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DYASTIMA: Simulating Air Showers in the Atmosphere of a Planet

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Abstract

As primary cosmic rays interact with the upper layers of the atmosphere of a planet, air showers of secondary cosmic ray particles are created. The modelling of these secondary cascades is of great importance for Space Weather studies. DYnamic Atmospheric Shower Tracking Interactive Model Application-DYASTIMA is a Monte Carlo simulation of the cascades produced in the atmosphere of a planet due to cosmic ray propagation. It is a standalone software application, based on a very friendly graphical user interface (GUI) and is implemented in Geant4 by the Athens Cosmic Ray Group. In order to perform a simulation, the primary cosmic ray spectra, the solar activity, the characteristics of the planet, the composition of the planet's atmosphere as well as the atmospheric profile are taken into account. As a result, DYASTIMA output provides all the necessary information about the secondary particles. DYASTIMA simulations have been used successfully for the atmospheres of Earth and Venus. Moreover, DYASTIMA-R, which is an additional simulation integrated into DYASTIMA software, performs radiation dosimetry calculations in the different atmospheric layers. More specifically, DYASTIMA-R provides the dose rate and the equivalent dose rate for various flight scenarios during different solar activity conditions and Space Weather phenomena. The simulations are being validated according to the recommendations set forth in ICRP 137 and ICRU 84 documents. These results are very useful for the aviation community for the determination of the biological effects of the ionizing space radiation on aircrews and passengers. The application of DYASTIMA and DYASTIMA-R on other planets can provide useful insights for the radiation accumulation of space crews during missions. It is foreseen that DYASTIMA will be provided through the European Space Agency Space Situational Awareness (ESA SSA) Space Radiation Expert Service Centre (http://swe.ssa.esa.int/space-radiation) as a federated product. The Athens Cosmic Ray Group and the Athens Neutron Monitor Station (A.Ne.Mo.S.) (http://cosray.phys.uoa.gr/) participates as an expert group in the ESA SSA SWE Programme providing federated products and tools for the research of Space Weather effects.

Keywords: Space Weather, Radiation Dosimetry, Aviation

Acronyms/Abbreviations

DYnamic Atmospheric Shower Tracking Interactive Model Application (DYASTIMA), graphical user interface (European Space Agency Space Situational Awareness (ESA SSA), Space Radiation Expert Service Centre (R-ESC), International Commission on Radiological Protection (ICRP), International Commission on Radiation Units and Measurements (ICRU), flying altitude (FL), cosmic rays (CR), galactic cosmic rays (GCR), solar cosmic rays (SCR), Solar Cycle (SC), International Standard Atmosphere (ISA), Athens Neutron Monitor Station (A.Ne.Mo.S.).

1. Introduction

CR consist of high energy charged particles, such as protons (89%), helium nuclei (10%) and nuclei of heavier elements (1%) [1]. The energy range of these primary particles is 10^9 eV – 10^{21} eV. Primary particles, which penetrate the geomagnetic field, reach the top of the Earth's atmosphere and interact with the atmospheric molecules, resulting in the production of secondary particles. The secondary particles, through further interactions with the atmospheric nuclei and electrons, lead to an evolving cascade in the atmosphere (see Fig. 1). The air showers consist of protons, neutrons, electrons, positrons, pions, gamma rays, muons, neutrinos and kaons [2]. These particles can be detected either by balloons inside the atmosphere or by a variety of ground-based detectors located at several altitudes and geographic coordinates, such as muon counters and neutron monitors. The study of the variation of the CR flux in the atmosphere is essential for the better comprehension of the mechanisms and effects of Space Weather. The results may be useful for radiation dosimetry and radiation protection of aviation crews and spacecraft crews, as well as for the prevention of damage on microelectronics.

