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Abstract

In Charged Coupled Devices (CCDs), radiation-induced events generate electron-holes pairs in silicon that cause artefacts and contribute to degrade image quality. In this work, the impact of natural radiation at ground level has been characterized at sea level, in altitude and underground for a commercial full-frame CCD device. Results have been carefully analysed in terms of event shape, size and hourly rates. The respective contributions of atmospheric radiation and telluric contamination from ultra-traces of alpha-particle emitters have been successfully separated and quantified. Experimental results have been compared with simulation results obtained from a dedicated radiation transport and interaction code.

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1. Introduction

Charged Coupled Devices (CCDs) are known to be very sensitive to natural or artificial sources of radiation. In particular, the interactions of single ionizing particles with the CCD materials generate electron-hole pairs that can be partially or totally collected at silicon (i.e. pixel) level, resulting in image artifacts [1-2]. These artifacts, named "cosmic rays" by astronomers (because mainly induced by secondary cosmic rays at terrestrial level), directly affect the reliability of high performance CCD imagers used in astronomy for example [3]. Radiation-induced artifacts can be isolated and fully characterized (in terms of pixel size, hourly rate and related charge event) considering image captures in total darkness [4].

In the present work, we used a commercial CCD-based astronomical camera to precisely characterize such artifacts induced by natural radiation at ground level. In order to also capture events linked to the internal radioactivity of CCD materials, we performed experiments deeply underground to suppress atmospheric radiation. Three different locations have thus been considered: at sea level (in Marseille), underground (at LSM laboratory [5]) and in altitude on the ASTEP platform [6]. Measurements reported in this work correspond to long-term experiments, with typical durations of several months. Our experimental results have been systematically compared with results deduced from numerical simulation performed with a dedicated radiation transport and interaction code developed in the framework of this study.

2. Experiments

Our different experiments are based on the use of a USB2.0 CCD monochrome camera (model Atik 383L) taking one full image per minute (i.e. 1 frame/min) in the complete darkness (Fig. 1). The KAF-8300 image sensor is a high performance monochrome full frame CCD with a square pixel (5.4×5.4 μm^2) array and 8.6×10^6 effective pixels. Each pixel contains blooming protection. The camera is a cooled system that maintains the CCD approximately 40°C below the room temperature, reducing by several orders of magnitude the dark noise due to thermal generation. The main characteristics of the image sensor are summarized in the table of Fig. 1.

Dedicated acquisition software has been developed under Matlab® to detect radiation-induced artifacts and to save and process related event images. All details about the capture procedure and image processing will be detailed in the final paper. Fig. 2 shows a panel of typical events detected during a one-year experiment performed at sea level. The detected events have been classified into single pixel event (SPE) that corresponds to isolated pixels and multiple pixel event (MPE) that corresponds to a group of adjacent or neighboring pixels (i.e. having pixel connectivity).

Experimental campaigns of measurements were performed in three different locations with the same camera and the same setup: at sea level in Marseille, underground at LSM laboratory (under 1700 m of rock, equivalent to 4800 m under water) to completely screen atmospheric radiation and in altitude (2552 m) on the ASTEP platform to increase (by a factor of ≈6 for neutrons) the atmospheric radiation. Fig. 3 shows the global (MPE+SPE) event hourly rate detected during these tests. By comparing event rates obtained at LSM and in Marseille, we can deduce that more than the half (58 %) of detected events at sea level are due to the CCD chip radioactivity, i.e. the contamination by alpha particle emitters present under the form of traces in CCD and/or packaging materials. This contribution of chip radioactivity decreases to 27% for altitude measurements, mainly dominated by atmospheric radiation in this case.

3. Modeling and numerical simulation

The complete modeling and numerical simulation of the different experiments has been performed. We constructed a simplified but realistic 3D model of the complete pixel array considering dimensions, materials

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and layers deduced from chip analysis using techniques and instruments used in IC failure analysis. The 3D geometry has been modeled using a C++ computational geometry library developed at IM2NP. The EXPACS atmospheric radiation model [7] has been also implemented in the code to compute the energy distributions of neutrons, protons and muons fluxes. In addition, for alpha-particle emitters, both ^{238}U and ^{232}Th decay chains have been simulated for contaminants uniformly distributed (for simplicity) in the bulk of all chip material layers. The interactions of neutrons and high-energy protons with circuit materials have been implemented on the basis of pre-calculated Geant4 databases. For all other ionizing particles (secondary products, low energy muons and protons, alpha particles), a direct ionization process has been considered. When a particle interacts with the CCD materials, the code evaluates the amount of charge (energy) directly deposited into the pixels and the additional amount of charge collected by the pixels from the substrate, considering a diffusion-collection model in the silicon region. For each interaction event impacting the pixel array, the code calculates the resulting numerical image and save it for post-processing and comparison with experimental signatures. Fig. 4 shows a few simulated images computed with this code for Marseille location. Fig. 3 shows that the sum of the pixel event rates for both atmospheric (neutrons + protons + muons) and telluric contributions (alpha) match very well the experimental values at ground level. These results also highlight the importance of atmospheric charged particles in the CCD response, especially at sea level and in altitude. All these results will be in-depth analyzed in the final paper in complement to the accurate description of the modeling/simulation approach.

Image sensor reference	KAF-8300
Architecture	Full frame, with square pixels
Total number of pixels	3448(H) × 2574(V) ≈ 8.9 M
Pixel size	5.4µm × 5.4µm
Saturation signal	> 25.5 ke$^-$
Blooming Protection	1000× saturation exposure

Figure 1: Used camera, experimental setup and CCD imager characteristics.

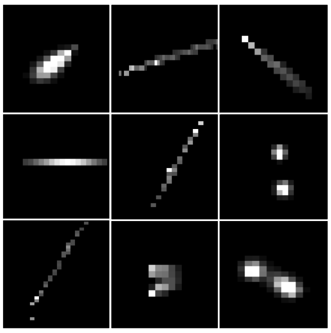

Figure 2: Some examples of radiation-induced events detected during the long-term experiments.

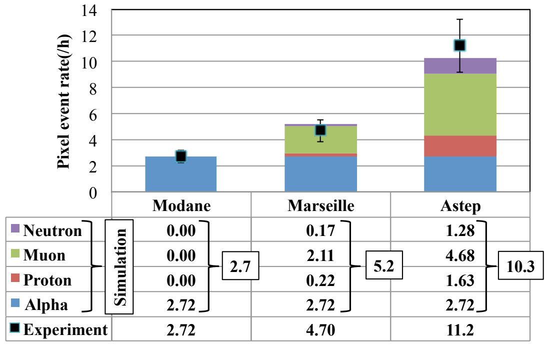

Figure 3: Comparison between experimental and simulated event rates at the different experiment locations. The contributions of the different atmospheric particles and alpha particle emitters are also reported.

Figure 4: Panel of images obtained with the developed simulation code.

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