The program Cutoff calculates geomagnetic cut off rigidity for fixed geographical point and date. From a given height the antiprotons of various energy are launched upward, and their trajectories are calculated. If the particle emerges from the magnetosphere, the rigidity is permitted, if it crashes into the Earth or turns too long (the duration of the flight is set), the rigidity is forbidden. The program can calculate trajectories in one of the magnetosphere model: dipole, IGRF, Tsyganenko-89, 96, 02. Particles are issued under given vertical and azimuth angles.

All the specified parameters are set in the file Cutoff.ini.

Input parameters for the program CUTOFF:
17.05.2014 Date
02:00:00   Time
0.4   Solar wind dynamic pressure (nPa)
-30.0   Dst-index (nT)
-7.8   IMF By (nT)
-2.9   IMF Bz (nT)
1.8   G1
7.0   G2
1.7   Kp-index
10   Model: 00-**dipole**, 10-**IGRF**, 89-**T89**, 96-**T96**, 01-**T01**
20.00   Height (km)
40.63   Geographic latitude (90 to -90)
-3.15   Geographic longitude (-180 to +180)
0.00   Vertical angle (0 - 90): 0 , 15 , 30 , 45 , 60 , 75 , 85
0.00   Azimutal angle (0 - 360)
3.00   lower limit
8.00   Rigidity upper limit (GV)
0.001 step
3.00   Maximum time of flight (s)
0   Output trace coordinates [1] or not [0]

where

- Date, time in UT.
- Further, 7 parameters for different models of the magnetosphere are going.
  Dipole and IGRF don't need enter parameters.
  T-89 – uses only Kp-index.
  T-96 – uses only the first 4 parameters
  T-01 - uses the first 6 parameters.

Model	Setting parameters	Range of the measured parameters
Dipole	no	no
IGRF	Epoch	1900–2050 (exstrapolation 2020–2050)
IGRF+T89	Date and Time Kp	1900–2050 (exstrapolation 2020–2050) 0÷9
IGRF+T96	Date and Time Dynamic pressure of the solar wind (nPa) D_{st}–index (nT) IMF B_y (nT) IMF B_z (nT)	1900–2050 0.1÷4 +50÷-500 ±30 ±20
IGRF+T01	Date and Time Dynamic pressure of the solar wind (nPa) D_{st}–index (nT) IMF B_y (nT)	1900–2050 0.1÷4 +50÷-500 ±30

	IMF B_z (nT) G_1 G_2	±20 0÷20 0÷20

• Next parameter is the height with which antiprotons are launched, (20 km).

• Further – geographic coordinates (grads with portions, latitudes from -180 to +180) and angles of launch.

• Next – range of rigidities which the program will scan, and step of scanning. When specifying a range of rigidities, it is necessary to ensure full coverage of the penumbra range, but at the same time it should not be too wide so as not to delay the calculation time.•

The next parameter is the allowed flight time. If the particle flies longer, we believe that it is trapped in the forbidden trajectory. For 3 seconds, the normal value does not delay the calculations too much and separates the trapped particles from the resolved particles well enough.

• In the end, there is still a check box to output the flight path to the file and the vector of magnetic field.

Output Data

1) During operation, the program displays one line (three numbers) for each rigidity on the screen and in the file Cutoff.dat: Rigidity, the flag of the path's resolution, the flight time. (Flag: 0 is forbidden trajectory, 1 permitted path in the screen; in the file it is in reverse). At the very end, the lower, upper, and effective cutoff rigidities are displayed.

... 0.490 0 15.000
0.491 0 12.000
0.492 1 15.045
0.493 2 180.000
0.494 1 18.166
0.495 1 15.202
0.496 0 11.000
0.497 0 7.310
0.498 0 14.000
...
1.998 0 0.727
1.999 0 0.735
2.000 0 0.743
Cutoff rigidities:
lower 0.465
upper 0.567
effective 0.499
Calculation time: 58.746

2) If *Output trace coordinates=1*, then for each rigidity the separate file is output, for example, *Trace00312.dat*: time of the particle flight, particle trajectory (the coordinates XYZ in the Earth radii) and the components of magnetic field in this point.

Time,s ***X_{GSM}, R_E*** ***Y*** ***Z*** ***Bx_{GSM}, nT*** ***By*** ***Bz***
…
0.00297 0.0456 -0.4232 1.0396 6776.1 17070.4 -34103.2
…

Total number of Trace-files is 1000 for each GV at the step of 0.001 GV – this huge number of files.

