

Oulu - Open-source Geomagnetosphere Propagation Tool (OTSO) User Manual

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Abstract

This manual outlines, in detail, all of the necessary information needed by a user to install and use the “Oulu - Open-source Geomagnetosphere Propagation Tool” (OTSO). The various different functions that OTSO provides are explained and an example utilising the tool is provided, showing what the inputs and outputs of OTSO are as well as how to utilise these outputs.

1 Introduction

OTSO is a tool that preforms the numerical integration of the equations of motion for a charged particle within the Earth’s magnetic field. This is done to simulate the trajectory of cosmic rays when they encounter the magnetosphere and to determine where said cosmic rays encounter the Earth’s surface. OTSO can do this for single cosmic rays to determine the trajectory or for many cosmic rays of varying rigidities in order to determine important parameters, such as cut-off rigidities and asymptotic cones. As such this tool is primarily designed to aid in cosmic ray research and the study of space weather events, namely ground level enhancements.

OTSO is written in two different programming languages, python and fortran. Python is used to enter the input parameters and run the program. The fortran section is responsible for the numerical integration and modelling the Earth’s magnetic field. This combination mixes together the user friendly nature of python with the older, more efficient, fortran which has access to many previous created open-access libraries designed for this field.

OTSO is designed to be open-source. The user of OTSO has free reign to edit the program how they see fit in order to achieve their goals. Additions to the base tool can be made by the community which will help develop the tool into a robust geomagnetic computation tool to aid the cosmic ray research community.

As new functions are added I will endeavour to update this manual and the supplied scripts to include information on the new applications as frequently as possible. I, however, implore those who made additional edits that are added to the base tool to provide their own documentation detailing the new features to the repository to simplify this process.

2 Installation

Please note that OTSO has been tested using the Windows, Linux, and Mac operating systems. Installation instructions are only provided for these operating systems.

In order to operate OTSO you will need to have Python installed on your computer alongside the necessary packages. It is recommended that you install the Anaconda program (<https://www.anaconda.com/>) as this includes all needed packages within it by default, OTSO is also designed around anaconda simplifying its use. Second, you will also need a working Fortran compiler in order to compile the Fortran section of OTSO. Please see <https://github.com/NLarsen15/OTSO> for in-depth details on how to install OTSO.

3 Functions

- Trajectory
- Asymptotic Cones
- Cutoff Rigidities
- Magnetic Field Line Tracing

There are four main functions within OTSO, these being the computation of: CR trajectories, cut-off rigidities, asymptotic cones, and magnetic field tracing. The cut-off and asymptotic cones are these functions are computed in conjunction with each other within the same routine, this saves time as the required computations for one of the results are also needed for the other. A separate function is provided specifically for the cut-off computation though allowing the user to select more cut-off computation variables. OTSO also provides a function for computing the cut-off rigidity for the entire globe, or region of the globe that the user specifies. A later addition to OTSO outside of it's original scope is magnetic field line tracing.

3.1 Trajectory

Invoking the trajectory function will make OTSO compute the path of a CR from a given point within the magnetosphere (typically 20km above the Earth's surface) using a numerical integration method selected by the user until one of three conditions are met. The conditions under which the computation stops are if the CR: encounters the model magnetopause, falls below an altitude of 20km, a certain amount of time passes in the CR's reference frame, or travels a distance of over 100 Earth radii (the minimum altitude, maximum time, and maximum distance travelled values can be edited within the code). The trajectory will be considered allowed if the first condition is met and forbidden if either of the latter three are met.

3.2 Cone

As mentioned prior the cone function conducts two of the key computations in tandem, these being the asymptotic cones computation and effective cut-off rigidity calculations. Both of these results require the modelling of cosmic ray trajectories over a range of rigidity values that is defined by the user.

3.2.1 Asymptotic Cone

In order to determine the asymptotic cone of a point on the Earth (typically a neutron monitor location is selected) OTSO will compute the asymptotic latitude (Λ) and longitude (Ψ) of a CR once the modelling has been completed for that rigidity value. The equations for these values in the spherical coordinate system are:

$$\tan \Lambda = \frac{-v_\theta \sin \theta + v_r \cos \theta}{\sqrt{v_\varphi^2 + (v_\theta \cos \theta + v_r \sin \theta)^2}} \quad (1)$$

$$\Psi = \varphi + \arctan \left(\frac{v_\varphi}{v_\theta \cos \theta + v_r \sin \theta} \right) \quad (2)$$

where θ is the co-latitude and φ is the longitude. These calculations are done regardless of where the cosmic ray is at the end of the modelling.

