass/fail criteria*

In a first run a downward flux of galactic proton with a cos law for the angular distribution and with the start position set in the middle of the atmosphere is tracked through the rest of the atmosphere. In a second run a mono-directional normal upward flux of proton with the same spectrum and start position than in the first run is tracked to the atmosphere. In both cases only the transportation process is considered (the EM and hadronic physics are neglected). For each run spectrum and angular distribution of protons are detected at the different user-defined altitudes in 1D and 2D histograms. The results are saved in xml files and ASCII files without normalisation, with normalisation per primary particle and with normalisation to the primary flux. The test is passed if : i)for the first run the downward proton flux histograms obtained at altitudes below the start position is equivalent to the primary flux histograms, ii) for the second run the upward proton flux histograms obtained at altitudes above the start position is equivalent to the primary flux histograms, iii) the normalised results are the one expected

#### *3.19.5 Test*

1. Type : PLANETOCOSMICS detection_flux_test2.g4mac

2. At the end of the simulation you can analysis, plot and compare with your favourite analysis/plotting tool the histograms contained in the different ASCII and xml file produce during the test.

## 3.20 Test Plan #17

### *3.20.1 Test Items*

For this test the macrofile edep_test.g4mac is used.

The command EdepVsAltitudeHisto and EdepVsDepthHisto of the directory /PLANETOCOSMICS/ANALYSIS are tested. The classes AnalysisManager, ATMOCOSEdepHit, and ATMOCOSSD are tested.

### *3.20.2 Features to be tested*

- Registering of energy deposited in function of altitude and/or depth.

### *3.20.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.20.4 Test pass/fail criteria*

The test consist into the simulation of the the interaction with the atmosphere of three source of normal incident mono-energetic protons with 1GeV, 100 MeV and 10 MeV kinetic energies respectively.

The test is passed if: i)for each case the energy deposited histograms show a realistic energy deposition in function of altitude and depth ii) the total energy deposited by incident is in the same order of magnitude but not greater than the total energy contained in the primary spectrum; iii)for the 100 and 10 MeV protons the registered energy deposited per depth interval at the top of the atmosphere should corresponds to the stopping power of protons in air at these respective energy, iv) when converting the altitude axis of the edep vs altitude histograms to depth the resulting histograms should be equivalent to the the edep vs depth histogram.

### *3.20.5 Test*

1. Type : PLANETOCOSMICS edep_test.g4mac
2. At the end of the simulation you can analyse, plot and compare with your favourite analysis/plotting tool the energy deposited histograms contained in the different ASCII and xml file produce during the test.

## 3.21 Test Plan #18

### *3.21.1 Test Items*

For this test the file random_test.g4mac is used.

The commands of the /PLANETOCOSMICS/RANDOM directory are tested. The PLANETOCOSMICS RunAction is tested.

### *3.21.2 Features to be tested*

- Random selection at the beginning of a run, of the seed of the random engine,

### *3.21.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.21.4 Test pass/fail criteria*

The test consist into running two times the simulation of the interaction of a protons with the atmosphere. If the respective atmospheric showers obtained during the two runs are different the test is passed.

### *3.21.5 Test*

1. Type : PLANETOCOSMICS random_test.g4mac > log1
2. Type : PLANETOCOSMICS random_test.g4mac > log2
3. By looking at the log1 and log2 files you should check that the atmospheric showers obtained for the different runs are different.

## 3.22 Test Plan #19

### *3.22.1 Test Items*

For this test the file stopenergy_test.g4mac is used.

The commands of the /PLANETOCOSMICS/STOPENERGY directory are tested. The class ATMOCOSStackingAction is tested.

### *3.22.2 Features to be tested*

- Stopping of particle at user defined energy

### *3.22.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.22.4 Test pass/fail criteria*

The test consist into the simulation of the interaction of 1 proton with the atmosphere. The test is passed if in the tracking/stepping information contained in the log file it is observed that no particles starting with an energy lower than its corresponding stop energy is tracked and that during a track a particle is stopped when it reaches an energy lower than its stop energy.

### *3.22.5 Test*

1. Type : PLANETOCOSMICS stopenergy_test.g4mac > log

## 3.23 Test Plan #20

### *3.23.1 Test Items*

For this test the file physics_model_test.g4mac is used.

The classes ATMOCOSPhysicsList, ATMOCOSElectroMagneticPhysics, and ATMOCOSHadronicPhysics are tested.

### *3.23.2 Features to be tested*

- That the different hadronic and electromagnetic models implemented in PLANETOCOSMICS do not lead to an unexpected bug that could interrupt the execution of the code and have therefore a bad influence on the mood of the user of the code for the rest of his day.

### *3.23.3 Test deliverables*

The test deliverables shall be a completed Test Sheet.

### *3.23.4 Test pass/fail criteria*

If the different run of the physics_model_test.g4mac macrofile for the different EM and Hadronic models do not lead to any bug.

### *3.23.5 Test*

1. In the file physics_model_test.g4mac:

    - Replace the parameter *model* in the command /PLANETOCOSMICS/PHYSICS/SelectTypeOfEMPhysics <*model*> to select the electromagnetic physics model to be tested

    - Replace the parameter *model* in the command /PLANETOCOSMICS/PHYSICS/SelectTypeOfHadronicPhysics <*model*> to select the hadronic physics model to be tested

    - Replace the parameter *model* in the command /PLANETOCOSMICS/PHYSICS/SelectTypeOfIonHadronicPhysics <*model*> to select the light ion hadronic physics model to be tested

2. Type : PLANETOCOSMICS physics_test.g4mac

3. The run should not be interrupted during the simulation

4. Repeat point 1-3 until all physics model available in PLANETOCOSMICS have been tested.

5.

# 4 Results of the Unit and Integration Test

We report here on the results of the Unit/integration test that has been performed on two Pentium4 computer with the Linux operating system and the 2.95.2 and 3.3.2 egs compilers. All visualisation output, log files and xml and ASCII files that have been produced during this test are contained in the directory PLANETOCOSMICS/verification. The histograms registered in ASCII files during the different test plans have been analysed and plotted by using idl programs that are located in the directory PLANETOCOSMICS/verification/idl. For reading of these ASCII files these programs make use of the python scripts extract_flux.py and g4PLANETOCOSMICS.py. The postscript files generated by these programs are also contained on this directory.

## 4.1 Geometry test : Test plan 1-4

The visualisation output resulting from the tests 1-4 have been saved after scaling in the vrml files geometry_test*.wrl. The visualisation outputs are correct.

The log files produced during the tests test 1-4 have been saved under the files geometry_test*.log. In these files a table representing the altitudes, depths and densities of the different atmospheric layers is printed below the title "Structure of the atmosphere". These tables have been copied for each cases into the files geometry_test*_material.txt. During each test a table representing the variation of the atmospheric density, pressure, temperature depth and mass concentration of the different atmospheric components in function of altitude is saved in the file AtmoTable.txt. These profiles are generated by the atmospheric models considered in the tests and are used later in the program for constructing the atmospheric materials and geometry. For the test 1-4 we have saved these tables in the files geometry_test*_atmo_table.txt. In order to check that the atmosphere geometry is implemented in the code as expected we have written the idl program test_geometry.pro that plots some informations contained in the tables geometry_test*_material.txt., and geometry_test*_atmo_table.txt. By running the different plot_test* programs contained in this file the different geometry_test*.ps files are produced. In Figure 1 we have reproduced one plot contained in the file geometry_test1.ps. The black line represents the depth vs altitude profile contained in the ASCII table geometry_test1_atmo_table.txt that is produced by the atmospheric model used for the test 1. The blue crosses are plotted a the altitude and depth of the top of the different atmospheric layers. The red squares are plotted a the altitude and depth of the bottom of the different atmospheric layers. The fact that the blue crosses and red squares are on the black line, show that the density of the atmosphere layers in the geometry are defined such that the depths at the altitudes of the layer boundaries are equivalent to the depths given by the atmospheric model at the same altitudes. For this test case detectors are set at 10 and 100 g/cm2 depth and at 10 km altitude. The fact that a blue star and a red square lie on the horizontal lines drawn at the depths 10 and 100 g/cm2, and on the vertical lines drawn at 10 km altitude shows that the position of the detectors coincide with boundaries between atmospheric layers. All the plots contained in the files geometry_test*.ps show that the atmosphere geometry is correctly implemented in the code.

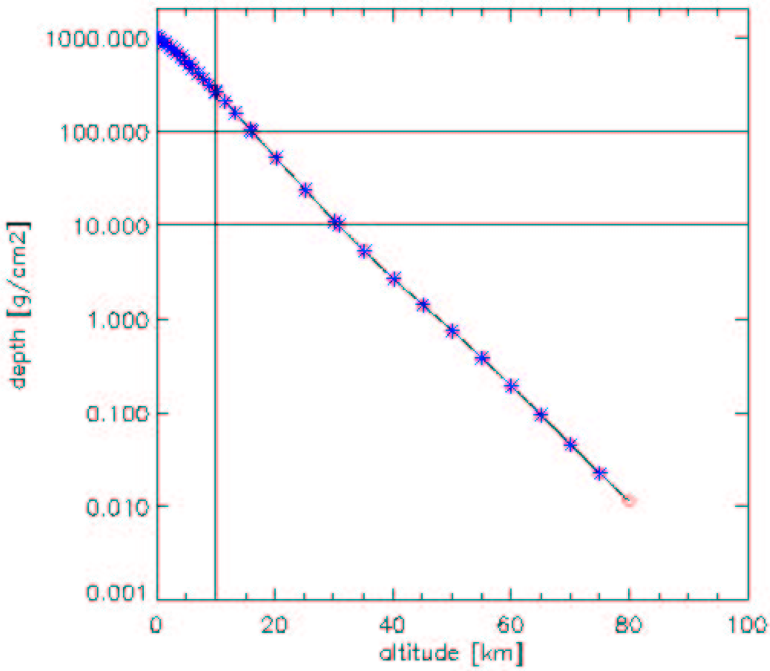



**Figure 1** *The solid line represents the depth vs altitude profile used for building the atmospheric geometry in the case of the test plan 1. The blue crosses and red curves mark the altitude and depth of the top and bottom of the different atmospheric layers.*

The different geometry_test*.log files contained also the stepping information of the tracking of a geantino through the atmosphere. The inspection of this tracking/stepping information confirm that the geometry is correctly implemented.

In conclusion the test 1-4 are passed.

## 4.2 Galactic proton and alpha source :Test 5

The different vrml files produced during this run allow to visualise the position and angular distribution of the primary source. We have scale one of this file and copied it in the source_test1.wrl file. Looking at this file its clear that the source is a point source located at the top of the atmosphere with a downward angular distribution.

The log file produced during this test is saved in the file source_test1.log. This file contains for each source simulated during this test, the stepping informations of the track of the first generated primary. The inspection of these stepping informations confirm that as expected the primary source is situated at the top of the atmosphere.

