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Investigating the Relationship Between GLE Neutron Monitor Data and Radiation Dose at Flight Altitudes

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The Earth is under a constant salvo of high-energy charged particles known as cosmic rays (CRs). These can penetrate the Earth's magnetosphere and enter the Earth's atmosphere, where they contribute to the radiation environment at high altitudes. During large solar eruptions, large fluxes of solar energetic particles (SEPs) can be created via acceleration processes at the Sun. SEPs can pose a serious space weather risk to aircrews and airline passengers if the eruption is directed towards the Earth by enhancing the radiation environment at aviation altitudes. SEPs with enough energy are detected at the ground by registering their secondary particles, created by induced atmospheric cascades, at ground-based detectors, such as neutron monitors (NMs), this event is known as a ground-level enhancement (GLE). With the impact of space weather events, such as GLEs, being further understood the desire for strong nowcasting capabilities for dangerous events is prominent within modern society. A newly developed model for computing the radiation dose at certain altitudes as a result of GCRs and SEPs was used to determine the effective dose received during numerous GLE events. A comparison of these computed doses and respective NM count rates during the GLEs shows a good correlation. A model with a good correlation, such as this, can provide invaluable assistance and gives the scientific basis for the development of space weather nowcasting tools, helping to mitigate the hazardous effects GLEs can have on the aviation industry.

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1. Introduction

Space is full of high-energy charged particles known as cosmic rays (CRs). CRs are typically produced outside of our solar system and are currently believed to be produced by supernova remnants [1]. These galactic cosmic rays (GCRs) continuously arrive at Earth and pose little threat to humans as their impact can be accounted for and mitigated. Variations in the flux of GCRs also occur over the solar cycle as a result of solar modulation [2]. This can not be said for CRs produced by our Sun, also known as solar energetic particles (SEPs). SEPs are produced at our Sun during solar eruptions when various acceleration mechanisms increase the energy of particles being released in the eruption to relativistic energies [3].

A solar eruption that is directed towards Earth can increase the flux of arriving CRs greatly above the GCR background. If the SEPs arriving have enough energy they are able to penetrate the Earth's magnetosphere and enter the atmosphere. Once this occurs SEPs will induce complex air showers of secondary particles as a result of colliding with the atmosphere's constituents. If the incident particle has sufficient energy the secondary particles can be detected at the surface by ground-based instruments, such as neutron monitors (NMs). In the event that several NMs detect a significant increase in measured counts, it is called a ground-level enhancement (GLE) [4]. The occurrence of GLEs is sporadic, with only a few happening per solar cycle [5]. Due to the rarity of these events understanding the impacts they had on Earth is crucial to mitigate any damage done by potential future events.

NM design has been fairly consistent since the 1957-1958 geophysical year, after which the standardised design has been used around the globe to create the global neutron monitor network [6]. This design consists of a tube of gas typically filled with boron trifluoride, some later NMs use helium-3, which is surrounded by a moderator, lead, and a reflector. The incoming nucleonic component of the atmospheric cascade interacts with the lead producer which produces lower-energy neutrons, the moderator then reduces the energy of the produced neutrons to thermal levels. The reflector acts to reflect the produced neutrons back towards the counter tube. The thermal neutron interacts with the gas in the counter tube and the ionisation of the gas by the products allows for a count to be detected. A map showing the global NM network can be seen in Fig. 1.

An increase in SEP flux has numerous impacts on the Earth which are dangerous to humans. The arrival of high-energy particles can lead to satellites being damaged and increases in the radiation field at high altitudes, this work focuses on the latter impact. The arrival of SEPs in the upper atmosphere can prove dangerous to humans in high altitudes, such as pilots and airline passengers, by subjecting them to greater doses of radiation than would typically be expected under quiet solar conditions. Naturally, this means that GLEs pose a significant space weather threat and efforts must be made to mitigate any potential damage caused as a result of them. This work uses a recently developed radiation model, that takes the SEP and GCR spectra at the time of past GLEs to compute the radiation doses at flight altitudes and compares the model to NM data from said GLE events to establish a relationship between the two values [7].

