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First Steps Toward the Verification of Models for the Assessment of the Radiation Exposure at Aviation Altitudes During Quiet Space Weather Conditions

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Key Points:
- CCMC, DLR, FAA, and NASA cooperate in the implementation of the models CARI-7A, PANDOCA, and NAIRAS for the assessment of the radiation exposure at aviation altitudes in the CCMC web page
- High-quality measuring data for ambient dose equivalent and absorbed dose in silicon were selected from literature
- Measuring data are compared with CARI-7A, PANDOCA, and NAIRAS model calculations

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Abstract Space weather is an important driver of the exposure of aircrew and passengers to cosmic rays at flight altitudes, which has been a matter of concern for several decades. The assessment of the corresponding radiation doses can be realized by measurements or model calculations that cover the whole range of the radiation field in terms of geomagnetic shielding, atmospheric shielding, and the effects of space weather. Since the radiation field at aviation altitudes is very complex in terms of particle composition and energy distribution, the accurate experimental determination of doses at aviation altitudes is still a challenging task. Accordingly, the amount of data with comparatively small uncertainties is scarce. The Community Coordinated Modeling Center invited the Federal Aviation Administration, the German Aerospace Center, and the National Aeronautics and Space Administration to make their radiation models for aviation CARI-7A, PANDOCA, and NAIRAS available for interested users via the Community Coordinated Modeling Center web site. A concomitant comparison of model calculations with measuring data provided information on the predicting capabilities and the uncertainties of the current versions of these models under quiet space weather conditions.

1. Introduction

The Community Coordinated Modeling Center (CCMC), situated at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, is a multiagency partnership to enable, support, and perform the research and development for next-generation space science and space weather models (CCMC, 2018). In an effort to provide information about the radiation exposure due to cosmic rays at aviation altitudes to the user community, the CCMC invited the relevant aviation research organizations from the United States and Germany to make their corresponding cutting-edge models via the CCMC web page available. The participating models are CARI-7A by the Federal Aviation Administration (FAA), PANDOCA by the German Aerospace Center (DLR, Deutsches Zentrum für Luft- und Raumfahrt), and NAIRAS by the National Aeronautics and Space Administration (NASA). The ongoing implementation of the models at the CCMC was supposed to be accompanied by an assessment of the predictive capabilities of the models by comparison with measuring data. The discussion on corresponding metrics for model verification was addressed by the Radiation and Plasma Effects Working Group at the International CCMC-LWS Working Meeting on Assessing Space Weather Understanding and Applications, held in Cape Canaveral 3–7 April 2017, and has been highly topical since then.

The main challenge for the validation of predictive models for the radiation exposure at aviation altitudes consists in acquiring corresponding reliable high-quality dose rate measurements. Since those data are not available for severe space weather radiation events yet, the first steps toward the verification of models for the assessment of the radiation exposure at aviation altitudes have to be based on measurements of the omnipresent radiation field due to galactic cosmic radiation (GCR). Several dedicated measuring campaigns have been performed since radiation protection for aircrew became legally regulated in the European Union in 1996, and corresponding dose data of the GCR component are available from scientific literature.

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In this study, we investigated data from several publications in order to identify reliable high-quality dose rate measurements meeting strict criteria for a first comparison with CARI-7A (FAA), PANDOCA (DLR), and NAIRAS (NASA) model calculations. The outcome of this comparison provides information about the uncertainties to the users and helps the participating scientists improve their models.

2. Method

The first step for a comparison of the different model calculations with measuring data was to identify suitable data sets acquired in dedicated flight missions from the literature. These data sets included information on longitude, latitude, barometric altitude, date, and time as well as corresponding measurements of at least one dose quantity. The investigated dose quantities were the rates of the ambient dose equivalent $dH^*(10)/dt$ and the absorbed dose in silicon dD_{Si}/dt. Relevant environmental parameters for the model calculations, for example, geomagnetic cutoff rigidity R_c and solar modulation, could be retrieved by the modelers from corresponding data sources, for example, from NOAA's Space Weather Prediction Center's Data Service (ftp://ftp.swpc.noaa.gov/pub/warehouse), using information on date and time. Furthermore, the flights investigated in this study were restricted to those performed under quiet space weather conditions, that is, an undisturbed magnetosphere. The selected data sets were given to the modelers from the participating organizations without the respective measuring value in order to calculate this dose quantity using their models.

