DEVELOPMENT OF SPACE DOSIMETRY SYSTEMS
PhD thesis

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Introduction and history

During the long-term future manned space missions, such as a Mars-mission, the expected dose to the members of the crew will be comparable to the lifetime dose limits for astronauts. For them, cosmic radiation poses probably the most important long-term risk during such a mission.

The development of a three dimensional silicon detector telescope (TriTel) started in the Atomic Energy Research Institute several years ago. A big advantage of TriTel, either as a stand-alone instrument or when operated together with the Pille thermoluminescent dosimeter [Fehér, 1981], is the capability of determining not only the absorbed dose but the LET-spectrum and the average quality factor of the cosmic radiation as well. From the absorbed dose and the quality factor the dose equivalent can be also determined, which characterizes the biological stochastical effects of the radiation. In the past years the theoretical background of the instrument was given [Pázmándi, 2003] and the system plan was accomplished.

Objectives

Since the absorbed dose and the quality factor of the radiation on board space stations and different spacecrafts are remarkably higher than on ground, and their values are changing in space and time, determining the LET spectrum of the cosmic radiation in orbit is essential. During my research at the MTA KFKI AEKI I joined the team developing the TriTel three-dimensional silicon detector telescope. With an almost isotropic sensitivity the 3D telescope will be capable of determining the LET-spectrum of the radiation and the dose equivalent.

In the course of my doctoral research I was taking part in the research & development activities of the Space Dosimetry Group, my tasks were as follows:

- to design the measurement system;
- to develop the electronic system;
- to reconcile the scientific, the electronic and the mechanical considerations of the development;
- to work out the algorithms of the on-board software;
- to coordinate, control and manage the development.

In my dissertation I focused on the scientific issues of the development, however I contributed to the reconciliation of the engineering considerations as well as the management of the development.

Methods

I have analyzed the main differences between determining the dose equivalent with one-dimensional and three-dimensional telescopes and elaborated a method for using the directional quality factors as a correction in calculating the dose equivalent. Taking into account the changes performed in the geometry of the telescope I recalculated the geometric parameters of TriTel and confirmed that, when considering the sensitivity of

the 3D telescope and the accuracy of determining the LET, these values are closer to the optimal value than it used to be in the early stage of the development.

By performing calculations with models of the cosmic radiation based on former measurements on different satellites and using Monte Carlo simulations I analyzed the effects of the angular-dependence of the geomagnetic cut-off, the shielding of the Earth and the east-west asymmetry of the trapped particles in the South Atlantic Anomaly on the measured deposited energy spectra. I developed a method for the assessment of the anisotropy of the radiation field based on the number of counts measured with the three orthogonal telescopes. I found that in an anisotropic radiation field, the dominant direction of the radiation can be estimated, the uncertainty of the estimation depends on the intensity of the isotropic component of the radiation, and the direction is determined up to an integer multiple of π.

By taking into account the need for complying with the different, sometimes contradictory requirements (scientific, mechanical and electrical requirements) I worked out the structure for several versions of the TriTel measurement system as well as the methods for signal processing and data management. I determined the dynamic range as well as the maximum acceptable noise level of the system by taking into account also the energy deposit of relativistic protons in the detectors. I suggested defining the last channel of the spectrum as an overflow channel that registers the number of particles with an energy deposit greater than the upper limit of the dynamic range. By using the results of earlier measurements with 1D telescopes and performing model calculations I have shown that the LET spectrum of these particles can be approximated with the LET spectrum measured with passive track detector stacks located on TriTel and it can be considered as a correction. I also worked out the logical scheme of the quasi-logarithmic multi-channel analyzer realized by a field programmable gate array and the microprocessor unit controlling the analyzer.

