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Content

Abstract

The aim of this report is to compare the doses and dose rates calculated by various codes assessing radiation exposure of aircraft crew due to cosmic radiation. Some of the codes are used routinely for radiation protection purposes while others are purely for scientific use. The calculations were done using a set of representative, real flight routes around the globe.

The results are presented in an anonymous way. This comparison is of major importance since a real determination of effective dose is not possible and, therefore, the different methods used to evaluate effective doses can be compared.

Eleven codes have been used in this comparison exercise organised by EURADOS on harmonization of aircrew dosimetry practices in European countries. Some of these codes are based on simulations of the secondary field of cosmic radiation by Monte Carlo techniques; others use analytical solutions of the problem, while still others are mainly based on a fit to experimental data. The overall agreement between the codes, however, is better than ±20 % from the median.

1 Introduction

1.1 Radiation Exposure of Aircrew

Since the primary and secondary fields of cosmic radiation in the atmosphere are very complex in terms of particle composition and particle energies, dose assessment for aircrew is a very difficult task. Many research projects have focused on this problem during the past decade. One of the main outcomes is that dose assessment can be performed using program codes which were developed during the past few years. Use of a code is possible since the radiation field is relatively constant and sudden changes in local dose rates are not expected, except for the rarely occurring case of ground level enhancements (GLE). Therefore, the dates, geographic information on latitudes and longitudes, and barometric altitudes of the routes flown are the basic input parameters for calculations of radiation exposure of aircraft crew due to galactic cosmic radiation.

1.1.1 European Union

Since 1996, aircraft crew in the European Union have been recognized as occupationally exposed workers owing to their exposure to primary and secondary cosmic radiation in the atmosphere at typical flight altitudes i. e. between 8 km and 12 km. By 2006, the EURATOM/96/29 directive had been implemented in all EU member states and proper measures had to be taken to assess the dose.

Since about 1990 there has been an extensive series of measurements of the cosmic radiation field at flight altitudes. Within Europe, these have included four multinational, multi-institutional coordinated measurement, research and development programmes funded by the European Commission (Beck, 1999; EC, 1997; O'Sullivan, 1999; O'Sullivan, 2004), and three workshops on cosmic radiation and aircrew exposure (Kelly, 1999; Reitz, 1993; Bottollier-Depois, 2009). The results obtained by these and other investigations, mainly European, have been partially summarized, and detailed descriptions of the measurement methods have been published by the European Commission (EC, 1996; EC, 2004) in two European Radiation Dosimetry Group (Eurados) reports. There was also an investigation within the Fifth European Research Framework Programme and the CAATER project (Coordinated Access to Aircraft for Transnational Environmental Research) comparing measurements and calculations of ambient dose equivalent rates on board an aircraft circulating in limited areas (Lillhök, 2007).

1.1.2 Canada

With the adoption of the recommendations of the International Commission on Radiological Protection in publication No. 60 (ICRP, 1990) by the nuclear regulator in Canada (Canadian Nuclear Safety Commission), Health Canada was asked to provide guidance to Transport Canada (TC) which is specifically responsible for the regulation of occupational exposure of aircrew in Canada. A Commercial and Business Aviation Advisory Circular (CBAAC) was subsequently issued by TC to advise Canadian-based air carriers to initiate a means of assessing flying aircrew in advance of forthcoming regulations. Extensive research, supported by the Director General Nuclear Safety (DGNS), the Air Transport Association of Canada (ATAC), Transport Canada (TC) and the Natural Sciences and Engineering Research Council of Canada (NSERC), has been undertaken by the Royal

Military College of Canada (RMC) to determine the radiation exposure of both Canadian Forces and commercial aircrew (Lewis, 2001; Lewis, 2002; Lewis, 2004).

1.1.3 Japan

In Japan, the National Institute of Radiological Sciences (NIRS) has carried out intensive research to develop cosmic radiation detectors and educational tools to provide aviation route dose values and related information. The Radiation Council has established a guideline for the management of cosmic radiation exposure of aircraft crew and, in May 2006, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and two other related ministries jointly urged domestic airlines to follow the guideline. It was suggested that cosmic radiation exposure of aircraft crew should be managed by voluntary efforts of airlines to keep the annual doses lower than 5 mSv. Proper measures against large solar flares are also required. It was also recommended that cosmic radiation doses of aircraft crew be evaluated by model calculation, verified by measurements.

1.1.4 United States

In the U.S., to promote radiation safety of aircrews, the Radiobiology Research Team at the Federal Aviation Administration's Civil Aerospace Medical Institute (CAMI) provides educational materials on radiation exposure, recommends limits for occupational exposure to ionizing radiation, develops computer programs available via the Internet to calculate flight doses, operates a Solar Radiation Alert system, and publishes original research and review articles in peer-reviewed journals.

The Federal Aviation Administration (FAA) formally recognizes that aircraft crews are occupationally exposed to ionizing radiation. It recommends that crew members be informed about their radiation exposure and associated health risks and that they be assisted in making informed decisions with regard to their work environment.

The FAA, with the cooperation of the National Oceanic and Atmospheric Administration (NOAA), operates a Solar Radiation Alert system that warns of increasing radiation levels that may cause air travellers to be exposed to excessive amounts of ionizing radiation. The system continuously evaluates measurements of high-energy protons made by instruments on GOES satellites. Solar Radiation Alerts are transmitted to the aviation community via the NOAA Weather Wire Service.

1.2 Quantities used for aircrew dosimetry

For routine radiation protection purposes, i.e. dose assessment of aircraft crew, a code must be able to calculate the effective dose *E*, the radiation protection quantity defined as the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by the expression:

$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} H_{\mathrm{T}} = \sum_{\mathrm{T}} w_{\mathrm{T}} \sum_{\mathrm{R}} w_{\mathrm{R}} D_{\mathrm{T,R}}$$

where H_{T} is the equivalent dose in a tissue or organ T given by $\sum_{\mathrm{R}} w_{\mathrm{R}} D_{\mathrm{T,R}}$; $D_{\mathrm{T,R}}$ is the mean absorbed dose from radiation type R in a tissue or organ T, and w_{R} and w_{T} are the radiation and tissue weighting factors, respectively, defined by the ICRP. The SI unit for the effective dose is joule per kilogram (J kg^{-1}) and its special name is sievert (Sv).

According to ICRP 103 (ICRP, 2007) use of the effective dose is recommended for *"the prospective dose assessment for planning and optimisation in radiological protection, and demonstration of compliance with dose limits for regulatory purposes"*. It is also recommended that the effective dose should not be used *"for epidemiological evaluations, nor should it be used for detailed specific retrospective investigations of individual exposure and risk"*.

In operational radiation protection the dose equivalent H is defined by the product of the absorbed dose D at a point of interest in tissue and the radiation quality factor Q at this point:

$$H = QD$$

where Q describes the biological effectiveness of radiation, taking into account the different ionisation densities. In this report, aircrew dosimetry deals with the dosimetry of external radiation as personal dosimetry is not an option for routine dose monitoring. Area monitoring at flight altitudes uses the ambient dose equivalent $H^*(10)$ as the operational quantity, defined by ICRP 103 as: "*The dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of 10 mm on the radius vector opposing the direction of the aligned field. The unit of ambient dose equivalent is joule per kilogram (J kg^{-1}) and its special name is sievert (Sv)*".

Codes calculating the doses received by aircrew members can only be validated by comparing the measured ambient dose equivalent $H^*(10)$ (or its rate) to the calculated value. For validation purposes, all codes must be able to calculate $H^*(10)$. This in turn means that the measured doses or dose rate values should be given in terms of ambient dose equivalent. This requirement can best be fulfilled if measurements are performed according to the ISO 20785 series. These standards define the way instruments are characterized and calibrated, and how measurements on board aircraft are to be performed. Codes providing effective doses only cannot be validated by experimental data, but can nevertheless be compared to other validated codes.

The codes involved in this comparison provided ambient dose equivalents or effective doses or both. It should be mentioned here that in the new ICRP 103 recommendations these radiation weighting factors have somewhat changed compared to the early ICRP 60 recommendations, making $H^*(10)$ values more similar to the effective dose values. However, since in most countries, especially in Europe, the current legal basis for calculations of aircrew exposure is based on ICRP 60 recommendations, effective doses given here are based on these recommendations.

1.3 Parameters influencing the secondary field of cosmic radiation

Primary cosmic radiation at the top of the Earth's atmosphere includes a continuous galactic component and a sporadic solar component. Both components consist mainly of protons and to a lesser extent helium ions, but electrons and heavier ions may also be present on a small scale. The intensity of galactic cosmic rays near Earth is modulated by the variation of the interplanetary magnetic field during the 11-year cycle of solar activity. The intensity of the sporadic solar cosmic radiation at the top of the Earth's atmosphere depends on the source location of the high-energy processes in the Sun, where the solar cosmic radiation particles are accelerated, and the configuration of the interplanetary magnetic field. Both components, i.e. the galactic and the solar cosmic radiation, are shielded by the geomagnetic field. In contrast to the interplanetary magnetic field, the geomagnetic field is rather constant, although it may occasionally be influenced by large coronal mass ejections from the Sun. Shielding by the geomagnetic field is most effective at low geomagnetic latitudes, and less effective close to the geomagnetic poles. For this reason, the dose rate from cosmic radiation at any point of interest in the atmosphere depends on geomagnetic coordinates.

The magnetic rigidity, r, of a charged particle traversing a magnetic field is:

$$r = \frac{p \cdot c}{q}$$

where p is the particle's momentum, q its charge, and c the speed of light. Particles with the same magnetic rigidity, same charge sign, and same initial conditions have identical trajectories in a constant magnetic field. The SI unit of magnetic rigidity is kg m s^{-2} A^{-1} = T m = V m^{-1} s. A frequently used unit is volt, V (or GV), in a system of units in which the magnetic rigidity is cp/q.

The parameter most commonly used to quantify the shielding effect of the Earth's magnetosphere at a given location is the effective vertical geomagnetic cut-off rigidity, r_c, (or shorter: vertical cut-off rigidity). The effective vertical cut-off rigidity lies in the so-called penumbral region, defined as the rigidity interval between the value below which no particle arrives in the vertical direction at the location of interest and the highest rigidity value above which all particles arrive in the vertical direction. In the penumbral region no clear separation can be made between rigidity intervals allowing or denying the vertical arrival of particles. A detailed discussion of cosmic ray cut-off terminology and a definition of the calculation procedure for the effective cut-off rigidity can be found elsewhere (Cooke, 1991). In order to account for the shielding effect of the magnetosphere at a given location, the effective vertical cut-off rigidity is converted to a cut-off energy for each primary particle under consideration, and only particles above this energy threshold are taken into account in the calculations.

Particles of cosmic radiation that hit the atmosphere produce a complex field of secondary particles including, for example, protons, neutrons, electrons, positrons, photons, muons (positive and negative), and pions (positive and negative). The energy range involved covers many orders of magnitude and depends on particle type. For example, secondary photons range from roughly 10 keV up to 1 GeV, and neutrons from thermal energies up to 10 GeV, while muons range from roughly 10 MeV up to 100 GeV. Due to the competing processes of secondary particle production and absorption, the fluence of secondary cosmic radiation – and thus the dose rate – increases with increasing altitude and reaches a maximum at an altitude of about 20 km. At typical flight altitudes, most of the effective dose is caused by neutrons and protons. More details on the various parameters that influence the doses due to cosmic radiation in aviation are given for example in (EURADOS, 2004).

1.4 Objective of the report

The aim of this report is to compare the dose and dose rates calculated by the various codes for which the providers have agreed to perform the calculations. Some of the codes are used routinely for radiation protection purposes, while others are purely for scientific use. The calculations were done using a set of representative real flight routes around the globe.

The results are presented in an anonymous way since recommendation of specific codes is not intended. Nevertheless, this comparison is of major importance since a real determination of effective dose is not possible and therefore the different methods used to evaluate effective doses can be compared.

In particular, there is a specific emphasis on quantifying the spread in both the ambient dose equivalent and the effective dose given by the various codes and models used in the present exercise. Because many of the codes are currently used in various countries worldwide in the assessment of aircrew doses from cosmic radiation, the present report may provide some idea of whether the calculated doses agree with each other within an uncertainty range that can be accepted for purposes of radiation protection.

2 Selection of Flight Routes and Justification

2.1 Definition of the data set

The comparison was organized using routes flown by typical passenger aircraft, obtained from various airlines. The input format used the coordinates of the departure and arrival airports, and several waypoints at which altitudes and/or course changed were defined in between. The code providers were asked to calculate the total route dose as well as the local dose rates at the given waypoints in terms of $H^*(10)$ and/or E. Results were to be given both for a date close to the solar maximum (08/2000) and minimum (09/2007). The 23 flights selected cover most of the major passenger flight routes in the world (see Fig. 2.1) as well as a wide range of latitudes (from North to South) and a wide range of vertical cut-off rigidities (from 0 GV to 18 GV). They also included six ultra-long range flights with flight durations of more than 13 hours (see Tab. 2.1).

Additionally, one specific flight (Singapore – Newark, No. 23 in Tab. 2.1) was selected, and dose rates ($dH^*(10)/dt$ and dE/dt) calculated for the individual waypoints along the flight route were used for comparison. This flight was chosen because it covers a wide range of vertical cut-off rigidities from almost 0 GV to about 17 GV.

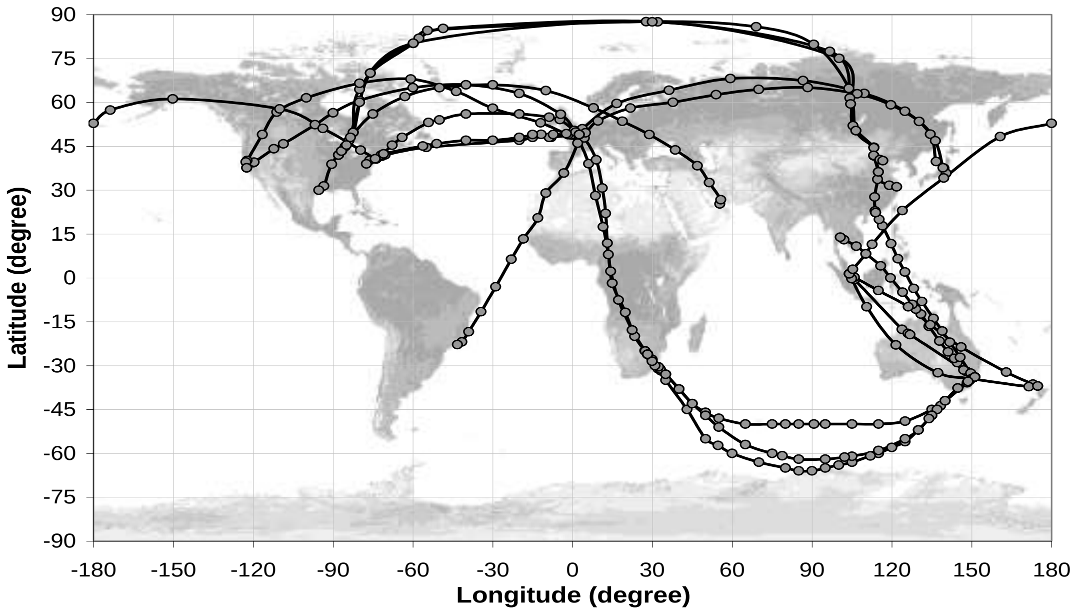


Figure 2.1. The selected flight routes of the 23 flights investigated. Grey dots denote waypoints with given latitude, longitude, altitude and time of flight. The solid lines do not represent flight routes but are meant only to guide the eve between the waypoints. (The background map was modified but was originally taken from NASA's "Visible Earth" catalogue http://visibleearth.nasa.gov/view_rec.php?id=2433; terms of use: http://visibleearth.nasa.gov/useterms.php)

Table 2.1. The 23 flights investigated with flight durations. The airport codes as defined by the International Civil Aviation Organization (ICAO) are shown in Appendix 1; the flight route profiles are in Appendix 2.

Flight number	Departure airport (ICAO code)	Destination airport (ICAO code)	Flight duration (hh:mm)
1	WSSS	YSSY	06:38
2	YSSY	VTBD	08:49
3	YSSY	VHHH	08:42
4	LFPG	FAJS	09:58
5	NZAA	WSSS	09:47
6	FAJS	LFPG	10:07
7	LFPG	SBGL	10:48
8	WSSS	NZAA	09:12
9	LFPG	KJFK	07:19
10	KJFK	LFPG	06:14
11	LFPG	KIAD	07:43
12	LFPG	RJAA	10:40
13	RJAA	LFPG	12:49
14	FAJS	YSSY	11:29
15	KSFO	LFPG	09:15
16	KORD	ZSPD	14:25
17	KORD	VHHH	15:24
18	KORD	ZBAA	13:11
19	LFPG	KSFO	11:38
20	YSSY	FAJS	13:45
21	OMDB	KIAH	15:36
22	YSSY	FAJS	13:51
23	WSSS	KEWR	17:21

2.2 Presentation and discussion of plausibility of input data

The flight data files for 23 selected flight routes (see Fig. 2.1) were distributed among the participants in the specific format shown in Appendix 2 of this report, for a date close to the solar maximum and solar minimum, respectively. Each flight data file consists of a so-called info-line containing essential information about the flight such as flight number, departure and destination airports in the four-letter alphanumeric code defined by the International Civil Aviation Organization (ICAO), and date and time of scheduled take-off and touch-down using the Universal Time Coordinated (UTC) specification. All values are separated by semicolons. As an example, the first line for flight number 00009 from Paris to New York (Table 2.2) is shown, with an explanation of the format:

00009;LFPG;KJFK;18/08/2000;01:00;18/08/2000;08:19;

Table 2.2. Explanations of fields used in the info-line for flight number 00009 from Paris to New York.