The different primary histograms registered during this test are saved in the ASCII and xml files files sol_max*, sol_min*, sol_mean*, and sol_modulated*. To check that the information contained in the ASCII files is correct we did use the idl program plot_test1 located in the file test_source.pro. The different plots generated when running this program are contained in the file galactic_flux.ps. The first two plots of these files are reproduced in Figure 2-3. Figure 2 represents the generated spectrum with normalisation to the primary flux of galactic proton and alpha at solar minimum, solar maximum and for a mean solar activity. The solar modulation effect appears clearly. The flux levels are in good agreement with typical galactic primary spectrum given in the literature [12]. Figure 3 represents the generated angular distribution for the primary galactic protons during solar minimum (black), maximum (red) and mean solar activity (green). It illustrates that the angular distribution of the generated primary source follows as expected a cosinus law. In conclusion the test has shown that the generation of modulated galactic cosmic ray protons and alpha is properly implemented into the code.

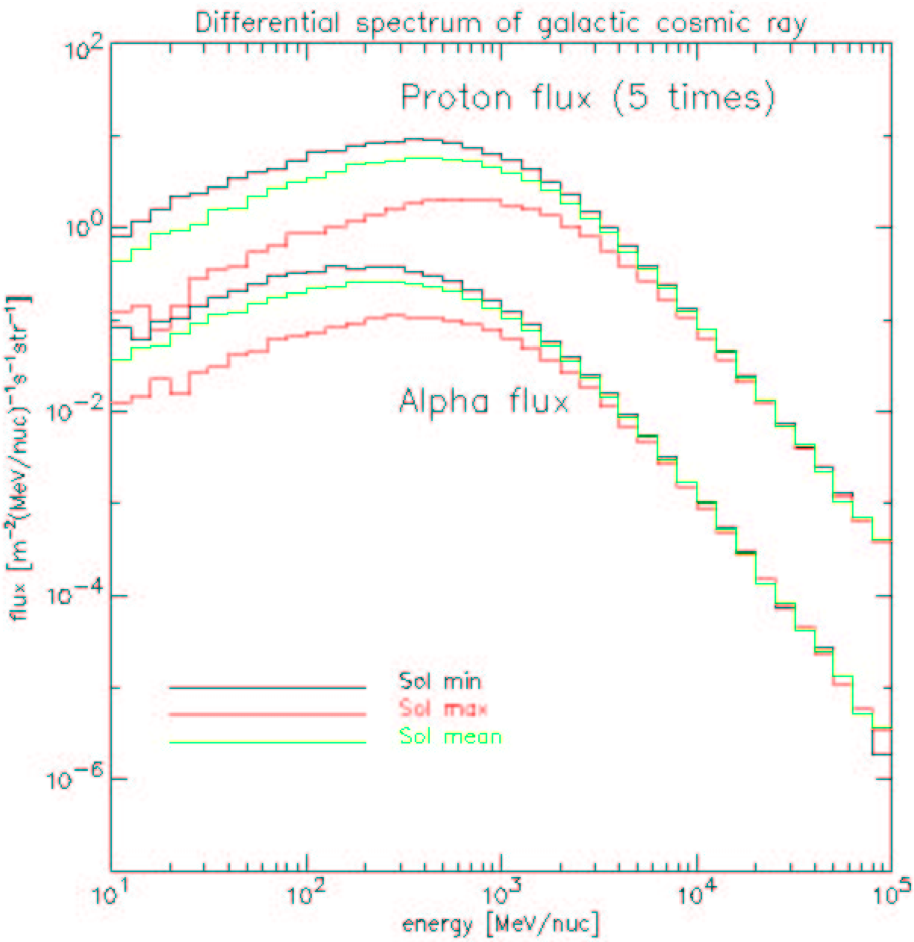



**Figure 2***Primary differential spectrum for galactic protons and alpha as generated into PLANETOCOSMICS during the test plan 5. The black, green and red histograms are for minimum, mean and maximum solar activity.*

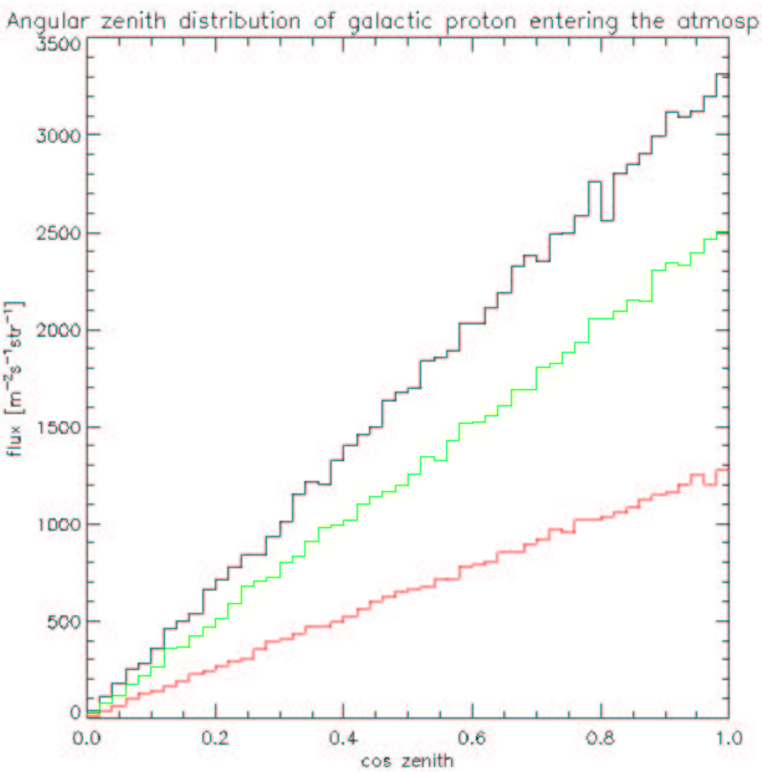



**Figure 3***Angular zenith distribution for primary galactic protons entering the atmosphere as generated with PLANETOCOSMICS during the test plan 5. The black, green and red curves are for minimum, mean and maximum solar activity.*

### 4.3 Galactic proton and alpha source with cutoff rigidity:Test 6

The different primary histograms registered during this test are saved in the ASCII and xml files

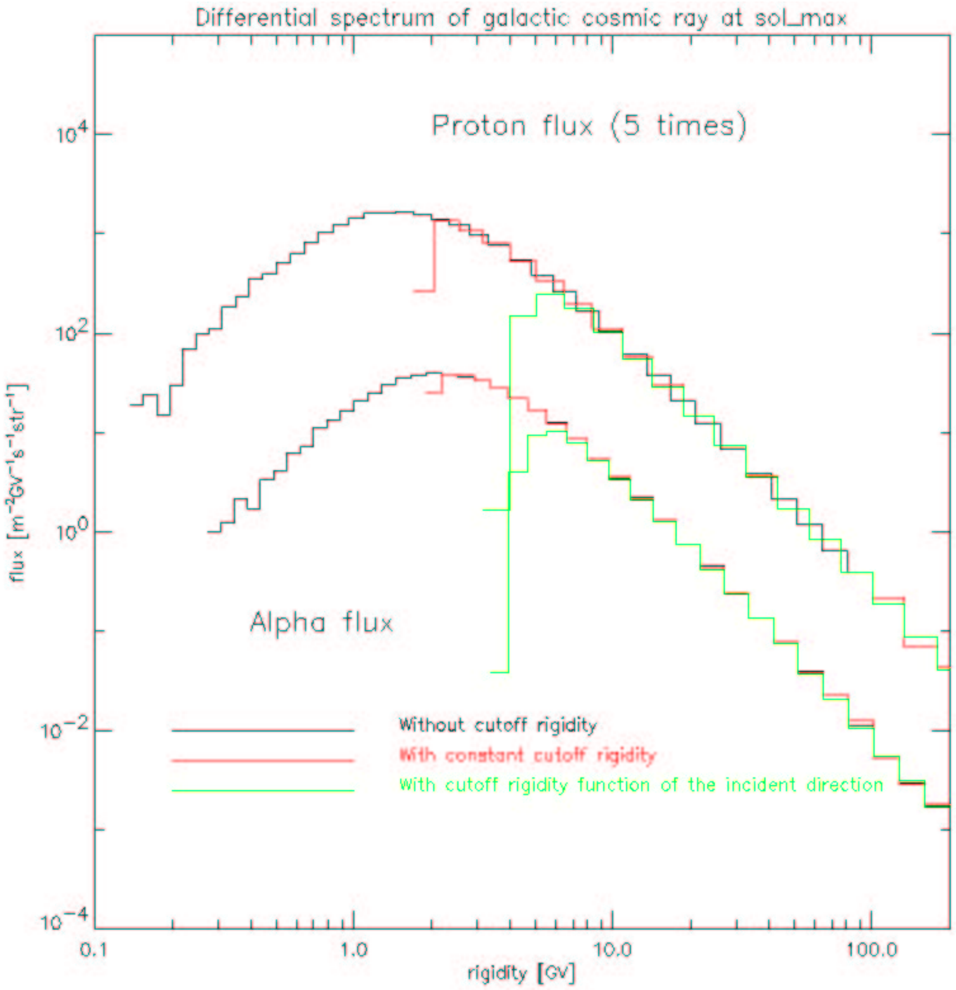



**Figure 4***Differential rigidity spectra of primary protons at sol max for different rigidity cutoff model, generated with PLANETOCOSMICS during test plan 6.*

proton_dir_cutoff*, proton_const_cutoff*, alpha_dir_cutoff* and alpha_const*. To check that the information contained in the ASCII files is correct we did use the idl program plot_test2 located in the file test_source.pro. The different plots generated when running this program are contained in the file flux_withcutoff.ps. Two of these plots are reproduced in Figure 4 and 5. Figure 4 represents the rigidity spectrum of the generated galactic proton and alpha primaries at solar maximum without cutoff rigidity (black), with a cutoff rigidity constant for all direction of incidence (red) and with the cut-off rigidity as a function of the direction of incidence (green). The red curves show as expected a cutoff rigidity at 2GeV., while for the green curves the decrease of the flux due to the rigidity cutoff is more smooth. At high rigidities the different curves are equivalent as it should be. Figure 5 represents the azimuth angular distribution for the case of the galactic proton flux with the cut-off rigidity as a function of the direction of incidence. This angular distribution shows as expected a east-west asymmetry. The test is passed.