CALCULATING PARAMETERS.

• Calculation of the dynamic pressure of the solar wind.

Of the solar wind pressure is determined by the –velocity and density of solar wind plasma, and it is calculated by the formula: $\boldsymbol{P}=1.673\ 10^{-6}\times\boldsymbol{n}\times\boldsymbol{V}^2$, where $\boldsymbol{P}$ – pressure [nPa], $\boldsymbol{n}$ – density of particles [cm^{-3}], $\boldsymbol{V}$ – particle velosity [km/s].

• **Calculation of G_1 , G_2 and G_3.**

On the web page by Tsyganenko http://geo.phys.spbu.ru/~tsyganenko/modeling.html there is the information about T02 model. There are the references on two papers (Paper I and Paper II), where this model is described. In the second article you can find formulas for G1 and G2.

• **The contribution of the current** in the tail of the magnetosphere, which has a large effect on the inner and out magnetosphere, is taken into account in the linear approximation by introducing the parameter **G1.**

$$G_1 = V \cdot h(B_\perp) Sin^3 \frac{\theta}{2} . \quad (1)$$

Here are hourly mean parameters obtained by any way.

V – Solar wind velocity,

$B_\perp$ -Transverse component IMF, i.e. $B_\perp^2 = B_y^2 + B_z^2$ and is always positive. Coordinate system is GSM. Function $h(B_\perp) = B_{\perp/40}^2 / (1 + B_{\perp/40})$, $B_{\perp/40} = B_\perp / B_0$ for >B_0=40 nT.

θ – Angle between $B_\perp$ and Z axis (Tsyganenko calls it "clock angle of the IMF transverse component", and Akasofy - "polar angle of the IMF"). This angle ranges from 0 to 180 grad.

If take *V*=400 km/s, $B_\perp$=5 nT, θ=180 grad, then for G_1 it will be $G_1=400\times0.014\times Sin^3(180/2) \approx 6$

• **Shift of the current in the magnetosphere tail** is accounted in linear approach with introducing of the parameter G_2, determined as [http://geo.phys.spbu.ru/~tsyganenko/T01b.pdf]:

$$G_2 = aVB_S , \quad (1)$$

where V and B_S are velocity of the solar wind and south component of the interplanetary magnetic field IMF (B_S=| B_z | for B_z<0 and B_S=0 at B_z>0) averaged by 1- hourly interval. Constanta a=0.005 was introduced only as convenience for to keep parameter G_2 within the region $0 \le G_2 \le 10$, for usually observed values V and B_S. For example, for normal interplanetary conditions (V=400 km/s, B_y=0 and B_z=5 nT) parameter G_2 is equal 10. Indeed, $G_2=a400\times5=10$.

Equation (1) is only one possible way to realize the hypothesis that variations of the convective electric field associated with the southern component of the IMF should lead to a proportional shift of the current sheet in the tail of the magnetosphere.

• **Modification T02 for the Storm conditions. Model T02s.**

[https://pdfs.semanticscholar.org/665a/f74079ff64c532e836746fe4fe22995d2fc0.pdf]

Instead of a linear dependence of the ring current on the Dst index in model T02, a nonlinear term with the control variable G3 is introduced, based on a dependence on the solar wind energy.

$$G_3 = anVB_S , \quad (3)$$

Like G2, parameter G3 was defined as the average over the previous 1-hour interval geoeffective characteristic of the solar wind. It differs from G2 in that in addition to the solar wind speed V and the southern IMF component BS, G3 also includes the density of the solar wind particles n. The constant factor a = 0.0005 is introduced for convenience in order to store the parameter G3 within the range 0 ≤ G3 ≤ 10, for the normally observed values of n, V and BS. For example, for normal interplanetary conditions (n = 10 cm-3, V = 400 km / s, By = 0 and Bz = 5 nT), the parameter G3 is 10. Actually, $G_3=a\times10\times400\times5=10$.

The idea of replacing Dst by the function G3 follows from the fact that the rapid buildup of the ring current is the result of a strong amplified, directly convection from the tail, and it must also fall off quickly during the recovery phase. This type of behavior is easily reproduced by the leading variable G3, while the Dst index can remain fairly low for many hours after the main phase of the storm, due to the much more slowly decaying symmetrical current ring