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Influence of geometry model approximations on Geant4 simulation results of the Columbus/ISS radiation environment

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Abstract

The influence of geometry model approximations on Geant4 Monte Carlo simulation results of the radiation environment on-board the Columbus module of the International Space Station (ISS) has been investigated. Three geometry models of Columbus with different levels of detail and a geometry model of ISS have been developed. These geometries have been used for Geant4 simulations of the radiation environment inside Columbus induced by trapped protons and Galactic Cosmic Ray protons. Simulated dose rates and particle spectra on-board Columbus for each of the three Columbus models, with or without the ISS geometry model included, are presented and compared.

From comparisons of simulated dose rates and particle spectra for the three different geometry models it was found that the most detailed geometry model (750 volumes) produced results similar to a much less detailed model (23 volumes). The most detailed geometry model was concluded to be a sufficiently detailed approximation of the physical Columbus for the purpose of proton induced space radiation studies. The simulated dose rates are compatible with measurements on-board the ISS. The simulation results also show that an increase in shielding thickness decreases the simulated dose rate induced by trapped protons. For Galactic Cosmic Ray protons the dose rate remains unchanged or is slightly increased.

Keywords: Radiation protection; Monte Carlo simulation; Space station; Biological effects of radiation; Geometry models

1. Introduction

Astronauts are subject to an increased level of radiation and it is important to evaluate the risks associated with extended visits to the International Space Station (ISS) and space travel in general. Estimation of the risks requires knowledge of the radiation environment in space, of the interactions and transport of the radiation in the hull and the interior of the spacecraft and of the radiobiological effects in humans to estimate the induced dose rates.

The DESIRE project[1] aims at simulating the radiation environment inside the Columbus module of the ISS and associated dose rates received by astronauts. The radiation transport simulations are carried out with the modern Geant4 Monte Carlo particle transport toolkit (Agostinelli et al., 2003) in combination with geometry models of the Columbus module and ISS.

The main focus of this paper is to study the influence of Columbus/ISS geometry model approximations on the simulated dose rates. In space radiation transport simulations the spacecraft geometry can be taken into account using

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[1] Dose Estimation by Simulation of the ISS Radiation Environment. See also: http://www.particle.kth.se/desire/.

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different degrees of approximation, such as representing the hull as a simple one-dimensional shield, or performing radiation transport calculations directly in an advanced CAD-like geometry. A detailed three-dimensional geometry model is required for a detailed assessment of the effects of the shielding provided by Columbus/ISS, such as studies of the influence of different amounts of shielding at different locations and of the directional anisotropy of trapped protons. To verify that the level of detail of the developed geometry models is adequate, several geometry models of the same vehicle can be developed, and assessed by their impact on the simulation results. In this paper, three different geometry models of the Columbus module are presented and their impact on the simulation results for trapped and Galactic Cosmic Ray (GCR) protons are evaluated.

Simulated dose rates and particle spectra on-board Columbus for each of the three Columbus geometry models, with or without the ISS geometry model enabled, are presented. Because the simulations only take into account incident proton spectra, but do not include contributions from GCR ions, the presented results have to be interpreted with care. Combining measurement made on ISS (Reitz et al., 2005) with information from Cucinotta et al. (2003), the studied incident proton environment accounts for about 70% of the dose rate and about 30% of the dose equivalent rate.

The developed geometry models will be used in future studies within the DESIRE project of the complete Columbus radiation environment, and it is anticipated that they will be used by other projects as the developed Geant4 geometry models have been exported as GDML-files. Currently such files can be used by the Geant4 and ROOT toolkits. However, due to the open-source nature of GDML it should be possible to implement interfaces also to other toolkits.

1.1. The radiation environment in the ISS orbit

There are contributions to the incident radiation field in the ISS orbit from several sources. Electrons and protons trapped in the Earth's magnetic field are one component. The trapped protons contribute a large fraction of the dose rates inside ISS and have energies up to several hundreds of MeV. The GCRs, consisting of 99% protons and He nuclei and 1% heavy ions with energies up to tens of GeV/nuc, is another component. Short-term high-intensity bursts of protons and ions accelerated to hundreds of MeV at the Sun (Solar Particle Events) also contribute transient increases to the radiation environment. Except for the most energetic GCRs these components are all modulated by the solar activity, which influences the transport of particles in interplanetary space through the Interplanetary Magnetic Field that is transported outwards from the sun by the solar wind. The solar wind also modifies the shape and extent of the Earth's magnetosphere, and thus also the trapped particle belts. During solar maximum the inner belt trapped particle populations are influenced through higher insolation, which results in greater losses of trapped particles through interactions with the expanded upper atmosphere.

