

ACORDE: A new method to calculate onboard radiation doses during commercial flights

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Atmospheric radiation is primarily produced during the interaction of high-energy cosmic rays with the atmosphere. At typical flight altitudes, the integrated flux of secondary particles can easily reach up to hundreds of thousands per square meter per second. This ionizing radiation constitutes a risk factor for radiation exposure for crew members, passengers, and avionics during commercial flights. Different methods have been implemented in the past two decades to estimate the dose during commercial flights. The main advantage of these methods is their low computing demand, as they rely on precalculated libraries and interpolate or extrapolate the expected doses during predefined commercial routes. However, their estimations may not be accurate enough. In this work, we present ACORDE (Application COde for the Radiation Dose Estimation), a new framework to estimate the dose onboard flights by exploiting Monte-Carlo capabilities on current HPC and cloud-based facilities.

The actual route of any commercial flight is obtained from public trackers and is segmented. The expected secondary flux is calculated along each segment by considering local and real-time atmospheric and geomagnetic conditions. This modulated flux of ionizing radiation is propagated through a Geant4 model of the used aircraft and an anthropomorphic phantom to compute the total dose. The flexibility of ACORDE allows us to calculate not only the actual dose but also other effects such as the impact of course or altitude changes during a particular flight, providing valuable information that could assist in operational decision-making.

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1. Introduction

Commercial flights, operating at altitudes over 10 km above sea level (asl), expose aircraft crews to higher levels of environmental ionizing radiation compared to ground level [1]. This atmospheric radiation, a byproduct of cosmic rays interacting with the Earth's atmosphere, poses health risks to crew members and passengers and can damage onboard electronics [2]. Since the '90s, efforts have been underway to estimate the effective radiation dose during flights. These efforts have led to revisions in national radiation protection laws globally, and have motivated the publication of revised safety standards that include exposure to natural sources of ionizing radiation as occupational exposure [3].

At flight altitudes, radiation dose rates can reach up to $5 \mu\text{Sv/h}$, with neutrons contributing over 55% [3]. While neutron flux measurements at flight altitudes have been conducted, conventional neutron detectors often underestimate the dose, as they lack sensitivity to high-energy neutrons [4]. Furthermore, additional characterization is needed for some commonly used instruments, as they were specifically designed to measure only part of the components of the atmospheric radiation and were not primarily intended for their use in a complex mixed radiation field and with much wider energy ranges [4].

Currently, the exposure to ionizing radiation can only be estimated using physical models. Some tools, such as the NAIRAS model and the CARI7/CARI7-A codes, use semi-analytical models, which rely on pre-calculated libraries and apply various corrections [5, 6]. However, these models cannot cover all the complexities associated with the physics mechanisms involved. In contrast, Monte Carlo based codes, although requiring more computing resources, can handle higher complexity levels. These codes calculate the expected flux of atmospheric radiation Ξ under different conditions, taking into account the interaction of cosmic rays with the atmosphere and the shielding effect of the aircraft's building materials. A significant part of these Monte Carlo codes is dedicated to calculating the shielding produced by the aircraft's building materials and the subsequent energy deposited by secondary particles in different types of tissues.

Thanks to advancements in computational power and modelling tools, more precise calculations of atmospheric radiation are now possible. This paper summarises the current developments of ACORDE (Application COde for the Radiation Dose Estimation), an automated framework that integrates these advancements to provide precise dose calculations along commercial flights [7].

2. Methods

2.1 Modeling of Extensive Air Showers

Cosmic rays (CRs) interact with atmospheric elements to produce Extensive Air Showers (EAS). The development and properties of an EAS depend on the energy (E_p) and composition of the incident CR. Simulating EAS is a complex task due to the need to model physical interactions and track a large number of particles.

The Latin American Giant Observatory (LAGO) has developed ARTI [8], a public toolkit that streamlines the calculation and analysis of atmospheric radiation. ARTI enables the estimation of expected cosmic radiation at any geographical position, taking into account realistic and dynamically changing atmospheric and geomagnetic conditions. To calculate the expected flux Ξ of

atmospheric radiation at any geographical position, ARTI integrates and articulates CORSIKA [9], Magnetocosmics, and Geant4 [10], and incorporates its own analysis package [8]. ARTI can handle different atmospheric models, such as the MODTRAN model, Linsley's layers model, and real-time atmospheric profiles using data from the Global Data Assimilation System (GDAS). It also accounts for changes in the Earth's magnetic field (EMF) and disturbances due to transient solar phenomena and has been extensively utilized for various applications [11].

