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CONCORD: comparison of cosmic radiation detectors in the radiation field at aviation altitudes

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ABSTRACT

Space weather can strongly affect the complex radiation field at aviation altitudes. The assessment of the corresponding radiation exposure of aircrew and passengers has been a challenging task as well as a legal obligation in the European Union for many years. The response of several radiation measuring instruments operated by different European research groups during joint measuring flights was investigated in the framework of the CONCORD (COmparisoN of COsmic Radiation Detectors) campaign in the radiation field at aviation altitudes. This cooperation offered the opportunity to measure under the same space weather conditions and contributed to an independent quality control among the participating groups. The CONCORD flight campaign was performed with the twin-jet research aircraft Dassault Falcon 20E operated by the flight facility Oberpfaffenhofen of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR). Dose rates were measured at four positions in the atmosphere in European airspace for about one hour at each position in order to obtain acceptable counting statistics. The analysis of the space weather situation during the measuring flights demonstrates that short-term solar activity did not affect the results which show a very good agreement between the readings of the instruments of the different institutes.

Key words. Aviation – Radiation exposure of aircrew – Comparison of radiation detectors – Galactic cosmic radiation – Ambient dose equivalent – Effective dose

1. Introduction

Radiation protection for aircrew has been regulated in the European Union since 1996. The member states of the EU were legally obliged to implement the corresponding regulations, stipulated in the EU-Directive 29/96/EURATOM, into their national legislation by 2000 (EURATOM 1996). A principal requirement consists of the dose assessment of the crew concerned. Technical guidance for the implementation by the European Commission recommends the use of an appropriate computer program for the dose assessment for flights below 15 km (European Commission 1997). Furthermore, the Commission recommends confirming these computer codes by occasional measurements with active or passive devices.

The radiation field at flight altitudes is the result of complex interactions of primary cosmic radiation with the different constituents of the Earth's atmosphere. Consequently, it is composed of a cascade of all particles which can be generated by these interactions and reach aviation altitudes with corresponding energies, e.g. p, n, e^+, e^-, π^+, π^-, μ^+, μ^- and γ. In terms of radiation protection, this mixed radiation field at aviation altitudes can be characterized by different dose quantities for operational purposes, e.g. effective dose E, ambient dose equivalent $H^*(10)$, and the corresponding dose rates. The principal dose quantity in radiation protection is the effective dose E which is defined by the International Commission on Radiological Protection (ICRP) as given in their Publication 103 (ICRP 2007) by a weighted sum of tissue equivalent doses as:

$$E = \sum_T w_T \sum_R w_R D_{T,R}, \quad (1)$$

where w_T is the tissue weighting factor for tissue T with $\sum w_T = 1$, w_R the radiation weighting factor for the particle type and energy incident on the body, and $D_{T,R}$ the mean absorbed dose in an organ or tissue T due to radiation of type R (ICRP 2007). The unit of effective dose E is J kg^{-1}, with the special name sievert (Sv) (ICRP 2007). Since the quantity effective dose is not measurable in practice, it is often estimated by the ambient dose equivalent $H^*(10)$ for strongly penetrating radiation. Generally speaking, the dose quantity $H^*(d)$ at a point in a radiation field, is defined as the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere (30 cm diameter soft-tissue-equivalent sphere with a density of 1 g cm^{-3}) at a depth, d, on the radius vector opposing the direction of the aligned field.

In their joint report "Cosmic-Radiation Exposure of Aircraft Crew", the International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiological Protection present calculated ratios of $E/H^*(10)$ for different values of vertical geomagnetic cut-off rigidity, R_c, from 0 GV to 17 GV and for the flight levels

FL310, FL350, and FL390 which imply that $H^*(10)$ can be also used as an acceptable substitute quantity for the effective dose in aviation (ICRU 2010).

