



Lookup tables generation of GCR exposure factor using MAGNETOCOSMICS

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ABSTRACT

This Technical Note presents the work carried-out by the *Center for Space Radiations* at the Université Catholique de Louvain within the frame of WP130 of "SPENVIS Geomagnetic Project".



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LIST OF ABBREVIATIONS

AD	Applicable Document
RD	Reference Document
GCR	Galactic Cosmic Rays
IGRF	International Geomagnetic Reference Field
SM	Solar Magnetic

DOCUMENTS

APPLICABLE DOCUMENTS

AD 1 Laurent Desorgher. *MAGNETOCOSMICS Software User Manual*.

REFERENCE DOCUMENTS

- RD 1 S. Agostinelli et al. *GEANT4 a simulation toolkit*. Nuclear Instruments and Methods A. Volume 506, Issue 3, 1 July 2003, Pages 250-303
- RD 2 J.H Adams, Jr Silberberg, *Cosmic Ray Effects on Microelectronics, Part1 The Near-Earth Particle Environment*. NRL Memorandum Report,4506, 1981,
- RD 3 D.F. Smart, M.A. Shea, *A review of geomagnetic cutoff rigidities for earth-orbiting spacecraft*. Advances in Space Research,36, 2005,2012-2020
- RD 4 <http://www.ccl.net/cca/software/SOURCES/FORTRAN/Lebedev-Laikov-Grids/index.shtml>
- RD 5 Lebedev, and D.N. Laikov. *A quadrature formula for the sphere of the 131st algebraic order of accuracy*. Doklady Mathematics, Vol. 59, No. 3, 1999, pp. 477-481.
- RD 6 Gräf, Manuel; Kunis, Stefan; Potts, Daniel. *On the computation of nonnegative quadrature weights on the sphere*. Technische Universität Chemnitz, Fakultät für Mathematik (Germany). Preprint 13, 2008
- RD 7 <http://eqsp.sourceforge.net>
- RD 8 P. Leopardi. *A partition of the unit sphere into regions of equal area and small diameter*. Electronic Transactions on Numerical Analysis. Volume 25, pp. 309-327, 2006.
- RD 9 <http://www.research.att.com/~njas/sphdesigns/>
- RD 10 R. H. Hardin and N. J. A. Sloane. *McLaren's Improved Snub Cube and Other New Spherical Designs in Three Dimensions*. Discrete and Computational Geometry, 15 (1996), pp. 429-441.

1 INTRODUCTION

In this Technical Note, we report on a procedure to generate lookup tables of GCR exposure factor based on MAGNETOCOSMICS results presented in previous reports. The procedure includes the following steps:

- The automatic generation of GEANT4 [RD 1] macros and shell scripts to run the MAGNETOCOSMICS code [AD 1] using a FORTRAN code.
- The evaluation of the exposure factor versus rigidity based on the asymptotic directions (by backwards tracing) at different positions and incidence angles in the magnetosphere.

A first attempt to interpolate the exposure factor from reduced data in lookup tables is also presented.

2 DEFINITIONS

2.1 RIGIDITY

The ability for a charged particle to penetrate in a magnetic field is related to its rigidity.

The rigidity is defined as the momentum divided by the charge and it is expressed in GV as [RD 2]

$$P = \frac{\text{momentum}}{\text{charge}} = \frac{A}{Z} \sqrt{E(E + 1862.0)} 10^{-3} [GV] \quad (1)$$

Where E is the incident particle energy expressed in MeV/u; A and Z are the atomic mass and charge, respectively.

In a dipole magnetic field, for any **geomagnetic** location (r, λ) and incidence direction $\Omega = (\theta, \phi)$, the Störmer formula gives the cutoff rigidity value below which the charged particle access is forbidden [RD 3].

$$P_c(r, \lambda; \Omega) = \frac{P_k \cos^4 \lambda}{r^2 (1 + \sqrt{1 - \cos^3 \lambda \sin \theta \sin \phi})^2} \text{ with } P_k = B_0 R_E c \quad (2)$$

Where $P_k [GV R_E^2]$ is a constant related to the dipole moment and calculated with terms of degree 1 in IGRF, for year 2000, $P_k = 57.5296 \text{ GV R}_E^2$. r is the position from the dipole center in Earth's radius (R_E) and λ is the magnetic latitude. θ is the zenith angle and ϕ is the azimuth angle measured clockwise from magnetic North.

2.2 EXPOSURE FACTOR

At each position (r, λ) inside the magnetosphere, the exposure factor gives the fraction of interplanetary flux, with rigidity P , that reaches this position. It is obtained integrating a step function $H(P(\Omega))$ over all incidence directions Ω taking the cutoff rigidity $P_c(\Omega)$ at the given position into account.

$$F(P) = \frac{1}{4\pi} \int_{4\pi} H(P(\Omega)) d\Omega \quad \text{with} \quad \begin{cases} H(P(\Omega)) = 0 & \text{if } P(\Omega) < P_c(\Omega) \\ H(P(\Omega)) = 1 & \text{if } P(\Omega) \geq P_c(\Omega) \end{cases} \quad (3)$$

In the case of a dipole field, the integration of Störmer equation gives the following expression.

$$F(P) = \frac{1}{2d} \left[d + 2\sqrt{\left(\frac{A}{P}\right) - \frac{A}{P}} \right] \quad \text{with} \quad \begin{cases} A = P_k \cos^4 \lambda \\ d = \cos^3 \lambda \end{cases} \quad (4)$$

To take the Earth Shadow into account at distance r , the exposure factor is multiplied by the fraction of the geometrical factor sustained by the Earth. This approximation is valid for straight trajectories.

$$ES = 1 - 0.5 \left(1 - \frac{\sqrt{r^2 - 1}}{r} \right) \quad (5)$$

Figure 1 is an example of exposure factor calculation (Eq. 4) for a dipole field at geomagnetic coordinates $r = 6771$ km (1.06 RE), $\lambda = 20^\circ$ (blue curve). This total exposure factor is reduced by the Earth Shadow (black curve).

