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Computation of dose rate at flight altitudes during ground level enhancements no. 69, 70 and 71

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Abstract

A new numerical model of estimating and monitoring the exposure of personnel due to secondary cosmic radiation onboard aircraft, in accordance with radiation safety standards as well as European and national regulations, has been developed. The model aims to calculate the effective dose at flight altitude (39,000 ft) due to secondary cosmic radiation of galactic and solar origin. In addition, the model allows the estimation of ambient dose equivalent at typical commercial airline altitudes in order to provide comparison with reference data. The basics, structure and function of the model are described. The model is based on a straightforward full Monte Carlo simulation of the cosmic ray induced atmospheric cascade. The cascade simulation is performed with the PLANETOCOSMICS code. The flux of secondary particles, namely neutrons, protons, gammas, electrons, positrons, muons and charged pions is calculated. A subsequent conversion of the particle fluence into the effective dose or ambient dose equivalent is performed as well as a comparison with reference data. An application of the model is demonstrated, using a computation of the effective dose rate at flight altitude during the ground level enhancements of 20 January 2005, 13 December 2006 and 17 May 2012.

Keywords: Radiation environment; Cosmic ray; Ground level enhancement; Monte Carlo; Space weather

1. Introduction

According to publication 60 of International Commission on Radiological Protection (ICRP, 1991) the exposure of flying personnel to cosmic radiation is recommended to be regarded as occupational. Accordingly, the Euratom Directive 96/12 (EURATOM, 1996) in Article 42 suggests measures to assess the individual doses of air crew and cabin personnel.

The Earth is constantly impinged by high energy subatomic particles – cosmic rays (CRs), mostly protons and α-particles and sporadically by solar energetic particles (SEP). Primary CR initiate a complicated nuclear-electromagnetic-muon cascade in the atmosphere generating large variety of secondary particles resulting in an ionization of the ambient air. In such a cascade a small fraction of the initial primary particle energy reaches the ground as high energy secondary particles. Most of the primary energy is released in the atmosphere by ionization and excitation of the air molecules (Bazilevskaya et al., 2008; Dorman, 2004; Usoskin et al., 2009). Therefore, CRs affect the radiation environment in the troposphere and stratosphere, specifically at flight altitudes. Although their contribution

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to exposure at ground levels is insignificant, they could contribute significantly at flight altitudes during some major ground level enhancements (GLEs) (O'Brien et al., 1997; Bütikofer et al., 2008; Matthiä et al., 2009a,b).

It is generally considered that the bulk of cosmic rays originate from the Galaxy, called galactic cosmic rays (GCR). Their intensity depends on the level of the solar activity, therefore it inversely follows the 11-year solar cycle and responds to long and short time scale solar–wind variations. Heliospheric transient phenomena also lead to strong, relatively short suppressions of GCR intensity in the vicinity of Earth, followed by a slower recovery on the time scale of several days, known as Forbush decrease (Forbush, 1958). The GCR near Earth are mostly composed of protons and helium nuclei and minor quantities of heavy ions. The abundances are approximately independent of the energy. For lower energies below 1 GeV/nucleon, the relative abundance of heavier nuclei increases, particularly around solar maximum because they are less modulated than protons.

Solar energetic particles are accelerated during explosive energy releases on the Sun (Cliver et al., 2004; Dorman, 2006; Reames, 1999; Aschwanden, 2012). The majority of SEP reach energies of the order of a few tens of MeV and are totally absorbed in the upper atmosphere. Accordingly, they do not contribute to increased exposure at commercial jet–flight altitudes. However, in some cases SEP can be accelerated to greater energies up to a few GeV and can penetrate deep into the atmosphere or even reach the ground, leading to the so-called ground level enhancements (GLEs). On average their occurrence is approximatively once per year with higher probabilities to occur during a solar maximum (Shea and Smart, 1990).

The transport of CR particles is affected by the Earth's magnetosphere, which prevents penetration of charged particles, i.e. it provides a shielding effect. The shielding is most effective near the geomagnetic equator. The capacity of the shielding is approximately quantified by the effective vertical rigidity cut-off R_C defined as particle's momentum over charge. Henceforth we consider the effective vertical rigidity cut-off (Cooke et al., 1991), which varies with the geographical location.