3.2.2 Effective Cut-off Rigidity

While OTSO repeats the same cosmic ray trajectories over the inputted range of rigidities it can encounter a region known as the penumbra. Within this region there is a mixture of allowed and forbidden cosmic ray trajectories, corresponding to being able to and not able to escape the magnetopause respectively. To make sense of the penumbral region an effective cut-off rigidity (R_c) is computed using the last accepted rigidity before the penumbra (R_U), the last accepted rigidity (R_L), and the size of the steps in rigidity over the range being tested (Δ). The equation for (R_c) is as follows:

$$R_c = R_U - \int_{R_U}^{R_L} \Delta R_{(allowed)} \quad (3)$$

This function can be used on a planetary scale and along a flight path. These are called using separate functions and are useful when wanting to compute cutoff rigidity maps under various conditions as well as computing exact cutoff values for aircraft and spacecraft during geomagnetic disturbances.

3.3 Magnetic Field Line Tracing

Invoking the trace function will make OTSO trace the path of the magnetic field lines for the magnetic configuration that you have selected. This has little application besides visualisation of the magnetosphere field lines during different levels of geomagnetic disturbance or novel non-standard magnetic field configurations, such as excursion events.

4 How to Use

OTSO scripts are standardised and all have similar inputs that the user must define for the computation. The user inputs parameters into python scripts that are located within the Parameters folder which is located within the Tool folder (these are named cone_params.py, trajectory_params.py, cutoff_params.py, planet_params.py, trace_params.py). Each of the scripts have very clear sections highlighted by comments in which the user enters input values for OTSO to use. The following list explains these sections separately and provides examples of the code within these sections.

4.1 Input

- The stations that you wish to test are entered into the list as strings, a separate .csv file containing many of the stations is included with OTSO to reduce the need to look up neutron monitor locations. Additional custom locations can be added to the list by entering the new locations into the Custom_Locations list (as seen below). Within this section, the start altitude, zenith, and azimuth for the modelled CRs are also entered.

```
List = ["Oulu"]
Alt = 20
Zenith = 0
Azimuth = 0
Custom_Locations = [{"Custom_Location_Name", Latitude, Longitude}]
```

- Within the cutoff and planet functions of OTSO you may compute either the vertical or apparent cutoff rigidity. The vertical cutoff rigidity will involve particle tracing backwards from a particle at a given location with a zenith angle of 0°. The apparent cutoff is computed in the same way suggested by [Bieber et al. \(1997\)](#) and is more computationally intensive, involving computing 9 separate cutoff rigidities, the vertical cutoff rigidity as well as 8 cutoff rigidities at a zenith angle of 30° for 45° azimuth angle intervals, and finding the average across the computed cutoffs. This option is not present for the cone and trajectory functions, which are designed for the user to input whatever zenith and azimuth angles they wish.

```
# 0 = Vertical cutoff rigidity, 1 = Apparent cutoff rigidity
CutoffComputation = 0
```

- The next section is dedicated to selecting the forbidden parameters for the simulation. The user may select the minimum altitude that the particle can go before being considered to have encountered the Earth, the maximum distance the particle can travel before being assumed trapped in the magnetosphere, and the maximum time that can pass in the CRs frame of reference before being considered trapped, under all three of these conditions the trajectory is taken to be forbidden. If the start altitude is set to a value lower than the minimum altitude by accident OTSO will print an error statement prompting the user to correct the mistake.

```
MinAlt = 20 #[km]
MaxDist = 100 #[Re]
MaxTime = 0 #[s]
```

- The solar wind conditions present at the time of the simulation are inputted in this section. Some other geomagnetic indices are included in this section, however, values are only required for these if later external magnetosphere models are used. It is useful to note that G1, G2, and G3 are special parameters needed for the use of the Tsyganenko 01 and 01S models (Tsyganenko, 2002a,b; Tsyganenko et al., 2003), a separate script is provided by OTSO to calculate these for the period of time desired. The W1 - W6 parameters are required for the use of Tsyganenko 04 model (Tsyganenko and Sitnov, 2005), the values for these parameters can be found online from https://geo.phys.spbu.ru/~tsyganenko/empirical-models/magnetic_field/ts05#yearly-input-parameter-files

```
Vx = -500.0 #[km/s]
Vy = 0.0 #[km/s]
Vz = 0.0 #[km/s]
By = 5 #[nT]
Bz = -5 #[nT]
Density = 1.0 #[cm^-2]
Dst = 0 #[nT]
G1 = 0
G2 = 0
G3 = 0
W1 = 0
W2 = 0
W3 = 0
W4 = 0
W5 = 0
W6 = 0
```