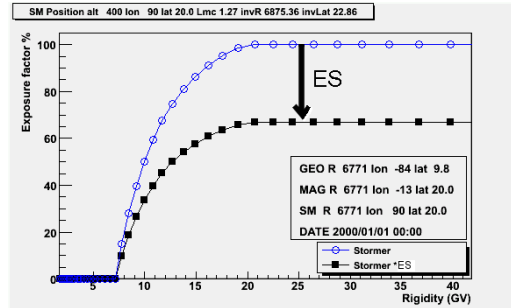


Figure 1: Total exposure factor (blue curve) and exposure factor reduced by the Earth Shadow (black curve) versus rigidity

This calculated exposure factor does not take into account the non dipole components of the geomagnetic field and the earth shadow is only an optical approximation which doesn't take into account the gyro radius of particles. More accurate calculations can be performed with backwards ray tracing using realistic geomagnetic fields. This backwards tracing has been carried-out with MAGNETOCOSMICS code.

3 MAGNETOCOSMICS CALCULATIONS

As explicitly defined in [AD 1], “the MAGNETOCOSMICS Geant4 application allows to compute the propagation of charged cosmic rays through different magnetic field models of the Earth's magnetosphere. It also permits to compute cutoff rigidities and asymptotic directions of incidence. Particle trajectories and magnetic field lines can be visualized by using one of the visualization driver available in the Geant4 toolkit”.

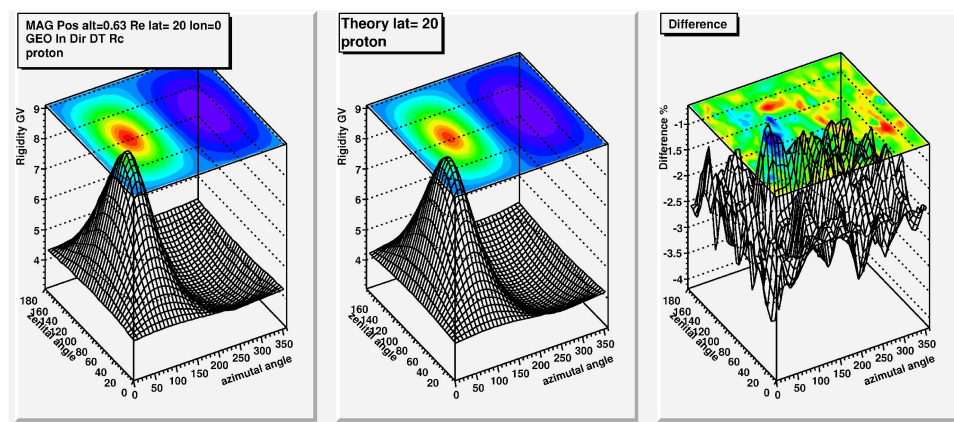


Figure 2: Cutoff rigidities for magnetic latitude 20° and $1.63 R_E$ radius. Left panel is the MAGNETOCOSMICS calculation, center panel is the Störmer formula and right panel is the relative difference.

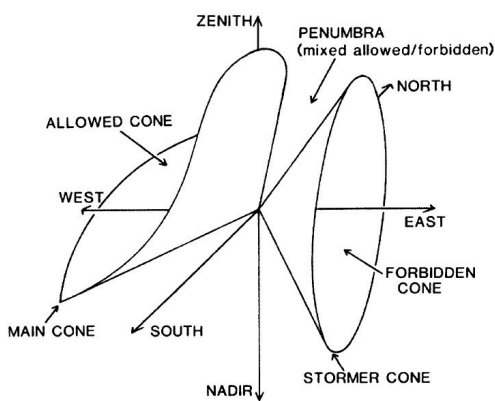


Figure 3: Allowed and forbidden cones for positive cosmic rays [RD 3]

The code has been installed and compiled on a Linux server at CSR. Then, it has been tested for positive and negative charges using only a dipole field without Earth (no Earth Shadow). With AutomaticDetectionOfPenumbra and RcutoffVsDirection scenario in MAGNETOCOSMICS the cutoff rigidities are automatically found from backwards trajectories and can be compared to the theoretical formula [Eq. 2]. Calculations for some positions and altitudes have been performed and absolute differences between results were found to be lower than 1%. Figure 2 shows an example of cutoff rigidities comparison for a proton at 4000 km altitude, 20° latitude and 0° longitude.

The left panel shows the MAGNETOCOSMICS calculation, the center panel shows the Störmer formula (Eq.2) and the right panel depicts absolute value of the relative difference which is less than 1%. In this figure, the high cutoff rigidity values around 90° degrees zenith angle (horizon) and azimuth = 90° (east direction) corresponds to the forbidden cone. The low values around the horizontal direction and the west direction are the allowed cone as in the schematic drawing in Figure 3.