### 4.4 User defined spectrum:Test 7

The different primary histograms registered during this test are saved in the ASCII and xml files omnidir_int*, omnidir_diff*, dir_int* and dir_diff*. To check that the information contained in the

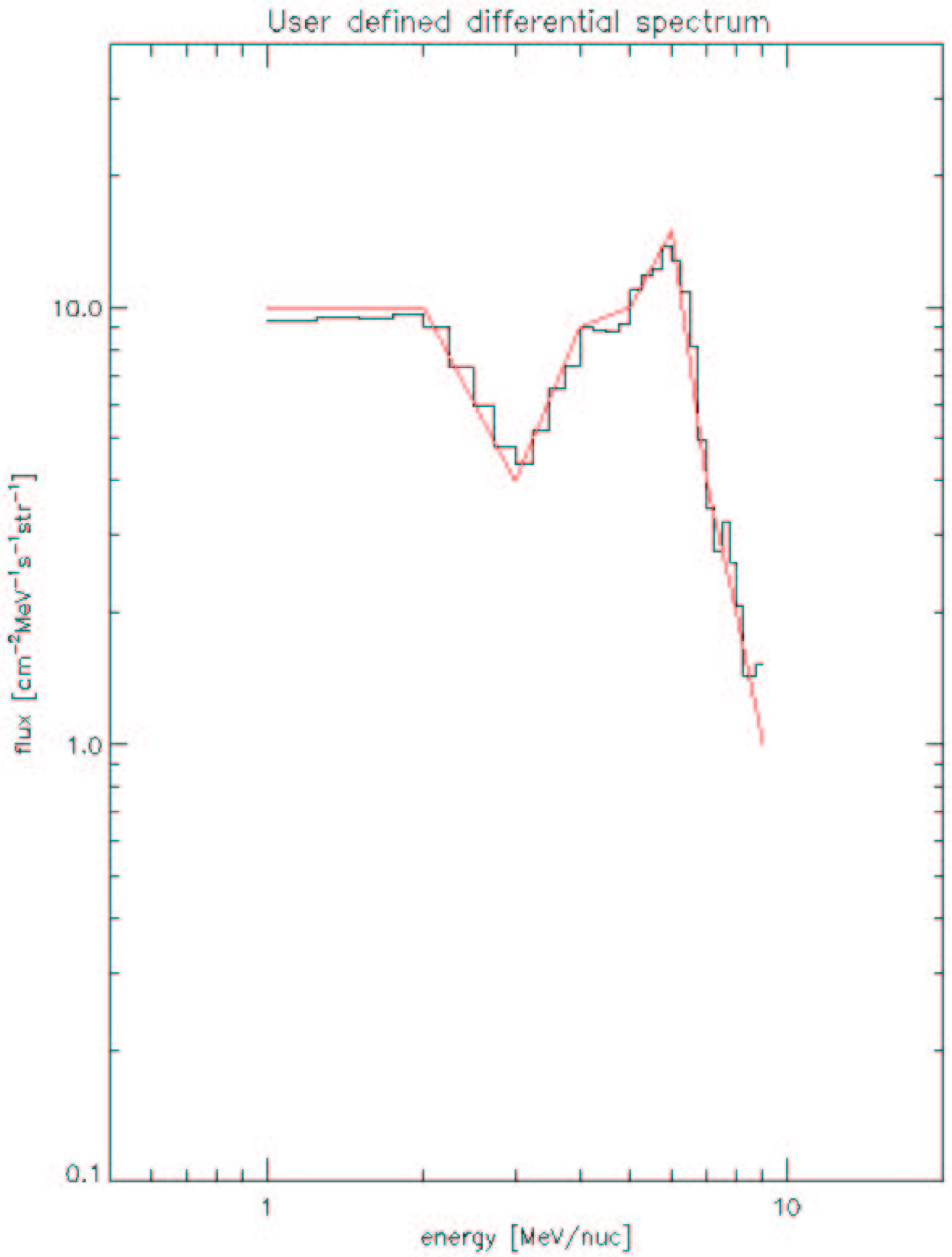



**Figure 6***The black histogram represents the generated spectrum obtained during the test 7 when using the file omnidir_diff_spectrum.txt for the definition of the primary spectrum. The red curve reproduces the spectrum defined in this txt file.*

ASCII files is correct we did use the idl program plot_test3 located in the file test_source.pro. The different plots generated when running this program are contained in the file user_defined_spectrum.ps. One plot of this file is reproduced in Figure 6. The black histogram represents the generated spectrum obtained when using the file omnidir_diff_spectrum.txt for the definition of the primary spectrum. The red curve reproduces the spectrum defined in this txt file. The good agreement between the black histogram and the red line shows that the generated user defined spectrum is the one expected. The same agreement is found for the other types of spectrum. The test is passed.

### 4.5 Definition of the altitude of the source for the flat geometry : Test8

The log file that has been produced during this test is contained in the file source_test4.log. The stepping information of the track of a downward vertical incident proton starting form the user defined altitude is given in this file. This stepping information shows that the primary source is correctly set at the user defined altitude of 55 km. The visualisation output of this test is saved in the file source_test4.wrl and is also as expected. The test is passed.

### 4.6 Orientation of the source for spherical geometry : Test 9

The visualisation output of this test is saved in the file source_test5.wrl. A snapshot of the visualisation of this file is given in Figure 7. It shows clearly that the position and orientation of the source is correct.

The zenith and azimuth distribution have been registered during the run in 1D histograms contained in the files source_test5.xml.gz and source_test5.ascii. To check that the information contained in the ASCII file is correct we did use the idl program plot_test5 located in the file test_source.pro. The plot generated when running this program is contained in the file source_test5.ps and is reproduced in Figure 8. It shows that the generated distribution is as expected. In conclusion the position of the source is correct and the angular distribution shows a rotational symmetry around the vertical direction. The test is passed.

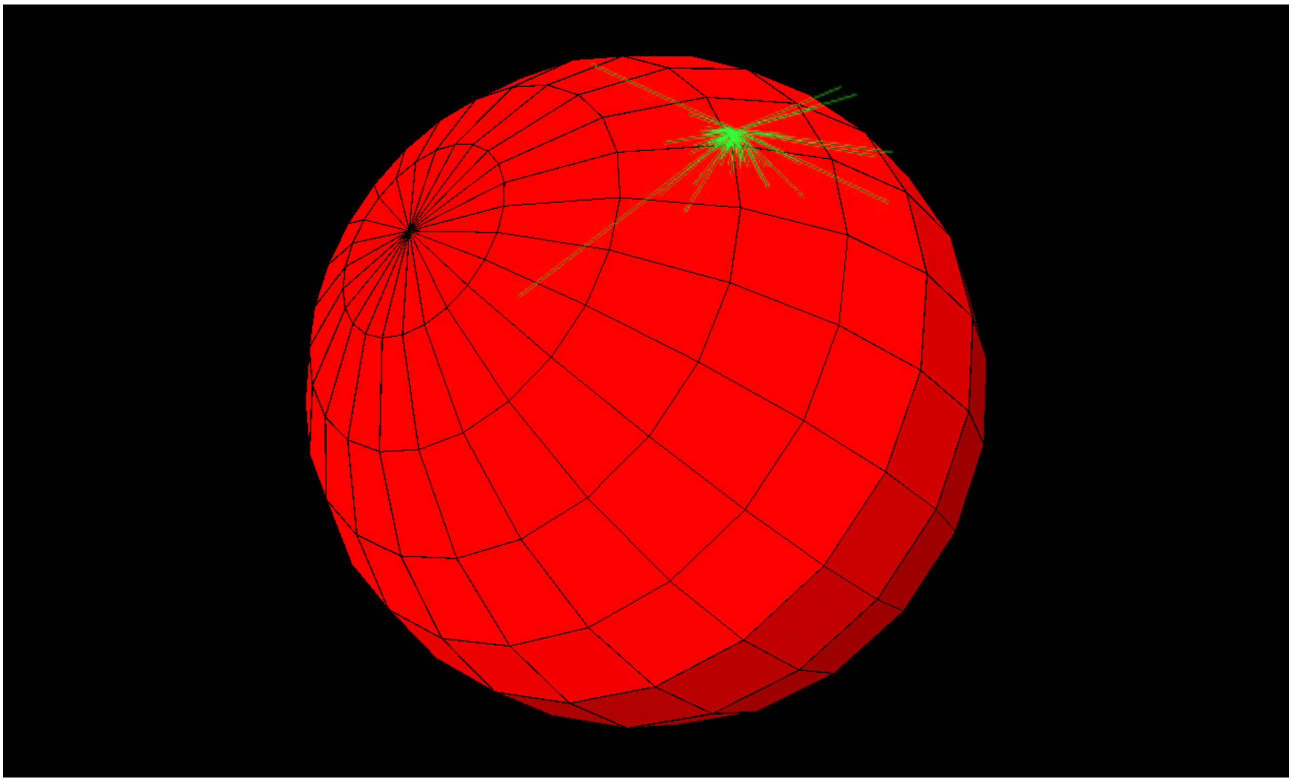


**Figure 7***Visualisation of the track of primary particle obtained during the test 9.*

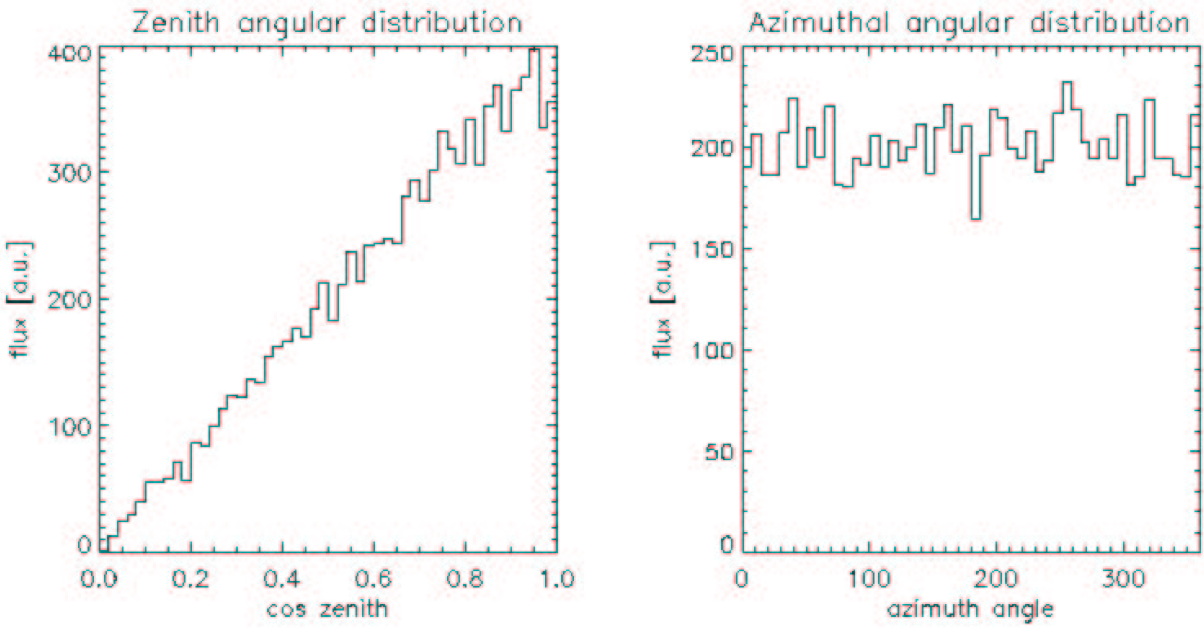



**Figure 8***Histograms representing the angular zenith (left) and azimuth (right) distribution of the primary source generated during the test 9.*

## 4.7 Visualisation of particle track : Test 10

The visualisation results of this test are contained in the vrml files vis_test1.wrl and vis_test2.wrl. Both files show clearly that the the track of primaries and secondaries particles generated during the runs are drawn correctly with the colours defined by the user. The test is passed.

