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Development of a Modern Open Source Magnetospheric Computation Tool

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Accurate modelling of cosmic-ray trajectories within the Earth's magnetosphere is important when analysing the impact of cosmic-rays at Earth as well studying their sources, especially cosmic-rays that have a solar origin. In order to compute these trajectories accurately a sophisticated computational tool is required to perform numerical integration over the particle's motion whilst also providing a realistic model of the Earth's magnetosphere. A new tool named "Oulu - Open-source geomagneToSphere prOpagation tool" (OTSO) is presented here to fulfil this role. A comparison between OTSO and an older, out of date, but widely used verified tool, namely MAGNETOCOSMICS, is conducted for various key geomagnetospheric phenomena. A good agreement is found between the two tools supporting the usefulness of OTSO as a more modern alternative tool which can be developed further by the community due to its open-source nature.

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1. Introduction

The Earth is under a constant barrage of high-energy particles, namely cosmic-rays (CRs), that can have solar, galactic, or extra-galactic origins. Solar eruptions, such as coronal mass ejections and solar flares, and their aftermaths create solar CRs which can then arrive at Earth [1]; whilst extra-solar CRs are currently believed to be created by supernova remnants [2]. Extra-solar CRs arrive at the Earth continuously in an isotropic fashion, however solar CRs are generally anistropic due to the local nature of their solar origin.

A CR arriving at Earth will first encounter the magnetosphere. As CRs are charged particles they are influenced by the Lorentz force while moving within the Earth's magnetic field and their trajectory is changed. CRs with an inadequate rigidity, a value that describes how impacted a charged particle is by a magnetic field which is typically used instead of CR energy as it is independent of the CR charge and species [3], are deflected away from the Earth. CRs with a high enough rigidity are able to penetrate the magnetosphere and encounter the Earth's atmosphere. CRs arriving at the atmosphere collide with the atmospheric constituents and create extensive air showers, producing more secondary particles as the shower travels towards the surface until a threshold energy is reached. If the initial CR has enough energy the secondary particles are able to reach the surface where they can be detected by instruments such as neutron monitors (NM). When NMs detect a significant increase in solar CR flux it is labelled a ground level enhancement (GLE), a rare event occurring only a few times a solar cycle [4].

NMs are static, being fixed to a single location, and count the number of precipitating particles arriving at its specific location making them especially useful in studying CRs with a solar origin, as they can reveal anisotropy [5, 6]. In order to study the data from NMs and unravel the anisotropy one must know the propagation of CRs that arrive at the location of the NM. This is no easy task as CRs can have incredibly intricate trajectories as they navigate the complex structure of the magnetosphere, this can be seen in Figure 1.

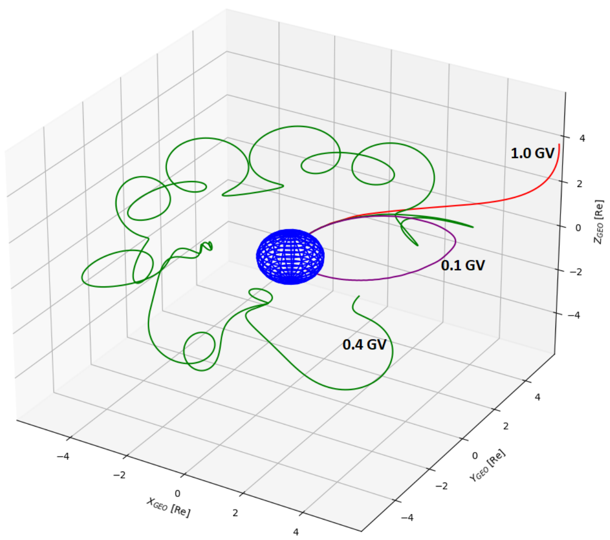

Figure 1: Plot of the trajectories of 3 CRs originating from the Oulu NM station (65.05°N, 25.47°E) with different rigidity values. Trajectories were computed by OTSO.

As a result, CRs arriving at a station don't necessarily arrive from directly above the NM and each NM has its own unique asymptotic direction of acceptance for CRs, dictating what region CRs need to arrive at the magnetosphere to be detected by said NM [7]. In addition to the asymptotic direction of acceptance, every location has an effective cut-off rigidity, that is the minimum rigidity particles need in order to be able to penetrate the magnetosphere and reach the surface at the specified location. The complex nature of CR propagation means that there isn't a clear rigidity value at which CRs are able to arrive at a location and a penumbra is seen, a collection off "allowed" and "forbidden" trajectories around the cut-off value, to address this issue an effective cut-off rigidity is calculated to obtain a useful quantitative cut-off value from the penumbra.

