The upgraded GLE database includes assessment of radiation exposure at flight altitudes

A. Mishev$^{1,2}$, I. Usoskin$^{1,2}$, S. Tuohino$^3$ and A. Ibragimov$^4$

$^1$Space Climate Research Unit, University of Oulu, Finland
$^2$Sodankylä Geophysical Observatory, University of Oulu, Finland
$^3$Faculty of Science, University of Oulu, Finland
$^4$Independent researcher, Helsinki, Finland

E-mail: alexander.mishev@oulu.fi

Abstract. The exposure to radiation due to cosmic rays at cruising aviation altitudes is an important topic in the field of space weather. While the effect of galactic cosmic rays can be easily assessed on the basis of recent models, assessments of the absorbed dose during strong solar particle events is rather complicated. A specific interest are events with energy about GeV/nucleon, which produce an atmospheric cascade registered by ground based detectors e.g. neutron monitors. Those events are known as ground level enhancements (GLEs) and can significantly enhance the radiation exposure at flight altitudes over the polar regions. A recent upgrade of the existing GLE database provides information on the estimated solar protons energy/rigidity spectra, the corresponding computed effective doses and the used bibliography. Using information retrieved from this upgrade we performed statistical analysis of maximum effective doses at commercial flight altitude of 35 kft during several GLEs, where the necessary information as energy/rigidity spectra of the solar protons is available. For the computations a recent model for assessment of effective dose due to cosmic ray particles was employed. A highly significant correlation between the maximum effective dose rate and neutron monitor peak count rate increase during GLEs is observed. Here, we propose to use the maximal count rate increase as a proxy for assessment of the effective dose at flight altitude during strong solar particle events.

1. Introduction

The Earth is continuously hit by high-energy particles with extra-terrestrial origin vs. cosmic rays (CRs). They collide with particles in the atmosphere and produce new, energetic particles, which also collide with other nuclei and in such a way produce cascade of secondary particles, i.e., an extensive air shower. The increased amount of particles compared to ground level determine the complex radiation environment at flight altitudes [1, 2]. Nowadays, the assessment of the exposure to the radiation in this complex field, henceforth exposure, is an important topic in the field of space weather [3, 4]. It is recommended to consider the exposure of aircrew as occupational [5]. Occasional, but important for the determination of the radiation environment source of particles, follows eruptive solar processes e.g. solar flares and coronal mass ejections (CMEs), leading to production of solar energetic particles (SEPs) [6, 7]. A special class of extreme SEPs [8] registered by ground based detectors such as neutron monitors (NMs) is called ground level enhancements (GLEs) [7, 9]. This type of events can dramatically enhance the radiation field in the Earth’s atmosphere [4].
A database developed over the years by the research community provides information of NM count rates during GLEs, presently hosted by the University of Oulu [10]. This database was developed over several decades by the research community with main contribution of L. Gentile, M. Shea, D. Smart, M. Duldig, J. Humble, H. Moraal, A. Belov, E. Eroshenko, V. Yanke.

The estimation of the exposure at flight altitudes due to CRs of both galactic and solar origin is not trivial. It depends on a geographic position and altitude, solar activity etc...[1]. In order to fulfil this task, it is necessary to possess information about GLE particles energy spectra and angular distribution. In the last years several models for computation of the exposure at aviation altitudes are developed e.g. [11, 12, 13, 14, 15]. We would like to stress that different reconstructed GLE spectra result on considerably different exposures even for the same event as reported by [16, 17]. In this study we compute the exposure during GLEs, where spectral information is available. The computations are carried out at flight altitude of 35 kft (10668 m) in a region with cut-off rigidity $R_c < 1$ GV using a model, which full description is given in [18].

The computed exposure during GLEs allowed us to upgrade the existing GLE database, which now provides information on the SEP energy/rigidity spectra, the corresponding effective doses and the used bibliography sources [19].