- IOPT is selected next and relates to the geomagnetic disturbance level (kp index). The IOPT value is typically entered as the kp index value + 1, unless the kp index is greater than or equal to 6 in which case IOPT is always set to 7. This is particularly important for earlier external magnetic field models, such as Tsyganenko 89 (Tsyganenko, 1989), it is not needed when using more modern models.

```
IOPT = 5
```

- This section allows the user to specify the type of cosmic ray to be modelled. OTSO provides the option to test cosmic rays that have heavier nuclei. In the base release elements up to beryllium can be tested, however, heavier elements can be added by users. The type of cosmic ray is selected via the AtomicNum variable. AntiCheck is a simple binary variable which will decide the charge of the cosmic ray, a value of one will make the cosmic ray its anti-particle counterpart and vice versa for zero (e.g. one = anti-proton, zero = proton).

```
AtomicNum = 1
AntiCheck = 1
```

- The date that the simulation is to take place is simply entered into the script by defining the year, month, day, hour, minute, and second.

```
Year = 2006
Month = 12
Day = 13
Hour = 3
```

```
Minute = 0
Second = 0
```

- Two magnetic models that are to be used within the computation are selected by entering integer values for the Internal and External variables. The internal model represents the Earth's dynamo and the external model accounts for the effect of magnetospheric currents. The list of currently available models is provided below. There are two options to enter your own Gauss coefficients into OTSO for modelling the internal magnetic field using the magnetic scalar potential model, which requires Gauss coefficients to define the spherical harmonic expansion of the magnetic scalar potential. To use your own Gauss coefficients replace the coefficients in the CustomGaussModule.mod file within the Library folder, re-compile OTSO, then set the internal variable in the parameter script to 3 or 4. The non-standard custom Gaussian option forces OTSO to perform computations in the geocentric (GEO) coordinate system, this is important for computations simulating when the Earth's magnetic field is non-standard, e.g. during an excursion event, as the typical geocentric solar magnetospheric system (GSM) coordinate system which OTSO uses relies on the geomagnetic dip of the Earth and Sun's location. During non-standard events the Earth's dipole is not a reliable way to determine a coordinate system, thus a geocentric coordinate system is recommended.

```
# Internal: 1 = IGRF, 2 = Dipole, 3 = Custom Gauss, 4 = Non-Standard Custom Gauss
# External: 0 = No External Field 1 = TSY87(short), 2 = TSY87(long), 3 = TSY89,
# 4 = TSY96, 5 = TSY01, 6 = TSY01(Storm), 7 = TSY04
Internal = 1
External = 3
```

- The numerical integration method used to resolve the equations of motion can be selected by the user. The four methods included in OTSO are the 4th order Runge-Kutta, Boris, Vay, and Higuera-Cary methods ([Costa Jr. and Leigui de Oliveira, 2019](#); [Ripperda et al., 2018](#)).

```
# 1 = 4th Order Runge-Kutta, 2 = Boris, 3 = Vay, 4 = Higuera-Cary
IntModel = 1
```

- The start, end, and step values for the rigidities are defined by the user. The program will go from the start value to the end value in the given step sizes to test cosmic rays of the various rigidities within the given range. When using the trajectory script only one rigidity value is given in this section instead of a range.

```
StartRigidity = 20
EndRigidity = 0
RigidityStep = 0.001
```

- For the cutoff and planet functions the user has the option to select whether a rigidity scan will be conducted. If the scan is chosen OTSO will first proceed through the given rigidity interval provided with a large rigidity step (0.5GV) to find approximate values for the upper and lower cutoff rigidities, it will then set the start and end rigidities as the upper and lower rigidities +1.0GV and -1.0GV respectively and begin the computation again using the inputted rigidity step. This can drastically reduce computation time by focusing on the area where the cutoff rigidity is estimated to be and reducing the overall number of trajectories needed to be computed but may sacrifice some overall accuracy. Selecting no scan will mean that OTSO will use the user-inputted parameters for the start rigidity, end rigidity, and rigidity step without conducting the scan.

```
# 0 = No Scan, 1 = Scan
RigidityScan = 1
```

