Cutoff rigidity and particle trajectories online Calculator and Visualizer

Belov S.M., Zobnin G.I.,Yanke V.G.

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation,
IZMIRAN, Kaluzhskoe Hwy 4, Troitsk, Moscow, Russia

Over the years, many authors have developed unique software packages for calculating the rigidities of geomagnetic cutoff and the asymptotic directions of particle arrival. Such programs are used for large amounts of calculations and require some qualifications. However, it is often necessary to carry out single calculations with the same accuracy. For this purpose, calculator programs have been created on the basis of the developed software packages. One of such programs is described in this paper.

The aim of this work is to create a geomagnetic cutoff rigidity calculator with the most complete graphical representation of the results. To carry out trajectory calculations, we use software packages developed and debugged earlier.

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How did the study of the magnetospheric effects of cosmic rays begin and develop?

1927 J. Clay discovered the magnetospheric (latitudinal) effect of cosmic rays when moving along the route Amsterdam-Sydney.

1930 Stermer [Stormer, 1930] in the dipole approximation obtained an analytic expression for the trajectories of cosmic rays (though only for those lying in the equatorial plane) and introduced the concept of forbidden trajectories.

1933 Lemartre and Vallarta (1936), developing the Stermer theory and the concept of a forbidden cone, introduced the concept of an allowed cone when all trajectories are allowed, and the concept of a main cone, which includes an allowed cone and a penumbra (penumbra) region, i.e. many permitted and forbidden trajectories. The penumbra region was detected when calculating in a dipole field on analog computers.

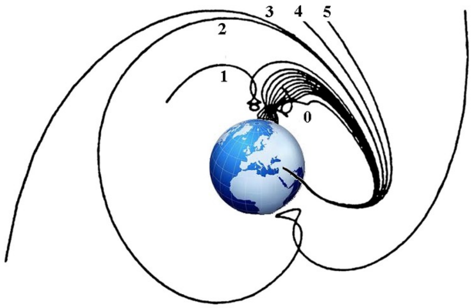
1956 Jory first performed numerical trajectory calculations of cosmic rays in the dipole field approximation in order to determine the equator of cosmic rays.

1962 McCracken [McCracken et al., 1962] performed numerical trajectory calculations of cosmic rays already in a real geomagnetic field represented by six spherical harmonics (integration step 0.01, without taking into account the primary spectrum of cosmic ray variations).

Extensive and most comprehensive studies of the magnetospheric effects of cosmic rays, their long-term changes, were carried out by M. Shea and D. Smart.

The global distributions of the vertical cutoff rigidities they calculated with a step of 5 ° × 15 ° in latitude and longitude and for all stations of the world network for the epochs from 1955 to 2000.

For the period 2000–2020 and the forecast up to 2050, such calculations were carried out and analyzed in a set of works [Gvozdevsky et al., 2016; 2017; 2018].



Examole of possible trajectories in geomagnetic field.

Method for calculating cutoff rigidities and geomagnetic field model

The generally accepted and most accurate way to determine the rigidity of geomagnetic cutoff is the trajectory calculation method, based on solving the equation of motion of charged particles in a geomagnetic field [McCraken].

The problem is solved numerically by the Runge-Kutta method of 4 orders of accuracy with an adaptive step.

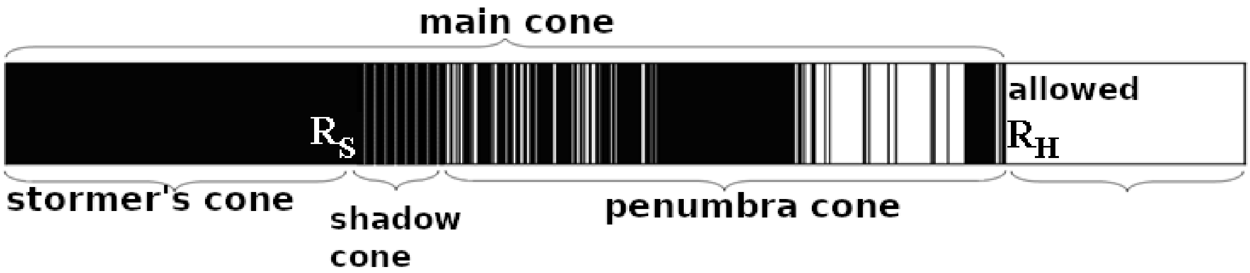
Particles start from a height of 20 km. Integration is completed in three cases:

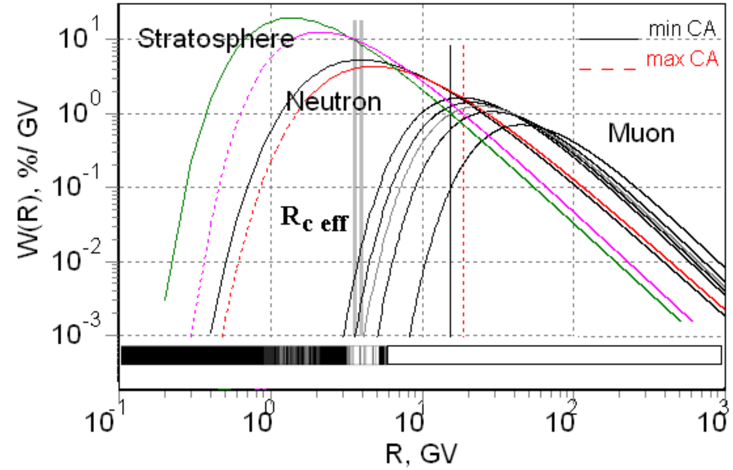
* or after a predetermined time (the particle is considered captured),
* or a particle crossed the surface of the magnetopause (went beyond the magnetosphere)
* or its radius vector turned out to be less than (RE + 20) km (RE means the radius of the Earth) (the particle returned to the atmosphere). In the second case, the trajectory is marked as permitted, otherwise – forbidden. As a result, a discrete function is formed taking the values "0" and "1" for all values of rigidity with a step of 0.1 - 0.001 GV.

The main magnetic field model IGRF is used, starting from 1900 to 2015 with a five-year interval. Given the secular variation of the magnetic field, the model is continued until 2020 [IGRF-12, 2015]. For forecasting purposes, the field was also continued until 2050 by linear extrapolation of all decomposition coefficients.

The field is represented by 13 spherical harmonics, but the predictive model is limited to 8 harmonics. For acconting external field Tsyganenko model is used.

Penumbra Area Accounting





Independent of the atmosphere. For the primary spectrum, for example, $J(R)=aR^{\gamma}$, the effective geomagnetic cutoff rigidity is determined from the equation:

$$\int J(R)dR = \int g(R)J(R)dR \;\cdot\cdot \Rightarrow \qquad R_{eff}^{\gamma+1} = R_H^{\gamma+1} - (\gamma+1)\int_{R_S}^{R_H} g(R)\cdot R^{\gamma}\, dR$$

For the primary spectrum, independent of energy (“white” or “flat”)