As previously mentioned, the trajectories of CRs can be very complex and predicting where a CR will arrive at Earth based on its arrival at the magnetosphere is effectively impossible. There is also no known closed form solution for the equations of motion for a charged particle in the Earth's magnetosphere. The only way that to address this issue currently is to preform numerical integration to determine the CR's trajectory backwards from the Earth's surface, typically the start altitude is set to 20km as this is the altitude cascades typically begin [8], to the CRs point of entry into the magnetosphere [9]. From these computations CR trajectories, effective cut-off rigidities, and asymptotic cones can be determined.

In order to perform the computationally intensive task of numerical integration for these CR trajectories computer programs are needed. One widely used verified tool is known as MAGNETOCOSMICS [10], however, this tool is no longer supported and is difficult to obtain. A new tool is therefore highly requested by the wider CR research community to replace this ageing program. Here, we present a new open-source and easily accessible tool designed to perform these difficult computations named the "Oulu - Open-source geomagneToSphere prOpagation tool" (OTSO) and provide direct comparisons to the older MAGNETOCOSMICS tool.

2. OTSO Design

OTSO is an open-source tool that is free to download and edit. The tool has been designed within the fortran and python programming languages. This takes advantage of the simplicity of the python language as well as the computational speed and previously made libraries of fortran, one such library being the IRBEM library. The main goal of OTSO is to act as a foundation for a community driven tool that can be developed beyond its current capabilities to accommodate more research needs.

To model the trajectories of CRs within the magnetosphere there must first be accurate models of the magnetosphere itself, with the most accurate models being a combination of internal and external magnetic field models, these fields being produced by the Earth's dynamo and magnetospheric currents respectively. OTSO provides a choice of two internal models, IGRF13 and dipole [11, 12], and five external models known as Tsyganenko models, TSY87, TSY89, TSY96, TSY01, and TSY01S [13–19]. This work only used a combination of the IGRF13 and TSY89 models as they allow for simple and fast computations whilst also providing a high level of precision.

The 4^{th} order Runge-Kutta method is used to preform the numerical integration, providing a good balance between operational speed and accuracy. Once OTSO is provided input values, such as the CR's rigidity value and geomagnetic condition parameters (e.g. solar wind speed and interplanetary magnetic field strength), the trajectory will be computed until one of three conditions are met. The particle is considered "allowed" if the CR reaches a model magnetopause or "forbidden" if the CR returns below its start altitude or travels more than 100Re without meeting either of the other prior conditions. When not computing a single trajectory OTSO will proceed through a range of rigidities, calculating the asymptotic latitude (Λ) and longitude (Ψ) for each CR once a condition to stop the integration is met. This is done using equations 1 and 2

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

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

where v is the velocity, θ is the co-latitude and φ is the longitude. These calculations are done regardless of the CR's final location at the end of the integration.

Afterwards effective cut-off rigidity is then computed using equation 3

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

where R_c is the effective cut-off rigidity, R_U is the upper cut-off rigidity (the last accepted rigidity before the penumbra), R_L is the lower cut-off rigidity (the last allowed rigidity), and Δ is the size of the steps in rigidity over the range being tested.

3. Examples and Comparison

To verify this new tool OTSO and MAGNETOCOSMICS were both applied to investigate GLE #70 which occurred on 13 December 2006 as a result of a X3.4/4 B class solar flare. Using the geomagnetospheric conditions of this event, both tools were used to compute the effective vertical cut-off rigidity and asymptotic cones for 12 selected NM stations, after which a comparison was done. The results of the effective vertical cut-off computations can be seen in table 1, in which it can be seen that there is a good agreement between the tools.

The asymptotic cones for 3 of the stations used (Apatity, Calgary, and Kingston) can be seen in figure 2. One can see that the cones are very similar, especially in the higher rigidities. Variations seen in the shape of the cones are a result of the different integration methods used by the tools, the integration method's precision becomes even more salient at lower rigidity values when trajectories become more complex.

In addition to the direct comparison of NM station characteristics, the global map of effective vertical cut-off rigidities was also computed at a $1^\circ \times 1^\circ$ resolution. The absolute difference between the global maps produced by OTSO and MAGNETOCOSMICS can be seen in figure 3. It is seen within this plot that in the polar and equatorial regions the difference is very small, with larger differences seen in the mid-latitude ranges. The penumbra in mid-latitude regions are generally more intricate as a result of more complex CR trajectories, the differences are therefore emphasised

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	Vertical Cutoff Rigidity [GV]	
Station	MAGNETOCOSMICS	OTSO
Apatity	0.516	0.527
Calgary	0.92	0.924
Cape Schmidt	0.368	0.377
Fort Smith	0.158	0.167
Kerguelen	0.933	0.947
Kingston	1.725	1.738
Lomnický štít	3.633	3.644
McMurdo	0.000	0.000
Oulu	0.622	0.647
Rome	6.091	6.089
Terre Adelie	0.000	0.000
Tixie Bay	0.416	0.441

Table 1: Effective vertical cut-off rigidities for 12 selected NM stations computed using OTSO and MAGNETOCOSMICS.