The comparison of model calculations d^{model} and measuring values d^{meas} was based on the relative deviation Δ of the investigated dose quantities:

$$\Delta_i = \frac{d_i^{\text{model}} - d_i^{\text{meas}}}{d_i^{\text{meas}}} \tag{1}$$

The index i indicates a particular data point as subset of the complete set of data points.

This becomes

$$\Delta_{i,H*(10)} = \frac{d_{i,H*(10)}^{\text{model}} - d_{i,H*(10)}^{\text{meas}}}{d_{i,H*(10)}^{\text{meas}}} \tag{2}$$

for the rate of the ambient dose equivalent $dH^*(10)/dt$ and

$$\Delta_{i,D_{Si}} = \frac{d_{i,D_{Si}}^{\text{model}} - d_{i,D_{Si}}^{\text{meas}}}{d_{i,D_{Si}}^{\text{meas}}} \tag{3}$$

for the rate of the absorbed dose in silicon dD_{Si}/dt, respectively.

The parameter Δ is positive, if the calculated model value is greater than the corresponding measurement and vice versa. This makes the analysis of the deviation between a measuring value and the respective model calculation in a specific exposure situation in terms of flight altitude, geomagnetic shielding, and space weather environment possible.

A more generalized assessment of the deviation between model calculations and measurements is given by the mean deviation $\overline{\Delta}$ of the investigated dose quantity:

$$\overline{\Delta} = \frac{\Sigma_{i=0}^{n} |\Delta_i|}{n} \tag{4}$$

The corresponding quantities $\overline{\Delta_{H*(10)}}$ and $\overline{\Delta_{D_{Si}}}$ were used for the evaluation of the models within the framework of this study.

3. Models

There are an increasing number of models for the assessment of the radiation environment at aviation altitudes, which are based on atmospheric modeling or measurements taken during measuring flights

Table 1
Data of the Flight Positions for the Comparison of Model Calculations and Measurements

i	Date	Time (UTC)	Latitude	Longitude	Flight level (FL)	Kp	Dose quantity
1	6 November 2007	0930	N 48.5	E 10.2	320	0	$dH^*(10)/dt$
2	7 November 2007	1110	N 59.9	E 8.7	320	0	$dH^*(10)/dt$
3	7 November 2007	1320	N 59.9	E 8.7	400	0	$dH^*(10)/dt$
4	14 May 2013	1321	N 48.3	E 10.3	400	3	$dH^*(10)/dt$
5	15 May 2013	1209	N 60.1	E 8.9	320	3	$dH^*(10)/dt$
6	15 May 2013	1357	N 60.1	E 8.9	400	3	$dH^*(10)/dt$
7	6 November 2007	1120	N 48.5	E 10.2	400	0	dD_{Si}/dt
8	14 May 2013	1200	N 48.3	E 10.3	320	3	dD_{Si}/dt
9	14 May 2013	1321	N 48.3	E 10.3	400	3	dD_{Si}/dt
10	15 May 2013	1209	N 60.1	E 8.9	320	3	dD_{Si}/dt

(Tobiska et al., 2018). The investigated models CARI-7A, PANDOCA, and NAIRAS are physics-based models that comprise a mathematical description of the spectra of the impinging particles, their transport through the Earth's magnetosphere, and their subsequent propagation through the atmosphere including the generation of the secondary radiation field that dominates the radiation exposure at aviation altitudes. The following overview of the three models is restricted to brief descriptions of each model. More detailed information is given in the corresponding references.

