Radiation dosimetry onboard the International Space Station ISS

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Received 26 February 2008; accepted 26 June 2008

Abstract

Besides the effects of the microgravity environment, and the psychological and psychosocial problems encountered in confined spaces, radiation is the main health detriment for long duration human space missions. The radiation environment encountered in space differs in nature from that on earth, consisting mostly of high energetic ions from protons up to iron, resulting in radiation levels far exceeding the ones encountered on earth for occupational radiation workers. Therefore the determination and the control of the radiation load on astronauts is a moral obligation of the space faring nations. The requirements for radiation detectors in space are very different to that on earth. Limitations in mass, power consumption and the complex nature of the space radiation environment define and limit the overall construction of radiation detectors. Radiation dosimetry onboard the International Space Station (ISS) is accomplished to one part as "operational" dosimetry aiming for area monitoring of the radiation environment as well as astronaut surveillance. Another part focuses on "scientific" dosimetry aiming for a better understanding of the radiation environment and its constitutes. Various research activities for a more detailed quantification of the radiation environment as well as its distribution in and outside the space station have been accomplished in the last years onboard the ISS. The paper will focus on the current radiation detectors onboard the ISS, their results, as well as on future planned activities.

Keywords: radiation dosimetry, radiation measurement, radiation detectors, international space station, cosmic radiation

Strahlendosimetrie an Bord der Internationalen Raumstation ISS

Zusammenfassung

Neben den Auswirkungen der Schwerelosigkeit und den psychologischen und psychosozialen Problemen durch das Zusammenleben auf engem Raum stellt die Strahlung einen weiteren limitierenden Faktor für den längeren Aufenthalt von Menschen im Weltraum dar. Das Strahlenfeld ist nicht nur in seiner Zusammensetzung, sondern auch in der damit verbundenen hohen biologischen Wirksamkeit mit keinem Feld vergleichbar, welchem Personen auf der Erde ausgesetzt sind. Die Strahlungsdosen entsprechen einem Vielfachen der Dosen auf der Erde. Die Bestimmung und Überwachung der Strahlungsdosen im Weltraum ist somit eine moralische Verpflichtung. Die Anforderungen an Messgeräte im Weltraum bezüglich der Limitierung von Masse, Leistungsverbrauch, Datenvolumen etc. sind enorm und stellen eine große Herausforderung für die Wissenschaftler dar. Strahlungsmessung auf der ISS besteht zu einem Teil aus der „Operationellen" Dosimetrie (Orts- bzw Personendosimetrie). Die „Wissenschaftliche" Dosimetrie hat das Ziel die Parameter des Strahlenfeldes besser zu quantifizieren, und somit genauere Kenntnisse über die Strahlungsumgebung im Weltraum zu erhalten. An Bord der ISS haben sich bisher die unterschiedlichsten Experimente mit diesen Fragestellungen beschäftigt. Die Publikation beinhaltet die Beschreibung der Messgeräte bzw. Experimente, stellt einige Resultate der Messungen dar und gibt einem Ausblick in die Zukunft.

Schlüsselwörter: Strahlungsdosimetrie, Strahlungsmessung, Strahlungsdetektoren, Internationale Raumstation, Kosmische Strahlung

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Z. Med. Phys. **18** (2008) 265–275
doi: 10.1016/j.zemedi.2008.06.014
http://www.elsevier.de/zemedi

Introduction

The human endeavour of exploring space has reached a new goal by the almost finished construction of the International Space Station (ISS). After the European Columbus Module has been mounted to the ISS in February 2008, the Japanese Experiment Module Kibo will be sent up in spring 2008, and by 2009 the space station will have a permanent crew of six astronauts for the demanding planned science tasks ahead. Ensuring the health of the astronauts for long duration missions is a moral obligation of the space faring nations. The health of astronauts is vitiated most by three major human factors: health detriments from ionizing space radiation, progressive loss of resilience due to bone de-mineralization, and adverse psychosocial reactions due to prolonged confinement and the "earth-out-of-view" syndrome [1–3]. The assessment of the radiation risk due to long duration spaceflight requires the adequate knowledge of the radiation environment and the doses engendered thereby in the body.