3.1 EXPOSURE FACTOR

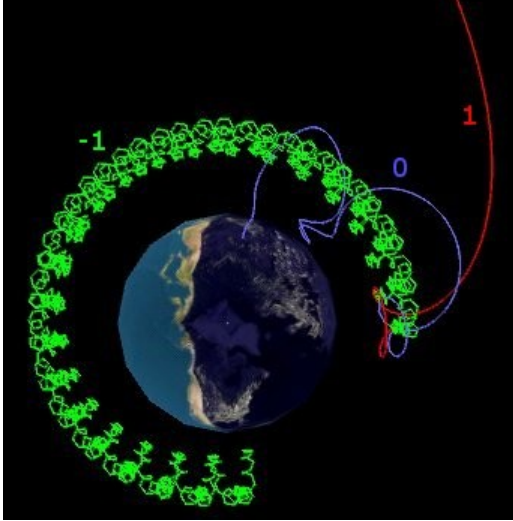


Figure 4: Different asymptotic directions for backwards trajectories

Figure 4 illustrates the computation of backwards trajectories at a given position r_i in the geomagnetic field for the same incidence direction Ω_i and three different rigidities. The asymptotic direction depends on the rigidity. In case 1, a GCR with rigidity P_i can reach the position r_i at Ω_i incidence direction. In case 0, any charged particle with rigidity P_0 should be only coming from the Earth (Earth Shadow) and thereby will never reaches the position r_i at incidence direction Ω_i . In case -1 the observed particle is a trapped one and not a GCR.

With this convention, the exposure factor (Eq.3) can be calculated using numerical integration.

$$F(P) \approx \sum_{i=0}^n w_i H(P(\Omega_i)) \quad \text{with} \quad (6)$$

$$H(P(\Omega_i)) = 0 \quad \text{for case -1 and 0}$$

$$H(P(\Omega_i)) = 1 \quad \text{for case 1}$$

Where Ω_i is a selected grid over the sphere and w_i are the integration weights which depend on the choice of the grid.

When RcutoffVsDirection with AutomaticDetectionOfPenumbra scenario is used in MAGNETOCOSMIS, the exact values of cutoff rigidities P_c are obtained and equation 6 can use the step function conditions

$$H(P(\Omega_i)) = 0 \quad \text{for } P(\Omega_i) < P_c(\Omega_i)$$

$$H(P(\Omega_i)) = 1 \quad \text{for } P(\Omega_i) \geq P_c(\Omega_i) \quad (7)$$

3.2 BEST GRID FOR NUMERICAL INTEGRATION.

To find the best grid of incidence directions Ω_i and weights w_i , a trade-off involving four different kind of grids in the numerical calculations of the exposure factor (Eq.6) was carried-out. A dipole magnetic field was used. The result was compared to the exact integration (Eq.3). The four kind of grids are:

1. Lebedev- Laikov-Grids [RD 4-RD 5].
2. Lebedev- Laikov-Grids corrected with positive weights for all points in the grid [RD 6].
3. Leopardi-Grid with equal weights [RD 7-RD 8].
4. Hardin-Grid with equal weights [RD 9-RD 10].

For each grid type, eleven different sizes with [50,74,86,110,146,170,194,230,266,302 and 350]

points were tested¹.

For each size the integration has been carried-out in a $15 \times 15 \times 7$ positions in the magnetosphere. [15 Altitudes from 400km to 36000 km, 15 latitudes from 75° to -75° and 7 longitudes 0° to 315° in Solar Magnetic coordinates]. UNILIB subroutines were used for transformation from SM to geomagnetic coordinates. At each position, exposure factor was calculated for a set of 10 rigidities P_j between the minimum and maximum cutoff rigidity. An example of comparison, at a given position, between analytical and numerical integration is show in figure 5.

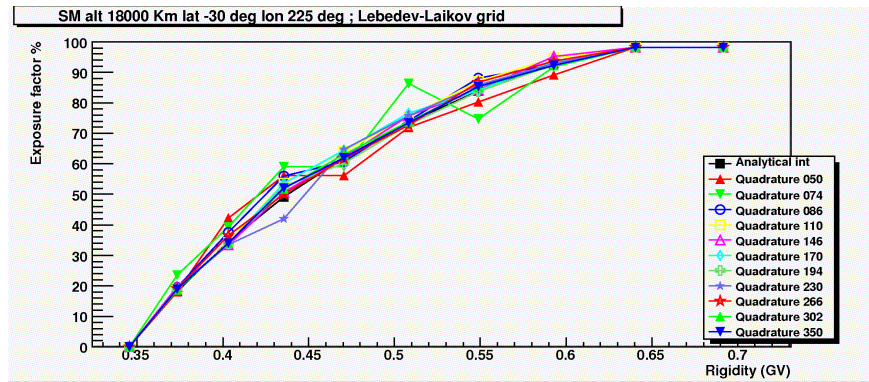


Figure 5: Comparison between analytical and numerical integration calculation of exposure factor for different number of points of a Lebedev-Laikov grid and for ten different rigidities.

The approximation error (the absolute value of difference between the numerical integration $F_n(P_j)$ and the exact integration $F_e(P_j)$) is estimate as

$$\sigma = \sqrt{\sum_{j=1}^{10} \frac{(F_e(P_j) - F_n(P_j))^2}{10}} \quad (8)$$

For each grid the maximum, minimum and mean approximation error over all position were calculated. The minimum error with the shorter grid was found to be Hardin's using 108 incidence directions. Figure 6 shows the evolution of the approximation errors for the Hardin grids of different sizes. It can be seen that the approximation error decrease until 108 points grid and stay constant for larger grids.

