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Cosmic radiation exposure of aviators for solar cycles 23 and 24

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Abstract

Assessing the radiation exposure of aviators and frequent flyers requires the study of the cosmic ray showers inside the Earth's atmosphere. DYASTIMA / DYASTIMA-R is a Geant4 based software application, implemented by the Athens Cosmic Ray Group which allows the study of the evolving secondary particles cascades inside the atmosphere, as well as radiation dosimetry calculations (ambient dose equivalent rate) at different atmospheric altitudes, geographic coordinates and magnetic cut-off rigidity. Results for various scenarios, as calculated by DYASTIMA/DYASTIMA-R, are provided as a federated product through the European Space Agency Space Situational Awareness of the Space Radiation Service Centre Network, while the DYASTIMA software is provided through the Athens Neutron Monitor Station (A.Ne.Mo.S.) portal. Initial results for the assessment of the radiation exposure during the last Solar Cycles 23 and 24 are presented in this work, covering the most usual flying altitudes. The results indicate the dependence of the dose rate on the magnetic cut-off rigidity threshold, with higher dose rates at high geographic latitudes, as well as the anti-correlation of cosmic ray intensity with the solar activity, as higher dose rates are observed during solar minimum conditions.

1. Introduction

As primary cosmic radiation interacts with the atmospheric matter, atmospheric showers of secondary cosmic ray particles are created. Understanding these cascades may provide useful insights for the study of various Space Weather phenomena and effects, such as the ionization of the atmosphere. At the same time, atmospheric showers can be used for the radiation assessment of technological systems, such as the prevention of damages on avionics, as well as human health, such as the radiation protection of aviation crews and passengers during commercial air-flights.

Under this scope, a free software application for the study of the secondary particles cascades inside the Earth's atmosphere has been created by the Athens Cosmic Ray Group, called Dynamic Atmospheric Shower Tracking Interactive Model Application (DYASTIMA) (Paschalis et al. 2014). This application is based on Geant4 software (Agostinelli et al. 2003; Allison et al. 2006, 2016) and is

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provided by the Athens Neutron Monitor Station (A.Ne.Mo.S.) portal (http://cosray.phys.uoa.gr/index.php/dyastima, last accessed April 8, 2021). DYASTIMA has already been successfully used for the study of the cascades inside the Earth's atmosphere (Paschalis et al. 2014), the estimation of the Earth's atmosphere ionisation during the Ground Level Enhancement (GLE71) on 17 May 2012 (Dorman et al. 2015) and the calculation of the ion production rate inside the Venusian atmosphere (Plainaki et al. 2016).

The latest version of DYASTIMA includes a new feature, DYASTIMA-R, which allows radiation dosimetry calculations due to atmospheric showers inside the atmosphere of Earth (Paschalis et al. 2016, 2018; Tezari et al. 2019, 2020). DYASTIMA / DYASTIMA-R have been validated according to international accepted standards, as provided by ICRP 132 (ICRP 2016) and ICRU Report 84 (ICRU 2010) documents. More specifically, dosimetry calculations were performed for three time periods (January 1998, January 2000, January 2002) covering different solar activity periods (early ascending phase and solar maximum of Solar Cycle 23 respectively), eighteen vertical cut-off rigidities (Rc = 0 GV – 17 GV) covering the whole energy spectrum, and three frequent commercial flying altitudes (FL310 (9.45 km), FL350 (10.67 km), FL390 (11.89 km)). These calculations were compared to reference data and the discrepancy observed did not exceed in general the acceptable limit of 30%, for cut-off rigidities up to 10 GV (Paschalis et al. 2016, 2018; Tezari et al. 2019, 2020). Therefore DYASTIMA-R can be a reliable tool for assessing the ionizing cosmic radiation exposure of aviation crews and frequent flyers during air flights. The results for specific flight scenarios, as calculated by DYASTIMA / DYASTIMA-R, are provided through the European Space Agency Space Situational Awareness Space Weather Service Centre Network (http://swe.ssa.esa.int/web/guest/dyastima-federated, last accessed April 8, 2021) as a federated product.