1.2. Radiation transport simulation using Geant4

The tool chosen for radiation transport in the DESIRE project is Geant4 (Agostinelli et al., 2003). Geant4 is a Monte Carlo particle transport toolkit that is being developed by a large international collaboration including ESA, CERN, and many other institutes and universities. At present, some commonly used particle transport programs for manned space applications (such as the NASA HZETRN code; Wilson et al., 1995) are not Monte Carlo based. Instead, they solve 1-D Boltzmann transport equations that describe how radiation fields are transformed when passing through a given mass thickness. The particle flux and dose rates can then be calculated for a location in the ISS 3-D geometry by evaluating the individual contributions from different directions (Qualls et al., 2001). On the Russian side the Monte Carlo program SHIELD (Dementyev and Sobolevsky, 1999) has been used for calculations of parts of the ISS radiation environment (Getselev et al., 2004).

The physics models required for transport of protons in Geant4 at energies corresponding to the trapped proton environment have been validated earlier in the DESIRE project (Ersmark et al., 2004; Ersmark, 2003). Further validation studies of the physics of Geant4 relevant for the present work have been published elsewhere (Agostinelli et al., 2003; Amako et al., 2005; Folger et al., 2004; Geant4 collaboration, 2006).

Geant4 version 7.0.p01 (released 23 February 2005) was used for all results presented in this document. The simulations used the LHEP_BIC_HP physics configuration distributed together with Geant4. The configuration uses the Binary Cascade model (Folger et al., 2004) for nucleon–nuclei reactions. A pre-compound model is used at energies below the cascade regime. These models provide e.g., proton-induced secondary neutrons and target fragments. Standard models for electromagnetic interactions and data-driven models of low-energy neutron interactions are also included in the configuration.

While the Geant4 studies presented in this paper do not take GCR ions into account, such studies are planned. At present, Geant4 includes two models of hadronic ion-nuclei interactions. Whether they are suitable for simulations of the GCR ion induced radiation environment on-board ISS has not yet been investigated. A description of these and other physics models of Geant4 can be found in Truscott (2004), Folger et al. (2004) and Agostinelli et al. (2003).

2. The DESIRE Geant4 Columbus and ISS geometry models

The aim of the DESIRE project is to simulate the radiation environment inside the Columbus module of the ISS. Thus, a 3-D model of Columbus specifying the geometry and materials is necessary. Because the presence of the ISS modifies the radiation field incident on Columbus, an ISS geometry model is also required. Such Geant4 geometry models have been implemented with various levels of detail, and are described in this section. These models will be used for radiation transport simulations of all incident radiation field components in future studies within the DESIRE project.

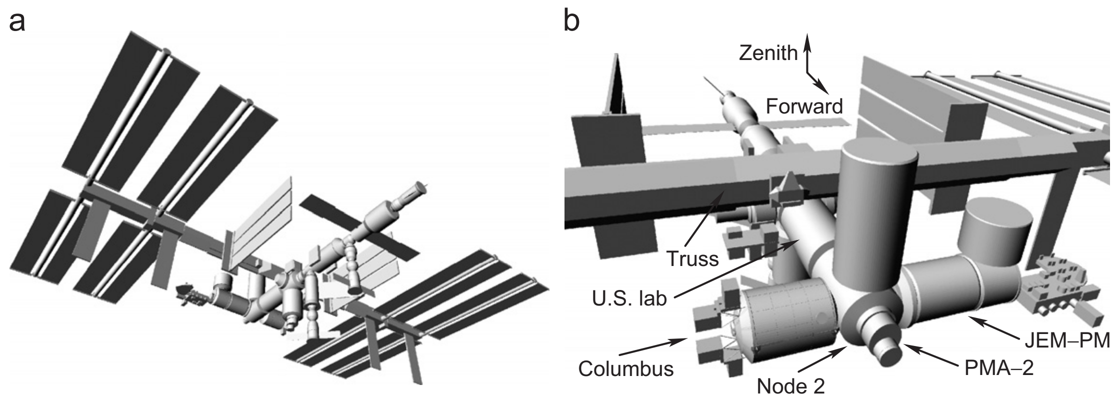

Fig. 1. The DESIRE Geant4 Columbus and ISS models: (a) the full ISS model; (b) the Columbus model and adjacent parts of the ISS model.

The objective when implementing a geometry model for radiation transport simulations is to capture the features influencing the studied quantities (e.g., particle fluxes or dose rates). An excessively detailed model may result in unnecessary CPU-time required for the simulations, or may result in superfluous work implementing the model. In contrast, a coarse model may result in incorrect simulation predictions. It is therefore necessary to investigate whether geometry models intended for radiation transport studies are adequately detailed.

In order to investigate the adequacy of the level of detail of the implemented models, three independent models of Columbus were developed. The influence on the simulated Columbus radiation environment due to inadequately detailed parts of the geometry models depends on their mass, distance and apparent solid angle seen from Columbus. Therefore, the most detailed Columbus geometry model is more detailed than the ISS model. Examples of the Columbus and ISS geometry models are shown in Fig. 1.