The calculation of Ξ requires long integration times to minimize statistical fluctuations. ARTI is optimized for running on high-performance computing (HPC) clusters and Docker containers in virtualized cloud-based environments, such as the European Open Science Cloud (EOSC). It can also store and access the produced data catalogs at public and verified cloud storage servers [12].

2.2 ACORDE

Leveraging the capabilities of ARTI, we developed ACORDE [7], a framework that automatically and unsupervised calculates the expected integrated dose a person would receive during a commercial flight. Distinct from existing methods, ACORDE conducts dedicated and intensive Monte Carlo simulations to estimate the secondary radiation at each point along the flight track and its interaction with the aircraft and human tissues on a flight-by-flight basis.

The ACORDE workflow is divided into four steps: 1) obtaining and segmenting the flight track along its route; 2) extracting the atmospheric profile and determining the geomagnetic conditions for each track segment; 3) simulating the secondary flux of particles in the observed conditions of each track; and 4) simulating the shielding effect of the aircraft fuselage and the corresponding effective dose over an anthropomorphic phantom model, and/or a radiation detector on board the plane.

ACORDE uses a unique alphanumeric code to identify each commercial flight and retrieves the flight's data from public databases. The flight track then segments into three automatically derived stages: takeoff, cruise, and landing. Depending on the determined duration of the cruise, flights fall into categories as short (< 2 h), intermediate (< 4 h), and long (> 4 h) flights. The cruise stage divides further into segments of $\Delta t \approx 600; 900;$ or $1,800$ s depending on the flight type, and a route waypoint is placed at the middle of each segment. In those particular cases where the time difference between two consecutive waypoints exceeds Δt , the track is completed by assuming an orthodromic (great-circle) route. Due to the stochastic nature of EAS development, the statistical significance of the calculation at each waypoint increases by artificially extending the flight time for each step. This is done by defining a coverage factor $\kappa = 3, 6$ or 9 for long, intermediate and short flights. Thus, the total integration time for calculating the flux at each waypoint is $t = \kappa \Delta t$. ACORDE also produces a .DEG file containing the same waypoints for the flight but in the format requested by the CARI7-A code, which will be used as the dose reference for each flight.

Consider, for instance, the flight IB3270_20211116 operated by Iberia, which flew from Madrid (MAD) to Hamburg (HAM) in an Airbus A320-216 on Nov, 16th, 2021. As this was an intermediate flight, the duration of each segment was set to $\Delta t_i = 910$ s, resulting in $N = 10$ waypoints (eight for the cruise, including the corresponding starting and ending cruise waypoints, and 2 at the intermediate points of the takeoff and landing stages) and 9 segments where the dose was calculated. For this flight, the coverage factor was set to $\kappa = 6$, so the total flux integration time

for each segment was $\tau_i = 5,460$ s. Figure 1 displays the flight track and the determined waypoints of the flight.

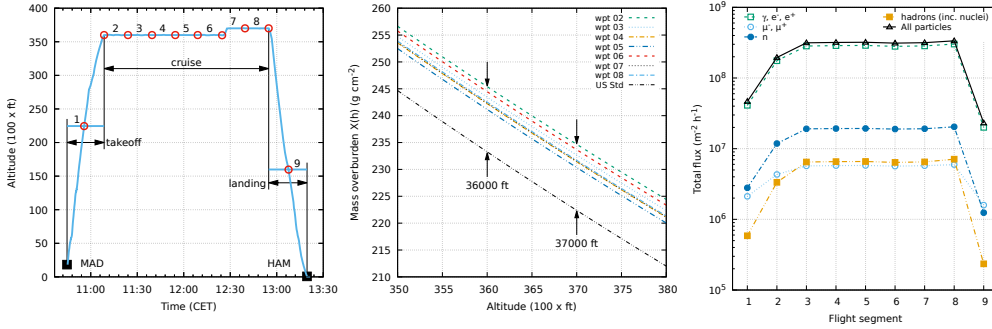


Figure 1: Left: The light blue line shows the airplane’s altitude over time, with the waypoints (red circles) of the flight MAD-HAM IB3270’s real track on 11/16/2021. ACORDE determined the start and end of the cruise stage and identified the waypoints (red circles). Center: The atmospheric mass overburden $X(h)$ as a function of altitude h for the seven cruise segments at flight altitude, compared with the US Standard atmosphere, observing differences of 1.3 kPa ($\sim 5\%$). Right: the evolution of the different components and the total flux for each segment.