## 4.8 Test 11

In the case of a flat geometry the simulation box represents a part of the Earth atmosphere at a given geographical position. The x, y, and z axes of the simulation box represent the north, east and vertical direction at a geographical position of reference specified by the user. To compute the magnetic field at a given position in the simulation box, the geographical components of this position should be first computed, then the magnetic field at this geographical position should be correctly oriented in the local cooordinate system. In this test we check that the bfield is correctly computed and oriented in the local coordinate system. In the log file bfield_test1.log the magnetic field components are given at different local positions, for different magnetic field models and for different geographical latitudes and longitude of reference. These magnetic field components are as expected. The vrml file bfield_test1.wrl shows the drawing of magnetic field lines passing through the local position (0,0,40 km) for different magnetic field models and geographical positions of reference. A snapshot obtained when visualising this file is given in Figure9. The configuration of the different field lines is as expected. The test is passed.

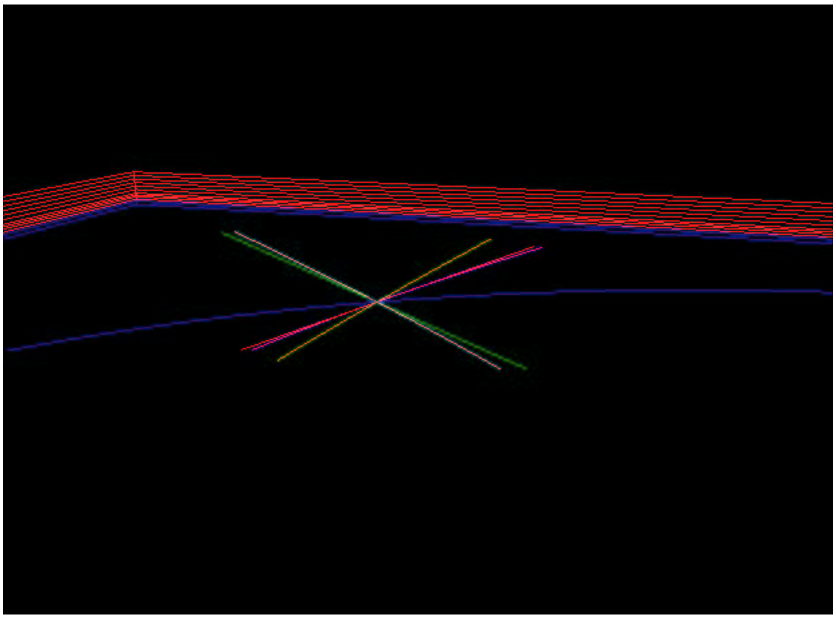


**Figure 9***Visualisation of magnetic field lines in flat geometry (test 11).*

### 4.9 Test 12

For this test case we did check if the implementation of the magnetic field in the case of the spherical geometry is correct. The log file bfield_test2.log contained the magnetic field components computed at different geographical position in different magnetic field models. These components are the one expected. The visualisation output of this test contained in the file bfield_test2.wrl represent the magnetic field lines at different geographical positions and for different magnetic field models. A snapshot obtained when visualising this vrml file is given in Figure10. The magnetic field lines are as expected .The test is passed.

### 4.10 Test 13

This test consist into the visualisation of the motion of 100 MeV electron in the case of flat geometry where the magnetic field is considered as homogeneous. The x,y and z component of this fields corresponds to the north, east and vertical components given by the IGRF magnetic field model at $0^0$ latitude , $0^0$ longitude and 40 km altitude. The visualisation output of this test is contained in the vrml file bfield_test3.wrl. A snapshot of the visualisation of this file is reproduced in Figure 11. The e- motion is represented in green while the blue line represents a magnetic field line. The e- is correctly gyrating along a direction parallel to the the magnetic field. The test is passed.

### 4.11 Test 14

This test consist into the visualisation of the motion of a 1 GeV proton in the geomagnetic field in the case of the spherical geometry The visualisation output of this test is contained in the vrml file bfield_test4.wrl. A snapshot of the visualisation of this file is reproduced in Figure 12. The motion of the proton is traced in green while the blue line represents a magnetic field line. The motion of the proton dancing around the Earth is as expected. The test is passed.

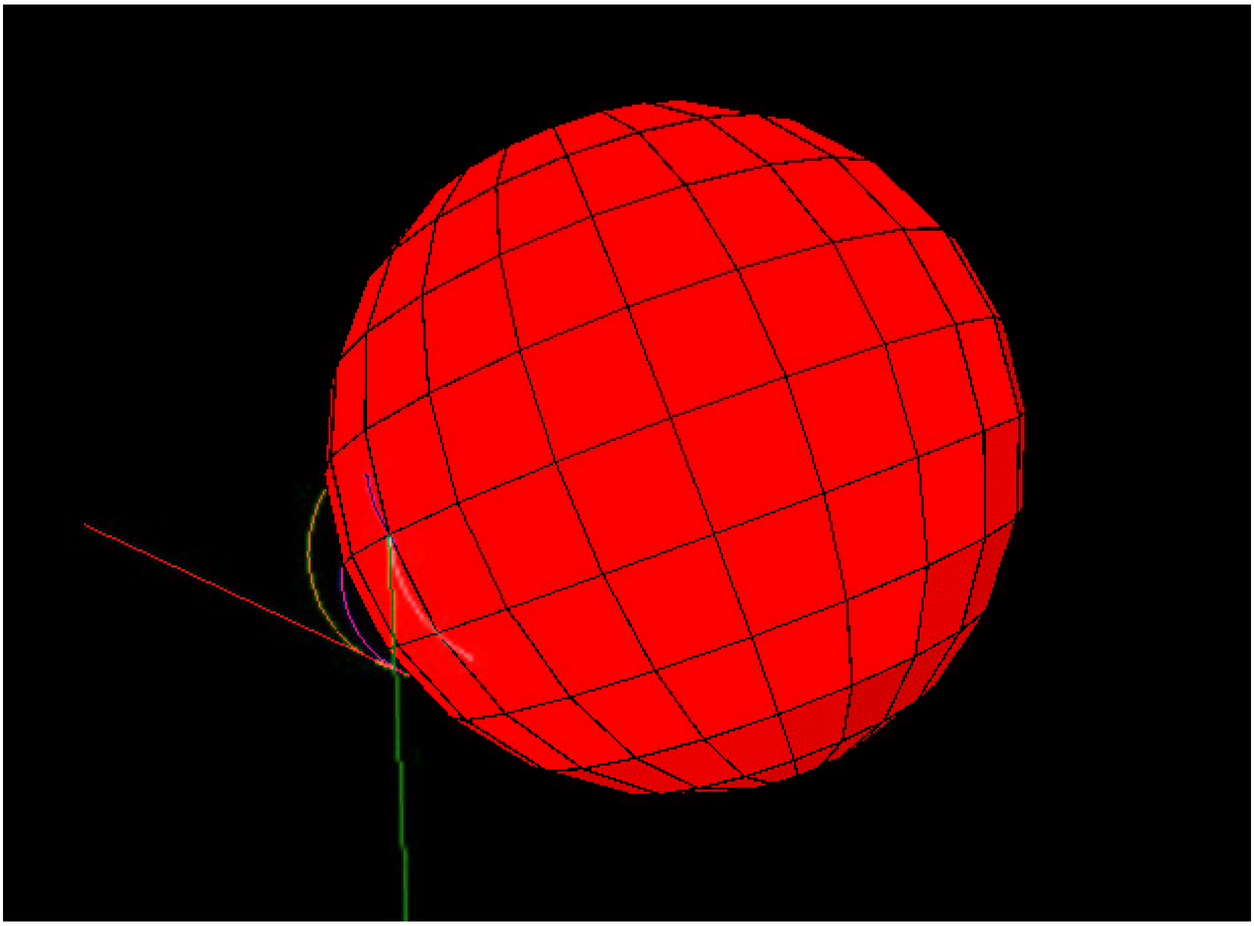


**Figure 10***Visualisation of magnetic field lines in spherical geometry (test 12).*

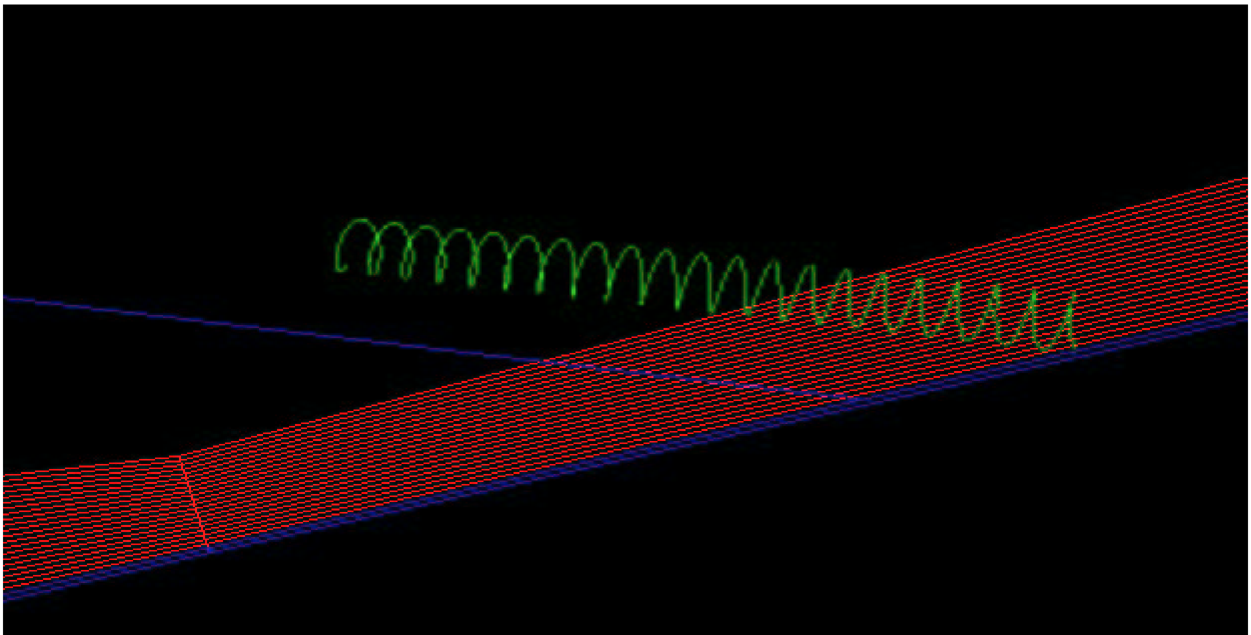


**Figure 11***Motion of a 100 MeV electron (green) in an homogeneous magnetic field in the case of the flat geometry (test 13) . The blue line represents a magnetic field line.*