Field	Explanation
00009	Flight number
LFPG	ICAO code of the departure airport
KJFK	ICAO code of the destination airport
18/08/2000	Take-off date (UTC) (dd/mm/yyyy)
01:00	Take-off time (UTC) (hh:mm)
18/08/2000	Touch-down date (UTC) (dd/mm/yyyy)
08:19	Touch-down time (UTC) (hh:mm)

The following lines in the flight file - so-called waypoint lines - start with the flight number, followed by air navigation data, separated by semicolons. There are three types of waypoint lines. The first and the last line in the block of waypoint lines are labelled as AER (aerodrome) to indicate the departure or arrival airport. The second and the last-but-one waypoints are taken as top of climb (TOC) and top of descent (TOD), respectively. Between the TOC and TOD waypoint lines there are several common waypoint lines (INT) depending on the flight route. Each waypoint flag (AER, TOC, TOD, and INT) is followed by the flight level or elevation, elapsed time, and geographic position (see Appendix 2). The flight level (FL) and elevation of airports are defined as barometric altitude in feet divided by 100. Elapsed time is given in hh:mm format and always begins with 00:00 in the departure airport line. The geographic coordinates are defined by North (N) and South (S) latitude (lat) in degrees, minutes, and seconds in DDMMSS format, and West (W) and East (E) longitude (long) in DDDMMSS format, respectively. As an example, the line with the common waypoint (INT) is shown below, with an explanation in Table 2.3.

00009;INT;360;00:24;485018N;0001500W;

The codes used in this comparison handle input data in different formats. Therefore, it was necessary for each participant to prepare his own input file fitting the specific data format of his code. The participants were themselves responsible for data transfer.

Before the flight data were distributed to the participants, all air navigation data were checked for typographical errors and corrected if required. The geographic positions of all destination airports and waypoints were reviewed. The ground level elevation of all airports was set to "000". Next, a simple plausibility check involving flight speed and duration was made.

Table 2.3. Explanations of fields used in the waypoint lines for flight number 00009 from Paris to New York.

Field	Explanation
00009	Flight number
INT	Waypoint flag
360	Altitude (FL)
00:24	Elapsed time (hh:mm)
485018N	Geographical latitude (DDMMSS)
0001500W	Geographical longitude (DDDMMSS)

Two departure dates during Solar Cycle 23 were predefined for all flights under the study. The first, 18th of August 2000, is close to the solar maximum, while the second, 12th of September 2007, is close to the solar minimum. Both dates were chosen during the quiet period of solar activity as can be seen in Figures 2.2 and 2.3, where hourly averaged counts measured by Neutron Monitors (NM) located at different geographic positions and elevations are shown. The figures also demonstrate the increased count rates during the solar minimum.

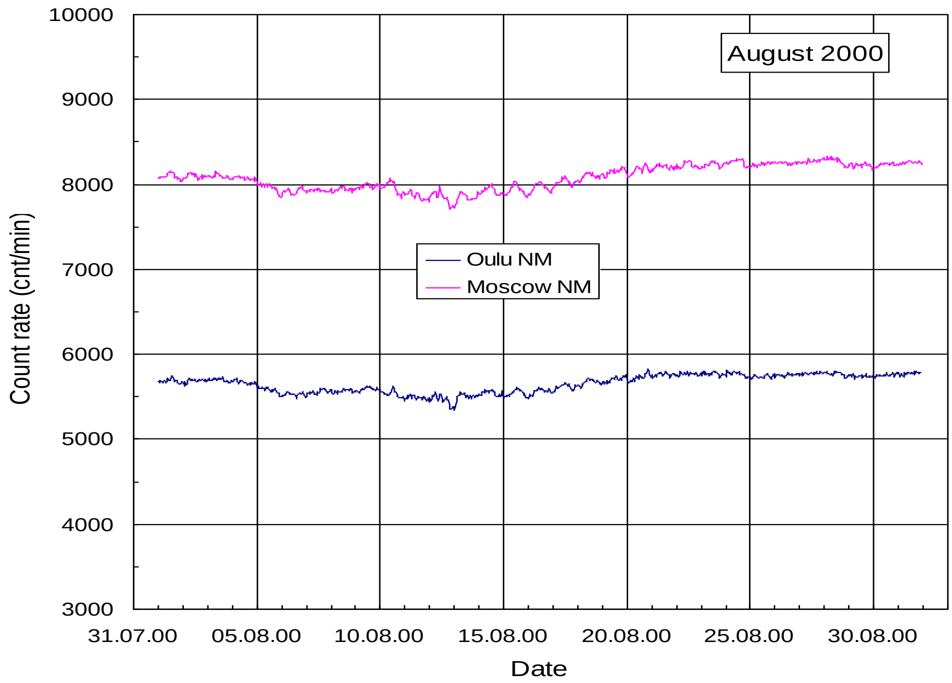


Figure 2.2. Hourly averaged count rates measured by the Moscow neutron monitor in Russia (top line) and the Oulu Cosmic Ray station in Finland (middle line) during August 2000. Data are corrected for air pressure.

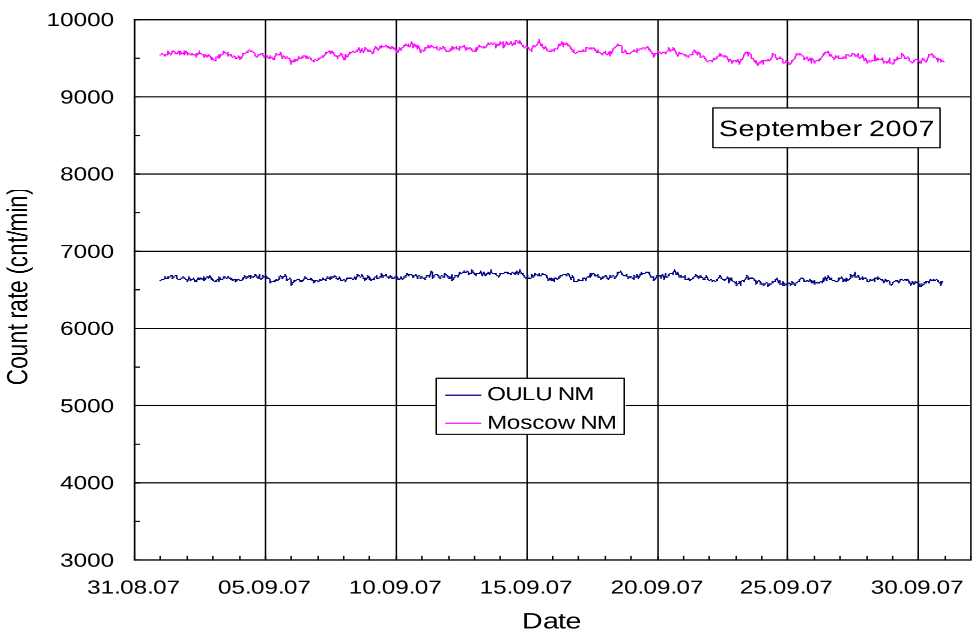


Figure 2.3. Hourly averaged count rates measured by the Moscow neutron monitor in Russia (top line) and by the Oulu Cosmic Ray station in Finland (bottom line) during September 2007. Data are corrected for air pressure.

2.3 Overview of the different codes

The different codes used are summarized in Table 2.4 and described in more detail in sections 2.3.1 to 2.3.11. Some of the codes are based on Monte Carlo simulations of the radiation field (AVIDOS, EPCARD, JISCARD EX, PANDOCA, PLANETOCOSMICS (Bern code), and QARM). The SIEVERT code uses a worldwide grid of dose rates calculated with EPCARD. Two codes (CARI, FREE) use an analytic calculation of particle transport through the atmosphere based on LUIN99/LUIN2000 and PLOTINUS calculations, respectively. Other codes are based on measurements only (FDOScalc, PCAIRE) and some use the $E/H^*(10)$ conversion as calculated by the Monte Carlo codes mentioned above.

Versions of the EPCARD, FREE and PCAIRE codes are approved for dose assessment by the civil aviation authority in Germany. For this comparison, however, the scientific version of PCAIRE, which is not approved in Germany, was used. Dose assessment with the AVIDOS 1.0 code is accredited according to European regulations and FREE 1.3.0 is accredited in Austria. The SIEVERT code was initiated by the French aviation authority to provide a common tool for airlines.

Table 2.4. Computer codes for calculation of the radiation exposure of aircraft crew due to galactic cosmic radiation. For detailed description and references see sections 2.3.1 to 2.3.11.

Computer Code	Method based on	Reference	Primary galactic cosmic radiation spectra (if applied)	Cut off rigidity	Dose conversion
AVIDOS 1.0	FLUKA Monte Carlo code calculations	(Beck, 2007; Roesler, 2002)	Gaisser *et al* modified by balloon measurements (Gaisser, 2001; Beck, 2007)	Vertical cut off rigidity (Smart, 1997)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
CARI-6M	LUIN99/LUIN2000 code calculations	(Friedberg, 1992)	below 10 GeV (Garcia-Munoz, 1975), above10 GeV (Peters, 1958) normalized to 10.6 GeV (Gaisser, 1998)	Vertical cut-off rigidity (Shea, 2000) non-vertical cut-off rigidities (Heinrich, 1979)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
EPCARD.Net 5.4.1	FLUKA Monte Carlo code calculations	(Mares, 2009; Roesler,2002)	(Badhwar, 2000)	Vertical cut-off rigidity (Bütikofer, 2007)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000; Mares, 2007)
FDOScalc 2.0	Experimental data (97-99; 03-06)	(Schrewe, 2000; Wissmann, 2006; Wissmann, 2010)	Not applied	Vertical cut-off rigidity MAGNETOCOSMICS (Desorgher, 2006)	
IASON-FREE 1.3.0	PLOTINUS code calculations	(Felsberger, 2009)	below 10 GeV (Garcia-Munoz, 1975), above10 GeV (Peters, 1958) normalized to 10.6 GeV (Gaisser, 1998)	Vertical cut-off rigidity (Shea, 2000) non-vertical cut-off rigidities (Heinrich, 1979)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
JISCARD EX	PHITS Monte Carlo code calculations	(Yasuda, 2008a; Yasuda, 2008b)	(Nymmik, 1992)	Vertical cut-off rigidity pre-calculated with MAGNETOCOSMICS (Desorgher, 2006)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
PANDOCA	PLANETOCOSMICS 2.0; GEANT4.9.1 Monte Carlo code calculations	(http://corsray.unibe.ch) (http://geant4.web.cern.ch/ geant4/)	(Gleeson, 1968) (Usoskin, 2005)	Vertical cut-off rigidity, pre-calculated with PLANETOCOSMICS 2.0	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
PCAIRE	Experimental data (since 97)	(Lewis, 2001; Lewis, 2002; Lewis, 2004; Takada, 2007)	Not applied	Vertical cut-off rigidity (Lewis, 2002)	ICRP 60 (ICRP, 1990)
PLANETOCOSMICS 2.0	GEANT4 Monte Carlo code calculations	(http://corsray.unibe.ch)	(Gleeson, 1968; Garcia-Munoz, 1975)	Vertical cut-off rigidity (Bütikofer, 2007)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)
QARM 1.0	MCNPX Monte Carlo code calculation	(Lei, 2004; Lei, 2006; Dyer, 2007; http://mcnpx.lanl.gov)	(Badhwar, 2000)	Vertical cut-off rigidity (Smart, 1997)	ICRP 74 (ICRP, 1996), (Pelliccioni, 2000)
SIEVERT 1.0	EPCARD version3.3.4 code calculations	(http://sievert-system.org; Bottollier-Depois, 2007)	(Badhwar, 2000)	Vertical cut-off rigidity (Smart, 1997)	ICRP 60 (ICRP, 1990) (Pelliccioni, 2000)

2.3.1 AVIDOS

AVIDOS is based on numerical calculations and an empirical model. Numerical calculations were performed using the FLUKA (Ferrari, 2005) Monte Carlo code. A spatial density profile of the Earth's atmosphere and an updated primary proton energy spectrum (Gaisser, 2001) were taken into account in modelling the Earth environment and galactic cosmic radiation. Resulting fluence rates were converted into ambient dose equivalent rates and into effective dose rates using Pelliccioni's conversion coefficients (Pelliccioni, 2000) according to the ICRP 60 publication. A multi-parameter model (Beck, 2007) was applied to the results of the FLUKA calculations, allowing the determination of ambient dose equivalent rates and effective dose rates over the full range of vertical cut-off rigidity (Smart, 1997), solar deceleration potential (Badhwar, 1997) and commercially used altitudes. The solution was implemented in a computational code called AVIDOS. Route doses are calculated by integrating dose rates calculated at each waypoint. A waypoint should give information on current flight time, geographical location and altitude. If the travel time between two following waypoints is larger than 5 minutes, sub-waypoints are created assuming constant altitude and route along a great circle. AVIDOS needs regularly updated neutron monitor records to reflect changes in solar activity. Aircraft crew dose assessment using AVIDOS is accredited by the Austrian office for accreditation. This accreditation is accepted and valid throughout the European Union.

An internet version of AVIDOS (AVIDOS-WEB1.0) is provided to the public with a simplified route (over a great circle) between departure and arrival positions. The effective dose between any two locations is estimated using a default flight altitude and estimated flight time. Additionally, a user can customize the flight profile by choosing altitudes between 8 km and 15 km and flight times between 1 hour and 15 hours 45 minutes. AVIDOS-WEB may not be used for radiation dosimetry services. AVIDOS is further described by Latocha, *et al.* (Latocha, 2009). AVIDOS-WEB is accessible at the internet address http://avidos.ait.ac.at.

2.3.2 CARI

The CARI program was initially developed in the late 1980's at the FAA's Civil Aerospace Medical Institute, and calculates the effective dose of galactic cosmic radiation received by an individual (based on an anthropomorphic phantom) in an aircraft flying at altitudes up to 87,000 feet (~ 26.5 km); in some versions the limit is 60,000 feet (~ 18.3 km). Since CARI-2, CARI has been based on the LUIN radiation transport program (Friedberg, 1992; Friedberg, 1993; O'Brien, 1992; O'Brien, 1994; O'Brien, 1996). The current version of the program is CARI-6, based on the LUIN99/LUIN2000 transport code of O'Brien (O'Brien, 2003).

There are 5 publicly available variants of CARI-6: CARI-6, CARI-6M, CARI-6P, CARI-6PM, and a set of web pages (US FAA, 2011). All versions report doses and dose rates in effective dose, using ICRP 60 radiation weighting factors (ICRP, 1990). In the present exercise CARI-6M was used.

In addition to the ICRP effective dose, the output of the "P" and "PM" variants also includes the effective dose (and dose rate for single locations) calculated using NCRP Report 116 (NCRP, 1993) radiation weighting factors and an estimate of the whole-body absorbed dose. For all three doses, the contributions from the principal contributing particle groups (muons, electromagnetic showers, charged pions, protons, and neutrons) are reported.

For flight dose calculations, "6", "6P", and the web pages assume a geodesic flight path (deviations from a geodesic route of 200 miles (~ 322 km), have only a small effect on the flight dose) between origin and destination airports and instantaneous altitude changes between cruising altitudes. Linear rates of altitude change are used for the initial climb and final descent. The "6M" and "6PM" variants assume the flight follows a geodesic path between user-entered waypoints, with all altitude changes performed smoothly. The next version, CARI-7, is expected to be ready for release in 2012.

2.3.3 EPCARD.Net

EPCARD.Net (the European Program Package for the Calculation of Aviation Route Doses) (Mares, 2009) is a completely new object-oriented code which can be run without recompilation on many state-of-the-art operating systems such as Microsoft® Windows NT/2K/XP/Vista (using both .Net® or Mono® runtime platform) or "UNIX kernel type" operating systems like Linux, Mac OS X or Solaris (using the Mono® runtime platform). The so called "XML-EPCARD application" for input and output guarantees error-free data exchange in heterogenic systems where the EPCARD.Net application is in use. It can be implemented in a broad spectrum of usage scenarios such as a WEB service or Operating System scripts component, or as a single standalone application with intuitive Graphic User Interface.

The physical basis for the EPCARD.Net version 5.4.1 developed by Helmholtz Zentrum München is version 3.34 of EPCARD (Schraube, 2002) which was approved by the civil aviation authority in Germany and also validated by measurements (Lindborg, 2004) in which an agreement between measured and calculated doses better than ±20 % was achieved.

The EPCARD.Net solution is based on the results of extensive Monte Carlo calculations (Roesler, 2002) performed with FLUKA (Ferrari, 2005), taking into account all physical processes that govern the interaction of cosmic radiation with the Earth's atmosphere. Using a NASA model (Badhwar, 1997) of primary cosmic radiation impinging upon the top of the atmosphere, the secondary particle spectra of neutrons, protons, photons, electrons and positrons, muons, and pions were calculated at various depths down to sea level for all possible physical circumstances of solar activity and geomagnetic shielding conditions.

A set of fluence-to-dose conversion coefficients for the respective particle types from the FLUKA calculations (Pelliccioni, 2000) is employed to calculate the ambient dose equivalent, $H^*(10)$, and effective dose, E, separately for each particle, i.e. the dose contributions from neutrons, protons, photons, electrons, muons, and pions. The EPCARD.Net parameter database includes energy-averaged dose conversion coefficients, calculated by folding each single-particle fluence spectrum with the appropriate dose conversion function (Mares, 2004; Mares, 2007), which depend on barometric altitude, cut-off rigidity, and solar activity, since the shapes of the particle energy spectra also depend on these parameters.

To determine the dose rates at specific locations in the atmosphere during a flight, the cut-off rigidity is calculated to include the structure of the geomagnetic field and its shielding capability in the dose calculation. Additionally, the solar deceleration potential (Badhwar, 1997; Badhwar, 2000) is derived from the flight date and neutron monitor data, to include solar activity in the dose calculation. Finally, the flight levels of a given flight profile are used to determine the respective depths in the atmosphere and quantify atmospheric shielding. EPCARD.Net calculates the doses for flights in the range of barometric altitudes from 5000 m to 25000 m, which is equivalent to atmospheric depths from 544 g cm^2 to 22.8 g cm^2. Between the given waypoints of a flight route, great circle navigation is assumed. The time period for possible calculation is determined by the validity range of the neutron monitor data used, i.e. from January 1964 to the present.