The radiation field in Low Earth Orbit (LEO) is quite different from the radiation field encountered for occupational workers on earth – e.g. mixed neutron gamma field at nuclear facilities. The field at the site of the ISS consists of contributions from the galactic cosmic rays (GCR – protons, helium and heavy ions up to iron), contributions from protons and electrons by passing through the South Atlantic Anomaly (SAA) of the radiation belts and contributions from Solar Particle Events (SPE) during the 11 year solar cycle [4]. While passing through this complex and variable external radiation field, the field inside the ISS and the astronaut's body becomes even more complex by the interactions of the primary particles with the atoms of the structural materials and finally with those of the body itself. Humans on earth are shielded by our atmosphere – equivalent to a 10 m high water column (1000 g/cm^2) – against cosmic radiation. A typical spacecraft provides only an average shielding in the order of 20 cm water column (20 g/cm^2) and a space suit for extravehicular activities (EVA) with only 1.5 cm water column (1.5 g/cm^2) gives even less shielding. Most of the primary particles can easily penetrate the currently constructed spacecraft walls, causing – during quiet solar times – an exposure of up to 1 mSv/d compared to an average total exposure from natural sources on earth of about 2.4 mSv/a [5] from which 0.3 mSv/a are due to cosmic radiation. Some of the more intense and energetic SPEs can increase exposures by more than several 100 mSv within a few days. Taken all this into account, the correct assessment of the radiation load on humans in space is a demanding and challenging task for the scientists, since contributions from the various radiation sources have to be measured very accurately. Since the beginning of the human space age research organizations, universities and the space agencies worked on the development of appropriate radiation detector systems.

The International Space Station ISS – Overview

The ISS is the biggest main made structure ever put into Low Earth Orbit (LEO) at an average altitude between 330–410 km orbiting the earth from -51.6° to $+51.6^\circ$ latitude. In a partnership between 10 European countries (represented by ESA), the United States (NASA), Japan (JAXA), Canada (CSA) and Russia (Roscosmos), ISS is the world's largest international cooperative programme in science and technology to date. Its construction started in 1998 with the launch of the Russian built Zarya Control module. In the following years the space station was expanded with research modules (Zvezda, Destiny, Columbus), connection nodes and solar arrays, as well as robotic arms for cargo manipulation. The current configuration (February 2008) of the ISS is shown in (Fig. 1). Visible from bottom to the top are the modules – Zvezda – Zarya – Unity – Destiny – Harmony – and the just attached European Columbus module, as well as the solar arrays for power distribution. When the construction is completed the ISS will cover an area as big as a football field and will have a weight of ~455 tonnes.

The stations first permanent crew arrived at the 2nd of November 2000 (Expedition 1). Currently the station is always manned with a crew of three astro – cosmonauts staying up there for 6 months. In addition to the long term crews "visiting" crews with the Russian Soyuz or the Space Shuttle stay onboard the station for a time periode of up to two weeks. The ISS is supplied with water, food and further equipment by the Russian unmanned Progress cargo ships, as well as by the European ATV.

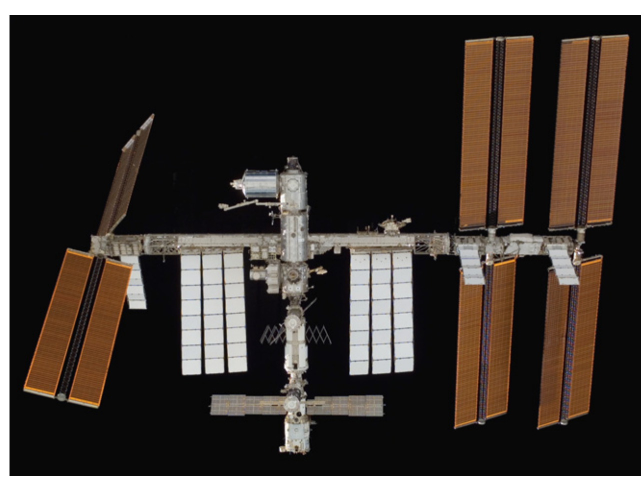

Figure 1. The International Space Station ISS – Picture taken from the Space Shuttle Atlantis on the 18. February 2008.

Starting with the year 2009 the station should have a permanent crew of six astro – cosmonauts to work and live in space, and to increase the knowledge of humanity in the field of space resarch.

