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Cosmic radiation monitoring in aeronautics and astronautics

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Abstract

The growth of the aerospace industry has made the detection of cosmic radiation essential. That led to a proposal for the development of an optoelectronic detector of cosmic radiation. This will allow continuous measurement of acceptable levels of radiation. The device is currently in its initial development phase, focusing on the detection of ionising radiation. Tests have been carried out with high-energy radiation simulators in the form of natural radioactive sources, confirming the performance of the overall system.

The cosmic ray sensor of the study has numerous potential applications, particularly in the aerospace industry. Crew safety could be enhanced by a miniature sensor that measures the absorbed dose of cosmic radiation. Existing passive methods of dose measurement have been ineffective because they provide information about radiation with a delay of several weeks. Active monitoring of irradiation levels enables ongoing control of the dose taken, which is crucial for employee health.

Keywords: cosmic radiation, detection and monitoring of security threats, scintillators

1 Introduction

The growth of the aerospace industry has made the detection of cosmic radiation essential. Aircraft and spacecraft crews are exposed to various harmful phenomena from physical field effects. These include cosmic rays, which can cause changes at the DNA level.

Cosmic radiation intensity and crew radiation exposure are monitored to ensure safety. According to Directive 2013/59/EURATOM [1], employers are required to assess the absorbed radiation if the dose of ionising radiation is

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likely to exceed 1 mSv per year. The maximum radiation limit is 6 mSv. Measurements should be carried out for aircraft crews flying above 8 km, as the amount of ionising radiation increases with altitude.

The measurement of cosmic radiation absorbed dose is currently carried out using thermoluminescent dosimeters (TLD) [2]. TLDs are advantageous due to their small size and reusability. However, they cannot measure absorbed dose in real-time, making it impossible to determine if the threshold has been exceeded. Therefore, in order to detect cosmic rays and provide information on the received radiation dose, an optoelectronic detector has been proposed. The paper presents the optoelectronic cosmic radiation detector system developed at the Institute of Optoelectronics of the Military University of Technology (MUT), which enables continuous measurement of the received radiation dose. The monitoring system utilises scintillation crystals to convert high-energy radiation into ultraviolet (UV), visible (VIS), or infrared (IR) radiation.

2 Cosmic rays

Cosmic rays are a stream of particles coming from the Sun or outside the Solar System, with energies between 10^8 eV and 10^{20} eV [3]. Low-energy particles originate from solar flares, which occur during coronal mass ejections. The solar activity, which follows an 11-year cycle, is the main determinant of the amount of cosmic rays reaching the Earth [4]. Interestingly, fewer cosmic ray particles reach Earth during the sun's maximum activity. This phenomenon is known as the Forbush effect, which expands the magnetic field lines of the sun and creates an extra layer of protection for the Earth against cosmic rays from outside the Solar System. Figure 1 provides a visualization of the solar component of cosmic radiation that reaches our planet. The Sun's activity generates a solar wind, which is partially obstructed by the Earth's magnetic field lines. In the magnetosphere, polar funnels (polar cusps) allow for an increased number of particles to approach the Earth's surface, resulting in the observation of auroras.

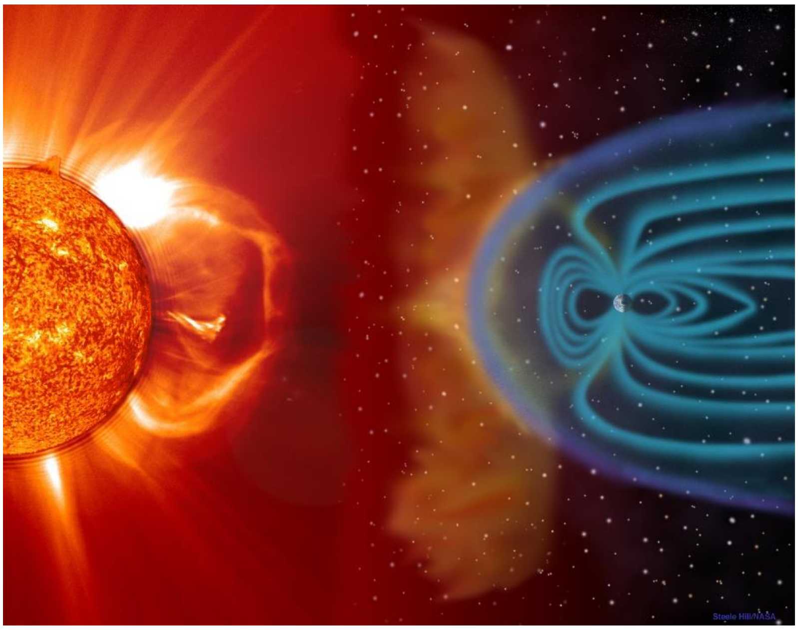

Figure 1. *Visualization of cosmic radiation reaching Earth from the Sun (Source: NASA/SOHO - Solar and Heliospheric Observatory)*

The chemical composition of radiation has been used to identify these particles, based on the frequency of specific elements. Figure 2 illustrates this relationship, highlighting the differing relative frequencies of these elements.