In practice, the effective dose is assessed by model calculations for most European airlines and a variety of corresponding models is available, e.g. PANDOCA, SIEVERT, etc. (Clairand et al. 2009; Bottollier-Depois et al. 2012; Matthiä et al. 2014). Furthermore, most models also permit to assess the dose quantity $H^*(10)$ which can be measured, either directly by a Tissue Equivalent Proportional Counter (TEPC) or indirectly by the absorbed dose in silicon with a corresponding conversion factor, determined either in particle accelerator experiments (Mitaroff & Silari 2002) or in the radiation field at flight altitudes (Wissmann et al. 2010). The research groups participating in the CONCORD (COmparisoN of COsmic Radiation Detectors) campaign play an important role in aviation dosimetry in their home countries, i.e. the Czech Republic, France and Germany.

Airline companies registered in the Czech Republic have been obliged to monitor radiation doses of aircraft crews since 1997. About 2000 aircrew members are evaluated every year. Most of them exceed 1 mSv per year and only few of them exceed 6 mSv per year. Systematic radiation measurements onboard aircraft using the Liulin detector have been performed since 2001 (Ploc et al. 2013).

In France, aircrew doses are assessed with the SIEVERT system. SIEVERT has been operational for use by airlines since the start of summer 2001 (Clairand et al. 2009). Furthermore, this system was opened to the public in March 2002 (http://www.sievert-system.org), so that every passenger can calculate the dose received during a flight. SIEVERT takes also into account Ground Level Enhancements (GLEs) using the SiGLE model (Lantos & Fuller 2004). Since 2001, four GLEs have been taken into account within SIEVERT dose calculation.

Since the implementation of the EU-Directive into national law in Germany, more than 7 million flights have been assessed by model calculations at the German Aerospace Center (DLR) and more than 70 measuring flights have been performed in order to compare the corresponding model calculations with independent measurements using different types of radiation detectors, e.g. tissue equivalent proportional counters, semiconductor devices, bubble detectors, etc. (Meier et al. 2009).

In this study we investigate the response of different radiation measuring instruments operated by the leading research groups in aviation dosimetry from the Czech Republic (NPI), France (IRSN) and Germany (DLR) during joint measuring flights with the DLR research aircraft Falcon 20E. This approach offers the opportunity to measure at the same flight position in the atmosphere under the same space weather conditions, i.e. solar activity. The comparison of the corresponding readings of the different instruments used is auxiliary for independent quality control among the participating groups which are very committed to dosimetry aboard aircraft in Europe. Furthermore, we observe a growing demand for quality dose measurements at aviation altitudes in the space weather community (Tobiska et al. 2015).

2. Equipment

The equipment used during the measuring flights consisted of two Tissue Equivalent Proportional Counters operated by IRSN (type HAWK 1) and DLR (type HAWK 2) as well as several Liulin silicon semiconductor detectors operated by NPI (type 4 J & 6C), IRSN (type 4F), and DLR (type 6G & 6SM5). All instruments used were commercially available.

2.1. The HAWK environmental monitoring system FW-AD

Two different versions of the HAWK environmental Monitoring System FW-AD designed by Far West Technology Inc. (Goleta, California, USA) were used for the CONCORD campaign. The radiation-sensitive part of both instruments is composed of a spherical chamber with a 127-mm diameter made of 2-mm thick A-150 tissue equivalent plastic and filled with a propane-based tissue-equivalent (TE) gas at about 9 hPa (Conroy 2004). This low pressure gas counter allows the simulation of the energy deposition in a tissue volume with a diameter of 2 μm. The dose equivalent is calculated as the sum of registered single events multiplied by the respective individual lineal energy and a corresponding radiation quality factor Q, determined by the $Q(L)$ relation given in ICRP Publication 103, where L denotes the unrestricted linear energy transfer (LET) in the exposed material assuming LET ≈ lineal energy (y) (ICRP 2007).