- Thanks to the incorporation of the IRBEM library the positional outputs of the computation (OTSO provides the location of the cosmic ray at the end of the simulation for each particle) can be given in a multitude of coordinate systems. As a result, the user can select a desired coordinate system for the positional output values. Please refer to the IRBEM library website for further information on the coordinate systems that can be selected <https://prbem.github.io/IRBEM/>.

```
# GDZ, GEO, GSM, GSE, SM, GEI, MAG, SPH (GEO in spherical), RLL
CoordinateSystem = "GEO"
```

- The numerical integration used within OTSO to resolve the closed-form equations of motion that determine the trajectory of the cosmic rays uses a variable time step. The time step is able to grow or be reduced depending on error checks within the program, these detect if the speed of the cosmic ray has grown by an unacceptable amount. The time step has a maximum value determined by the user, preventing the time step from growing too large. This maximum value is determined to be a specific percentage of the time taken for the cosmic ray to complete one gyration within the magnetic field at its current location in the magnetic field. The user can determine the percentage used to determine this maximum time step. The smaller the percentage is set the slower the computation and the more accurate the result will be, however, testing has shown that a good compromise between the speed of the computation and result accuracy appears to be a percentage value of 0.15 - 0.4. Values higher than this range start to lead to inaccuracies in exchange for slight increases in the computation speed, see Figure 1.

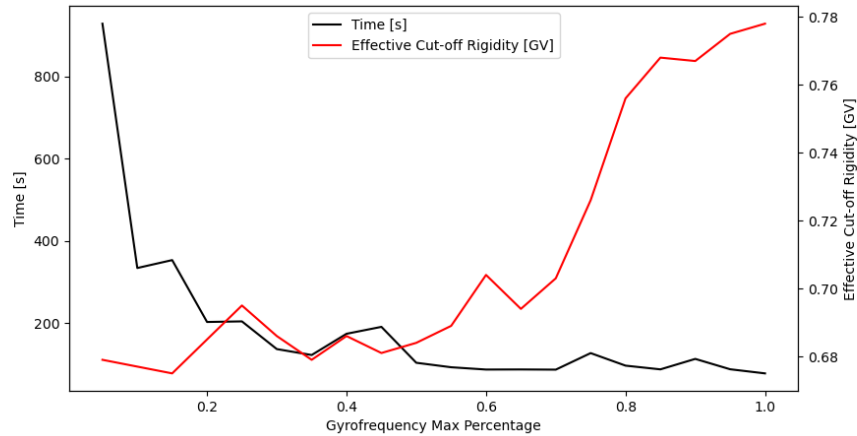


Figure 1: Comparison of computation time and effective cut-off rigidity against the max percentage of the gyrofrequency used within the said computation. The OTSO computation done was the same as is shown within the Example section.

```
MaxStepPercent = 15
```

- Most modern external magnetic field models have an associated magnetopause model included within them, enclosing the field model. However, some of the earlier models, namely Tsyganenko 87 and 89 (Tsyganenko, 1987, 1989), do not have a specific magnetopause model. In the case that the user wishes to use these earlier models a “de-facto” magnetopause boundary must be selected. OTSO currently provides several empirical models to choose from, with the possibility of more being added later. It is useful to note that if using an external field model with an explicitly defined magnetopause the users choice in this section will be overwritten in favour of the magnetopause model used in the field model selected.

```
# 0 = 25Re Sphere, 1 = Aberrated Formisano, 2 = Sibeck, 3 = Kobel
Magnetopause = 3
```

- OTSO can produce many files for computations containing many locations. To organise these files the user can input a string that will be added to the name of the produced files as well as provide a name for a folder in which the created files will be stored. Within the created folder a README file is produced that will provide all the information about the computation performed so it is easy to know what the input values were for the files within the folder.

```
FolderName = "Example Folder"
FileName = "_Example_File"
```

- The final section deals with multi-core processing. The user can enter the number of cores they wish to split the computations over which reduces the time taken for OTSO to complete the computation for each given location. OTSO will also read the number of cores on the user's computer and prevent too many cores from being used as this will cause the program to either fail or take an irrationally long time to complete.

```
CoreNum = 1
```