Dose quantities and dose limits

The effects of radiation on humans can roughly be grouped into acute and late effects [6]. The acute effects are deterministic and occur only if certain thresholds are exceeded. The orbit of the ISS is well enough shielded by the earth magnetic field, that the probability for acute effects – even during intense solar particle events (SPE) – is nearly absent. Nevertheless, in the case of an intense SPE the astronauts remain precautionary in heavier shielded parts of the ISS. Radiation protection for near earth orbits mostly deals with late stochastic effects, represented by genetic effects and the risk of cancer induction. Taking into account the current radiation protection concept, these effects are considered to have no threshold. The system of radiation protection on earth is based on the guidelines provided by the International Commission on Radiological Protection (ICRP) in its Report 60 [7]. Herein, the ICRP introduced the concept of equivalent dose (H_T) in an organ, defined by the absorbed organ Dose (D_T) multiplied with ''radiation weighting factors w_R''. The summation of the equivalent organ doses over the whole body – weighted by the ''tissue weighting factor w_T'' – leads to the Effective Dose (E). The Effective Dose (E) – in itself a risk related quantitiy – is the baseline for risk estimation calculations as well as the baseline for the setting of radiation protection limits for stochastic effects.

Table 1 shows the current career dose limits for astronauts, recommended by the National Council on Radiation Protection and Measurements (NCRP) in its Report 132 ''Radiation Protection Guidance for Activities in Low Earth Orbit'' [8]. These limits are based on a three percent excess lifetime risk of fatal cancer. In comparison, the current limits for occupational workers on earth are 100 mSv for a five year time period, but not more than 50 mSv/a in this time period. Applying the concept of equivalent dose and effective dose as defined by ICRP in quantifying the radiation exposure of astronauts assumes a nearly complete knowledge of the composition, energy spectrum and spatial (directional) distribution of the incident radiation field. In the current situation and with the radiation detectors currently available onboard the ISS, this is not achievable from an operational point of view. ICRP 60 has addressed this problem by still applying the quantity of dose equivalent, where the dose is calculated by summing up the absorbed dose contribution in dependence on the linear energy transfer (LET) multiplied by the LET dependent quality factor Q (see Equation 1). The current definition of the quality factor Q in dependence on the LET is given in ICRP 60, with Q = 1 up to an LET value of 10 keV/µm, an increase of Q up to 29.8 at 100 keV/µm, followed by a slow decrease with increasing LET.

Table 1
Ten year career dose limits for astronauts [8].

	E (Sv)	
Age of exposure (y)	Female	Male
25	0.4	0.7
35	0.6	1.0
45	0.9	1.5
55	1.7	3.0

$$H = \sum_{L} Q(L) \cdot D(L) \qquad (1)$$

In contrast to the definition of equivalent dose, dose equivalent is a measurable quantity, applying the current active as well as passive radiation detector systems. In its Report 142 [9] the NRCP recommended for the operational safety program in LEO, that the organ dose equivalent derived by equation (1) shall be used as a measurable quantity and approximation for equivalent dose.

Space radiation intercomparison

The assessment of the radiation load on humans in space has been performed starting with the first human space missions (See as examples: [10–13]). Various detector systems have been applied over the last decades, either in the form of passive integrating devices or as active real time radiation monitors onboard various space missions (Shuttle, Mir, Spacelab) (See as examples: [14, 15]). Measurements with these active and passive detectors have often been performed side by side and data derived by different systems has been compared, without directly knowing the exact detection properties of the instruments for the complex space radiation field. With the upcoming construction of the ISS in the mid 1990s, and the increased cooperation between the international partners and the space faring nations, the space dosimetry community established an annual international workshop [16] aiming for the discussion of space radiation data, data intercomparison and space radiation instruments development with the focal point on the upcoming new ISS space era. One of its first recommendations to the space radiation community was the establishment of a ground based instrument intercomparison campaign using different particle accelerators. Only if one knows the exact properties of their applied instruments to the space radiation environment, one can compare data with other groups. The ICCHIBAN project [17] was established in the year 2000 – and up to now 12 ground based inter-calibration campaigns with active and passive radiation detector systems applied in space have been performed. Table 2 gives the locations and the simulated radiation environments, starting from protons, heavy ions to mixed and mono-energetic neutron fields applied during the studies.

The studies performed up to now [18,19] have tremendously increased our knowledge and understanding of the properties of the applied detector systems in space and provided for valuable inputs for the future application of joint radiation measurement experiments onboard the ISS.

ISS – The radiation detectors

The radiation detector systems applied for the monitoring of the radiation environment onboard the ISS can be grouped in two main categories. The first category comprises the "Operational Radiation Monitoring Devices". The second category focuses on the "Science-driven Experiments" and the herein applied detector systems. Based on the recommendations in NRCP 142 [9] operational radiation monitoring consist of **area monitors** and **personal dosimeters** and shall provide measured data of sufficient accuracy for:

- Determination of field quantities and organ or tissue doses to be used for normalizing radiation transport calculations.
- Dose assessment and record keeping purposes.
- Real-time or near real-time estimates of dose rates for purposes of immediate dose management or ALARA (As Low As Reasonably Achievable).