The HAWK system uses two linear Multi-Channel Analyzers (MCAs) working in parallel with different gains. The main difference between both HAWK versions used consists in the MCA. A low-gain analogue digital converter (ADC) measures LET spectra up to 1024 keV μm^{-1} with 1 keV μm^{-1} resolution for HAWK 1 (IRSN) and up to 1535 keV μm^{-1} with 1.5 keV μm^{-1} resolution for HAWK 2 (DLR). The high-gain channel of both HAWK versions uses an ADC measuring up to a lineal energy of 25.6 keV μm^{-1} with a resolution of 0.1 keV μm^{-1}. The low and high LET components of the accumulated dose equivalent and the associated quality factor are stored in an output file once per minute. The separation between the low and the high LET component is set at 10 keV μm^{-1} according to the $Q(L)$ relationship (ICRP 2007). The LET scale of the HAWK system is calibrated using the 5.9 MeV alpha particles emitted by an internal ^{244}Cm source. The low- and high-LET dose equivalent components are calculated as contributions below and above 10 keV μm^{-1}. Below 0.3 keV μm^{-1}, no event is recorded inducing a loss of counts for the low LET components. In the instrument HAWK 1, no compensation of the loss is included in the analysis software, whereas this effect is accounted for in the HAWK 2 version where a function extrapolates the LET spectrum to zero.

Each group uses their own procedure to estimate the low- and high-LET component in terms of ambient dose equivalent $H^*(10)$. IRSN uses calibration factors, N_{low} and N_{high} for the low and high LET components of the dose equivalent measured with the HAWK 1. N_{low} was determined in photon radiation fields with ^{60}Co and ^{137}Cs sources. This factor also corrects the reading for the loss of counts below 0.3 keV μm^{-1}. N_{high} is defined using the IRSN neutron reference source of ^{241}Am-Be. N_{low} and N_{high} are respectively set at 1.1 and 0.8 for HAWK 1 (IRSN). The HAWK 2 (DLR) was calibrated by the manufacturer at the Pacific Northwest National Laboratory with sources that had been calibrated at the National Institute of Standards and Technology (Conroy, T., private communications 2005, 2006, 2007, and 2011). This calibration was checked before the measuring flights with the internal ^{244}Cm source. The operation of different versions of HAWK instruments in cosmic radiation fields had been studied by onboard aircraft measurements during different space weather conditions by several groups before (e.g. Bottollier-Depois et al. 2004; Latocha et al. 2007; Lillhök et al. 2007; Lindborg et al. 2007; Meier et al. 2009; Wissmann et al. 2010).

2.2. The mobile dosimetry unit (MDU) Liulin

The Liulin Mobile Dosimetry Unit (MDU) is a silicon spectrometer based on a Hamamatsu S2744 PIN diode. It has been developed at the Bulgarian Academy of Sciences for aircrew dosimetry and space applications and has been used for dosimetric measurements at several airlines for many years (Spurný & Dachev 2002; Meier et al. 2009; Ploc et al. 2013). Energy deposition events can be collected within configurable time intervals between 10 s and 10 min. The readout signals are directly processed by pulse analysis technique with an MCA and stored as corresponding distribution for further dosimetric analysis (256-channel spectrum). The scale of the deposited energy is adjusted with the 60 keV photons of ^{241}Am. The absorbed dose in silicon D(Si), given in Gy, can then be derived from the spectrum as:

$$D_{\mathrm{Si}} = \frac{1}{m_D} \times \sum_{i=1}^{256} N_i \times E_i, \tag{2}$$

where E_i is the energy deposition in channel i with $E_i = i \times 81.4$ keV (Uchihori et al. 2002), N_i is the number of events in this channel, and m_D is the mass of the detector. The mass of the sensitive detector volume is given by the size of the chip (21.2 mm × 11.2 mm), the thickness of the depletion layer (0.3 mm), and the density of silicon (2.33 g cm^{-3}) (Hamamatsu, Simon Kempf, private communication). The corresponding mass is 0.16597 g. Since the Liulin software uses a different, but incorrect mass in some instruments, the respective readings have to be corrected with an appropriate correction factor.

In this study, the absorbed dose in silicon, i.e. the fundamental dose quantity measurable with a silicon semiconductor detector, is determined with the different Liulin instruments. The uncertainty of this type of detector is estimated in the order of 10% for measuring the dose in silicon. Further information on the Liulin instrument and its calibration for different purposes, e.g. determination of $H^*(10)$ using spectral analysis, can be found in (Dachev et al. 2002; Uchihori et al. 2002; Dachev et al. 2007; Ploc et al. 2011; Kubancak et al. 2013; Ploc et al. 2013).