¹ The Hardin's grids are of sizes [50,74,86,108,144,180,240]

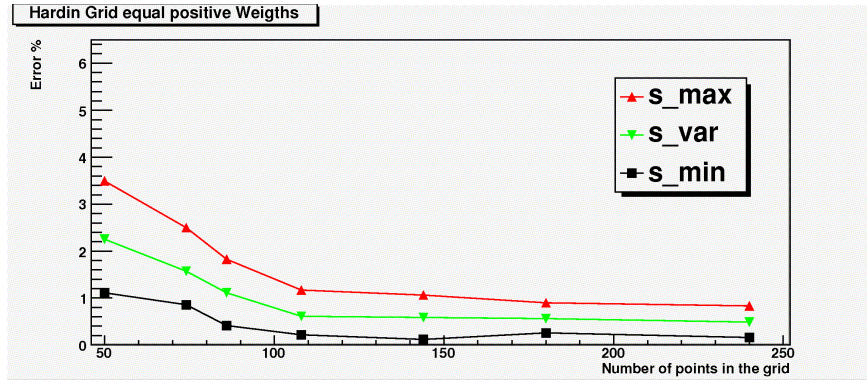


Figure 6: Maximum (s_{max}), minimum (s_{min}) and mean of approximation errors (s_{var}) for each Hardin grid with equal weights ($1/N$).

4 LOOKUP TABLES GENERATION

In this work a Fortran program to generate the lookup tables was developed. The user has to run it twice. The first time, *stormer2magneto* program writes the MAGNETOCOSMICS macros and shell scripts for the calculation of asymptotic directions for different positions in the magnetosphere. The second time, it reads the MAGNETOCOSMICS output files to calculate the exposure factor and generates the lookup tables.

4.1 MACROS CREATION

The *stormer2magneto* program reads an input file where user can define the geomagnetic field and the positions. The program creates macros and shell scripts to run MAGNETOCOSMICS. An example of this input file is given hereafter:

```
1          K_ORD   (machine type: 1-> csrsrv 1 or 2; 2-> lemaitre)
12345678901234567890123456789012 Job Name in max 32 char (only lemaitre machine)
dipole_R0_lem
12345678901234567890123456789012 Notification mail max 32 char (only lemaitre)
juan.cabrera@uclouvain.be

57.5296D0    CUTM   (Stormer constant in GV*Re^2)
3            KINT   (Internal field : 0 DGRF/IGRF; 3 Dipole magnetic field)
0            KEXT   (External field : 0 None; 7 Tsyganenko [1996])
-30.00D0     DST    (Disturbance storm-time index Dst (nT))
3.00D0       SWP    (Solar wind pressure (nP))
0.00D0       BIMFY  (Interplanetary magnetic field Y component (nT))
0.00D0       BIMFZ  (Interplanetary magnetic field Z component (nT))
1            CORDSYS (System of coordinates: 1-> GEO; 3-> MAG; 4->SM)
20.00D0      STPALT (Stop altitude km 999.999 <= STPALT <= 0.001)
0            VSDIR  ( 0-> Only Asymptotic Directions calculations )
```

```

( 1-> Rc vs Dir with automatic Penumbra detection)
////////////////////////////////////////////////////////////////
1.1D0      LMLO      (McIlwain L parameter lower limit in Re)
6.0D0      LMHI      (McIlwain L parameter upper limit in Re)
0.1D0      RCLO      (Vertical rigidity cutoff lower limit in GV)
500.0D0     RCHI      (Vertical rigidity cutoff upper limit in GV)
0.0D0      IRLO      (Invariant Radius lower limit in km)
////////////////////////////////////////////////////////////////
1          TYPINT     (Integration type 1 Hardin; 2 Lebedev; 3 Lebedev Positive)
108        N_INT      (Number of integration points)
3          N_POS      (Number MAGCOS runs per shell macro)
////////////////////////////////////////////////////////////////
1          N_DAT      (Number of dates <= 10) YEAR MONTH DAY HOUR MINUTE SECONDS
2000 1 1 0 0 0
////////////////////////////////////////////////////////////////
3          N_ALT      (Number of altitudes <= 20)
400.0D0     (Altitudes in km)
4000.0D0    (Altitudes in km)
20000.0D0   (Altitudes in km)
////////////////////////////////////////////////////////////////
3          N_LON      (Number of longitudes <= 20)
0.0D0       (longitudes in degree)
90.0D0      (longitudes in degree)
180.0D0     (longitudes in degree)
////////////////////////////////////////////////////////////////
5          N_LAT      (Number of latitudes <= 20)
60.0D0      (latitudes in degree)
20.0D0      (latitudes in degree)
00.0D0      (latitudes in degree)
-20.0D0     (latitudes in degree)
-60.0D0     (latitudes in degree)

```

The first variable **K_ORD** is a flag to set the kind of server which will run MAGNETOCOSMICS. The shell scripts to be produce by *stormer2magneto* will depend on it. Value 1 is for a standard Linux server and value 2 is for a multiprocessor server. Next two values are only used for the multiprocessor shell script.

The **CUTM** variable is the Störmer constant of equation 7.

KINT, **KEXT**, define the type of magnetic field used by MAGNETOCOSMICS. **DST**, **SWP**, **BIMFY**, **BIMFZ** variables are used in external field evaluation.

CORDSYS variable is the system of coordinates chosen for position data.

STPALT is the lower altitude where MAGNETOCOSMICS stops backtrack calculation and considers that the particle hits the Earth.

For debugging purposes, if **VSDIR** is set to 1, **RcutoffVsDirection** is calculated to compare exposure factor results with the **ComputeAsymptoticDirections** scenario.