$$\boxed{R_{eff} = R_H - \int_{R_S}^{R_H} g(R)\, dR}$$

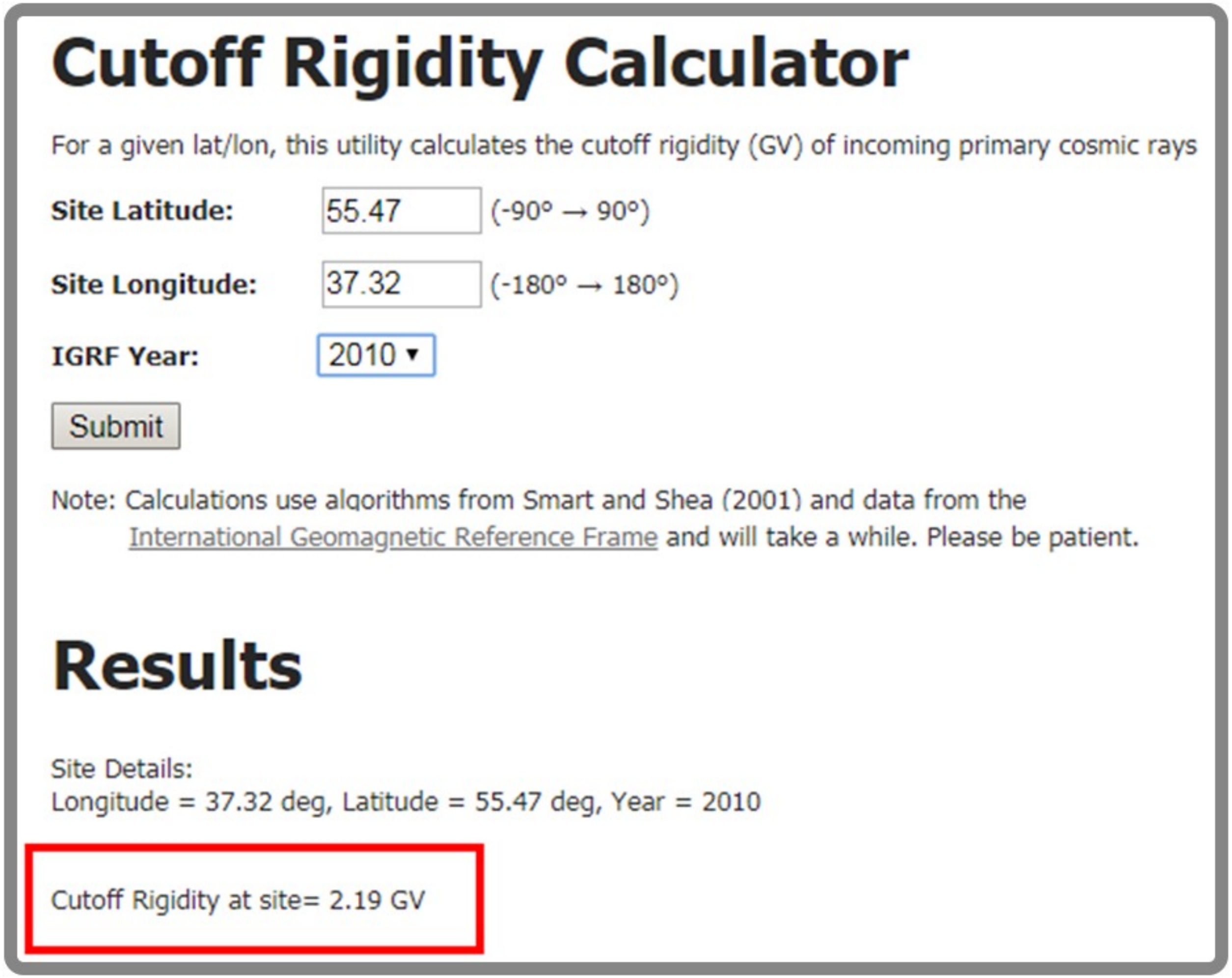
With atmosphere account. In this case for function of penumbra area $W(R)=cR^{\eta}$, effective geomagnetic cutoff rigidity is determined from the equation:

$$\int W(R,h)\cdot \delta J / J(R)\cdot dR = \int g(R)\cdot W(R,h)\cdot \delta J / J(R)\cdot dR$$

$$R_{eff}^{\gamma+\eta+1} = R_H^{\gamma+\eta+1} - (\gamma+\eta+1)\int_{R_S}^{R_H} g(R)\cdot R^{\eta+\gamma}\, dR$$