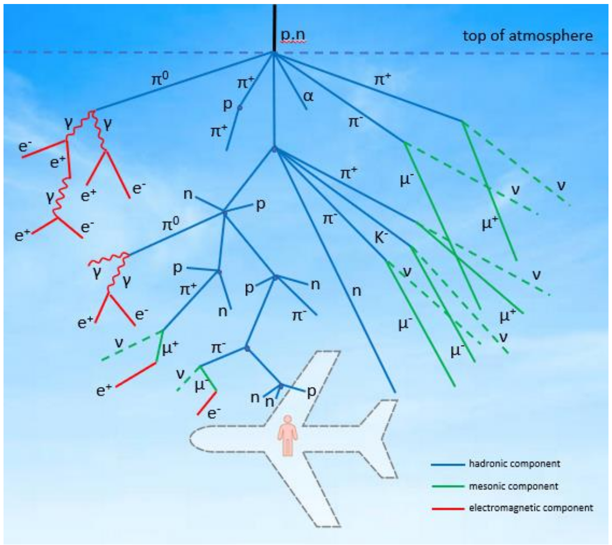


Fig. 1. Air showers of secondary particles in the Earth's atmosphere.

Various programs have been developed for the representation of the air-showers in the atmosphere using the Geant4 [3][4][5] and FLUKA [6][7] simulation toolkits. Here are some typical examples. PLANETOCOSMICS is a Monte Carlo simulation of the cascade evolution in the atmosphere developed in Geant4 [8][9]. CORIMIA can be used for the study of CR ionization at atmospheric altitudes above 30 km for a specific time and location, and geomagnetic and solar activity, by taking into account the ionization losses in the atmosphere [10]. CORSIKA is a Monte-Carlo simulation tool, developed with the FLUKA package, for the study of the low – energy cascade development below 30 km [11][12].

Additionally, several models and software applications have been developed for monitoring the radiation dose received by aircrews as well as space crews. Typical examples are AVIDOS [13], SIEVERT [14][15], PCAIRE [16], EPCARD [17] and CARI [18]. These products provide valuable information about the equivalent dose received by aviators and passengers during different flight profiles.

DYASTIMA is a simulating tool of the CR particles' propagation through the Earth's atmosphere or generally through the atmosphere of a planet [19]. DYASTIMA-R is a special feature of DYASTIMA which allows the calculation of dose rate and equivalent dose rate during various flight profiles [20]. DYASTIMA will soon be provided as a federated product through the ESA SSA R-ESC portal (http://swe.ssa.esa.int/space-radiation).

The purpose of this work is to discuss the validation process of DYASTIMA according to the worldwide acceptable standards provided by ICRP [21] and ICRU [22].

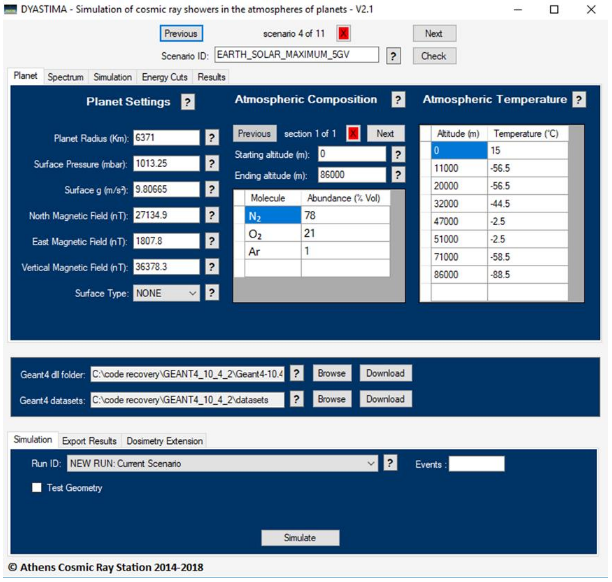
2. Material and methods

As mentioned above, DYASTIMA is a Monte Carlo simulation of the cascades developed inside the atmosphere of a planet [19]. DYASTIMA GUI provides a very user-friendly environment allowing easy parameterization (see Fig. 2). DYASTIMA-R is featured in this GUI [20].

2.1 Simulation input

The required input is provided by the user and includes:

- The characteristics of the planet, such as the radius, the surface magnetic field, the surface pressure, etc.
- The structure of the atmosphere such as the composition and the temperature profile.
- The primary CR spectra such as the type of particle, the flux, etc.
- The Geant4 and the simulation geometry settings such as the geometry model, the division of the atmosphere, the physics list, etc.
- The altitudes in which the tracking of particles is taking place.
- The dosimetry setup (see 2.2).