4.2 Bulk Computations

OTSO offers the option to perform bulk computations, allowing for repeat execution of functions over a list of inputted variables. The option for bulk computations is available for the Cone, Cutoff, and Planet functions. Inputs for these are done within their respective params files, which shares many input variables as the singular OTSO functions, and bulk_params csv files. You may iterate over a list of space weather parameters or Gaussian coefficients. You must choose over with you wish to perform the bulk computations.

```
# 0 = (Space weather) Bulk_Space_Weather_Params.csv used, 1 = (Gaussian)
   Bulk_Gaussian_Coefficients.csv used
Bulkcomp = 0
```

4.2.1 Bulk Space Weather

Much like the inputs outlined above the space weather variables need to be entered, except this time within a given csv file within the parameters folder. See Figure 2 for an example of the input csv for this. It is important to note that the x component of solar wind speed should be entered as a negative value using (i.e. GEO coordinate system) and the time option should match the layout (dd:MM:yyyy HH:mm:ss).

```
Time,Kp,Vx,Vy,Vz,By,Bz,Density,Pdyn,Dst,G1,G2,G3,W1,W2,W3,W4,W5,W6
01/04/2024 12:00:00,3,-500,0,0,5,5,1,0,0,0,0,0,0,0,0,0,0
02/01/2024 12:00:00,5,-1000,0,0,13,-12,3,0,-240,0,0,0,0,0,0,0,0
```

Figure 2: csv input file for bulk computations over a list of space weather parameters with placeholder values.

4.3 Bulk Gaussian Coefficients

If this option is selected the Gaussian coefficients for the spherical harmonic expansion of the magnetic scalar potential will be replaced with inputted values. Note that if you select this option it will overwrite any selection of internal magnetic field model to use the custom Gaussian magnetic field model outlined above. See Figure 3 for an example of the input csv for this.

```

g/h,n,m,Example 1,Example 2,Example 3
g,0,0,0,0,0
g,1,0,-22532.73625,-1452.054996,-26281.16305
g,1,1,1562.821228,-312.6254388,-1683.806897
g,2,0,-341.2165174,-606.0507724,-2700.38847
g,2,1,726.9655903,2446.93886,-336.5763711
g,2,2,-808.4174915,133.0761494,3095.650072
g,3,0,-231.3196614,1291.983819,-191.1868543
g,3,1,254.0982774,3120.296134,-222.8210143
g,3,2,568.1473687,-579.8233552,-663.7042422
g,3,3,-110.2994678,450.6319271,-93.09060348
g,4,0,238.3653318,-46.56640308,581.8501549
g,4,1,-154.6914516,28.83996855,37.85426907
g,4,2,257.7518465,43.22806388,512.6891084
g,4,3,-396.5762653,678.3233029,250.1465925

```

Figure 3: csv input file for bulk computations over a list of Gaussian Coefficients with placeholder values.

4.4 Flight Inputs

Similar to the inputs for bulk space weather variable computations when using the flight function you enter in space weather and time variables in the Flight.Params.csv file alongside the latitude, longitude, and altitude at the given times. See Figure 4 for an example of flight input.

```

Time,altitude,latitude,longitude,Kp,Vx,Vy,Vz,Bz,Density,Pdyn,Dst,G1,G2,G3,W1,W2,W3,W4,W5,W6
29/10/2003 11:00:00,300,30,30,8,-500,0,0,5,5,1,0,-20,0,0,0,0,0,0,0,0
29/10/2003 12:00:00,400,60,60,8,-500,0,0,5,5,1,0,-20,0,0,0,0,0,0,0,0
29/10/2003 13:00:00,500,90,90,8,-500,0,0,5,5,1,0,-20,0,0,0,0,0,0,0,0
30/10/2003 20:00:00,500,90,90,8,-500,0,0,5,5,1,0,-20,0,0,0,0,0,0,0,0
15/11/2003 13:00:00,500,90,90,8,-500,0,0,5,5,1,0,-20,0,0,0,0,0,0,0,0

```

Figure 4: csv input file for a flight computation.