Cutoff rigidity Calculator

http://cosmos.hwr.arizona.edu/Util/rigidity.php



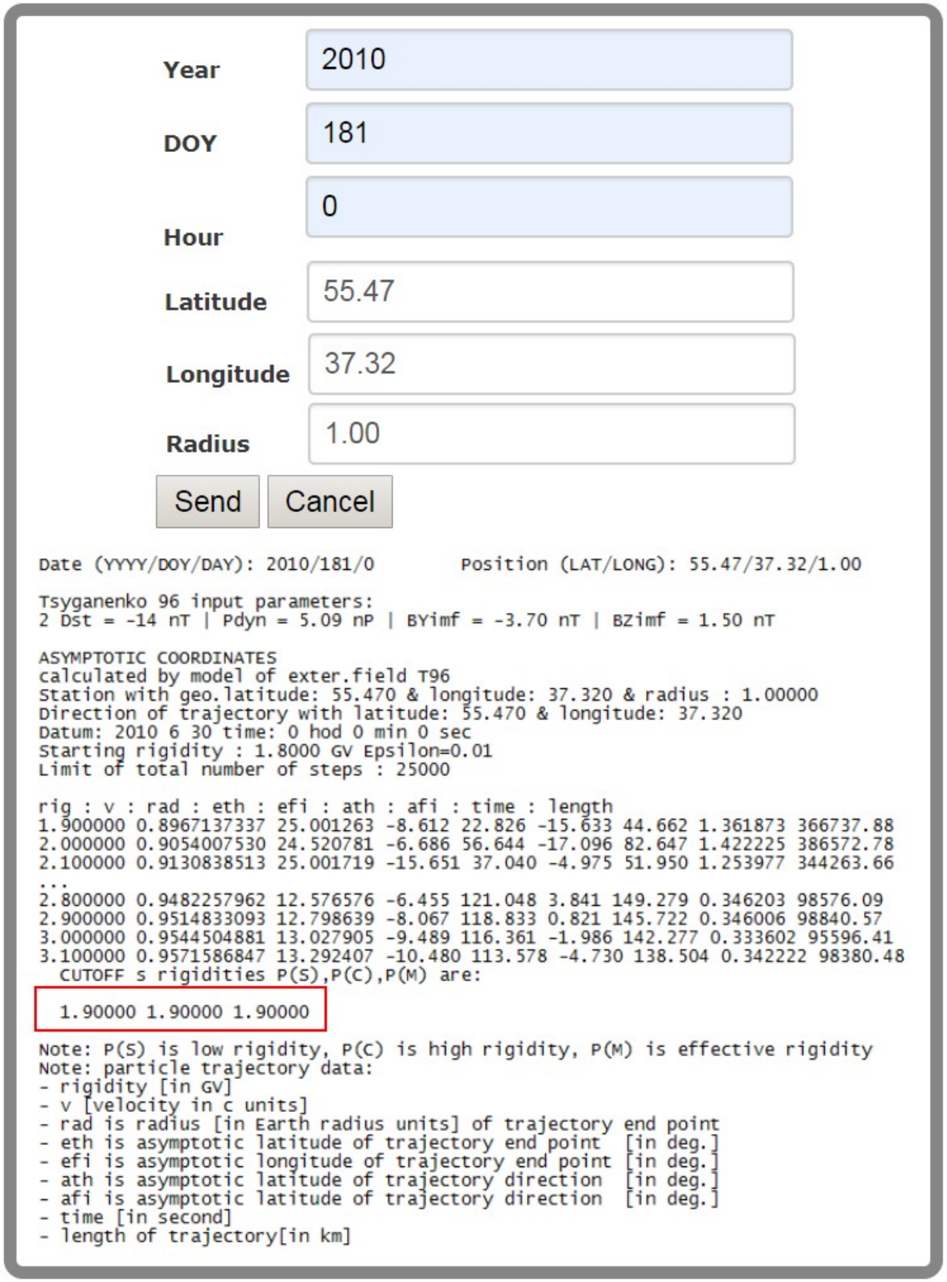
A simple online calculator project, based on the IGRF model, and only vertically falling particles are considered. The algorithm described in Smart and Shea [2001] is applied.

— The external magnetosphere is not taken into account;
only vertical particles are considered;
no penumbra or trajectories visualiztion

Zreda Marek. COSMOS project University of Arizona.

Web Calculators

http://www.geomagsphere.org


Year 2010
DOY 181
Hour 0
Latitude 55.47
Longitude 37.32
Radius 1.00
Send Cancel

```
Date (YYYY/DOY/DAY): 2010/181/0        Position (LAT/LONG): 55.47/37.32/1.00

Tsyganenko 96 input parameters:
2 Dst = -14 nT | Pdyn = 5.09 nP | BYimf = -3.70 nT | BZimf = 1.50 nT

ASYMPTOTIC COORDINATES
calculated by model of exter.field T96
Station with geo.latitude: 55.470 & longitude: 37.320 & radius : 1.00000
Direction of trajectory with latitude: 55.470 & longitude: 37.320
Datum: 2010 6 30 time: 0 hod 0 min 0 sec
Starting rigidity : 1.8000 GV Epsilon=0.01
Limit of total number of steps : 25000

rig : v : rad : eth : efi : ath : afi : time : length
1.900000 0.8967137337 25.001263 -8.612 22.826 -15.633 44.662 1.361873 366737.88
2.000000 0.9054007530 24.520781 -6.686 56.644 -17.096 82.647 1.422225 386572.78
2.100000 0.9130838513 25.001719 -15.651 37.040 -4.975 51.950 1.253977 344263.66
...
2.800000 0.9482257962 12.576576 -6.455 121.048 3.841 149.279 0.346203 98576.09
2.900000 0.9514833093 12.798639 -8.067 118.833 0.821 145.722 0.346006 98840.57
3.000000 0.9544504881 13.027905 -9.489 116.361 -1.986 142.277 0.333602 95596.41
3.100000 0.9571586847 13.292407 -10.480 113.578 -4.730 138.504 0.342222 98380.48
  CUTOFF s rigidities P(S),P(C),P(M) are:

  1.90000 1.90000 1.90000

Note: P(S) is low rigidity, P(C) is high rigidity, P(M) is effective rigidity
Note: particle trajectory data:
- rigidity [in GV]
- v [velocity in c units]
- rad is radius [in Earth radius units] of trajectory end point
- eth is asymptotic latitude of trajectory end point  [in deg.]
- efi is asymptotic longitude of trajectory end point [in deg.]
- ath is asymptotic latitude of trajectory direction  [in deg.]
- afi is asymptotic latitude of trajectory direction  [in deg.]
- time [in second]
- length of trajectory[in km]
```

