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RaD-X: Complementary measurements of dose rates at aviation altitudes

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Special Section:
Initial Results from the NASA Radiation Dosimetry Experiment (RaD-X) Balloon Flight Mission

Key Points:

- The RaD-X mission was supported with measured dose rates during a Lufthansa roundtrip from Germany to Japan under similar SWx conditions
- Ambient dose equivalent and absorbed dose in silicon were measured with instruments validated in the European flight campaign CONCORD
- Measuring data are compared with PANDOCA and NAIRAS model calculations

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Abstract The RaD-X stratospheric balloon flight organized by the National Aeronautics and Space Administration was launched from Fort Sumner on 25 September 2015 and carried several instruments to measure the radiation field in the upper atmosphere at the average vertical cutoff rigidity R_c of 4.1 GV. The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt) in cooperation with Lufthansa German Airlines supported this campaign with an independent measuring flight at the altitudes of civil aviation on a round trip from Germany to Japan. The goal was to measure dose rates under similar space weather conditions over an area on the Northern Hemisphere opposite to the RaD-X flight. Dose rates were measured in the target areas, i.e., around vertical cutoff rigidity R_c of 4.1 GV, at two flight altitudes for about 1 h at each position with acceptable counting statistics. The analysis of the space weather situation during the flights shows that measuring data were acquired under stable and moderate space weather conditions with a virtually undisturbed magnetosphere. The measured rates of absorbed dose in silicon and ambient dose equivalent complement the data recorded during the balloon flight. The combined measurements provide a set of experimental data suitable for validating and improving numerical models for the calculation of radiation exposure at aviation altitudes.

1. Introduction

The RaD-X science mission is targeted at the acquisition of dosimetric data and properties of cosmic ray particles in the atmosphere, such as the rate of ambient dose equivalent $\mathrm{d}H^*(10)/\mathrm{d}t$. An important step in this direction was the RaD-X stratospheric balloon flight which was launched from Fort Sumner on 25 September 2015 in order to measure dose rates in the atmosphere above 32 km altitude (barometric pressure 4.5 hPa) and between 21 km and 27 km altitude using different dosimetric instruments, e.g., a HAWK 3.0 Tissue Equivalent Proportional Counter (TEPC) by Far West Technologies and a Liulin semiconductor detector.

Information on measured dose rates at high altitudes, i.e., low atmospheric shielding, is important for the understanding and modeling of the radiation transport through the atmosphere and the development of the secondary radiation field at aviation altitudes. Furthermore, it is indispensable to measure the dose rates at altitudes of commercial aviation in order to validate numerical models for the assessment of occupational radiation exposure of aircrew [*Bottollier-Depois et al.,* 2012], such as PANDOCA [*Matthiä et al.,* 2014] and NAIRAS [*Mertens et al.,* 2013], and to identify potential for their improvement. Consequently, a comprehensive study of the development of the radiation field in the atmosphere requires measurements in the stratosphere complemented by corresponding data acquired at aviation altitudes, i.e., under the same space weather conditions and the same geomagnetic shielding. Eliminating the influence of the solar modulation and space weather by measuring at the same time and during very similar magnetic shielding conditions, i.e., by measuring at the same geomagnetic cutoff rigidity, reduces the dose rate dependence to a single parameter: the altitude, which is equivalent to atmospheric shielding. The altitudes of commercial aviation correspond to atmospheric column densities of approximately 350 g/cm^2 to 200 g/cm^2, while the balloon altitude of 32 km corresponds to about 10 g/cm^2. As a consequence, the combination of such measurements provides information about the development of the radiation field caused by cosmic radiation over a very large range of shielding. These data are particularly valuable as it is technically impossible to create a radiation field similar to galactic cosmic radiation under laboratory conditions. The information gained from the measurements also helps those involved with planning of future manned space missions, e.g., to Mars, to understand, quantify, and mitigate the risks of radiation exposure on other planetary bodies where similar shielding thicknesses may be realized. Lunar and Martian regolith, for instance, contain a large fraction of oxygen and contributions of heavier elements (Mg, Al, Si, and others). Thus, the Earth's atmosphere, the main constituents of which are nitrogen and oxygen, is comparable to the regolith in terms of atomic number of the target nuclei. Typical densities of regolith are a few g/cm^3 which means that the maximum balloon flight altitude (~10 g/cm^2) corresponds to the shielding provided by a few centimeters of regolith, while the flight altitude (200 g/cm^2–350 g/cm^2) is equivalent to about 1 m of regolith. Especially, the biologically relevant dose equivalent is strongly dependent on shielding as heavy nuclei from the galactic cosmic radiation significantly contribute for low shielding but undergo nuclear fragmentation while passing through the material. On the other hand, the formation of a secondary field, mainly neutrons, with depth has an opposing effect. The combination of experimental data from the balloon flight and aviation altitudes taken under comparable conditions allows benchmarking and improving numerical models which can eventually be used to estimate the radiation exposure of astronauts on planetary bodies in radiation shelters underground.