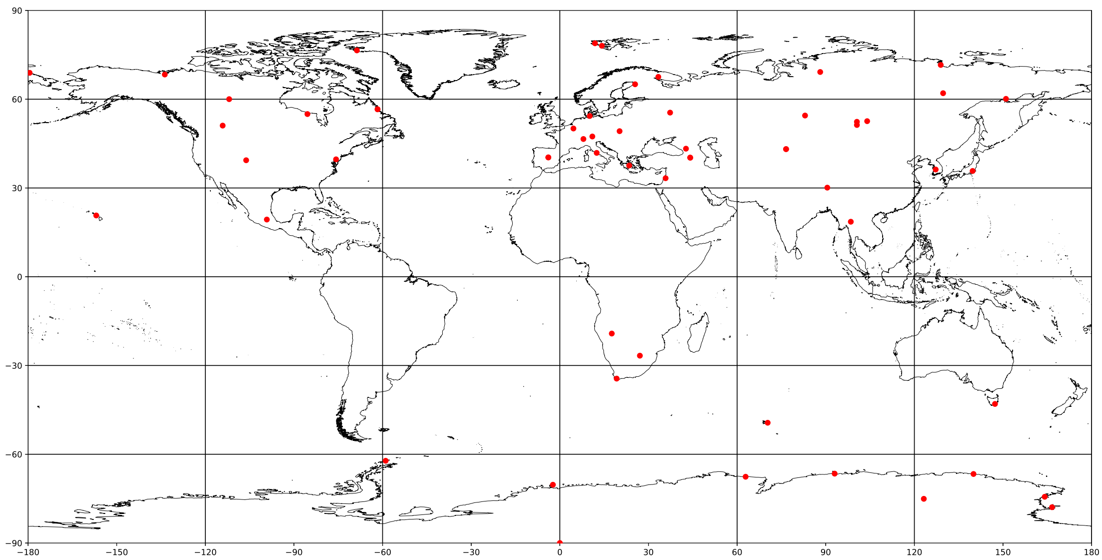

Figure 1: Map of NMs around the globe. NM monitor locations are indicated by red points.

2. Radiation Model

The SEP spectra during GLE events are obtained by exploiting the stationary nature of the NMs around the globe. Each NM is sensitive to different particle rigidities, rigidity is used in place of energy due to it being independent of particle species [8]. The rigidities an NM can detect depend on the NM location, arriving directions of particles, and space weather conditions. In order to determine this the trajectories of incoming SEPs to the NM are computed using tools that can tell us the effective cut-off rigidity and asymptotic cone of acceptance for each NM, one such tool is the recently developed OTSO [9]. By modelling the response of the global NM network and performing model optimisations over the GLE event we can determine the spectra of the SEPs and angular distribution during the event by using the Earth's magnetic field as a giant spectrometer. This is done using a method outlined in prior work, [10–12], which was recently verified by measurements taken by a HEMERA-2 stratospheric scientific balloon [13]. The Levenberg-Marquadt algorithm [14, 15] was utilised to unfold the NM data in order to obtain the SEP spectra. The SEP spectra are fitted to two different modified power-laws depending on the rigidity of the SEP, Eq. 1 for rigidities greater than 1 GV and Eq. 2 for equal to and lower than 1 GV.

$$J_{||}(P) = J_0 P^{-(\gamma+\delta\gamma(P-1))} \tag{1}$$

$$J_{||}(P) = J_0 P^{-(\gamma+\delta\gamma\cdot P)} \tag{2}$$

Where $J_{||}(P)$ is the flux of particles along the axis of symmetry in [$\mathrm{m^{-2}s^{-1}sr^{-1}GV^{-1}}$], J_0 is the flux of particles at 1 GV, P is the rigidity in [GV], γ is the power-law exponent, and $\delta\gamma$ is the steepening.

The effective dose rate at a given atmospheric depth h is then found using Eq. 3

$$E(h, T, \theta, \varphi) = \sum_i \int_{T_{P_{cut}}}^{\infty} \int_{\Omega} J_i(T) Y_i(T, h) d\Omega(\theta, \varphi) dT, \tag{3}$$

where $J_i(T)$ is the differential energy spectrum of the primary CR and Y_i is the associated effective dose yield function for a given altitude and energy. The effective dose is found when integrating over the kinetic energy (T) to infinity, starting at the energy corresponding to the cut-off rigidity ($T_{P_{cut}}$) of the location being investigated. The effective dose yield functions at various altitudes have been previously computed using complex Monte-Carlo simulations [16] and are presented in tables 1 and 2. Note that for the computations within this work, the FL350 (35kft) yield functions were selected to find the effective doses that correspond with typical aviation altitudes.