For each waypoint, we obtained the local atmospheric profile from the GDAS database, characterized within a ± 1.5 h window relative to the plane’s arrival at the waypoint. This characterization allowed us to determine the density $\rho(h)$ and the mass overburden $X(h)$ as functions of altitude. The right panel of Fig.1 presents the reconstructed $X(h)$ for the seven cruise stage segments of flight IB3270_20211116, alongside the US standard model, a common reference for such calculations. Notable, albeit slight, differences are evident between the local profiles. These differences are significant considering that the development of atmospheric radiation Ξ_i depends not only on local conditions but also on the integral from the top of the atmosphere to the segment altitude. When comparing these profiles with the standard atmospheric profile, the differences become even more pronounced. For instance, at an altitude of $h = 37,000$, the difference between X_2 and X_{Std} is $12.5 \text{ g cm}^{-2} \approx 1.3 \text{ kPa}$ ($\sim 5\%$). These differences can exceed 15% for near-polar flights[7]. We also determined the EMF at each waypoint. Transient space weather phenomena that could affect the EMF were also considered. For this particular flight, no significant geomagnetic disturbances were observed during the example flight, so the secular values of the geomagnetic field as well as the local rigidity cutoff tensor were calculated.

The ACORDE computation relies on two different Docker images and a special set of internal and external daemons for controlling the execution and reporting the progress of the calculation through the different stages. The first Docker, called ARTI, performs the calculations to obtain the expected flux of secondary particles Ξ for each segment in the third step of ACORDE’s workflow. Within this container, a pre-compiled instance of CORSIKA and a specially modified version of the ARTI background simulation framework are included.

The flux is predominantly composed of electromagnetic particles, but when considering the dose, this may not always be the case due to the Relative Biological Effectiveness (RBE) of each particle type. The right panel of Figure 1 illustrates the evolution of $\Xi_{i,j}$, representing different types of particles j (photons and electrons, muons, neutrons, nuclei, and other hadrons) along the

flight track. The altitude's impact on Ξ_i is clearly visible, both in terms of atmospheric absorption and the development of Extensive Air Showers (EAS). The neutron flux, for instance, can increase by more than two orders of magnitude compared to similar spectra at ground level.

The second Docker image, DOSE, contains a Geant4 application consisting of a realistic model of the aircraft fuselage, currently based on the Airbus A320-200 or the A350-900 aircraft and filled with dry air at the flight altitude pressure, and an anthropomorphic phantom based on current and validated voxelized phantoms [13]. The fourth and last stage of ACORDE begins with the deployment of the DOSE Docker. It is important to note that the flux of cosmic rays is isotropic and homogeneous at the relevant energies for this calculation, and given the Poissonian characteristics of the background flux and the stochastic evolution of the EAS, the atmospheric flux can be considered self-similar [8]. For this reason, all the secondary particles present in the secondary flux at each waypoint are propagated in the direction of their initial momentum through the aircraft and the anthropomorphic phantom models. All the relevant interactions, including mini-showers that can be produced by the interaction of high energy secondaries with, for example, the fuselage components, are taken into account for the calculation of the absorbed dose D within the phantom. Once it is obtained, the equivalent dose H for each organ/tissue is calculated by including the radiation weighting factors, which account for the relative biological effectiveness (RBE) of different types of ionizing radiation. After that, the effective dose E is determined following the International Commission on Radiological Protection (ICRP) recommendations [14]. The total dose is obtained by summing the single doses calculated at each waypoint after being corrected by the corresponding coverage factor. In the case of the flight we analyzed as an example, the total effective dose calculated using the ACORDE framework amounted to $E_A = 11.6 \mu\text{Sv}$. As previously mentioned, ACORDE also generates a waypoint file that is compatible with CARI7-A, enabling us to obtain a reference dose for each flight. Using CARI7-A in its standard configuration, we calculated a dose of $E_C = 9.2 \mu\text{Sv}$. This resulted in a difference of $\Delta E = E_A - E_C = 2.4 \mu\text{Sv}$ between the doses calculated by ACORDE and CARI7-A. In relative terms, the difference was $\Delta E\% = 2\Delta E / (E_A + E_C) = +23\%$ for this specific flight.

