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Space Weather Alerts for Air Navigation

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Abstract

The aim of this work is to determine the total integrated flux of cosmic radiation which a commercial aircraft is exposed to along specific flight trajectories. Selection of these trajectories is based on its utilization and geomagnectical effects along them, for example the South Atlantic Anomaly. In order to study the radiation background during a flight and its modulation by effects such as altitude, latitude, exposure time and solar events, we perform simulations based on codes *Magnetocosmics* and *CORSIKA*, the former designed to calculate the geomagnetical effects on cosmic rays propagation and the latter allows us to simulate the development of extended air showers. Considering the energy range for primary particles from 5 Gev to 1 Pev, we obtain the total flux of secondary particles by means of point-to-point numerical integration.

Keywords: Cosmic rays, aircraft, CORSIKA, Magnetocosmics

1. Introduction

The Earth is constantly being bombarded by subatomic particles which come from the Sun, the Milky Way and extragalactic sources. These particles, known as *primaries*, reach our planet with energies that vary over a wide range: it begins at 10^5 eV for particles from solar wind and ends beyond 10^{20} eV for intergalactic particles. The lower energy primaries are deflected by Earth's magnetosphere, but the higher energy ones penetrate the atmosphere colliding with atoms in the air and generating a cascade of *secondary particles*. As altitude increases, the atmosphere protective layer becomes thinner and less dense, that's why the incidence of cosmic radiation on an airplane flying between 10 km - 12 km is much higher than at ground levels. Besides altitude, there are other factors that may affect the dose received, such as latitude, space weather, and time of exposure. This phenomenon has been investigated only in the last two decades and it has become an occupational health issue in some countries (see, for example [1]). To calculate the number of particles incident on an aircraft flying several routes, simulations will be performed using *CORSIKA* and *Magnetocosmics*. *CORSIKA* (COsmic Ray SImulations for KAscade) [2] is a detailed Monte Carlo program to study the evolution and properties of extensive air showers in the atmosphere. *Magnetocosmics* [3] is a code based on Geant4 that allows to calculate the trajectories of charged particles through different geomagnetic field models.

2. Rigidity of a particle

The motion of a charged particle through a magnetic field is described by the relativistic Lorentz equation of motion:

$$\frac{d\vec{p}}{dt} = \frac{q}{c}\vec{v} \times \vec{B} \tag{1}$$

This equation of motion conserves the magnitude of the momentum p, and therefore the energy of the particle. After some transformations, it becomes:

$$\frac{d\hat{\boldsymbol{I}}_v}{ds} = \frac{q}{pc}\hat{\boldsymbol{I}}_v \times \vec{B} \tag{2}$$

where $\hat{\boldsymbol{I}}_v$ is the unit vector in the direction of velocity and s is the path length along the particle trajectory. The rigidity of the particle is defined by:

$$R = \frac{pc}{q} \tag{3}$$

And it is a measure of the resistance of the particle to the bending of its trajectory by the magnetic field.

Rigidity cut-off

It is the lower rigidity limit above which cosmic rays can cross the Earth magnetosphere and reach a specific position from a specific observational direction. It depends on the geographical coordinates and on particle's direction of arrival.

3. Earth magnetic field models

Internal field ($r < 5R_E$)

The International Geomagnetic Reference Field (IGRF) [4] is an internationally agreed and widely used mathematical model of the Earth magnetic field of internal origin. In this model:

$$\vec{B} = -\vec{\nabla} V \qquad \nabla^2 V = 0 \tag{4}$$

Each constituent model of the IGRF is a set of spherical harmonics of degree n and order m, representing a solution to Laplace's equation for the magnetic potential arising from sources inside the Earth at a given epoch; the harmonics are associated with the Gauss coefficients g_n^m and h_n^m:

$$V(r,\theta,\lambda) = a \sum_{n=1}^{n_{max}} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^{n} (g_n^m \cos m\lambda + h_n^m \sin m\lambda)\, P_n^m(\theta) \tag{5}$$

External field ($r > 5R_E$)

Beyond five Earth radii, the Earth magnetic field is increasingly affected by the solar wind interaction with the Earth magnetosphere. The distortions can be described by several external source fields caused by magnetospheric current systems.
The Tsyganenko model [5] is a semi-empirical best-fit representation for the magnetic field, based on a large number of satellite observations (IMP, HEOS, ISEE, POLAR, Geotail, etc). The model includes the contributions from external magnetospheric sources: ring current, magnetotail current system, magnetopause currents and large-scale system of field-aligned currents.

4. Strategy

1. Simulation of showers at a specific site (longitude, latitude, altitude) using *CORSIKA*. Features of injected primaries at the top of the atmosphere:
   - Nuclei considered: $1 \le Z_p \le 26$, $1 \le A_p \le 56$
   - Very low cut-off rigidity: $R_c = 4GV$
   - Energy and direction of arrival: $(R_c \times Z_p) \le (E_p/GeV) \le 10^6$, $0° \le \theta_p \le 90°$, $0° \le \phi_p \le 360°$
   - Simulation time: $t = 7200s$ (primary particles flux is constant and isotropic)
2. Selection and discretization of routes.
3. Computation of cut-off rigidities for each point in the trajectory using *Magnetocosmics*.
4. Filter of the first simulated showers according to the cut-off rigidities computed for each point of the trajectory: showers generated by primary particles with rigidities below the cut-off rigidities are discarded.
5. Computation of the total amount of particles that hit the aircraft. This is done asuming a constant flux of secondaries on each interval of the trajectory and adding them together.
6. To consider diferent magnetospheric conditions, it is possible to vary the DST index (Disturbance Storm Index).