3.1. CARI-7A

Development of the CARI (Civil Aeromedical Research Institute) program for calculating doses of cosmic radiation on aircraft flights began in the late 1980s. Development of version 7 began in 2009 with calculations of needed fluence to dose conversion coefficients for light ions and alpha particles (e.g., Copeland et al., 2010, 2012). CARI-7A development and validation are described in Copeland (2017). It was first made widely available in February 2017 and has been improved continuously by user feedback since it was released. The Monte Carlo program MCNPX 2.7.0 (Oak Ridge National Laboratory, 2011) was used for radiation transport. The primary cosmic ray spectrum model and handling of cutoff rigidities are all user-selectable at runtime. For this study, the Badhwar-O'Neill 2011 update to the 2010 (O'Neill, 2010, 2012) GCR model was used, and vertical cutoff rigidities R_c as calculated by interpolation from tables calculated by Smart and Shea (2005, 2012) were used as whole-sky effective cutoff rigidities. The primary radiation field includes nuclei from H to Fe, while the secondary radiation field also includes neutrons, photons, e^-, e^+, μ^-, μ^+, π^-, π^+, kaons (no dosimetry), neutrinos (no dosimetry), deuterons, tritons, and helions. The capability to calculate dose in 0.3 mm silicon was developed and added for this report using fluence to dose conversion coefficients developed for PANDOCA (Matthiä et al., 2014).

3.2. PANDOCA

The development of PANDOCA (Professional Aviation Dose Calculator) based on the Monte Carlo program package GEANT4 began in 2005. The first version that was verified with measurements taken during the transition of solar cycle 23 and 24 was released in 2009 and has been constantly improved since then. The current PANDOCA core version used for this comparison corresponds to the new operational product PANDOCA 2.0.0. The impinging primary cosmic particles and their energy spectra, respectively, are described by the galactic cosmic ray model by Matthiä et al. (2013). The variation due to the solar modulation is modeled using the corresponding W-parameter (Matthiä et al., 2013). The transport through the magnetosphere is parameterized by the effective vertical cutoff rigidities R_c, which were calculated with the GEANT4 application PLANETOCOSMICS using the International Geomagnetic Reference Field model for 2005 (Maus & MacMillan, 2005). The propagation of the primary particles through the atmosphere and the generation of the respective secondary radiation field are described by the particle fluxes at a given altitude consisting of protons, neutrons, photons, e^-, e^+, μ^-, μ^+, π^-, and π^+. These particle fluxes are converted into dose quantities using corresponding conversion factors, for details see Matthiä et al. (2014).

3.3. NAIRAS

The first version of the NAIRAS (Nowcast of Atmospheric Ionizing Radiation for Aviation Safety) model was released in 2011. The graphical and tabular data products are available from the project's public web site

Table 2
Comparison of the Average Ambient Dose Equivalent Rates dH(10)/dt in μSv/hr Measured at Flight Position i With the Corresponding Model Calculations*

i	$dH^*(10)/dt$ measured	$\Delta_{CARI\text{-}7A}$ (%)	$\Delta_{PANDOCA}$ (%)	Δ_{NAIRAS} (%)
1	4.3 ± 0.4	−8	−3	15
2	4.9 ± 0.4	6	14	52
3	9.0 ± 0.6	−3	2	8
4	5.8 ± 0.3	−6	−6	−21
5	4.2 ± 0.3	5	12	27
6	7.7 ± 0.5	−6	−3	−14

at http://sol.spacenvironment.net/~nairas/. The NAIRAS model provides data-driven, global, real-time predictions of radiation exposure rates from galactic cosmic rays (GCR) and solar energetic particles (SEPs) on a geographic 1 × 1 degree latitude and longitude grid, and from the surface of the Earth to 90 km with a vertical resolution of 1 km. The real-time, global predictions are updated every hour. Deterministic, physics-based models are employed to transport cosmic rays through the heliosphere, Earth's magnetosphere, and the neutral atmosphere (Mertens et al., 2012, 2013). GCR are transported through the heliosphere using a modification of the 2010 Badhwar and O'Neill GCR model (Mertens et al., 2013), denoted *H-BON10*, while the energy spectra of SEPs are specified in situ outside the magnetosphere using NOAA Geostationary Operational Environmental Satellite (GOES) ion flux measurements (Mertens et al., 2010, 2012). Transport through the magnetosphere is parameterized in terms of effective vertical cutoff rigidity, which is based on charged particle trajectory tracing in a dynamically varying geomagnetic field (Kress et al., 2010; Mertens et al., 2010). Cosmic rays are transported through the neutral atmosphere using the High Charge (Z) and Energy TRaNsport (HZETRN) code (Slaba, Blattnig, & Badavi, 2010; Slaba, Blattnig, Aghara, et al., 2010; Wilson et al., 1991). An initial validation of the NAIRAS model version 1.0 was presented for GCR exposures by Mertens et al. (2013). Recently, NAIRAS was updated to HZETRN2015, which includes pion-initiated electromagnetic cascade processes (Norman et al., 2012; Slaba et al., 2013). In addition, a correction was derived for the primary cosmic ray proton and alpha flux in the H-BON10 model, during solar cycle minimum conditions, based on measurements from the satellite-borne Payload for Antimatter Exploration and Light-nuclei Astrophysics (PAMELA) experiment (Adriani et al., 2013, 2016). The NAIRAS results presented in this work are based on the updated version, NAIRAS model version 2.0.