The aim of the DESIRE project was originally to use CAD models of Columbus in the STEP format (Standard for the Exchange of Product model data) for radiation transport. However, the Geant4 STEP-interface (Agostinelli et al., 2003) was removed in Geant4 6.0 due to incompatibilities with most STEP files generated by CAD programs. Because of this deficiency in Geant4, all geometry models described in this paper were manually implemented from hardcopy specifications. A detailed description of the geometry models, as well as geometry data in the form of GDML-files (Geometry Description Markup Language, see Chytracek, 2001), are available from the authors upon request.

2.1. Columbus geometry models

Three Geant4 geometry models of Columbus have been implemented to study the radiation fields inside Columbus and how these are influenced by the level of detail of the models. The models are labeled C1, C2 and C3, in order of increasing detail. Simulation results obtained with a Columbus geometry model only (i.e., ignoring effects of the presence of ISS) are labeled analogously, while results obtained with a combined Columbus and ISS geometry model are labeled C1 + ISS, etc.

The C1 model was developed from the short specifications at the ESA Columbus web page (ESA, 2003). The most detailed Columbus model, C3, contain 750 volumes and was developed according to a set of drawings (Astrium Gmbh, 2004a) provided by the ESA Houston office. In an attempt to study if the C3 model is a sufficiently detailed approximation of the physical Columbus, the C2 model (which contains 23 volumes) was developed. Because the difference in detail between the C2 and C3 models is greater than between C3 and the physical Columbus, identical results for the C2 and C3 models, would indicate that minor improvements to the C3 model are irrelevant. Given that the C3 model is already very detailed, there is no room for such major increases in the level of detail.

To investigate the influence of the presence of ISS on the radiation environment inside Columbus, the Columbus models have been used for simulation studies both with or without the ISS model present. In these cases additional material has been added to the hatches of the C2 and C3 models to avoid direct exposure of the cabin to the incident primary radiation.

2.1.1. The C1 model of Columbus

The C1 model consists of 10 volumes with a total mass of 4386 kg. It models the approximate boundary dimensions of Columbus (including the External Payload Facility (EPF)). This model provides a baseline to which more refined models can be compared, although the geometry of the model is a crude approximation of the physical Columbus and the total mass of the model is only about 25% of the correct total mass.

The C1 hull consists of aluminum 2219 (aluminum with 5% copper) and is shaped like a closed barrel. The Columbus hull is protected from breaches by a Meteoroid and Debris Protection System (MDPS) enveloping the entire module. Both the Columbus hull and the MDPS provide a significant part of the radiation shielding capability for on-board astronauts. The C1 model contains material as described in Table 1, in the forward, aft, port and starboard directions. No other components are included in this model.

Table 1
The MDPS and hull thicknesses and materials for different surfaces of Columbus

Module surface	MDPS1 Al. 6061T6 (mm)	MDPS2 Kevlar (mm)	MDPS3 NextTel 650 (mm)	Hull Al. 2219 (mm)
Forward	2.57	5.6	5.3	4.8
Aft	1.6			4.8
Port	1.6			3.8
Starboard	2.57	5.6	5.3	3.8

Secondary and Tertiary MDPS are not present on the aft and port surfaces. Table headings: MDPS1—Primary MDPS, etc. Al.—Aluminum.

2.1.2. The C3 model of Columbus

The C3 model is the most detailed of the Columbus models. It consists of about 750 volumes, has the correct total mass of 16 750 kg (SEMDA Laboratory Team, 2003) and is far more detailed and realistic than the C1 model. The external surface of the C3 model is shown in Fig. 1(b) and includes the primary MDPS and EPF. The MDPS layers are implemented according to Table 1 and are shown in detail in Fig. 2(a) together with parts of their mountings. No information on the material used for the mountings was available in the specifications (Astrium Gmbh, 2004a). In this, and similar cases of incomplete specifications, the geometry models uses aluminum with e.g., a density one-fifth of that of normal aluminum.

Removing the MDPS structures leaves the hull and its support structures visible, see Fig. 2(b). The total hull mass of Columbus is 3004 kg according to ESA (2000). Using the hull thicknesses from Table 1, the hull mass is, however, only about 2250 kg. The difference is due to lack of structural thickening of the hull around interfaces between the main hull parts as well as lack of minor hull details in general. Therefore, the C3 hull thicknesses have been increased by about 50% to fit the correct total hull mass.

