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SIMULATION OF TEPC RESPONSE TO COSMIC RADIATION DURING DEDICATED FLIGHT CAMPAIGN

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ABSTRACT

In order to assess the aircraft crew exposure to cosmic radiation both measurements on board of aircrafts and calculations must be considered. Comparison between cosmic ray simulations and measurement results has been done at different geographical position, altitudes and solar potential. To analyze the statistical uncertainty of the dose rate measurements, a dedicated campaign of measurements, called CAATER (Co-ordinated Access to Aircraft for Transnational Environmental Research), has been made by several institutes [1]. A common flight with several instruments from 6 European Institutes was organized onboard of a special meteorological research aircraft. The aircraft circled for a long time (two hours) in the same geographical position, at two different altitudes of 10 and 12 kilometres. This has been done above Rome (42N, 12E), Italy, for high cut-off rigidity and above Aalborg (57N, 10E), Denmark, for low cut-off rigidity.

The present paper provides the results of a simulation done with the FLUKA Monte Carlo code of the same experimental conditions. The goal is to evaluate the sensitivity of the code to both the different geographical positions and altitudes. Since the measurements have been done at the same primary proton condition and at the same location inside the aircraft, the influence of these parameters can be neglected. We present comparison of simulation and measurement results of ambient dose equivalent, absorbed dose, and dose equivalent assessed by TEPC instruments used by ARC Seibersdorf research (ARCS) in Austria and the Institut de radioprotection et de sûreté nucléaire (IRSN) in France.

***Key Words*: TEPC, Cosmic Rays, FLUKA, Microdosimetry**

1 INTRODUCTION

In order to assess the aircraft crew exposure to cosmic radiation both measurements on board of aircrafts and calculations must be considered. A large set of measurements have already been gathered to monitor the on-board dose from many different groups [2-5]. At the same time, the secondary radiation produced by galactic cosmic rays and energetic solar particles events in atmosphere have been calculated by different authors [6-8]. The fluence rate of secondary particles produced during the shower in atmosphere has been calculated as a function of altitude and vertical geomagnetic cut-off for different solar activities.

Numerical simulations are also useful to understand the instrument response to unknown sources and to evaluate the relation between different quantities used in radiation protection, such as absorbed dose, ambient dose equivalent and effective dose, and characterize the instrument. For this purpose, the Monte Carlo code FLUKA [9] was used to simulate the energy deposition inside a Tissue Equivalent Proportional Counter (TEPC), since this is currently used as the reference instrument for cosmic radiation measurements. The agreement between the simulated and measured microdosimetric spectra in mixed radiation fields on Earth [10] and at flight altitude, taking into account also the influence of the aircraft shielding [11] were well demonstrated.

The present paper provides the results of a simulation done with the FLUKA code of the same experimental conditions achieved during a dedicated campaign of measurements. The goal is to evaluate the sensitivity of the code to both the different geographical positions and altitudes. Since the measurements have been done at the same primary proton condition and at the same location inside the aircraft, the influence of these parameters can be neglected and a check of the dependence of the code results on position and altitude can be performed.

1.1 Flights and Measurements description

To analyse the statistical uncertainty of dose rate measurements on-board of aircrafts, a dedicated campaign of measurements, called CAATER (Co-ordinated Access to Aircraft for Transnational Environmental Research) [1] has been funded by the European Commission through the Human Research Potential Programme of Framework Programme V. A common flight with several instruments from 6 European Institutes was organized onboard of a special meteorological research aircraft. The aircraft circled for a long time (two hours) in the same geographical position, at two different altitudes of 10 and 12 kilometers. This has been done above Rome (42N, 12E), Italy, for high cut-off rigidity (r_c = 6.4 GV) and above Aalborg (57N, 10E), Denmark, for low cut-off rigidity (r_c = 1.8 GV). The flight route was confined to a narrow circle to keep the flight conditions as constant as possible. The latitude and longitude variations were less than 1 degree. The dose equivalent measured with the different instruments was compared and found in agreement within 20%. The measurements were done in cooperation with the German Aviation Center DLR (Deutches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany) using a Mystere Falcon 20 D-CMET. The flights were done in 2003 on May the 5th over Aalborg and on May the 6th over Rome.