Operational Devices – Area Monitoring Active Systems

Table 3 gives an overview of the current applied active area radiation monitoring systems, their heritage, and the radiation field parameters measured by these devices.

The systems are based on the concepts of microdosimetry (NASA Tissue Equivalent Proportional Counter – TEPC), on silicon detector technology (NASA Charged Particle Directional Spectrometer – CPDS and Russian DB8) and on ionisation chamber principles (Russian R-16). A semi-active device is the Hungarian PILLE system, which is an automatic onboard reader for passive thermoluminescence detectors (TLDs), which are also applied on a regular base for dose determination during cosmonauts′ EVA. The main advantage of the active systems lays in the real time data viewing capabilities as well as in the built in "Radiation Alarm Functions", as in the NASA TEPC, therefore providing "real time" information about the radiation load and rapid changes due to an upcoming Solar Particle Event.

Operational Devices – Passive Systems and Personal Dosimeters for Astronauts

Although some surveys are performed with active instruments, the area monitoring data are mostly achieved by

Table 2
ICCHIBAN runs performed since 2001 [17–19].

ICCHIBAN Runs	Location	Particles
ICCHIBAN 1–8	HIMAC, NIRS, Japan	Heavy Ions (He – Kr)
Proton ICCHIBAN	Loma Linda, USA	Protons
NSRL ICCHIBAN	BNL, Brookhaven, USA	Heavy Ions (Protons to Fe)
CERF ICCHIBAN	CERN, Geneva, Switzerland	Mixed neutron reference field
iThemba ICCHIBAN	iThemba, Capetown, South Africa	Mono-energetic neutrons

Table 3
Operational active and semi-active area monitoring detectors onboard the ISS.

Instrument		Heritage	Measured parameters
Tissue equivalent proportional counter (TEPC)	[20]		LET spectra, absorbed dose, dose equivalent
Charged particle detector system (IV-CPDS)	[21]	NASA Johnson Space Center, Houston, USA	LET spectra, particle energy spectra, Nuclear abundances up to Oxygen
Charged particle detector system (EV-CPDS)			
Ionisation Chamber (R-16)	[22]	Moscow State University, Moscow,Russia	Absorbed dose, dose rate
Silicon detector units (DB8)		Space Research Institute, Sofia, Bulgaria	Absorbed dose, dose rate
TL – system (PILLE)	[23,24]	KFKI, Budapest, Hungary	Absorbed dose, dose rate

passive systems, which are distributed at numerous locations throughout the Russian as well as in the US part of the Station. These passive systems use thermoluminescence detectors (TLDs) and nuclear track etch detectors (CR-39) for the assessment of absorbed dose, LET spectra and dose equivalent at the point of interest.

Detection Principles for CR-39 and TLDs

Heavy charged particles traversing the nuclear track detectors induce latent tracks, which after etching in caustic solution develop into microscopically measurable etch cones. The LET of the crossing particle is obtained from the cone angle by an empirical calibration function which is established from exposures to heavy ions of known LET at accelerators, taking also into account the long term fading properties of the detector material [25]. The LET registration threshold of plastic detectors for ionising radiation is about 10 keV/μm. Below 10 keV/μm the TLDs are required whose efficiency is approximately equal to 1 in the lower LET range. TLD crystals accumulate energy deposited by ionising radiation in interstitial energy levels. Upon heating, the stored energy is released as light emitted by the crystals whose intensity is proportional to the absorbed dose [26]. TLDs and CR-39 detectors were calibrated and intercompared also in the framework of the ICCHIBAN project and their response relative to the reference radiation was established as a function of LET from high-energy accelerator exposures [27,28]. Applying a combination of these two detector systems gives a small, robust, and easy to handle passive radiation detector system, with the only main disadvantage, that data evaluation has to be performed on ground after the exposure.

Operational Devices – Selected Results

As an example of the area monitoring activities onboard ISS Figure 2 shows the absorbed dose values measured with TLDs (TLD 100 detectors) in the years 2000–2006 at various locations inside the American and Russian part of the ISS [29]. Measurement periods account for up to 6 months for each measurement point. The variation in dose is due to different altitudes of the ISS, the influence of the solar cycle as well as different shielding thicknesses of the various locations.

