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A small active dosimeter for applications in space

Birgit Ritter [a,b,*], Karel Maršálek [a], Thomas Berger [a], Sönke Burmeister [b], Günther Reitz [a], Bernd Heber [b]

[a] German Aerospace Center, Institute of Aerospace Medicine, Linder Höhe, 51147 Cologne, Germany
[b] Christian-Albrechts-University Kiel, Institute of Experimental and Applied Physics, Leibnizstr. 11, 24118 Kiel, Germany

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ABSTRACT

The radiation field in low Earth orbits (LEO) differs significantly from the radiation environment on Earth's surface. Exposures are by far higher and pose an additional health risk for astronauts. Continuous monitoring is therefore a necessary task in the frame of radiation protection measures. A small battery-driven active dosimeter telescope based on silicon detectors meeting the requirements for LEO applications has been developed. The instrument, the Mobile Dosimetric Telescope (MDT), is designed to measure the absorbed dose rate and the linear energy transfer (LET) spectra. From the latter the mean quality factor of the radiation field can be derived and hence an estimate of the dose equivalent as a measure of the exposure. The calibration of the device is done using radioactive isotopes and heavy ions. Fragmentation products of heavy ions are used to show the ability of the MDT to reliably detect energy depositions from high energetic nuclei. Radiation measurements inside aircraft during long distance flights, serving as field tests of the instrument, prove the good performance of the instrument.

1. Introduction

On the Earth's surface the radiation environment is dominated by radioactive decay products from natural radionuclides. Secondary radiation produced by the interaction of cosmic rays with atmospheric molecules contributes less due to the shielding provided by the atmosphere. Contrary in civil air flight altitudes, the complex radiation field consists of charged and neutral secondary particles leading to an enhanced exposure, while further out, e.g. in LEO, the radiation exposure is caused by contributions from primary cosmic radiation as well as from secondary particles.

The primary components of cosmic radiation are galactic cosmic rays (GCR) and solar particles, both comprising mainly protons and heavier elements. GCR are composed of protons (87%), helium nuclei (12%) and heavier nuclei (1%) including all stable elements, with significantly dropping abundance for nuclei heavier than iron [1]. Above a few GeV, energy spectra of GCR follow a power law over ten orders of magnitudes. Hence they have a high penetration depth and are extremely difficult to shield. Although heavier ions are low in flux, the relative contribution from these ions up to iron is significant for the dose equivalent for orbits of the International Space Station (ISS). Therefore not only hydrogen and helium, but also high Z particles must be considered when measuring the radiation exposure in space. In solar energetic particle (SEP) events, particles originating from the Sun can reach energies up to about 1 GeV or even higher in rare cases. The high particle fluxes during SEP events can lead to an extra exposure on a short time scale. Electrons and protons from the radiation belts, which are a product of the interaction of primary cosmic radiation with the geomagnetic field and the Earth's atmosphere, contribute additionally to the exposure, depending on the inclination and the altitude of the orbit. Of special importance is here the region of the South Atlantic anomaly (SAA) above the Eastern coast of South America. Due to a tilt of the geomagnetic dipole axis towards the Earth's rotation axis by 11° and a displacement of their interception of about 500 km to the North with respect to the center of Earth, the inner radiation belt reaches down to an altitude of 200 km. The ISS orbits Earth at altitudes between 350 km and 400 km with an inclination of 51.6° and passes the SAA five to six times per day. This additional exposure contributes up to one third of the dose equivalent received by an astronaut [2].

Therefore the radiation exposure is considered to be one of the main health detriments for humans in space and poses a limiting factor for long duration space flights. Hence it is essential to continuously monitor the radiation exposure of astronauts, which is currently conducted with passive personal dosimeters [3] and active area monitors onboard ISS [4]. Depending on the location inside the ISS, the radiation exposure can however differ by

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* Corresponding author at: German Aerospace Center Institute of Aerospace Medicine, Linder Höhe, 51147 Cologne, Germany.
E-mail address: birgit.ritter@dlr.de (B. Ritter).

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a factor of two due to the ISS attitude and different shielding of the modules [5,6] and can further increase during extra-vehicular activities (EVAs) of an astronaut [7]. Naturally it additionally depends on the ISS altitude and on the solar activity, It also shows a directional dependence, due to shielding effects of the solid Earth's shadow and its magnetic field on the one hand and because of the particle trajectories of the trapped radiation along the magnetic field lines especially in the region of the SAA (e.g. [8]). This complex radiation environment therefore poses a challenge for the design of any radiation detector to be applied in space.

An astronaut's dosimeter must be able to cover the major contributions from this radiation field to the radiation exposure, while being a small and easy to handle instrument that can be worn by the astronaut all the time, inside and outside the space station. It shall provide real time dose rates and derive the biologically relevant dose equivalent.