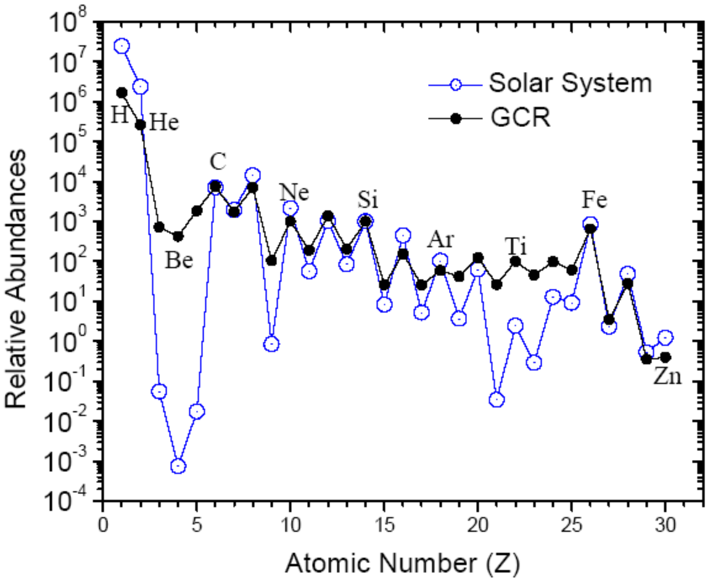

Figure 2. *The relative frequency of elements appearing in Solar System and Galactic Cosmic Rays GCR (Based on [5])*

Galactic Cosmic Rays (GCR) are a slowly varying source of energy that continuously bombard the Earth with high-energy particles. They originate outside the solar system and are likely formed by explosive events such as supernova. GCR consist mostly of baryons which includes every element from hydrogen to uranium [6]. These nuclei are completely ionised, indicating that all electrons have been removed from the atoms. As a result, these particles interact with and are affected by magnetic fields. The powerful magnetic fields of the Sun alter the flux and spectrum of GCRs at Earth.

During a solar cycle, the solar wind affects the proportion of lower-energy GCR particles, making it difficult for the majority of them to reach Earth near solar maximum. By contrast, near solar minimum, in the absence of many coronal mass ejections and their associated magnetic fields, GCR particles have easier access to Earth. The GCR cycle also follows an approximately 11-year cycle, with its maximum occurring near solar minimum. However, unlike the solar cycle, which can rapidly alter the environment due to bursts of activity, the GCR spectrum remains relatively constant in both energy and composition, changing only gradually over time [3].

Organisms living on Earth are protected from the cosmic rays by the Earth's magnetic field, which acts to deflect low-energy particles flying towards the planet. The magnetic poles are the points of closest approach to the surface of the Earth, where the particles collide with atmospheric particles. This interaction results in the ionisation of the atmosphere, which is manifested as polar lights. The particles with the highest energy create secondary cosmic rays and large air showers. The phenomenon was first observed in 1938 by Pierre Auger and his students at the Jean Perrin Observatory [5], where a network of detectors was used to identify cosmic rays. The process of how air showers are created is shown in figure 3.

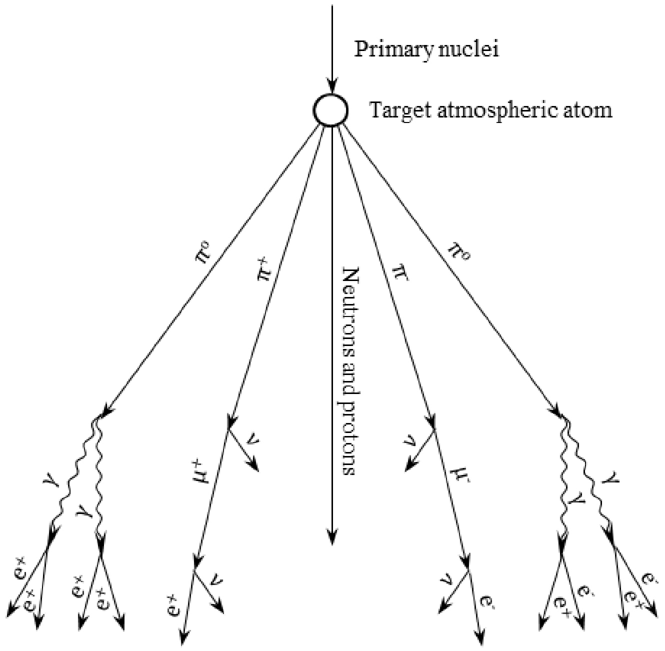

Figure 3. *Air shower formation in the atmosphere (Based on [7]).*

3 Cosmic radiation safety standards

Ionising radiation has a significant impact on living matter. The greater the altitude, the higher the proportion of corpuscular radiation absorbed by organisms. This relationship is presented in Figure 4.