The Columbus interior consists of 16 racks, four stand-offs and the interiors of the port- and starboard cones. Rack and standoff profiles are shown in Fig. 2(c). The masses of the stand-offs and port- and starboard cone interiors were not available in the specifications and were estimated by Dellantonio (2005) and implemented accordingly. Also the rack materials were unavailable, and were estimated to be mixtures of aluminum, copper, steel and traces of water. The Columbus specification (Astrium Gmbh, 2004a) gives the approximate general shape of a rack but does not specify the rack mass or the actual equipment in the racks. Because the masses of all other components of the Columbus was at this point determined, the masses of the racks were adjusted to obtain the correct total Columbus mass. This resulted in rack masses of 67% of the maximum allowed rack masses (Astrium Gmbh, 2004a). The material of the racks have been estimated to be a mixture of aluminum, steel and, plastics (Guisan, 2005).

As previously stated, the influence of inadequately detailed parts of models depends on their mass, distance and apparent solid angle from the Columbus cabin. The C3 racks are located next to the Columbus cabin and constitute a large fraction of the total Columbus mass. Although several approximations were introduced implementing the racks, the impact of this on general purpose calculations is decreased by the fact that the rack configuration will change over time with rearrangements and availability of new experiments.

2.1.3. The C2 model of Columbus

The C2 model consists of only 23 volumes and, like the C3 model, implements the correct total Columbus mass. By implementing this simplified model, the relevance of the level of detail of the models can be studied. The external appearance of C2 is very similar to C3, with the main cylinder, slanted end-cones and the EPF being present. The MDPS layers described in Table 1 are implemented. The hull is present with a correct total hull mass. In the C2 model the hull mass is evenly distributed over the main cylinder and end-cones, in contrast to the C3 model where e.g., support structures are implemented, see Fig. 2(b). Inside C2 there is a rectangularly shaped cabin surrounded by an interior consisting of the rack-material described in Section 2.1.2.

2.2. The ISS geometry model

The DESIRE ISS model corresponds to ISS in the so-called 14A configuration. The mass of ISS (excluding Columbus) in this configuration is 352 metric tons and the model consists of about 350 volumes. The ISS model, including the C3 model, is shown in Fig. 1. The main visible features of ISS in Fig. 1(a) are the main solar panels and the 108 m long truss structure. A detailed view of the forward ISS modules is shown in Fig. 1(b). The Columbus module (C3) is included in Fig. 1(b) and has a length of 6.6 m.

The specification used for the ISS geometry contains the mass of individual ISS modules and in some cases parts of such modules. Each module/module part/vehicle in the ISS model has been assigned the correct mass. Since no material specifications for the modules were available, all ISS modules were constructed from aluminum. The total module mass was distributed in different ways depending on module type.

The habitable ISS modules and their interiors have been implemented by dividing the total module mass equally between the hull and the module interior. The hull is modeled as normal-density aluminum. Inside the hull of each habitable module there is an interior (e.g., equipment racks) along the module walls. The interior mass is distributed evenly in the interior. Hatches between the module cabins have been implemented only in some cases. E.g., the Node 2 model (see Fig. 1(b)) has hatches only at the connections to the US laboratory and PMA-2. The hatches leading to Columbus and the Japanese laboratory (JEM-PM) are not modeled.

All non-habitable modules of the ISS (e.g., solar panels, radiators, truss segments) are implemented according to their approximate boundary surfaces and a homogeneous aluminum-type material. The geometry of certain parts of ISS is very complex (e.g., the truss sections). In general, complex geometries have been simplified to consist of only a few volumes.

Fig. 2. Parts of the C3 model of Columbus. (a) MDPS panels and support structures viewed from the port direction. (b) Hull, support structures and stabilizer fittings. (c) Profiles of racks and stand-offs. Detector surface visible in the cabin (central part of figure).

The level of detail of the ISS model is less significant for studies of the Columbus radiation environment than the level of detail of the Columbus model. Nevertheless, the implemented ISS model is more detailed than geometry models used for recent Monte Carlo studies, e.g., (Getselev et al., 2004). In that study, also the space station modules under investigation (analogous to Columbus in our case) were modelled in less detail than the present ISS model.

3. The Columbus radiation environment

To evaluate the impact of different levels of detail of geometry models, simulations of the Columbus radiation environment due to incident trapped protons and GCR protons has been carried out. Simulated dose rates and spectra of particles entering Columbus are presented and compared with respect to associated geometry model as well as measurements. Incident energy spectra for solar maximum have been retrieved from SPENVIS (Heynderickx et al., 2000) according to the AP8 model (Vette, 1991) in the case of trapped protons and from CREME96 (Tylka et al., 1997) in the case of GCR protons. Both energy spectra are averages along a 51.6° inclination ISS orbit of 380 km altitude. For GCR protons quiet magnetospheric conditions were assumed. The directional anisotropy of the trapped proton flux is the subject of another study (Ersmark et al., 2007).

3.1. Computational details

Simulations have been performed for six geometry configurations: the C1, C2 and C3 models, with and without the ISS model (labeled C1, C1+ISS, etc.). This allows for studies of the influence of the bulk ISS structure on the Columbus radiation environment as well as the different shielding capabilities of a very lightly shielded ISS module (C1) as compared to the realistically shielded C3 model. The influence of the detail-level of the C3 model compared to the more coarse C2 model can also be studied.