3. Extended simulation campaign

The ACORDE's effectiveness was tested by calculating the total effective dose received in over 300 flights. The same flights were also calculated using CARI7-A, with the same path used for ACORDE calculations to minimize differences. These calculations were performed for 287 random Iberia flights and 37 specific flights operated by Japan Airlines and Cathay Pacific. These specific flights were chosen to evaluate ACORDE's performance during a solar activity period for these particular East-West or West-East routes.

While we have conducted a comprehensive analysis of the entire dataset in this section, it's crucial to remember that each flight is essentially unique. Even for the same route, factors such as weather conditions, crowded routes, or operational changes can alter the actual flight path, significantly impacting the total dose. This is especially true for changes related to flight altitude. Furthermore, local variations in atmospheric and geomagnetic conditions, or the use of a different aircraft, can significantly affect the distribution of internal secondary particles and the corresponding

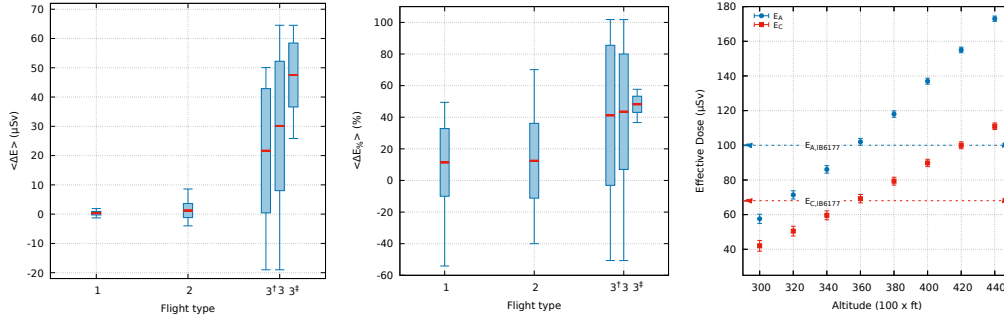


Figure 2: Left: The figure presents the average absolute differences $\langle \Delta E \rangle$ for the three flight categories and subsets of long flights: all (type 3), regular (3^\dagger), and polar (3^\ddagger), as explained in the text. The candlestick plots illustrate the observed range and $1\text{-}\sigma$ deviation from the mean (marked by the red line) of the observed differences. Center: The relative differences ($\langle \Delta E_{\%} \rangle$) observed. Right: The effective dose in relation to the cruise altitude of the artificially modified flight IB6177 (MAD-LAX), from November 11th, 2021, as determined by ACORDE (blue circles) and with the standard configuration of CARI7-A (red squares). The doses calculated for the original flight are indicated by the respective arrows for reference.

effective onboard dose. Although ACORDE considers all these factors in its calculations, different evaluation methods used by other codes can potentially lead to varying final results.

We classified the analyzed flights into three categories based on their duration: short (1), intermediate (2), and long (3) flights. When comparing the doses calculated by ACORDE and CARI7-A, we observed systematic differences. For short and intermediate flights, the average absolute differences in dose, denoted as ΔE , fall within the ranges of $[-1.3, 1.9] \mu\text{Sv}$ and $[-4.0, 8.6] \mu\text{Sv}$ respectively. The relative differences, $\Delta E_{\%}$, can reach up to $+50\%$ and $+70\%$ for these categories. However, as depicted in the left and central panels of Fig. 2, these average absolute differences are compatible with zero within a 1-sigma confidence interval.