4. Sources of Measuring Data

An overview of a variety of in-flight measurements performed by different European research institutes between 1992 and 2003 is given in a comprehensive report by European Radiation Dosimetry Group (EURADOS) Working Group 5, which contains a compilation of measured data, primarily route dose data (Lindborg et al., 2004). However, detailed information about environmental parameters is missing, which makes it impossible to select measuring values for specific geographic positions under well-defined, preferably quiet space weather conditions. The EURADOS Working Group 5 report concludes that the measurements taken individually by the participating research institutes agree within about ±25% (2 standard deviations). Although this accuracy is deemed acceptable for operational radiation protection measurements, the acquisition of data with reduced uncertainties is desirable for a comparison with high-quality models to be used in the framework of the CCMC platform.

Table 3
Comparison of the Average Absorbed Dose Rates in Silicon dD_{Si}/dt in μGy/hr Measured at Flight Position i With the Corresponding Model Calculations

i	dD_{Si}/dt measured	$\Delta_{CARI\text{-}7A}$ (%)	$\Delta_{PANDOCA}$ (%)	Δ_{NAIRAS} (%)
7	2.4 ± 0.1	0	−11	−12
8	1.2 ± 0.1	10	5	33
9	2.0 ± 0.1	11	−1	−13
10	1.3 ± 0.1	11	9	35

Consequentially, the measurements of the rates of the ambient dose equivalent $dH^*(10)/dt$ and the absorbed dose in silicon dD_{Si}/dt needed for a comparison with model calculations must have been acquired under well-defined conditions in terms of flight position (longitude, latitude, and barometric altitude), date, time, and space weather. Furthermore, different independent research institutes should have been involved in the same flight campaign and the scientists should have operated their instruments themselves in order to identify any irregular flight situations that might have affected the measuring results, for example, turbulences.

The survey of reports about correspondingly dedicated flight missions in different scientific journals revealed three potential sources of measuring data for the comparison with model calculations, namely, the Coordinated Access to Aircraft for Transnational Environmental Research (CAATER) flight campaign (Lillhök et al., 2007), the Comparison of Airborne RAdiation Measuring Equipment for implementation of Legal requirements (CARAMEL) campaign (Wissmann et al., 2010), and the COmparisoN of COsmic Radiation Detectors (CONCORD) campaign (Meier et al., 2016). The interested reader is referred to the corresponding references for more detailed information.

The next step consisted in identifying suitable data sets from these publications meeting the following selection criteria in order to obtain reliable data with comparatively small uncertainties:

1. Calibration: The sources used to calibrate the instruments were traceable to a national standard.
2. Operations: The instruments were operated by the scientists themselves during the flights.
3. Space Weather: SEPs were not present and the Kp-index was not greater than 3 during the period when the data were taken, which is indicative of a virtually undisturbed magnetosphere.
4. Independence: Measuring data were taken by at least two independent institutes during a flight for each selected data point.
5. Deviation: The individual measuring values did not deviate more than 5% from the average of all instruments with the Tissue Equivalent Proportional Counters for the ambient dose equivalent rate $dH^*(10)/dt$ and not more than 10% with the semiconductor devices for the rate of the absorbed dose in silicon dD_{Si}/dt.