LMLO, **LMHI**, **RCLO**, **RCHI**, **IRLO**, are coordinates transformations and MAGNETOCOSMICS limits.

Variables **TYPINT**, **N_INT** are the type of grid and the number of point of the grid used for numeric integration (Eq.6)

N_POS Is the number of MAGNETOCOSMICS runs executed by the shell script. In multiple processors machines, each shell executes the runs on a different processor.

For each date N_DAT a directory tYYYYMMDD is created (YYYY is the year, MM the month, DD the day). Inside this directory, a subdirectory 'macros' is create where the program will write the MAGNETOCOSMICS macros. Also subdirectories formatted as: pAAAAA.A_+/-LLL.LL, with AAAAA.A the altitude in km and +/-LLL.LL the longitude, are created where MAGNETOCOSMICS will write the results.

The program calculates, for each position, the vertical cut-off rigidity with Störmer formula (Eq.2) using the constant CUTM. (In the example it is the value for DGRF 2000). A vector in logarithmic scale with rigidity values around the vertical cutoff rigidity is generated at each position. For each position in altitude and longitude, a macro to set this rigidities in MAGNETOCOSMICS is stored in the macros subdirectory. An example of macro is shown below.

```
###
### Macro generated by stormer2magneto prog
###
/control/execute macros/magneto_expfact_init.g4mac
#
# position      2
/control/alias pos p00400.0_+000.00
/control/alias lat _+60.00
/MAGCOS/SOURCE/SetPosition GEO      400.00 km    60.00    0.00 degree
# L= 4.735 K= 4.426E+04 RCv= 0.6447 GV

/MAGCOS/RIGIDITYVECTOR/Reset
/MAGCOS/RIGIDITYVECTOR/AddValues    1.3632 -0.0001 1
/MAGCOS/RIGIDITYVECTOR/AddValues    1.2889 -0.0001 1
...
...
...
/MAGCOS/RIGIDITYVECTOR/AddValues    0.1619 -0.0001 1
/MAGCOS/RIGIDITYVECTOR/AddValues    0.1531 -0.0001 1
/control/execute macros/magneto_expfact_exec.g4mac
#
# position      3
/control/alias pos p00400.0_+000.00
/control/alias lat _+20.00
/MAGCOS/SOURCE/SetPosition GEO      400.00 km    20.00    0.00 degree
# L= 1.265 K= 2.085E+03 RCv= 9.1501 GV

/MAGCOS/RIGIDITYVECTOR/Reset
/MAGCOS/RIGIDITYVECTOR/AddValues    33.9431 -0.0001 1
...
...
...
```

Example of m_t20000101_p00400.0_+000.00.g4mac file

This macro executes two others macros generated by *stormer2magneto* program. *magneto_expfact_init.g4mac* is called at the beginning. It sets the particle, the magnetic field defined by KINT and KEXT values in input file, the stop altitude STPALT, the date and sets the AutomaticDetectionOfPenumbra to false. An example of this input file is as follows:

```
/tracking/storeTrajectory 0
/control/verbose 1

/gps/particle proton

/MAGCOS/INTEGRATION/SelectG4IntegrationMethod
```

```
/MAGCOS/INTEGRATION/SetDefaultIntegrationParameters

/MAGCOS/USERLIMIT/SetStopAltitude 0.001 km
###
### Set date
###
/MAGCOS/BFIELD/SetStartDate 2000 01 01 00 00 00
/control/alias date t20000101

/MAGCOS/BFIELD/SetGeomagneticFieldModel DIPOLE
/MAGCOS/BFIELD/SetDipoleAxis 0.0 0.0 deg
/MAGCOS/BFIELD/SetDipoleCenter 0.0 0.0 0.0 m

/MAGCOS/BFIELD/SetExternalFieldModel NOFIELD

/MAGCOS/SCENARIO/AutomaticDetectionOfPenumbra false
```

Example of magneto_expfact_init.g4mac file

For each position `magneto_expfact_exec.g4mac` macro is executed by MAGNETOCOSMICS. This macro is generated by *stormer2magneto* program to set the incidence directions and calculate the asymptotic directions for rigidities set in the previous macro and store results in files of type `{pos}/{date}_{pos}{lat}_d081.89_309.19.txt`. `{date}`, `{pos}`, `{lat}` are aliases set in previous macro. `TYPINT` and `N_INT` determine the type of grid and thus set the values and the number of points of incidence directions involved in the numerical integration over the sphere used to calculate the exposure factor. The set of 108 Hardin's quadrature points has been found to be the best choice to calculate the exposure factor as it gives results close to the Störmer formula and with the minimum number of points. An example of `magneto_expfact_exec.g4mac` file shown hereunder:

```
/MAGCOS/SOURCE/SetDirection GEO 81.89437 309.18550 degree
/MAGCOS/SCENARIO/ComputeAsymptoticDirections {pos}/{date}_{pos}{lat}_d081.89_309.19.txt
/MAGCOS/SOURCE/SetDirection GEO 128.72922 169.57860 degree
/MAGCOS/SCENARIO/ComputeAsymptoticDirections {pos}/{date}_{pos}{lat}_d128.73_169.58.txt
/MAGCOS/SOURCE/SetDirection GEO 81.87949 50.81487 degree
...
...
...
/MAGCOS/SCENARIO/ComputeAsymptoticDirections {pos}/{date}_{pos}{lat}_d115.43_142.40.txt
/MAGCOS/SOURCE/SetDirection GEO 115.42364 217.59538 degree
/MAGCOS/SCENARIO/ComputeAsymptoticDirections {pos}/{date}_{pos}{lat}_d115.42_217.60.txt

/MAGCOS/SCENARIO/AutomaticDetectionOfPenumbra true

/MAGCOS/SCENARIO/RCutoffVsDirection GEO 0 15 14 0 15 28 {pos}/{date}_{pos}{lat}.txt

/MAGCOS/SCENARIO/AutomaticDetectionOfPenumbra false
```

Example of magneto_expfact_exec.g4mac

Once the macros and the shell scripts have been created, the user executed the shells to run MAGNETOCOSMICS.