The scientific objective of measuring dose rates simultaneously at different atmospheric shielding with the same geomagnetic shielding was pursued in a cooperation of the National Aeronautics and Space Administration, the German Aerospace Center, and Lufthansa German Airlines. In order to measure dose rates at aviation altitudes during the RaD-X stratospheric balloon flight, a suitable scheduled Lufthansa flight covering an area with comparable geomagnetic shielding at the same time was identified and designated for the corresponding measuring flight.

In this study we investigate the rates of absorbed dose in silicon and ambient dose equivalent measured at two different flight altitudes of civil aviation (FL340 and FL370, i.e., 34,000 ft and 37,000 ft) at an average effective cutoff rigidity of 4.1 GV on a regular flight from Germany to Japan, i.e., in an area on the Northern Hemisphere which is opposite to the RaD-X stratospheric balloon flight.

2. The Measuring Flight

The scientific constraint on the measuring flight was that an area corresponding to the same magnetospheric conditions, i.e., geomagnetic shielding, as during the RaD-X balloon flight had to be covered on the flight route to the destination airport as long as possible in order to obtain best possible counting statistics. The geomagnetic shielding was described in terms of the effective vertical cutoff rigidity R_c, which can be interpreted as the threshold below which no charged particle from outside the magnetosphere arrives vertically at the point of interest in the atmosphere [*Cooke et al.,* 1991]. R_c is typically used as a model parameter to calculate a corresponding lower threshold for penetrating particles in the energy spectrum of the primary particles incident on the top of atmosphere. The effective vertical cutoff rigidity in this work was calculated for an undisturbed magnetosphere using the PLANETOCOSMICS tool (http://cosray.unibe.ch/~laurent/planetocosmics/) based on GEANT4 [*Agostinelli et al.,* 2003; *Allison et al.,* 2006]. The corresponding value for the launching site of the RaD-X balloon flight (Fort Sumner, NM) had to be estimated for planning our complementary flight in order to cover a target area with comparable geomagnetic shielding. An analysis of the Lufthansa flight plan showed that the requirement for a comparatively long coverage of an area around this effective vertical cutoff rigidity R_c of approximately 4 GV could be met with a flight from Frankfurt (Germany) to Nagoya (Japan).

The equipment used during the measuring flights consisted of a Tissue Equivalent Proportional Counter (HAWK 2) as well as two silicon semiconductor detectors (Liulin 6G). A detailed description of the instruments and their calibration can be found, e.g., in *Meier et al.* [2009, 2016], *Dachev et al.* [2002], *Uchihori et al.* [2002], and *Kubancak et al.* [2013]. All instruments were commercially available and had been tested for safety according to Radio Technical Commission for Aeronautics (RTCA)/DO-160E [*Radio Technical Commission for Aeronautics*, 2004] by an independent accredited notified body that certified compliance with Cat. H. Furthermore, the radiation measuring instruments used for the complementary measurements of dose rates at the altitudes of commercial aviation had been internationally compared and validated within the Comparison of Cosmic Radiation Detectors flight campaign [*Meier et al.,* 2016].

The RaD-X stratospheric balloon flight was originally scheduled for launch on Monday, 14 September 2015 with a launch window between 1230 UTC and 1530 UTC since this week seemed to be optimal for a long duration flight based on historic data. The successful performance of a measuring flight within the framework of a scheduled flight operated by a commercial airline requires a thorough preparation at least 2 months in