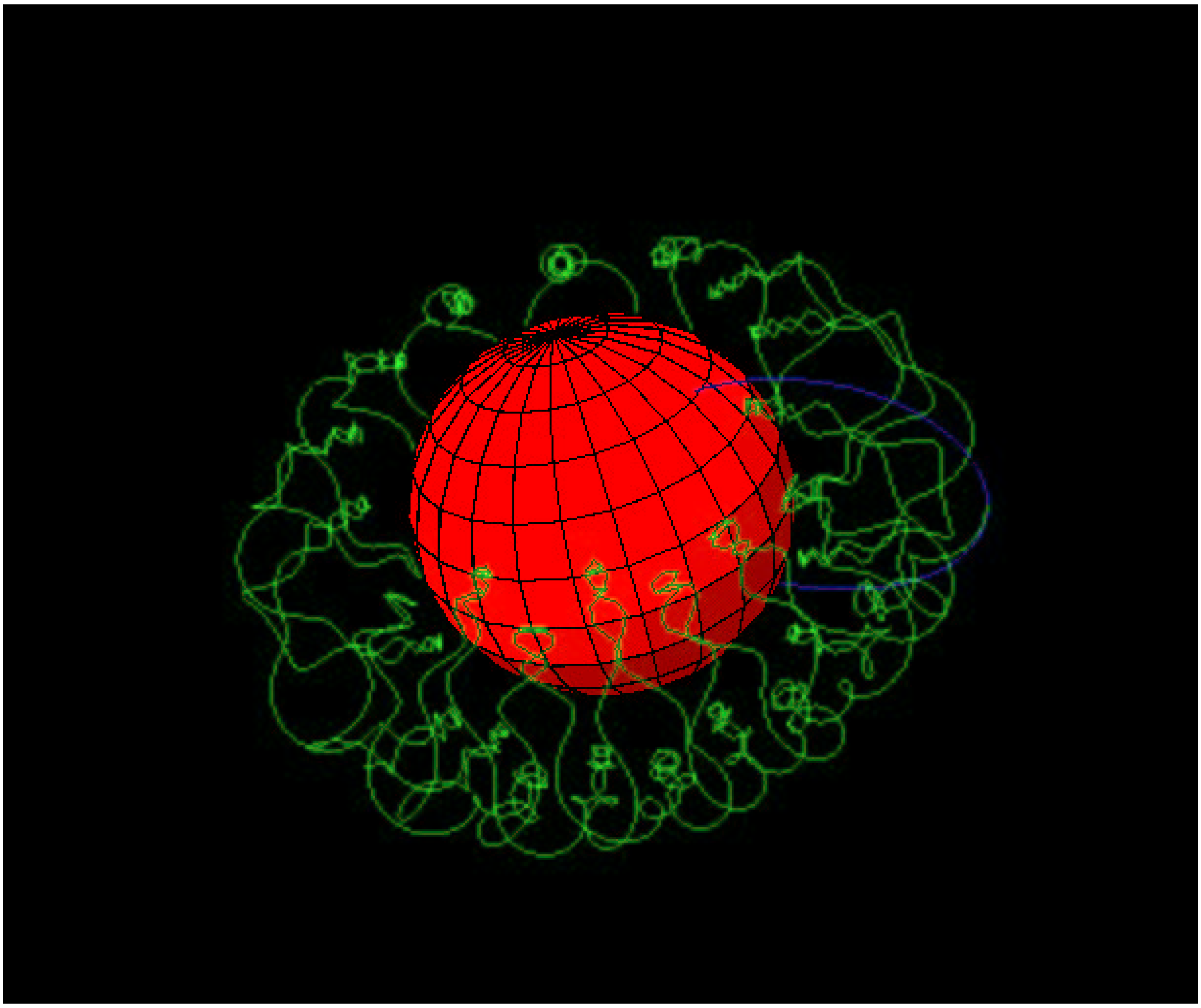


**Figure 12***Visualisation of the motion of a 1GeV proton (green) in the geomagnetic field in the case of the spherical geometry (test 14). The blue line represents a magnetic field line.*

## 4.12 Test 15

The different primary histograms registered during this test are saved in the ASCII and xml files detection_flux_test1*.ASCII and detection_flux_test1*.xml.gz .To check that the information contained in the ASCII files is correct we did use the idl program detection_flux_test1 located in the file test_detection_flux.pro. The different plots generated when running this program are contained in the file detection_flux_test1.ps. The third plots of this file is reproduced in Figure 13. The black curve gives the flux registered in the primary flux histogram divided by a factor p to convert it to a directional flux .The red curve represent the flux of protons registered on the third detector (downward of the start position). In this case the weight of a registered proton was not divided by cos theta. For this reason the flux was divided by a factor p to correspond to a directional flux. The green curves correspond to the flux of proton at the fourth detector. For this histogram the weight of a registered proton was divided by cos theta. For this reason this flux was divided by a factor 2p to correspond to a directional flux. The three curves are in very good agreements. From the analysis of the results by using the idl program detection_flux_test we can say that: i) the flux of particles at user defined altitude and depth are correctly detected ii) the normalisation of the results to the primary flux or per number of primaries is correct iii) the save and addition of histogram tree are correctly implemented , iv) the security save is working correctly. In conclusion we are glad to announce that the test is passed.

## 4.13 Test 16

The different primary histograms registered during this test are saved in the files detection_flux_test2*.ascii and detection_flux_test2*.xml.gz . To check that the information contained in the ASCII files is correct we did  use the idl program detection_flux_test2 located in the file test_detection_flux.pro. The different plots generated when running this program are contained in the file detection_flux_test2.ps. From these plots we can conclude that the detection of particle flux at user defined altitude and or depth in the case of the spherical geometry is correctly implemented. The test is passed.

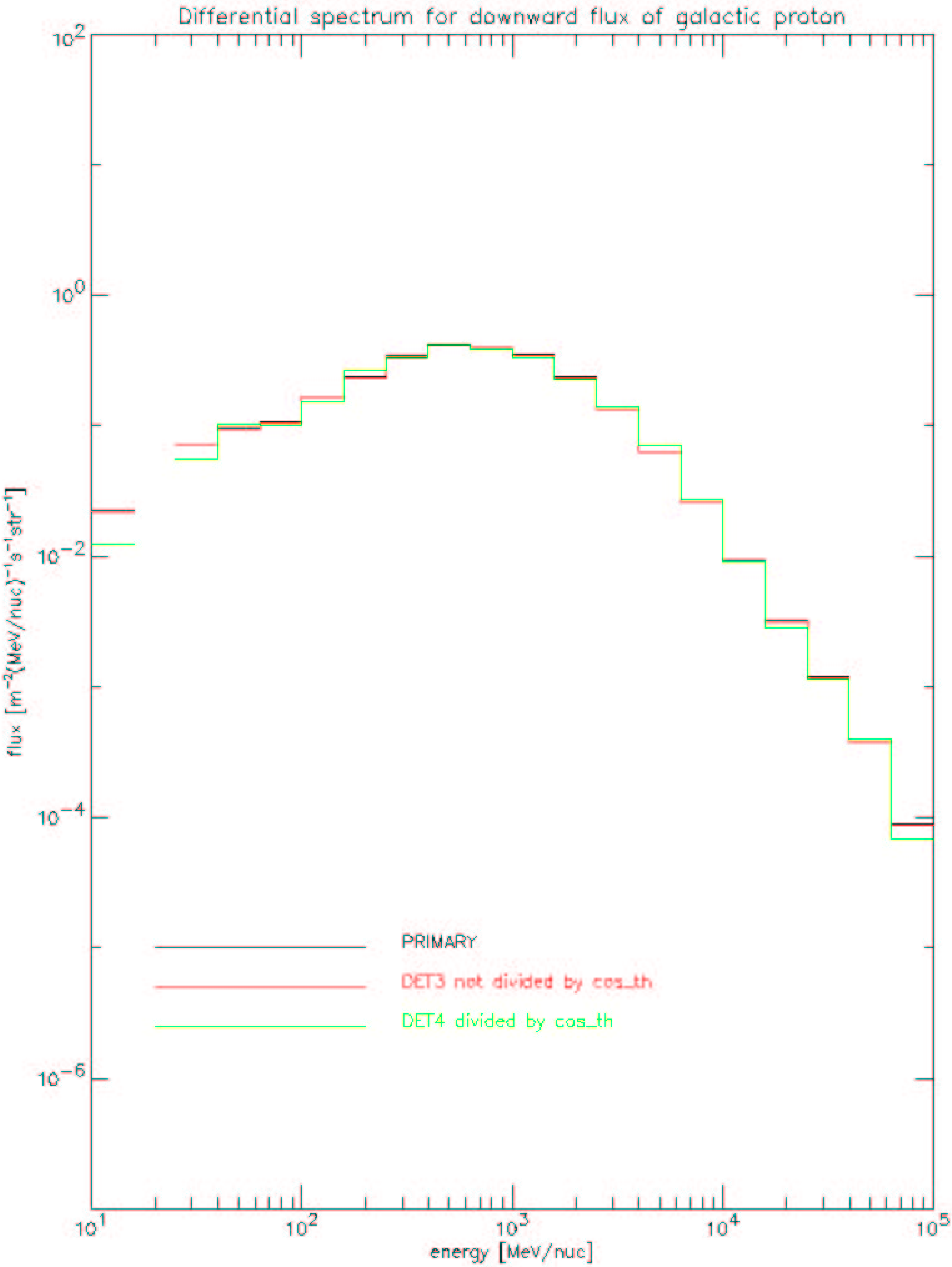



**Figure 13** *Histograms representing the primary flux of primary protons (black) and the downward flux of protons detected at the detector 3 (red) and 4(green) during the test 16. In this example a normalisation to the primary flux has been selected. See details in text.*

## 4.14 Test 17

The energy deposited histograms registered during this test are saved in the files edep_test*.ASCII and edep_test*.xml.gz . To check that the information contained in the ASCII files is correct we have used the idl program plot_edep located in the file test_edep.pro. The different plots generated when running this program are contained in the file edep_test.ps. In the figure 14-15 we reproduce two plots contained in this file. The Figure 14 represent the energy deposited per atmospheric depth in function of atmospheric depth by a 1 GeV normal incident proton. The red curved is obtained by using the information contained in the energy deposited vs depth histogram. The black curve has been obtained by using the energy deposited vs altitude histogram and converting the altitude axis to its equivalent in depth. Both curves are in very good agreement as it should be. Figure 15 represents the stopping power of 100 MeV normal incident proton in the atmosphere in function of altitude. This curve has been obtained from the energy deposited versus altitude histogram resulting from the simulation of the interaction of 100 MeV normal incident protons with the atmosphere. The stopping power at the top of the atmosphere is ~ 7 MeV*cm2/g which is the typical stopping power of a 100 MeV proton in air that can be found int the literature [12]. The stopping power profile in function of altitude is a typical stopping power profile of protons in matter with a constant stopping power over a large distance before a typical Bragg peak. From the energy deposited histograms we have computed that the the mean energy deposited by 1GeV, 100 MeV and 10 MeV normal incident protons is 723.6, 97.7 and 10. MeV respectively. These results are realistic. The test is passed.