A simulation run is performed by generating incident particles on a source sphere enveloping the entire ISS or Columbus model using the Geant4 General Particle Source module. The starting positions and directions of the particles are generated to create an isotropic flux of particles inside the sphere. Therefore, in the full ISS model (corresponding to a 150 m diameter source sphere), most of the particles fail to hit any part of the ISS or Columbus at all.

Particles entering the Columbus cabin are recorded when they pass the cylindrical surface shown in the central part of Fig. 2(c). The size and location of the surface with respect to the port side of Columbus are the same also in the C1 and C2 models. Dose rates have been calculated using an ICRU sphere (ICRU, 1992), which has a diameter of 30 cm, placed at the center of the Columbus cabin (i.e., at the center of the cylindrical detector surface). The dose rates were calculated in a 1 mm thick shell at 10 mm depth in the ICRU sphere. Data on the track energy deposition of the individual particles in the shell was recorded.

To decrease the CPU requirements of the simulations, only a single incident proton spectrum has been generated for each geometry configuration. Each time a particle track intersects the sensitive surface in the Columbus cabin or deposit energy in the ICRU sphere, information on the primary particle energy is saved. During analysis, when dose rates or spectra of particles entering Columbus are calculated, the primary proton energy is used to evaluate the relative difference between the simulated spectrum and the desired incident proton spectrum. The difference corresponds to a weight of a particle when producing energy spectra of particles entering the Columbus cabin. For dose rate calculations, the track energy deposition is scaled instead. This allows for the use of the same data set for multiple incident spectra.

The required computation time can be decreased in several ways. Most generated particles do not hit the ISS at all. Using a source surface enveloping ISS more tightly than a sphere would reduce this problem. The dimensions of the full ISS are huge compared to Columbus, and especially the ICRU sphere, and removing remote parts of the ISS would reduce the computation time. Additionally, various kinds of volume biasing, allowing particles hitting Columbus (or the ICRU sphere) to

Table 2
Number of CPU-days required on AMD Athlon 2000+ processors for the results presented in this paper

Geometry configuration	CPU-days
C1	6
C1 + ISS	43
C2	18
C2 + ISS	37
C3	68
C3 + ISS	82
Total	254

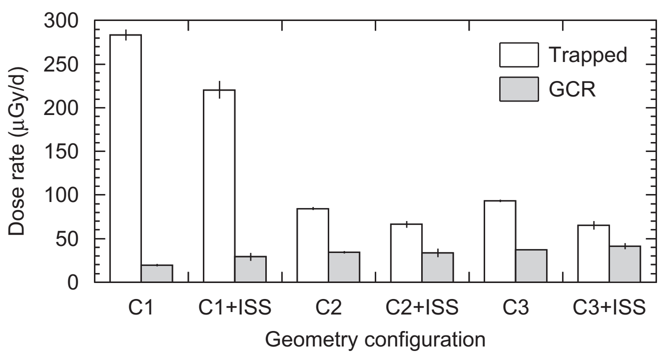

Fig. 3. Dose rates at 10 mm depth in an ICRU sphere placed at the center of the Columbus cabin for trapped- and GCR protons and all six geometry configurations.

be transported several times, would decrease statistical fluctuations in this part of the simulation. These possibilities would improve the statistics for both the reported energy spectra and the dose rates. Furthermore, to decrease the statistical uncertainties in the reported dose rates, several ICRU spheres placed at various locations inside the Columbus cabin could be used. The results presented in this paper were computed on a cluster with ten AMD Athlon 2000+ processors and required a total of 254 CPU-days (itemized by geometry configuration in Table 2).

3.2. Simulated dose rates

Dose rates at the center of the Columbus cabin have been simulated for incident trapped and GCR protons at solar maximum. Fig. 3 shows the dose rates for the different geometry configurations. It is clear that the C3 model results in dose rates similar to those of the C2 mode, both when ignoring and including the presence of the ISS model. Because of the low detail of the C2 model compared to the C3 model, this indicates that further minor improvements to the C3 model are irrelevant.

In the case of trapped protons, additional shielding in the form of the more massive C3 model or the presence of ISS is advantageous and reduces the dose rates, compared to the lighter C1 model. The dose rates due to GCR protons exhibit the opposite behavior; increased shielding is either irrelevant or increases the induced dose rate. This is because the protons in the GCR spectrum have higher energies than those in the trapped proton spectrum. Interactions of these high-energy protons induces a shower of particles in the Columbus/ISS hull, resulting in a greater number of secondary particles entering the Columbus cabin. Consequently, this results in a greater dose rate. Qualitatively similar results for GCRs have been observed in experimental measurements at different shielding depths in aluminum on STS-89 (Badhwar and Cucinotta, 2000).