3. Flight conditions

The flight facility of the German Aerospace Center in Oberpfaffenhofen operates a variety of aircraft for atmospheric research and provides a unique opportunity for joint measuring flights. The CONCORD campaign was performed with the twin-jet plane Dassault Falcon 20E (aircraft registration D-CMET). The equipment was secured at different locations inside the cabin. Measuring instruments of the same or similar type were stowed as close to each other as possible, e.g. the two HAWKs operated by DLR & IRSN next to each other on the cabin floor.

The frame conditions for the dose measurements in terms of effective cut-off rigidity R_c as model parameter for the geomagnetic shielding and flight altitude as model parameter for the atmospheric shielding were specified by the scientists. The rigidity of a charged particle describes its ability to penetrate a magnetic field and is defined as the particle's momentum divided by its charge. The effective vertical cut-off rigidity R_c at a point in the atmosphere can be interpreted as the threshold below which no charged particle from outside the magnetosphere arrives vertically at the point of interest penumbral effects taken into account and can also be used to calculate a lower threshold in the energy spectrum of the primary particles incident on the top of atmosphere (Cooke et al. 1991). In this work the effective vertical cut-off rigidity was calculated using the PLANETOCOSMICS tool (http://cosray.unibe.ch/~laurent/planetocosmics/) based on GEANT4 (Agostinelli et al. 2003; Allison et al. 2006), for calculation details see (Matthiä et al. 2014). The altitudes were parameterized by the barometric Flight Level (FL) that is expressed by the barometric altitude given in feet divided by 100, i.e. FL320 corresponds to a flight altitude of 32,000 ft. and FL400 to an altitude of 40,000 ft. The barometric altitude is based on the atmospheric pressure and can be calculated by a fixed relationship as given by ICAO for the standard atmosphere (ICAO 1993). According to this relationship, it reflects the amount of shielding matter in the atmosphere above the aircraft. Therefore, the barometric altitude is a better indicator for the shielding of the atmosphere than the geographic altitude which does not account for e.g. the influence of terrestrial weather.

The requirements for the flight planning were to circle around a position corresponding to $R_c \approx 1.3$ GV for low geomagnetic shielding and $R_c \approx 4.0$ GV for moderate geomagnetic shielding at FL320 (lower airspace) and FL400 (upper airspace), respectively. A further requirement was to circle at each of these four positions for at least 1 h in order to reduce the random error of the dose measurements to a reasonably achievable minimum. The destination areas corresponding to the specified cut-off rigidities were selected by DLR Flight Operations with attention to weather and Air Traffic Control (ATC) restrictions. Finally, the flight campaign CONCORD was performed on two successive days in designated airspace in South Germany near Augsburg for moderate geomagnetic shielding and South Norway near Oslo for low geomagnetic shielding. An overview of the different flight positions and the corresponding parameters in terms of effective cut-off rigidity R_c and barometric flight altitude is given in Table 1.

3.1. South Germany

The first flight of the campaign took off at the airport Oberpfaffenhofen (OBF) on 14 May 2013 at 1047 UTC. The destination area was within the rectangle of 48.13°N – 48.52°N latitude and 9.88°E – 10.73°E longitude. Stable flight conditions at the first position of data acquisition on FL320 were reached at 1123 UTC at an average geographic altitude of 9808 m. The total flight time at this position was 74 min (Table 1, Position 1). After a consecutive climb the second position on FL400 was reached at 1250 UTC at an average geographic altitude of 12,215 m with a remaining measuring time of 62 min (Table 1, Position 2). The calculated effective vertical cutoff rigidities in this destination area vary from 3.95 GV to 4.10 GV with an average cutoff rigidity of 4.03 GV independent of the flight level.

3.2. South Norway

The first flight on the following day (15 May 2013) was a shuttle flight to Aalborg (AAL). After a short preparation of the aircraft and the measuring equipment, the flight to the second destination area in the Norwegian airspace took off at 1050 UTC. The corresponding destination area was within

Table 1. Flight positions and parameters during the CONCORD campaign.