The analysis of the published data according to these criteria showed that none of the four measuring values of the ambient dose equivalent rate $dH^*(10)/dt$ from the CAATER flight campaign could be considered for the comparison, since two values had to be excluded due to the space weather conditions during the flight (criterion 3) and the other ones due to the variation of the individual measurements (criterion 5). Rates of the absorbed dose in silicon dD_{Si}/dt are not given in this publication. Although the space weather situation was quiet during the CARAMEL and the CONCORD flight campaigns, a few data points had to be excluded due to criterion 5 as well. An overview of the remaining data points and the corresponding parameters in terms of the enumeration index *i*, date, time (as median of the time spent at the flight level in UTC), latitude, longitude, barometric flight level, Kp, and the respective dose quantity is given in Table 1.

5. Results and Discussion

The numerical results of the comparison of the three models with the selected measuring data in terms of the relative deviation Δ are given in Table 2 for the ambient dose equivalent rate $dH^*(10)/dt$ and in Table 3 for the absorbed dose rate in silicon dD_{Si}/dt. The uncertainties (1σ) of the measuring values are assumed to be on the order of 5% for the ambient dose equivalent rate $dH^*(10)/dt$ and on the order of 10% for the rate of the absorbed dose in silicon dD_{Si}/dt, respectively. The investigated models contain a variety of sources of uncertainty as well, for example, cross sections for all particle interactions, approximations for the cutoff rigidities, and fluence to dose conversion coefficients. Since all models need input data for the parameterization of the solar modulation, the respective uncertainties propagate through the transport calculations and affect the results correspondingly. It is generally difficult to assess the uncertainties of model calculations, and the detailed assessment of the uncertainties of the investigated models is beyond the scope of this study. Nevertheless, the comparison of the model calculations with the selected high-quality dose rate measurements indicates that the upper limit of the uncertainties of the model calculations is on the order of some 20% over the range of the investigated part of the atmosphere for all models. This can be inferred from the general agreement between the measuring values and the model calculations within the overlap of

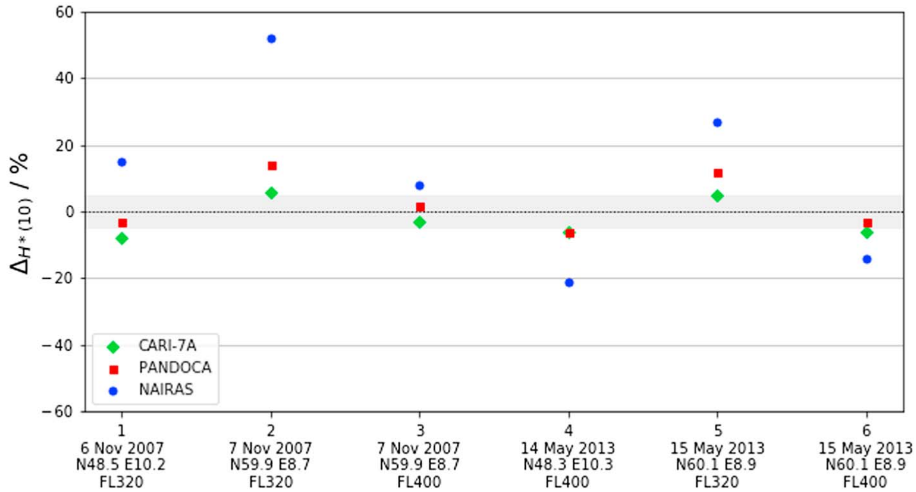

Figure 1. Relative deviation Δ between the model calculations and the measuring data for the ambient dose equivalent rate *dH**(10)/*dt*. The uncertainties of the measurements are indicated by the shaded areas.

the assumed uncertainties. The relative deviation Δ between model calculations and measuring data is depicted in Figure 1 for the ambient dose equivalent rate *dH**(10)/*dt* and in Figure 2 for the absorbed dose rate in silicon dD_{Si}/dt. The uncertainties of the measurements are indicated by the shaded areas. The variations of the model calculations for the individual data points show no indication of a systematic deviation for any particular model. The mean deviations $\overline{\Delta_{H*(10)}}$ and $\overline{\Delta_{D_{Si}}}$ between measuring data and model calculations are given in Table 4. These figures are more indicative of individual uncertainties of the investigated models.

