PROCEEDINGS OF SCIENCE

Development of a new Open-Source Tool for Computing Cosmic Ray Trajectories in the Earth's Magnetosphere (OTSO)

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Simulations of cosmic-ray (CR) trajectories within the Earth's magnetosphere are crucial for investigating how said CRs interact with our planet. Conducting these simulations is no easy task, as CR trajectories can be heavily influenced by the Earth's magnetic environment. As a result, these simulations require sophisticated programs that can perform computationally intense numerical integration to resolve these trajectories. There are multiple tools that have been developed to do this very task, however, these tools can be challenging to work with by being hard to access, no longer supported, and difficult to edit. In order to address the community's desire for a new tool to conduct such computations an alternate new open-source program named the "Oulu – Open-source geomagneToSpheric prOpagation tool" (OTSO) has been developed. This tool aims to supply the community with a user-friendly tool that can conduct the necessary computations required for CR study in the magnetosphere, whilst also providing a robust foundation a tool that can be developed further by the community to meet the field's needs, this removes the need to constantly develop new programs once the old ones become abandoned. OTSO has been able to replicate the results of an older widely used and validated tool, MAGNETOCOSMICS, and was successfully used to analyse two ground-level enhancement events, obtaining results in good agreement with prior studies and in-situ space-borne measurements.

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1. Introduction

Cosmic rays (CRs) are high-energy particles that can be generated within our solar system, by solar eruptions [1], and outside our solar system, with the leading theory of generation outside our local system being supernova remnants [2]. When a solar eruption directed at Earth occurs the flux of solar CRs, also known as solar energetic particles (SEPs), becomes dominant over the typical CR background seen at the Earth. These SEPs can cause numerous space weather effects that can impact human infrastructure as well as be hazardous to human health at high altitudes [3, 4]. In order to study the impact SEPs can have on the Earth, we must first be able to reliably and accurately model the trajectory of the SEPs once they arrive at the Earth's magnetosphere.

SEPs are charged particles, and are thus subjected to the Lorentz force while within the Earth's magnetosphere, causing their trajectory to be altered. A useful way to quantify the amount a particle's trajectory is affected by a magnetic field is by its rigidity, which is preferred to using the energy of a particle as it is independent of the particle's species and charge [5]. If a particle has a sufficiently high rigidity it is able to penetrate the magnetosphere and reach the Earth's atmosphere, otherwise, it is deflected away by the Earth's magnetic field. Particles that penetrate the atmosphere cause atmospheric cascades as a result of colliding with the atmospheric constituents, the secondary particles of these cascades, if the incident particle had enough energy, can be detected on the Earth's surface by ground-based detectors, such as neutron monitors (NMs). When a solar eruption causes a significant increase in NM count rate it is called a ground-level enhancement (GLE).

NMs are especially useful in revealing the anisotropy of the incoming SEPs, which helps in determining the origin of said SEPs. This is due to the NMs being fixed in specific locations, with each NM being sensitive to certain rigidities and incoming directions of particles [6]. The trajectory of the incoming CRs needs to be computed in order to determine what CRs the NMs are sensitive to. This must be done via computer programs as the trajectory of a CR in the Earth's dynamic magnetic field can be incredibly complex, leading to NMs being sensitive to particles that can be arriving above locations on the Earth that are far away from the NM that detects them [7]. The complex nature of the trajectories can be seen in Fig. 1.

As can be seen in Fig. 1 we see the trajectories of the particles originating from the Oulu NM and being traced backwards from the Earth's surface. This is the standard way of investigating CR trajectories in the magnetosphere, as it is impractical to start computations from the beginning of the magnetosphere boundary to the surface when interested in specific locations. Computations are typically started from 20km above the Earth's surface, this is the altitude that air showers typically occur [8], and the CR velocity and charge of the incoming CR are reversed and numerical integration is conducted to determine the trajectory until it encounters an imposed magnetopause. Note that there is currently no known closed-form solution for the motion of a charged particle within the Earth's magnetic field and numerical integration is needed to resolve this [9]. If the particle reaches the magnetopause boundary, escaping the magnetosphere, it is an allowed trajectory, if it fails to do so by returning to Earth or getting trapped in the magnetosphere, travelling more than 100 Re without escaping, it is forbidden. From these computations, the effective cut-off rigidity and asymptotic cones for NM stations can be derived. The effective cut-off rigidity is needed as there is typically no clear rigidity value that an NM is sensitive to as there is a penumbra of allowed and forbidden trajectories during the transition from all trajectories being allowed to forbidden [5].