	Altitude						
E [GeV/n]	FL100	FL200	FL300	FL350	FL400	FL450	FL500
0.1	5.1E-19	5.42E-17	8.9E-16	2.5E-15	7.9E-15	2.5E-14	5.2E-14
0.3	3.1E-16	4.67E-15	2.3E-14	4.6E-14	1.7E-13	3.5E-13	9.98E-13
0.5	1.8E-14	3.3E-13	1.6E-12	3.8E-12	5.5E-12	6.1E-12	6.8E-12
1	4.1E-13	5.56E-12	2.5E-11	4.4E-11	6.2E-11	8.3E-11	1.1E-10
5	6.97E-12	5.31E-11	1.7E-10	2.7E-10	3.4E-10	3.97E-10	4.9E-10
10	2.33E-11	1.31E-10	3.6E-10	5.2E-10	6.4E-10	7.2E-10	8.97E-10
50	1.03E-10	5.73E-10	1.5E-9	2.2E-9	2.7E-9	3.3E-9	3.7E-9
100	1.99E-10	1.12E-9	2.98E-9	4.5E-9	5.5E-9	6.2E-9	7.2E-9
500	8.25E-10	6.1E-9	1.8E-8	2.5E-8	2.7E-8	2.96E-8	3.1E-8
1000	1.69E-9	1.31E-8	3.75E-8	5.4E-8	5.7E-8	5.9E-8	6.0E-8

Table 1: Proton yield functions

	Altitude						
E [GeV/n]	FL100	FL200	FL300	FL350	FL400	FL450	FL500
0.1	1.3E-19	2.51E-17	2.8E-16	1.8E-15	5.8E-15	1.8E-14	3.3E-14
0.3	2.7E-16	2.17E-15	1.9E-14	6.6E-15	8.1E-14	1.0E-13	7.3E-13
0.5	1.6E-14	2.93E-13	1.4E-12	2.5E-12	4.2E-12	5.2E-12	5.4E-12
1	1.2E-13	3.22E-12	1.8E-11	3.5E-11	5.0E-11	6.8E-11	9.3E-11
5	6.95E-12	4.95E-11	1.5E-10	2.2E-10	2.9E-10	3.5E-10	4.1E-10
10	2.3E-11	1.08E-10	3.1E-10	4.4E-10	5.3E-10	6.4E-10	7.4E-10
50	1.03E-10	5.73E-10	1.5E-9	2.2E-9	2.7E-9	3.3E-9	3.7E-9
100	1.99E-10	1.12E-9	2.98E-9	4.5E-9	5.5E-9	6.2E-9	7.2E-9
500	8.25E-10	6.1E-9	1.8E-8	2.5E-8	2.7E-8	2.96E-8	3.1E-8
1000	1.69E-9	1.31E-8	3.75E-8	5.4E-8	5.7E-8	5.9E-8	6.0E-8

Table 2: Alpha yield functions

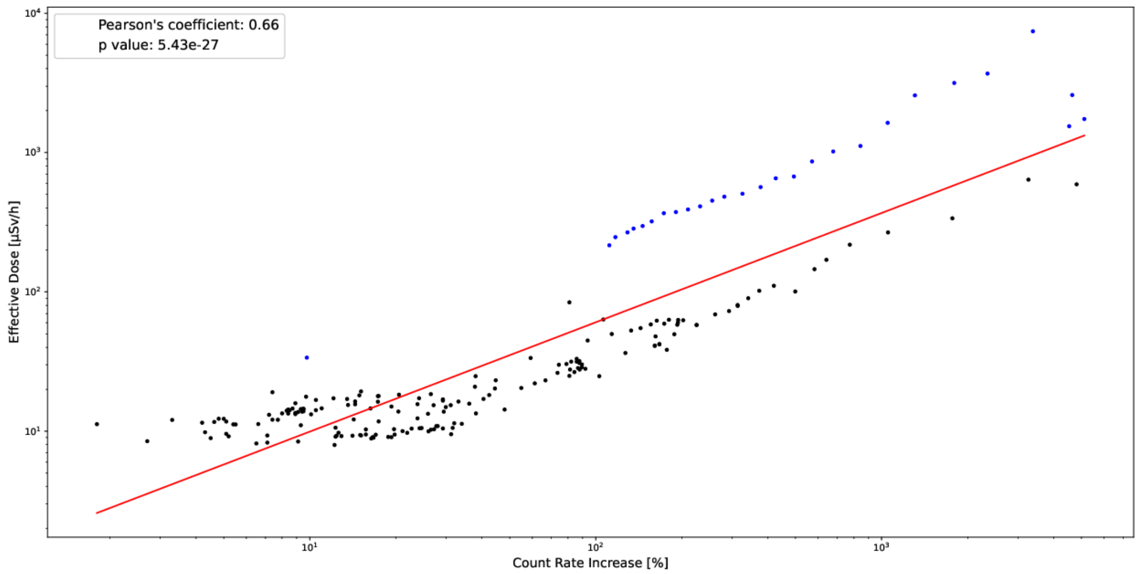

Figure 2: Computed doses for GLEs in comparison to the greatest percentage increase in count rate detected by the NM network. The red line represents the best fit for the data. GLE 5 data is shown in blue.