Dose equivalent rates derived from the evaluation of area dosemeters (combination of TLD and CR-39 detectors) of the NASA Space Radiation Analysis Group (SRAG) during Expedition 12 (30. September 2005–8. April 2006) at various locations inside the ISS [25] are given in Table 4. The highest dose equivalent rate (784 μSv/d) was observed for Panel 442 in the Russian Service Module Zvezda which is inside the starboard crew quarters. Of particular interest is the lowest dose equivalent rate (488 μSv/d) for the "Temporary Sleep Station" (TeSS) in the US Destiny Module, where the astronauts surround themselves during sleep with polyethylene bricks acting as a passive shield against space radiation. The increase in dose equivalent of 60% from the US to the Russian part of the station – due to different shielding configurations – highlights the importance of detailed area monitoring and mapping of the radiation environment throughout the whole space station.

Besides the area monitoring [25,30–33] also the personal radiation monitoring of the astronauts is currently achieved by applying the combination of TLDs and CR-39 detectors. This detector combination is also recommended in the NCRP 142 [9] for the personal dose assessment of astronauts. While for the astronauts from the US the personal dosimetry is accomplished by the Space Radiation Analysis Group (SRAG) at NASA Johnson Space Center in Houston; for the Russian cosmonauts the Institute of Biomedical Problems (IBMP) in Moscow is responsible. For ESA astronauts the German Aerospace Center (DLR) works as contractor for the European Astronaut Center (EAC) on the radiation assessment for

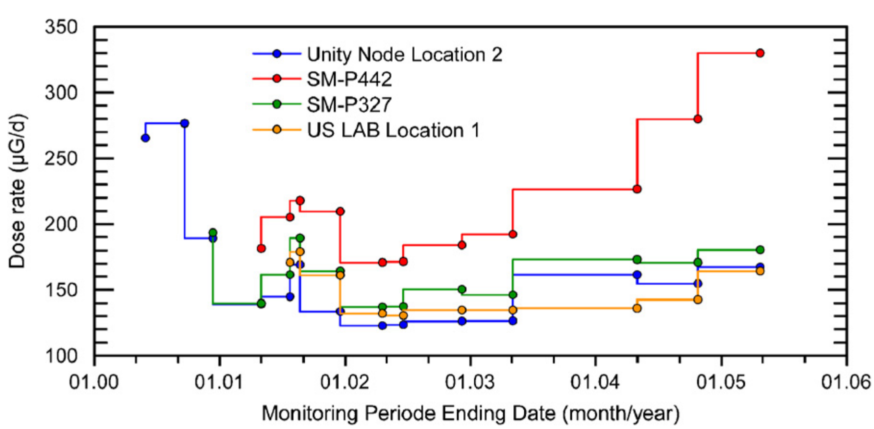

Figure 2. Area monitoring with passive thermoluminescence detectors (TLD 100) performed by NASA in the years 2000–2005 at various positions inside the ISS [Data taken from 29].

Table 4
Dose equivalent (μSv/d) and absorbed dose (μGy/d) rate as well as the mean quality factor measured for various locations inside the ISS by SRAG during expedition 12 applying a combination of TLDs and CR-39 detectors (data from [25]).

Dosemeter location	Absorbed dose (μGy/d)	Dose equivalent (μSv/d)	Quality factor Q
Russian Service Module Zvezda – Panel 327	189±4	552±29	2.92
Russian Service Module Zvezda – Panel 442	299±4	784±34	2.63
US Module Destiny – TeSS Temporary Sleep Station	173±3	488±22	2.82

personal astronaut dosimetry in the framework of the European Crew Personal Dosemeter (EuCPD) program.

Figure 3 shows the European astronauts Thomas Reiter and Christer Fuglesang, both equipped with their EuCPDs (blue belt). Further on Thomas Reiter was also wearing a Russian and an US personal dosemeter, thereby enabling the first "space based intercomparison" of personal radiation monitors. Due to the fact, that personal radiation records are categorized as medical documents no data can be published.

Science-driven Experiments

Besides the "Operational Radiation Monitoring Devices" the aim of the "Science-driven Experiments" onboard the ISS is to increase our knowledge in the field of space radiation. Therefore a suite of scientific instruments have been and are currently onboard the ISS oriented for various scientific "endpoints". Table 5 gives a small overview of active radiation detectors employed by various research groups over the last years onboard the ISS, as well as their heritage and the radiation field parameters studied within the experiments.