Position	Date	Destination area	Flight level [FL]	$\overline{R_c}$ [GV]	W parameter
1	14 May 2013	South Germany	320	4.0	66.4
2	14 May 2013	South Germany	400	4.0	66.0
3	15 May 2013	South Norway	320	1.3	66.3
4	15 May 2013	South Norway	400	1.3	65.6

the rectangle of 60.00°N – 60.26°N latitude and 8.32°E – 9.51°E longitude. After stable flight conditions at the first position on FL320 at an average geographic altitude of 9599 m had been reached, data acquisition started at 1119 UTC for a measuring period of 101 min (Table 1, Position 3). Subsequently, the second position within the destination area on FL400 at an average geographic altitude of 12,055 m was reached at 1324 UTC with a remaining measuring time of 67 min (Table 1, Position 4). The corresponding calculated effective vertical cut-off rigidities in this area range from 1.29 GV to 1.33 GV with an average cut-off rigidity of 1.31 GV independent of the flight level.

The differences in the geographic altitudes associated with the same FL in the different destination areas in German and Norwegian airspace demonstrate the influence of local conditions on the atmospheric shielding, e.g. due to weather.

3.3. Space Weather situation during the CONCORD flight campaign

The complex radiation field at flight altitudes shows also a dependence on the respective space weather conditions since it is generated by primary cosmic radiation. According to the European definition of space weather by the COST 724 action, space weather is 'the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them, and also at forecasting and nowcasting the potential impacts on biological and technological systems' (Lilensten & Belehaki 2009). With regard to radiation protection in aviation, this generic definition of space weather implies three effects that influence the radiation field at aviation altitudes:

1. modulation of the galactic cosmic radiation (GCR) by the interplanetary magnetic field (IMF);
2. additional contribution to the exposure to GCR by high-energy solar particles during severe solar particle events (SPEs);
3. disturbances of the magnetosphere.

The galactic cosmic radiation, which is the principal source of the radiation field at aviation altitudes, is modulated by the IMF. Therefore, the GCR represents a strong seasonal component varying with the solar cycle. Short term effects such as SPEs can in principle cause an increase in dose rates in rare events if a significant part of the incoming solar particles is energetic enough to traverse the magnetosphere and penetrate deep enough into the atmosphere to contribute to the radiation exposure. In addition to this potential direct contribution, a coronal mass ejection (CME) related to an SPE can also affect the radiation field at aviation altitudes indirectly by changing the IMF so that a significant part of the GCR is deflected which would result in a decrease in dose rates. This phenomenon can be observed as a Forbush-Decrease (FD), e.g. by neutron monitors (Meier & Matthiä 2014).

When the flight campaign was planned, the maximum of solar cycle 24 had been forecast for May 2013 with a peak sun spot number (SSN) of 90 (http://www.swpc.noaa.gov/sites/default/files/images/u33/Biesecker_SolarCycle24.pdf). The updated analysis of cycle 24 showed, however, that the actual maximum did not peak until April 2014 at an SSN of 81.9 (http://www.swpc.noaa.gov/sites/default/files/images/u33/Biesecker-Solar-Maximum.pdf). The effect of the modulation of the GCR component on the radiation field at aviation altitudes can be described by the GCR modulation parameter W as defined in (Matthiä et al. 2013), which is not to be confused with the SSN, although the numerical values are similar, in particular during periods of very small time lag between SSN and GCR intensity. The W parameters for the CONCORD campaign were determined with the count rates of the neutron monitor (NM) of the University of Oulu, which is located north of the destination areas of the flight campaign at 65.05°N, 25.47°E (http://cosmicrays. oulu.fi/), according to the method described in (Matthiä et al. 2013). The corresponding values were derived from the average count rate for the time spent at each position and are given in Table 1 as well. The rounded W-parameter was 66 for each flight position which can be used as a combined input parameter for model calculations.

