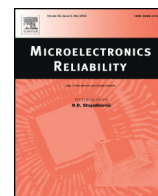




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Natural radiation events in CCD imagers at ground level

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ABSTRACT

In charged coupled devices (CCDs), radiation-induced events generate electron hole pairs in silicon that cause artifacts 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 analyzed 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

As most solid-state devices, charged coupled devices (CCDs) are known to be very sensitive to natural or artificial sources of radiation [1,2]. Depending on the context of use of such devices, this extreme sensitivity is an advantage if one tries to detect radiation [3–17] or a disadvantage if we try to avoid them [18]. Indeed, 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. The effects are not permanent and the spurious charge is swept out during readout, but these single event effects (SEEs) constitute a significant source of noise in the image/video data. Named “cosmic rays” by astronomers (because mainly induced by secondary cosmic rays at terrestrial level) [19], these nonsense signals directly affect the reliability of high performance CCD imagers used in astronomy for example [20].

Schematically, SEEs in CCDs can be generated by direct or indirect ionization [21], as summarized and illustrated in Fig. 1. On one hand, direct ionization (Fig. 1 left) is achieved through Coulomb interactions between a charged particle and atoms of the device. The charged particle strips electrons of atoms as it passes through the device thereby causing ionizations. Heavy ions (including charged nuclear recoils), low energy protons and muons directly ionize matter. As a function of the incidence angle of the particle with respect to the CCD plan, different signatures

(spots, straight lines) can be obtained [22]. On the other hand, indirect ionization (Fig. 1 right) is of concern for atmospheric neutrons and high-energy protons (>100 MeV) that are able to ionize by collision with the target nuclei. Neutrons ionize indirectly, they do not interact via the Coulomb force, and so they can travel through several centimeters of material without interacting with other particles and can remain undetected with CCD. Indirect ionization is accomplished through two mechanisms: elastic and inelastic scattering [23]. Elastic scattering occurs when a neutron knocks out a target nucleus from its lattice but the nucleus remains in the same energy state. During inelastic scattering, the striking neutron interacts with the target nucleus such that the nucleus captures the neutron and thereby the nucleus becomes an isotope. The isotope then deexcites by the emission of secondary charged and uncharged radiation. The residual nucleus and the evaporation products may be highly ionizing and are able to deposit significant amounts of charge at various locations in a device and cause SEEs. Fig. 1 (right) illustrates the case of an indirect ionization event induced by a neutron-silicon interaction within the volume of the CCD. As a function of the number and the momentum direction of the reaction products, the signature of the event can be more complex than a simple spot or straight line.

In this work, we used a commercial CCD-based astronomical camera to precisely detect, count and characterize (in terms of pixel size, hourly rate and related charge event) artifacts induced by natural radiation at ground level from the continuous analysis of images captured in total darkness. In order to also isolate and characterize events directly induced by the internal and residual radioactivity of the CCD materials, we performed experiments deeply underground

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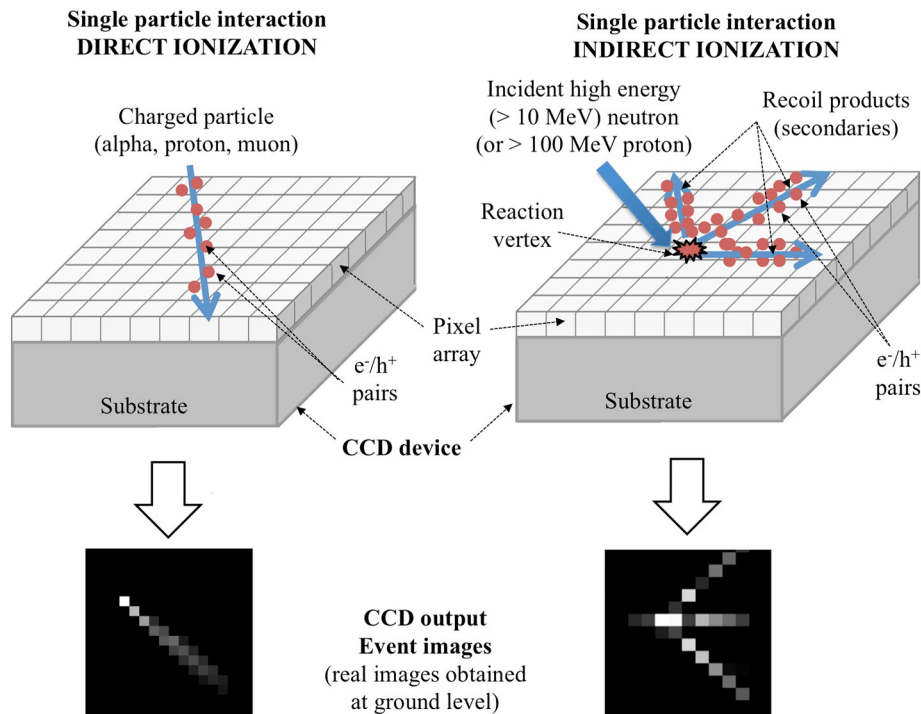