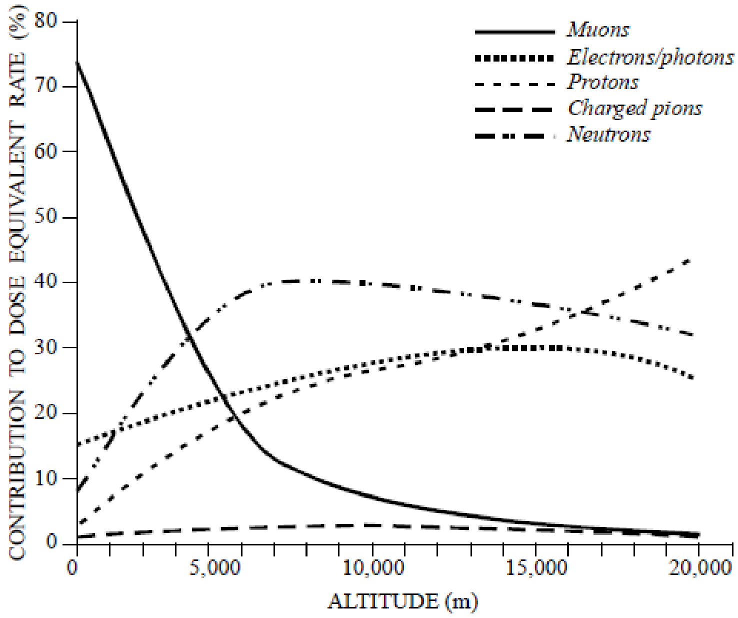

Figure 4. *The relationship between the amount of absorbed doses of a given type of cosmic rays and altitude [8]*

The advancement of technology that permits individuals to ascend to altitudes where the intensity of ionising radiation is augmented has elevated the significance of investigation into the consequences of high-energy particles on living organisms. Figure 5 illustrates the phases of interaction between high-energy radiation and living matter. It can be observed that radiation acting on an organism for 1 µs causes DNA damage. The longer the exposure lasts, the more changes occur in the body and the more difficult it is to repair any damage. This results in time limits for pilots that determine their working time on certain routes, or astronauts limiting their working time on the International Space Station.

The increase in cosmic radiation intensity resulting from altitude above the Earth's surface represents a significant factor in the radiological risk associated with the possibility of absorption of a dangerous dose of ionising radiation by living organisms. In recent years, the problem of exposure has arisen for civilian and military aircrew members, who spend several hundred hours a year in the air at increasingly higher flight ceilings, often exceeding 15 km.