In this paper we only consider the measurements done using the same type of TEPCs by two different institutes: the Austrian Research Center Seibersdorf (ARCS) in Austria and the Institut de radioprotection et de sûreté nucléaire (IRSN) in France. The detectors are spherical counters of the Rossi type [12] of 125 mm inner diameter. Since the TEPC is filled with pure propane gas, at low pressure (933.2 Pa) it simulates a tissue volume with a diameter of 2µm. The wall of the sphere is made of a tissue equivalent plastic (A150) of 0.21 mm thickness. The TEPC sphere is contained in an aluminum cylindrical structure together with the required electronics. The complete assembly, cased inside a portable trolley of an aircraft hand-baggage dimension, is manufactured by Far West Technologies and is called HAWK [13].

The TEPC has been calibrated in photon, neutron and in mixed radiation fields. Photon measurements were performed at ARCS with ^{137}Cs and ^{60}Co sources. Measurements with neutrons of energy below 20 MeV were performed in the reference field of PTB. The detector was also exposed at the CERN Reference neutron Facility (CERF) where a neutron spectrum similar to that present at commercial flight altitude is provided [14]. In such a way two different calibration factors for low-LET and high-LET have been determined.

In the following we will consider tree different dose quantities: 1- the absorbed dose D measured by the TEPC as a function of lineal energy (y), 2- the dose equivalent H_{TEPC} calculated folding the absorbed dose distribution with the quality factor, as defined in ICRP74 [15] and 3- the ambient dose equivalent $H^*(10)$ obtained by multiplying the low-LET and high-LET dose rate contribution of H_{TEPC} by two different calibration factors, investigated during measurements in standard calibration fields.