To take into account the most recent geomagnetic shielding data, EPCARD.Net uses effective vertical cut-off rigidity data for the current epoch, calculated by the MAGNETOCOSMICS code (Bütikofer, 2007) developed at the University of Bern by the Cosmic Ray Group (Desorgher, 2006). Cut-off rigidity parameters for a complete world grid with a resolution of 5° in latitude and 5° in longitude (5° X 5°) are stored in the parameter database. More general information about the EPCARD.Net solution is available on the web site http://www.helmholtz-muenchen.de/epcard, where a simplified on-line version of the EPCARD calculator for public use can also be found.

2.3.4 FDOScalc

FDOScalc is based on a mathematical model which provides a fit to the complete dataset of ambient dose equivalent rates measured by PTB. The dataset includes 892 data points measured between 1997 and 1999 with an ionization counter and a modified rem counter (Schrewe, 2000), and 1537 data points measured with a tissue-equivalent proportional counter (TEPC) system between 2003 and 2006 (Wissmann, 2006). The model includes all relevant influencing parameters, such as altitude, vertical cut-off rigidity, and neutron monitor rate. The goal was to have a simple-to-use, functional description of the dose rate distribution for different flight altitudes, geographical locations, and levels of solar activity. Since the problem was approached with Bayesian statistical methods, tools were available to investigate and compare various competing mathematical models that could be used to describe the data; it was also possible to evaluate an uncertainty for each dose rate value calculated with the final model function.

In references (Schrewe, 2000; Wissmann, 2006), it was shown that relatively simple relations can be used to describe the measured dose rate as a function of the altitude, geomagnetic latitude, and fluence rate of secondary neutrons at ground level. Since the neutron monitor rate is a direct measure of the fluence rate of primary cosmic ray particles entering into the atmosphere, it can be used to evaluate the change in the dose rate at flight altitudes due to changes in solar activity. The neutron monitor at Oulu, Finland, was selected for monitoring the secondary neutron fluence rate at ground level.

The geomagnetic latitude is not the best parameter to describe the influence of the Earth's magnetic field. A better parameter is the vertical cut-off rigidity, r_c, which describes the minimum rigidity required for a charged particle to enter the magnetic field and to reach a certain altitude. It was shown in references (Schrewe, 2000; Wissmann, 2006) that the measured data, when normalized to a common altitude of FL350, smoothly follow a simple function of vertical cut-off rigidity r_c,

$$\dot{H}_{\mathrm{FDOScalc}} = \dot{H}_0 + \dot{H}_1\,\mathrm{e}^{-(r_c/c)^d}$$

where $\dot{H}_0$ and $\dot{H}_1$ are assumed to be constant and c, d are fitting parameters. In FDOScalc, a more general expression in which the coefficients are described by a Taylor expansion was used.

A detailed analysis using tools of Bayesian data analysis showed that not all expansion coefficients are necessary to describe the data. This approach prevents over- or under-parameterization of the mathematical model. The final equations used in FDOScalc are (Wissmann, 2010):

$$\dot{H}_0 = a_{00} + a_{01}(h - h^0)$$
$$\dot{H}_1 = a_{00} + b_{10}(N_{\mathrm{NM}} - N^0_{\mathrm{NM}}) + c_{10}(N_{\mathrm{NM}} - N^0_{\mathrm{NM}})^2 + [a_{11} + b_{11}(N_{\mathrm{NM}} - N^0_{\mathrm{NM}}) + c_{11}(N_{\mathrm{NM}} - N^0_{\mathrm{NM}})^2](h - h^0)$$

where h is the altitude, N_{NM} is the count rate of the neutron monitor in Oulu, and a_{xx}, b_{xx}, and c_{xx} are fitting parameters. The exponent "0" indicates the reference values. The validity of this function is restricted to the data range of the fitted data. Therefore, only calculations for Oulu neutron monitor count rates N_{NM} between 5700 counts/min and 6500 counts/min and flight levels between FL230 and FL415 are allowed.

2.3.5 IASON-FREE

IASON-FREE (EC, 2004; Felsberger, 2009; Felsberger, 2011) is based on the work of O'Brien (http://physics.nau.edu). His theoretical framework is a numerical-analytical solution of the Boltzmann transport equation and is well documented in the scientific literature. In addition to many others, it includes base codes for the calculation of the galactic cosmic radiation (GCR) components and their associated dosimetry (O'Brien, 2005) and the dosimetric contributions of those Solar Particle Events (SPE) called ground level enhancements (GLE) (O'Brien, 2000; O'Brien, 2005). It also includes the theoretical basis for an operational Forbush decrease (FD) procedure (O'Brien, 2007). All base codes have been extensively tested, compared and verified with measurements.

As base codes are rather slow and difficult to handle in professional commercial environments, a flight code intended solely for operational use was developed. This central calculation program was created primarily to mirror O'Brien's base codes as accurately as possible. Therefore, to avoid a possible 'flight code effect', no approximations or data reduction techniques were used, and the problem was solved with a 'brute force attack'. The enormous number of 1 338 650 single points on a properly triangulated four dimensional grid in space and modulation parameter was pre-calculated. These base results were interpolated in space with sophisticated three-dimensional B-Spline methods. The modulation parameter was determined by a piecewise linear interpolation procedure. The whole procedure leads to an ultrafast access mechanism for every possible set of input parameters. A flight dose result is determined by integrating the dose rates over the flight trajectory in space and time. The flight trajectory is not limited in the number of points; standard flight trajectories with a temporal sample size of one minute are generated from input data. Neither implicit assumptions nor tacit modifications of the flight trajectory are made – great circle navigation between the waypoints is assumed.

Compared to other available solutions, this flight code is different in the degree of detail covered (O'Brien, 2008); no energy-averaged particle fluence-to-dose conversion coefficients independent of any input parameter are used. It takes into account the non-vertical cut-offs and the concave dependence of dose rates on solar activity. Solar activity is treated with the completely local heliocentric potential model and considered on an hourly basis. Short-term variations (FDs and

GLEs) are correctly included. Additionally, an overall $H^*(10)$ output possibility was built in – crucial for comparison with measurements and for all verification purposes.

The flight code was created on modern component-based software architecture. It is fully scalable, supporting the possibilities of modern computer hardware. It calculates all results very rapidly and is not limited in the possible input file size (number of flights). The flight code was approved by the civil aviation authority in Germany in 2004 and IASON acts as the accredited aircrew dose assessment service according to the laboratory standard ISO IEC 17025, which covers and includes approval of both conformity and competence. Despite the fact that newer developments exist internally (O'Brien, 2010), the flight code has remained stable since then and version FREE 1.3.0 has never been changed.

2.3.6 JISCARD EX

In Japan, the government has requested domestic airline companies to follow the guidelines set by the Radiation Council in 2006 (MEXT, 2006), which state that annual aviation doses of aircraft crew are to be kept below 5 mSv per year. The National Institute of Radiological Sciences (NIRS) has helped the airline companies follow this guideline, particularly in calculation of aviation route doses. For this purpose, an easy-to-use program for calculation of aviation doses, "JISCARD EX", has been developed at the National Institute of Radiological Sciences (Yasuda, 2008a; Yasuda, 2008b). JISCARD EX is now also open to the general public from the NIRS web page as an educational tool "JISCARD" (NIRS, 2006).

JISCARD EX is written with the Excel VBA (Visual Basic for Applications) language and runs on the Microsoft Excel 2003/2007 platform. The dose rates along a flight route are calculated with a PHITS-based "PARMA" analytical model (Sato, 2008) developed from comprehensive simulations using the "PHITS" Monte Carlo code (Iwase, 2002) coupled with the JENDL High-Energy File nuclear data library (Watanabe, 2005). PARMA can calculate cosmic radiation dose rates in the atmosphere up to an altitude of 20 km as precisely as the Monte Carlo code in a very short time.

The incident particle spectra of galactic cosmic radiation (GCR) around the Earth are taken from local interstellar (LIS) spectra (Nymmik, 1992) and the effects of solar modulation are also evaluated with the Nymmik model, coupled with modified empirical parameters based on the force-field formalism. The effects of geomagnetic shielding, i.e., effective vertical cut-off rigidities, are calculated using the GEANT4-based "MAGNETOCOSMICS" particle tracing code (Desorgher, 2006) developed at the University of Bern by the Cosmic Ray Group. The newest version of the MAGNETOCOSMICS code, which was available in 2010, has been employed.

In the version of JISCARD EX used here, the conversion coefficients for the calculation of effective dose and ambient dose equivalent were originally determined for each of the seven essential radiation components (neutrons, protons, photons, electrons, positrons, muons and helium ions) and isotropic irradiation geometry using the PHITS code; the dependencies of neutron spectra on aircraft structure were considered as local geometry effects. A large number of these coefficients are identical to those previously published by (ICRP, 1996; Pelliccioni, 2000). The conversion coefficient values are being updated for adaptation to the 2007 ICRP recommendations (ICRP, 2007) and the new reference computational phantoms.

2.3.7 PANDOCA

The PANDOCA (Professional AviatioN DOse CAlculator) code was developed at the German Aerospace Center (DLR) at the Institute of Aerospace Medicine and is presently used for scientific purposes only. The radiation exposure is calculated using the GEANT4 version 4.9.1 Monte Carlo code (Agostinelli, 2003) in combination with the model of the atmosphere (Picone, 2002) and the magnetic field of the Earth (Maus, 2005) provided by the PLANETOCOSMICS tool (http://cosray.unibe.ch). Galactic cosmic hydrogen and helium are considered as primary particles in the energy range from 100 MeV to 1.5 TeV (hydrogen) and 100 MeV to 850 GeV (helium). The primary particle energy spectra as described by Usoskin *et al.* (2005) are used, taking into account the solar modulation in the force-field approximation and using the modulation parameter φ (http://cosmicrays.oulu.fi). The GEANT4 interface to the JAM/JQMD model by Koi *et al.* (Koi, 2003) is used to calculate the helium transport at energies larger than 10 GeV/n. The resulting energy spectra of secondary protons, neutrons, photons, electrons, positrons, muons and pions at a given altitude are converted to effective dose and ambient dose equivalent using fluence-to-dose conversion factors (http://inf.infn.it).

The geomagnetic shielding effect was taken into account using the effective vertical cut-off rigidity calculated with PLANETOCOSMICS on a two-times-three degree grid in geographic latitude and longitude. The calculations of effective cut-off rigidity are based on the IGRF model of the geomagnetic field for 2005. In order to account for geomagnetic shielding, the geographic location is then converted to cut-off rigidity and the corresponding cut-off energy by interpolating between the calculated values on the coordinate grid. For a given flight profile, the model provides the effective dose rate dE/dt and the ambient dose equivalent $dH^*(10)/dt$ at each waypoint and the resulting flight-integrated values of E and $H^*(10)$.

2.3.8 PCAIRE

The Predictive Code for AIrcrew Radiation Exposure, known as PCAIRE, is a semi-empirical model to calculate radiation exposure for commercial aircrew and frequent flyers (available online at www.pcaire.com), with one of the world's largest repositories of measured global flights spanning a range of geomagnetic latitudes from -40° to 85° (Lewis, 2001). These flight data have been collected on commercial and military aircrafts by PCAIRE in cooperation with the Royal Military College of Canada, since 1997, with 15-30 instrumented flights flown each year (Lewis, 2002; Lewis, 2004).

A tissue-equivalent proportional counter (TEPC) is used to collect ambient dose equivalent data at one-minute intervals. All data are correlated with the specific altitude and global position and then averaged over five-minute intervals using a standard smoothing technique. An altitude correction function has been developed to account for the effect of altitude. In addition, a theoretical analysis scales the data to account for the smaller effect of varying solar modulation (for a given date). The heliocentric potential and altitude correction functions are then used to normalize all of the data. The final result is a single correlation of all dose rate data versus vertical cut-off rigidity. This relationship allows the dose rate for any global position, altitude and date to be interpolated. PCAIRE provides a total ambient dose equivalent, $H^*(10)$, estimate by integrating this dose rate function over a given flight path, accounting for altitude and heliocentric potential effects.

PCAIRE requires user input for the flight duration time, altitudes and time flown at these altitudes, departure and destination locations and the date of the flight. The code provides a rapid route-dose output in total ambient dose equivalent and/or effective dose (using either a FLUKA or LUIN conversion function). PCAIRE maintains complete crew profiles and can associate individuals with flights flown, allowing exposure to be reported on a per-crew basis; likewise, PCAIRE can report a per-flight exposure which can be exported in a format acceptable to HR systems. PCAIRE can be run on corporate servers, via the internet, on an iPhone or on a laptop.

2.3.9 PLANTEOCOSMICS Model (Bern model)

The PLANETOCOSMICS software suite (Desorgher, 2005) is based on the Geant4 software, a platform for simulating passage of particles through matter using Monte Carlo methods (http://geant4.cern.ch/). The PLANETOCOSMICS application allows the propagation of charged particles in the planetary magnetic field, and/or the hadronic and electromagnetic interactions of cosmic radiation with the environment of Earth, Mars, or Mercury, including the planet's atmosphere and soil, to be computed. Possible outputs of the program are the fluence rate of particles at user-defined altitudes or the energy deposited by atmospheric shower particles in the atmosphere. Applications of the PLANETOCOSMICS code include albedo fluence rate estimates, solar particle fluence rate studies, computation of the ionization rate in the atmosphere by cosmic radiation, and study of energetic electron precipitation events at high latitudes.

With the PLANETOCOSMICS code, radiation dose rates in the Earth's atmosphere due to cosmic radiation are computed in individual steps. First, the vertical cut-off rigidities, i.e. the minimum rigidity needed so that a cosmic radiation particle can reach the top of the atmosphere in the vertical direction, are computed at the grid points of a 5° X 5° network in geographic coordinates. Here, the Earth’s magnetic field is described by the IGRF model for the internal field and by the Tsyganenko89 magnetic field model for the magnetic field caused by variable external sources subject to the dynamic interactions of the solar wind with the geomagnetosphere. In the second step the near-Earth galactic cosmic radiation spectrum outside the geomagnetosphere is described by the heliocentric potential as based on the work of Gleeson and Axford (Gleeson, 1968), Garcia-Munoz *et al.* (Garcia-Munoz, 1975), and Caballero-Lopez and Moraal (Caballero-Lopez, 2004). The cut-off rigidities and the near-Earth cosmic radiation fluence rate are the basis for the third step, computing the cosmic radiation fluence rate at the top of the Earth’s atmosphere for the 5° X 5° grid. In the fourth step, the secondary cosmic radiation fluence rate in the atmosphere at specified altitudes is processed at each grid point. Finally, the radiation dose rates are calculated for selected atmospheric depths at the specified locations from the secondary particle fluence rate, using the fluence-to-dose conversion factors based on FLUKA calculations by Pelliccioni (Pelliccioni, 2000). The Bern model is non-commercial and is only used for scientific purposes.

2.3.10 QARM

The QinetiQ Atmospheric Radiation Model (QARM) (Lei, 2004; Dyer, 2007) employs atmospheric response functions generated by Monte Carlo radiation transport codes, in conjunction with cosmic radiation and solar particle spectra and computed particle cut-off rigidities, to generate the radiation field in the atmosphere at any given location and time. In the current version (available through the website http://qarm.space.qinetiq.com), the solar-modulated cosmic radiation spectra for both protons and alpha particles are generated from the Badhwar and O'Neill model (O'Neill, 2006), while the solar particle spectra are calculated from ground level neutron monitor data in conjunction with spacecraft data as described in (Dyer, 2003a; Dyer, 2003b). In the current version the response functions are calculated for both protons and alpha particles using the MCNPX code (http://mcnpx.lanl.gov). The radiation along a flight path may be calculated using either a nominal great circle route or actual flight coordinates. Both directionality and all significant particle species are modelled and the outputs can be used to estimate integral properties of the environment such as ambient dose equivalent to aircrew, using the conversion coefficients of Pelliccioni (Pelliccioni, 2000), and rates of single event effects (SEEs) in avionics, using either measured input cross-sections for neutrons and protons or Weibull fits to such data. The geomagnetic cut-off rigidity can be computed using the latest model of the magnetic field, including both internal and external source terms from the International Geomagnetic Reference Field (IGRF) and the Tsyganenko model respectively. Hence, allowance can be made for both long-term variations and short-term disturbances during geomagnetic storms. A future version is planned to include heavy ions (Z>2).

2.3.11 SIEVERT

In France, the computerized system for flight assessment of exposure to cosmic radiation in air transport (SIEVERT) (http://sievert-system.org; Bottollier-Depois, 2007) is delivered to airlines to assist them in applying the European directive. The SIEVERT system was designed to be an operational tool dedicated to legal dosimetry of aircraft crews, and uses pre-existing codes like EPCARD to create dosimetric inputs during normal solar activity. This system provides doses that take into account the routes flown by aircraft. These values are calculated using models verified over several tens of flights with a satisfactory uncertainty margin. A model has also been developed for the case of a solar particle event that allows the impact on the dose received to be assessed. This service is provided by the Institute for Radiological Protection and Nuclear Safety (IRSN).

Airspace is divided into cells. Each one is 1000 feet (304.8 meters) in altitude, 10° in longitude and 2° in latitude. Altogether they form a map of 265,000 cells; an effective dose rate value is assigned to each of these cells. The time spent by the plane in each cell and the corresponding dose are calculated; their cumulative total gives the dose received during the flight.

The map of dose rates is updated every month, taking solar activity into account. This map is obtained using an existing model for the radiation component of galactic origin (GCR), currently EPCARD, which allows the dose to be obtained at any point in space up to an altitude of 80,000 feet (24,384 km). In the case of a significant solar particle event with an effect on the dose at flight levels, a so-called ground level event (GLE), a specific model has been developed, and a specific dose map is then created. This model is based on the atmospheric attenuation of particles with energy comparable to those of the solar particle events and on the data from neutron monitors located on the ground, which provide the intensity of the GLE. Forbush decreases, inducing a dose rate decrease, are not taken into account in this dose model because a realistic conservative approach was considered for radiation protection. In addition, regular radiation measurements, from dosimeters installed on the ground and on aircraft, are then used to confirm and if necessary correct the values obtained. Doses are calculated according to flight characteristics. If the information is minimal (for instance, information available on the flight ticket), the dose value is assessed using a standard route profile.