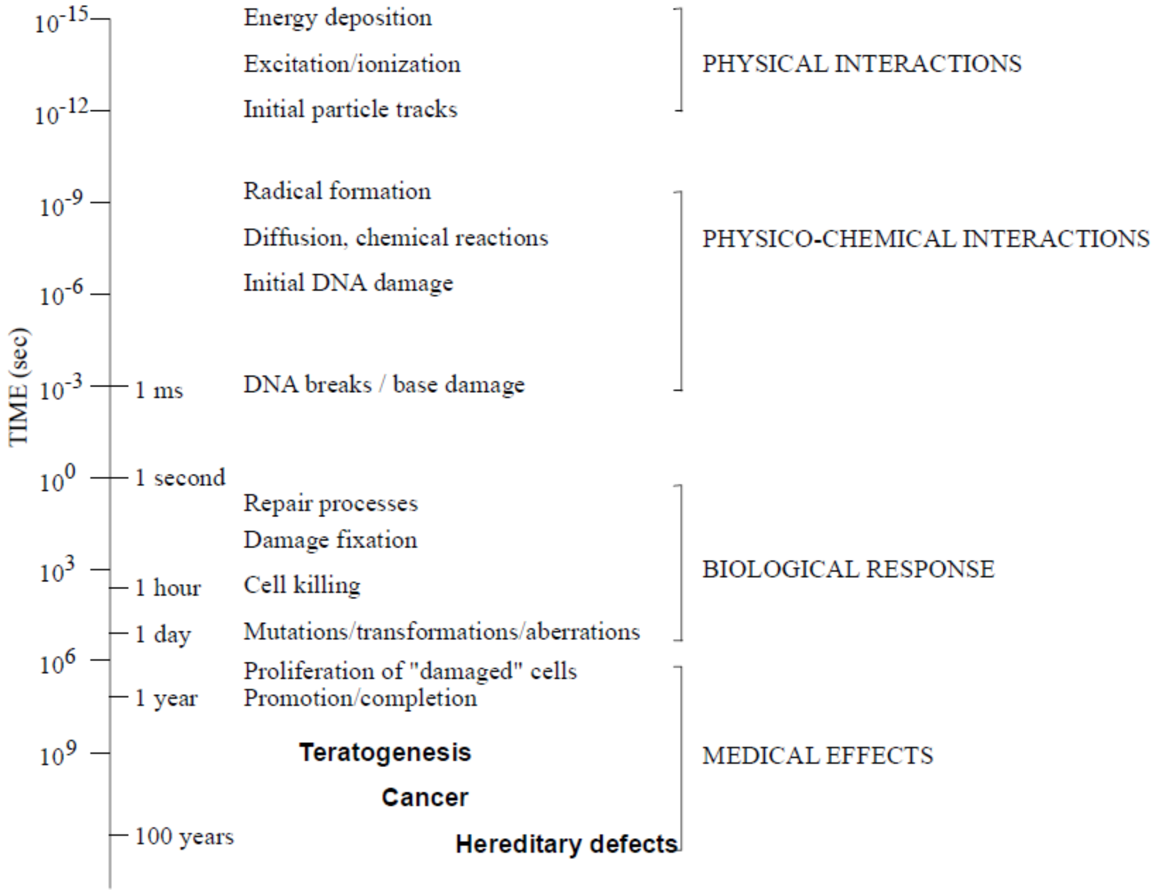

Figure 5. *Effects of cosmic rays on living matter [9]*

In accordance with the European Union recommendations, it is obligatory to conduct an assessment of radiation doses received by crews, provided that the annual doses exceed 1 mSv. Furthermore, it is necessary to strive to ensure that they do not exceed 6 mSv. This equates to approximately 20 flights on the Warsaw-New York route. Consequently, it is essential to implement measurements for all aircrews with flight ceilings above 8 km.

It is important to note that special requirements apply to supersonic aircraft with a high flight ceiling. This is due to the fact that significant amounts of radiation from solar flares can reach very high altitudes. As a result, these aircraft must be equipped with radiation sensors to detect a sudden increase in radiation and automatically lower the flight altitude.

In light of the aforementioned conditions and the Polish Aeronautical Group's interest in developing a miniature sensor for measuring the absorbed dose of cosmic radiation by aircraft crews, scientific research and implementation work has been conducted at the Institute of Optoelectronics in Military University of Technology. The thesis objective is to examine the efficiency of selected scintillation crystals in a cosmic radiation detection system, thereby enabling the optimization of the absorbed dose sensor under development.

Figure 6 illustrates the dose power of ionizing radiation occurring at different altitudes, with a breakdown of its components. These include neutrons, protons, electrons and positrons, photons and muons. The data presented demonstrate that the dose power increases significantly in the range of 10-16 km above the Earth's surface. This altitude range includes the altitude ceiling for passenger and supersonic aircraft flights. Above an altitude of 16 km, the increase in dose power with altitude is less pronounced, reaching a maximum at an altitude of 25 km.

