Use of CCD to Detect Terrestrial Cosmic Rays at Ground Level: Altitude vs. Underground Experiments, Modeling and Numerical Monte Carlo Simulation

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***Abstract*—In this work, we used a commercial charge-coupled device (CCD) camera to detect and monitor terrestrial cosmic rays at ground level. Multi-site characterization has been performed at sea level (Marseille), underground (Modane Underground Laboratory) and at mountain altitude (Aiguille du Midi–Chamonix Mont-Blanc at $+3,780$ m of altitude) to separate the atmospheric and alpha particle emitter's contributions in the CCD response. An additional experiment at avionics altitude during a long-haul flight has been also conducted. Experiment results demonstrate the importance of the alpha contamination in the CCD response at ground level and its sensitivity to charged particles. Experimental data as a function of CCD orientation also suggests an anisotropy of the particle flux for which the device is sensitive. A complete computational modeling of the CCD imager has been conducted, based on a simplified 3D CCD architecture deduced from a reverse engineering study using electron microscopy and physico-chemical analysis. Monte Carlo simulations evidence the major contribution of low energy (below a few MeV) protons and muons in the CCD response. Comparison between experiments and simulation shows a good agreement at ground level, fully validated at avionics altitudes with a much higher particle flux and a different particle cocktail composition.**

***Index Terms*—Alpha-particle emitters, atmospheric neutrons, avionics measurements, Charge-Coupled Devices (CCD), Monte Carlo simulation, muons, protons, terrestrial cosmic rays, underground test.**

Manuscript received July 11, 2014; revised September 16, 2014; accepted October 17, 2014. Date of publication November 12, 2014; date of current version December 11, 2014. This work has been supported by the French National Research Agency under Project ANR-09-BLAN-0155-01 (HAMLET project).

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Digital Object Identifier 10.1109/TNS.2014.2365038

I. Introduction

THE metrology of cosmic ray induced particles is an important challenge for the understanding of basic mechanisms and the estimation of soft errors in electronics. If the effort has so far focused mainly on the characterization of atmospheric neutrons, one must no longer neglect protons and muons at ground level (specially low energy particles), which are susceptible to contribute to single event effects (SEE) in modern nanoelectronics [1][2].

Charge-Coupled Devices (CCDs) and other solid-state image sensors [3][4] are very attractive devices to detect and investigate interactions between radiation and electronics. In particular: i) the target material is mainly silicon as in any integrated circuit, a link between events observed in CCDs with phenomena occurring in circuits can be envisaged; ii) the CCD can "image" with a pixel size resolution (a few μm^2) the charge deposited by ionizing particles; iii) CCD has a high sensitivity of a few tens of electrons at pixel-level [4], ideal for the detection of lightly ionizing particles.

In the present work, we used a simple commercial CCD camera as atmospheric radiation detector. Previous works [5]–[14] published in literature have already demonstrated the capability of such CCDs or other solid state image sensors in general to investigate, with a high spatial resolution (in the range of order of the pixel size, typically a few microns in these studies) and a high sensitivity (of a few tens of electrons collected at pixel-level), the interactions between atmospheric particles and silicon in the natural radiation background or using artificial sources of radiation. With respect to these studies, the present work focuses on complementary issues, reporting new experimental evidences concerning the following points detailed in Section II: i) the predominant role of charged particles in the CCD outdoor response, ii) the impact of contamination by alpha-particle emitters from underground experiments, iii) the influence of CCD orientation and the characterization of particle flux anisotropy at ground level. Our experimental conclusions are supported by the results of numerical simulation detailed in Section III that considers a simplified 3D architecture of the device and takes into account the impact of both alpha contamination and atmospheric particles on the CCD response for the different radiation environments.