It is possible for the general public to assess the dose received during one or more flights by accessing the SIEVERT Internet site (www.sievert-system.com). This assessment is carried out using information contained on the flight ticket. Furthermore, general information about cosmic rays, regulations and the risk associated with radiation is available on this web site.

3 Dose Data Comparison

3.1 Route doses in terms of ambient dose equivalent, *H**(10), and effective dose, *E*

The results presented in this report are showed in an anonymous way. It is not intended to recommend any of the participating codes in particular for radiation protection services.

Comparisons of calculations for the 23 investigated flights (Table 2.1) performed with the eleven computer codes (Table 2.4) were made in terms of ambient dose equivalent, *H**(10), and effective dose, *E*, for both flight route doses and, for a specific flight, dose rates.

Figures 3.1a and 3.1b show an anonymous comparison of the total ambient dose equivalent, *H**(10), and effective dose, *E,* respectively, due to galactic cosmic radiation for different mid- and long-haul flights, during solar minimum (upper diagrams) and solar maximum (lower diagrams) conditions.

In order to discuss the data in more detail, the median for each flight was calculated and marked as full symbols in the figures. Note that not all codes provide both quantities ambient dose equivalent, *H**(10), and effective dose, *E*, and therefore not all are shown in the two figures. The sequence of flights in these figures is prepared solely for visualisation purposes and does not reflect increasing route doses or duration of flights.

The two figures allow for a general observation: both ambient dose equivalent and effective dose calculated for solar minimum conditions are, as expected, greater than those calculated for solar maximum.

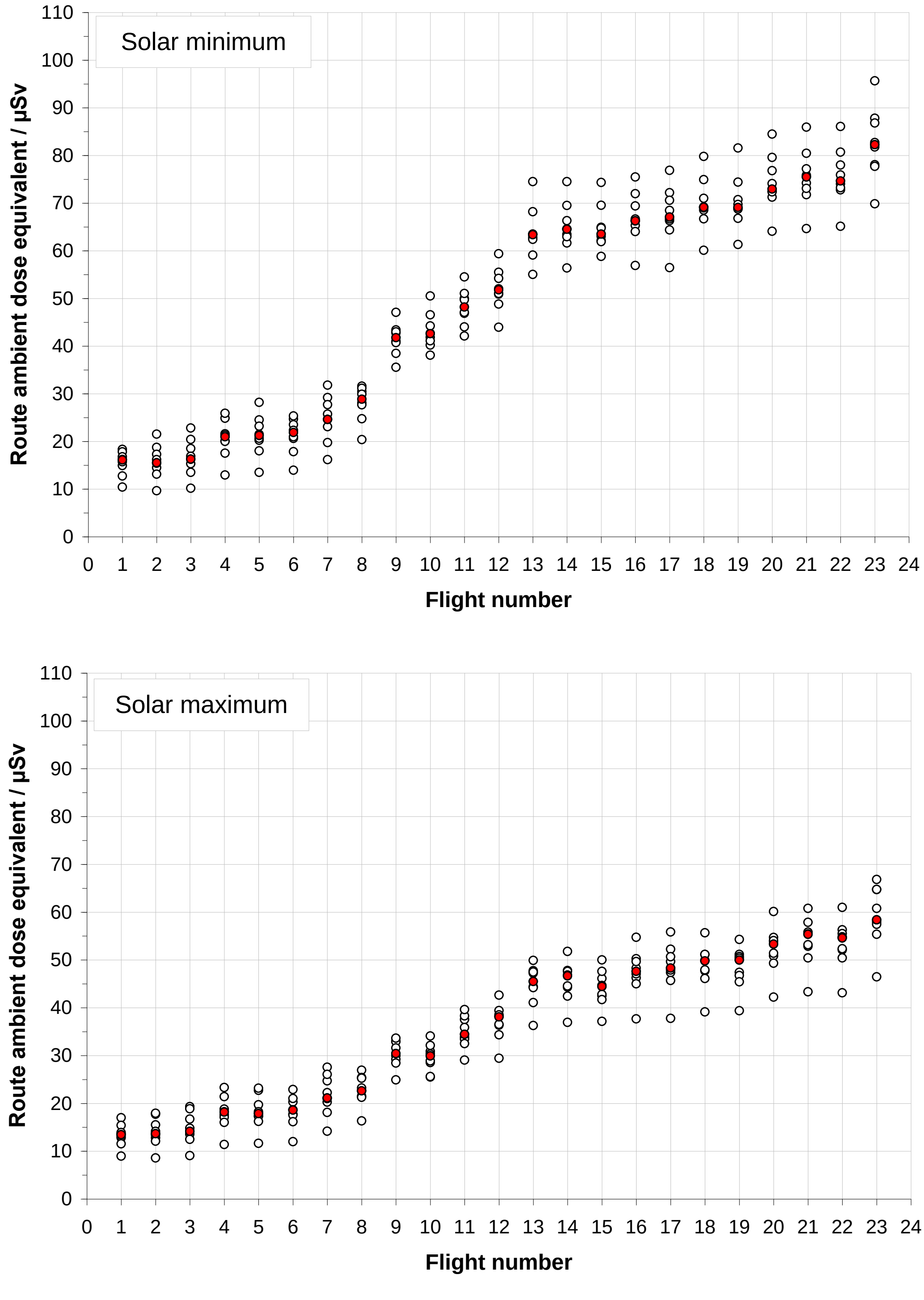


Figure 3.1a Anonymous comparison of the total ambient dose equivalent, H*(10), for different mid- and long-haul flights due to galactic cosmic radiation, during solar minimum (upper diagram) and solar maximum (lower diagram) conditions. The median is marked with full symbols. Not all codes provide both quantities ambient dose equivalent, H*(10), and effective dose, E, and therefore not all are shown in the two figures.

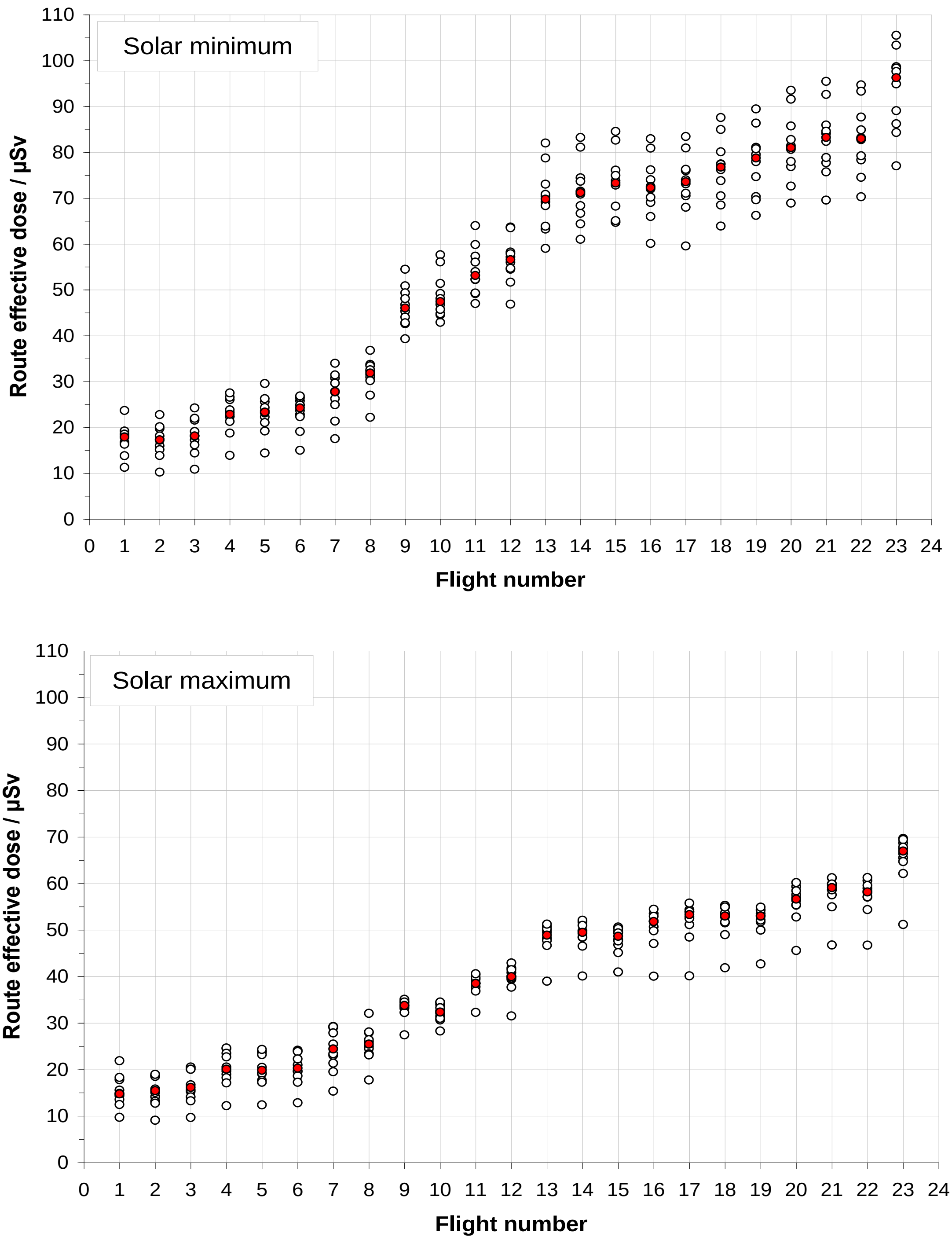


Figure 3.1b Anonymous comparison of the total effective dose, E, for different mid- and long-haul flights due to galactic cosmic radiation, during solar minimum (upper diagram) and solar maximum (lower diagram) conditions. The median is marked with full symbols. Not all codes provide both quantities ambient dose equivalent, H*(10), and effective dose, E, and therefore not all are shown in the two figures.

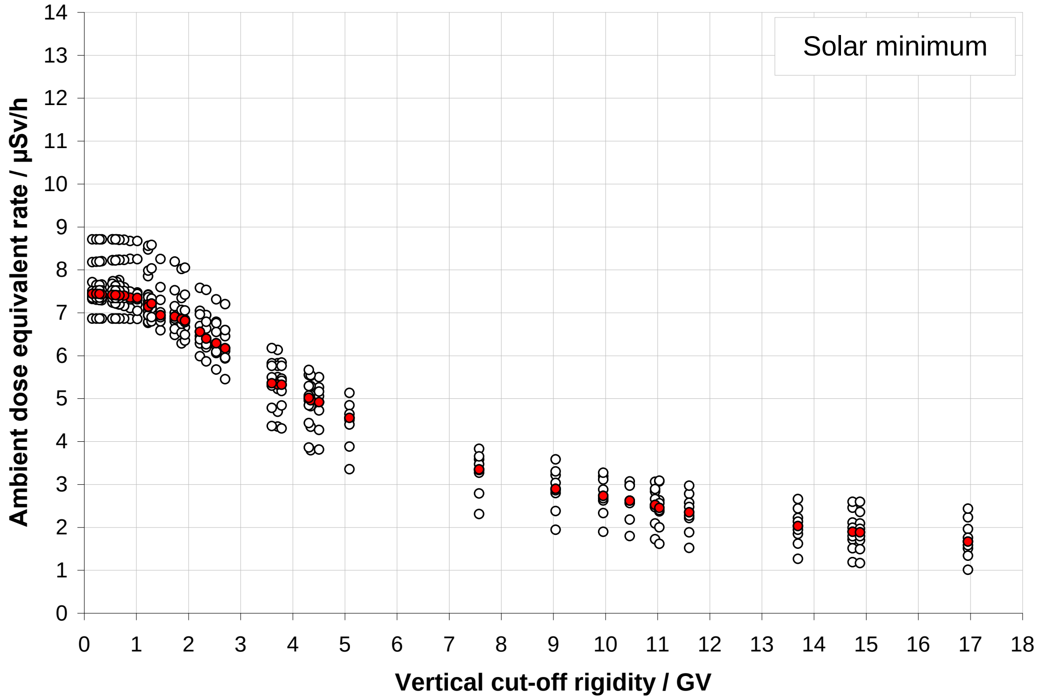
3.2 Dose rate vs. cut-off rigidity and altitude

Figures 3.2a and 3.2b show the dose rates (in terms of ambient dose equivalent, $H^*(10)$, and effective dose, E, respectively) obtained by the codes for different vertical cut-off rigidity values, both for solar minimum (upper diagrams) and solar maximum (lower diagrams) conditions. To give a representative example, flight level FL370 was chosen. In order to discuss the data in more detail, the median for each flight was calculated and marked with full symbols in the figures. Note again that not all codes are investigated in these figures. One code provided systematically lower dose values than the other codes. Figures 3.2a and 3.2b indicate that all data are in general in agreement with each other within a dose rate of about ± 1 µSv/h. This implies that the relative data spread is greater at high vertical cut-off rigidity values (i.e. close to the equator), approaching some 50 %, while it is as low as about 20 % at low cut-off rigidity values (i.e. close to the geomagnetic poles). It can also be deduced from these figures that the difference in dose rate between solar minimum and solar maximum conditions is quite small at high vertical cut-off rigidity values. In contrast, at low vertical cut-off rigidity values the dose rates at solar minimum conditions are some 50 % higher than those during solar maximum conditions.

The change in dose rate with flight altitude is investigated in Figures 3.3a and 3.3b by grouping the waypoints in different cut-off rigidity intervals (Smart, 2008) and plotting the corresponding dose rate values at all waypoints in these intervals versus the flight altitude. In Figures 3.3a and 3.3b the two rigidity intervals $r_c < 0.25$ GV and $r_c > 16.75$ GV are chosen as examples, as they represent the lowest and largest geomagnetic shielding in this exercise, respectively. The group of larger values in each figure corresponds to lower geomagnetic shielding, and vice versa.

Figure 3.3a shows the ambient dose equivalent rate at the solar minimum (upper diagram) and solar maximum (lower diagram) and reveals an almost linear increase in dose rate with altitude for all models considered. While the values of the ambient dose equivalent rate barely change between the solar minimum and solar maximum for the high cut-off rigidity interval (median values: $dH^*(10)/dt$ ~ 1 µSv/h at FL300 and $dH^*(10)/dt$ ~ 1.8 µSv/h at FL390), the median dose rate decreases from ~ 4.5 µSv/h to ~ 3.5 µSv/h at FL310 and from ~ 8.5 µSv/h to ~ 5.5 µSv/h at FL390, respectively, when the solar activity changes from solar minimum to maximum.

The differences between the ambient dose equivalent rate (Figure 3.3a) and the effective dose rate (Figure 3.3b) are very small in the high cut-off rigidity interval. At low cut-off rigidity values below 0.25 GV, however, the median of the effective dose rate is somewhat larger than that of the ambient dose equivalent rate (solar minimum: dE/dt ~ 5 µSv/h at FL310 up to dE/dt ~ 10 µSv/h at FL390; solar maximum: dE/dt ~ 3.5 µSv/h at FL310 up to dE/dt ~ 6.5 µSv/h at FL390).



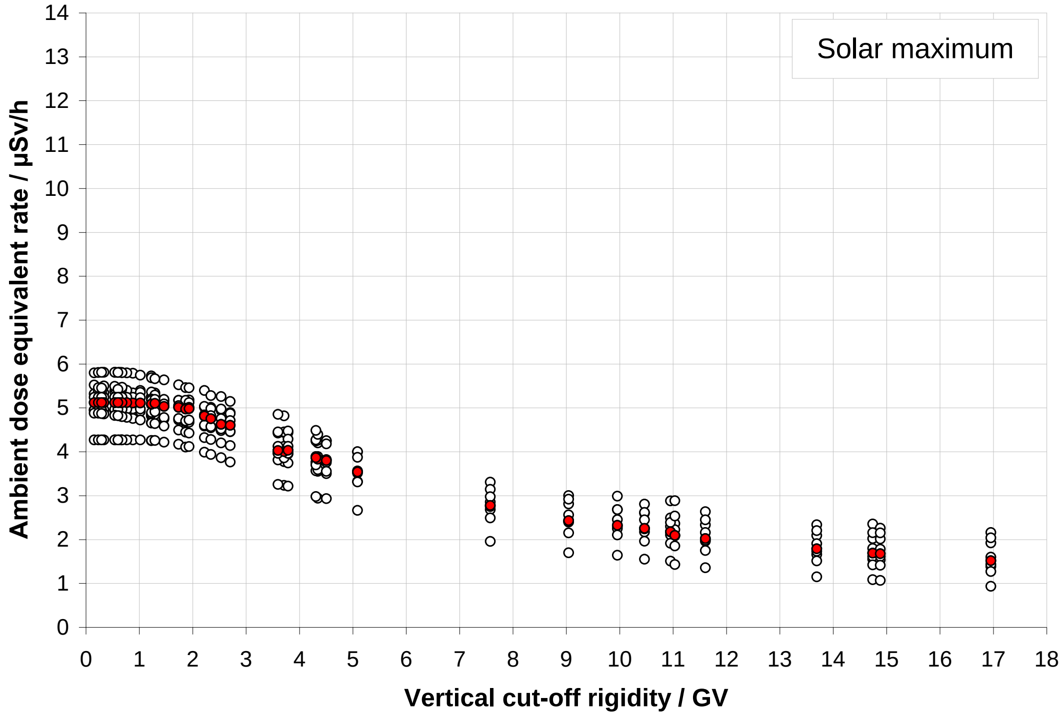


Figure 3.2a Anonymous comparison of the total ambient dose equivalent rate for different mid- and long-haul flights due to galactic cosmic radiation for FL370, during solar minimum (upper diagram) and solar maximum (lower diagram) conditions. The median is marked with full symbols. Not all codes provide both quantities ambient dose equivalent, $H^*(10)$, and effective dose, E, and therefore not all are shown in the two figures.