4.2 LOOK UP TABLES

After backtrack and asymptotic directions calculations performed with MAGNETOCOSMICS,

stormer2magneto program must be run again. The program will read MAGNETOCOSMICS output files and integrate the results to obtain the exposure factors. The exposure factors versus rigidity for all positions defined in the input file are stored in a text file called *macos_res.txt*. For each position, the contents of this file are:

TYPOS,ALT,LAT,LON,

Type of input position coordinates system (GEO,SM,MAG) and input position. Altitude, latitude, longitude [km, degrees,degrees].

M_GEO%RADIUS,M_GEO%ELONG,M_GEO%COLAT,

Input position in geographic coordinates. Radial distance, longitude, colatitude [km, degrees,degrees].

M_MAG%RADIUS,M_MAG%ELONG,M_MAG%COLAT,

Input position in geomagnetic coordinates. Radial distance, longitude, colatitude [km, degrees,degrees].

M_SM%RADIUS ,M_SM%ELONG ,M_SM%COLAT ,

Input position in Solar Magnetic coordinates. Radial distance, longitude, colatitude [km, degrees,degrees].

M_INV%RADIUS,M_INV%ELONG,M_INV%COLAT,

Input position in invariant coordinates. Radial distance, longitude, colatitude [km, degrees,degrees].

YEAR(K_DAT),MONTH(K_DAT),DAY(K_DAT),

Date used for IGRF and external field calculations

HOURL(K_DAT),MINUTE(K_DAT),SECONDS(K_DAT),

Time used for IGRF and external field calculations

FLM,SF,AFIT,BFIT,CORL,XMLT,XLAT,

McIlwain L paramater [R_E], Earth Shadow (eq.5), slope, intersection and correlation of linear regression, Magnetic Local Time, Magnetic Latitude [degrees].

(RLIST(K_R) , K_R=1, N_R),

Rigidity values. [GV]

(REFF(K_R) , K_R=1, N_R),

Effective rigidities used for linear regression. (see section 4.3 Eq 9 and 10). [GV]

(EF(K_R) *SF, K_R=1, N_R),

Exposure factor for a dipole field calculated with Störmer analytical integration (Eq.4). [%]

(EFN(K_R) *SF, K_R=1, N_R),

Exposure factor for a dipole field calculated with Störmer numerical integration (Eq 6 and 7).[%]

(EFMAG(K_R) , K_R=1, N_R),

Exposure factor calculated using MAGNETOCOSMICS results. In this case

ComputeAsymptoticDirections scenario was set and numerical integration uses step function with 1,0,-1 limits in equation 6. [%]

(EFMAG2(K_R) , K_R=1, N_R),

Exposure factor calculated using MAGNETOCOSMICS results. When user set $VSDIR = 1$

$R_{cutoffVsDirection}$ with AutomaticDetectionOfPenumbra is used in MAGNETOCOSMIS. In this case exact values of cutoff rigidities are obtained and the program do the numerical integration (eq.6) with step function conditions (Eq.7). [%]

(EFFIT(K_R) *SF, K_R=1, N_R)

Exposure factor calculated using linear regression. (see section 4.3 Eq. 9 and 10)

4.3 LINEAR REGRESSION

To reduce the size of lookup tables, a fit of exposure factor versus rigidity has been investigated. In first step, a set of effective rigidities P_{eff} (defined by Eq.9) is evaluated by comparing MAGNETOCOSMICS results and their Störmer counterpart (Eq. 4) taking the Earth Shadow (Eq.5) into account.

$$F_{MACOS}(P) = F_{Störmer}(P_{eff}) \times ES \quad (9)$$

The linear regression is performed to find the parameters of the equation 10 which links the logarithmic values of P and P_{eff} .

$$\ln(P_{eff}) = a \ln(P) + b \quad (10)$$

An example of the linear regression is present in figure 7. All the rigidities used for MAGNETOCOSMICS backtracking are in red, only the blue triangles are used for the fit, since the data represented in red has a constant exposure factor (see figure 8)

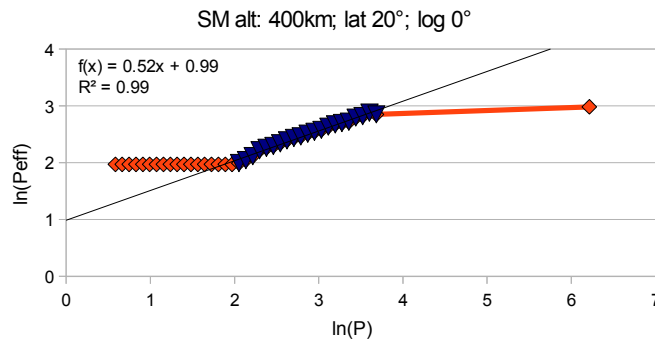


Figure 7: linear regression between the logarithmic values of P and P_{eff} .