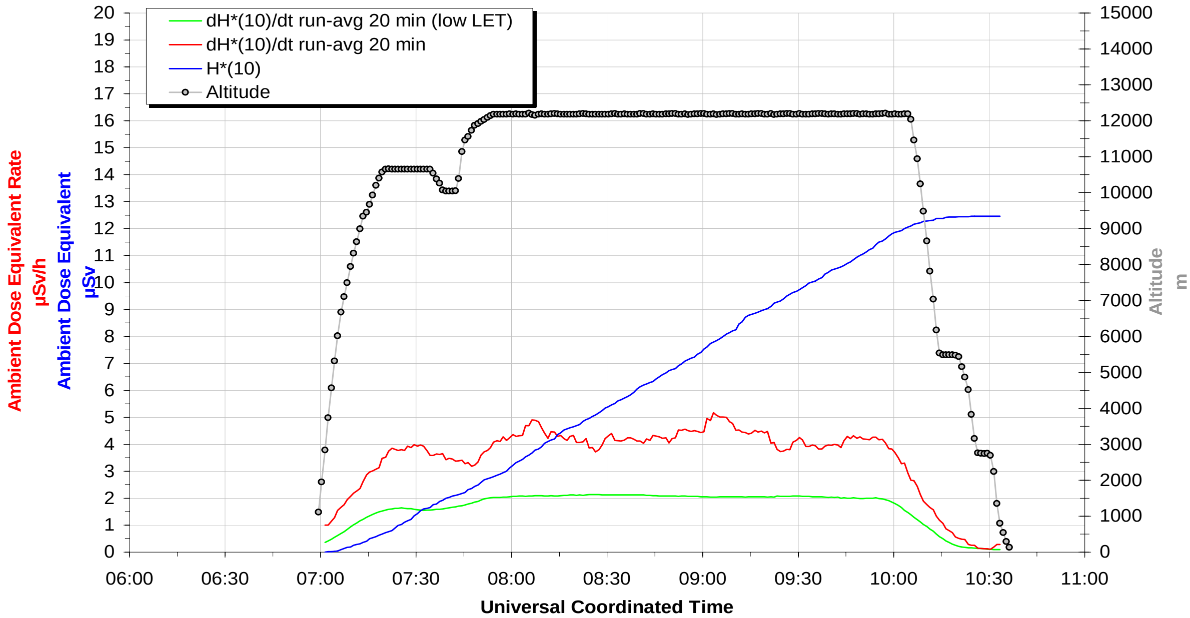

Figure 1. Flight (3) profile over Rome as a function of time.

In this paper, four flights are considered: (1) – above Aalborg at 12 km altitude, (2) – above Aalborg at 10 km altitude, (3) – above Rome at 12 km altitude, (4) – above Rome at 10 km altitude. As an example, the profile of the flight number 3 above Rome is presented in Figure 1 as a function of time. The grey dots are measurements of the standard barometric altitude (SBA); the corresponding values in meter are shown on the right vertical axis. The red line shows 20 minutes running average of the ambient dose equivalent rate (both high and low LET components) of measurements of one minute time period; the green line shows the low-LET dose rate contribution. The blue line gives the ambient dose equivalent rate integrated during the flight. In the following the measurements considered for the comparison are taken during the flat part of the flight, while the altitude is constant (between 8:00 and 10:00 hour in Fig. 1).

1.2 FLUKA simulations

FLUKA is a Monte Carlo code able to simulate transport and interaction of electromagnetic and hadronic particles in any target material over a wide energy range (from 20 TeV down to 1 keV for all particles and down to thermal energy for neutrons). In this paper the main components of the radiation field at civil aviation altitude have been calculated using the FLUKA code taking into account the interactions of the primary cosmic rays with the nuclei in the Earth's atmosphere. A 3D spherical representation of the whole Earth and the surrounding atmosphere is considered in the FLUKA geometrical description. A standard atmosphere with height-density profile and a proper mixture of N, O and Ar, arranged in 100 concentric shells, extends as far as 70 km of altitude. An updated version of the primary spectrum is used to consider the Galactic Cosmic Rays (GCR) component of the cosmic ray flux for all elemental groups from Z=1 to Z=28. To this steady baseline a modulation due to the influence of the solar wind is added using the solar modulation model [16] taking into account count rates from the CLIMAX neutron monitor.

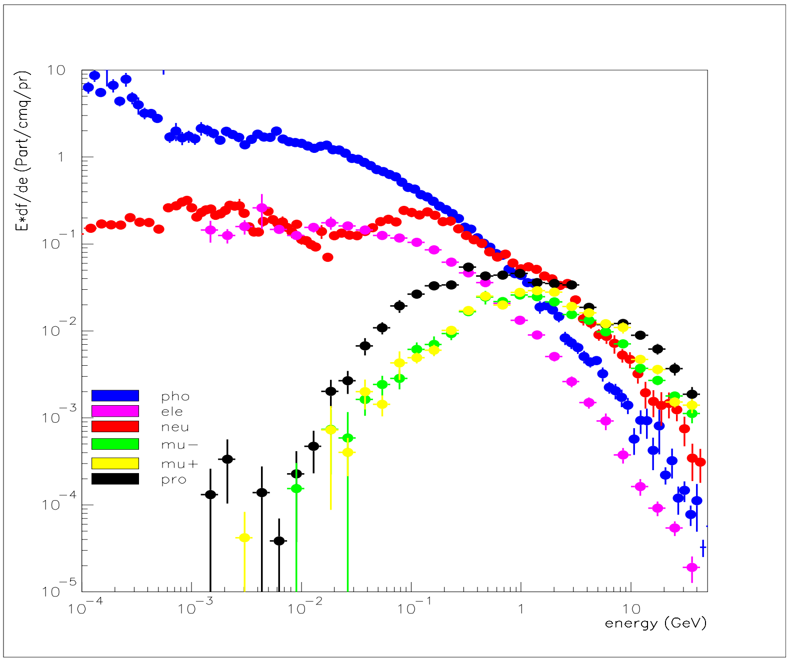

Figure 2. Spectral fluences of different particles as calculated by FLUKA for flight N. 3.