4.5 Output

<pre> Rigidity(GV),Filter,Latitude,Longitude,X,Y,Z 20.0000,1,41.0066,60.9246,6.27301,10.0045,11.3669 19.9990,1,41.0056,60.9245,6.27195,10.0025,11.3645 19.9980,1,41.0047,60.9243,6.27090,10.0005,11.3622 19.9970,1,41.0037,60.9242,6.26985,9.99846,11.3598 19.9960,1,41.0028,60.9240,6.26879,9.99646,11.3574 19.9950,1,41.0018,60.9239,6.26774,9.99446,11.3550 19.9940,1,41.0008,60.9238,6.26668,9.99246,11.3526 19.9930,1,40.9999,60.9236,6.26563,9.99046,11.3502 19.9920,1,40.9989,60.9235,6.26452,9.98836,11.3477 19.9910,1,40.9980,60.9233,6.26338,9.98621,11.3452 19.9900,1,40.9970,60.9232,6.26225,9.98406,11.3426 </pre>	<pre> 0.110000E-1,-1,27.5107,40.1165,0.283900,0.491600,-0.825604 0.100000E-1,-1,48.0840,46.0148,0.284328,0.491168,-0.825710 0.900000E-2,-1,28.2255,24.9671,0.284816,0.490650,-0.825850 0.800000E-2,-1,27.4454,39.7879,0.285347,0.490174,-0.825951 0.700000E-2,-1,42.3870,16.7790,0.285866,0.489673,-0.826069 0.600000E-2,-1,50.0045,23.7422,0.286488,0.489147,-0.826161 0.500000E-2,-1,42.8513,49.2183,0.287241,0.488571,-0.826243 0.400000E-2,-1,26.1784,33.1889,0.288158,0.487898,-0.826322 0.300000E-2,-1,34.5534,17.8472,0.289432,0.487087,-0.826353 0.200000E-2,-1,42.3993,16.5798,0.291646,0.485892,-0.826279 Ru:0.789000, Rc:0.679000, Rl:0.508000 </pre>
(a) Top of file	(b) Bottom of file

Figure 5: The output file for the cone function has seven columns, shown clearly on the left. Rigidity, Filter (1 = allowed, 0 and -1 = forbidden. 0 = exceeded travel distance without escaping, -1 = encountered the Earth), Latitude (asymptotic), Longitude (asymptotic), and X, Y, and Z (location the computation ended in the user inputted coordinate system). The bottom of the file on the right shows that underneath all of the rigidity computations the upper, lower, and effective cut-off rigidities (Ru, Rl, and Rc respectively) are given.

5 Examples

OTSO provides some basic plotting scripts that can be easily edited to plot the outputs created by the user. These scripts are contained within the "Plotting Tools" folder and are shown by files with names ending in 'plot'. These files are 3Dplot (plots the 3D trajectory of a particle, see Figure 8), ConePlot (plots the asymptotic cone on a 2D map of the Earth, see Figure 7), CutoffPlot (plots the allowed and forbidden trajectories to show the penumbral region, see Figure 6), PlanetPlot (plots a contour plot for the cut-off over the globe), and 3DFieldLinePlot (plots the traced field lines in a 3D map. it will access all csv files in it's directory so either edit to acces required files or move to a folder contain all the files of traced field lines, see Figure 9).

5.1 Cone

Values used within the example code of the Input section were used to calculate the cut-off rigidity and asymptotic cone for the Oulu neutron monitor. The results of this are shown within Figures 6 and 7.

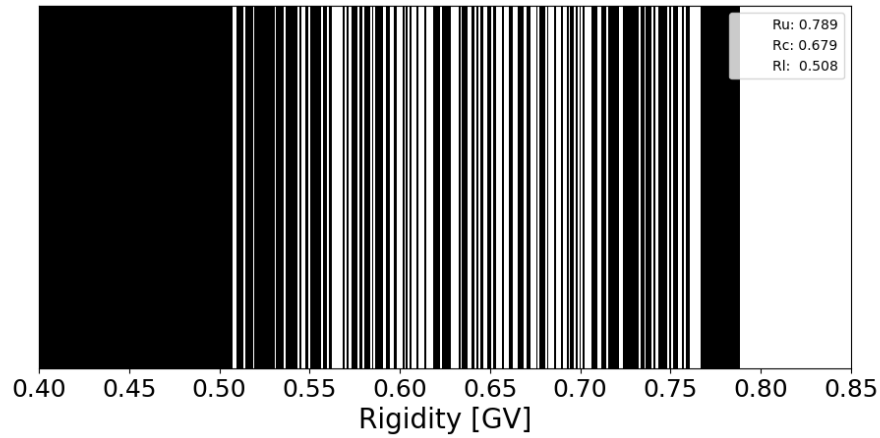


Figure 6: Allowed (white) and forbidden (black) rigidities for a CR arriving at the Oulu neutron monitor station using the input values given in the Input section. The upper, lower, and effective rigidities are shown as R_u , R_l , and R_c respectively.