A direct comparison of calculated dose rates to measurements in the present ISS is difficult. Dose rates for GCR ions are not negligible and are yet to be calculated. Assuming the dose rate contribution from trapped protons is about half of the total dose rate (Benton and Benton, 2001), the calculated total dose rate for the C3 with ISS geometry is estimated to be $131 \pm 10\,\mu\text{Gy/d}$. Even then no exact comparison can be made since the Columbus module is not yet launched, and thus no measured dose rates exist. Dose rates due to ionizing radiation in the range of 153–231 µGy/d have been measured at various locations in the US Lab and Node 1 for altitudes in the range of 386–404 km (Reitz et al., 2005). These measurements were made in 2001, i.e., during a solar maximum and with ISS in a much less massive configuration. The difference between these dose rates and the calculations can be attributed to different ISS shielding capabilities, different ISS altitudes, as well as environmental model uncertainties.

Comparison of the presented Geant4 Monte Carlo results to experimental data are sensitive to uncertainties in the incident radiation environment, imperfections in the Geant4 physics models and to limitations in the statistics generated by a finite Monte Carlo simulation. The de facto standard AP8 model of trapped protons has been criticized for underestimating the high-energy proton flux (Heynderickx et al., 1999), which is very important for radiation shielding on the ISS, and for being based on extrapolations at low altitudes. The uncertainty in the AP8 model is commonly quoted as "about a factor of two" (Vette, 1991). The performance of relevant Geant4 physics models have been demonstrated to have less uncertainty than this, see e.g., Agostinelli et al. (2003); Ersmark et al. (2004); Amako et al. (2005). Also uncertainties due to finite statistics are bounded by uncertainties in the incident radiation environment. The statistical uncertainties reported in Fig. 3 are the uncertainties of the mean dose rates, estimated by dividing each data set into 10 parts and calculating the RMS of the dose rate deviation of the smaller data sets. Schemes for decreasing the statistical uncertainty have been suggested in Section 3.1.

3.3. Simulated energy spectra of particles entering the Columbus cabin

Kinetic energy spectra of primary protons and secondary particles entering Columbus have been simulated. Fig. 4 shows spectra of protons and neutrons entering the Columbus cabin as a result of the incident trapped proton environment. The incident trapped proton spectrum is also shown for clarity. For comparison purposes, the same ranges of the plot axes are used in Figs. 4 and 5. The results for C2 deviate only slightly from

