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Extensive air shower Monte Carlo modeling at the ground and aircraft flight altitude in the South Atlantic Magnetic Anomaly and comparison with neutron measurements

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ABSTRACT

Modeling cosmic-ray-induced particle fluxes in the atmosphere is very important for developing many applications in aeronautics, space weather and on ground experimental arrangements. There is a lack of measurements and modeling at flight altitude and on ground in the South Atlantic Magnetic Anomaly. In this work we have developed an application based on the Geant4 toolkit called *gPartAt* that is aimed at the analysis of extensive air shower particle spectra. Another application has been developed using the MCNPX code with the same approach in order to evaluate the models and nuclear data libraries used in each application. Moreover, measurements were performed to determine the ambient dose equivalent rate of neutrons at flight altitude in different regions and dates in the Brazilian airspace; these results were also compared with the simulations.

The results from simulations of the neutron spectra at ground level were also compared to data from a neutron spectrometer in operation since February 2015 at the Pico dos Dias Observatory in Brazil, at 1864 m above sea level, as part of a collaboration between the Institute for Advanced Studies (IEAv) and the French Aerospace Lab (ONERA). This measuring station is being operated with support from the National Astrophysics Laboratory (LNA). The modeling approaches were also compared to the AtmoRad computational platform, QARM, EXPACS codes and with measurements of the neutron spectrum taken in 2009 at the Pico dos Dias Observatory.

1. Introduction

The characterization of the cosmic-ray-induced particles in the atmosphere is of importance for aeronautical applications, space weather and on ground experimental arrangements. A comprehensive description of the transport of such ionizing particles in the atmosphere (atmospheric cosmic radiation) is very important to evaluate Single Event Effects (SEE) in electronics [1–3], as well as the dose received by aircrew members and frequent flyers [4–7].

A large part of Brazilian territory, as well as the southern part of South America, are located in the South Atlantic Magnetic Anomaly (SAMA) region. In this region, there is a lack of measurements of the cosmic-ray-induced particles at flight altitude that would permit the evaluation of the possible effects of this magnetic anomaly on the behavior of these particles.

Also, the majority of the codes used to characterize atmospheric cosmic radiation at flight altitudes neglect the Earth's magnetic field at low altitudes. The capacity of the software to simulate the cosmic radiation in the atmosphere is limited for external users and, when available, a detailed description of this field from the ground up to altitudes of aeronautical interest is not considered. Moreover, they do not consider the transport the cosmic radiation into the atmosphere along the Earth's magnetic field lines and, therefore, do not appear to be adequate for assessment of the effect of the SAMA on cosmic radiation transport in the atmosphere in this region.

The study of the effects of the atmospheric cosmic radiation in avionic systems, aircrew members and onboard radiation dosime-

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ters requires a detailed description of the incident radiation on the aircraft, such as the composition of this radiation field and the spectra and angular distributions of secondary particles, in order to obtain an accurate description of this radiation field inside the aircraft. Indeed, there are indicators that the structure of the aircraft and materials such as fuel and also passengers could change the composition and energy of the radiation field inside the aircraft [8].

In order to characterize the extensive air shower in the atmosphere in a specific position from ground level up to 80 km altitude, while taking into the SAMA effects, we have developed an application called *gPartAt* based on Monte Carlo simulations using the Geant4 toolkit [9,10].

Results of the comic-ray-induced neutron spectra at ground level and the ambient equivalent dose rate at ground and flight altitudes for two different regions of Brazil in the SAMA and for two calendar dates using this application are reported in this work.

Another application using the same approach was developed using the MCNPX code [11] in order to verify differences with the previous application and to evaluate the suitability of the physical models used. Moreover, additional results obtained with other codes that are based on different approaches, such as the AtmoRad computational platform, QARM and EXPACS codes, will be shown.

2. Computational modeling

In this section the main aspects of the methodology developed for the computational modeling using the Monte Carlo codes are described.

2.1. Determination of the fluence on a planar surface

According to Attix [12], the definition of planar fluence is the number of particles that cross a unit area of surface, independently of their direction. The fluence is the ratio of the number of particles dN incident on a sphere with sectional area $d\alpha$, $\phi_i = dN/d\alpha$, as defined by the International Commission on Radiation Units & Measurements (ICRU) [13].