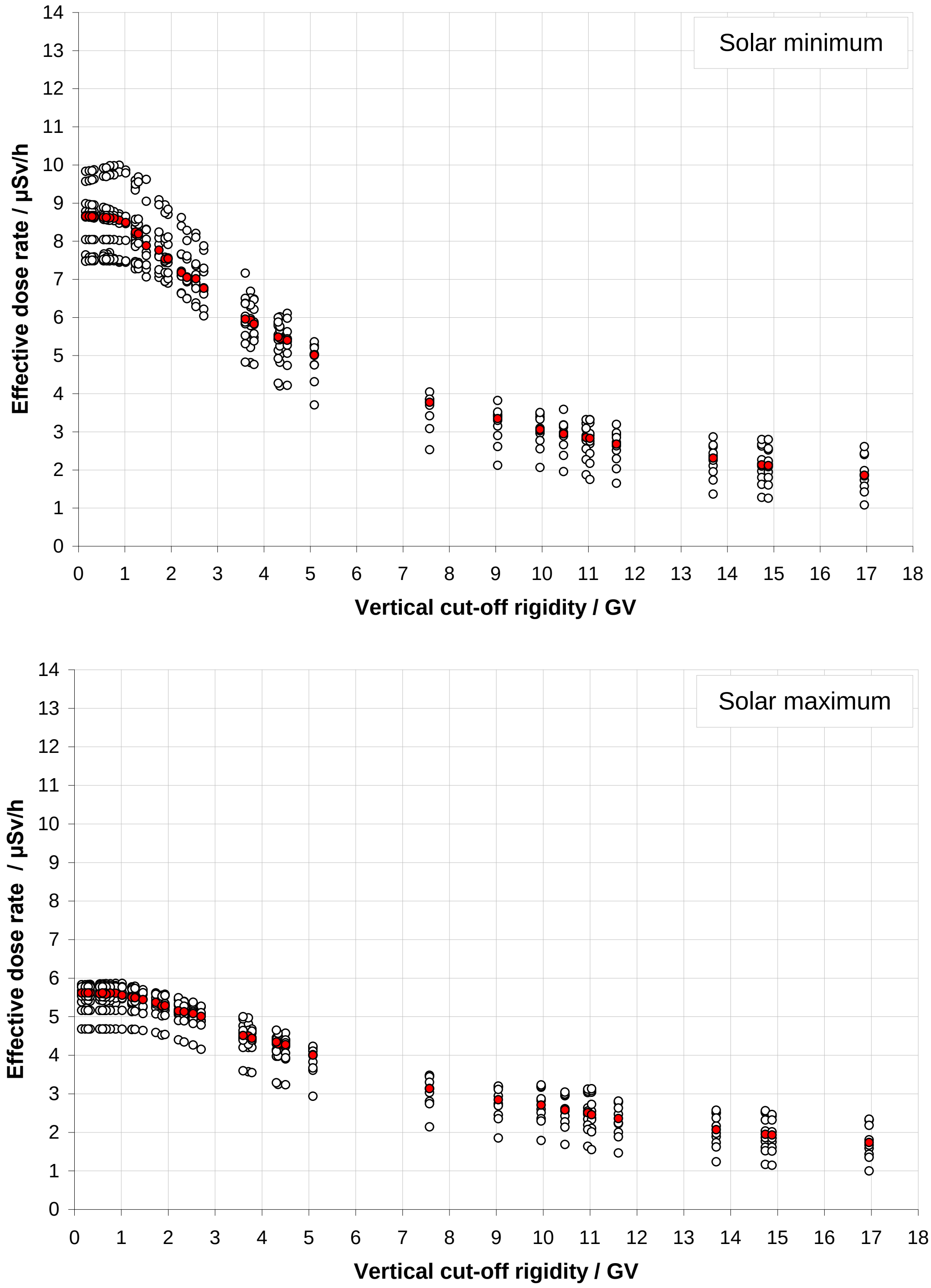


Figure 3.2b Anonymous comparison of the total effective dose rate for different mid- and long-haul flights due to galactic cosmic radiation for FL370, during solar minimum (upper diagram) and solar maximum (lower diagram) conditions. The median is marked with full symbols. Not all codes provide both quantities ambient dose equivalent, *H**(10), and effective dose, *E*, and therefore not all are shown in the two figures.

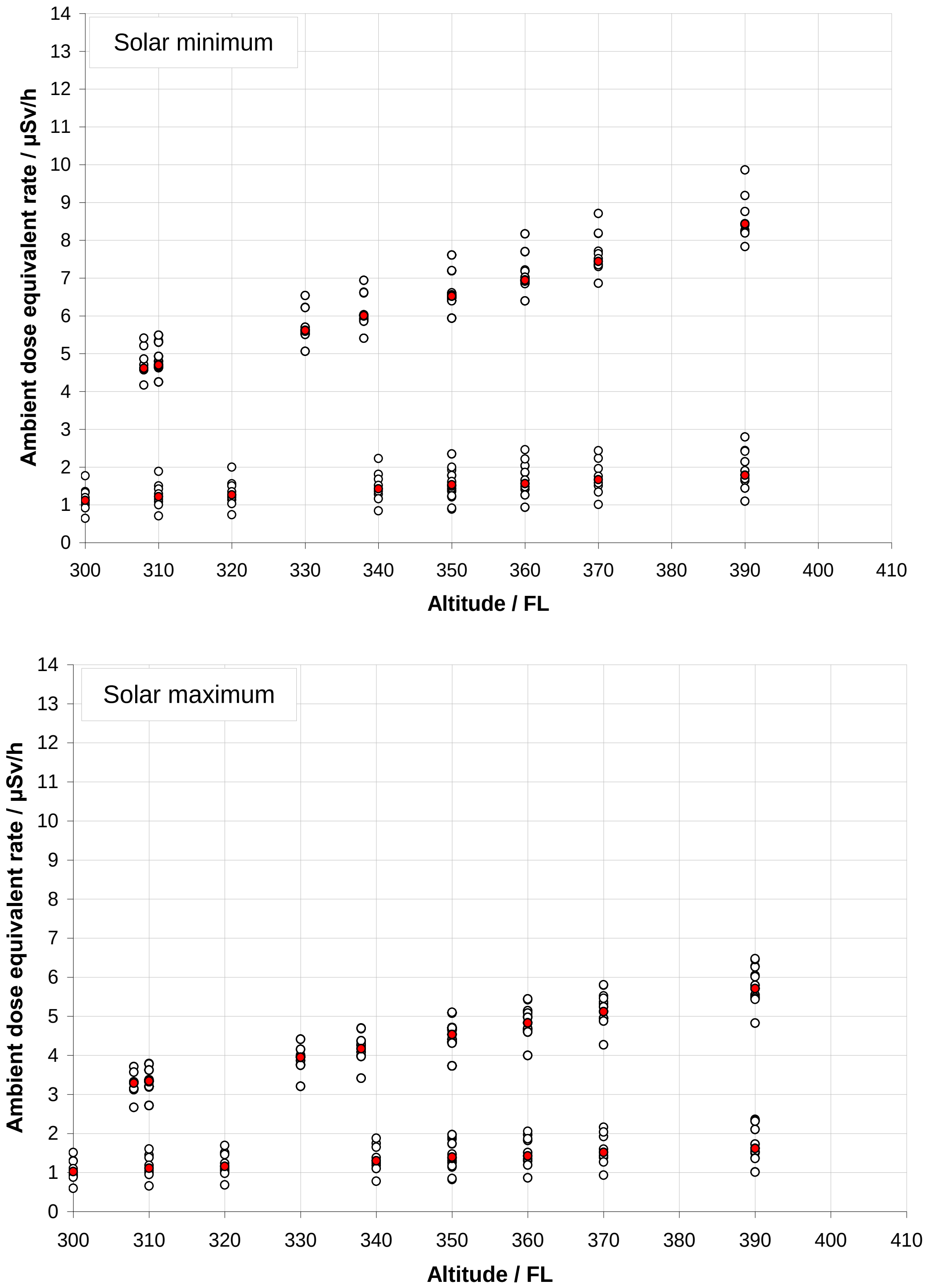
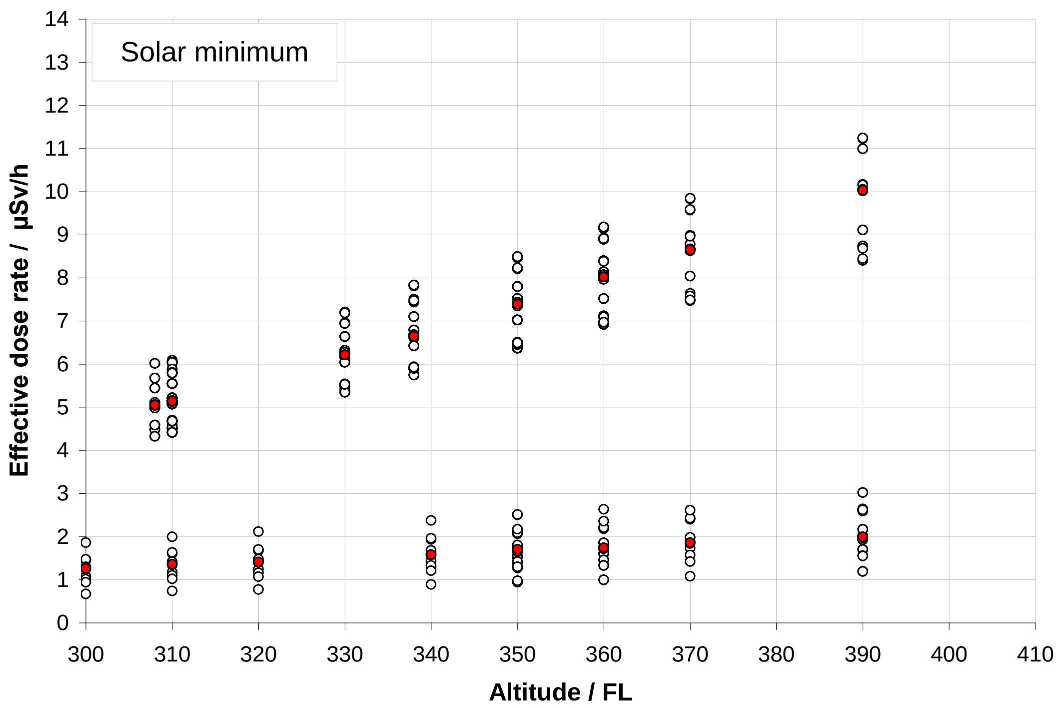


Figure 3.3a Anonymous comparison of the total ambient dose equivalent rate as a function of altitude for rigidity values $r_c < 0.25$ GV (upper data group) and $r_c > 16.75$ GV (lower data group), during solar minimum (upper diagram) and solar maximum (lower diagram) conditions. The median is marked with full symbols. Not all codes provide both quantities ambient dose equivalent, $H^*(10)$, and effective dose, E, and therefore not all are shown in the two figures.



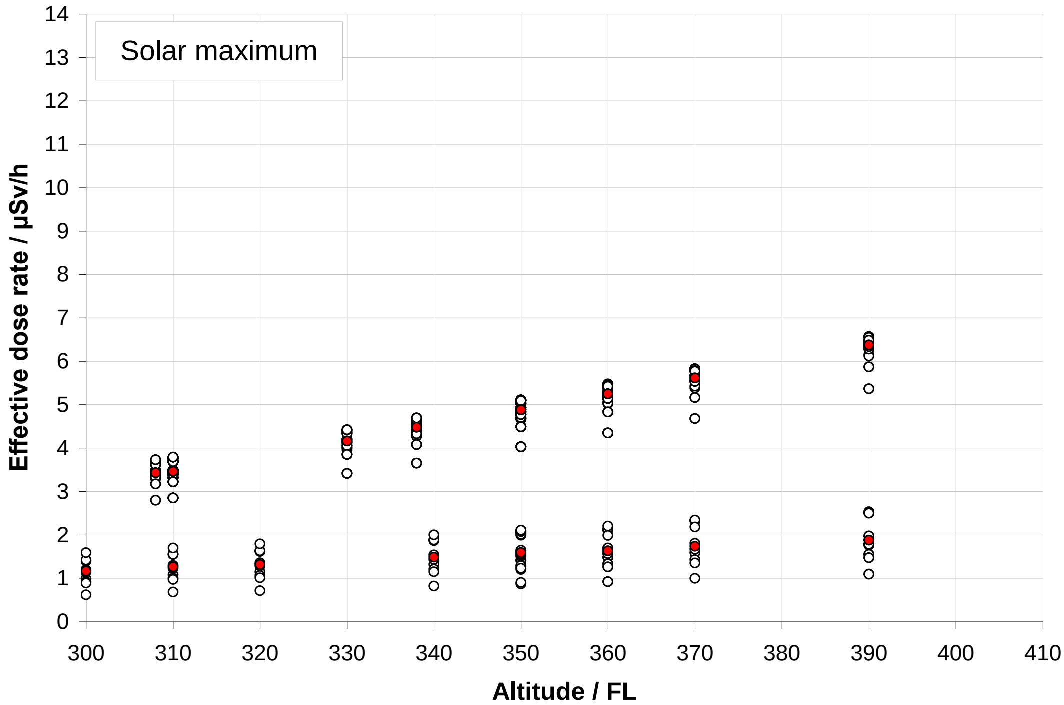


Figure 3.3b Anonymous comparison of the effective dose rate as a function of altitude for rigidity values $r_c < 0.25$ GV (upper data group) and $r_c > 16.75$ GV (lower data group), during solar minimum (upper diagram) and solar maximum (lower diagram) conditions. The median is marked with full symbols. Not all codes provide both quantities ambient dose equivalent, *H**(10), and effective dose, *E*, and therefore not all are shown in the two figures.

3.3 Dose rate profile over flight time

In order to investigate the behaviour of the different codes with regard to calculation of dose rates, both for the ambient dose equivalent rate, $dH^*(10)/dt$, and the effective dose rate, dE/dt, a single flight profile was selected and the results from the different participants were compared. The flight was selected to cover a cut-off rigidity and altitude range as extensive as possible. These preconditions are especially met by the long-haul flight (number 23 in Table 2.1) from Singapore (WSSS) to Newark (KEWR) that lasts for more than 17 hours and covers cruising altitudes between FL300 and FL410, with vertical cut-off rigidity values roughly between 0 GV and 17 GV. The vertical cut-off rigidity obtained from (Smart, 2008) and the flight altitude as a function of flight time are illustrated in Figure 3.4. The exact waypoint data of this flight are given in Appendix 2.

It must be emphasized that the dashed lines in the figure do not represent the actual flight profile but are meant only to guide the eye between the waypoints. The symbols mark the individual waypoints for which the exact time, position and altitude are available; the way in which time integration of the dose values is performed in between depends on the individual codes.

In the beginning of the flight the geomagnetic shielding is on the order of 17 GV or more, roughly the global maximum. In combination with the very low cruising altitude (FL300), the dose rates during the first hours of the flight can be interpreted as an estimate for the lowest values to be expected at a given time in the solar cycle at commercially flown altitudes. Towards the end of the flight, on the other hand, the geomagnetic shielding is close to zero and the flight altitude increases to FL410. This combination leads to dose rates which can be seen as an estimate for the maximum dose rates to be expected during a given time in the solar cycle.

In Figure 3.5a, the resulting values of the ambient dose equivalent rate are shown for solar minimum (upper panel) and maximum (lower panel) conditions. The expected increase in the dose rates towards the end of the flight is clearly visible, and the general slope is reproduced by all participating codes. The median of the ambient dose equivalent rate ranges from about 1 µSv/h for very low altitudes and high geomagnetic shielding for both solar minimum and maximum conditions up to about 9 µSv/h (solar minimum) and 6 µSv/h (solar maximum), respectively.

The corresponding effective dose rates are presented in Figure 3.5b. The median values of the effective dose rates in the beginning of the flight are slightly higher than, but very similar to, those of the ambient dose equivalent rates. At later times, however, and especially close to the end of the flight, when the geomagnetic shielding is low and the altitude large, the effective dose rates are somewhat higher: $dE/dt \sim$ 10-11 µSv/h (solar minimum) and $dE/dt \sim$ 7 µSv/h (solar maximum) compared to $dH^*(10)/dt \sim$ 9 µSv/h (solar minimum) and $dH^*(10)/dt \sim$ 6 µSv/h (solar maximum).