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scenario 4 of 11

Scenario ID: EARTH_SOLAR_MAXIMUM_5GV

Planet Radius (Km): 6371
Surface Pressure (mbar): 1013.25
Surface g (m/s²): 9.80665
North Magnetic Field (nT): 27134.9
East Magnetic Field (nT): 1807.8
Vertical Magnetic Field (nT): 36378.3
Surface Type: NONE

section 1 of 1
Starting altitude (m): 0
Ending altitude (m): 86000

Molecule	Abundance (% Vol)
N_2	78
O_2	21
Ar	1

Altitude (m)	Temperature (°C)
0	15
11000	-56.5
20000	-56.5
32000	-44.5
47000	-2.5
51000	-2.5
71000	-58.5
86000	-88.5

Geant4 dll folder: C:\code recovery\GEANT4_10_4_2\Geant4-10.4
Geant4 datasets: C:\code recovery\GEANT4_10_4_2\datasets

Run ID: NEW RUN: Current Scenario
Events :
☐ Test Geometry

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Fig. 2. DYASTIMA GUI

Two basic factors necessary for DYASTIMA / DYASTIMA-R operation are the atmosphere of the planet and the primary CR spectrum at the top of the atmosphere (in case of Earth at 86 km altitude). A detailed description of these input parameters used for the validation process is presented.

2.1.1 The Atmosphere of the Earth

For the validation purpose, ISA has been used for the description of the Earth's atmosphere [23], as it is defined by the International Civil Aviation Organization and considered as an international standard by the International Organization for Standardization [24].

ISA is the optimal model of atmosphere to be used since the flying altitude corresponds to the pressure altitude. It should be noted that the model provided by ISA is based on average conditions at middle geographic latitudes, therefore its usage on the equator or the polar regions may affect the results.

2.1.2 CR Spectrum at 86 km

There are many models providing the primary CR spectrum such as CREME96 [25][26][27], ISO-15390 [28], and Nymmik et al. model [29]. There are also various online tools and websites providing access to these models, such as SPENVIS by BIRA-IASB and ESA [30] and OMERE by TRAD [31].

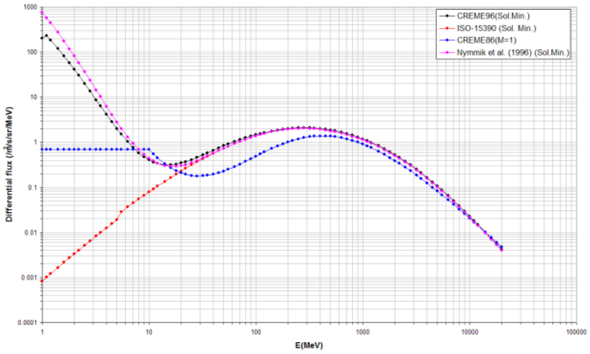

Fig. 3. The $_1$H spectrum near Earth provided by the different GCR flux models during solar minimum conditions [30].

For the validation purposes of this work, the primary CR spectrum used is based on the ISO model. ISO 15390:2004 specifies a model for estimating the radiation effects of GCR modulated by the solar activity both on technological and biological systems in space.

The GCR models by CREME96 and Nymmik et al. (1996) are very similar to the ISO model for energies above 10 MeV/nucleon (see Fig. 3). However, the ISO model is more appropriate on the scope of our study, since CREME96 and Nymmik et al. models do not allow the definition of a single vertical magnetic rigidity threshold (Rc) orbit. Moreover, the Geomagnetic Transmission Routine files used by these models are not valid for the specific time periods, required for the validation of DYASTIMA-R.

In this work the spectra were extracted by using the tool OMERE [31]. OMERE allows the definition of a point at a specific location within the magnetosphere, by defining the orbital parameters as well as the geographic coordinates. Even though ISO model is also provided through SPENVIS website, SPENVIS does not allow neither the definition of a single point inside the Earth's magnetosphere nor the definition of orbital parameters (apogee/perigee less than 100km). Moreover, DYASTIMA integrates the earth shadowing effect by principle, so a spectrum without the shadow effect correction must be used. OMERE provides this choice in contrary with the other tools.

In order to take the effect of the geomagnetic field into account, the vertical cut-off rigidity values for various geographic longitudes and latitudes as proposed by Shea and Smart were used [32]. These values were calculated using the International Geomagnetic Reference Field for Epoch 2000.0 and show the continuous evolution of the geomagnetic field. A map of the vertical cut-off rigidity threshold values as a function of geographic latitude and longitude for the year 2000 is given in Figure 4 [33]. The calculation of the dose and equivalent dose rate is very important in greater geographic latitudes, as the CR intensity increases towards the Polar Regions.