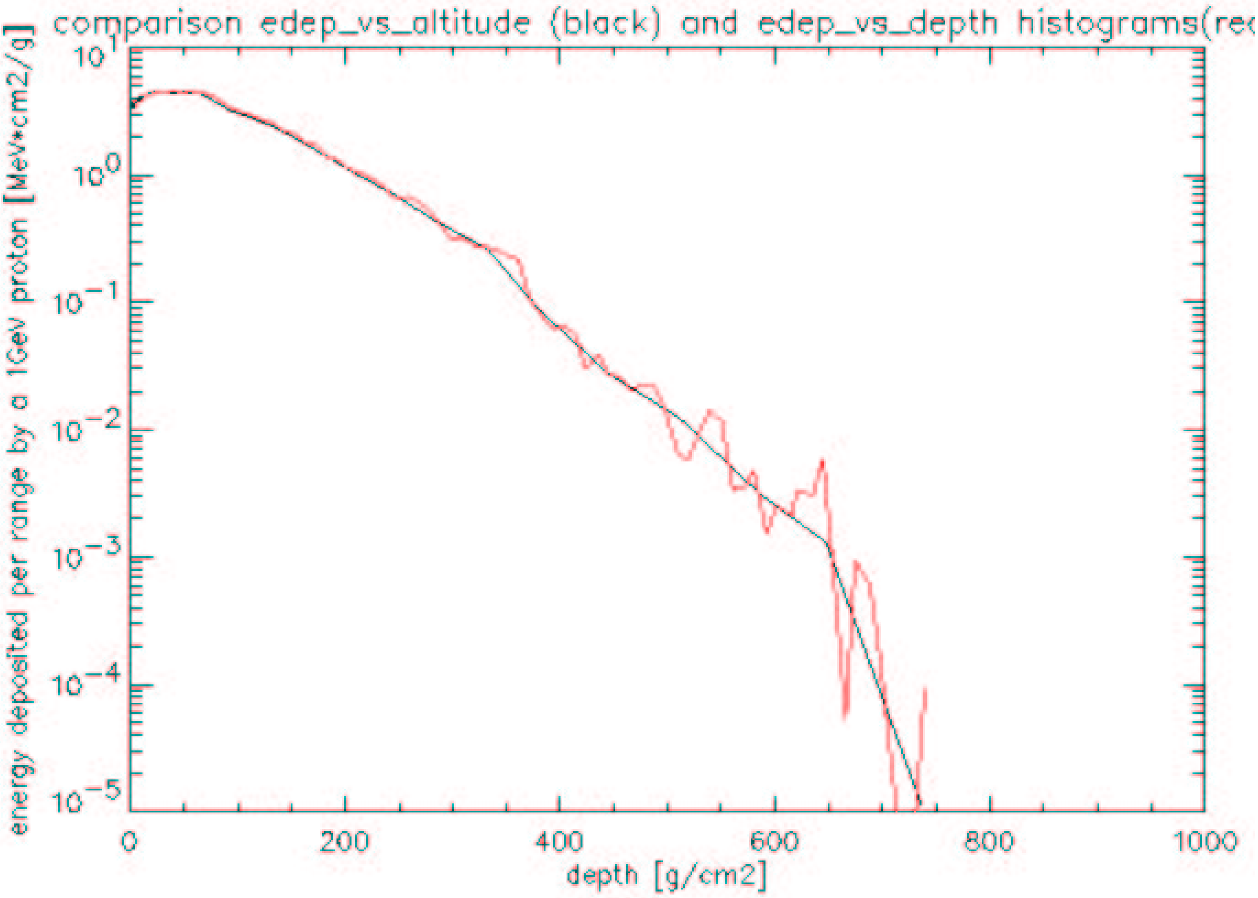



**Figure 14***Mean energy deposited per atmospheric depth vs depth by a 1GeV proton as simulated during the test 17. The red curves is taken from the energy deposited vs depth histogram while the black curve is deduced from the energy deposited vs altitude histogram by converting the altitude axis to its equivalent in depth. Both curves are in good agreement.*

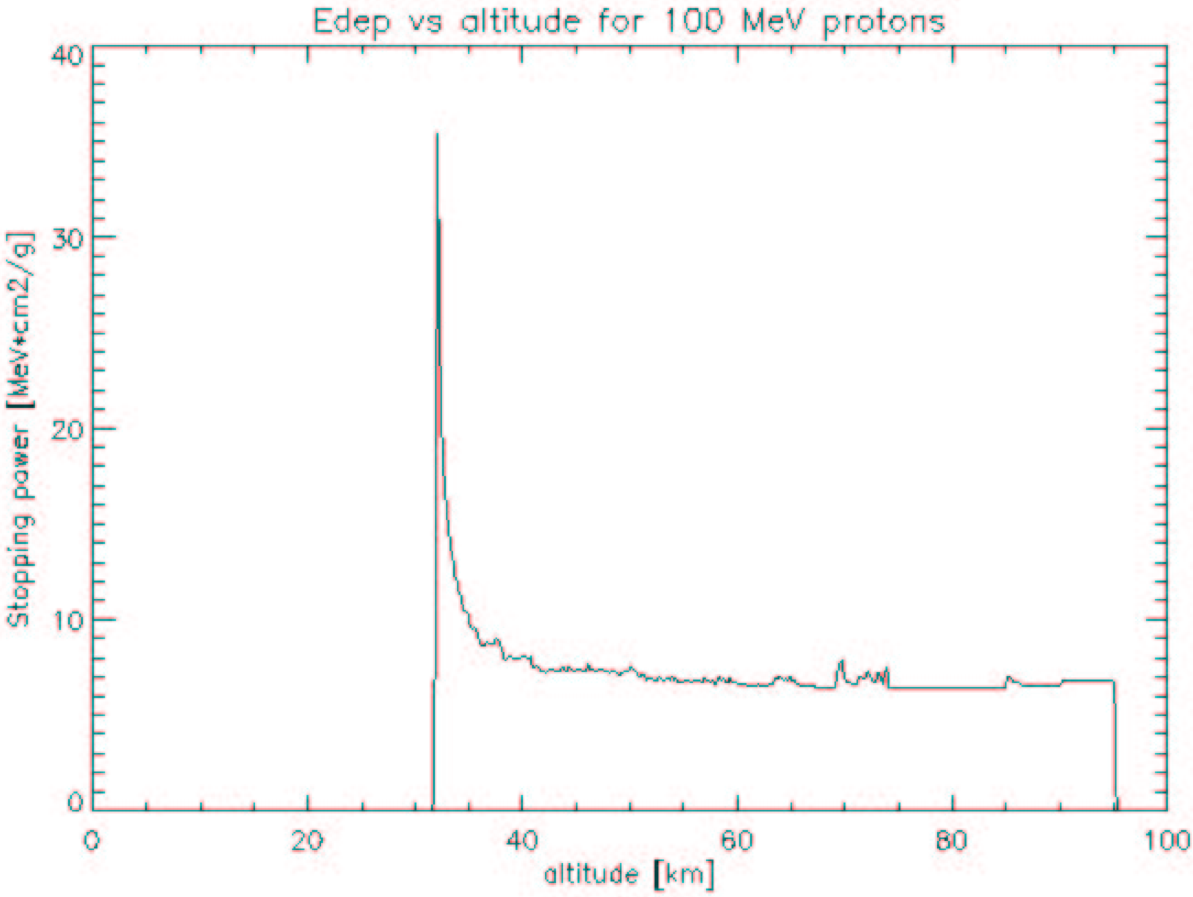



**Figure 15** *Mean energy deposited per atmospheric depth (stopping power) vs altitude by 100 MeV protons. This curve was extracted from energy deposited histograms registered during the test 17. At high altitude the stopping power is ~ 7 MeVcm$^2$/g. This value is in good agreement with the stopping power value of a 100 MeV proton in the air that can be find in the literature. Note the Bragg peak at lower altitude.*

### 4.15 Test 18

The results of the two runs executed during this test are contained in the log files random_test1.log and random_test2.log. The stepping information contained in these files shows that the showers obtained during the two different runs are different. The test is passed.

### 4.16 Test 19

The file stop_energy.log represents the log file obtained by running this test. The stepping information contained in this file shows that particles are correctly stopped below their corresponding stopping energy. The test is passed.

### 4.17 Test 20

By doing this test for to the LHEP_BIC, QGSP_BIC, LHEP_BIC_HP and QGSP_BIC_HP hadronic models under Geant4.6.1 we have found that the use of the binary cascade model leads to a bug when simulating the interaction of protons with the atmosphere. This model produces some times secondary particles that have their total energy that differs to the sum of their kinetic energy and their mass at rest. After their productions these non physical particles can lead to the blocking or the interruption of the code when hey are scattered elastically on an atmospheric nucleus. In order to avoid the interruption of the code when using the binary cascade model we have modified the PLANETOCOSMICS code in such a way that an event is aborted as soon as it leads to the production of a secondary particle with uncorrected total energy. This bug has been reported as bug #607 in the bug report web page of Geant4. Developers of the binary cascade code have found that the source of the bug was in the pre-equilibrium phase after the cascade phase. They have brought some corrections relative to this bug in the binary cascade model in the geant4.6.2 release. Unfortunately we have observed that despite these corrections the bug was still occurring but with a significantly smaller frequency. We have done some debugging concerning this bug in the Geant4.6.2 release. We have found that the bug takes place in the binary cascade model during the de-excitation phase when the evaporation model is used. In the binary cascade model, the de-excitation handler uses only the evaporation model because the maximum charge number $A_{max}^{FB}$ and atomic number $Z_{max}^{FB}$ for the Fermi break-up model are both set to 0 and because the minimum energy for the multi fragmentation model $E_{min}^{MF}$ is set to 5GeV/nuc. We have found that the occurrence of the bug is considerably reduced when setting $A_{max}^{FB}$ and $Z_{max}^{FB}$ to 12 and 6 respectively. In this case the evaporation model is only used for A>12 and Z>6 and therefore less bug occurs. With this modification the bug is only occurring for ~0.7 % of all the events. We have also tried to fix $A_{max}^{FB}$ and $Z_{max}^{FB}$ to 16 and 8 respectively as it it should be according to the Geant4 physics reference manual [4]. In this case no bug occurs at all but the computing time is multiplied by roughly a factor 2.5. It seems that in this case the number of secondary gamma's produced is much more important than for the other cases. We have also tried to set the minimum energy for the MutiFragmentation model $E_{min}^{MF}$ to 4 MeV/nuc as it should be according to the Geant4 physics reference manual [4]. However by doing such an additional bug occurs leading to the blocking of the code after a few ten thousands of events. We have asked the binary cascade developers which values of $A_{max}^{FB}$ , $Z_{max}^{FB}$ and $E_{min}^{MF}$ should be used in the model but we did not get any answer yet. Finally to get a good compromise between the occurrence of bad events and the computing time , and to have a code that is stable we have decided to set by default $A_{max}^{FB}$ and $Z_{max}^{FB}$ to 12 and 6 respectively and to set $E_{min}^{MF}$ to 10 GeV. With these modifications only 0.7 of bad events have to be aborted and now interruption of the code occurs. WE have also add G4UI macro commands that allow the user to fix $A_{max}^{FB}$ , $Z_{max}^{FB}$ and $E_{min}^{MF}$ himself.