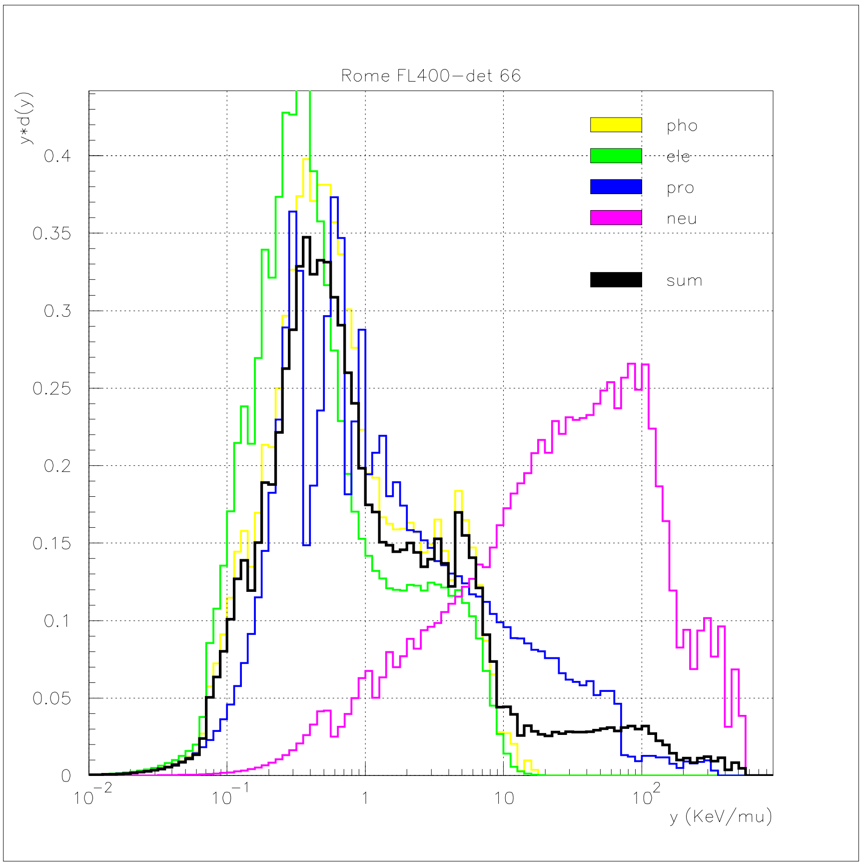

Figure 3. Microdosimetric spectra y·d(y) for each particle as seen by the FLUKA simulated TEPC for flight N. 3.

The energy spectra for neutrons, protons, photons, electrons and muons in free atmosphere were calculated at 10 and 12 km altitude above Rome and Aalborg. As an example, Figure 2 shows the fluence rate and energy distribution for all particles calculated with FLUKA above Rome at an altitude of 12 km (flight no. 3). This and all subsequent figures are normalized to one source particle. For the simulations, the ambient dose equivalent *H*(10)* values are obtained folding these fluences with the appropriate conversion coefficients [17].

These spectra have been used as sources for the irradiation of the TEPC as described in detail in reference [10]. In summary, the distribution of the energy deposition inside the TEPC gas is calculated considering the particles transport and reactions in the surrounding structures. The recoils protons produced in the neutrons reactions on hydrogen and nitrogen are explicitly produced, transported and their energy losses are accounted for as ionization losses and not taken into account in the kerma factor. The absorbed dose distribution is calculated as a function of lineal energy inside the TEPC for all the different kinds of particles and spectral energies distributions. The corresponding simulated microdosimetric spectra y·d(y) seen by the TEPC are shown in Figure 3. As expected, the bulk of the distribution for high LET particles, such as neutron, appears mainly above y = 10 keV·μm^{-1}. The distribution of low LET particles, such as electrons, and photons, is very similar and below y = 10 keV·μm^{-1}. The total absorbed dose distribution is computed summing up the contribution of each particle weighted with its relative fluence value. The dose equivalent, called in the following H_{TEPC}, is calculated folding this distribution with the quality factor as a function of LET, as defined in ICRP74 [15].