5. First results

The trajectory chosen was Bogotá - Buenos Aires, this route was divided into 12 intervals of equal flight time and the flux of secondaries along each of them was assumed to be constant and equal to the flux in the midpoint (blue dots). Takeoff and landing was not included in this preliminar analysis and the aircraft was supposed to fly at a constant altitude of 11 km along the whole trajectory. The data used corresponds to flight ARG1361, made on 24-11-2014. To study the effect of geomagnetic field on the flux of particles and as a way to validate simulations, we calculated the spectrum of secondary particles when geomagnetic field was present and when it was not (figures 1 and 2). We noted, as expected, that there is a significant reduction of the flux for low energies when the field is taken into account. In figure 3 it is shown the distribution of particles along the whole trajectory and in figure 4 it is possible to compare the flux of particles when being on the ground with the flux when being on an airplane.

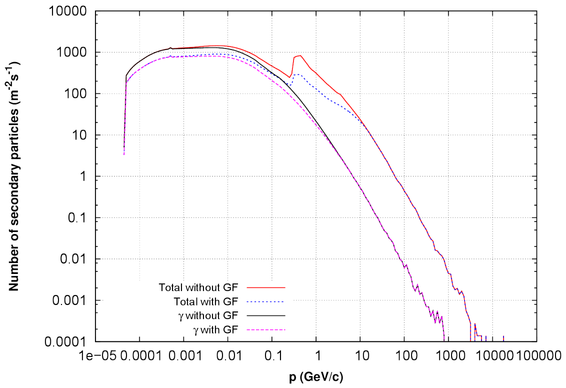

Figure 1: *Distribution of particles considering the Geomagnetic Field (dashed lines) and not considering it (continuous lines). Location:* $14.74°S$ $67.27°W$.

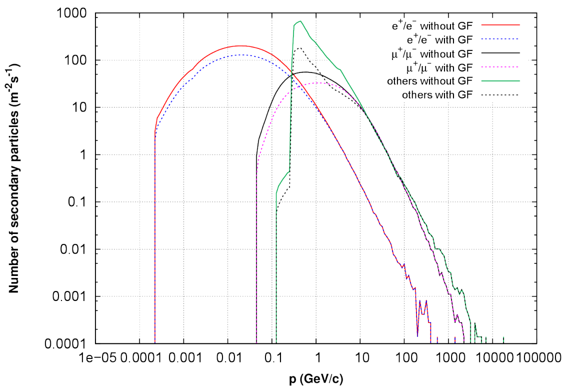

Figure 2: *Distribution of particles considering the Geomagnetic Field (dashed lines) and not considering it (continuous lines). Location:* $14.74°S$ $67.27°W$.

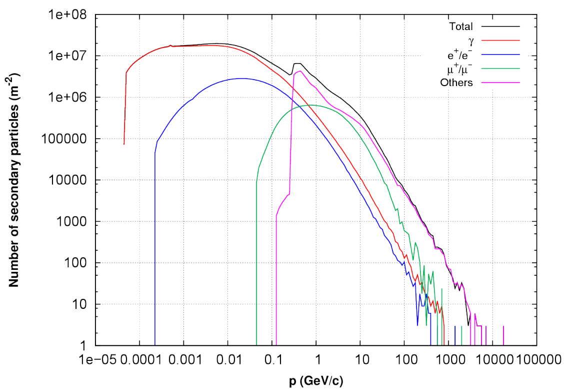

Figure 3: *Distribution of particles during the flight Bogotá - Buenos Aires.*

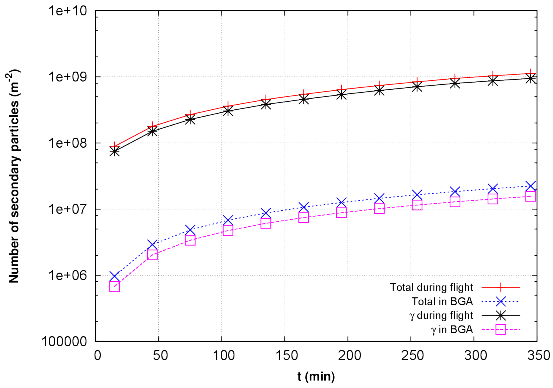

Figure 4: *Integrated flux as function of time during the flight (continuous lines) and staying quiet in Bucaramanga (dashed lines).*

6. Conclusions and acknowledgements

The simulations performed show that at flight level, the number of secondary particles is two orders of magnitude greater than at 1000 m.a.s.l. When calculating the dose absorbed, geomagnetical effects must be taken into account since they reduce the number of primary particles that generate showers. To make more accurate calculations, aircraft's takeoff and landing will be included in the simulations. In order to study space weather effects, simulations will be performed including geomagnectic storm conditions. The authors of this work want to thank the support of COLCIENCIAS under the Grant 617/2014 ”Semillero de Investigación: Ciencia de datos y astropartículas”.

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