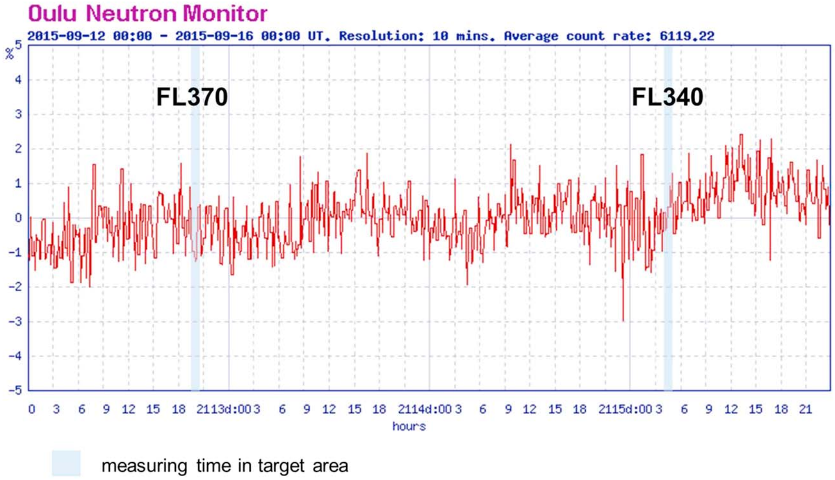

Figure 1. The modulation of the GCR component observed with the neutron monitor of the University of Oulu. The variation was in the order of 2% for both measuring periods shown as shaded areas (source: http://cosmicrays.oulu.fi/).

advance in order to select a dedicated crew and to coordinate the necessary safety and security issues with the competent authorities. The flight from NGO (Nagoya) to FRA (Frankfurt) on Tuesday, 15 September 2015 departing 0040 UTC, was chosen based on the information available at the time of planning and offered an ideal overlap time with the schedule of the RaD-X balloon flight. Consequently, the round trip from Germany to Japan comprised the flights FRA-NGO departing 12 September 2015 and NGO-FRA departing 15 September 2015.

When the RaD-X stratospheric balloon flight had to be postponed due to weather conditions at short notice, a corresponding change of the measuring flight was not possible anymore. Thus, the dose rate measurements in the stratosphere and at aviation altitudes had to be acquired at different times and the comparison and assessment of the data requires a corresponding analysis of the space weather situation during the different flight times with regard to the modulation of the galactic cosmic radiation (GCR) by the interplanetary magnetic field, potential additional contributions to the exposure from GCR by high-energy solar particles during severe solar particle events, and disturbances of the magnetosphere [*Meier et al.*, 2016].

3. Results and Discussion

Space weather is a determining factor for the interpretation and understanding of measured dose rates in the atmosphere. Thus, possible influences of space weather on the measurements are discussed first. The proton flux measured aboard the operational GOES-13 spacecraft (ftp://ftp.swpc.noaa.gov/pub/warehouse/2015/2015_plots/proton/20150912_proton.gif, ftp://ftp.swpc.noaa.gov/pub/warehouse/2015/2015_plots/proton/20150915_proton.gif) did not show an increase above background during the measuring flights which would be a necessary but not sufficient condition for an additional contribution of high-energy solar radiation to the omnipresent GCR. Figure 1 shows the modulation of the GCR component observed with the neutron monitor of the University of Oulu (http://cosmicrays.oulu.fi/). The maximum variation of the NM count rates was below 2% for both measuring periods in the target areas and below 3% for the whole time period shown in Figure 1. Therefore, the occurrence of a significant contribution of solar energetic particles can be excluded.

The condition of the magnetosphere can be assessed using the *Kp* index [*Bartels et al.*, 1939; *Smart and Shea*, 2005; *Adriani et al.*, 2016]. During the measuring time in the target area the *Kp* index was 1+ on the flight from Frankfurt to Nagoya on 12 September 2015 and 3+ on the flight from Nagoya to Frankfurt on 15 September 2015, respectively (Table 1, source: ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/tab/kp1509.tab). Calculations [*Smart and Shea*, 2005] and recent measurements [*Adriani et al.*, 2016] relate these *Kp* values to latitude shifts below 1 to 2° at a given cutoff rigidity around 4 GV. We infer from the *Kp* indices during the measuring flights that the magnetosphere was virtually undisturbed. As a consequence it can be assumed that space weather effects on the magnetosphere can be neglected for the target areas during the times when the measurements were performed.