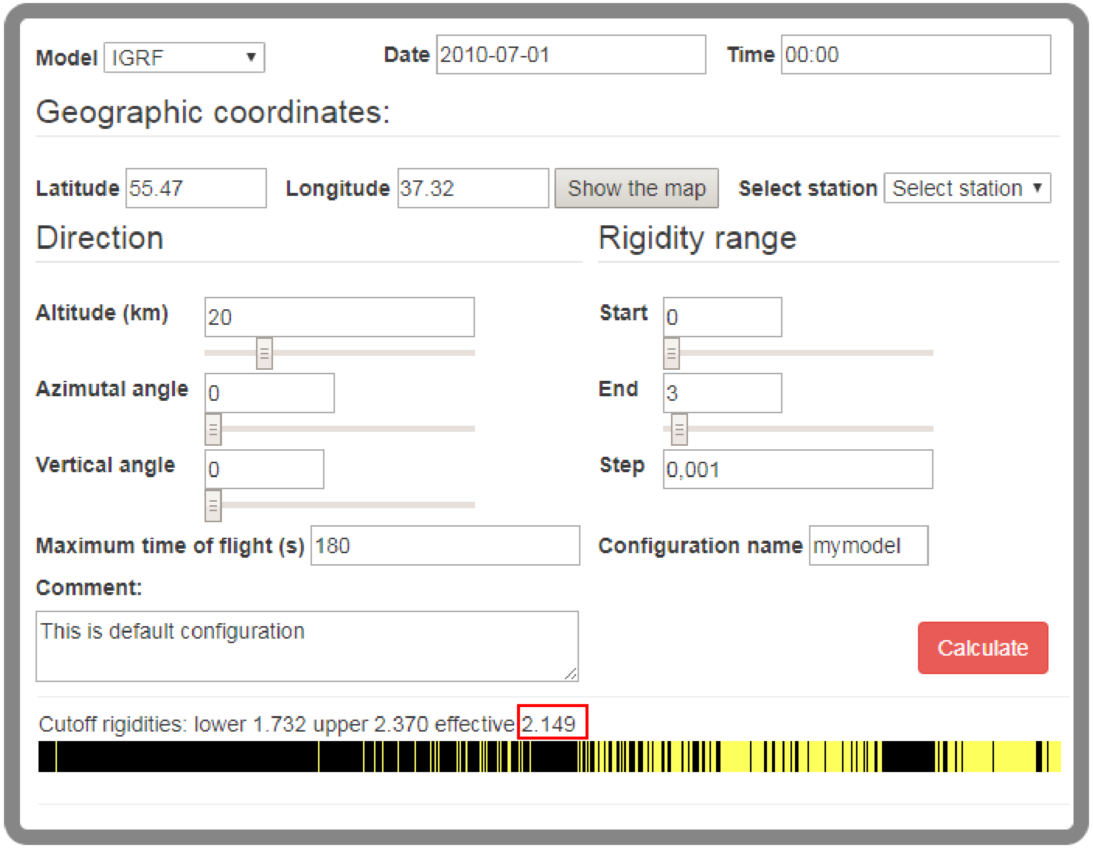
The online Internet project is based on more complex models of the magnetosphere (Tsyganenko T96 and Tsyganenko and Sitnova TS05) with automatic involvement of the input parameters of the interplanetary medium necessary for the magnetosphere model, which is a very useful option. The program also restores the trajectories of particles inside the magnetosphere.

— Only vertical particles are considered;
No penumbra or trajectories visualization

Boschini M.J., Della T.S., Gervasi M., Grandi D., Rancoita P. G., Bobik P., Kudela K.