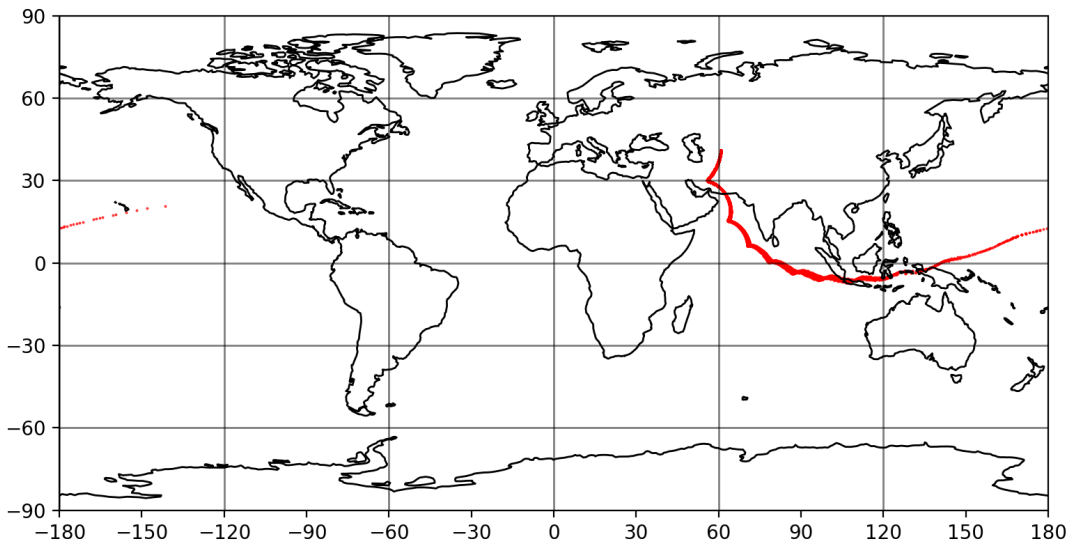


Figure 7: Asymptotic cone for the Oulu neutron monitor station using the input values given in the Input section.

5.2 Trajectory

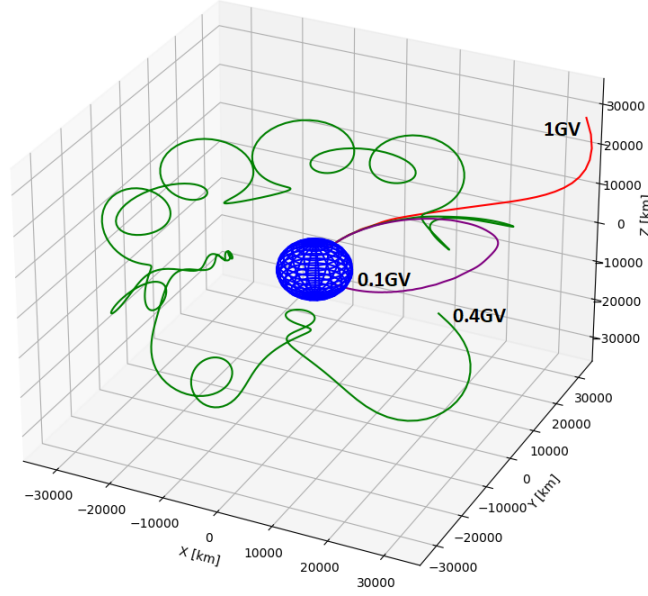


Figure 8: Trajectories of three CRs with differing rigidities originating from the Oulu neutron monitor station, the same geomagnetospheric conditions as seen in the Input section were used. The three CRs were modelled with rigidities of 1GV, 0.4GV, and 0.1GV.