1.3 Comparison between Simulations and Measurements

Both the measured and simulated absorbed dose rate distributions are shown in Figure 4. The used TEPC has an instrument threshold of $y = 0.6\ keV{\cdot}\mu m^{-1}$. To take into account the contribution below this threshold an extrapolation with a ^{60}Co spectrum has been applied [13]. The integral of each curve is the absolute value of the absorbed dose rate. For both measurements and simulations in the low-LET region the curves are in the same decreasing order starting from the highest altitude and lowest rigidity cut-off (Aalborg, 12 km) down to lowest altitude and higher rigidity cut-off (Rome, 10 km). For the high-LET region the differences between the flights are smaller and for the measurements of the order of the statistical fluctuations, even if it's still possible to appreciate a higher contribution for the lower cut-off rigidity, as expected.

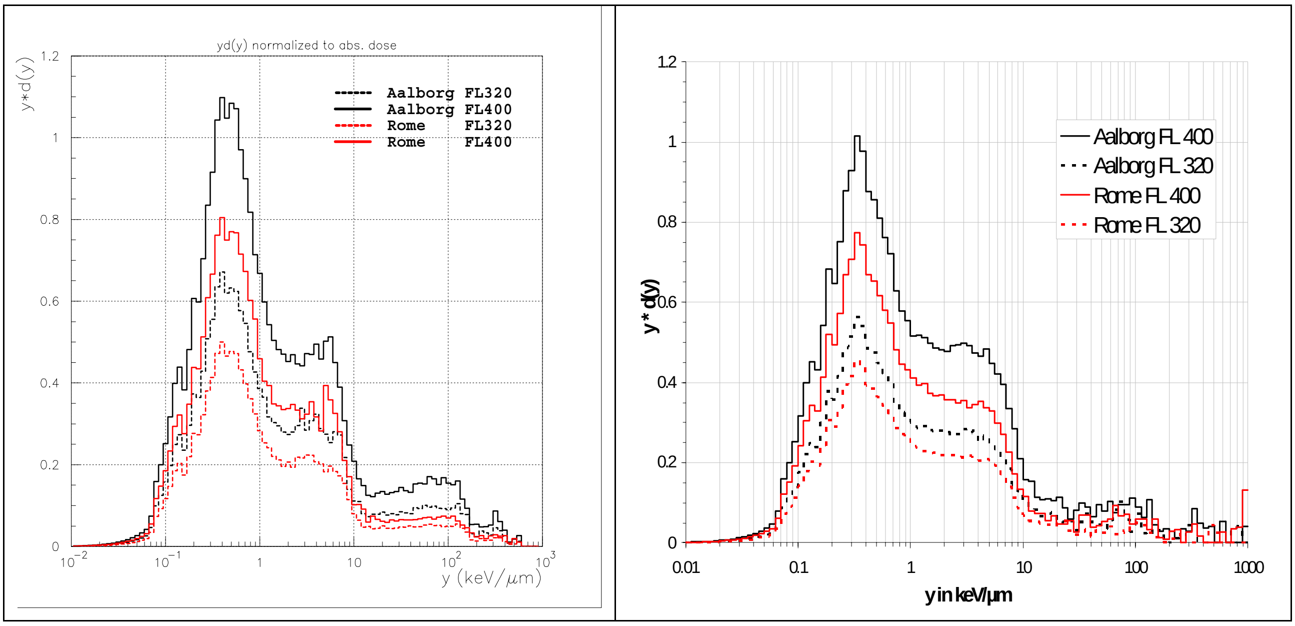

Figure 4. Microdosimetric spectra distribution y·d(y) for the 4 considered flights: simulation (left) and measurements (right). The integral of each curve is normalized to the absolute values of the absorbed dose rate.