During the simulation, no specific magnetic field values inside the atmosphere were used, as the contribution of the Earth's magnetic field is already considered by the approach of the vertical cut-off rigidity.

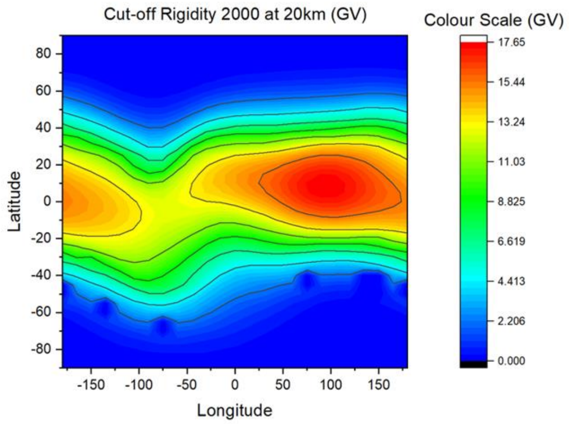

Fig. 4. A map of the vertical cut-off rigidity as a function of geographic latitude and longitude for the year 2000 is given [33].

2.2 Dosimetry Setup

DYASTIMA-R performs calculation of dose rate (Gy/sec) and equivalent dose rate (Sv/sec) at each atmospheric layer, based on the output provided by DYASTIMA runs. The user can define the reference physics list, the number of iterations as well as several characteristics of the phantom, such as material and dimensions.

3. Theory and calculation

In order to determine the exposure of aircrews and passengers to the ionizing galactic and solar cosmic radiation during a flight, several radiometric and dosimetric quantities should be taken under consideration, such as the absorbed dose, the equivalent dose and the effective dose [21][34].

The mean absorbed dose D_T corresponds to the mean energy dε due to a type of ionizing radiation R deposited on a mass dm over an organ or a tissue T. For a mixed radiation field, the mean absorbed dose $D_{T,R}$ is given by

$$D_T = \frac{d\varepsilon}{dm} \rightarrow D_{T,R} = \sum_R D_T \quad (Gy) \qquad (1)$$

The equivalent dose H_T considers the radiobiological effectiveness of each radiation type by introducing the radiation weighting factor w_R [34] and is given by

$$H_T = \sum_R w_R \cdot D_{T,R} \quad (Sv) \qquad (2)$$

The effective dose E takes additionally into account the type of organ or tissue that is irradiated by introducing the tissue weighting factor w_T [34] and is given by

$$E = \sum_T w_T \cdot H_T \quad (Sv) \qquad (3)$$

The effective dose is widely used for the determination of the exposure limits to radiation; however, it is not a measurable quantity and therefore not suitable for radiation protection applications. Therefore, other operational quantities should be used for the radiation risk assessment during an air flight, such as the ambient dose equivalent, as proposed by the ICRP and the ICRU [21][22], such as the ambient dose equivalent H*(10).

H*(10) is 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 [21], a reference phantom of 30 cm diameter and a density of 1 g/cm^3 made of soft tissue equivalent material, at a depth of 10 mm on the radius vector opposing the direction of the aligned field [1][2]. It is also expressed in Sv (S.I.). The radiation weighting factors used for the determination of the ambient equivalent dose are proposed by ICRP [21][34].

ICRP and ICRU have provided recommendations as well as reference data for ambient-dose-equivalent rates due to the exposure to cosmic radiation exposure for air flights [21][22]. These reference data are derived from onboard aircraft measurements of ambient equivalent dose rate at the most common commercial flying altitudes from 1992 to 2006 and can be used for the assessment of the radiation quantities calculated by different models. The recommended acceptable uncertainty limit for the comparison of the model-calculated values and the reference data is ±30%.

More specifically, the flight scenarios proposed for the validation of the different models cover:

- Three different flying altitudes (FL310, FL350, FL390) corresponding to the usual flying range of large passenger-jet aircraft flights,
- Eighteen vertical geomagnetic cut-off rigidity values Rc (0 GV to 17 GV, with an increment of 1 GV) corresponding to the full range of geographic latitudes, and
- Three different time periods (January 1998, January 2000, January 2002) covering different periods of solar activity and solar magnetic field polarity.