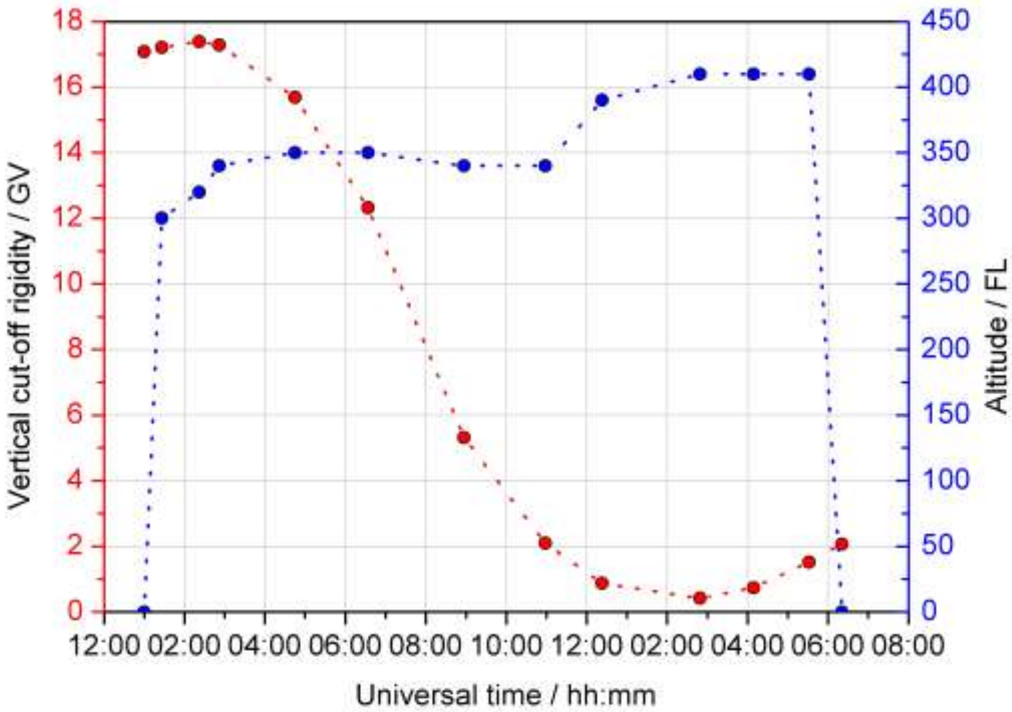
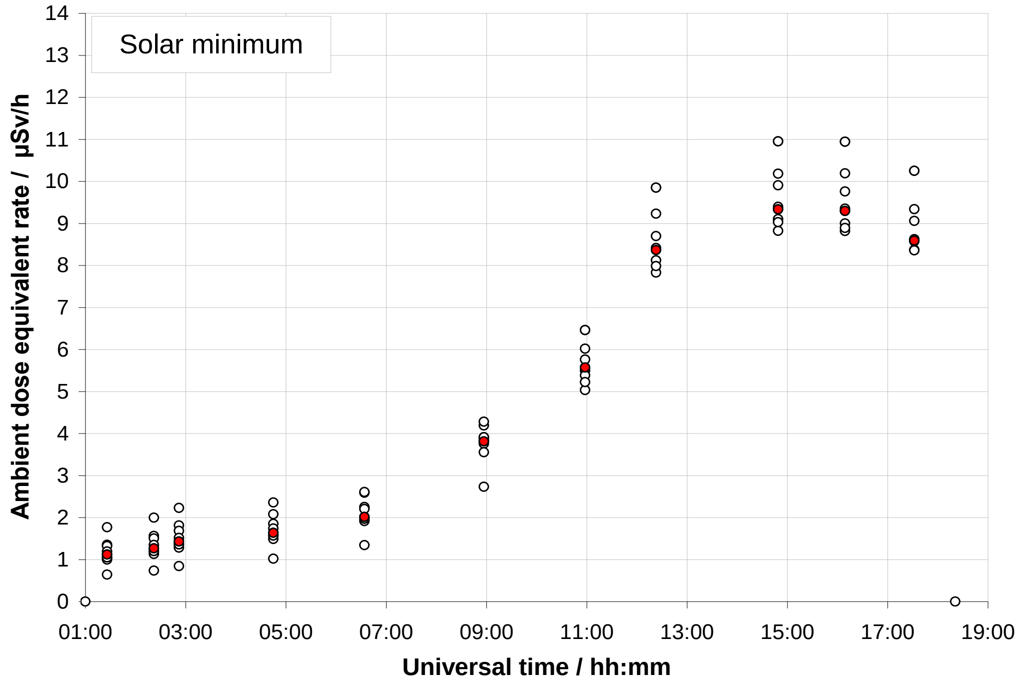


Figure. 3.4 Flight profile for Singapore-Newark (flight 23 in Table 2.1). Cut-off data (red dashed curve) shown here as an example are calculated based on (Smart, 2008). Altitude is shown as the dashed blue curve. Note that the dashed lines do not represent an actual flight profile but are meant only to guide the eve between the waypoints. Similar figures for the other flights are shown in Appendix 2.



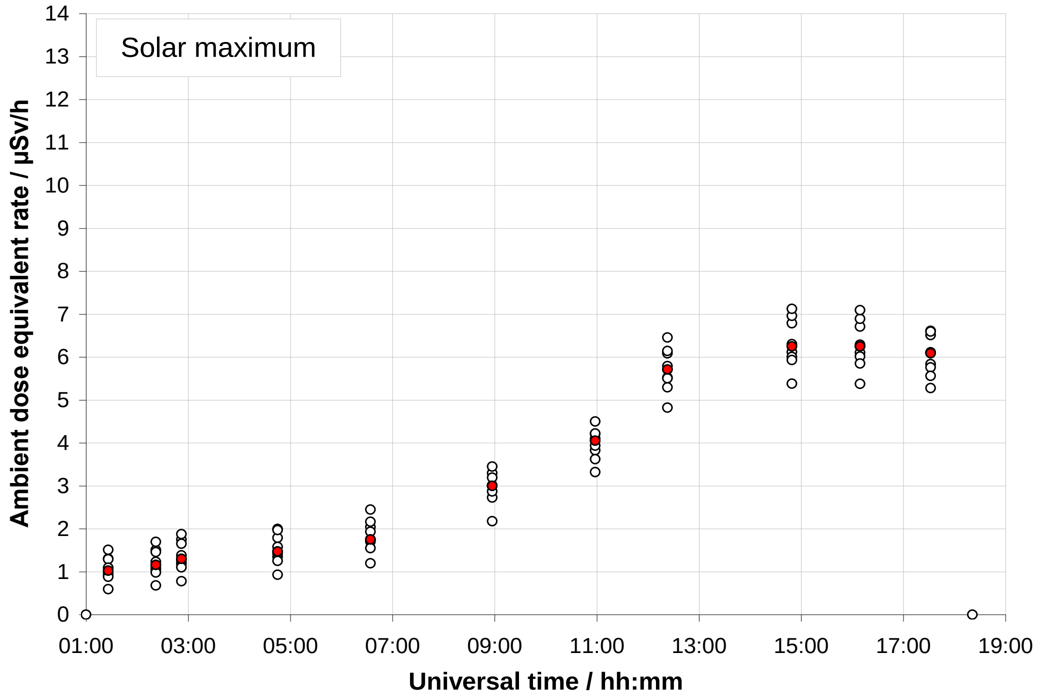
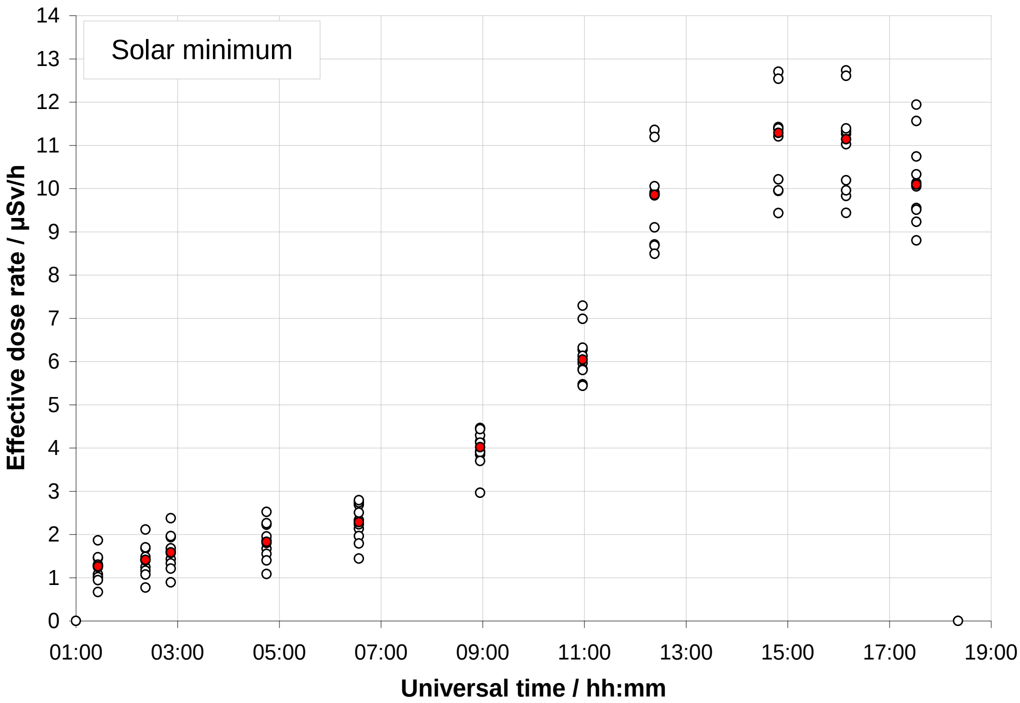


Figure 3.5a Anonymous comparison of the radiation exposure profile of a flight route from Singapore to Newark (flight 23 in Table 2.1) in terms of ambient dose equivalent rate, *dH**(10)/*dt*, at solar minimum (upper figure) and solar maximum (lower figures). The median is marked with full symbols. Not all codes provide both quantities ambient dose equivalent, *H**(10) and effective dose *E*, and therefore not all are shown in the two figures.



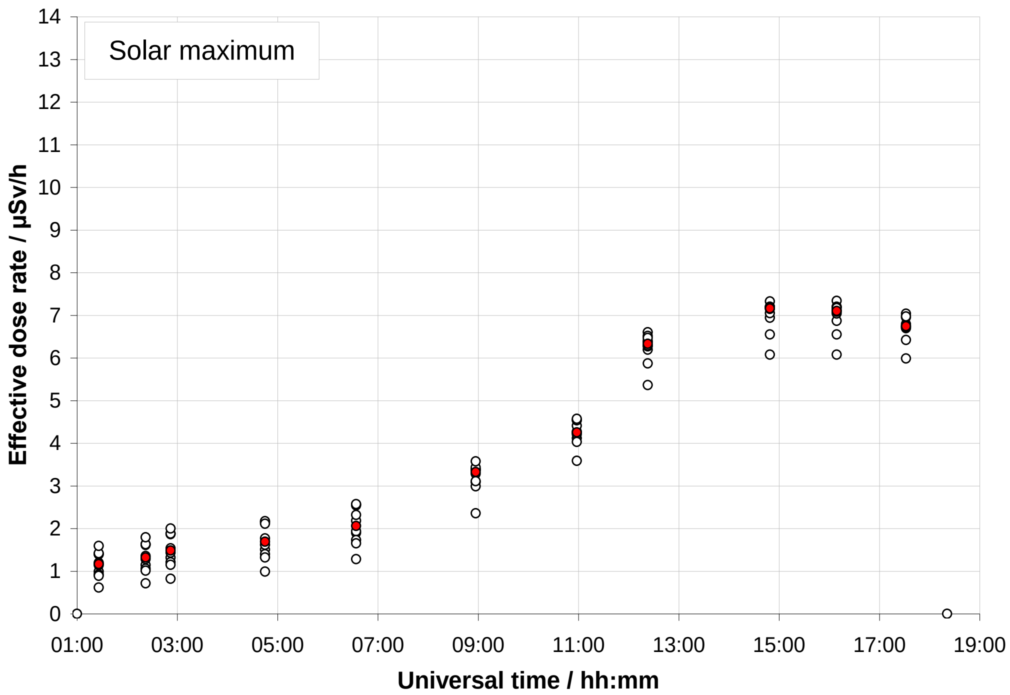


Figure 3.5b Anonymous comparison of the radiation exposure profile of a flight route from Singapore to Newark (flight 23 in Table 2.1) in terms of the effective dose rate *dE*/*dt* due to galactic cosmic radiation at solar minimum (upper figures) and solar maximum (lower figures). The median is marked with full symbols. Not all codes provide both quantities ambient dose equivalent, *H**(10), and effective dose, *E*, and therefore not all are shown in the two figures.

4 Discussion

In Figures 3.1a and 3.1b, the results obtained by the different codes for the selected flights are summarized, both in terms of $H^*(10)$ and effective dose E. Clearly, the rough trend of increasing doses for flights 1 to 23 was reproduced by all codes. As expected, doses for a given flight calculated at solar minimum are higher than those calculated at solar maximum, due to the lower shielding effect of the interplanetary magnetic field against the galactic component of cosmic radiation during solar minimum. Similarly, the calculated results for shorter flights at lower latitudes result in lower doses ($H^*(10)$ or E) than those for longer flights at higher latitudes, reflecting the fact that the flight time and the shielding effect of the geomagnetic field are important parameters in the dose from cosmic radiation.

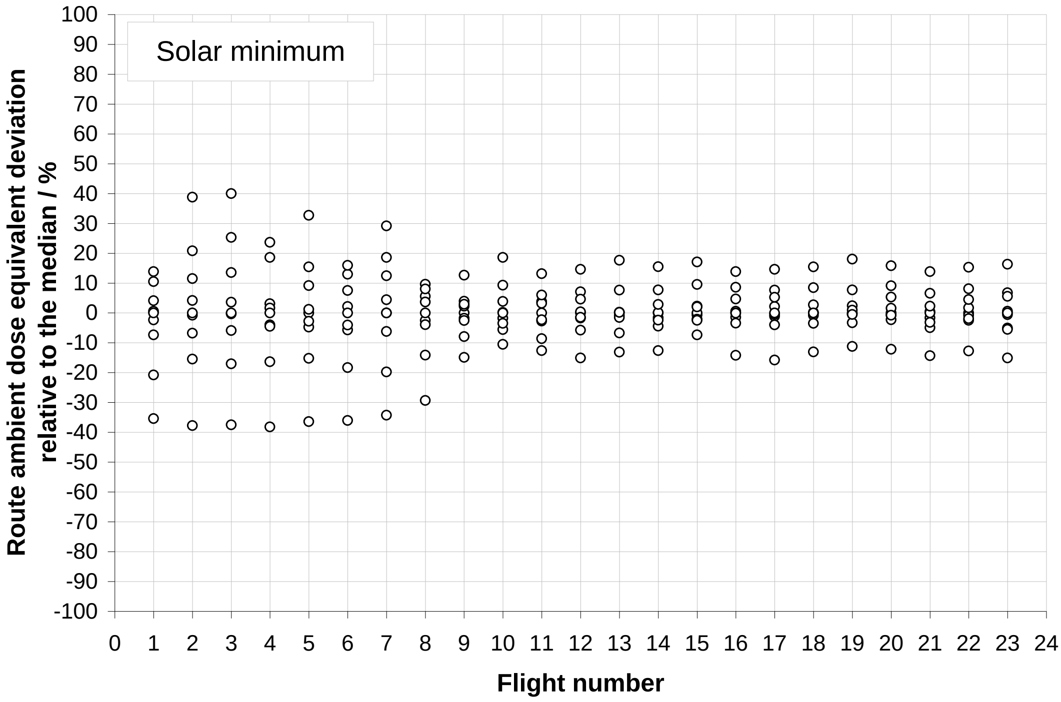
In order to compare the results in more detail, Figs. 4.1a and 4.1b show the same data, but now the relative deviation $(H_{calc} - H_{median})/H_{median}$ of the calculated dose for a given flight from the median of all results for that flight is shown. There is obviously an increased spread in the dose ratios for lower route doses, but not for larger ones. The reason for this could not be investigated in this comparison, as this would require a detailed description by all code providers of their mathematical procedures to calculate the dose or dose rates in between the given waypoints, especially during the ascent and descent phase. All that can be deduced is that for flights with low route doses the scatter in the dose ratios of the different codes is larger than that for flights with larger route doses.

The recommendation on acceptable uncertainties in radiation protection as formulated by the ICRP in 1997 may help in determining whether a code can be accepted for aircraft crew radiation protection purposes. In its publication 75 (ICRP, 1997) it is stated that in workplace fields the

"... overall uncertainty at the 95 % confidence level in the estimation of effective dose around the relevant dose limit may well be a factor of 1.5 in either direction for photons and may be substantially greater for neutrons of uncertain energy and for electrons. Greater uncertainties are also inevitable at low levels of effective dose for all qualities of radiation."

Frequency distributions have been produced from the data in Figures 4.1a and 4.1b for the relative deviations from the median for both the $H^*(10)$ and E data (see Figure 4.2). The scatter in the data as shown above is not statistical in nature but it can be used to estimate a type B uncertainty, also called a systematic uncertainty, for all the codes participating in this comparison exercise. The results of this comparison are that most of the calculated route doses are within a range of about 10 % from their median (1 σ is 9 % for $H^*(10)$ data, and 11 % for E data). In general, for most flights and codes, the calculated doses ($H^*(10)$ or E) differ by less than about ±30 % from their median at a 95 % confidence level.

In the case of aircrew exposure, single route doses presented in this report do not exceed 100 µSv per flight. Therefore, the annual doses of air crew members will not exceed 10 mSv after the maximum allowed block flying time of 900 h per year for aircrew (EC 2000) is taken into account.