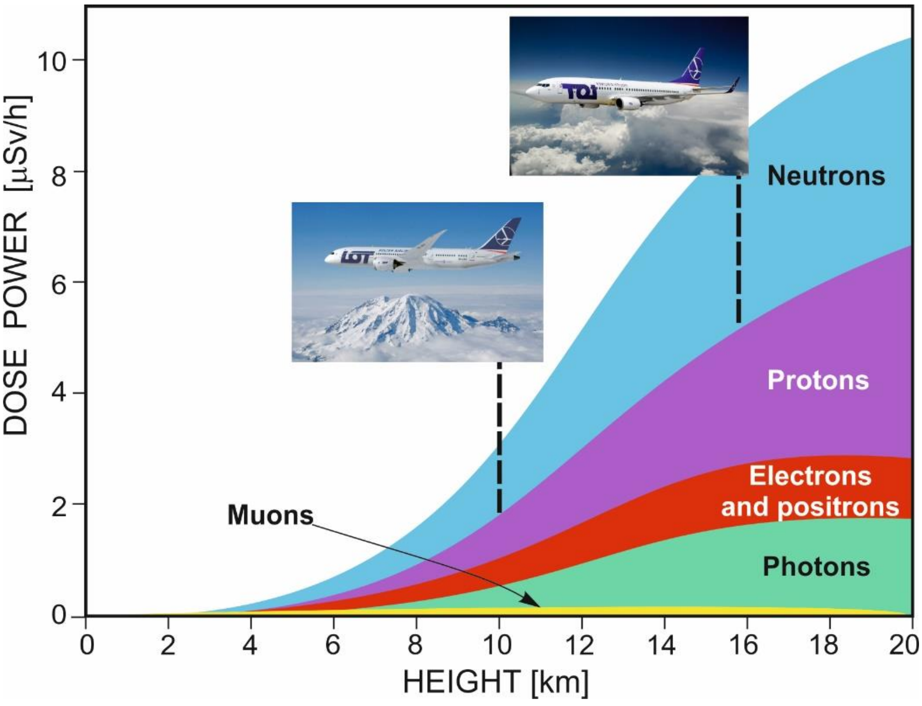

Figure 6. *Dose power of ionizing radiation by type of particles at different heights above the Earth's surface, with aircraft cruising altitudes marked (source: MUT)*

A variety of programs use mathematical models of cosmic radiation occurring on Earth at different altitudes to estimate the dose received by aircraft crews. One of these is CARI, created by the Federal Aviation Administration's Civil Aeronautics Medical Institute. It enables the effective dose of galactic cosmic radiation received by an individual on an aircraft to be calculated along flight paths and by geodetic coordinates, i.e. by a straight line. Additional functions permit the dose received to be divided by particle type, radiation type and flight altitude (up to a limit of approximately 91 km).

4 Methods of monitoring and detecting cosmic rays

The primary objective of cosmic-ray studies is the precise measurement of the energy and chemical composition of particles with extreme energies. Large and sophisticated detectors are employed to identify events that appear as showers in the Earth’s atmosphere, with energies recorded at levels above 10^{20} eV. However, a Cosmic-Ray Ensemble (CRE) that develops before reaching the Earth as a group of correlated particles may spread over greater distances and necessitate the use of an extended set of detectors for discovery.

The Cosmic-Ray Extremely Distributed Observatory (CREDO) is a solution to find such phenomena [11]. The Cosmic-Ray Extremely Distributed Observatory (CREDO) is a project dedicated to global studies of extremely extended cosmic-ray phenomena, the cosmic-ray ensembles (CRE), beyond the capabilities of existing detectors and observatories. Up to date cosmic-ray research has been focused on detecting single air showers, while the search for ensembles of cosmic-rays, which may overspread a significant fraction of the Earth, is a scientific terra incognita.

Instead of developing and commissioning a completely new global detector infrastructure, CREDO proposes approaching the global cosmic-ray analysis objectives with all types of available detectors, from professional to pocket size, merged into a worldwide network. Such a network enables the search for evidence of correlated cosmic-ray ensembles. One of the observables that can be investigated in CREDO is a number of spatially isolated events collected in a small time window, which could shed light on fundamental physics issues. The CREDO mission and strategy necessitate the active engagement of a large number of participants, including non-experts, who will contribute to the project by using common electronic devices (e.g. smartphones). This note presents an overview of the current status and future prospects of the project.

The CREDO project was initiated in 2016 at the Institute of Nuclear Physics of the Polish Academy of Sciences in Krakow. The observations of cosmic ray correlation carried out on the basis of measurements made by participants without specialized knowledge or skills represent a unique approach to scientific research. The recording or documentation of the absence of cosmic rays through such measurements represents a new method of studying the universe [12] and represents a new information channel in particle astrophysics research.

One of the constituents of secondary cosmic radiation is the electromagnetic component, which includes electrons and photons. Consequently, it was proposed that mentioned particles will be detected with CCD arrays used in smartphones. As a result, there was no need to build new infrastructure, but was limited to developing an application to count the particles passing through the array [12]. The data from each device is sent to a control panel and synchronized to determine whether traces of atmospheric burst have been recorded in a given area.

Research using the CREDO application is carried out at the Biomedical Engineering Centre (BEC) of the Institute of Optoelectronics at the Military University of Technology. Figure 4 shows the trace left by a high-energy particle through the camera of a mobile phone. The registration of such images is possible due to the interaction of a secondary cosmic ray particle with the CCD/CMOS array.

The passage of a particle through a detector results in the acquisition of a 2D image of the particle's trajectory. The shape and appearance of this image depend on the particle type, the direction of its arrival, and the type of matrix on which the image was registered (Figure 7).