The first attempt to characterize the radiation environment on the ISS was made as part of the science program of NASA's Human Research Facility (HRF) in the year 2001. A suite of radiation detectors was flown. These detectors included the instruments flown as part of the DosMap [34] instrumentation – the first german experiment on the US LAB of the ISS – a TEPC (NASA), an anthrophomorphic upper torso equipped with passive radiation detectors (NASA) and the Japanese BonnerBall experiment [36]. DosMap measured with active (DOSTEL and LIULIN) and passive devices the radiation environment in the US LAB during expedition 2. The Japanese Bonner Ball [36] experiment aimed for the exact determination of the secondary neutron spectra generated by the interaction of the primary radiation field with the hull of the ISS – a research topic still under heavy discussion, since the exact determination of the neutron spectra is crucial for the evaluation of the neutron dose, and can only be achieved with high radiation detector instrument complexity. Italy provided various silicon strip detectors

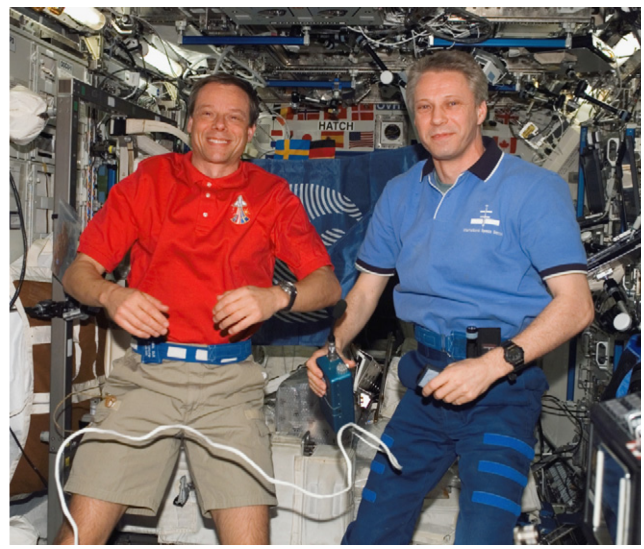

Figure 3. European Astronauts Thomas Reiter (right) and Christer Fuglesang (left) with European Crew Personal Dosimeters (EuCPDs) – carried on the blue belts – onboard the ISS (15. December 2006).

over the last years – as the ALTCRISS [37] and the ALTEA [38] facility, which aim for a precise abundance determination of the heavy ion component of the space radiation environment, and also (ALTEA) are equipped to study the "light flash phenomena" [38,39]. In 2004 the MATROSHKA facility was launched for the study of depth dose and organ dose distribution in a human upper torso phantom [40,41] (see ISS – The Matroshka Experiment).

Science driven experiments – Selected Results

Besides the experiments performed with active instruments a lot of research is done with passive dosimetry – mostly achieved as described before by the combination of TLDs and CR-39 detectors. One of these is the Russian "BRADOS" experiment, where passive detectors from different groups are positioned in standardized exposure containers, situated in various positions inside the Russian part of the ISS [42–45]. As an example Table 6 shows

Table 5
Scientific active radiation detectors applied onboard the ISS in the last years.

Instrument		Heritage	Measured parameters
DosMap Experiment	[34]		
DOSTEL – Silicon Telescope		Christian Albrechts University Kiel; German Aerospace Center, Germany	LET spectra, absorbed dose, dose equivalent
LIULIN – Silicon Detectors	[35]	Solar Terrestrial Influences Laboratory, Sofia, Bulgaria	Absorbed dose, dose rate
BBND – Bonner Ball Neutron Detector	[36]	Japan Aerospace Exploration Agency, JAXA, Japan	Neutron spectra and neutron dose
ALTCRISS – Silicon strip detector	[37]	INFN and University of Rome Tor Vergata, Rome, Italy	Particle spectra up to Iron Nuclei
ALTEA – Silicon strip detector	[38,39]		LET spectra, dose equivalent
MATROSHKA Experiment	[40]		
DOSTEL – Silicon Telescope	[41]	Christian Albrechts University Kiel; German Aerospace Center, Germany	LET spectra, absorbed dose, dose equivalent
SSD – Silicon Scintillation Detectors			Absorbed dose, neutron dose, organ dose
Tissue equivalent proportional counter (TEPC)		NASA Johnson Space Center, Houston, USA	LET spectra, absorbed dose, dose equivalent

Table 6
Comparison of TLD 700 measured absorbed dose rates at various locations in the US Lab Destiny during the DOSMAP [34] experiment and in the Russian Service Module Zvezda during the BRADOS 1 [42–45] experiment in 2001.