Figure 8 shows the exposure factor calculated with MAGNETOCOSMICS data using IGRF+Tsyganenko magnetic field (red diamonds). It is compared to Störmer equation multiplied by the Earth Shadow (blue square). The fit result is close to MAGNETOCOSMIC data (white triangles).

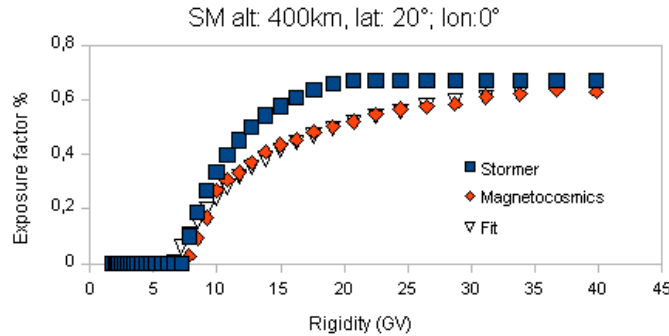


Figure 8: Comparison of exposure factor from MAGNETOCOSMIC (IGRF+Tsyganenko), Sörmer (dipole with Earth Shadow) and fit results.

Unfortunately this regression method is not good enough for high altitudes (see figures 9 and 10 section 4.4). An alternative way to fit the data should be found if the reduction of the size of lookup

tables is considered mandatory.

4.4 RESULTS

MAGNETOCOSMICS calculations has been carried-out for $3 \times 4 \times 5$ positions in Solar Magnetic coordinates :

- Altitudes : 400, 4000, 20000 km
- Longitudes: 0° , 90° , 180° , 270°
- Latitudes: -60° , -20° , 0° , 20° , 60°

The internal magnetic field was IGRF 2000 and the external magnetic field Tsyganenko 96 for a quiet magnetosphere with solar activity parameters

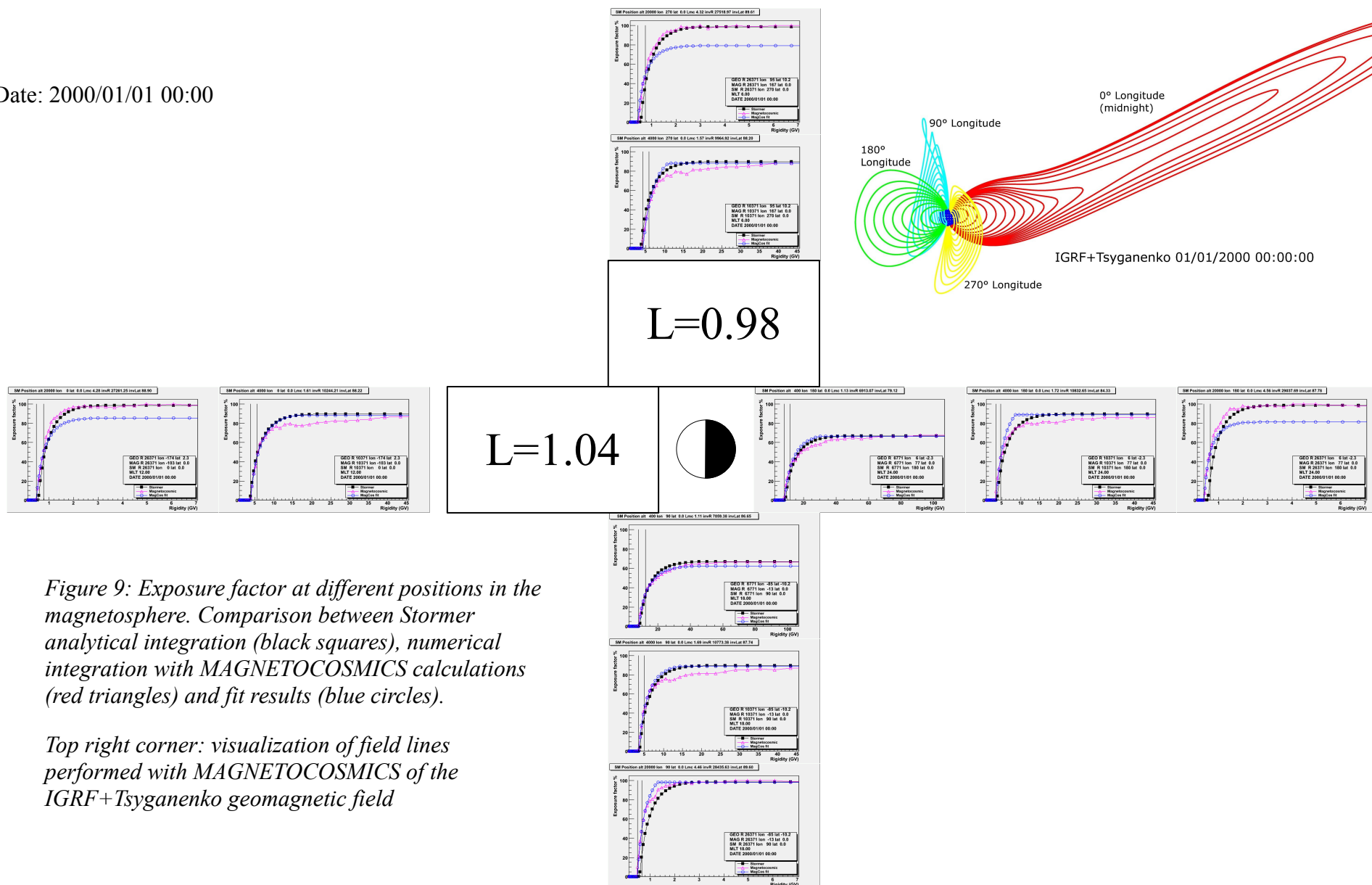
$Dst = -30 \text{ nT}$, $ImfBz = ImfBy = 0 \text{ nT}$, $P_{dyn} = 3 \text{ nPa}$

Exposure factor for two different dates in year 2000 with 6 month interval were calculated.