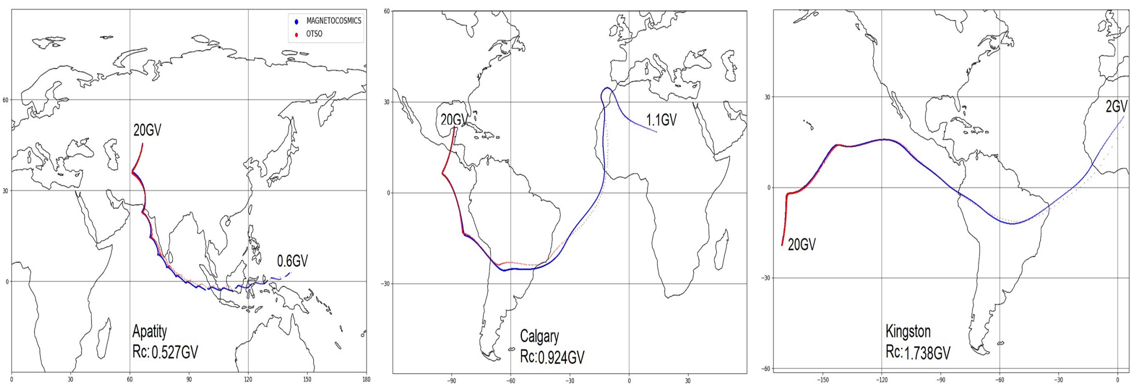

Figure 2: Computed asymptotic cones over selected rigidity ranges for three selected NMs during GLE #70 using both OTSO and MAGNETOCOSMICS, as denoted in the legend. The NMs, as well as their OTSO computed Rc value, shown are: Apatity (left), Calgary (middle), and Kingston (right).

in these areas as a result of the two tools having different integration methods. There are also noticeable regions of higher difference between the tools, such as in the South Pacific Ocean.

This general comparison between OTSO and MAGNETOCOSMICS shows a good agreement between the two tools. Variations in results between the two tools are expected as a result of the differing methods in which the two tools approach the computations.

4. Conclusions

A new open-source tool named the "Oulu - Open-source geomagneToSphere prOpagation tool" (OTSO) has been presented. This tool is designed to perform computations of CR propagation within the Earth's magnetosphere to aid in the study of CR physics and space weather events (e.g.

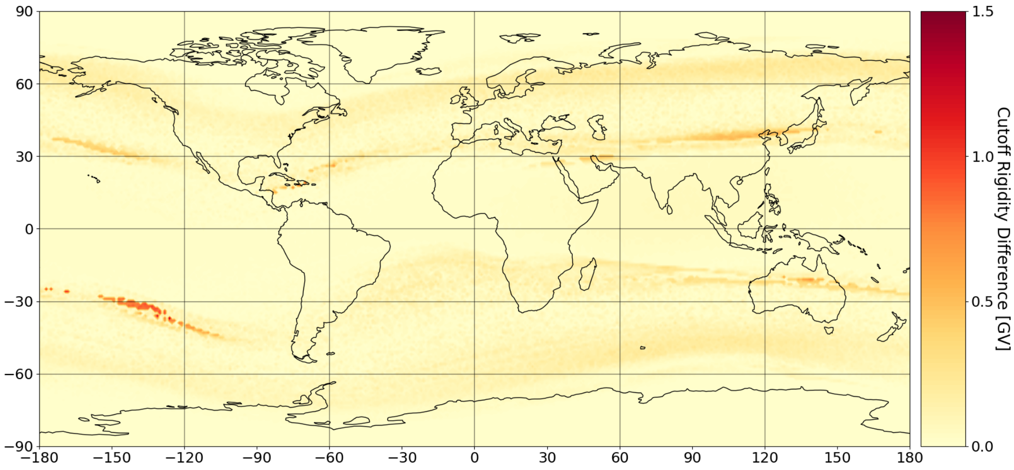

Figure 3: Absolute difference in the computed effective vertical cut-off rigidities for the globe during GLE #70 using both OTSO and MAGNETOCOSMICS.

GLEs). OTSO is an open-source tool that is freely available to everyone with the goal of being further developed by the community to incorporate new methods and models. CR community support will help develop OTSO into a robust CR research tool which can accommodate many research interests.

OTSO has been shown to recreate the computed values of the verified MAGNETOCOSMICS tool to a good degree of accuracy, proving its capability in preforming the intensive computations required for the study of CRs in the magnetosphere. These positive results mean that the foundations for the OTSO tool are solid and that it can already be used in CR analysis, it also means that the tool is ready for the CR community to adopt and further develop for the benefit of the research field as a whole.

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