The systematic differences become more pronounced for the 113 long flights (type 3 in Fig. 2), with a significant absolute excess of $\langle \Delta E \rangle = (+30.1 \pm 22.1) \mu\text{Sv}$ and a relative excess of $\langle \Delta E_{\%} \rangle = (+43.5 \pm 36.5)\%$. However, these differences diminish when we separate the 76 regular long flights (3^\dagger) from the 37 special flights (3^\ddagger). These special flights, including routes CX843 (JFK-HKG), CX829 (YYZ-HKG), JL42 (LHR-HND), CX844 (HKG-JFK), CX826 (HKG-YYZ), and JL41 (HND-LHR), took place between October 22nd and November 21st, 2021. They were selected to evaluate ACORDE's response to a period of heightened solar activity observed in late October and early November 2021. This activity, attributed to the solar active region NOAA 2887, generated M-class flares, an X1 flare, and the ground-level enhancement GLE73. It also resulted in geomagnetic storms and a slow interplanetary coronal mass ejection (iCME) directed towards Earth. A subsequent fast iCME from the NOAA 2891 region interacted with the slower iCME, creating a complex structure that reached Earth on November 3rd and caused geomagnetic disturbances with a disturbance storm index (DST) of -5 nT . Significant differences were observed in these flights, with average absolute and relative differences of $47.5 \pm 10.9 \mu\text{Sv}$ and $48.2 \pm 5.1\%$, respectively. Comprehensive information about these flights is provided in the supplementary material of this work [7].

Atmospheric and geomagnetic conditions can influence the calculated dose values, but altitude changes during flight have the most significant impact. To showcase ACORDE's ability to calculate

dose under different conditions, we modified the cruise altitude of flight IB6177_20211211 (MAD-LAX) between 30,000 and 44,000 feet in 2,000-foot increments. All other flight conditions and selected waypoints were kept constant to eliminate other potential sources of variation. The results of this altitude variation study are shown in the left panel of Fig. 2. As can be seen, the effect of altitude on the total effective dose calculated by both ACORDE and CARI7-A is evident. Significant differences, up to a factor of more than 3, can be seen in the reconstructed doses for both flights when comparing their values as the altitude changes between 30,000 and 44,000 feet, the maximum altitude that the new generation of airplanes can reach.

4. Towards an Experimental Verification of ACORDE

ACORDE's calculations, unlike methods relying on interpolations or extrapolations, consider real-time atmospheric conditions, specific aircraft fuselage models, and precise flight paths. However, the overall methodology awaits experimental validation under field conditions by comparing ACORDE's results with onboard measurements from calculated flights. To facilitate this, ACORDE includes a module designed to simulate expected doses that can be registered by a Gamma-Scout (GS), a commonly used dosimeter in the industry. This feature allows for the calculation of doses on a flight-by-flight basis, providing a straightforward way to test ACORDE predictions without the need for additional detectors.

Both ACORDE and CARI7-A estimate effective doses by considering all types of atmospheric radiation. However, devices like the GS based on Geiger-Müller tubes, limit the detection of energetic particles and can not detect neutrons. For example, for flight IB3270, the estimated measurement by the GS module of ACORDE is $E_{GS} = 5.4 \mu\text{Sv}$, compared to a total estimated dose of $E_A = 11.6 \mu\text{Sv}$. The inclusion of this module in ACORDE allows for experimental verification by comparing simulated doses with measurements taken by a GS detector installed on an airplane. If validated, it could affirm ACORDE's estimation of the absorbed dose, suggesting that ACORDE's estimation considering the entire spectrum of radiation could also be accurate.

5. Conclusions and future perspectives

This work presents ACORDE, a novel code that integrates state-of-the-art Monte Carlo simulation codes for cosmic ray interaction with the atmosphere and radiation interaction with matter. ACORDE calculates the effective dose that aircrew and passengers could receive during a commercial flight. It uses real flight data, including the plane's track, to determine local atmospheric and geomagnetic conditions for each segment of the flight. ACORDE can also simulate the expected radiation that onboard commercial dosimeters would measure under the same conditions.

For long flights, the dose estimation from ACORDE was generally higher compared to CARI7-A. However, these differences were within the systematic error bars for all three flight groups studied. While ACORDE integrates extensively validated codes and techniques, it still lacks an overall experimental validation of the calculated doses. This could be resolved by a flight-by-flight measurement campaign using compact neutron detectors and commercial GM dosimeters.

ACORDE is designed to run autonomously and unsupervised on a single desktop computer, controlling all required simulations that can be performed on small local clusters or large HPC

and cloud-based public and federated infrastructures. Future versions of ACORDE will include enhancements such as improved fuselage models, complete human male and female ICRP-110 phantoms, an extension of the atmospheric neutrons energy range, and the integration of blockchain technology for reproducibility and traceability.

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