We have also encountered the bug described in the previous paragraph when using the light ion binary cascade model for simulating the interaction of alphas with the atmosphere. For this model there is no way to change the value of the parameters $A_{max}^{FB}$ , $Z_{max}^{FB}$ and $E_{min}^{MF}$ that are set by default to 0, 0 and 5GeV/nuc. Within a simulation of the interaction of 50000 alphas (20, 5, 1 GeV) with the atmosphere we have shown that bad events occurs in roughly 2% of the time and that no bug and interruption of the code occur.

The test of the Bertini cascade model leads to a segmentation fault after a few events. More work is needed to localise the source of this bug.

On computers with the gcc 3.3* compilers, and with the Geant4.6.2 release we have observed a funny feature when using the QGSP model. Sometimes when simulating the interaction of protons with energy > 15 GeV, the following message appears:

" G4HadronBuilder::Build()

" Invalid total charge found for on input *charge*: PGDcode input quark1/quark2 : *code1 code2* "

where *charge* represents the total charge of the two quarks defined by PGDcode *code1 code2.* The source of this message is in the Barion and Meson methods of the G4HadronBuilder class used in the parton string model. At the beginning of these methods the error message described above is printed if the following test is fulfilled:

if (abs(charge) > 2 || abs(3.*charge - 3*G4int(charge)) > perCent )

This test check that the total charge of the two quarks involved in the process simulated in this part of the code is an integer and that its absolute value is not higher than 2. If this is not the case the error message is printed. By printing the total charge for debugging purpose we have observed that in all the case the “if” test should always be rejected. It means that the total charge of both quarks involved here is always correct. However with the Geant4 toolkit compiled with gcc 3.* compilers it appears that sometimes the error message is printed  because the “if” test is passed while according to the value of the charge it should not be the case. The source of this funny features is that sometimes for a charge of 1(2) the expression G4int(charge)) in the right part of the “if” test returns 0(1) while it should return 1(2). We have also find that when adding the lines

```
G4cerr << " test1 " <<abs(3.*charge - 3*G4int(charge)) << G4endl;
```

```
G4cerr << " percent " <<perCent<< G4endl;
```

in the G4HadronBuilder.cc before the lines corresponding to the printing of the error message, the bug disappears. Strange isn't it! We have not yet tested if this problem occurs also with other code than PLANETOCOSMICS.   In conclusion the QGSP model is behaving  correctly. Only the test described above is not working correctly from time to time.

The test of the other hadronic models and of all electromagnetic models available in PLANETOCOSMICS has been successfully passed.

In conclusion after modification of the binary cascade model all hadronic physics models and electromagnetic physics model can be used in PLANETOCOSMICS without interruption of execution except for the Bertini cascade model (QGSP_BERTINI_HP) . By default the QGSP_BIC_HP and light ions binary cascade models are  selected for the hadronic physics, while the G4StandardEM  model is used for simulating the electromagnetic physics.

# 5 Comparison of simulation results with experiment

In this section we compare some simulations results with measurements from two different cosmic ray experiments. The first experiment consists into the measurement of the atmospheric ionisation rate induced by cosmic rays from 1950 to 1970 by Neher [13]. The second experiment is the measurement of cosmic ray in the atmosphere by the balloon radio-sondes developed by the Moscow Lebedev institute [14].

## 5.1 Ionisation rates

In the past Neher has used ionising chambers carried by atmospheric balloons to measure the ionisation rate of the atmosphere induced by cosmic rays. From 1959 to 1968 different series of measurements have been performed over Thule to study the variation of atmospheric ionisation with solar activity [13]. By using the PLANETOCOSMICS code we have computed the radiation dose rate in the atmosphere induced by galactic protons at solar minimum and solar maximum at Thule. For this simulation we have considered a primary spectrum with the energy range 10 MeV-1TeV. We have selected the QGSP_BIC_HP model for simulating the hadronic physics. As Thule is located at high geomagnetic latitude the shielding effect of the geomagnetic field at this location can be neglected and therefore no cut-off rigidity has been considered. By considering a mean ionisation energy of 34.5 eV in the atmosphere the dose rate has been converted into an ionisation rate that can be compared directly to Neher's measurements. To take into account the contribution of galactic alpha cosmic rays we have multiplied the ionisation rate by the ratio between the total flux of energy contained in the alpha and proton galactic spectra divide by the flux of energy contained in the proton spectrum only. The flux of energy being defined by

$$J_E = \int J(E) E dE$$

with $J(E)$ representing the differential flux. We obtain a factor of 1.31 and 1.35 for the period of minimum and maximum solar activity, respectively. We have used this approximation because in the last release of Geant4 (6.2) the high energy limit of physical models that allow to compute the hadronic interaction of alphas with nuclei is 5GeV/nuc . Galactic alphas with energy > 5GeV/nuc contained at solar minimum and solar maximu 42% and ~52% of the total energy flux respectively and their contribition cannot be neglected.

Comparison of simulation results with Neher's measurements are presented in Figure 16. The different black lines represent Neher ionisation rate measurements from 1959 to 1965 [13]. The lowest line is for solar maximum in 1959 and the highest one is for solar minimum in 1965. The precision of the ionisation chamber measurements was estimated to ~1%. As suggested by Neher we have multiplied the ionisation rates by factor 0.95 to take into account the effect of the wall effect of the ionisation chamber at high latitude . The green and red lines represent the simulation results at solar minimum and maximum respectively. At lower latitude (<10 km) the simulation results are in good agreement with the measurements. The maximum ionisation rate obtained with the simulation is lower by ~12 % and is shifted toward lower altitude compare to the measurements. At higher latitude 15-30% of differences are observed between simulation results and measurements. A possible explanation for the discrepancies at altitude >10 km is that our approximation of the interaction of alpha with the atmosphere leads probably to ionisation rates shifted to lower altitude compare to the reality. Indeed as alpha particles have smaller mean free path than protons in matter, the maximum and the shape of the atmospheric profile of the ionisation rate induced by alpha cosmic rays should be shifted to higher energy compared to galactic protons. It is also possible that our model of galactic primary protons underestimate the flux of cosmic rays that was present from 1959 to 1965. In conclusion we consider that simulation results are in rather good agreement with Neher's measurements.

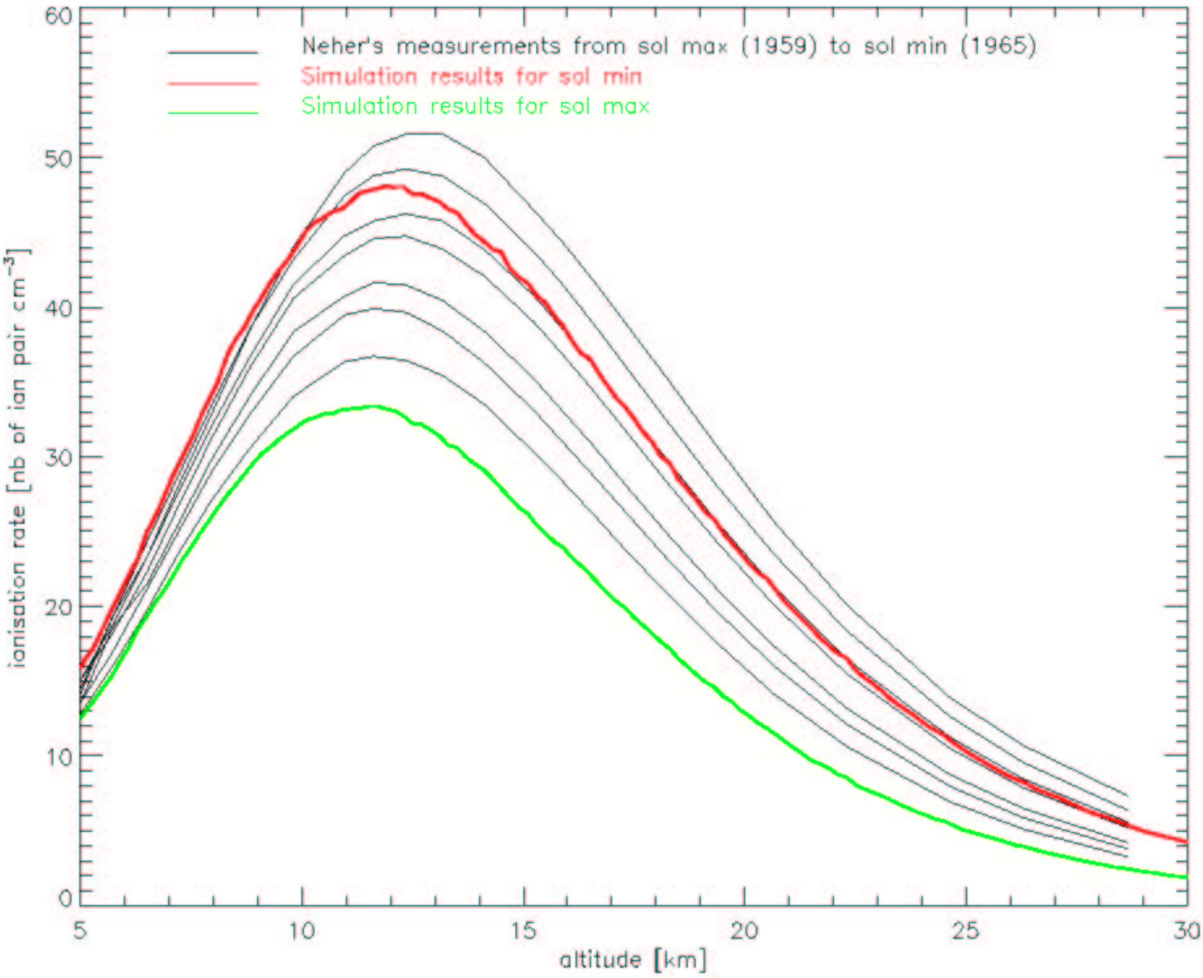



**Figure 16** *Atmospheric ionisation rate induced by cosmic rays at Thule as measured by Neher experiments from 1959 to 1965 (balck curve) and as obtained from results of PLANETOCOSMICS simulations at minim (red curve) and maximum (green curve) solar activity*.