Fig. 1. Schematics of direct/indirect ionization events resulting from the interaction of a single particle within the CCD structure and corresponding real images recorded with a CDD camera.

to suppress atmospheric radiation. Three different locations have thus been considered: at sea level, underground and at mountain altitude. Measurements reported in this work correspond to long-term experiments, with typical durations of several months.

Section 2 of the present paper details the experimental setup, the acquisition procedure and the image processing for radiation-induced event characterization. Experimental results for the different locations are reported and discussed in Section 3. Finally, in Section 4, these data have been compared with results deduced from numerical simulation performed with a dedicated radiation transport and interaction code developed in the framework of this study.

2. Experimental details

The different experiments of this work have been conducted using a USB2.0 CCD monochrome camera (model Atik 383L [24], see Fig. 1) taking one full image per minute (i.e. 1 frame/min) in the complete darkness. The KAF-8300 image sensor [25] is a high performance monochrome full frame CCD with a square pixel ($5.4 \times 5.4 \mu\text{m}^2$) array and 8.6×10^6 effective pixels (2.428 cm^2 of active surface). Each pixel contains a lateral overflow drain for blooming protection (only in case of high light level conditions). The camera is based on a 16bit Analog to Digital Converter (ADC) and is thermally stabilized. The system contains a cooled thermoelectric device that maintains the CCD approximately 40°C below the room temperature, reducing by several orders of magnitude the dark noise due to thermal generation [24]. The main characteristics of the image sensor are summarized in the table of Fig. 1.

In addition to the camera, the experimental setup (Fig. 1) also includes a Windows 7 computer and a homemade image processing software integrating Matlab routines. The program performs image cleaning and analysis, radiation-induced event extraction and the storage of these “event images” and related information into a MySQL open source database server running on the same PC. The database also contains information about all CCD artifacts, i.e. damaged and instable pixels, subjected to random telegraph signal noise or other characteristic electrical instabilities [4–6]. These additional

data are used by the program to eliminate all image instabilities not directly linked with radiation events.

At the end of each acquisition period (1 min) in the complete darkness, the CCD is read and a raw image is returned to the computer. This image is cleaned (noise removal) by subtracting a reference dark frame (obtained from a combination of multiple dark frames at the same temperature to get a better model for the noise in an image). Radiation-induced events are then detected by applying to this new image a series of mathematical treatments that isolate pixels or group(s) of connected pixels with an electrical charge clearly above the background and verifying certain threshold criteria. This operation consists in identifying pixels above a first threshold value and to examine if the neighboring pixels (up to the second neighbors) are also above a second value (inferior to the first threshold but superior to the image background).

Fig. 2 shows a panel of typical events detected during a one-year experiment performed at sea level. The deposited charge corresponding to each detected event is estimated by summing the values (i.e. the readings) of the event pixels, considering a linear dependence between a pixel value and its electrical charge up to the charge saturation. Similarly to [17], the detected events are automatically classified by the software into single pixel event (SPE) that corresponds to isolated pixels or into multiple pixel event (MPE) that corresponds to a group of adjacent or neighboring pixels (i.e. having pixel connectivity). Finally, the software estimated the corresponding hourly event rates (single pixel rate, SPER, and multiple pixel rate, MPER) occurring during the experiment.

3. Experimental results

Experimental campaigns of measurements were performed in three different locations with exactly the same camera and the same setup: i) at sea level in Marseille [26] during more than one year (14 months), ii) underground at the underground laboratory of Modane (LSM [27], under 1700 m of rock, equivalent to 4800 m under water) during two weeks and iii) at mountain altitude (2552 m) on the ASTEP platform [28] during three months. Underground measurements represent the only way to screen the atmospheric radiation and to directly measure, i.e. quantify, the occurrence of events due to the residual ultra-traces

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