An increased solar activity in terms of a slightly elevated proton flux measured aboard the operational GOES-13 spacecraft could already be observed on the eve of the first measuring flight of the CONCORD campaign. A further increase during 14 May 2013 resulted in issuing an S1 solar radiation storm alert of the NOAA S-scale by the Space Weather Prediction Center (SWPC) on 15 May 2013 at 1325 UTC when the corresponding threshold of 10 particle flux units (pfu) was exceeded; one pfu is defined as one particle cm^{-2} s^{-1} sr^{-1}. This event reached a maximum flux of 41 pfu on 17 May at 1720 UTC, and ended on 18 May at 1445 UTC (Space Weather Highlights 13 May – 19 May 2013, SWPC PRF 1968, 20 May 2013, available at http://legacy-www.swpc.noaa.gov/weekly/2013_WeeklyPDF/prf1968.pdf). The data presented in Figure 1 show that the particle flux above 100 MeV was not significantly increased, thus a direct effect of this solar event on the radiation field at aviation altitudes can be excluded. An indirect effect on this radiation field by an increased shielding from the GCR component due to a temporarily augmented IMF is usually delayed by several hours up to a few days (Forbush-Decrease). The corresponding space weather situation was assessed by the neutron monitor of the University of Oulu. Figure 2 shows the variation of the count rates of this NM during the measuring flights over South Germany and South Norway on the 14th and 15th May 2013. The actual flight periods are marked by the shaded areas. The variations during the measuring flights were in the order of 1% only which is an indicator of stable space weather conditions in terms of the radiation exposure at aviation

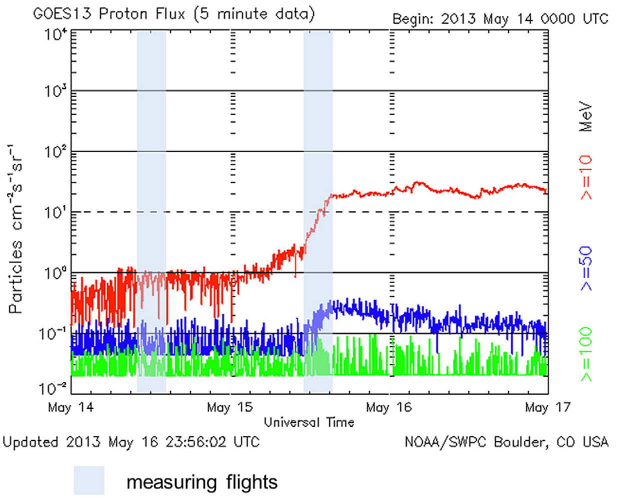

Fig. 1. GOES 5-min averaged integral proton flux (protons cm^{-2} s^{-1} sr^{-1}) as measured by the SWPC primary GOES satellite for energy thresholds of ≥10 (red line), ≥50 (blue line), and ≥100 MeV (green line) between 13th and 16th May 2013. SWPC's proton event threshold for issuing an S1 solar radiation storm alert of the NOAA S-scale is 10 protons cm^{-2} s^{-1} sr^{-1} at ≥10 MeV (ftp://ftp.swpc.noaa.gov/pub/warehouse/2013/2013_plots/proton/20130515_proton.gif).

altitudes. Furthermore, it can be seen that a slight FD set in shortly after the flight over South Norway.

Furthermore, a disturbed magnetosphere could lead to a significant shift in cut-off rigidities, which is the parameter used in this study for describing the influence of the geomagnetic field (Smart & Shea 2003). During the flights of the CONCORD campaign there was no alert according to the NOAA G-Scale for geomagnetic storms that is based on the *Kp* index as physical measure for geomagnetic activity. Strictly speaking, the *Kp* index was 3 for all measuring flights which corresponds to the average or most probable *Kp* level (Moldwin 2008). Therefore, potential magnetic disturbances can be neglected (Smart & Shea 2003).

In summary, short-term solar activity did not affect the results of the measuring flights of the CONCORD campaign and the measured dose rates can be considered as solely caused by primary and secondary particles of galactic cosmic origin in a virtually undisturbed magnetosphere.

Table 2. Average ambient dose equivalent rates dH*(10)/dt measured at the different flight positions with the HAWK instruments (TEPCs) operated by DLR and IRSN in [µSv/h].