2. Model for computation of effective dose rate at aviation altitudes

The employed model here for computation of the exposure at aviation altitudes is based on pre-computed effective dose yield functions. The effective dose rate at a given altitude $h$ induced by primary CR particles is computed using the expression:

$$E(h, R_c, \theta, \varphi) = \sum_i \int_{E_{cut,i}(R_c)}^{\infty} \int J_i(T) Y_i(T, h) d\Omega dT,$$

where $h$ is the altitude above sea level, $R_c$ is the local cut-off rigidity, $\theta$ and $\varphi$ are the angles of incidence of the arriving particle, $J_i(T)$ is the differential energy spectrum of the primary CR arriving at the top of the atmosphere for $i$ component (proton and/or $\alpha$–particle) and $Y_i$ is the effective dose yield function for the corresponding primary CR component. The integration is over the kinetic energy above $T_{cut,i}(R_c)$, which is defined by $R_c$ for a nuclei of type $i$ by the expression:

$$T_{cut,i} = \sqrt{\left(\frac{Z_i}{A_i}\right)^2 P_c^2 + E_0^2 - E_0},$$

where $E_0 = 0.938$ GeV/c$^2$ is the proton’s rest mass, $T_{cut,i}$ is given in [GeV], respectively $P_c$ in [GV].

Accordingly the effective dose yield function $Y_i$ is defined as:

$$Y_i(T, T^*, h) = \sum_j \int F_{i,j}(h,T,T^*,\theta,\varphi) C_j(T^*)dT^*,$$

where $C_j(T^*)$ is the fluence-to-effective dose conversion coefficient for a secondary particle of type $j$ (neutron, proton, $\gamma$, $e^−, e^+, \mu^−, \mu^+, \pi^−, \pi^+$) with energy $T^*$, $F_{i,j}(h,T,T^*,\theta,\varphi)$ is the secondary particle fluence of type $j$, produced by a primary particle of type $i$ (proton and/or $\alpha$–particle) with a given primary energy $T$. The conversion coefficients $C_j(T^*)$ are considered according to [20].

For GCR equations 1 and 3 lead to

$$E = 4\pi^2 \left[ \int_{E_{cut}}^{\infty} J_p(T') Y_p(T')dT' + \int_{E_{cut}}^{\infty} J_\alpha(T') Y_\alpha(T')dT' \right],$$

2
Equation 4 has two integral terms, the first reveals the contribution of CR protons. The second term describes accordingly $\alpha-$particles and includes effectively also heavier nuclei [21, 22]. During GLEs, the exposure is a superposition of GCRs and SEPs contributions. For GCRs we employ the force field model [23, 24, 25] and for SEPs we employ various reconstructions, the details are given in [19]. Note, that for GLE particles contribution to the exposure we are using only the first term in equation 3. In this study we used GLE spectra derived mostly on the basis of data from the global NM network, which is an integral detector and does not allow to obtain information about the mass composition of SEPs. In addition, we assume an isotropic SEP flux, which lead to a conservative estimation of the exposure, similarly to [26].

3. Upgrade of GLE database

The occurrence rate of GLEs is roughly one per year [27, 28]. Using the model described in Section 2 (equations 1–4) and multiple sets of derived energy/rigidity SEP spectra we compute the effective dose rate during selected GLEs. The computations are performed at flight altitude of 35 kft (10668 m) in a region with low cut-off rigidity $R_c < 1$ GV, where the exposure is maximal. The results are shown for various reconstructions of SEPs spectra, available in literature. This naturally lead to different results for one event. The computed exposures during GLEs were incorporated in the existing GLE database. The upgraded database provides, for each GLE event, where possible, information on reconstructed energy/rigidity spectra and the corresponding exposure http://gle.oulu.fi/#/dose. An example is shown in figure 1, where is presented the NM count rate increase during GLE 43 observed by several stations.

![Figure 1. Global NM count rate increase during GLE 43 on 19 October 1989.](image)

An illustration, namely computed exposures during GLE 45 is shown in figure 2 with the corresponding references.