Therefore, the radiation environment, and accordingly the air-crew exposure due to CR of galactic and solar origin, varies with geographic position, altitude and solar activity (Spurny et al., 1996). Here we present a new model to calculate the exposure for three recent GLE events.

2. Numerical model for computation of effective dose rate and ambient dose equivalent at flight altitude

In general, determination of the radiation dose hazard due to CR of galactic and solar origin involves: precise knowledge of particle flux at the top of the atmosphere, realistic modeling of the nuclear cascade in the atmosphere, an appropriate model for calculation of the radiation dose as a function of altitude i.e. conversion of secondary particle fluence to dose and estimation of radiobiological effects.

It is possible to estimate the energy spectra of secondary particles resulting from interactions of primary CR with atmospheric nuclei and subsequently to compute the dose rate as a function of geomagnetic cut-off and altitude using a full Monte Carlo simulation of the atmospheric cascade (Ferrari et al., 2001; Roesler et al., 2002). Obviously, a detailed information about spectrum, composition and angular distribution of incoming CR particles is necessary as well as a tool for atmospheric cascade simulation. A large variety of primary and secondary CR ionizing particles, their wide energy range results in different exposure at different aviation routes (Spurny et al., 1996). Several models have been proposed of estimation the contribution of CR to dose rate (effective and ambient dose equivalent) at flight altitudes (Schraube et al., 2000; Ferrari et al., 2001; Roesler et al., 2002; Lewis et al., 2005; Copeland et al., 2008; Sihver et al., 2008; Sato et al., 2008; Kataoka et al., 2011; Mishev and Hristova, 2012; Mertens et al., 2013; Mishev, 2014).

Here we present a model based on simulations of the atmospheric cascade performed with GEANT4 (Agostinelli et al., 2003) based PLANETOCOSMICS (Desorgher et al., 2005) code. A realistic atmospheric model NRLMSISE2000 is assumed (Picone et al., 2002). The PLANETOCOSMICS code is a Monte Carlo tool for a detailed simulation of the cascade evolution in the atmosphere. The code simulates interactions and decay of nuclei, hadrons, muons, electrons and photons in the atmosphere up to high and very high energies. It yields detailed information about the secondary particle flux at a given observation level. In addition, the influence of the magnetic field of Earth is explicitly considered (the shielding effect) by simulation of particle trajectories in a model magnetosphere (see below).

The absorbed dose is defined as the energy deposited in a medium by ionizing radiation per unit mass. It is usually measured as joules per kilogram, represented by the equivalent SI unit Gy. For assessing the health risk due to radiation exposure it is convenient to use quantity most directly related to biological risk: the effective dose. Moreover, for various purposes of radiological protection conversion coefficients of fluence to effective dose for different kind of radiation (neutrons, protons photons, electrons, positrons, muons, charged pions) have been recently calculated (see Pelliccioni, 2000; Petoussi-Henss et al., 2010 and references therein). Since the effective dose is not a measurable quantity, International Commission on Radiological Protection suggest for operational purpose for radiation protection applications the ambient dose equivalent (ICRP, 2007) denoted as $H^*(d)$. It is defined as the dose equivalent that would be produced by the corresponding expanded and aligned field at a depth d in International Commission on Radiation Units and Measurements (ICRU) sphere on the radius vector opposing the direction of the aligned field. The ambient dose equivalent at a depth of 10 mm, $H^*(10)$, is recommended as a reasonable proxy for the effective dose. It should be stressed that ambient dose equivalent overestimates effective dose but is not a conservative estimate for cosmic radiation exposure at aviation altitudes according to Pelliccioni (2000) and Mertens et al. (2013). Nevertheless, it is regarded as an acceptable approximation for effective dose at aircraft altitudes (Meier et al., 2009; Mertens et al., 2013).

