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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 esti-