After an overview of the main methods of calibrating and testing the subunits and the TriTel system as a whole, I proposed and also investigated the effects of a LED-based testing subsystem, realized with light emitting diodes built in the mounting of the telescopes, on the design of the instrument and the noise level of the TriTel system. By using an alpha-particle-emitting source (Po-210) and a pulse generator I proved that the noise level of the analogue circuits developed for TriTel is below the maximum allowable noise level. I developed an algorithm to be executed in the central unit of TriTel for determining the dose equivalent rate. By using this algorithm astronauts can read the measured dose equivalent rates on-board before the on-ground evaluation of the measurement data. I elaborated a method for determining automatically the crossing of the South Atlantic Anomaly (SAA) on-board; I tested the algorithm with earlier results of the measurements performed with 1D telescopes in low Earth orbit. I showed that the 3D silicon detector telescope can be used for measurements in geostationary transfer orbit. In the region where the telescopes cannot be used due to a dead time higher than 10%, I suggested using a miniature GM-tube to determine the integral flux of the trapped particles. Using Monte Carlo methods I estimated the number of coincidences triggered by electrons as well as the contribution of electrons to the deposited energy spectra in case of coincidences. I also developed an algorithm for determining the electron-to-proton ratio from the coincidence spectra.

New scientific results (theses)

The new scientific results related to my PhD research are summarized in the following theses:

1. I performed calculations in relation with the anisotropy of the cosmic radiation field in low Earth orbit in order to compare the uncertainties in determining the dose equivalent on board the International Space Station with 1D and 3D telescopes. In my calculations I analyzed the effects of the angular dependence of the geomagnetic cut-off, the shielding of the Earth and the east-west asymmetry of the trapped particles in the South Atlantic Anomaly on the measured deposited energy spectra. I developed a method for the assessment of the anisotropy of the radiation field based on the number of counts measured with the three orthogonal telescopes. I pointed out that in an anisotropic radiation field, the dominant direction of the radiation can be estimated; the uncertainty of the estimation depends on the intensity of the isotropic component of the radiation. (Chapter 6 in the dissertation) [7] [8]

2. I worked out the logical scheme of the quasi-logarithmic multi-channel analyzer realized by a field programmable gate array (FPGA) and the microprocessor unit controlling the FPGA. I realized the quasi-logarithmic analyzer with a 16-bit linear analyzer and the use of a transformation algorithm. I suggested defining the last channel of the spectrum as an overflow channel that registers the number of particles with an energy deposit greater than the upper limit of the dynamic range. I have shown that the LET spectrum of these particles can be approximated with the LET spectrum obtained after the evaluation of the passive track detector stacks located on TriTel and can be considered as a correction. (Chapter 8 and 9 in the dissertation) [7]

3. I worked out the build-up of the software of the TriTel's electrical ground support equipment and the on-ground data processing software. I developed an algorithm to be executed in the central unit of TriTel for determining the dose equivalent rate. By using this algorithm astronauts can read the measured dose equivalent rates on-board well before the on-ground evaluation of the measurement data. I elaborated a method for detecting automatically the crossing of the South Atlantic Anomaly (SAA) on-board. Based on the time spectra provided by measurements performed with 1D telescopes in the past, I determined the optimal value for the parameter of the method. (Chapter 5 and 11 in the dissertation) [1]

4. In the course of the development of the different versions of the TriTel system suitable for measurements on board the International Space Station and satellites or space probes, I determined the dynamic range as well as the maximum acceptable noise level of the system by taking into account also the energy deposit of relativistic protons in the detectors. After analyzing the characteristics of the cosmic radiation expected during the different missions, I determined several requirements related to the measurement techniques as well as electronic and mechanical requirements on the TriTel system and its components. (Chapter 7 and 8 in the dissertation) [3] [5] [6] [7]

5. I showed that the 3D silicon detector telescope can be used for measurements in geostationary transfer orbit. I identified the regions of the orbit where determining the dose equivalent is possible with TriTel and where the telescopes cannot be used due to a dead time higher than 10%. I suggested using a miniature GM-tube to determine the integral flux of the trapped particles in the latter region. Using Monte Carlo methods I estimated the number of coincidences triggered by electrons as well as the contribution of electrons to the deposited energy spectra in case of coincidences. I developed an algorithm for determining the electron-to-proton ratio from the coincidence spectra and estimated the uncertainties in determining the average quality factor as a function of the total electron-ratio. (Chapter 12 in the dissertation) [1] [2]
6. During the development of TriTel I worked out the methods of calibrating and testing the subunits and the TriTel system as a whole and optimizing the parameters of the system. For the testing of the entire analogue system I suggested developing a LED-based testing subsystem. I have shown that by using light emitting diodes built in the mounting of the telescopes and operated in pulse mode, the testing of the total analogue system can be performed including the measurements of the resolving time of the coincidence circuits. I performed the energy calibration with an alpha source and a pulse generator. (Chapter 10 in the dissertation) [4]