Table 1. Comparison of the Flight and Space Weather Parameters of RaD-X Balloon Flight and the Lufthansa Flights in the Target Area at $< R_c > = 4.1$ GV on 12 and 15 September 2015

	FRA-NGO 12 September 2015	NGO-FRA 15 September 2015	RaD-X balloon flight 25 September 2015
FL	370	340	N/A
ΔR_c (GV)	$3.2 \leq R_c \leq 4.9$	$3.2 \leq R_c \leq 4.9$	$3.6 \leq R_c \leq 4.3$
Time period in target area (UTC)	1942–2041	0348–0450	1706–1410 (+1)
Measuring time (min)	60	63	1265
Kp index	1+	3+	≤1+
Modulation parameter *W*	73.6 ± 0.94	70.1 ± 0.92	60.9 ± 3.9

In addition to the variations in the geomagnetic field and the corresponding cutoff rigidities, the dose rates at aviation altitudes are influenced by changes in the solar modulation of the GCR. The *W* parameter, defined in *Matthiä et al.* [2013], characterizes the influence of solar activity on the GCR component of the radiation field and can be derived from the count rate of the Oulu neutron monitor (http://cosmicrays.oulu.fi/). For the flight times spent in the target areas, i.e., around the vertical cutoff rigidity R_c of 4.1 GV, corresponding count rates have been extracted from the data base of the Oulu neutron monitor website. Within the measuring periods on 12 September 2015 and on 15 September 2015 the count rate averages are 6076.47 ± 10.1 min^{-1} and 6114.4 ± 9.9 min^{-1}, respectively. The corresponding values of the *W* parameter according to *Matthiä et al.* [2013] are $W = 73.6$ and $W = 70.1$. From numerical calculations the difference in dose rates in the target areas from changes in the solar modulation between the 2 days is estimated to be less than 2% and is considered negligible [*Matthiä et al.,* 2014].

The beforehand identified areas corresponding to vertical cutoff rigidities around the reference value $R_c = 4.1$ GV were passed on flight levels that were kept constant sufficiently long to measure the dose rates with comparatively small statistical uncertainties. Using calculated R_c profiles for the actual flight, ranges in R_c suited for averaging the measurement data were selected to be $3.2\ \mathrm{GV} \leq R_c \leq 4.9\ \mathrm{GV}$. The selection of this range was done according to three criteria: (a) all data in the range were measured on the same flight level, (b) the averaged cutoff rigidity of all measuring positions in the range equals the reference value, and (c) the difference between the reference value and either end of the range is less than 1 GV.

The corresponding integration times of 60 and 63 min, respectively, were sufficient to obtain reasonably small statistical uncertainties. Differences between the respective average cutoff rigidities and the reference value are negligible. Table 1 lists the flight and space weather parameters for both Lufthansa flights in comparison with the corresponding parameters for the RaD-X balloon flight.

The dose rates within the target areas with an average $R_C = 4.1$ GV were measured with two Liulin 6G detectors and a HAWK 2 (TEPC). Liulin 6G semiconductor silicon detectors measure the energy deposition of charged particles in the charge sensitive region of a Hamamatsu S2744-08 positive intrinsic negative photodiode (PIN-diode) with a thickness of approximately 300 μm and a mass of 0.16597 g. For details see, e.g., *Meier et al.* [2016] and *Kubancak et al.* [2013]. The sensitive volume of the HAWK 2 (TEPC) is a 4.95 inches diameter plastic sphere that is filled with a tissue equivalent gas consisting of 99.7% propane at a pressure of about 7 torr [*Conroy*, 2004], simulating a cell size of 2 μm. The HAWK 2 instrument is also sensitive to indirectly ionizing particles, e.g., neutrons [*Meier et al.,* 2016]. The measured rates of absorbed dose in silicon dD_{Si}/dt

Table 2. Results of the Lufthansa Flights on 12 September and 15 September 2015 and Comparison With Model Calculations

	$dH^*(10)/dt$ (μSv/h)	dD_{Si}/dt (μGy/h)	C_{field}
	FL340: Atmospheric Shielding 254 g/cm^2		
Measuring data	4.73 ± 0.37	1.43 ± 0.15	3.30 ± 0.40
PANDOCA	4.16	1.44	2.89
NAIRAS	4.71	0.93	5.06
	FL370: Atmospheric Shielding 219 g/cm^2		
Measuring data	5.54 ± 0.45	1.77 ± 0.18	3.13 ± 0.41
PANDOCA	4.83	1.69	2.86
NAIRAS	5.06	1.03	4.91