The effective dose rate at a given atmospheric depth h induced by a primary cosmic ray particle can be determined as:

$$D(h,\lambda_m) = \sum_{i,j} \int_{E(\lambda_m)} \int_{E'} \int_{\Omega} J_j(E) C_i(E') F_{i,j}(h,E,E'\theta,\varphi) dE d\Omega dE'. \tag{1}$$

$C_i(E')$ is the conversion coefficient for a secondary particle of type i (neutron, proton, γ, e^-, e^+, μ^-, μ^+, π^-, π^+) with energy E', $F_{i,j}(h,E,E'\theta,\varphi)$ is the secondary particle flux of type i, produced by a primary particle of type j (proton and/or α-particle) with a given primary energy E arriving from zenith angle θ and azimuth angle $\varphi, J(E)$ is the differential primary cosmic ray spectrum at the top of the atmosphere for j component (proton and/or α-particle), λ_m is a geomagnetic latitude, Ω is a solid angle. The geomagnetic latitude λ_m defines the integration limit. The conversion coefficients $C_i(E')$ for a secondary particle of type i are obtained on the basis of Monte Carlo simulations with several codes: FLUKA (Fasso et al., 2005; Battistoni et al., 2007), MCNPx (Briesmeister, 1997), PHITS (Iwase et al., 2002; Niita et al., 2006), GEANT4 (Agostinelli et al., 2003) and EGSnrc (Kawrakow, 2002). Those calculations are made by the DOCAL task Group using reference computational phantom (ICRP, 2009). In the work presented here we assume the data sets for isotropic particle fluence from Annex A of Petoussi-Henss et al. (2010). The term $F_{i,j}(h,E,E'\theta,\varphi)$ includes the complexity of atmospheric cascade development, since it brings information of particle fluence and spectrum at given altitude in the atmosphere (39,000 ft or 12,000 m above sea level (a.s.l.)). Since we apply a full target modeling of the atmospheric cascade, the model allows computations at any altitude. Thus this term includes the transport, production and attenuation of secondary CR particles. The term $J_j(E)$ refers to primary CR spectrum (solar or galactic). The assumed SEP spectra and angular distribution are taken from ground based reconstruction using neutron monitor data. Accordingly, the ambient dose equivalent can be estimated with similar equation, using the corresponding conversion coefficient from Appendix 2 in Pelliccioni (2000).

2.1. Force field model for GCR

A detailed description of the assumed model for GCR spectrum is given in Usoskin et al. (2005). The GCR flux is affected by the interplanetary magnetic field and solar wind, resulting in modulation of their flux and differential energy spectrum in the vicinity of the Earth. The modulation varies with solar activity and is often described in terms of the force field model (Gleeson and Axford, 1968; Caballero-Lopez and Moraal, 2004). The only explicit parameter of this model is the modulation potential ϕ given in units of MV. The value of $Ze\phi$ corresponds to the average energy loss of cosmic rays inside the heliosphere. The differential intensity J_j of cosmic ray nuclei of type j at 1 AU is given as

$$J_j(T,\phi) = J_{LIS,j}(T+\Phi_j)\frac{(T)(T+2T_r)}{(T+\Phi_j)(T+\Phi_j+2T_r)}, \tag{2}$$

where T is the kinetic energy per nucleon of primary CR with charge Z and atomic A and $\Phi_j = (Z_j e/A_j)\phi$. The proton rest mass energy is $T_r = 938$ MeV . $J_{LIS,j}$ is the local interstellar spectrum (LIS) of primary CR nuclei of type j, considered here for protons by the approximation (Burger et al., 2000; Usoskin et al., 2005)

$$J_{LIS,p}(T) = \frac{1.9\times10^4\cdot P(T)^{-2.78}}{1+0.4866P(T)^{-2.51}}, \tag{3}$$

where $P(T) = \sqrt{T(T+2T_r)}$, J is expressed in [particles/ m^2 sr s GeV/nuelon], T in [GeV/nucleon]. Accordingly we consider the nucleonic ratio of heavier particles including α-particles to protons in the interstellar medium as 0.3 (Nakamura et al., 2010) similarly to Kovaltsov et al. (2012).

This model with the corresponding parametrization of LIS provides very good fitting of the measured spectra (for details see Usoskin et al., 2005).