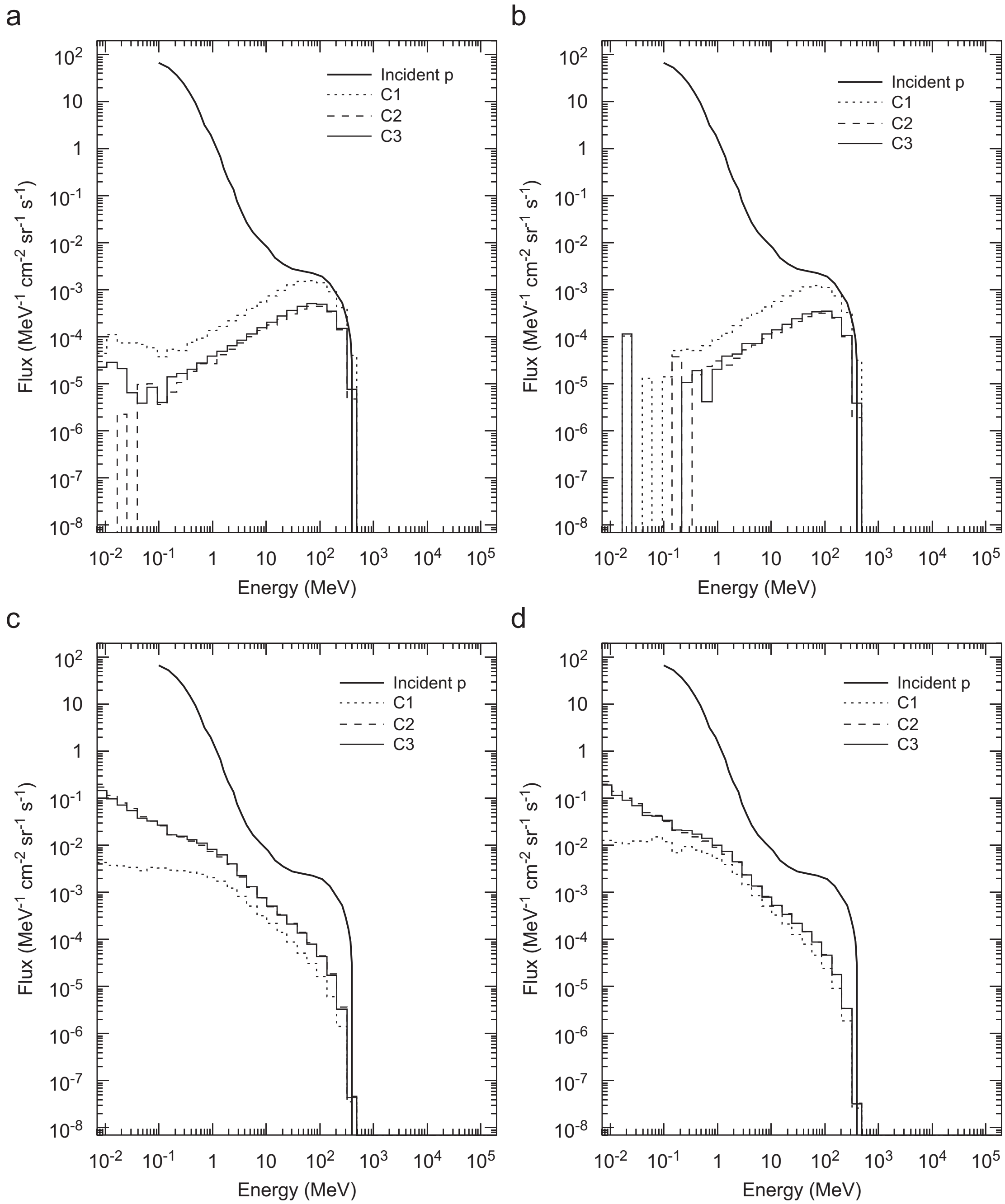

Fig. 4. Kinetic energy spectra of particles entering the Columbus cabin due to incident trapped radiation belt protons. (a) Primary and secondary protons entering Columbus (ISS model not included). (b) Primary and secondary protons entering Columbus (ISS model included). (c) Secondary neutrons entering Columbus (ISS model not included). The incident trapped proton spectrum is shown for comparison. (d) Secondary neutrons entering Columbus (ISS model included). The incident trapped proton spectrum is shown for comparison.

the C3 results, suggesting that minor improvements to the C3 model would be irrelevant.

In Fig. 4(a) the increased shielding capability of the massive C3 model compared to the lighter C1 model is evident. The peak proton flux is approximately a factor of three lower for C3. The neutron production is increased with thicker shielding, see Fig. 4(c). This results in almost an order of magnitude greater neutron flux in the radiobiologically most dangerous energy range of 100 keV–1 MeV (ICRP, 1990, 2003). Introducing additional mass in the form of the bulk ISS structure is also seen to reduce the proton flux (compare Fig. 4(a) and (b)) while increasing the neutron flux (compare Fig. 4(c) and (d)).

Fig. 5 shows corresponding results for incident GCR protons. In this case the shielding influences incident protons above 1 GeV very little. A tail of low-energy protons is present as a result of primary proton interactions. In contrast to Fig. 4, there are now more low-energy (< 1 GeV) protons with increased mass (C2/3 compared to C1). The increase of the neutron flux in