5.3 Field Line Tracing

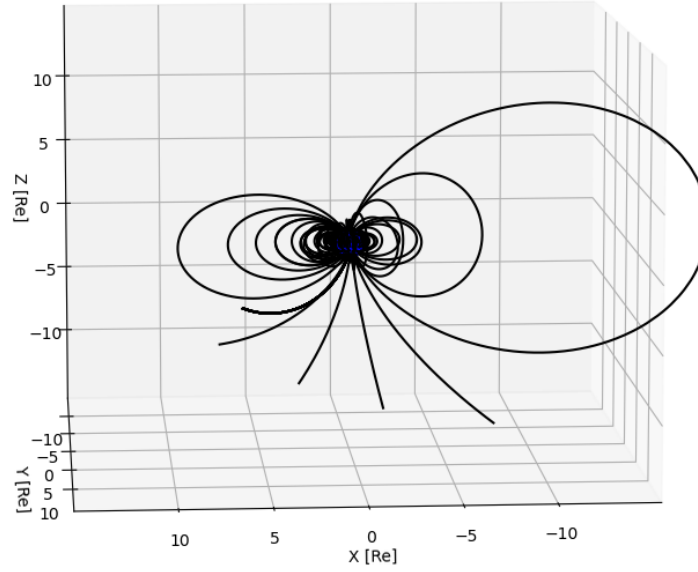


Figure 9: Traced magnetic field lines showing the magnetosphere structure on a standard quiet day, $k_p = 1$. No external field is applied to this model.

6 Editing

If the user decides to make changes within the fortran section of the code the tool must be recompiled to apply the new changes. The fortran section of the code uses pointers for key parts of the computation that may want to be edited, this prevents IF ELSE bottlenecks in the code. These pointers apply to the magnetic field models and magnetopause models. If the user wishes to add a model to these sections it is quite straightforward to add new models to these sections, due to the modular design. As long as the new model inputs are the same as prior models one need only copy and paste a pointer assigning function and change the function name. Unfortunately, a limitation of fortran is that when using pointers the inputs must be the same for all the models, to combat this the user should alter the module files to include any extra parameters needed so that the model can access any additional values needed that aren't provided in the function input. An example of this is the solar wind module file that contains many variables that apply to specific magnetic field models.

References

- Bieber, J.W., Clem, J., Evenson, P., 1997. Efficient Computation of Apparent Cutoffs, in: International Cosmic Ray Conference, p. 389.
- Costa Jr., R., Leigui de Oliveira, M., 2019. Analysis of the performance of numerical integration methods for the tracking of ultra-high energy cosmic rays. *Journal of Computational Physics* 392, 432–443. URL: <https://www.sciencedirect.com/science/article/pii/S0021999119303110>, doi:<https://doi.org/10.1016/j.jcp.2019.04.058>.
- Ripperda, B., Bacchini, F., Teunissen, J., Xia, C., Porth, O., Sironi, L., Lapenta, G., Keppens, R., 2018. A comprehensive comparison of relativistic particle integrators. *The Astrophysical Journal Supplement Series* 235, 21. URL: <https://dx.doi.org/10.3847/1538-4365/aab114>, doi:[10.3847/1538-4365/aab114](https://doi.org/10.3847/1538-4365/aab114).
- Tsyganenko, N., 1987. Global quantitative models of the geomagnetic field in the cislunar magnetosphere for different disturbance levels. *Planetary and Space Science* 35, 1347–1358. URL: <https://www.sciencedirect.com/science/article/pii/0032063387900468>, doi:[https://doi.org/10.1016/0032-0633\(87\)90046-8](https://doi.org/10.1016/0032-0633(87)90046-8).
- Tsyganenko, N., 1989. A magnetospheric magnetic field model with a warped tail current sheet. *Planetary and Space Science* 37, 5–20. URL: <https://www.sciencedirect.com/science/article/pii/0032063389900664>, doi:[https://doi.org/10.1016/0032-0633\(89\)90066-4](https://doi.org/10.1016/0032-0633(89)90066-4).
- Tsyganenko, N., Singer, H., Kasper, J., 2003. Storm-time distortion of the inner magnetosphere: How severe can it get. *Journal of Geophysical Research* 108. doi:[10.1029/2002JA009808](https://doi.org/10.1029/2002JA009808).
- Tsyganenko, N.A., 2002a. A model of the near magnetosphere with a dawn-dusk asymmetry 1. mathematical structure. *Journal of Geophysical Research: Space Physics* 107, SMP 12–1–SMP 12–15. URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001JA000219>, doi:<https://doi.org/10.1029/2001JA000219>, arXiv:<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2001JA000219>.
- Tsyganenko, N.A., 2002b. A model of the near magnetosphere with a dawn-dusk asymmetry 2. parameterization and fitting to observations. *Journal of Geophysical Research: Space Physics* 107, SMP 10–1–SMP 10–17. URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001JA000220>, doi:<https://doi.org/10.1029/2001JA000220>, arXiv:<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2001JA000220>.
- Tsyganenko, N.A., Sitnov, M.I., 2005. Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms. *Journal of Geophysical Research: Space Physics* 110. URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004JA010798>, doi:<https://doi.org/10.1029/2004JA010798>.