Figure 7. *Recorded images by the CCD array of a cell phone showing the passage of a high-energy particle (Source: MUT)*

At the Biomedical Engineering Centre, research is being conducted on cosmic ray particle counts. Graphs showing counts over time are presented in Figures 8, 9, and 10. In April 2023 (Figure 8), daily counts dropped significantly compared to measurements made in March 2019 (Figure 9) and April 2019 (Figure 10). As previously discussed in subsection 2, the number of cosmic ray particles reaching Earth can be affected by solar activity. In December, a minimum of solar activity was registered in 2019, marking the start of a new solar cycle [12]. The minimum of activity resulted in a weakening of the Sun's magnetic field, which in turn led to an increase in the number of galactic cosmic rays (GCR) entering the Earth's atmosphere. This phenomenon can be observed in Figures 9 and 10, which present observations from solar minimum, where the number of counts per day is higher than in Figure 8, which provides data from almost solar maximum.

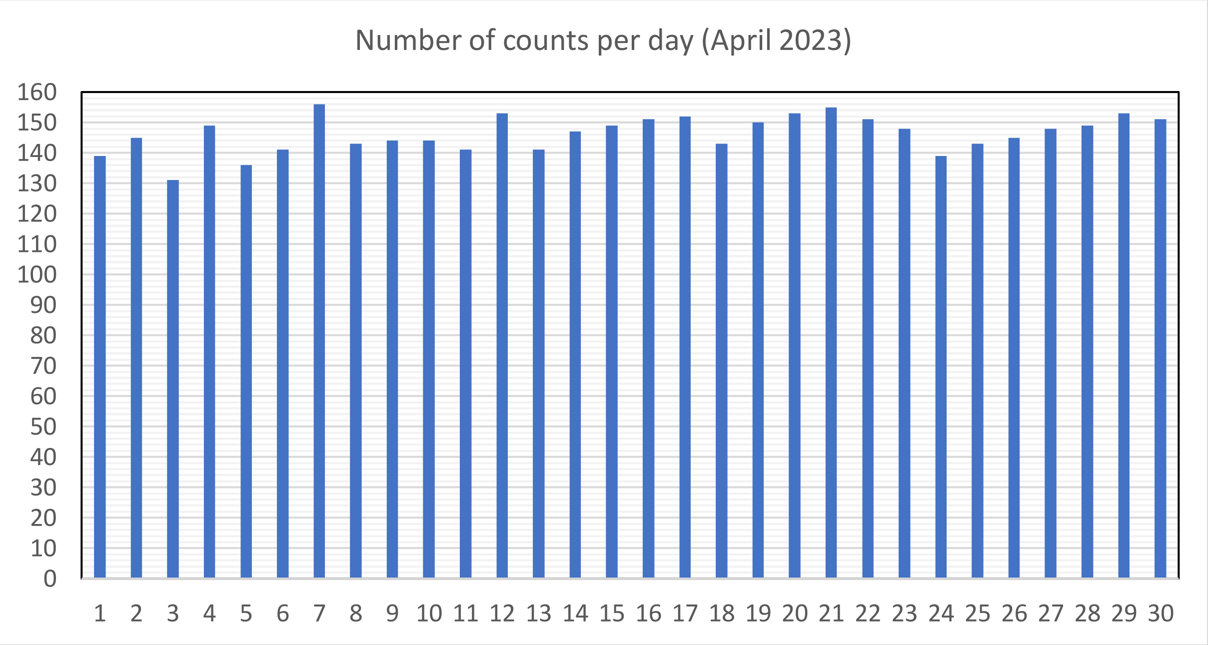

Figure 8. *Counts of high-energy particle transitions through the CCD array in April 2023 (Source: MUT)*