2. Dosimetry calculations with DYASTIMA / DYASTIMA-R

2.1 DYASTIMA configuration

DYASTIMA software is based on a graphical user interface (GUI), allowing the user to perform easy parameterization of both the input parameters and the simulation environment. Several input parameters are required, all defined by the user (Athens Cosmic Ray Group 2019). These parameters concern the general characteristics of the planet as well as the atmospheric structure and temperature profile. More specifically, the atmospheric profile is based on the International Standard Atmosphere model (ISO 2007), while the mean annual values for the North, East and Vertical components of the magnetic field are provided by the National Oceanic and Atmospheric Administration (NOAA), based on the International Geomagnetic Reference Field (IGRF) (https://www.ngdc.noaa.gov/geomag/, last accessed April 8, 2021) at mean sea level. One of the most crucial input parameters are the primary cosmic ray spectra, which can be extracted by various models and tools. For the calculations presented in this work, the primary cosmic ray spectra (^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{28}Si, ^{56}Fe) are based on the ISO15390 model (ISO 2004) and the model by Nymmik et al. (1996). More specifically, ISO was used for lower energies (below 10 MeV/nuc), while the Nymmik et al. (1996) model was used for higher energies, since these models are quite similar for energies above 10 MeV/nuc. The effect of the geomagnetic field continuous evolution for various geographic coordinates is also taken under consideration by using vertical cut-off rigidity values in the primary spectra calculations, as calculated with the IGRF for Epoch 2000.0 (Smart & Shea 2007). It should be noted that the primary spectra in this work is provided by OMERE software offered by TRAD (http://www.trad.fr/en/space/omere-software/, last accessed April 8, 2021). The geometry model, the division of the atmosphere into layers, the appropriate Geant4 physics lists and the definition of the tracking atmospheric altitudes should also be taken into consideration by the user.

By performing a simulation with DYASTIMA, all the information concerning the cascade is available to the user, such as the energy of the secondary particles, the energy deposition on the different atmospheric layers, the time of arrival etc. This output can be used as input to a second Monte Carlo simulation, performed with DYASTIMA-R, in order to perform radiation dosimetry calculations

KIEL-UP • DOI: 10.38072/2748-3150/p13

(dose rate and equivalent dose rate) for various flight scenarios covering different geographic coordinates, atmospheric altitudes and solar activity periods. The radiation weighting factors used for the calculation of the equivalent dose rate are according to ICRP standards (ICRP 2007, 2016). The parameters of the simulation, including the characteristics of the cylindrical phantom simulating the human body, the number of iterations and the reference Geant4 physics lists, are also defined by the user.

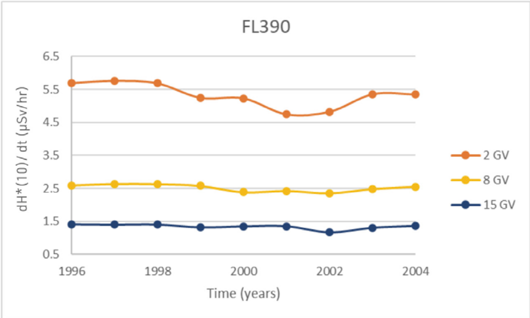

Figure 1: Ambient dose equivalent rate as a function of cut-off rigidity (Rc) and time covering 1996-2004 for the specific flying altitude (FL390).

2.2 Initial results

The average annual ambient dose equivalent rate dH*(10)/dt (μSv / hr) for FL390 and different cut-off rigidity values (Rc = 2 GV, 8 GV, 15GV) for the time period 1996 – 2004 (covering almost the whole Solar Cycle 23) is given in figure 1. It is observed that the dose rate presents high variation at higher geographic latitudes (low cut-off rigidity) and little or no variation at areas of middle geographic latitudes and equatorial regions (high cut-off rigidity). This phenomenon is also observed on the two panels of figure 2, where the dH*(10)/dt as a function of cut-off rigidity for three flying altitudes for specific years (1997 and 2004 respectively) is presented. Due to the dependence of the dose rate on the geographic latitude, it is evident, dH*(10)/dt decreases as the rigidity threshold increases. This effect is more dominant at higher atmospheric altitudes.