For the validation purpose only, a special version of DYASTIMA-R was created for the calculation of the ambient dose equivalent H*(10). More specifically, the phantom was substituted by the ICRU sphere, which is a reference phantom of 30 cm diameter and a density of 1 g/cm3 made of soft tissue equivalent material [35]. The sphere was luminated with the particles collected at each atmospheric altitude. A cylindrical volume (1 cm radius and 2 mm width) was defined at a 10 mm depth from the sphere surface in order to calculate ambient dose equivalent H*(10). The dosimetry setup as described above has already been proposed and used successfully by Pelliccioni [36]. The radiation weighting factors used for the determination of the ambient equivalent dose are proposed by ICRP [21]. DYASTIMA runs have been performed for all the proposed flight scenarios by ICRU (3 flying altitudes, 18 vertical cut-off rigidities, 3 time periods).

The ambient dose equivalent rate in μSv/h, as calculated by DYASTIMA-R (blue line), as well as the ICRU Reference data (green line) as a function of the geomagnetic cut-off rigidity (GV) at three flight levels (FL310, FL350 and FL390) for three time periods (Jan 1998, Jan 2000 and Jan 2002) are presented in the corresponding Figures 5, 6 and 7. January 1998 (see Fig. 5) and January 2002 (see Fig. 7) corresponds to the minimum and the maximum of the SC 23 respectively, while January 2000 (see Fig. 6)

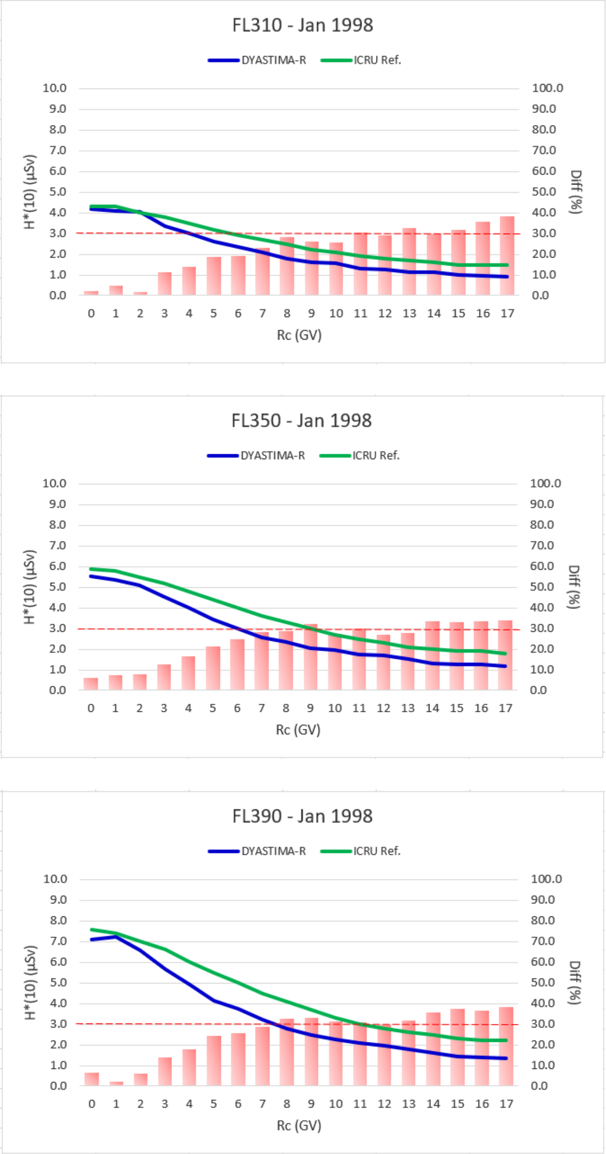

Fig. 5. The ambient dose equivalent as a function of the geomagnetic cut-off rigidity as calculated by DYASTIMA-R, alongside with the ICRU Reference data, for 3 different flying altitudes, for January 1998. The percentage difference is also shown.