Details about the upgrade of the GLE database, with full list of the events and used bibliography sources are given in [19]. Note, that the creation of such database is an open process. Therefore the database will be updated when new information and/or events occur and/or new information is retrieved including computation(s) with improved models when available.
4. Application of upgraded GLE database

The assessed exposure during various stages of GLEs allow one to compute the distribution of the effective dose rate and to estimate the radiation hazard and radiation environment in the troposphere and stratosphere [29, 30, 31]. As example we present the distribution of the exposure over the globe during the main phase of GLE 70 on 13 December 2006 (figure 3). The SEP spectra are considered according to [32]. Here, the cut-off rigidities over the globe are obtained using the MAGNETOCOSMICS code [33], employing combination of Tsyganenko 1989 (external) [34] and IGRF (internal) [35] geomagnetic models, which allows precise and relatively straightforward computation [36, 37, 38]. The distribution of exposure depicts a maximum at polar and sub-polar regions and smoothly decreases at regions with higher cut-off rigidity.

**Figure 2.** Computed effective dose rate at altitude of 35 kft a.s.l. during GLE 43 on 19 October 1989 with the corresponding SEP spectra and bibliography.

**Figure 3.** Map of the exposure during the main phase (03:30 UT) of GLE 70 on 13 December 2006.
In addition, we performed a statistical study of a number of GLEs, where the information about their spectra was available. Using the GLE database and the computed exposures during GLEs, we computed the peak exposure at the aviation altitude of 35 kft during these events. In a such a way we study the peak exposure for 34 GLEs, which yields 47 different sets of assessments. The peak exposure due to GLE particles varies from several μSv.h\(^{-1}\) to tens or hundreds μSv.h\(^{-1}\). For the two strongest GLE events, the estimated exposure was in the range 1–2.5 mSv.h\(^{-1}\).

Subsequently, we build a distribution: peak exposure – peak NM count rate increase during the event. A highly significant correlation (the Pearson’s linear correlation coefficient of about 0.84, with high significance level \(p\)-value \(\ll 0.01\)), between the peak exposure rate and peak NM count rate increase was found (figure 4). Therefore, the NM peak count rate increase can be used as a proxy to assess the peak exposure at flight altitudes [39].

5. Conclusions

We upgraded the existing GLE database by including information about the exposure during selected GLE events. The new database is linked to the existing GLE database http://gle.oulu.fi/#!/dose. The database will be updated when new events occur and/or new information, namely GLE spectra for historical events is retrieved. The upgrade provides, for each observed GLE where data are available, information on the GLE spectra, the corresponding effective dose rates at cruise flight altitude of 35 kft and bibliographic source(s). The upgraded GLE database allows one to estimate the exposure over several solar cycles and gives the possibility to compare different models for estimation of the radiation hazard at flight altitude(s) and measurements.

The derived highly significant correlation between peak exposure – maximum NM count rate increases during GLEs, gives good basis to obtain a quick estimate of the exposure due to SEPs during GLE events on the basis of records from the global NM network, using mainly low cut-off rigidity stations. The peak exposure is due in most cases to the hard – prompt component of SEPs. Using the fact, that the most energetic SEPs from the prompt component arrive in the vicinity of Earth before the bulk of solar protons, a quick assessment of the exposure can be achieved instantly as in [40]. Therefore, the global NM network is a useful tool for assessment of space weather effect such as the radiation exposure of aircrew during strong SEP events.
Acknowledgments
This work was supported by the Academy of Finland (project No. 272157, Center of Excellence ReSoLVE and project No. 267186). This study was supported by VarSITI Program of ICSU Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). We warmly acknowledge all the researchers and NM station managers who collected GLE data and performed the corresponding processing and analysis.