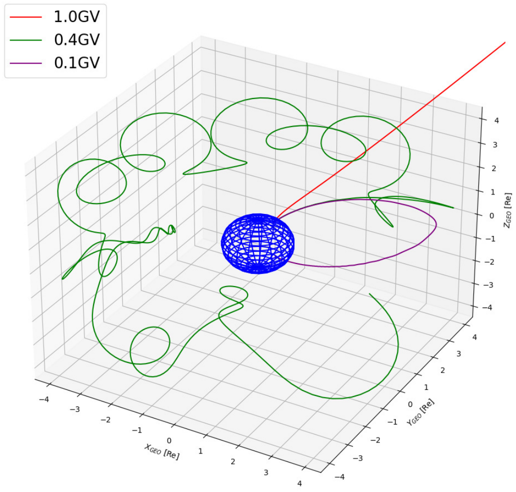

Figure 1: Trajectory of three different CRs originating from the Oulu NM station with different rigidity values, 1.0GV (red), 0.4GV (green), 0.1GV (purple). 1.0GV CR has an allowed trajectory while the other two are forbidden.

The need for modelling CR trajectories in the magnetosphere has led to the development of multiple tools over the years [9]. One such tool that is verified and widely used is MAGNETOCOSMICS [10]. Unfortunately, MAGNETOCOSMICS is no longer supported and hard to get function on modern software. In the absence of a MAGNETOCOSMICS update, we present an open-source, user-friendly, alternative called "Oulu - Open-source geomagneToSphere prOpagation tool” (OTSO) [11]. OTSO is designed to be easy to use and modify in order to create a community-driven tool for CR trajectory computations in the magnetosphere. In this work, we present comparisons between OTSO and MAGNETOCOSMICS when both are used to analyse GLEs in order to verify the validity of OTSO's results.

2. OTSO's Design

To make OTSO as modifiable as possible it is designed as a library that can be downloaded from GitHub (`https://github.com/NLarsen15/OTSO`), as opposed to alternative tools that require the use of servers to host their software. This makes it much easier for the user to utilise OTSO how they see fit without limitations. OTSO is a combination of Python and Fortran. Python is used to enter variables and run computations, with this language being selected due to its simple nature and widespread use in the scientific community. Fortran was selected to conduct the intense numerical integration using the 4^{th} order Runge-Kutta method. Fortran was selected over other compiled languages due to the vast amount of space physics and magnetospheric models that are contained within public Fortran libraries, such as IRBEM, the use of which sped up OTSO's development significantly.

To accurately model the Earth's magnetosphere OTSO uses a combination of internal and external magnetic field models for the Earth, accounting for the Earth's dynamo and magnetospheric currents respectively. The current version of OTSO has the IGRF13 and dipole models [12, 13] for the internal magnetic field and uses the Tsyganenko models for the external magnetic field: TSY87, TSY89, TSY96, TSY01 and TSY01S [14–19]. More models are planned to be added in future updates. Any combination of the external and internal models can be selected in OTSO, however, the best compromise between computation speed and accuracy is IGRF13 with TSY89, the results in this work are obtained using this combination of magnetic field models.