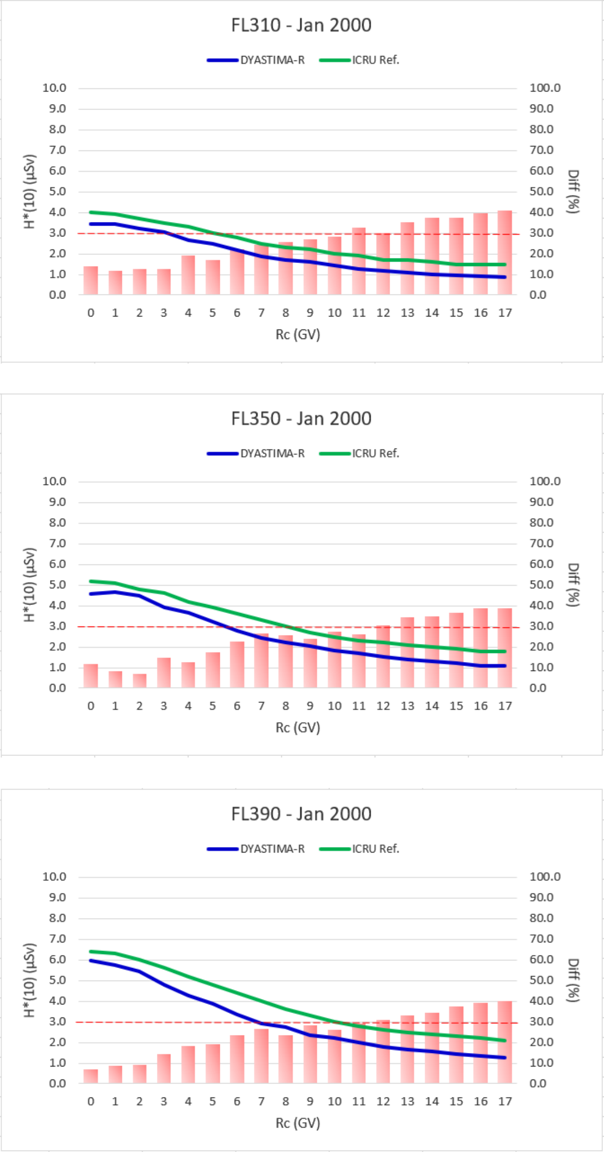

Fig. 6. The ambient dose equivalent as a function of the geomagnetic cut-off rigidity as calculated by DYASTIMA-R, alongside with the ICRU Reference data, for 3 different flying altitudes, for January 2000. The percentage difference is also shown.

corresponds to the transition phase. The percentage difference of the calculated and the reference values is also shown (in red). The red line corresponds to the recommended acceptable uncertainty limit of ±30%, as proposed by the ICRP and ICRU documents.

4. Results and Discussion

For a better comparison the obtained results of the DYASTIMA-R simulations are presented in Figures 5, 6 and 7, alongside with the reference data. As it was expected, the ambient dose equivalent rate is greater for higher latitudes, as more particles can penetrate through the atmosphere due to the lower cut-off rigidity threshold.