2.2. Magnetospheric model

Here we use the MAGNETOCOSMICS code (Desorgher et al., 2005) to calculate particle's transport in the geomagnetic field. As the internal field we consider the IGRF geomagnetic model (Langel, 1987) which is a Gauss spherical harmonic model of the geomagnetic field, based on magnetic field measurements from geomagnetic stations, magnetometers and satellites. As the external field model we use a semi-empirical Tsyganenko 1989 (Tsyganenko, 1989) model which is based on a large number of satellite observations. The model takes into account contributions from external magnetospheric sources: ring current, magnetotail current system, magnetopause currents and a large-scale system of field-aligned currents. The model takes into consideration seasonal and diurnal changes of the magnetospheric field as well as the geomagnetic activity level K_p. Thus the Tsyganenko 89 model provides seven different states of the magnetosphere corresponding to different levels of geomagnetic activity. It is driven only by the geomagnetic activity index K_p and provides perfect balance between simplicity (Nevalainen et al., 2013) and realism (Kudela and Usoskin, 2004; Kudela et al., 2008).

2.3. Comparison of the model results with the reference data

Since the ambient dose equivalent can be estimated by measuring the linear energy transfer spectrum of absorbed dose in a tissue-equivalent material, followed by a conversion to $H^*(10)$ using the radiation quality factor and corresponding calibration, there exists a reference data set (Menzel, 2010). In order to compare the model results with the reference data we estimate the ambient dose equivalent due to GCR corresponding to different solar activity conditions.

Contribution of GCR to the effective dose rate, and respectively the ambient dose equivalent at flight altitude in different regions of the Earth is estimated on the basis of the described above numerical model. We perform simulations of 10^6 primary CR induced atmospheric cascade events using the PLANETOCOSMICS code. We assume the isotropic spatial distribution and the energy spectrum parameterized with the force field model described above. The modulation parameter ϕ is adopted from the reconstruction (Usoskin et al., 2011) based on ground based NM data. The simulations are performed applying a realistic mass composition of the primary CR (Nakamura et al., 2010) since the contribution of α- particles to the secondary particles flux in the atmosphere is important. The contribution of heavier species is scaled to that for α- particles (cf. Usoskin and Kovaltsov, 2006; Mishev and Velinov, 2011; Kovaltsov et al., 2012).

The flux of various secondary particles, namely neutron, proton, γ, e^-, e^+, μ^-, μ^+, π^-, π^+ computed for the flight altitude. Subsequently, the ambient dose equivalent is computed on the basis of Eq. (1) and conversion coefficients from Appendix 2 of Pelliccioni (2000).

The estimated ambient dose equivalent at the flight altitude due to GCR, at locations with various rigidity cut-offs are presented in Figs. 1–3 for 1998, 2000 and 2002, respectively. The error bars in the plot represent the statistical accuracy of the simulations. The model systematic uncertainty due to the assumed GCR spectrum and hadron generator model is also plotted (Usoskin and Kovaltsov, 2006; Mishev and Velinov, 2008; Usoskin et al., 2009; Mishev and Velinov, 2010). The computed ambient dose equivalent is compared with reference data of the Menzel (2010) based on different measurements, mostly from Goldhagen (2000). A reasonable agreement is achieved, which allows subsequent computation of radiation exposure during some GLEs.

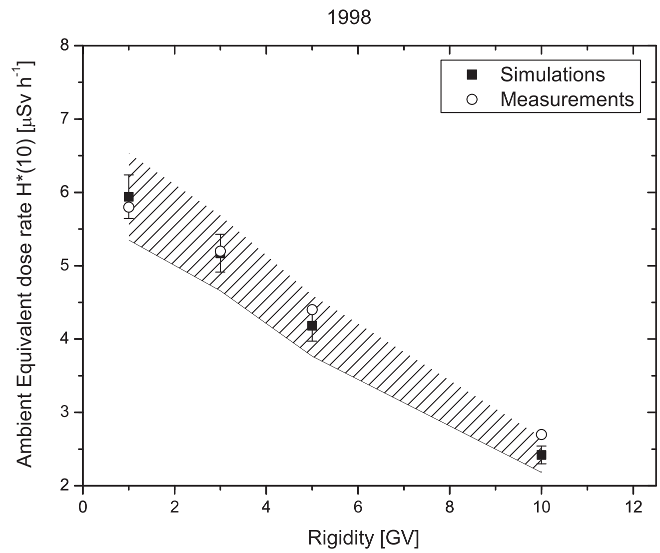

Fig. 1. Ambient dose equivalent at flight altitude (39,000 ft a.s.l) due to GCR for year 1998 ($\phi = 550$ MV) obtained with PLANETOCOSMICS code simulation compared with reference data. The hatched region represents the model uncertainty due to assumed GCR spectrum and atmospheric cascade simulations.