The counting of particles in the simulations performed by Geant4 and MCNPX was calculated for a circular planar surface (planar fluence) with radius equal to that of the source of primary particles. In order to calculate the fluence rate from the planar fluence, we used Chilton's Theorem [14]. To do this, it was necessary to use the angle of incidence of the particles on the circular surface.

In the space industry, the quantity "fluence" is commonly referred to as "flux". The quantity "fluence" used on this work can be compared directly to the "flux" from codes such as QARM and EXPACS.

2.2. Primary cosmic radiation

To correctly reproduce the primary cosmic radiation in the simulations, an external routine that determines the spectra of the cosmic rays (CR) that arrives at the top of the atmosphere was implemented in Geant4 and MCNPX. To do this, we used as a basis the methodology described by Matthia et al. [15].

The main idea of this methodology is to parameterize the fluence rate of the cosmic radiation incident in the atmosphere as a function of the on ground neutron counting rate from the Oulu monitoring station [16]. In this way, one determines the differential fluence rate as a function of the energy and time $F_i(E, t)$:

$$F_i(E,t) = \frac{dN}{dA dt d\Omega}(E,t) = \Phi_i(R(E),t)\frac{A_i}{|Z_i|}\frac{1}{\beta} = \frac{C_i\beta^{\alpha_i}}{R(E)\gamma_i}\left[\frac{R(E)}{R(E)+\left(0.37+3\cdot 10^{-4}\cdot W(t)^{1.45}\right)}\right]^{b\cdot W(t)+c}\frac{A_i}{|Z_i|}\frac{1}{\beta} \tag{1}$$

in which:

- Φ_i is the differential fluence rate of a particle i from the galactic cosmic ray flux as a function of the magnetic rigidity R (GV) for a given time t;
- N is the number of particles, A is the area and Ω the solid angle;
- C_i, α_i, γ_i are parameters taken from the ISO model [17] and dependent on the kind of particle;
- A_i and Z_i are, respectively, the atomic mass and atomic number of the particle that composes the galactic cosmic ray flux.
- The parameter W is related to the solar activity and is parameterized in terms of a specific on ground neutron counting rate.

In order to determine the constants b and c, one uses the data obtained from the CRIS experiment (Cosmic Ray Isotope Spectrometer) of the ACE spacecraft. In a second step, the data from ACE/CRIS were correlated to the on ground neutron counting of the Oulu neutron monitoring station, so that the parameter W has a linear relationship with the particles flux from the CRIS experiment [18]:

$$W_{Oulu} = -0.093 \cdot cr + 638.7 \tag{2}$$

where cr is the neutron counting rate given in counts/min. In this way it is possible to consistently normalize the spectra of incident particles that arrives at the top of the atmosphere.

The cosmic radiation incident on the atmosphere is mainly composed of protons (≈87%) and alphas (≈12%) [19]. Therefore, in this work we consider only these two particles as the primary particles incident on the atmosphere. For each primary particle the magnetic rigidity was calculated as a function of the kinetic energy. The cutoff rigidity was calculated at a given altitude and geographic position from [20],[21]. As a first order approximation, we applied the cutoff rigidity as a threshold such that particles with a magnetic rigidity below this value are trapped or deflected by the Earth's magnetic field and are thus excluded from the input spectrum.

As an example, the city of São José dos Campos (Brazil) is at the coordinate 23°11′11′′ S 45°52′43′′ W. For this geographic position, the cutoff rigidity was 9.6 GV during February 15, 2010. The kinetic energy of alpha particles with a magnetic rigidity of 9.6 GV is 15.83 GeV while for protons it is 8.71 GeV. Therefore, only protons with energies above 8.71 GeV from the spectrum of Eq. (1) are considered as primary particles incident on the atmosphere. For alpha particles, only those with energies above 15.83 GeV were taken into account.

Fig. 1 shows the proton and alpha spectra incident in the atmosphere for a cutoff rigidity of 0 GV, that is equivalent to a situation in which there is no shielding effect against the primary cosmic radiation. The dotted lines correspond to the cutoff energies of protons (black line) and alphas (red line) for the São José dos Campos region.

A comparison between the results from this methodology and the QARM code was made in order to verify the implementation of the methodology in our platform. With QARM, the fluence rates of protons and alphas at 85 km altitude in 02/15/2010 in the São José dos Campos region were calculated. For these conditions, the cutoff rigidity was 9.6 GV and the neutron counting rate at the