### 5.2 Secondary fluxes vs depth

Since 1957, the Moscow Lebedev Physical Institute is operating a long term program of cosmic ray measurements by balloon experiments [14]. Since this period the fluxes of atmospheric charged particles are measured three times per week with standard radio-sondes at several locations with different values of geomagnetic cut-off rigidity. On this experiment the omnidirectional fluxes of charged particles is measured by Geiger counters that are sensitive to electrons with energy E>0.2 MeV and protons with E> 5 MeV. The precision of the measurements is estimated to be within 5%. In Figure 17 the black curve represents the year 2000 averaged values of atmospheric cosmic ray measurements vs depth at Moscow (Rc = ~2.3 GV). The time periods with Forbush decreases , solar protons events and with important geomagnetic activity have been removed from the data set to obtain these averaged values. To test our code with these measurements we have simulated the interaction of galactic protons with the Earth's atmosphere at Moscow for the year 2000. For the primary spectrum we have considered a galactic proton flux at maximum solar activity with a vertical cut-off rigidity of 2.2 GV, and a maximum energy of 500 GeV. We have selected the QGSP_BIC_HP model for simulating the hadronic physics. In this simulation we have registered the differential omnidirectional fluxes of e-, e+, gammas, protons and muons at different atmospheric depths. These differential fluxes have been integrated over energy in order to obtain the variation of the integral omnidirectional fluxes vs depth. To take into account the contribution of galactic alpha cosmic rays at maximum solar activity, we have multiplied the fluxes by a factor 1.35 (for explanations see section 5.1). The red curve in Figure 17 represents the computed atmospheric profiles of the sum of omnidirectional fluxes of electrons with energy >200 keV , and protons with energy >5 MeV. If the detector was only sensitive to electron and protons fluxes (as we first thought), it is clear that the computed fluxes would present important discrepancies compared with the measurements specially at high depth (low altitude). However as the detectors consist into Geiger counters, the flux of muons is also detected. By adding the computed muon fluxes to the simulation results we obtain the blue curve which is clearly much closer to the experimental curve. Finally the detector is also sensitive to ~1% of the flux of gamma rays. The green curve is obtained by adding this gamma ray contribution to the simulation results. This curve is in very good agreement with the experiments for depth <700 g/cm2. The discrepancy with the experiment at depth > 700 g/cm2 could be explained by the fact that we have only considered galactic protons with energy <500GeV. It is probable that cosmic rays with energy >500 GeV are the source of atmospheric muon fluxes that cannot be neglected at higher depth. In conclusion from this comparison of the simulation results with experimental values we can say that the PLANETOCOSMICS code is providing quite good results.

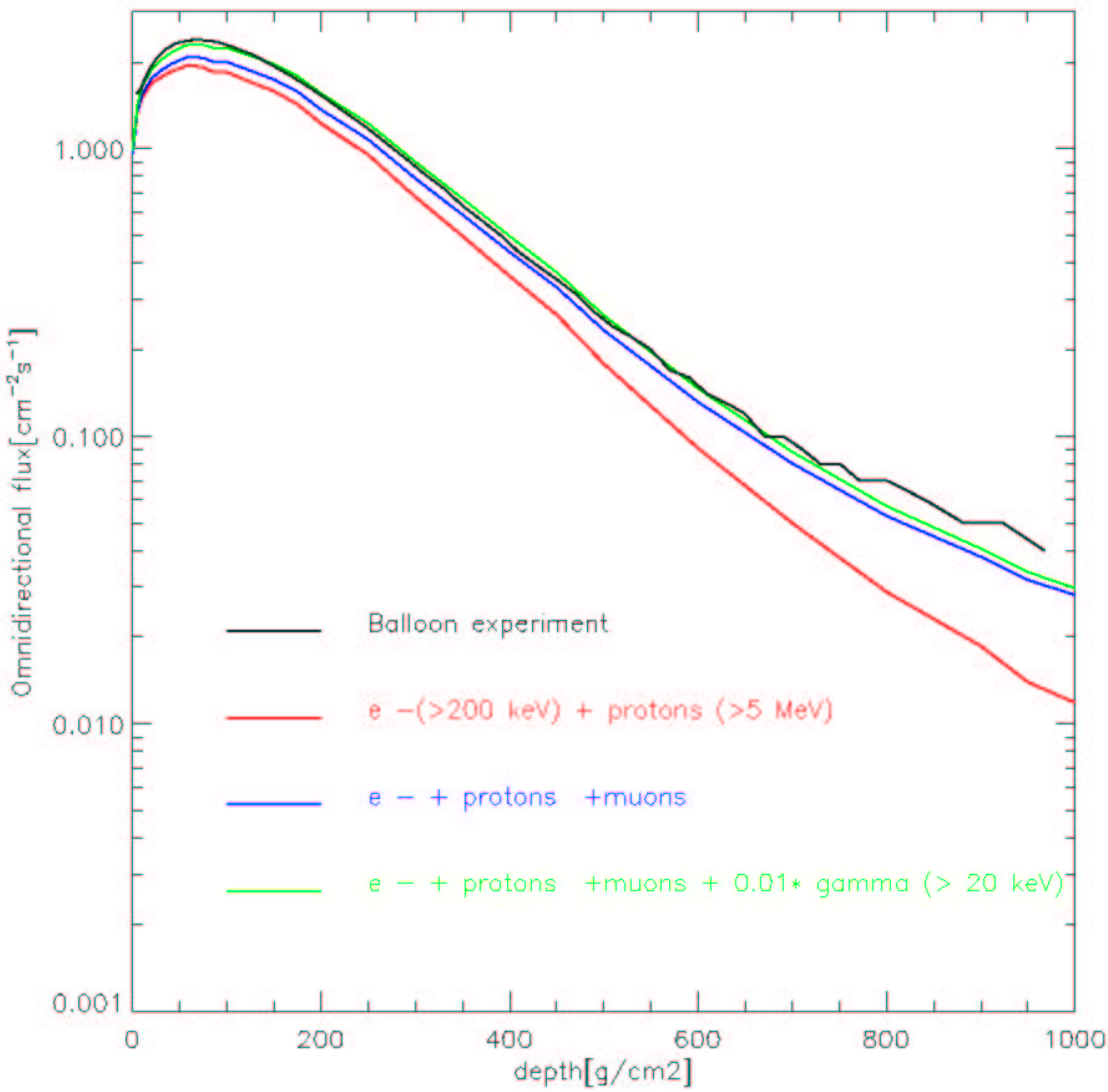



**Figure 17***The black curve represents the omnidirectional flux of secondary cosmic rays measured in the atmosphere during the year 2000 over Moscow by the balloon experiment of the Lebedev Physical Institute. It represents yearly averaged values where quiet period of intense geomagnetic activity and of solar protons events have been removed from the data set. This experiment is sensitive to fluxes of electrons with energy >200keV, protons with energy > 5MeV, muons and 1% of gamma rays with energy >20 keV. The different coloured curves represent these different secondary fluxes as obtained from the PLANETOCOSMICS simulations.*

# 6 Acceptance test procedures

## 6.1 Description of the test

The acceptance tests shall comprise the Unit/Integration Test results performed on a computer identified by the customer.

## 6.2 Test deliverables

The test deliverables shall be the Unit/Integration Test deliverables and the results generated at acceptance. The results of the acceptance tests shall be held in the Software Transfer Document.

## 6.3 Test case pass/fail criteria

The GSPM is considered to have passed the acceptance tests if it passes all the Unit/Integration Tests.

# 7 Software requirements versus test traceability matrix

Table 6.1 shows a cross-reference of the software requirements 1-8 and Unit/Integration Tests. This shows that the software requirements can be met with the proposed test plan.

| S\T | UIT1 | UIT2 | UIT3 | UIT4 | UIT5 | UIT6 | UIT7 | UIT8 | UIT9 | UIT10 | UIT11 | UIT12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 | X | X | X | X | | | | | | | | |
| 1.2 | X | X | X | X | | | | | | | | |
| 1.3 | X | X | X | X | | | | | | | | |
| 2.1 | X | X | X | X | | | | | | | | |
| 2.2 | X | X | X | X | | | | | | | | |
| 2.3 | X | X | X | X | | | | | | | | |
| 2.4 | X | X | X | X | | | | | | | | |
| 2.5 | X | X | X | X | | | | | | | | |
| 2.6 | X | X | X | X | | | | | | | | |
| 3.1 | | | | | | | | | | | X | X |
| 3.2 | | | | | | | | | | | X | X |
| 3.3 | | | | | | | | | | | X | X |
| 4.1 | | | | | | | | | | | | |
| 4.2 | | | | | | | | | | | | |
| 4.3 | | | | | | | | | | | | |
| 5.1 | | | | | X | X | X | X | X | | | |
| 5.2 | | | | | | X | | | | | | |
| 5.3 | | | | | X | X | | | | | | |
| 5.4 | | | | | | | X | | | | | |
| 5.5 | | | | | X | X | | | | | | |
| 6.1 | | | | | | | | | | | | |
| 6.2 | | | | | | | | | | | | |
| 6.3 | | | | | | | | | | | | |
| 7.1 | | | | | | | | | | X | | |
| 7.2 | | | | | | | | | | X | | |
| 8.1 | | | | | | | | | | | | |
| 8.2 | | | | | | | | | | | | |
| 8.3 | | | | | | | | | | | | |
| 8.4 | | | | | | | | | | | | |
| 8.5 | | | | | | | | | | | | |
| 8.6 | | | | | | | | | | | | |

*Table 6.1. Traceability matrix for software requirements versus unit/integration tests*

| S\T | UIT13 | UIT14 | UIT15 | UIT16 | UIT17 | UIT18 | UIT19 | UIT20 |
|---|---|---|---|---|---|---|---|---|
| 1.1 | | | | | | | | |
| 1.2 | | | | | | | | |
| 1.3 | | | | | | | | |
| 2.1 | | | | | | | | |
| 2.2 | | | | | | | | |
| 2.3 | | | | | | | | |
| 2.4 | | | | | | | | |
| 2.5 | | | | | | | | |
| 2.6 | | | | | | | | |
| 3.1 | X | X | | | | | | |
| 3.2 | X | X | | | | | | |
| 3.3 | X | X | | | | | | |
| 4.1 | | | | | | | | X |
| 4.2 | | | | | | | | X |
| 4.3 | | | | | | | | X |
| 5.1 | | | | | | | | |
| 5.2 | | | | | | | | |
| 5.3 | | | | | | | | |
| 5.4 | | | | | | | | |
| 5.5 | | | | | | | | |
| 6.1 | | | X | X | X | | X | |
| 6.2 | | | | | | | X | |
| 6.3 | | | | | | | | X |
| 7.1 | | | | | | | | |
| 7.2 | | | | | | | | |
| 8.1 | | | X | X | | | | |
| 8.2 | | | X | X | | | | |
| 8.3 | | | X | X | | | | |
| 8.4 | | | X | X | | | | |
| 8.5 | | | X | X | | | | |
| 8.6 | | | X | X | | | | |

*Table 6.1. Continued*