As mentioned prior, once the computation for the CRs trajectory begins there are only three conditions under which the computation stops, encountering the magnetopause (allowed), returning to Earth (forbidden), and travelling more than 100 Re without meeting any prior conditions (forbidden). It is important to know which rigidity values are forbidden and allowed as this allows for the effective cut-off rigidity (P_c) to be computed using Eq. 1.

$$P_c = P_U - \int_{P_U}^{P_L} \Delta P_{(allowed)} \tag{1}$$

where P_U is the upper cut-off rigidity (rigidity of particle before the first forbidden rigidity), P_L is the lower cut-off rigidity (last allowed rigidity), and Δ is the rigidity step size. Whilst proceeding through the range of rigidities dictated by the user OTSO will also compute the asymptotic latitude (Λ) and longitude (Ψ) for each CR being simulated, using Eq. 2 and Eq. 3, in order to ascertain the asymptotic cone of acceptance for given locations on the Earth.

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

$$\Psi = \varphi + \arctan\left(\frac{v_\varphi}{v_\theta \cos\theta + v_r \sin\theta}\right) \tag{3}$$

In Eq. 2 and Eq. 3, v is the CR velocity, θ and φ are the co-latitude and longitude respectively. Note that (Λ) and (Ψ) are computed regardless of whether the CR is allowed or forbidden, in the latter case the last position of the CR is used. A value is given in the output to inform the user if the rigidity was allowed or forbidden. Computed asymptotic cones for 8 NMs, during GLE 70, using OTSO are shown in Fig. 2.

3. Verification of OTSO

In order to verify the results of OTSO a comparison between it and MAGNETOCOSMICS, a verified tool, was done by investigating GLE 70, which occurred on 13 December 2006. Table 1 shows the computed effective cut-off rigidities for 8 NMs using both OTSO and MAGNETOCOSMICS with a generally good agreement between the two tools being found.

This comparison was extended to a global scale, in which a 1° × 1° resolution effective cut-off rigidity map of the Earth during GLE 70 was computed using both tools. Fig. 3 shows the relative difference between OTSO and MAGNETOCOSMICS, omitting values greater than 5% that are present in polar regions due to the small cut-off values in the region. Fig. 3 shows that the agreement between the tools is good, particularly in low-latitude regions with the differences

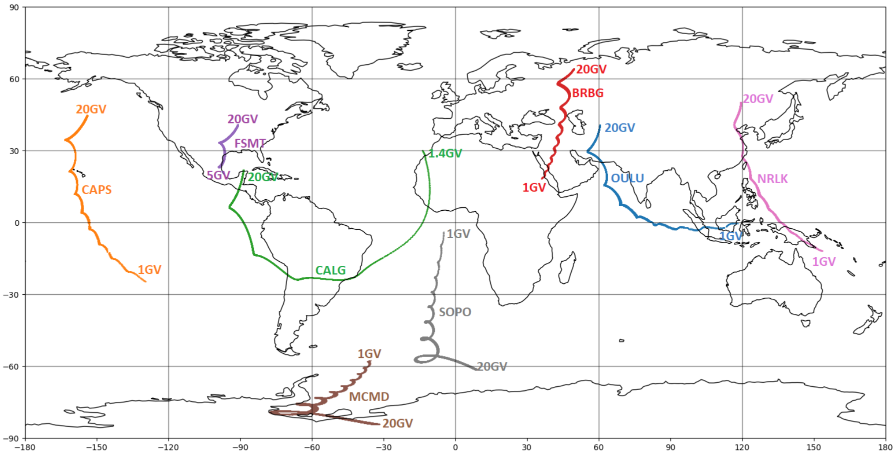

Figure 2: Asymptotic cones for multiple NMs during GLE 70: Cape Schmidt (orange), Fort Smith (purple), Calgary (green), McMurdo (brown), South Pole (grey), Barentsburg (red), Oulu (blue), and Norilsk (pink).