References
[1] Spurný F, Votockova I and Bottollier-Depois J 1996 Radioprotection 31 275–280
[2] Shea M and Smart D 2000 Space Science Reviews 93 187–205
[3] Liliensten L and Bornarel J 2009 Space Weather, Environment and Societies (Dordrecht: Springer) ISBN 978-1-4020-4332-1
[4] Vainio R, Desorgher L, Heynderickx D, Storini M, Flückiger E, Horne R, Kovaltsov G, Kudela K, Laurenza M, McKenna-Lawlor S, Rothkaehl H and Usoskin I 2009 Space Science Reviews 147 187–231
[5] ICRP 2007 Annals of the ICRP 37
[6] Reames D 2013 Space Science Reviews 175 53–92
[7] Desai M and Giacalone J 2016 Living Reviews in Solar Physics 13 3
[8] Gopalswamy N, Xie H, Yashiro S, Akiyama S, Mäkelä P and Usoskin I 2012 Space Science Reviews 171 23–60
[9] Aschwanden M 2012 Space Science Reviews 171 3–21
[10] Usoskin I, Ibragimov A, Shea M and Smart D 2015 Proceedings of Science, Proc. of 34th ICRC Hague, Netherlands, 30 July - 6 August 2015, 054
[11] Ferrari A, Pelliccioni M and Rancati T 2001 Radiation Protection Dosimetry 93 101–114
[12] Sato T, Yasuda H, Niita K, Endo A and Silhver L 2008 Radiation Research 170 244–259
[13] Matthiä D, Silhver L and Meier M 2008 Radiation Protection Dosimetry 131 222–228
[14] Mishev A, Adibpour F, Usoskin I and Felsberger E 2014 Advances in Space Research 55 354–362
[15] Copeland K 2017 Radiation Protection Dosimetry 175 419–431
[16] Bütikofer R and Flückiger E 2013 Journal of Physics: Conference Series 409 012166
[17] Bütikofer R and Flückiger E 2015 Journal of Physics: Conference Series 632 012053
[18] Mishev A and Usoskin I 2015 Journal of Space Weather and Space Climate 5 A10
[19] Tuohino S, Ibragimov A, Usoskin I and Mishev A 2018 Advances in Space Research 62 398–407
[20] Petoussi-Henss N, Bolch W, Eckerman K, Endo A, Hertel N, Hunt J, Pelliccioni M, Schlattl H and Zankl M 2010 Annals of the ICRP 40 1–257
[21] Usoskin I and Kovaltsov G 2006 Journal of Geophysical Research 111 D21206
[22] Mishev A and Velinov P 2011 Advances of Space Research 48 19–24
[23] Gleeson L and Axford W 1968 Astrophysical Journal 154 1011–1026
[24] Burger R, Potgieter M and Heber B 2000 Journal of Geophysical Research 105 27447–27445
[25] Usoskin I, Alanko-Huotari K, Kovaltsov G and Mursula K 2005 Journal of Geophysical Research 110 A12108
[26] Copeland K, Sauer H, Duke F and Friedberg W 2008 Advances in Space Research 42 1008–1029
[27] Shea M and Smart D 1990 Solar Physics 127 297–320
[28] Stoker P 1995 Space Science Reviews 73 327–385
[29] Mishev A and Velinov P 2015 Journal of Atmospheric and Solar-Terrestrial Physics 129 78–86
[30] Mishev A, Poluianov S and Usoskin I 2017 Journal of Space Weather and Space Climate 7 A28
[31] Mishev A and Velinov P 2018 Advances in Space Research 61 316–325
[32] Mishev A and Usoskin I 2016 Solar Physics 291 1225–1239
[33] Desorgher L, Flückiger E, Gurtner M, Moser M and Bütikofer R 2005 International Journal of Modern Physics A 20 6802–6804
[34] Tsyganenko N 1989 Planetary and Space Science 37 5–20
[35] Langel R 1987 Geomagnetism (London: J.A. Jacobs Academic Press) chap 1, pp 249–512
[36] Kudela K and Usoskin I 2004 Czechoslovak Journal of Physics 54 239–254
[37] Mishev A and Usoskin I 2013 Journal of Physics: Conference Series 409 012152
[38] Nevalainen J, Usoskin I and Mishev A 2013 Advances in Space Research 52 22–29
[39] Mishev A, Tuohino S and Usoskin I 2018 Journal of Space Weather and Space Climate 8 A468
[40] Latocha M, Beck P and Rollet S 2009 Radiation Protection Dosimetry 136 286–290