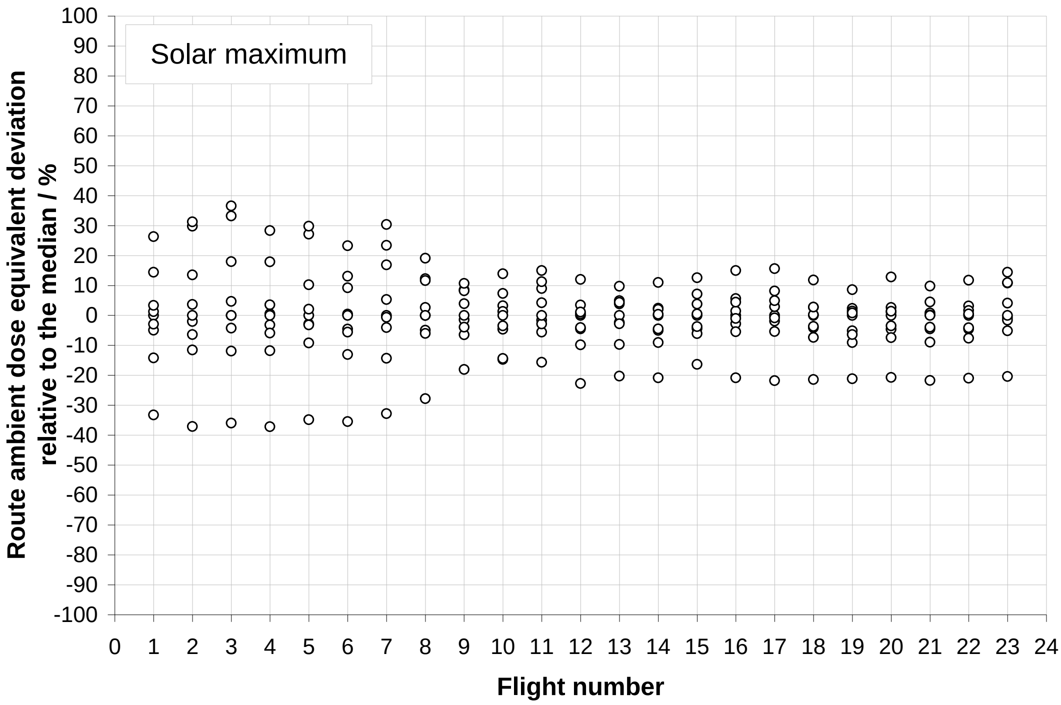
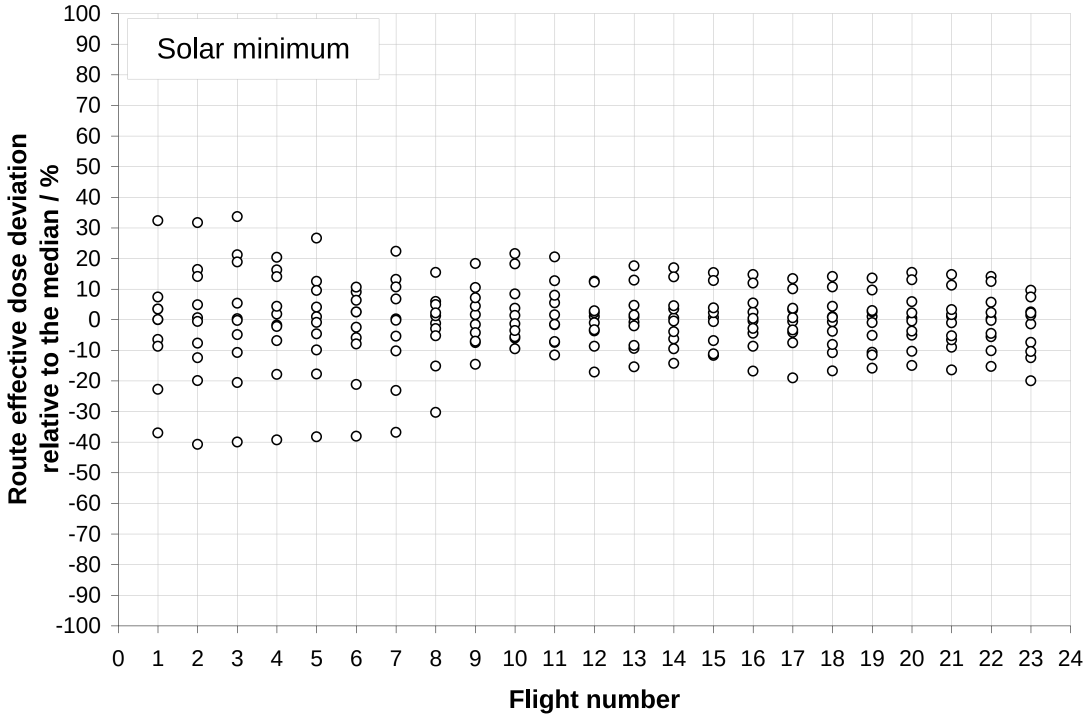


Figure 4.1a Anonymous comparison of the deviation of *H**(10) relative to the median at solar minimum (upper figure) and solar maximum (lower figure). Not all codes provide both quantities *H**(10) and *E*, and therefore not all are shown in the two figures.



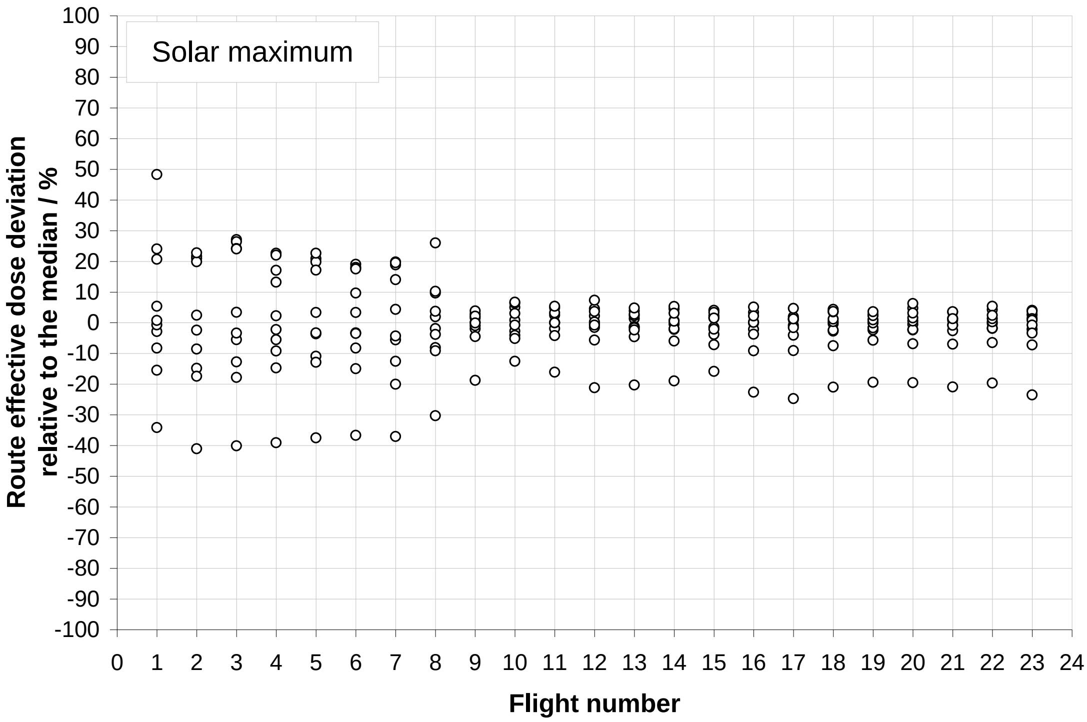


Figure 4.1b Anonymous comparison of the deviation of the effective dose *E* relative to the median at solar minimum (upper figure) and solar maximum (lower figure). Not all codes provide both quantities *H**(10) and *E*, and therefore not all are shown in the two figures.

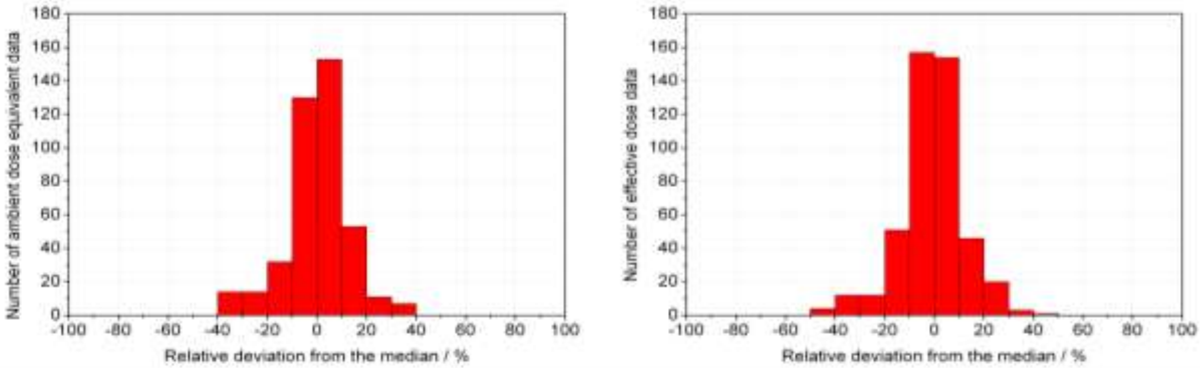


Figure 4.2 Relative deviation of all calculated route ambient dose equivalent values $H^*(10)$ (left) and effective dose values E (right) from their medians.

5 Conclusions

Eleven codes used for calculating doses to pilots and cabin crew members have been used in a comparison exercise organised by the EURADOS Working Group 11 on High Energy Radiation Fields on harmonization of aircrew dosimetry practices in European countries. Some of these codes are based on simulation of the secondary field of cosmic radiation by Monte Carlo techniques; others use analytical solutions of the problem, while still others are mainly based on a fit to experimental data. One code provided systematically lower dose and dose rate values (up to -40 % at low latitudes compared to the median) than all the other participating codes, while another code showed a few dose and dose rate values that were higher by some +30 % (also at low latitude). The overall agreement between the codes, however, was better than ±20 % from the median.

The agreement between the codes is considered to be fully satisfactory. Actually dose estimates in radiation protection generally include uncertainties no better than ±20 % to ±30 %. This conclusion is further substantiated by the fact that most of these codes have also previously been validated by measurements (Lindborg, 2004), with an agreement between measured and calculated doses better than ±20 %. In any case, it is recommended that any code to be used for dose assessment of radiation exposure due to secondary cosmic radiation at aviation altitudes should be validated by experimental data or by a comparison as presented in this report. The agreement should be within ±30 % at a 95 % confidence level.

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Appendix 1: ICAO Airport Codes

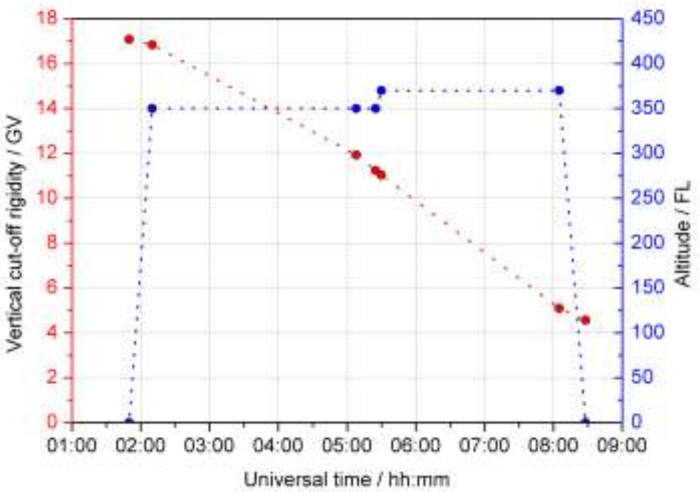
Table. A-1.1: The four-letter alphanumeric code of airports as defined by the International Civil Aviation Organization (ICAO).

ICAO code	Airport
LFPG	Paris
KJFK	New York
KIAD	Washington
KSFO	San Francisco
SBGL	Rio de Janeiro
RJAA	Tokyo
FAJS	Johannesburg
WSSS	Singapore
KEWR	Newark
OMDB	Dubai
KIAH	Houston
KORD	Chicago
ZBAA	Beijing
ZSPD	Shanghai
VHHH	Hong Kong
VTBD	Bangkok
YSSY	Sydney
NZAA	Auckland

Appendix 2: Flight Profiles

The dashed lines shown in the figures do not represent an actual flight profile but are meant only to guide the eye between the waypoints. Note that the way in which calculations are performed between the waypoints depends on the individual codes.

Air navigation data of the 23 investigated flights during solar maximum (09/2007) and solar minimum (08/2000). Flight profiles are graphically presented (left) and waypoints are listed (right).



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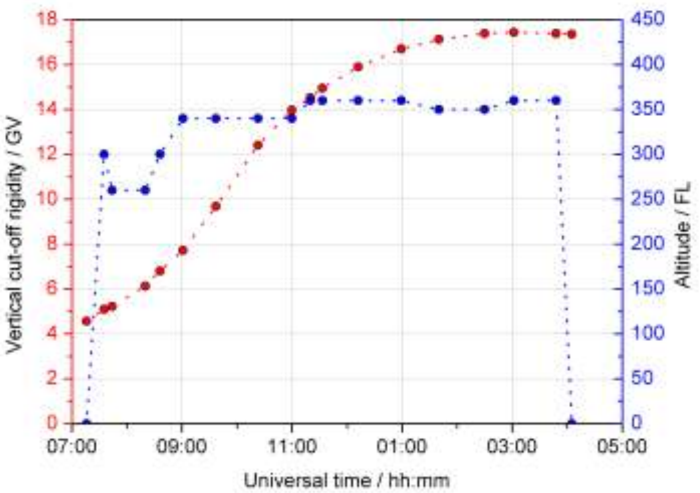

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002;INT;350;06:24;040600N;1154800E;
002;INT;350;07:14;081200N;1101200E;
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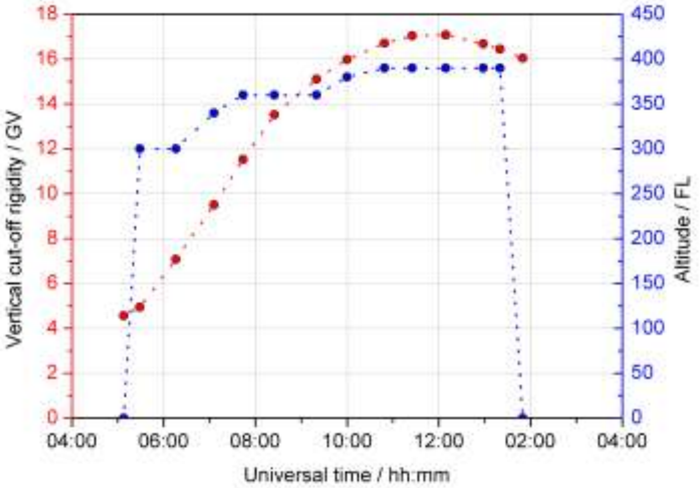

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003;INT;360;02:36;181200S;1385400E;
003;INT;360;03:17;135400S;1353600E;
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003;INT;380;04:52;033600S;1281200E;
003;INT;390;05:41;020000N;1245400E;
003;INT;390;06:17;063300N;1221500E;
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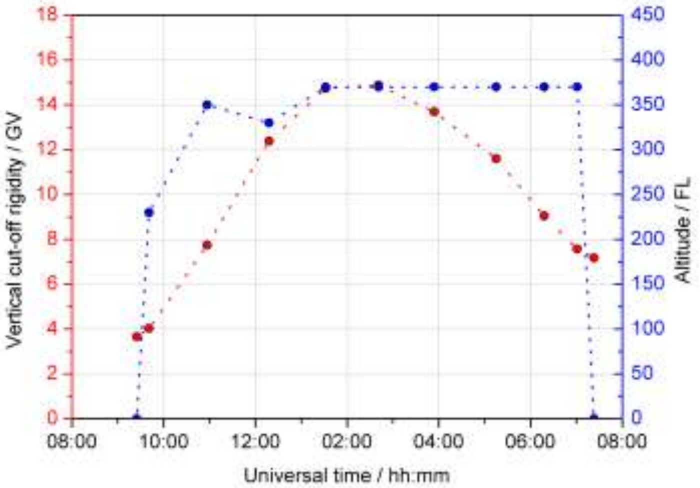

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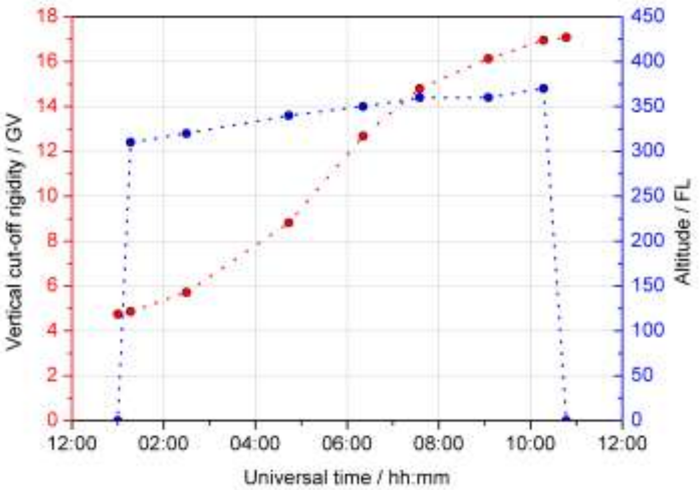

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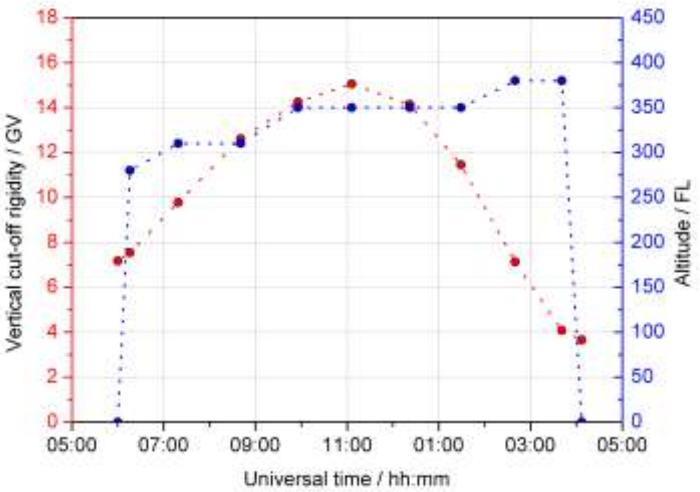

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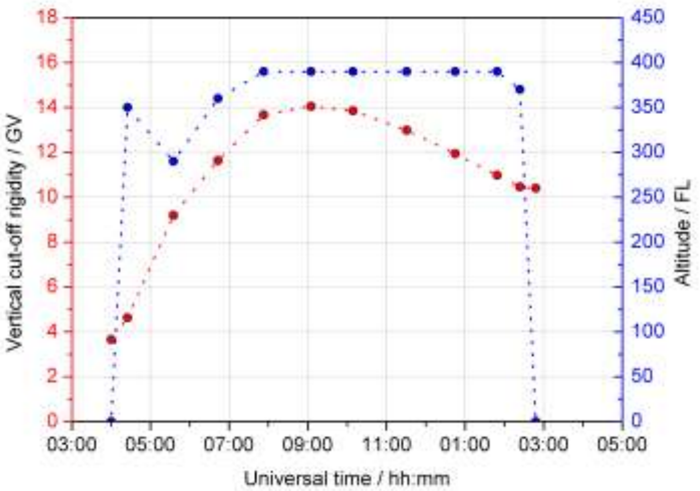