Position	HAWK 1 (IRSN)	HAWK 2 (DLR)	$\overline{\text{HAWK}}$
1	3.3 ± 0.2	4.0 ± 0.4	3.4 ± 0.2
2	5.7 ± 0.4	6.1 ± 0.6	5.8 ± 0.3
3	4.1 ± 0.3	4.4 ± 0.5	4.2 ± 0.3
4	7.6 ± 0.6	7.9 ± 0.8	7.7 ± 0.5

4. Results and discussion

The exposure of humans to a mixed radiation field, e.g. at aviation altitudes, can be described by the quantity ambient dose equivalent H*(10). This quantity was determined at different positions in the atmosphere during the CONCORD campaign with two HAWK instruments, which are tissue equivalent proportional counters (TEPCs), operated by DLR and IRSN. Furthermore, several semiconductor devices of the Liulin type were used by all partners of the CONCORD collaboration for measuring the related absorbed dose in silicon D_{Si} which can be converted to H*(10) with a corresponding conversion factor. This factor is, however, not independent of the position in the atmosphere due to the complex structure of the radiation field in terms of particle composition and energy distribution. All dose quantities were normalized with regard to exposure time which results in the corresponding dose rates.

4.1. Ambient dose equivalent

The average ambient dose equivalent rates dH*(10)/dt measured at different flight positions with the HAWK instruments by DLR and IRSN are given in Table 2. The values of both instruments were also combined and the weighted averages are presented as $\overline{\text{HAWK}}$. Although the statistical uncertainties of the readings are similar due to the same size of the sensitive detector volume, the different total uncertainties originate from

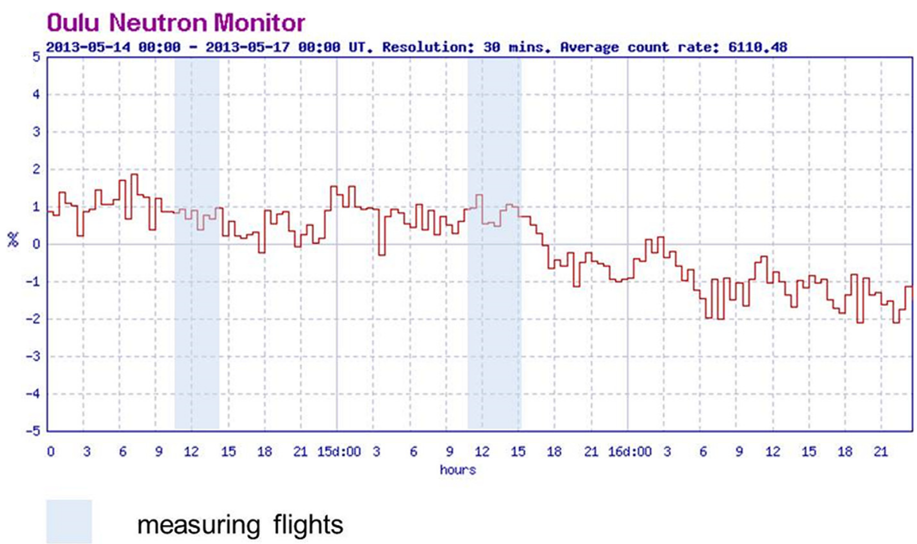

Fig. 2. Variation of the count rates of the Oulu neutron monitor during the measuring flights over South Germany and South Norway on the 14th and 15th May 2013 (http://cosmicrays.oulu.fi/). The corresponding W-parameter was 66 for each flight position (rounded, see Table 1).

Table 3. Absorbed dose rates in silicon $\mathrm{d}D_{\mathrm{Si}}/\mathrm{d}t$ measured at the different flight positions with the Liulin detectors operated by DLR, IRSN, and NPI in [μGy/h].

Position	Liulin (DLR)	Liulin (IRSN)	Liulin (NPI)	$\overline{\text{Liulin}}$	C_{field} [μSv/μGy]
1	1.2 ± 0.1	1.1 ± 0.2	1.3 ± 0.2	1.2 ± 0.1	2.8 ± 0.3
2	2.0 ± 0.2	1.8 ± 0.2	2.2 ± 0.3	2.0 ± 0.1	2.9 ± 0.2
3	1.3 ± 0.1	1.3 ± 0.2	1.5 ± 0.2	1.3 ± 0.1	3.2 ± 0.3
4	2.4 ± 0.2	2.1 ± 0.3	2.6 ± 0.3	2.4 ± 0.2	3.2 ± 0.3

different assumptions of the systematic errors for both instruments. It can be seen that the deviation between the HAWK data is less than 10% on average.