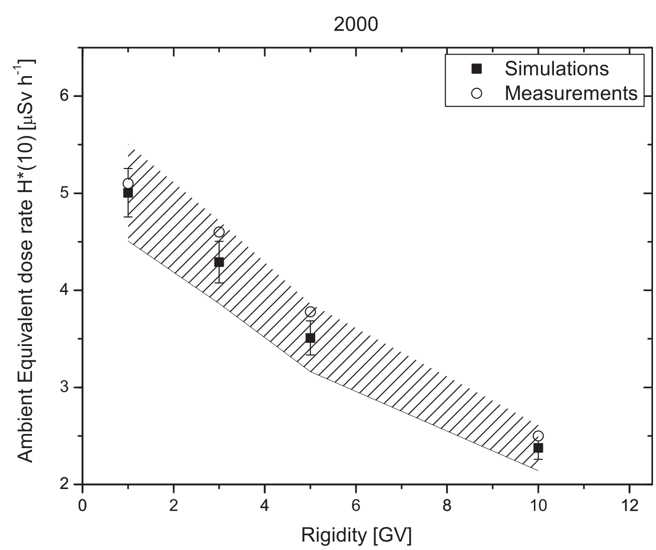

Fig. 2. Ambient dose equivalent at flight altitude (39,000 ft a.s.l) due to GCR for year 2000 ($\phi = 750$ MV) obtained with PLANETOCOSMICS code simulation compared with reference data. The hatched region represents the model uncertainty due to assumed GCR spectrum and atmospheric cascade simulations.

3. Computation of the effective dose rate at flight altitude for GLEs 69, 70 and 71

The effective dose rate during a major GLE is a superposition of those due to GCR and SEP flux. The maximum effect of GLEs on radiation environment in the sense of ionization is expected during the first hours from the event onset (Bazilevskaya, 2005; Usoskin et al., 2009; Mishev et al., 2011, 2012; Mishev and Velinov, 2013). In addition, it is shown that the results of computations of the expected dose rate at flight altitude strongly depend on the considered model assumptions and assumed CR spectra (Butikofer and Fluckiger, 2013). In order to estimate the radiation exposure at the flight altitude, a full Monte Carlo simulation of the atmospheric cascade is performed using PLANETOCOSMICS code and applying SEP spectra and angular distribution, which plays a considerable role for primary CR intensity distribution over the globe, as reconstructed from NM measurements (Vashenyuk et al., 2006a, 2008). Subsequently, the effective dose rate is computed on the basis of Eq. (1) and conversion coefficients from Annex A of Petoussi-Henss et al. (2010).

The method of reconstruction of SEP spectra and angular distribution using neutron monitor (NM) data consists of determination of the asymptotic viewing cones of the NM stations with computation of particle trajectories in

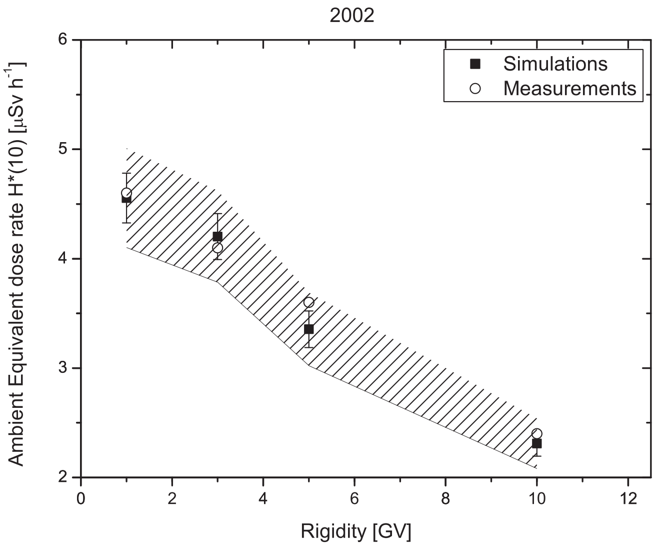

Fig. 3. Ambient dose equivalent at flight altitude (39,000 ft a.s.l) due to GCR for year 2002 ($\phi = 950$ MV) obtained with PLANETOCOSMICS code simulation compared with reference data. The hatched region represents the model uncertainty due to assumed GCR spectrum and atmospheric cascade simulations.

a model magnetosphere and solution of the inverse problem for fitting the world NM network response (Cramp et al., 1997; Vashenyuk et al., 2006a; Mishev et al., 2013).