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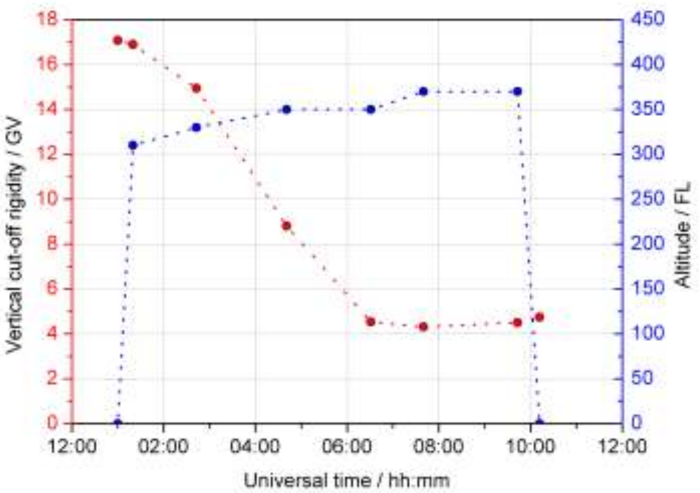

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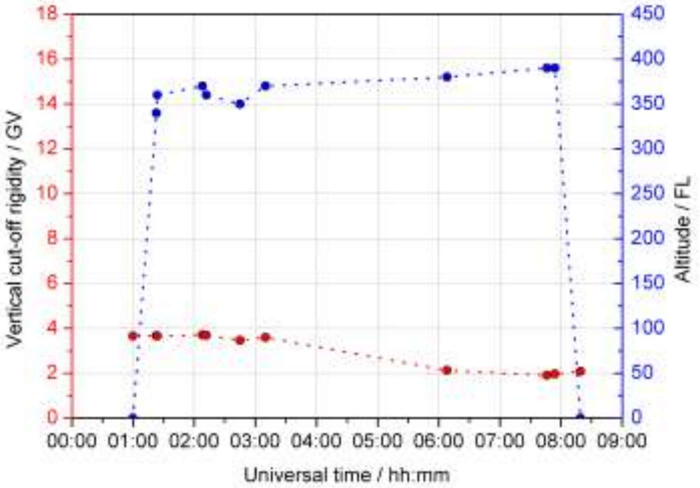

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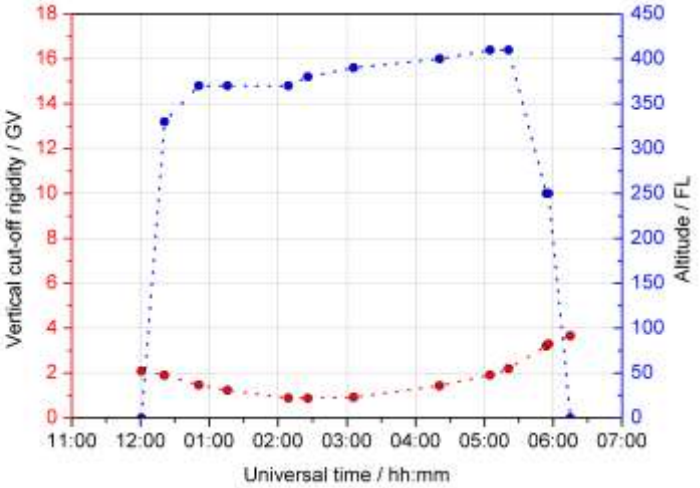

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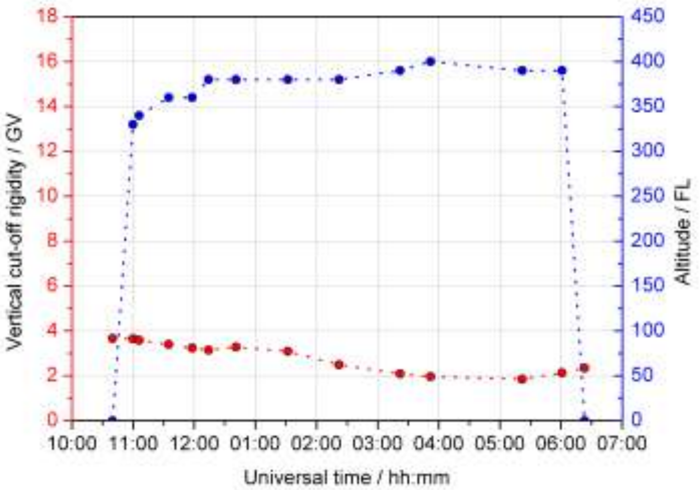

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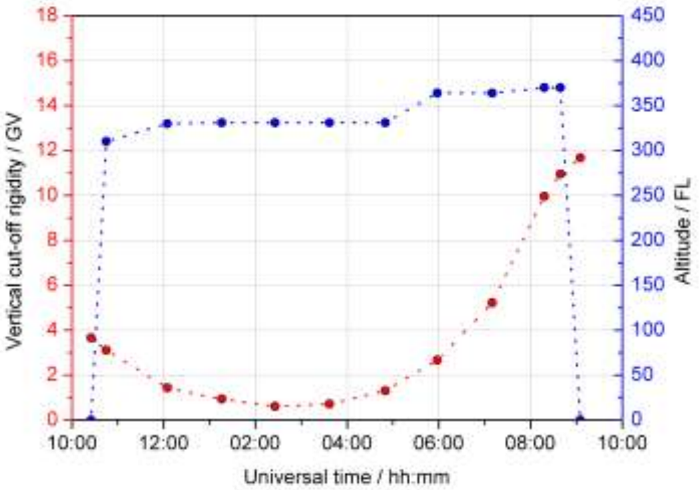

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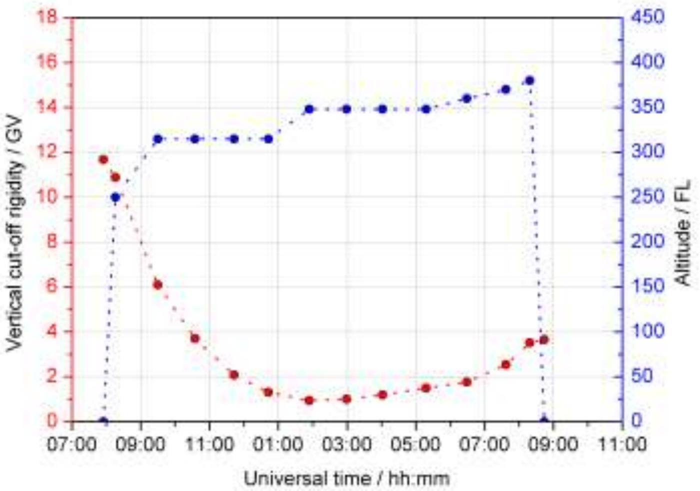

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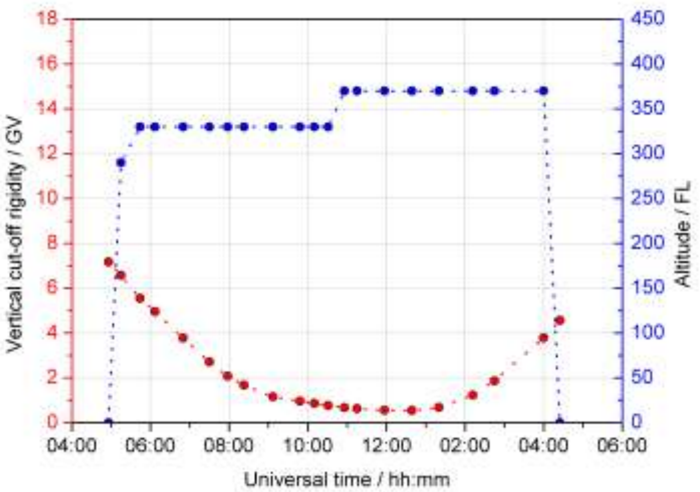

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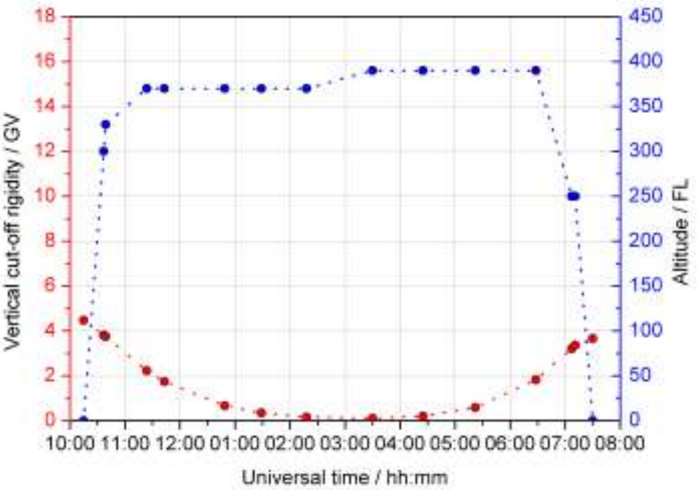

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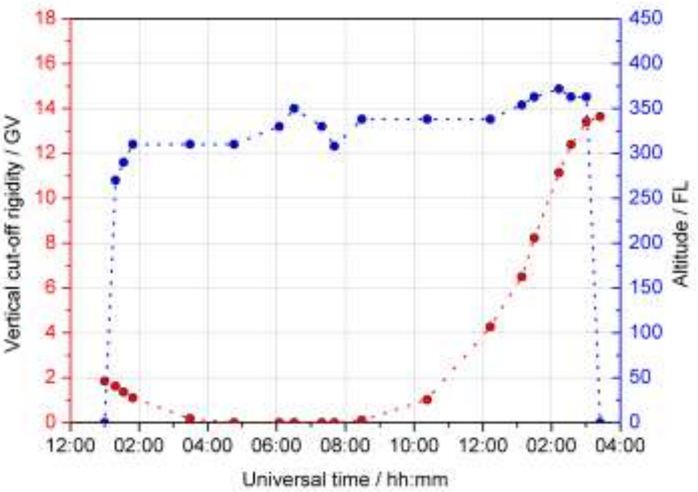

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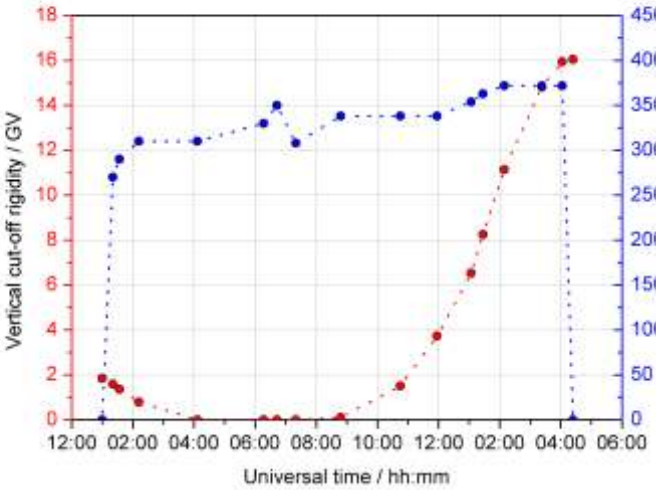

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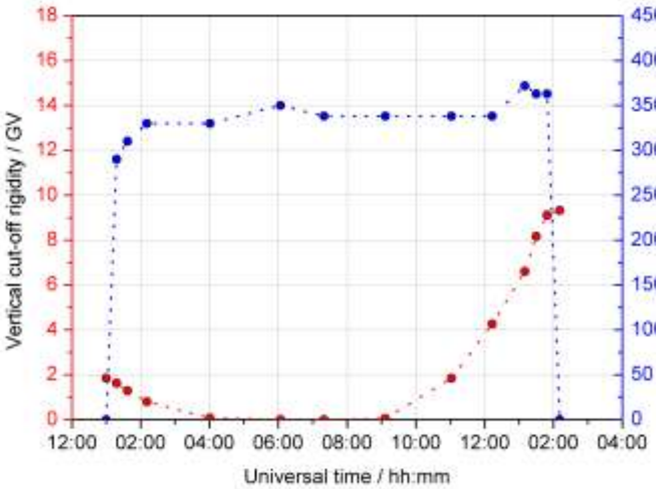

018;KORD;ZBAA;12/09/2007;01:00;12/09/2007;14:11;
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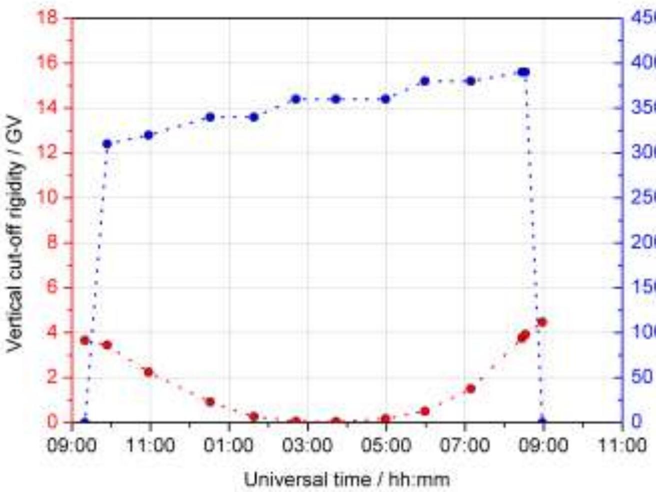

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019;INT;380;09:49;490000N;1163154W;
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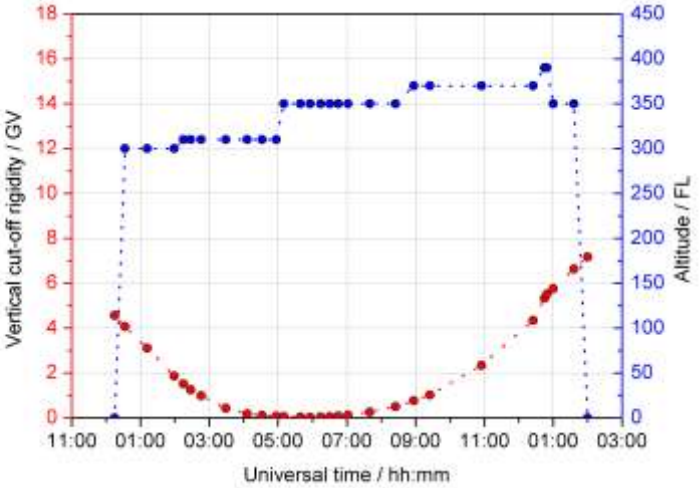

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020;INT;300;01:44;420000S;1400000E;
020;INT;310;02:00;434200S;1381800E;
020;INT;310;02:13;450000S;1370000E;
020;INT;310;02:31;470000S;1350000E;
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020;INT;350;05:59;650000S;0950000E;
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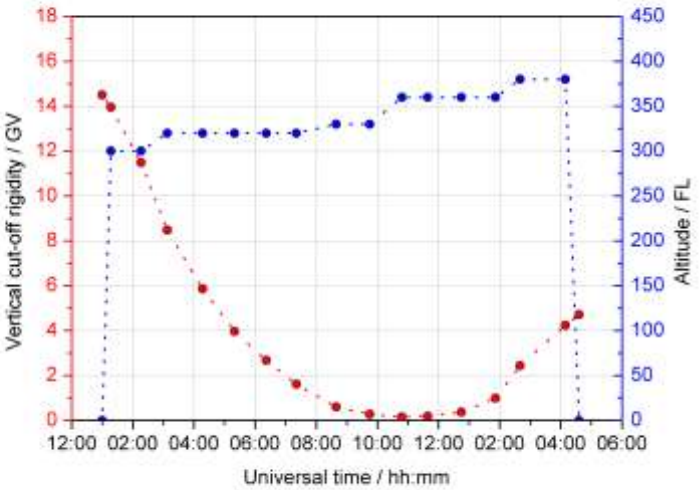

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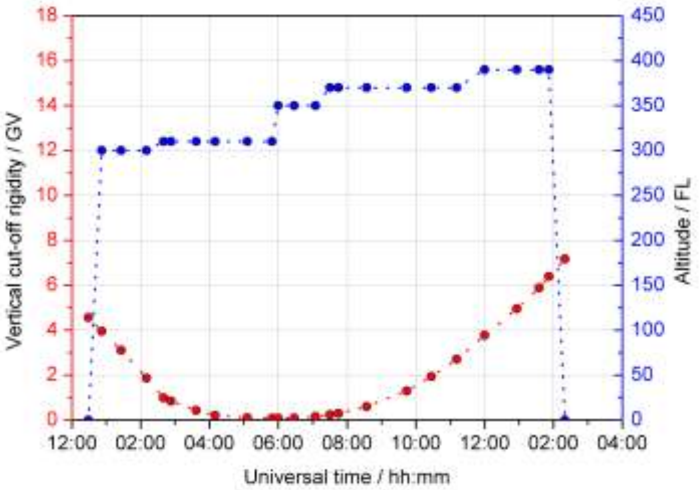

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022;INT;310;02:24;480600S;1335400E;
022;INT;310;03:08;520000S;1300000E;
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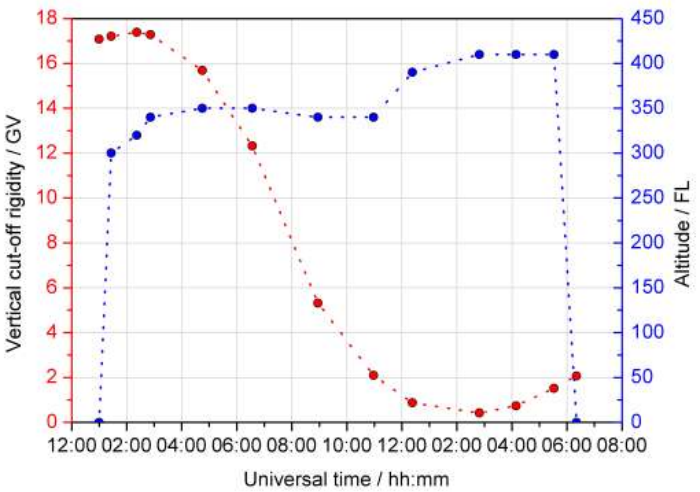

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