Finally, the dH*(10)/dt on annual basis, for the rigidity threshold of 2 GV and for three flying altitudes (FL310, FL350, FL390), is presented in figure 3, for the time period 1996-2019 covering the two recent Solar Cycles 23 and 24. The anti-correlation of the cosmic ray intensity with the solar activity is clearly observed, as the higher dose rate takes place during the extended solar minimum between the two solar cycles, while the lower dose rate is observed during the solar maximum of Solar Cycle 24.

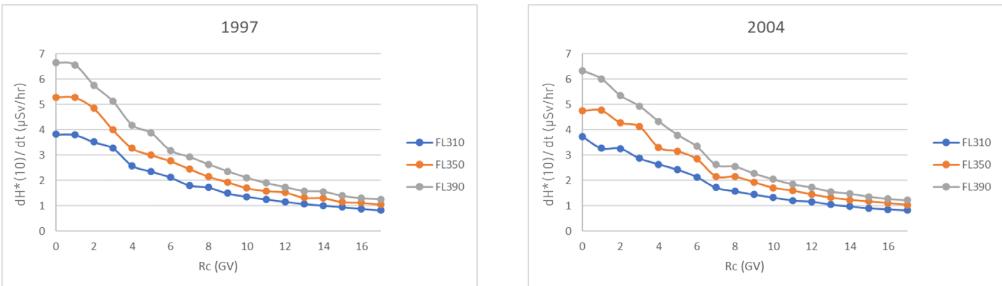

Figure 2: Ambient dose equivalent rate as a function of cut-off rigidity Rc for 1997 (left panel) and 2004 (right panel) for three frequent flying altitudes (FL310, FL350, FL390).

KIEL-UP • DOI: 10.38072/2748-3150/p13

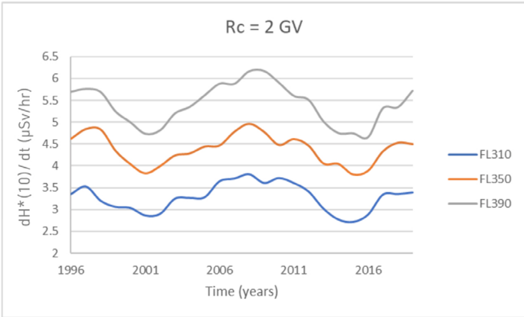

Figure 3: Ambient dose equivalent rate as a function of time for a specific cut-off rigidity (Rc=2 GV) for 3 frequent flying altitudes (FL310, FL350, FL390), covering Solar Cycles 23 and 24 (1996-2019).

3. Discussion and conclusion

DYASTIMA / DYASTIMA-R can be a useful tool for the reliable radiation assessment of aviators and passengers during air flights. The initial results are very promising clearly indicating the dependence of the dose rate on the cut-off rigidity threshold and the period of solar activity, with the dose rate decreasing with the increase of the cut-off rigidity threshold and the increase of solar activity.

So far, DYASTIMA simulations have been performed for specific points inside the Earth's atmosphere (specific geographic coordinates, cut-off rigidity and atmospheric altitudes). Future steps include dosimetry calculations performed during a whole flight, by considering the flight route as well as the time period and duration of the flight. Simulation of the atmospheric cascades in other planets will also be performed, such as the atmosphere of Mars, after the identification of the proper input parameters. These results may be useful for the evaluation of the radiation exposure of spacecraft crews.

Acknowledgments

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Questions and answers

Ludwig Klein: How do you validate your model (you alluded to validation in the paper in press)?

Answer: DYASTIMA-R has been validated according to ICRP standards (ICRP 132, 2016) and the reference data found at Report 84 by ICRU (2010). The validation process is discussed in the recent publication by Tezari A., Paschalis P., Mavromichalaki H., Karaiskos P., Crosby N., and Dierckxsens M. at Oxford Academic Journal Radiation Protection Dosimetry (DOI: https://dx.doi.org/10.1093/rpd/ncaa112).