The present comparison of model calculations with measurements is based on data available from literature that cover the lower (FL320) and the upper (FL400) airspace of commercial aviation at low (~1 GV) and medium (~4 GV) effective cutoff rigidities. The data were taken close to solar minimum during the transition from solar cycle 23 to 24 and close to the solar maximum of cycle 24 during quiet space weather conditions. Although the amount of data for the comparison is quite limited, information about those areas of the atmosphere where dose rates are comparatively high due to the reduced geomagnetic and atmospheric shielding as well as to the corresponding solar modulation is available. In this context, it is worth mentioning that these regions are particularly relevant to radiation protection measures in aviation, for example, dose assessment and monitoring of recommended or legally stipulated dose limits. A detailed statistical analysis of the deviations between measurements and model calculations is a future challenge and is to be based on a high amount of reliable data meeting strict quality criteria over the whole range of the relevant parameters for geomagnetic shielding, atmospheric shielding, solar modulation, and the influence of space weather effects.

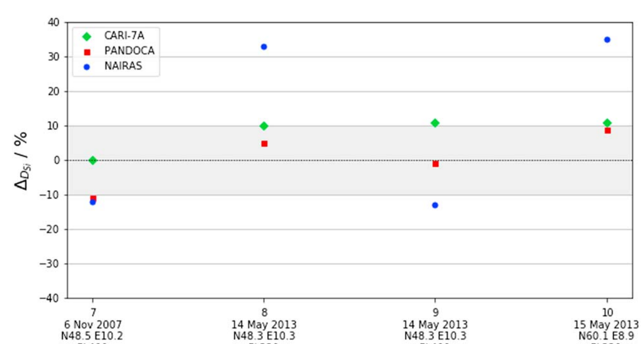

Figure 2. Relative deviation Δ between the model calculations and the measuring data for the absorbed dose rate in silicon dD_{Si}/dt. The uncertainties of the measurements are indicated by the shaded areas.

Table 4
Mean Deviations $\overline{\Delta_{H*(10)}}$ and $\overline{\Delta_{D_{Si}}}$ Between Measuring Data and Model Calculations

Model	$\overline{\Delta_{H*(10)}}$ (%)	$\overline{\Delta_{D_{Si}}}$ (%)
CARI-7A	6	8
PANDOCA	7	7
NAIRAS	23	23

6. Conclusion

The first comparison of models that are designated to be implemented into the CCMC's web page, namely, CARI-7, PANDOCA, and NAIRAS, with reliable dose rate measurements was based on data acquired during dedicated flight missions that were available from the literature and analyzed for compliance with strict quality criteria. The application of the chosen criteria for the selection of data revealed that only few data points could be identified for the comparison. All models show agreement with the measuring data within the uncertainties, the upper limit of which could be inferred from the comparison to be on the order of some 20% over the range of the investigated area of the atmosphere. This encouraging result will promote further cooperation between the participating organizations and help improve their models. Furthermore, the analysis of published measurements has underlined the need for high-quality measuring data, acquired under standardized conditions in terms of height, position, and space weather, covering the complete airspace of civil aviation. In our study, the amount of data used for the comparison was restricted to measurements that had been taken by the scientists themselves during the respective flights in order to exclude data acquired under irregular flight conditions, for example, turbulences that might have affected the measuring results, for example, by microphonics. Therefore, future developments should also focus on the use of unattended ruggedized measuring devices that are qualified to meet the essential requirements for sufficiently accurate measurements onboard aircraft, which includes monitoring of the operating conditions, for example, temperature, air pressure, humidity, and vibrations, as well. Although it will take some time to establish a correspondingly comprehensive database, our comparison of the models with available measuring data and the method used can be regarded as the first steps on a long road toward the verification of models for the assessment of the radiation exposure at aviation altitudes that are to be implemented into the CCMC's web page.

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