Folding the absorbed dose rate distribution with the quality factor as a function of LET we obtain the dose equivalent rate distribution y·h(y) shown in Figure 5. The integral of each curve is the absolute value of the dose equivalent rate. Due to the high value of the Q factor at high-LET this region gives a bigger contribution to the dose equivalent.

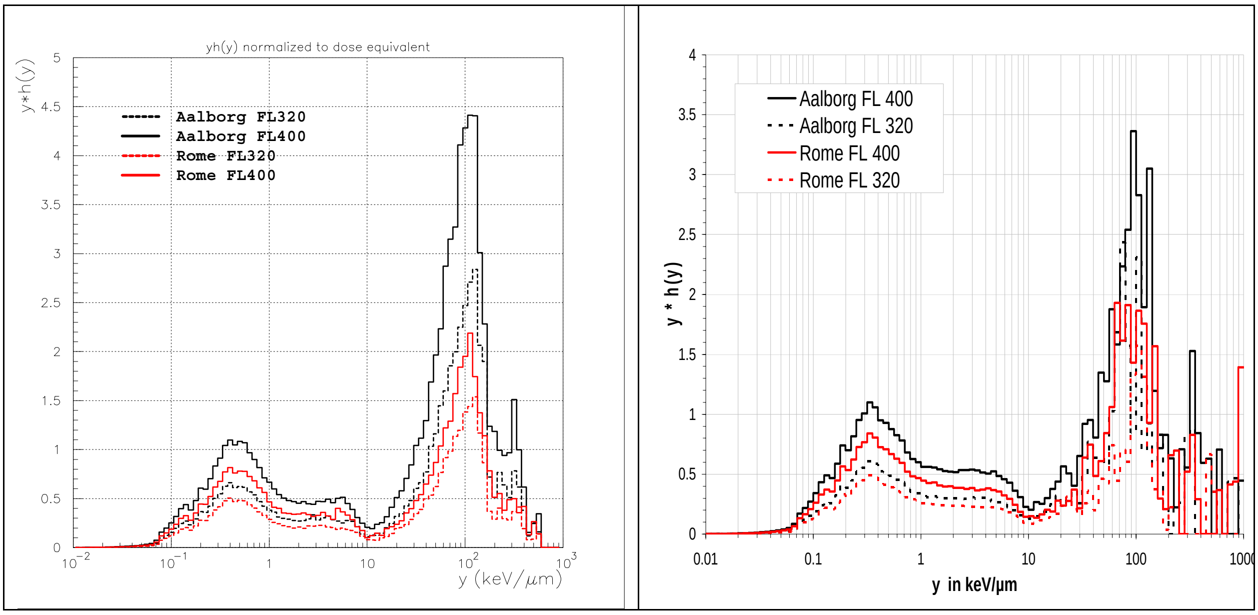

Figure 5. Microdosimetric spectra distribution y·h(y) for the 4 considered flights: simulation (left) and measurements (right). The integral of each curve is normalized to the absolute values of the dose equivalent rate.

A comparison of the simulated and measured dose rates is shown in Table I for the two different flight locations and standard barometric altitude (SBA). The absorbed dose rate $\dot{D}$ given in µGy/h, the ambient dose equivalent rate $\dot{H}^*(10)$ in µSv/h and the dose equivalent rate $\dot{H}_{TEPC}$ in µSv/h results measured by ARCS and IRSN are compared to the simulated ones.