Solar cycle 23 has provided some of the largest SEP events, namely those in mid-January 2005 and on 13 December 2006 (Shea and Smart, 2012). On 20 January 2005 all the energy channels of GOES satellite registered a large enhancement of proton flux with SEP onset at 6:50 UT. This event was characterized by an anisotropic component with a very hard spectrum at the onset of the event, followed by a long isotropic emission with a softer spectrum (McCracken et al., 2008; Plainaki et al., 2007). The event occurred during the recovery phase of a large Forbush decrease leading to a reduced GCR flux. The modulation potential ϕ was adopted from Table 3 in Usoskin et al. (2011). In addition, the assumed GCR flux was reduced explicitly with the amplitude of the Forbush effect i.e. with some 15%. The large anisotropy of the event was explicitly considered. The CR flux at the top of the atmosphere was considered according to the derived spectra and pitch angle distribution (PAD). Therefore, the computations are performed at North and South polar regions separately.

The event of 13 December 2006 occurred during the decline phase of solar cycle 23 when the conditions on the Sun and in the interplanetary medium were corresponding to a minimum solar activity. However, this event was among the largest ones. The event depicted a large anisotropy in its initial phase (Bütikofer et al., 2009; Plainaki et al., 2009).

We consider here the SEP spectra for GLEs 69 and 70 as reconstructed previously by Vashenyuk et al. (2006a,b, 2008, 2009) using the NM data.

These events have been studied in the sense of exposure, specifically at the flight altitude (Bütikofer et al., 2008; Beck, 2009; Matthiä et al., 2009a,b). Here we consider these events using the SEP spectra reconstructed for the initial phase of the event (see Table 1 in Vashenyuk et al., 2006a, 2008), when the enhanced exposure due to SEP is important. We also consider the delayed component, when the particle flux is lower and the resulting effective dose rate is less important. For the computations we consider the flux and anisotropy distribution of SEP particles at polar region in order to evaluate a maximal effect. A summary of the computed effective dose rates is presented in Table 1. A good agreement with previously published results is observed.

The observed difference can be attributed to the different assumed SEP spectra, which can lead to uncertainties of the computed effective dose rate up to an order of magnitude (Butikofer and Fluckiger, 2013).

Next we model a new recent event of GLE 71. On 01:25 UT 17 of May 2012 the active region NOAA 11476 at the Sun produced a moderately strong (class M5.1) flare. The active region was located at N07 W88 at the Sun. Around 01:50 UT the NM worldwide network detected the first enhancement since December 2006. The count rate of polar NMs remained above the background for about an hour, as registered by several NM stations. The highest signal was detected at South Pole, Oulu and Apatity NMs with maximal count rate increase of about 22%. The remaining NM stations registered moderate increases of only a few %. This implies a large anisotropy at the beginning of the event is observed.

Table 1
Effective dose rate [μSv/h] during GLE69, GLE70 and GLE 71 at commercial flight altitude (39,000 ft a.s.l.). The previously reported computations: *, **, ***. SP refers to South pole region, while NP to North pole.

GLE69			GLE70		GLE71
Initial phase (07:00 UT) SP	Initial phase (07:00 UT) NP	Late phase (08:00 UT)	Initial phase (03:00 UT)	Late phase (04:00 UT)	Initial phase (02:00 UT)
986 1000*–1500**	145 ≈100*,**	186 ≈120*,**	56.2 25–30***	14.2 ≈20***	21.1 –

* Refers to Matthiä et al. (2009a).
** Refers to Bütikofer et al. (2008).
*** Refers to Matthiä et al. (2009b).