References

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Exploitation of the results

There are several flight opportunities for the different versions of TriTel for the coming years:

- In cooperation with the Institute of Biomedical Problems (IBMP, Moscow), TriTel will be installed onto the Russian segment of the ISS in the near future.
- Within the framework of the European SURE (International Space Station: a Unique REsearch Infrastructure) program, another version of the instrument will perform dosimetry measurements on board the European Columbus module of the ISS.
- Within the framework of the ESEO (European Student Earth Orbiter) program of the Education Office of the European Space Agency a satellite version of TriTel will be flown on board the student satellite ESEO.

By using the TriTel system, the characteristics of the cosmic radiation on board spacecrafts can be determined with higher accuracy than in the case of the formerly used methods. Measurements on board a Mars-probe in the future will have implications also for the design and implementation of manned missions to Mars and beyond.

While the dissertation was being written the development of the different versions of the 3D telescope TriTel actually moved into its final phase; the technical solutions that I suggested in my dissertation have been adopted. In order to improve the algorithms developed during my thesis work, measurements in high energy accelerators and on board space vehicles will be necessary.

Related publications

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[4] Hirn, A., Apáthy, I., Bodnár, L., Csőke, A., Deme, S., Nagy, V., Pázmándi, T., A TriTel 3D űrdozimetriai teleszkóp LED-es ellenőrző rendszere, Nukleon (2009) – under publication

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[5] Hirn, A., Pázmándi, T., Deme, S., Apáthy, I., Csőke, A., Bodnár, L., 3D Silicon Detector Telescope for Determining the Equivalent Dose of Astronauts, 57th International Astronautical Congress, Valencia, Spain, Paper IAC-06-A1.P.2.05, 2006

[6] Hirn A., Apáthy I., Bodnár L., Csőke A., Deme S., Pázmándi T., Új módszer az űrhajósok egyenérték dózisának meghatározására, IV. Nukleáris Technika Szimpózium, ISBN-13: 978-963-420-885-3, 2006

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[8] Hirn, A., Comparison of the characteristics of 1D and 3D dosimetric telescopes in an anisotropic radiation field in low Earth orbit, 59th International Astronautical Congress, Glasgow, UK, Paper IAC-08-A1.4.4, 2008

Conference abstracts:

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[10] Hirn, A., Pázmándi, T., Apáthy, I., Bodnár, L., Csőke, A., Deme, S., Tritel – Space Dosimetry with a Novel Hungarian Instrument, From Our Star to Far Stars: Variation and Variability, British-Hungarian-French N+N+N Workshop for Young Researchers, Budapest, 15-17 January 2007

[11] Hirn, A., Űrhajósok dózisterhelésének meghatározása, Tavaszi Szél 2007 Konferencia, Budapest, 2007. május 17-20.

[12] Hirn, A., TriTel Dosimeter for the SSETI ESEO satellite, First Hungarian-Polish Student Space Conference, Budapest, 6-7 September 2007

[13] Hirn, A., Pázmándi, T., Deme, S., Apáthy, I., Csőke, A., Bodnár, L., Space Dosimetry with a 3D Silicon Detector Telescope – the ISS Versions of TriTel, 12th Workshop on Radiation Monitoring for the International Space Station, Stillwater, 10-12 September 2007

Further publications

[14] Apáthy, I., Akatov, Yu. A., Arkhangelski, V. V., Deme, S., Hirn, A., Pázmándi, T., Simonyi, C., Szántó, P., Radiation Risk of Space Tourists, Paper IAC-07-A1.9.-A2.7.04, 58th International Astronautical Congress, Hyderabad, India, ISSN 1995-6258, 2007