	Vertical Effective Cut-off Rigidity [GV]	
Station	MAGNETOCOSMICS	OTSO
Barentsburg	0.000	0.000
Calgary	0.92	0.924
Cape Schmidt	0.368	0.377
Fort Smith	0.158	0.167
McMurdo	0.000	0.000
Norilsk	0.538	0.548
Oulu	0.622	0.647
South Pole	0.000	0.000

Table 1: Effective vertical cut-off rigidities for 8 selected NM stations computed using OTSO and MAGNETOCOSMICS during GLE70.

generally increasing alongside latitude. The differences in these regions arise from different integration methods used when resolving the equations of motion. Mid-to-high latitudes have more complex trajectories and the effect of varying integration methods becomes more pronounced in these regions. One can also see that there are regions of greater difference that stand out, such as in the South Pacific Ocean. These areas of difference arise from MAGNETOCOSMICS having significantly, and unexpectedly, lower P_U than OTSO. With the rest of the globe showing a good agreement between the tools these areas are hard to explain, with the only key difference in tools being the integration methods used.

One application of the results generated by OTSO is to use the asymptotic cones and cut-off rigidities of multiple NMs as inputs into a method to reconstruct the SEP spectrum during GLEs. OTSO data for GLE 66 and 71 were used to determine the SEP spectra for the events and compare them with prior studies and measurements. The method used involves using the Levenberg-Marquardt algorithm and merit function alongside inputs of NM data and space weather

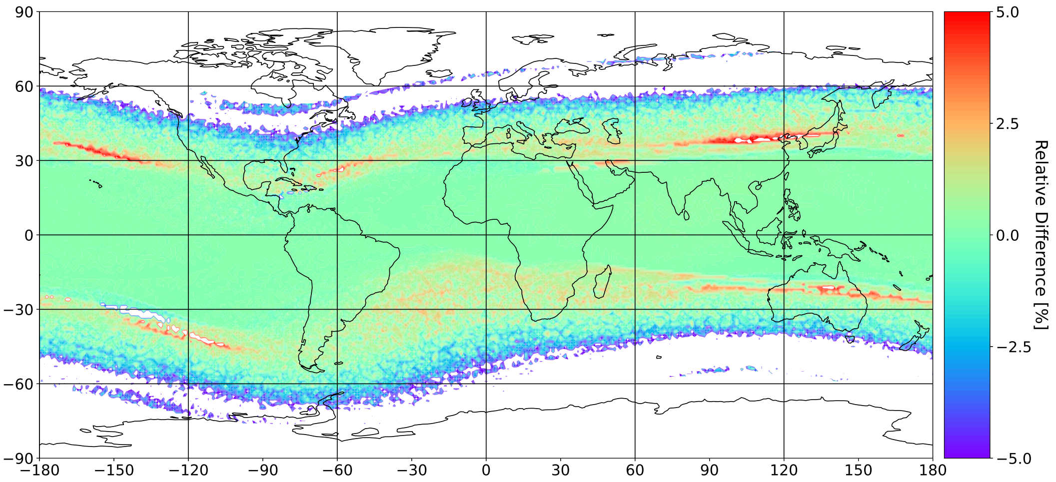

Figure 3: Relative differences within the range -5% to 5% between computed cut-off rigidities using OTSO and MAGNETOCOSMICS.

conditions to determine the best fit of a modified power-law (for details see [20]). When OTSO data was used during this process the resulting spectra were in good agreement with prior studies and in-situ measurements of GLE 66 and 71 [11].

4. Conclusions

Within this work, a new open-source tool for CR trajectory computations within the magnetosphere called the "Oulu - Open source geomageToSphere prOpagation tool" (OTSO) has been presented. OTSO is designed within the Python and Fortran programming language to conduct the complex numerical integration over the equations of motion for charged particles within the magnetosphere. The purpose of such a tool is to help in the study of space weather events (e.g. GLEs) and aid in the development of projects aimed at creating nowcasting tools designed to mitigate the impacts of such events (e.g. radiation exposure). OTSO has been shown to have a good agreement with the older verified MAGNETOCOSMICS tool, as well as being successfully used to analyse GLE 66 and 71. These results help validate OTSO as an alternative tool to MAGNETOCOSMICS. These positive results show that OTSO is currently able to do the necessary complex computations needed for CR research. OTSO's open-source nature also means that a strong foundation for a community-driven tool is in place within its current release. If OTSO is adopted by the community it can be further developed from this starting point to fully accommodate all the community's needs as the research field develops.

5. Acknowledgements

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