For GLE 71 we applied the SEP spectrum recently reconstructed on the basis of the world NM database (Mishev et al., 2013). Modeling of NM responses was performed using the recently published new NM yield function (Mishev and Usoskin, 2013; Mishev et al., 2013) assuming a modified power law rigidity spectrum of solar particles

$$J_{||}(P) = J_0 P^{-(\gamma+\delta\gamma(P-1))}, \tag{4}$$

where $J_{||}$ is the SEP flux arriving from the Sun along the pitch angle distribution with respect to the axis of symmetry defined by geographic coordinate angles Ψ and Λ, γ is the power-law spectral exponent at rigidity $P = 1$ GV, $\delta\gamma$ is the rate of the spectrum steepening. PAD is modeled as a superposition of two Gaussians

$$G(\alpha) = exp(-\alpha^2/\sigma_1^2) + B * exp(-(\alpha - \alpha')^2/\sigma_2^2), \tag{5}$$

where α is the particle's pitch angle, σ_1 and σ_2 are the width parameters of PAD, B and α' are parameters of the flux from a second direction likely to be approximately opposite to the fitted arrival axis of symmetry. The pitch angle is defined as the angle between the asymptotic direction and the axis of anisotropy. Compared with previous analyses, the more general pitch angle formalism allows more realistic interpretation of the local characteristics of the particle propagation. An example of derived SEP spectra and PAD at several moments of the GLE 71 are shown in Fig. 4. Details are given in Table 1 of Mishev et al. (2013).

We have performed computations of the effective dose rates in the polar region for this event. The rigidity cut-off on a grid of $1 \times 1^\circ$ in a polar and sub-polar regions was computed using the IGRF geomagnetic model (epoch 2010) as the internal field model with the Tsyganenko 89 model as the external field using MAGNETOCOSMICS code. Asymptotic directions of SEP were computed on a grid of $15 \times 5^\circ$ in polar and sub-polar regions.

By applying the PAD, the SEP energy spectrum and the anisotropy axis direction as reconstructed by Mishev et al. (2013), we performed a Monte Carlo simulation of the atmospheric cascade for these events. Subsequently, on the basis of the described above numerical model we computed the effective dose rates at various geographical points. The computed effective dose rates during the main phase of GLE 71 are presented in Table 1. The corresponding map of the effective dose rate during the initial phase of GLE71 on 17 May 2012 in a polar and sub-polar region is shown in Fig. 5.

4. Summary and discussion

Studies of the contribution of CR particles of galactic and solar origin during some major GLEs on aircrew exposure is of great importance (Reitz, 1993; O'Brien et al., 1997; Spurny et al., 2002; Vainio et al., 2009). The potential biological risk of radiation doses, specifically of aircrew exposure is still a matter of scientific debate (Sigurdson and Ron, 2004; Ballarini et al., 2007).

In this paper we assessed the effective dose rates during several major GLEs of solar cycle 23, namely GLE 69, GLE 70 and GLE 71. During these events the effective dose rate was computed as a superposition of the effects caused by GCR and SEP fluxes. The spectral and angular distributions of SEPs were explicitly considered during the computations. The results were obtained using a numerical model on the basis of a full Monte Carlo simulation of the atmospheric cascade induced by CR of galactic and solar origin. The model can be used at various altitudes above sea level, since we perform a full target simulation of the atmospheric cascade.

It is shown that during the initial phase of the major event of 20 January 2005 the effective dose rate at the flight