DOSMAP – Locations	Dose (μG/d)	BRADOS – Locations inside the Zvezda Module	Dose (μG/d)
US Lab – BBND unit X-axes	168±3	Panel # 443	292±5
US Lab – BBND unit Y-axes	175±4	Panel # 240	247±3
US Lab – BBND unit Z-axes	197±4	Panel # 110	239±3
Node – 1	216±6	Panel # 457	200±7
US Lab – Zenith area	165±3	Panel # 318	198±2

a comparison of TLD data measured during the BRADOS experiment in the Russian Part of the Station and the DOSMAP experiment in the US Lab in the year 2001. What becomes clear from the data is the wide spread in absorbed dose values – US Lab 165–216 μGy/d – Zvezda Module 198–292 μGy/d – clearly indicating, that even inside a small module of the space station the dose may vary by as much as 50% and more due to different shielding configurations.

Further results of the DosMap experiment – measured by the active DOSTEL – Silicon Telescope are provided in Fig. 4, as well as in Table 7. The cycle variation in the dose rate profile in Figure 4 (in a 45 minutes intervall) are contributions from galactic cosmic rays, influenced by the changing of geomagnetic cutoff due to latitute changes of the space station. The lowest dose rate is while passing over the equator, where the geomagnetic cutoff is highest. A fast increase in dose is observed when the ISS is entering the South Atlantic Anomaly, where the proton flux is increased due to the protons trapped in the Van Allen Belts. Table 7 gives the dose rate contributions for the GCR part, the SAA part and the summation of these two contributions. The contribution from the SAA has a low quality factor (Q = 1.2) due to the SAA protons while the mean quality factor for GCR (Q = 4.4) is higher due to the contributions from the heavy charged particles. The total dose equivalent rate accounts to 535 μSv/d.

Phantom Experiments

An essential parameter for the assessment of radiation risk on humans in space is the determination of the organ dose. Measurements inside tissue-equivalent phantoms are therefore essential in order to solve this complex task and to obtain a better knowledge of the dose distribution inside the human body. Up to now, only three space experiments dealt with the determination of the depth dose profile inside tissue-equivalent phantoms. They contained measurements inside a phantom head [46], and an Alderson phantom upper torso [47,48], applying a combination of various active and passive dosemeter systems,

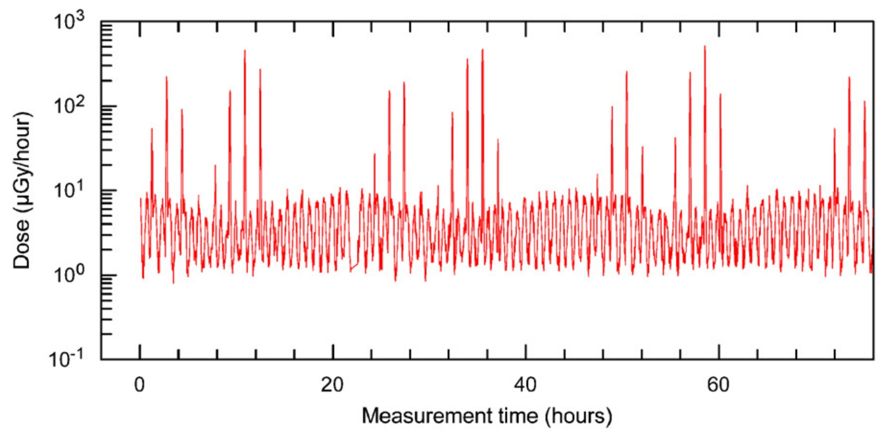

Figure 4. Shows the dose rate measured with the silicon telescope DOSTEL during the DosMap experiment onboard the ISS in 2001. The low dose variations are due to galactic cosmic rays – increasing with increasing latitude due to the lower geomagnetic cut off. The pronounced peaks in the dose rate are due to increased proton fluxs by passing through the South Atlantic Anomaly.

Table 7
Dose and dose equivalent rates for DOSTEL on DosMap for SAA and GCR contribution as well as the total dose and dose equvialent rates [data from 34]. Further on the mean quality factors for SAA, GCR and the total average quality factor is given. Data from measurement periods from March–August 2001.