3. Results

Using the method presented above, the time-dependent SEP spectra for 15 different GLE events were derived. The GLEs used were: 5, 43, 44, 45, 52, 60, 61, 63, 64, 65, 66, 67, 69, 71, and 72. This list includes GLEs from four different solar cycles, namely solar cycles 19, 22, 23, and 24, and two of the strongest GLEs ever recorded, GLEs 5 and 69 [17]. The effective dose as a result of SEPs and GCRs was computed at regular intervals throughout each event, assuming an altitude of 35kft for the yield functions and a cut-off rigidity of 0 GV, which was then compared to the corresponding greatest count rate increase detected by the NM network. The NM which detected the greatest increase in count rate was typically the south pole NM (SOPO), due to its high altitude and the low local geomagnetic cut-off rigidity, as such its data is primarily used. The one exception to this is for GLE 5 in which the Leeds NM in the UK (LEED) recorded the greatest increase, this was due to the lack of NMs operational at the time, GLE 5 occurred on 23 February 1956, in lower cut-off rigidity zones, such as SOPO in Antarctica. The resulting comparison can be seen in Fig. 2.

One can see from Fig. 2 that there is a correlation between the effective dose and NM count rate increase, with a correlation coefficient of 0.66 and a p-value of 5.43e-27 showing the statistical significance of the correlation. However, the data for GLE 5 (blue points) is seen to be an outlier in the plot with the dose being much higher than expected for the event. This suggests there is an underlying issue in the derivation of the spectra for GLE 5 which needs to be investigated further. This is further shown in Fig. 3 when GLE 5 data is removed from the plot and a much better agreement is found.

Once GLE 5 is removed from the data pool the correlation coefficient increases to 0.96 and the p-value becomes 8.12e-97. This is a much stronger correlation than seen in Fig. 2 and implies an issue with the fundamental assumptions around GLE 5.

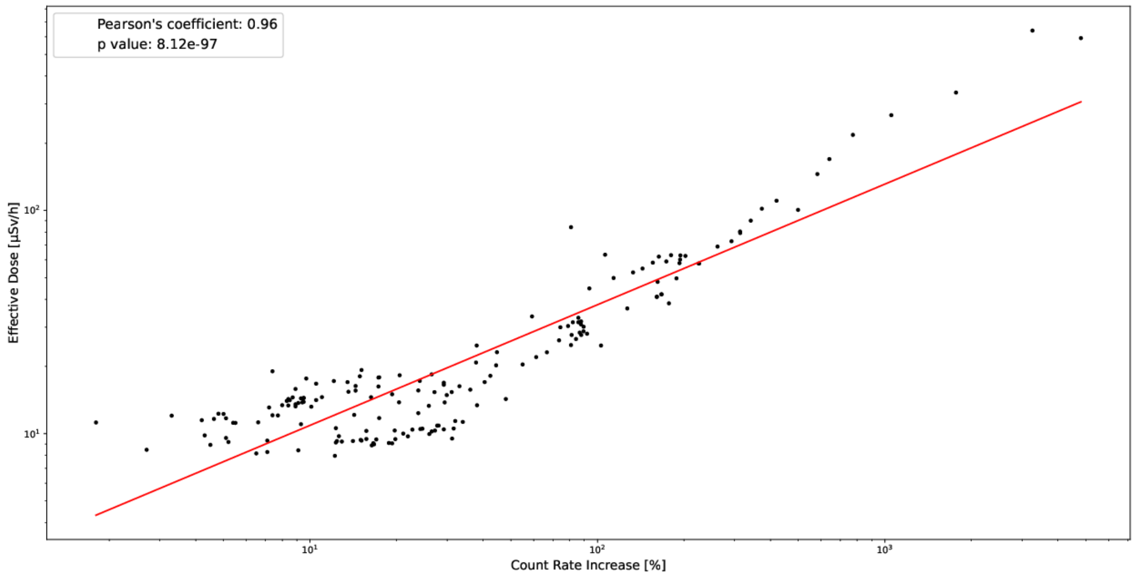

Figure 3: Computed doses for GLEs in comparison to the greatest percentage increase in count rate detected by the NM network, data for GLE 5 is omitted. The red line is the line of best fit.