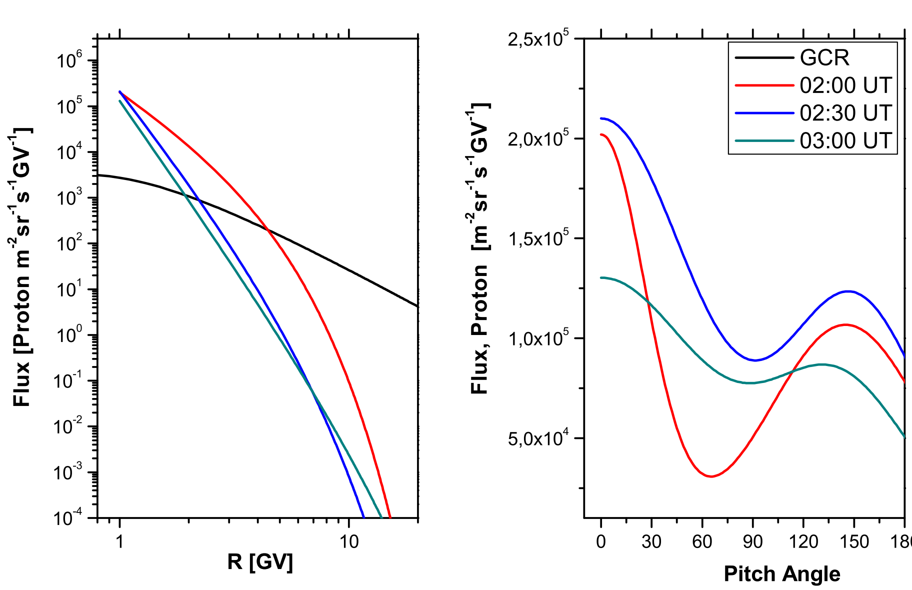

Fig. 4. Derived spectra and pitch angle distribution of high-energy SEP during GLE 71 on May, 17 2012 for several time intervals.

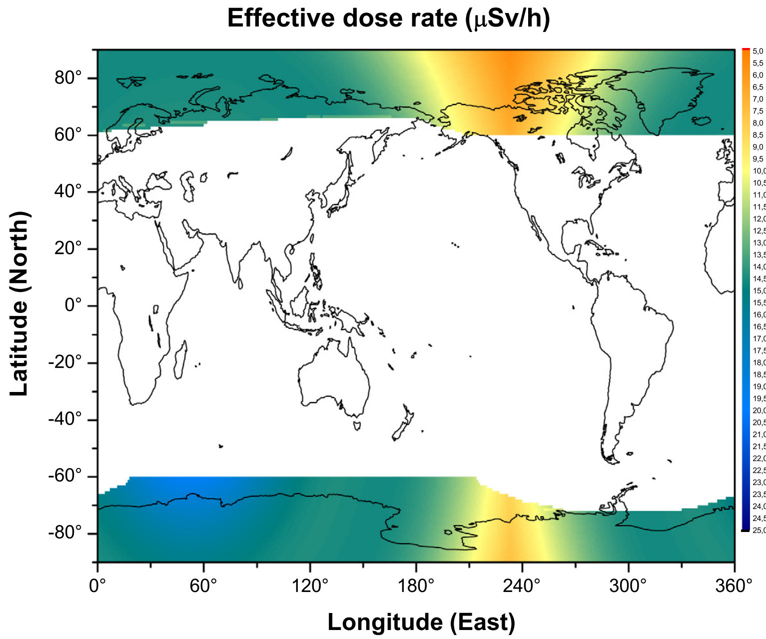

Fig. 5. Map of the computed effective dose rate at flight altitude (39,000 ft a.s.l) in a polar and sub-polar region during the initial phase (02:00 UT) of GLE 71 on May, 17 2012.

altitude (39,000 ft or 12,000 m above sea level) was ≈150 μSv/h at North polar region and ≈1000 μSv/h at South polar region. During the late phase of this event the computed effective dose rate was still significant ≈200 μSv/h. Therefore, this event could increase significantly the potential biological risk of aircrew members and passengers. The computed effective dose rate at the flight altitude during the initial phase of GLE70 on 13 December 2006 was about 50 μSv/h, thus the expected risk is comparable to the declining phase of GLE69. However, the computed effective dose rate at flight altitude during the late phase of GLE70 is considerably lower. The computed effective dose rate at flight altitude during the initial phase of GLE71 on 17 of May 2012 was greater than the for the late phase of GLE70. It is roughly three times greater than the average due to GCR.

As recently demonstrated the expected computed effective dose rate at flight altitude during some major GLEs is highly dependent on assumed SEP spectra (Butikofer and Fluckiger, 2013). In addition, other model assumptions (Mishev and Velinov, 2010) lead to about 15% difference of secondary particle characteristics, accordingly the effective dose rate. In this respect, the obtained computations are in a full agreement with some previously reported results (Bütikofer et al., 2008; Matthiä et al., 2009a,b). The applied 3-D model is a contribution to the recent Monte Carlo studies related to radiation measurements (O'Sullivan et al., 2002; Makovicka et al., 2009) as well as to registration of SEP and their exposure effect during intercontinental flights (Regulla and David, 1993; Spurny et al., 2002, 2008).

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