The dose rate values shown in Table 1 are the average over two hours of measurements based on 1 minute integration time. For this single average measurement the absorbed dose rate values show a standard deviation of about 1% and about 5% on $\dot{H}_{TEPC}$. The uncertainty on the ambient dose equivalent rates takes into account the uncertainty in the calibration factors (4% for the low-LET and 10% for the high-LET) and hence it is about 7%. Analyzing the scattering between the dose measurements done with the ARCS and IRSN instruments the total uncertainty of the TEPC measurements is estimated to be 10% for absorbed dose and 15% for dose equivalent and ambient dose equivalent rate.

For the simulations, the uncertainty on the integral fluence rates is in the range of 2-6% depending on the type of particle and altitude. The statistical uncertainty of the absorbed dose is around 5%. The total uncertainty is higher considering the several possible sources of uncertainties (i.e. cross sections data, uncertainties on position etc.) and it is in the order of 10%. Folding the fluence energy distribution with the conversion coefficients the statistical uncertainty on the ambient dose equivalent is of the order of 8%. Because of the low frequency of the high-LET particles, depositing a small fraction of the absorbed dose but giving a large contribution to the ambient dose equivalent, the total uncertainties for $\dot{H}^*(10)$ and $\dot{H}_{TEPC}$ are bigger, and are about 15-20% for one standard deviation, depending on the location.

Table I. Comparison between measurements and simulations

Flight	Location	SBA		Absorbed dose rate $\dot{D}$ in µGyh^{-1}			Ambient dose equivalent rate $\dot{H}^{*}(10)$ in µSvh^{-1}			Dose equivalent rate $\dot{H}_{TEPC}$ in µSvh^{-1}		
		FL	m	Meas. ARCS	Sim. ARCS	Meas. IRSN	Meas. ARCS	Sim. ARCS	Meas. IRSN	Meas. ARCS	Sim. ARCS	Meas. IRSN
1- Aalborg	57N, 10E	400	12 185	3.1	3.3	3.4	6.0	7.4	6.5	7.4	9.1	7.1
2- Aalborg	57N, 10E	320	9 755	1.7	2.0	1.9	3.4	4.6	3.8	4.1	5.5	4.2
3- Rome	42N, 12E	400	12 188	2.3	2.3	2.5	4.3	4.2	4.2	5.2	5.0	4.4
4- Rome	42N, 12E	320	9 754	1.3	1.4	1.6	2.4	2.9	2.9	2.9	3.4	3.1

The relative increase of the absorbed dose rate between the simulated values at FL400 and FL320 compared to the reference at FL320 at each location is between 3 and 4 standard deviations s. Conversely, fixing the altitude, the relative increase of the simulated absorbed dose rates between Rome and Aalborg is about 3 s. The simulated values of the absorbed dose rate agree within the mean values of both instruments within one standard deviation. Hence, the code can properly reproduce the measured absorbed dose and its variation both as a function of altitude and position. In the high cut off region (Rome) for both, dose equivalent and ambient dose equivalent rate the agreement of simulation and measurement is within one standard deviation. While in the low cut off region (Aalborg) the agreement is within about two standard deviations. The same behaviour but only for ambient dose equivalent rate can be seen in [18] where a large number of experimental results are compared.

2 CONCLUSIONS

With the FLUKA Monte Carlo code it is possible to calculate the particle cascades caused by the interaction of the primary cosmic rays in the atmosphere for very different geographical positions and altitudes. The capability of the code to evaluate the absorbed dose, dose equivalent and ambient dose equivalent as measured by a TEPC has been benchmarked against a set of measurements done on board of a special flight at constant boundary conditions (location and altitude). The code can properly reproduce the measured absorbed dose and its variation both as a function of altitude and position. The uncertainties on the dose rate values for this dedicated flight are much smaller than the ones usually encountered at commercial flights and a preliminary estimate of the order of 10-15% is assumed for measurements and simulations. The measured and simulated dose rate values are in a good agreement within this uncertainty. For high cut off regions uncertainties of 25% between measured and simulated ambient dose equivalent values have been observed.

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