	Total average			GCR average			SAA average		
	(µG/d)	Q	(µSv/d)	(µG/d)	Q	(µSv/d)	(µG/d)	Q	(µSv/d)
DOSTEL	194	2.8	535	92	4.4	409	102	1.2	126

e.g. silicon detectors, TEPCs, TLDs and CR-39 detectors. These experiments were performed on space shuttle flights, resulting in an exposure time limited by the time-frame of the space shuttle missions (up to a maximum of 16 days). In 2001 during ISS expedition 2 an Alderson phantom torso was also flown inside the US LAB module Human Research Facility (HRF) onboard the ISS [49]. In addition Russian scientists simplified the phantom to a spherical water filled phantom, which was first exposed on Space Station Mir [50] and its successor – a tissue equivalent spherical phantom – is currently measuring the radiation load on the ISS [51].

ISS – The MATROSHKA EXPERIMENT

Data from the previous phantom experiments – especially inside the ISS – are only partly available, and did not cover any exposures outside the ISS – e.g. an astronaut performing an EVA. The MATROSHKA experiment – developed as an ESA facility – under the scientific and logistics coordination of DLR aims for closing this ‘‘missing link’’. It is the biggest international effort in terms of gaining scientific knowledge about depth dose, organ dose and skin dose distribution and applies an anthropomorphic upper torso phantom, equipped with a Carbon Fibre container, simulating the astronauts space suit. [40,41] In a cooperation of 20 research institutes, universities and space agencies MATROSHKA aims by applying over 6000 passive thermoluminescence detectors, plastic nuclear track etch detectors and seven active detector systems [40,41] for the exact determination of depth dose distribution, the evaluation of organ doses as well as organ dose equivalent and the calculation of skin to organ dose ratios. MATROSHKA was launched in 2004 and was exposed outside the ISS – as a ‘‘simulated astronaut’’ performing an EVA for 539 days – as part of the MATROSHKA 1 experiment. As an example of first results Table 8 shows the dose contributions from GCR and SAA measured with a silicon telescope DOSTEL mounted on top of the head of the phantom for the outside exposure periode in April 2004 [52].

Compared to Table 7 where a similar DOSTEL measured in the year 2001 inside the space station the total dose equivalent increased by a factor of ~2.4 – due to the lower shielding of the MATROSHKA experiment outside the ISS. The difference from out – to inside exposure is also clearly visible in the enhanced contribution of protons from the SAA – which are normally already absorbed in the hull of the space station – to dose equivalent by a

Table 8
Dose and dose equivalent rates for DOSTEL located on top of the head of MATROSHKA outside the ISS for SAA and GCR contribution as well as the total dose and dose equivalent rates [52]. Further on the mean quality factors for SAA, GCR and the total average quality factor is given. Data from measurement periods in April 2004.

	Total average			GCR average			SAA average		
	(μG/d)	Q	(μSv/d)	(μG/d)	Q	(μSv/d)	(μG/d)	Q	(μSv/d)
DOSTEL	510	2.5	1265	267	3.1	828	243	1.8	437

Figure 5. European Astronaut Thomas Reiter removing the passive radiation detectors for the depth dose determination from the MATROSHKA 2A experiment (December 2006).

factor of ~3.5 compared to the inside measurements. In the framework of the follow up MATROSHKA 2A experiment, the facility was applied for depth dose determination inside the ISS. Figure 5 shows European astronaut Thomas Reiter in December 2006 removing the passive detectors from the MATROSHKA phantom for returning them safely to earth with the space shuttle (Mission STS-116) for data evaluation. MATROSHKA is currently in its third exposure periode (MATROSHKA 2B) onboard the ISS, being after four years in use the longest scientific radiation experiment performed onboard the ISS. The scientific data gathered during the exposure phases will serve as the baseline for further verification and benchmarking of radiation transport codes, being the requisite for better risk assessment for future long duration space flights.

Conclusion and Outlook

The exact determination of the radiation dose in space is a demanding and challenging task, and is fulfilled in a close cooperation of all the partners working on the International Space Station. The daily dose rates – up to a few hundred of μSv – are the highest reached for humans working in a natural radiation environment. Various research activities – including the current biggest radiation experiment MATROSHKA – aim for a better understanding of the interactions of the space radiation environment with the human body, and for a better future risk estimation for long duration space flight. With the Columbus module just brought into orbit Europe gained a new and fascinating research plattform where already radiation instruments from European Universities and research organisations are measuring the radiation environment outside the module. The current plane foresees in addition to add active and passive area monitoring devices inside the Columbus module, starting in late 2008. Further on the Japanese Experiment Module Kibo will provide – after its successful deployment to the ISS – various radiation detectors based on Japanese heritage to increase the capabilities of the space radiation community in this demanding and challenging tasks.

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