4. Conclusion

A new radiation model was used to compute the effective dose at flight altitudes during various GLE events. This new model utilises the time-dependent SEP spectra present during the GLE events allowing for a comparison to be done with real-time measurements from the NM network. 15 different GLE events were analysed using the new radiation model and most of them showed a very strong correlation between the computed doses and the respective NM count rate increase, with the exception of GLE 5. With GLE 5 being the only outlier to the general trend, it would suggest that there is an issue in the derivation of the SEP spectra for this event. GLE 5 is one of the strongest GLE events recorded and helps in the prediction of potential worst-case scenarios, as such an accurate SEP spectrum for this event would be incredibly beneficial to the community. This event will be looked into in further detail in future work. Once GLE 5 is excluded from the data the strong correlation is revealed. This proves that there is a strong scientific basis for developing nowcasting models that use real-time NM data to determine the effective dose that crew and passengers on aircraft might experience, an accurate tool that can do such predictions for GLEs is greatly sought after by the aviation industry. This relationship also means that a potential proxy between the NM data and dose could be determined allowing for the investigation of potential worst-case scenario events, helping with preparedness in the situation that such an event occurs in the future.

5. Acknowledgements

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References

[1] P. Blasi, *The origin of galactic cosmic rays*, *The Astronomy and Astrophysics Review* **21** (2013) .

[2] M. Potgieter, *Solar modulation of cosmic rays*, *Living Reviews in Solar Physics* **10** (2013) .

[3] M. Desai and J. Giacalone, *Large gradual solar energetic particle events*, *Living Reviews in Solar Physics* **13** (2016) 3.

[4] S. Poluianov, I. Usoskin, A. Mishev, M. Shea and D. Smart, *Gle and sub-gle redefinition in the light of high-altitude polar neutron monitors*, *Solar Physics* **292** (2017) 176.

[5] M. Shea and D. Smart, *Space weather and the ground-level solar proton events of the 23rd solar cycle*, *Space Science Reviews* **171** (2012) 161.

[6] J. Simpson, *The cosmic ray nucleonic component: The invention and scientific uses of the neutron monitor*, *Space Science Reviews* **93** (2000) 11.

[7] A. Mishev, S. Tuohino and I. Usoskin, *Neutron monitor count rate increase as a proxy for dose rate assessment at aviation altitudes during gles*, *Journal of Space Weather and Space Climate* **8** (2018) A46.

[8] D. Cooke, J. Humble, M. Shea, D. Smart, N. Lund, I. Rasmussen et al., *On cosmic-ray cutoff terminology*, *Il Nuovo Cimento C* **14** (1991) 213.

[9] N. Larsen, A. Mishev and I. Usoskin, *A new open-source geomagnetosphere propagation tool (otso) and its applications*, *Journal of Geophysical Research: Space Physics* **128** (2023) e2022JA031061 [https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2022JA031061].

[10] A. Mishev, I. Usoskin, O. Raukunen, M. Paassilta, E. Valtonen, L. Kocharov et al., *First analysis of gle 72 event on 10 september 2017: Spectral and anisotropy characteristics*, *Solar Physics* **293** (2018) 136.

[11] A. Mishev, S. Koldobskiy, I. Usoskin, L. Kocharov and G. Kovaltsov, *Application of the verified neutron monitor yield function for an extended analysis of the gle # 71 on 17 may 2012*, *Space Weather* **19** (2021) e2020SW002626.

[12] A. Mishev, L. Kocharov, S. Koldobskiy, N. Larsen, E. Riihonen, R. Vainio et al., *High-resolution spectral and anisotropy characteristics of solar protons during the gle n°73 on 28 october 2021 derived with neutron-monitor data analysis*, *Solar Physics* **297** (2022) 88.

[13] A. Mishev, A. Binios, E. Turunen, A.-P. Leppänen, N. Larsen, E. Tanskanen et al., *Measurements of natural radiation with an mdu liulin type device at ground and in the atmosphere at various conditions in the arctic region*, *Radiation Measurements* **154** (2022) 106757.

[14] K. Levenberg, *A method for the solution of certain non-linear problems in least squares*, *Quarterly of Applied Mathematics* **2** (1944) 164.

[15] D. Marquardt, *An algorithm for least-squares estimation of nonlinear parameters*, *SIAM Journal on Applied Mathematics* **11** (1963) 431.

[16] A.L. Mishev, S.A. Koldobskiy, G.A. Kovaltsov, A. Gil and I.G. Usoskin, *Updated neutron-monitor yield function: Bridging between in situ and ground-based cosmic ray measurements*, *Journal of Geophysical Research: Space Physics* **125** (2020) e2019JA027433.

[17] E. Vashenyuk, Y. Balabin, J. Perez-Peraza, A. Gallegos-Cruz and L. Miroshnichenko, *Some features of the sources of relativistic particles at the sun in the solar cycles 21–23*, *Advances in Space Research* **38** (2006) 411.