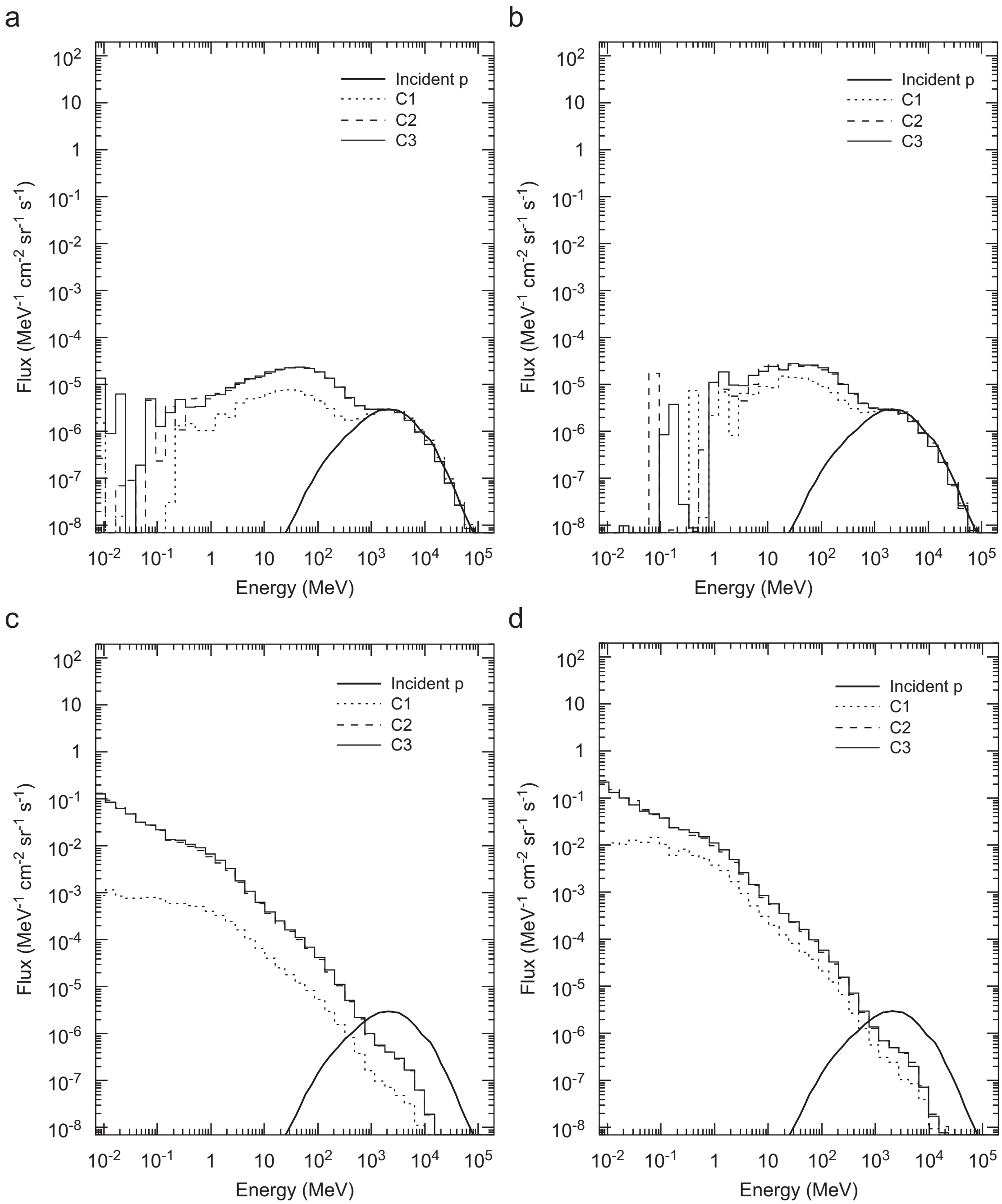

Fig. 5. Kinetic energy spectra of particles entering the Columbus cabin due to incident GCR protons. (a) Primary and secondary protons entering Columbus (ISS model not included). (b) Primary and secondary protons entering Columbus (ISS model included). (c) Secondary neutrons entering Columbus (ISS model not included). The incident GCR proton spectrum is shown for comparison. (d) Secondary neutrons entering Columbus (ISS model included). The incident GCR proton spectrum is shown for comparison.

the case of GCR protons is greater than for the trapped protons; the flux in the neutron energy range of 100 keV–1 MeV for C3 without ISS is up to a factor 30 greater than for C1 without ISS. As for trapped protons, the neutron flux is greater when ISS is present.

Artifacts from the energy biasing scheme described in Section 3.1 is visible in the low-energy tails of the proton spectra. Histogram bins in this energy range may have a greater statistical uncertainty than the associated bin content indicates.

4. Conclusions

The influence of geometry model approximations on Geant4 simulation results of the radiation environment inside the Columbus module of the International Space Station (ISS) has been investigated. Three geometry models of Columbus with different levels of detail, as well as a geometry model of ISS have been developed. The level of detail of the ISS model, especially of the remote parts, is of limited importance for studies of the Columbus radiation environment, and the ISS geometry model is therefore less detailed than the detailed Columbus model. These geometries have been used for Geant4 Monte Carlo calculations of the radiation environment inside Columbus induced by trapped protons and Galactic Cosmic Ray (GCR) protons. Simulated dose rates and particle spectra inside Columbus for each of the three Columbus models, both with or without the ISS geometry model enabled, are presented.

The simulated dose rates and particle spectra for the three different models were compared, and it was found that the most detailed geometry model (C3, 750 volumes) produced results similar to a much less detailed model (C2, 23 volumes). The great difference in level of detail of these models, leads to the conclusion that minor improvements to the C3 model would be irrelevant for general studies of trapped and GCR protons inside Columbus. There is also no room for major improvements compared to the physical Columbus and the C3 model is thus considered to be of adequate detail level for the present studies. An increased level of detail could only possibly be motivated for more detailed studies of the Columbus radiation environment, such as the dose rate dependency on the position or radiation flux from different solid angles.

The simulated dose rates are compatible with measurements on-board the ISS. The simulation results also show that an increase in shielding thickness decreases the simulated dose rate induced by trapped protons, while for GCR protons the dose rate remains unchanged or is slightly increased.

The important effects of GCR ions are not presented here, but will together with studies of effects of the trapped proton anisotropy and simulations of dose equivalent rates be the subject of future publications using the C3 geometry model. These studies will complete the goal of the DESIRE project, a detailed characterization of the Columbus radiation environment.

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