and ambient dose equivalent d*H*(10)/*d*t* with their uncertainties are given in Table 2. The uncertainties take into account both statistical and systematic influences. Systematic effects for the measurement of the ambient dose equivalent with the HAWK 2 are estimated to be 5% [*Conroy*, 2004; *Wissmann et al.,* 2010; *Meier et al.,* 2016]. Systematic uncertainties of the rates of absorbed dose in silicon measured with the Liulin detector are estimated to be 10% [*Kubancak et al.,* 2013]. The data of both Liulin instruments agree within the uncertainties and have been averaged in order to obtain a higher statistical accuracy. During the flight from Frankfurt to Japan on 12 September 2015, the measured dose rates in the target area, i.e., corresponding to cutoff rigidities around 4.1 GV, at FL370, were (1.77 ± 0.18) μGy/h for the absorbed dose in silicon and (5.54 ± 0.45) μSv/h for the ambient dose equivalent. During the return flight on 15 September 2015, the measured dose rates were (1.43 ± 0.15) μGy/h and (4.73 ± 0.37) μSv/h, respectively, which is significantly lower due to the greater atmospheric shielding at FL340. The measured dose rates complement recently published results performed with the same detectors for comparable solar modulation ($W \approx 66$) at different cutoff rigidities and altitudes [*Meier et al.,* 2016].

The application of silicon detectors for measuring radiation exposure at aviation altitudes requires precise knowledge of their response to this complex radiation field. The very low sensitivity of silicon detectors to neutrons, which contribute significantly to the dose rate at aviation altitudes, has to be taken into account. This is especially true if biologically relevant weighted quantities, like the ambient dose equivalent, are considered due to the large biological effectiveness of neutrons. Silicon detectors can nevertheless be used to measure the dose rate at aviation altitudes if an applicable conversion factor C_{field} is determined beforehand with a reference instrument that is calibrated to measure *H*(10)*, e.g., a TEPC. C_{field} is the proportionality factor between the absorbed dose in silicon and the ambient dose equivalent:

$$\mathrm{d}H^*(10)/\mathrm{d}t \;=\; C_{\text{field}} \cdot \mathrm{d}D_{Si}/\mathrm{d}t \tag{1}$$

The corresponding values deduced from this flight campaign at 4.1 GV are $C_{\text{field}} = 3.1 \pm 0.4$ at FL370 and $C_{\text{field}} = 3.3 \pm 0.4$ at FL340. Although comparable within the uncertainties for the two measurements, C_{field} is generally expected to vary with altitude, cutoff rigidity, and the influence by solar modulation due to the changing composition of the radiation field in the atmosphere. It has to be emphasized that these estimated conversion factors are only applicable to the radiation field caused by GCR. In particular, in case of a solar energetic particle event, the field is expected to change both in composition and in energy distribution.

The measuring data have been compared with model calculations using the NAIRAS model [*Mertens et al.,* 2013] and the PANDOCA model [*Matthiä et al.,* 2014]. The results show a good agreement for the dosimetric quantities at the altitudes of commercial aviation (see table 2). This finding is helpful for the further analysis of the behavior of these models at lower atmospheric shielding, i.e., higher altitudes.

4. Conclusion

Measuring the dose rates at aviation altitudes is imperative to better understand the radiation exposure in the atmosphere, to check the quality and accuracy of models, and to improve their predictions. The RaD-X balloon flight campaign offered an excellent opportunity to combine measurements at aviation altitudes with the acquisition of data from the upper atmosphere. Appropriate scheduled flights made it possible to simultaneously measure absorbed dose in silicon and ambient dose equivalent for very similar space weather conditions and identical geomagnetic shielding as encountered during the RaD-X balloon flight. The measured dose rates are (1.77 ± 0.18) μGy/h for the absorbed dose in silicon and (5.54 ± 0.45) μSv/h for the ambient dose equivalent at FL370 (37,000 ft) and (1.43 ± 0.15) μGy/h and (4.73 ± 0.37) μSv/h at FL340 (34,000 ft), respectively. These results and the corresponding conversion factors $C_{\text{field}} = 3.1 \pm 0.4$ at FL370 and $C_{\text{field}} = 3.3 \pm 0.4$ at FL340 help validate and improve numerical models for the calculation of the radiation exposure in aviation and space.

With increasing altitudes the importance of heavy nuclei from the galactic cosmic radiation, especially in biologically weighted quantities like the ambient dose equivalent, is expected to increase significantly [*Copeland*, 2015]. As a consequence, the comparison of the results of this study to measurements at the balloon flight altitudes will broaden our understanding of the interactions of highly energetic, heavy nuclei from the galactic cosmic radiation with the atmosphere, as well.

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