4.2. Semiconductor devices

Each cooperation partner operated several Liulin semiconductor devices during the CONCORD campaign. The comparison of the results is based on the averaged values of all devices of the respective institution. The numerical results of the measured absorbed dose rates in silicon $\mathrm{d}D_{\mathrm{Si}}/\mathrm{d}t$ are given in Table 3, supplemented by the weighted averages as $\overline{\text{Liulin}}$. The measurement uncertainty is similar for all Liulin instruments and it is, due to the good counting statistics at each flight position, dominated by the assumed systematic uncertainties of the Liulin instruments of the order of 10%. The measured absorbed dose rates in silicon show a deviation from the mean value $\overline{\text{Liulin}}$ of less than 10% on average which is of the same quality as the measured variations of $\mathrm{d}H^*(10)/\mathrm{d}t$. The comparison between the measuring values shows a good agreement for the absorbed dose rates in silicon $\mathrm{d}D_{\mathrm{Si}}/\mathrm{d}t$, measured with different Liulin instruments as well. The results of the CONCORD campaign also permit to calculate a field conversion factor C_{field} for each flight position in order to transform $\mathrm{d}D_{\mathrm{Si}}/\mathrm{d}t$ into $\mathrm{d}H^*(10)/\mathrm{d}t$:

$$\mathrm{d}H^*(10)/\mathrm{d}t = C_{\text{field}} \times \mathrm{d}D_{\mathrm{Si}}/\mathrm{d}t. \qquad (3)$$

Generally speaking, C_{field} depends on the composition and the energy distributions of all components of the corresponding radiation field. With regard to the radiation field at aviation altitudes, C_{field} depends on the effective cut-off rigidity R_c, the flight altitude FL, and the space weather situation, the GCR component of which can be characterized by the *W*-parameter. The respective field conversion factor for each flight position is also given in Table 3.

5. Conclusion

The goal of the joint measuring flights within the framework of this study was a comparison of the readings of the instruments operated by the participating groups from the Czech Republic, France and Germany for quality management. In their technical guidance for the implementation of the radiation protection regulations for aircrew, the European Commission states that "it is highly desirable for different employers to use the same software and that both calculations and instrument measurement protocols produce compatible results" (European Commission 1997).

In this context, the most important outcome of the CONCORD campaign was that all instruments showed consistent readings within the corresponding measuring uncertainties at all flight positions. Furthermore, the space weather situation during the measuring flights was quite stable. It could be shown that short-term solar activity did not affect the measuring values. These results, independently validated by the participating research groups, can be used as reference for the corresponding flight positions during moderate solar activity, described by a *W*-parameter of 66. Such reference values are important for the verification of models for the assessment of the radiation exposure of aircrew.

The assessment of the radiation field at aviation altitudes, characterized by the rate of the ambient dose equivalent $\mathrm{d}H^*(10)/\mathrm{d}t$, using calibrated and validated measuring devices also permits to derive the Space Weather D-Index for individual flights during severe space weather events (Meier & Matthiä 2014). Since the radiation field during these events may significantly differ from the space weather situation dominated by the GCR-component in terms of composition and energy distribution, it can be assumed that the readings of instruments that are not similarly sensitive to low- and high-LET radiation need to be corrected correspondingly.

In the European Commission report Radiation Protection 140 – "Cosmic Radiation Exposure of Aircraft Crew" the working group 5 of the EUropean RAdiation DOSimetry group (EURADOS) recommends to maintain an expert group on aircraft crew dosimetry instrumentation in order to ensure the quality of dosimetric measurements (EURADOS 2004). Furthermore, the demand for inflight measurements in order to better understand the weather of atmospheric radiation is expressed and well-founded in a recent publication by a comprehensive group of stakeholders (Tobiska et al. 2015). The joint flight campaign CONCORD of the leading research groups in aviation dosimetry from the Czech Republic, France and Germany contributed to these goals.

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