Figures 9 and 10 show the result for some positions at the equator. Two position don't have results as the McIlwain parameter is lower than the selected limit $L < 1.1 \text{ Re}$. The black squares are the analytical integration of Störmer equation 4, the red triangles are the numerical integration using MAGNETOCOSMICS calculations and the blue circles are the fit results.

4.5 CONCLUSIONS

In this work a procedure to create lookup tables of GCR exposure factor in the geomagnetic field was established. A Fortran code was developed to generate, in a first step, GEANT4 macros and shell scripts to run MAGNETOCOSMICS. Then, MAGNETOCOSMICS is used to evaluate the GCR asymptotic directions using backtrack calculations. In a second step, the program reads the results and calculates the lookup tables.



Top right corner: visualization of field lines performed with MAGNETOCOSMICS of the IGRF+Tsyganenko geomagnetic field

Date: 2000/06/01 00:00

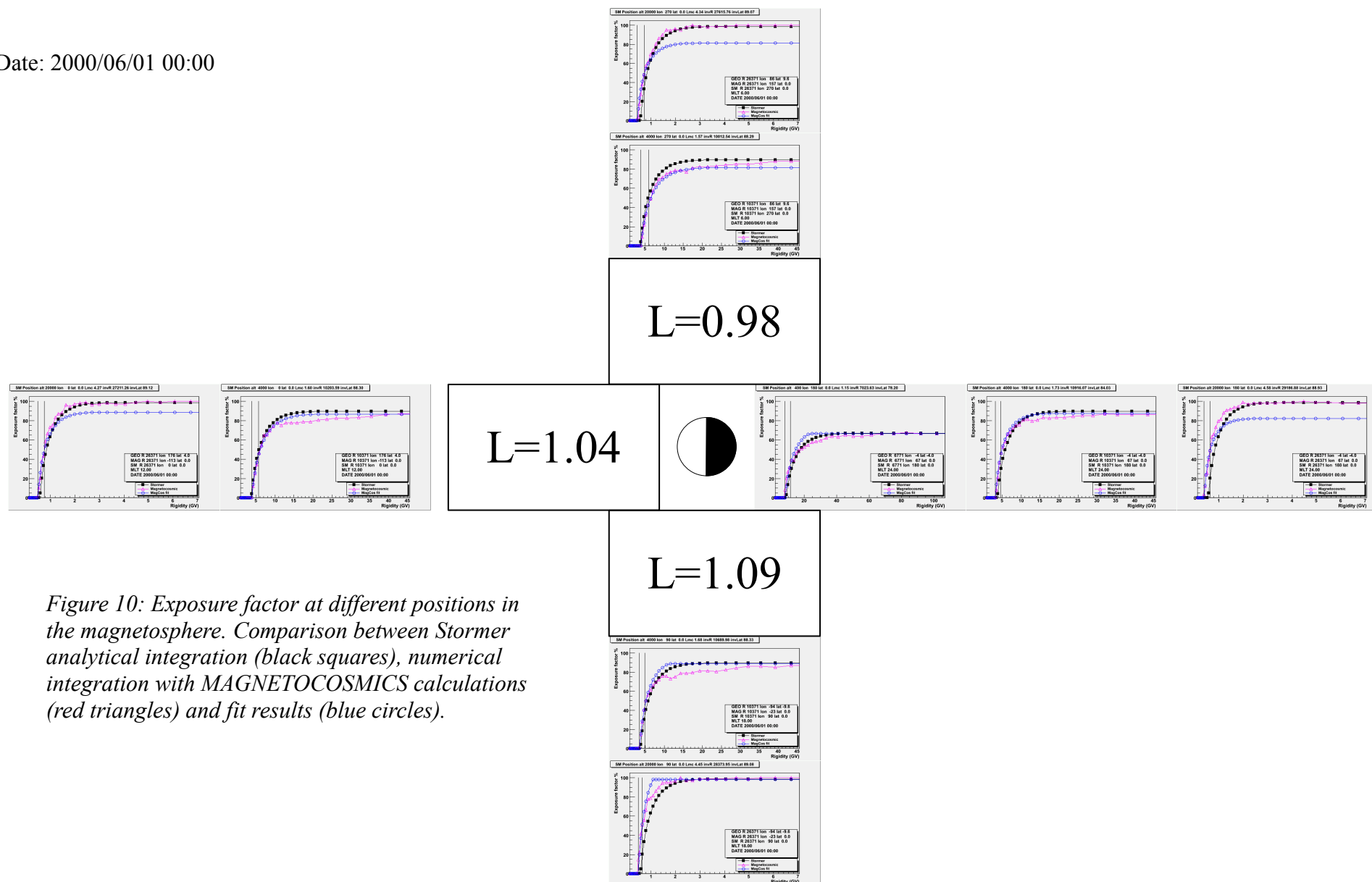


Figure 10: Exposure factor at different positions in the magnetosphere. Comparison between Stormer analytical integration (black squares), numerical integration with MAGNETOCOSMICS calculations (red triangles) and fit results (blue circles).