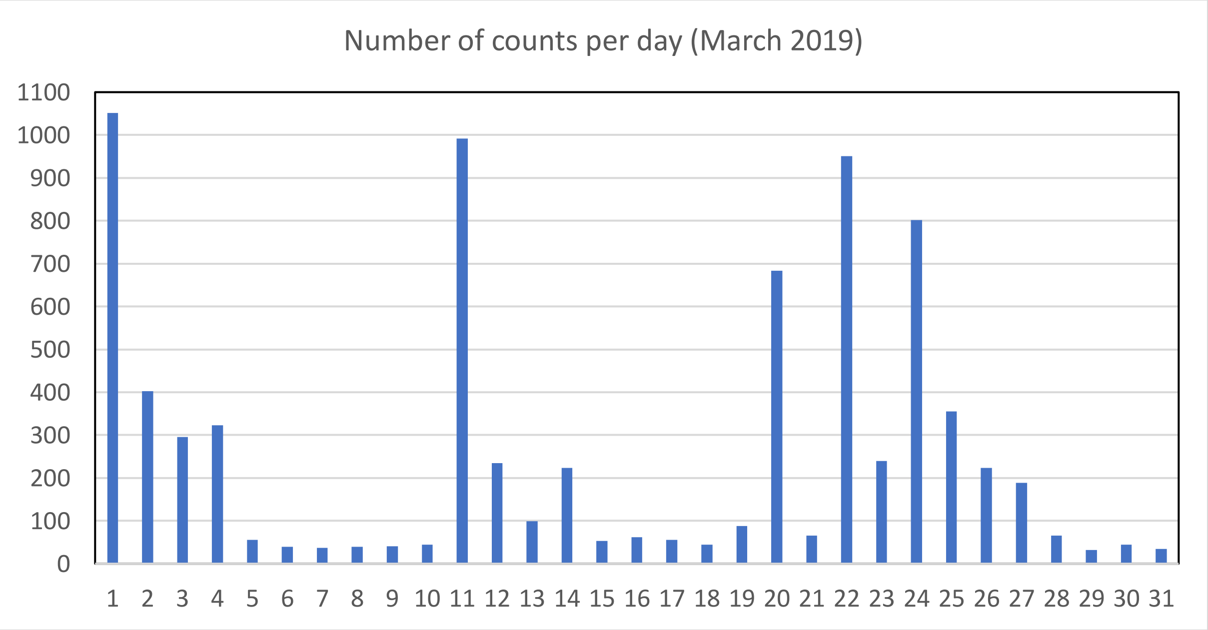

Figure 9. *Counts of high-energy particle transitions through the CCD array in March 2019 (Source: MUT)*

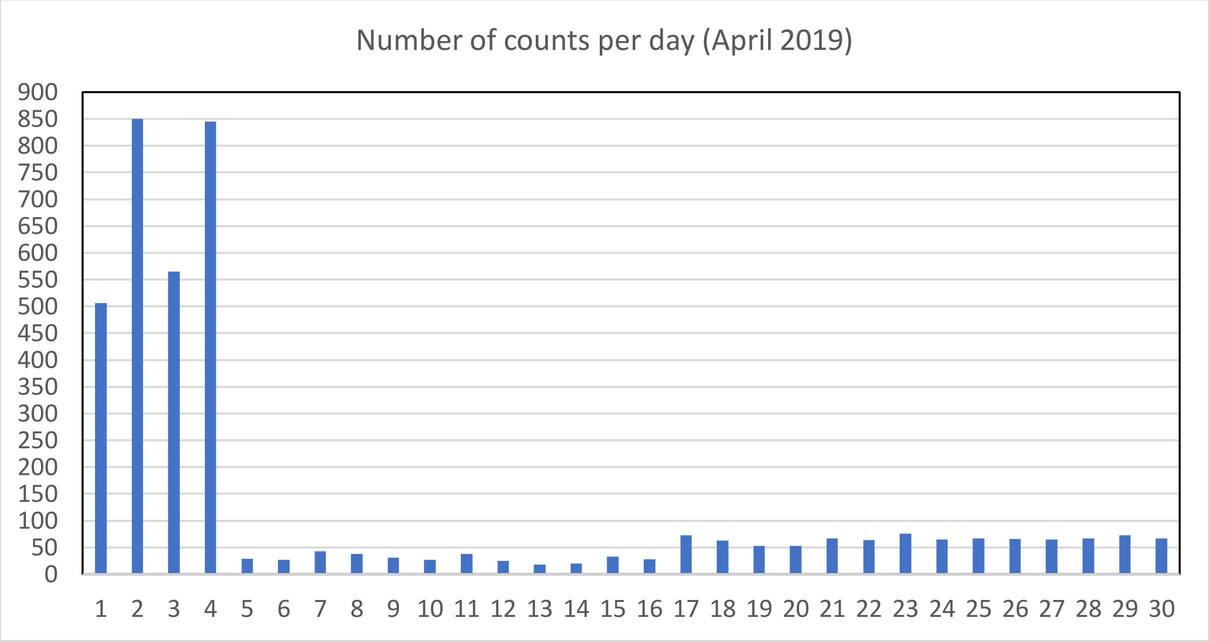

Figure 10. *Counts of high-energy particle transitions through the CCD array in April 2019 (Source: MUT)*

The detection of high-energy radiation involves the study and measurement of the effects of its interaction with matter. Ionising radiation detectors are categorised into five main groups: gas, semiconductor, luminescent, thermoluminescent, and detectors based on chemical transformations or thermodynamic transformations. Each detector is characterised by certain parameters, including sensitivity, which defines the minimum detectable value of a particle's energy, and efficiency, defined by the ratio of the number of registered particles to the number of particles falling into the detector's active volume. The efficiency of a detector is influenced by two key factors: the value of the linear absorption coefficient and the active volume of the detector. Further parameters include the detector response, which describes the dependence of the charge/amplitude of the output signal on the energy of the recorded particle, and the response time, dead time, energy resolving capacity and sensitivity to interference.