In order to measure the absorbed dose from the main fraction of charged particles of the radiation field, the instrument must cover energy depositions caused by electrons, protons, and heavier nuclei up to relativistic iron. For estimating the dose equivalent, the instrument shall be able to measure the LET of the traversing particles. From LET spectra the mean quality factor of the radiation field can be derived, which is a measure of the biological effectiveness of the radiation. The product of the absorbed dose and the quality factor is the dose equivalent, a relevant quantity in radiation protection. Furthermore, the device must be battery-driven, hence the power consumption has to be minimized.

2. The Mobile Dosimetric Telescope (MDT)

The MDT is a small silicon telescope detector and serves as a prototype of an active personal dosimeter for the application in space. In the frame of the development phase two instruments (MDT-01-000 and MDT-01-001) comprising the same electronics have been built. Due to the development process, the housing and the batteries of the two prototypes are different, which do not affect the performance. Each MDT consists of a front-end compartment, including the silicon detectors and preamplifiers, and a main electronics board for analog and digital signal processing including user interfaces, such as micro SD card, display and USB interface. As it is the more recent version, the following pictures and specifications regarding the size of the instrument refer to MDT-01-001 only. Table 1 summarizes the key properties of the MDT, which will be discussed in the following sections. In Fig. 1a, the open MDT is seen, with the separate front-end compartment and the top of the electronics board under which the battery is implemented. Furthermore the display on top and the slot for the micro SD card on the side are visible. In panel b the 290 g instrument of dimensions 14 cm × 6 cm × 3.9 cm is shown next to a micro SD card for scaling.

Table 1
Key properties of the MDT-01-001.

Detector setup	Telescope of 2 silicon diodes
Sensitive detector area	2×1.21 cm^2
Diode thickness	300 μm
Geometry factor	3.8 cm^2 sr (single diode) 1.7 cm^2 sr (telescope)
Size	$14 \times 6 \times 3.9$ cm^3
Weight	290 g (incl. battery)
Supply Voltage	3.7 V battery
Power consumption	40 mA, 150 mW
Battery runtime	>40 h
System clock	1.8 MHz
Dead time	440 μs
Interfaces	Display, mini-USB, μSD card
Dynamic range	60 keV–140 MeV
LET range	0.1–208 keV/μm
Energy resolution	20 keV (high-gain) 70 keV (low-gain)

2.1. Detector setup and measurement principle

The instrument uses two commercially available squared Hamamatsu silicon diodes with a sensitive area of 1.21 cm² and a thickness of 300 μm each. The diodes are arranged in a telescope configuration (Fig. 2) with a distance of 5 mm between them resulting in a geometry factor of 1.7 cm^2 sr. The telescope arrangement enables measurements of the LET of charged particles. In case a particle is detected in both diodes (coincidence event), the path length it traveled within the detector is restricted by the opening angle of the telescope. Thereby the energy deposition along the path length, i.e. the LET, can be estimated by assuming a mean path length. From Monte Carlo simulations the mean angle of incident within an isotropic field distribution is calculated to be 32.45°, resulting in a path length of 356 μm. Applying this mean path length results in an uncertainty of about 20% in LET for an individual event.

For the interpretation of the recorded data for dosimetric purposes, the following issues should be considered. The directionality of the radiation field can especially influence the measurement of the LET [9] and hence the derivation of the quality factor. However, in the case of a personal dosimeter these uncertainties are likely to be less pronounced than for stationary radiation detectors as the effects average out due to the motion of the astronaut inside the space station. EVAs, during which the astronaut might be staying at a given position and orientation for a longer time period, are omitted when the ISS is passing the SAA.

Additionally it should be noted that silicon as detector material has a low efficiency to detect neutrons. Interactions of GCR with the hull of the ISS produce a large amount of neutrons that contribute significantly to the radiation exposure inside the station [10] (compare also Section 5).

2.2. Electronics and signal processing

Figs. 3 and 4 visualize schematically the instrument's electronics and working principle. The detector system is powered by a rechargeable lithium ion battery cell of 3.7 V chargeable through the mini-USB interface. The nominal power consumption is 150 mW (40 mA). Internal DC–DC converters generate the bias voltage of +45 V for the silicon detectors as well as the analog and digital supply voltages of ±5.5 V and +3.0 V, respectively. The detector system is controlled by a single Atmel microcontroller working with a system clock frequency of 1.8 MHz. The rather low system clock frequency ensures reliable detection at the expected highest count rates in the region of the SAA of about 100–200 cts/s/cm² [11], while the power consumption is kept low at the same time.

The analog signal processing chains are the same for both diodes. An Amptek A250F/NF charge sensitive preamplifier (CSA, Fig. 4) is used to transfer charge into voltage. Preamplifiers and silicon diode telescope are placed together as front-end in a separate electromagnetically shielded compartment of the detector (compare Fig. 1a).

The preamplifier signal is filtered by a passive band-pass filter (SHA) with a time constant of 1 μs. As the instrument shall be able to detect ions from minimal ionizing protons up to relativistic iron nuclei, the lower detection threshold is 60 keV and the upper limit is set to 140 MeV. In order to cover the dynamic range of detectable energy depositions of 3.5 orders of magnitude, two subsequent amplification stages are employed using pulse amplifiers with an amplification factor of 1.3 for the