Calculator "CutOff Rigidity"

http://crsv.izmiran.ru/cutoff



This program calculate the geomagnetic cut off rigidity for fixed date and fixed geographic point. It can calculate trajectories by one of model of magnetosphere: **dipole**, **IGRF**, Tsyganenko models **IGRF+T89**, **IGRF+T96**, **IGRF+T02**. In result the program gives lowest R_S, upper R_H ,effective R_c geomagnetic cut off rigidities and penumbra – set of allowed and forbidden rigidities between Rs and R_H with the step of 0.001 GV.

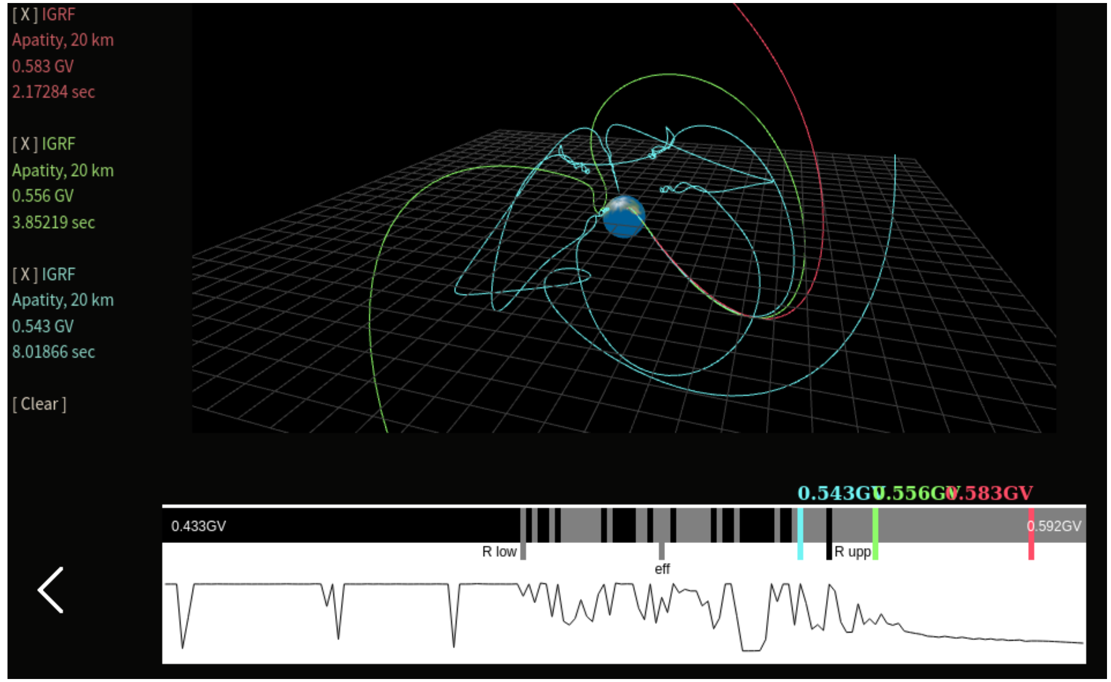
— No particle trajectories

Screenshot of the interface of calculator "CutOff Rigidity". Smirnov D.V., IZMIRAN

The CutOff-2050 visualizer program

https://tools.izmiran.ru/cutoff2050

Cutoff2050 program calculates geomagnetic cutoff rigidities with the ability to trace particle trajectories. It runs for certain geographic point and launch direction, for any date with period of 1900-2015 with extrapolation up to 2050. Supported magnetosphere models are: **dipole**, **IGRF**, Tsyganenko models: **IGRF + T89, [IGRF + T96, IGRF + T02]**.