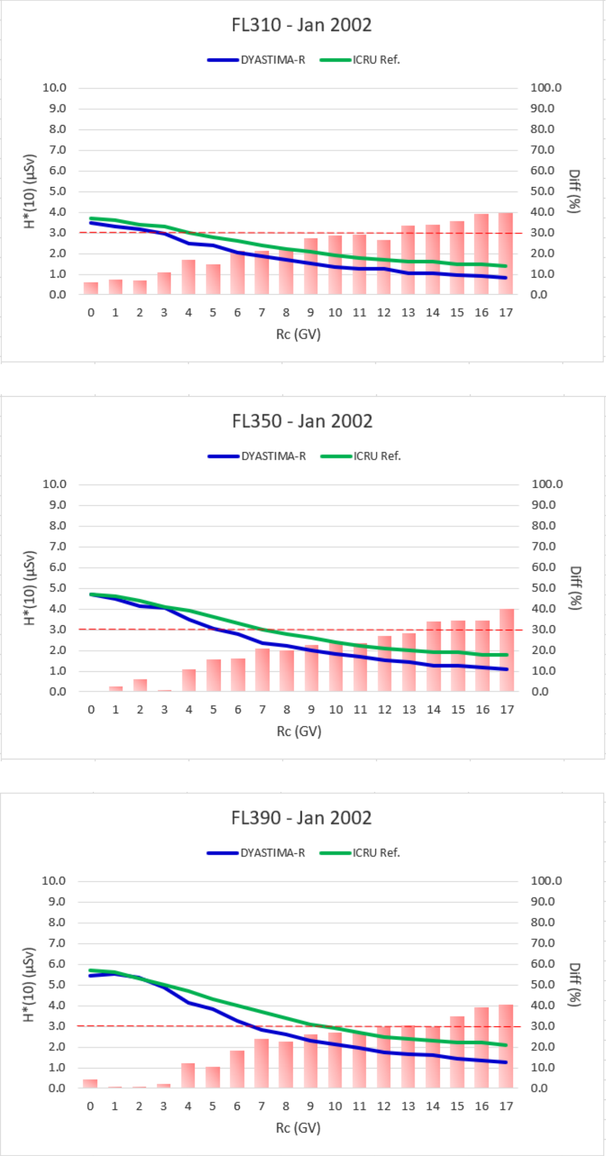

Fig. 7. The ambient dose equivalent as a function of the geomagnetic cut-off rigidity as calculated by DYASTIMA-R, alongside with the ICRU Reference data, for 3 different flying altitudes, for January 2002. The percentage difference is also shown.

It can be easily observed from these figures that from 0 GV to 10 GV, i.e. polar, middle and high geographic latitudes, the DYASTIMA-R calculated values of ambient dose equivalent are in good agreement with the reference data, without exceeding the 30% uncertainty proposed by the ICRU document. Above 10 GV, that means equatorial regions as it is shown in Fig. 4, a greater deviation seems to be observed, with a maximum uncertainty of about 41%, probably due to the more complicated geomagnetic field near the equatorial places. Moreover, DYASTIMA-R tends to underestimate the ambient dose equivalent. It is noted that these results are in good agreement with the ones of other models [37][38].

In the year 1998 where solar minimum conditions prevail, it is observed from Fig. 4 that the obtained values are almost identical to the reference ones up to 3 GV (higher geographic latitudes). The percentage difference between them and the reference data becomes greater as we approach higher cut-off rigidity values and it varies from 30% to 40% in the Rc range of 10 GV to 17 GV. This deviation is greater in the case of the higher examined here flying altitude FL390. This may be due to the fact that the CR intensity is greater during solar minimum conditions due to the anticorrelation between CR intensity and solar activity, and therefore the cosmic ray behaviour is not perfectly described by the models used in the simulation.

In the year 2000 that is during the ascending phase of the SC 23, the deviation between the obtained and the reference values is constant in almost during the entire rigidity region from 0 GV to 17 GV, as it is seen in Fig. 6.

In the year 2002 that is during the solar maximum of the SC 23, where the cosmic ray intensity is lower, a very good approximation between the values obtained by DYASTIMA-R and the reference ones is observed in the polar regions from 0 GV to 3 GV. Furthermore, the deviation is significantly lower compared to the one of the years 1998 and 2000, with the DYASTIMA-R values being in good accordance with the reference ones up to 12 GV, which is clearly seen in Figure 7.

The deviation observed in all flying scenarios examined here may also be attributed to the input parameters of the used simulation, as the atmospheric profile and the primary cosmic ray spectra are based on different models. Therefore, DYASTIMA is being constantly improved in order to provide more precise results.

5. Conclusions

The study of the atmospheric cascades is of great interest for the calculation of several radiobiological quantities, that are useful for the radiation dose assessment during air flights and manned spacecraft missions. Therefore, the results provided by DYASTIMA and DYASTIMA-R may be useful for aviators and flight attendants, frequent travellers, airlines, manufacturers as well as legislators and Civil Aviation.

From our analysis it is concluded that in general the new product DYASTIMA/DYASTIMA meets the ICRU/ICRP criteria satisfactorily and can be used for a reliable determination of the exposure of aircrews and passengers to ionizing CR. It is a new product of the ESA SSA R-ESC promising successful applications to Space Weather activities, since it will soon be applied for the radiation dose assessment during extreme events of Space Weather, such as ground level enhancements.

The cascades in the atmosphere of Venus have already been simulated successfully with DYASTIMA [39], while the next steps include the simulation of the showers of the Martian atmosphere, in order to study the possible radiation accumulation for future space missions.

Acknowledgements

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