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

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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:

$$E(h, R_c, \theta, \varphi) = \sum_i \int_{E_{cut,i}(R_c)}^{\infty} \int_\Omega J_i(T) Y_i(T, h) d\Omega dT, \qquad (1)$$

where h is the altitude above sea level, R_c is the local cut-off rigidity, θ and φ 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:

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

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:

$$Y_i(T, T^*, h) = \sum_j \int_{T^*} F_{i,j}(h, T, T^*, \theta, \varphi) C_j(T^*) dT^*, \qquad (3)$$

where $C_j(T^*)$ is the fluence-to-effective dose conversion coefficient for a secondary particle of type j (neutron, proton, γ, e^-, e^+, μ^-, μ^+, π^-, π^+) 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

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

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.
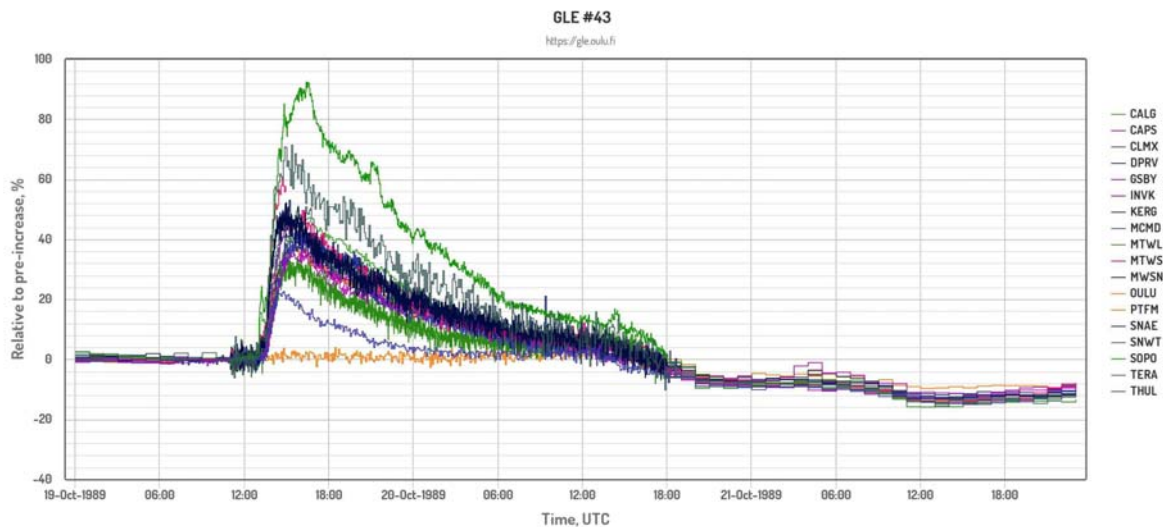
Figure 1. Global NM count rate increase during GLE 43 on 19 October 1989.

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.

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.

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 20006 (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.
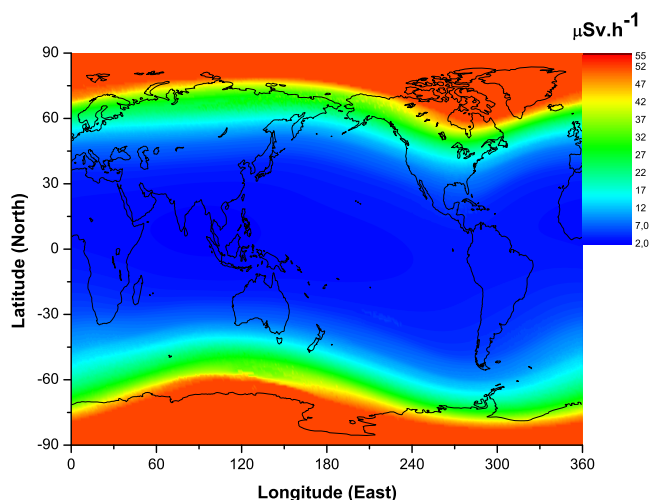
Figure 3. Map of the exposure during the main phase (03:30 UT) of GLE 70 on 13 December 2006.
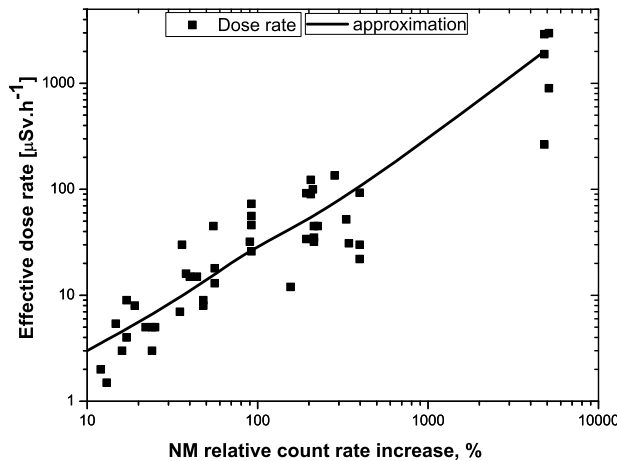
Figure 4. Peak effective dose rate during GLEs versus maximum NM count rate increase.

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

References

[1] Spurny 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] Lilensten 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 Sihver L 2008 *Radiation Research* **170** 244–259
[13] Matthiä D, Sihver 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 S 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 *Internationl 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