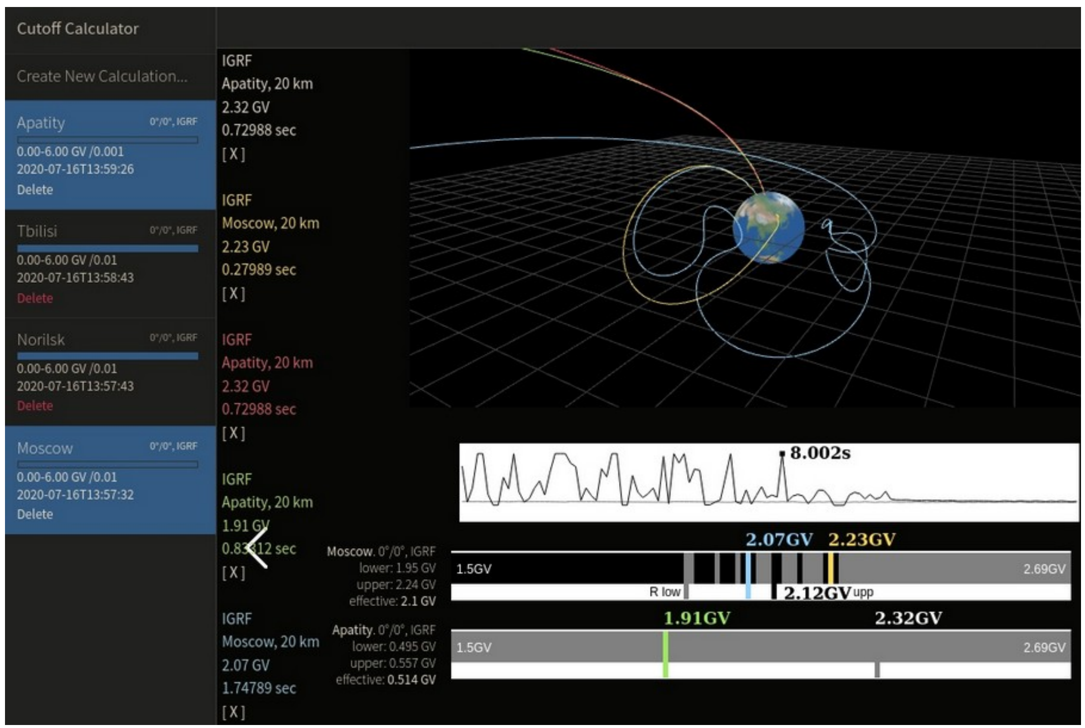


Screenshot of the interactive penumbra with 3 drawn trajectories

Software package developed and described by [Gvozdevsky et al., 2016-2018] is used for calculations. Program outputs lowest Rs, upper Rh, effective Rc geomagnetic cut off rigidities and penumbra - set of allowed and forbidden rigidities, with graph of particles flight time for each energy with given step. Application allows to request particle trajectory for any rigidity of that set by clicking on required energy on interactive penumbra. Trajectory will be visualized as shown on attached picture.

Storage and Comparison

The calculator program is hosted on tools.izmiran.ru/cutoff2050 as web application with some features that make it more convinient to use. User can register with their email to have their calculations stored on server. This allows to request calculations with different input parameters (such as model, time etc.) and then, when they are complete, compare the results (and/or traces). And this data will be saved on server so you can return to your work later.



Comparison between two different instances

List of users calculations

General information

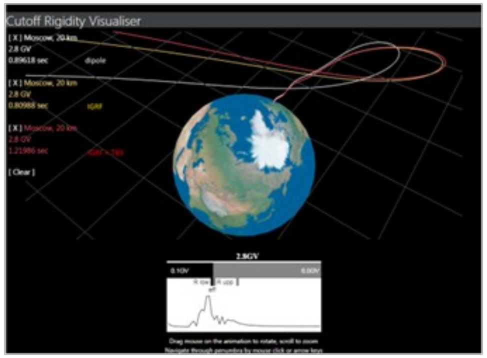
Our target was to make individual calculations visualization and comparison convinent, fast and easy to perform. This solution may be not the best for large scale calculations, higher models with precise step take too much time. But it can perfetcly fit for educational and presentational purposes.

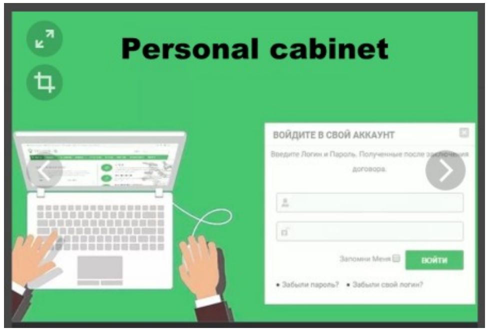
This product is still in active development so we apologize for possible technical issues that may appear in next few months. We plan to implement some other features like exporing or publishing data in different formats, or automated model settings. If you expirience any problems, please email to cutoff@izmiran.ru. Full user manual and service updates info will be accessible on the calculator website.