The most commonly used detectors are the Geiger-Müller counter, the scintillation counter, the thermoluminescent detectors and the Cherenkov's radiation detectors.

5 The optelectronic cosmic ray detector project

The diagram of the developed cosmic ray detection system is shown in Figure 11. The detection system consists of a scintillation crystal (SC) [13], a Silicon Photomultiplier (SiPM) detector [14] and a transimpedance amplifier, housed in a casing providing shielding from electromagnetic radiation in a wide spectral range. The detection system uses a signal amplifier, a comparator, a digital system that counts pulses per unit of time and transmits the measurement data to a computer where it is archived.

In order to simulate cosmic radiation, various sources of ionizing radiation were used for the tests. For each of them, the spatial equivalent of the radiation dose rate was measured using the Geiger-Müller counter MIER-EKOC-ABGX-S with the measurement range spanning from 0.01 µSv/h to 1000 µSv/h.

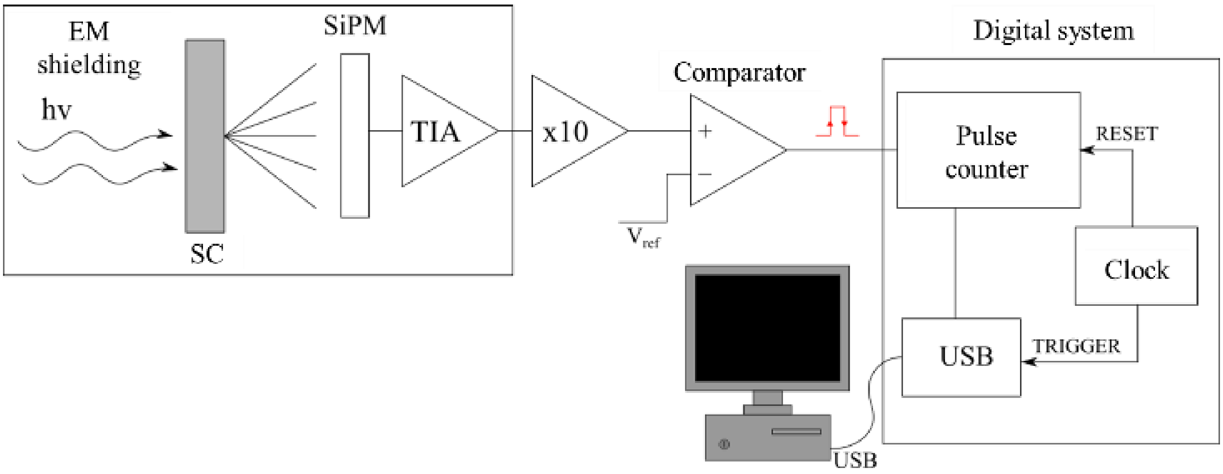

Figure 11. *Scheme of the detection system:*

SC – scintillation crystal,

SiPM – Silicon Photomultiplier detector

TIA – transimpedance amplifier

The detection of cosmic radiation in the designed system is dependent on the detection of secondary radiation emitted by the scintillator. The scintillator crystal, along with the detector and transimpedance amplifier, was placed in an electromagnetic shielded enclosure. The enclosure was used to minimize the level of background radiation as much as possible and to reduce the noise level of the detector. In order to achieve the lowest possible transmission of low-energy radiation from outside, the enclosure must be made from a suitable material. An example of a suitable material is aluminium, which is able to meet this requirement. It should be noted that cosmic radiation is characterised by sufficiently high energy levels to penetrate the housing and, after passing through the scintillator, cause luminescence.

The SiPM detector is a parallel combination of multiple avalanche photodiodes. Their number depends on the selected model, differing in detector area and single pixel size. The SiPM type MICROFC-30035-SMT was used in the measurement system.

Figure 12 presents the counting characteristics in the time function of the developed cosmic ray detector. The experiment was conducted in two phases: the first phase comprised 300 seconds of measurements without the source, while the second phase comprised 300 seconds with the source present.

5 Conclusions

There are many possible applications of the cosmic ray sensor developed in this study, but the aerospace industry is of particular importance. The implementation of a miniature sensor for the measurement of the absorbed dose of cosmic radiation would enhance the safety of the crew members who are exposed to cosmic radiation during their work. The passive methods of dose measurement currently in use are ineffective due to the delay of several weeks in obtaining information on irradiation. Active monitoring of the irradiation level will permit the dose to be controlled on an ongoing basis, which is important from the perspective of employee health.

Acknowledgments

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