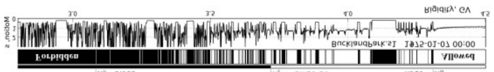
Model	Parametrs					Result			
						Cutoff rigidities, GV			Calcu lation time for , sec
	Kp	P_{sw}(nPa), Solar wind dynamic pressure	D_{st}-index (nT)	IMF B_y and IMF B_z, nT	G_1 and G_2	lower	upper	effective	
Dipole						2.337	2.737	2.498	6
IGRF						1.765	2.416	2.185	33
IGRF+T89	4					1.582	2.190	1.922	42
IGRF+T96		2	-50.0	0 and 5		1.518	2.156	1.906	1188
IGRF+T02		2	-50.0	0 and 5	6 and 10	1.649	2.234	1.947	3964

Approximate calculation time rating

Conclusion tools.izmiran.ru/cutoff2050







1) **Cutoff2050** program calculates geomagnetic cutoff rigidities with the ability to trace practicle trajectories. It runs for certain geographic point and launch direction, for date in 1900-2050 for this models: **dipole**, **IGRF**, Tsyganenko models: **IGRF + T89, [IGRF + T96, IGRF + T02]**.

2) Users are able to register on server to have their calculation results saved, which allows to visually compare different results.

3) All results are visualized: rigidities penumra, particle flight times and particle traces.

4) **Cutoff2050** calculator is effective and convinient tool for single geomagnetic cutoff rigidity calculations.

5) Program interface allows to perform comparative analysis of results and traces got for different models and parameters.

6) The problem has educational or presentational potential and can be used by students of corresponding profiles.

Thank you for your attention!

The Cutoff2050 online
rigidity calculator/visualizer:
https://tools.izmiran.ru/cutoff2050/
Or just: tools.izmiran.ru

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Motion of the charged particles in the geomagnetic field. Source equations

$$\boxed{\ddot{r}m = \frac{e}{c}[\dot{r}B]}$$

$$m = m_0\left(1 - v^2/c^2\right)^{-1/2}$$

$$B = B_E + B_M$$

$$\begin{cases} \dfrac{dv}{dt}m = \dfrac{e}{c}[vB] \\ \dfrac{dr}{dt} = v \end{cases}$$

It is reduced to a system of 6 equations. Relatively unknown

$$(r, v) = (x, y, z, v_x, v_y, v_z)$$

This work of magnetologists, our task is to solve the equation of motion of a charged particle in a magnetic field

Representation of the internal and external fields in the form of a Gaussian series.

The scalar potential of the magnetic field U

$$U(r,\theta,\phi) = \sum_{n=1}^{\infty}\sum_{m=0}^{n} R_E\left(\frac{R_E}{r}\right)^{n+1}\left(g_n^m \cos m\phi + h_n^m \sin m\varphi\right)P_n^m(\cos\phi) + \sum_{n=1}^{\infty}\sum_{m=0}^{n} R_E\left(\frac{r}{R_E}\right)^{n}\left(b_n^m \cos m\phi + c_n^m \sin m\varphi\right)P_n^m(\cos\phi)$$

The magnetic field B is determined through the potential gradient $B = -\nabla U$ or

$$X(r,\theta,\varphi) = -\frac{\partial U_2}{r\partial\theta} = -\sum_{n=1}^{\infty}\left(\frac{r_E}{r}\right)^{n+2}\sum_{m=0}^{n}\left(g_n^m \cos m\varphi + h_n^m \sin m\varphi\right)\frac{dP_n^m(\cos\theta)}{d\theta}$$

$$Y(r,\theta,\varphi) = -\frac{\partial U_2}{r\sin\theta\partial\varphi} = \sum_{n=1}^{\infty}\left(\frac{r_E}{r}\right)^{n+2}\sum_{m=0}^{n}\left(mg_n^m \sin m\varphi - mh_n^m \cos m\varphi\right)\frac{P_n^m(\cos\theta)}{\sin\theta},$$

$$Z(r,\theta,\varphi) = -\frac{\partial U_2}{\partial r} = \sum_{n=1}^{\infty}\left(\frac{r_E}{r}\right)^{n+2}(n+1)\sum_{m=0}^{n}\left(g_n^m \cos m\varphi + h_n^m \sin m\varphi\right)P_n^m(\cos\theta)$$

At n harmonics the number of coefficients g_n^m, h_n^m N=n(n+2)