MODELLING OF AIRCREW RADIATION EXPOSURE DURING SOLAR PARTICLE EVENTS

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Abstract

A transport code analysis using the Monte Carlo N-Particle eXtended code, MCNPX, has been used to propagate an extrapolated particle spectrum based on satellite measurements through the atmosphere to estimate radiation exposure during solar storms at high altitudes. Neutron monitor count rate data from stations around the world were used to benchmark the model calculations during a Ground Level Event. A comparison was made between the model predictions and actual flight measurements taken with various types of instruments used to measure the mixed radiation field during GLE 60. A computer-code has been developed to implement the model for routine analysis.

1. Introduction

In 1990, the International Commission on Radiological Protection (ICRP) recognized the occupational exposure of aircrew to cosmic radiation[1]. In Canada, a Commercial and Business Aviation Advisory Circular (CBAAC) was issued by Transport Canada suggesting that action should be taken to manage such exposure[2]. In anticipation of possible regulations on exposure of Canadian-based aircrew in the near future, an extensive study was carried out at the Royal Military College of Canada (RMC) to measure the radiation exposure during flights.

The radiation exposure to aircrew is a result of a complex mixed-radiation field resulting from *Galactic Cosmic Rays* (GCRs) and *Solar Energetic Particles* (SEPs). Supernova explosions and active galactic nuclei are responsible for GCRs which consist of 90% protons, 9% alpha particles, and 1% heavy nuclei[3]. While they have a fairly constant fluence rate, their interaction with the magnetic field of the Earth varies throughout the solar cycles, which has a period of approximately 11 years. The radiation dose absorbed on airplanes due to GCR has been thoroughly studied and the empirically-based PCAire code developed at RMC can predict the radiation dose with good accuracy.

SEPs are highly sporadic events that are associated with solar flares and coronal mass ejections. While contributing less than 1% to the overall career exposure, this type of exposure may be of concern to certain aircrew members, such as pregnant flight crew, for which the annual effective dose is limited to 1 mSv over the remainder of the pregnancy[4]. The composition of SEPs is very similar to GCRs, in that they consist of mostly protons, some alpha particles and a few heavy nuclei, but with a softer energy spectrum.

To estimate the additional exposure due to solar flares, a model was developed using a Monte-Carlo radiation transport code, MCNPX. The model transports an extrapolated flux spectrum through the atmosphere using the MCNPX analysis. This code produces the estimated flux at a specific altitude where ICRP conversion coefficients are applied to convert the particle flux into an ambient dose equivalent. Transporting the flux through the atmosphere to ground level enables calculations of expected neutron-monitor count rates, which can be compared against neutron monitor (NM) data obtained from stations around the world. A cut-off rigidity model accounts for the shielding effects of the Earth's magnetic field.

2. Model Development

2.1 Solar Flare Particle Spectrum

The particle spectrum resulting from a solar flare is highly variable and sporadic. Satellite measurements provide near real-time data. One specific instrument is the Space Environment Monitor (SEM) on the Geostationary Operational Environmental Satellites (GOES). The SEM is capable of measuring the flux of solar and galactic particles and X-rays. The proton flux measurements necessary for our model are provided by energetic particle sensors (EPS) and the high-energy proton and alpha detector (HEPAD), which operate over a large range of energies.

In order to transport the particle spectrum through the atmosphere, the GOES measurements must be extrapolated to a high energy of 10 GeV, which is accomplished by fitting the GOES data to a power-law equation for the differential flux using:

$$\phi(E) = \frac{C}{\beta}\left(\frac{R}{R_o}\right)^{-\gamma} \tag{1}$$

where C and γ are fitting parameters. C is calculated using actual GOES measurements and γ is adjusted until the average variance between the extrapolated flux and the HEPAD measurements falls below 1%.

The particle rigidity R (in MV) is related to its energy E (in MeV) by the relation:

$$R = \sqrt{E\left(E + 2E_o\right)} \tag{2}$$

where E_o is the rest mass energy of the particle (in MeV) and $\beta = R/\,(R^2 + E_o^{\,2})^{1/2}$ is the particle velocity v normalized by the speed of light c. The parameter R_o = 239 MV in **(1)** corresponds to a particle energy of E = 30 MeV.

An example of the extrapolated spectrum using satellite data is shown in Figure 1.

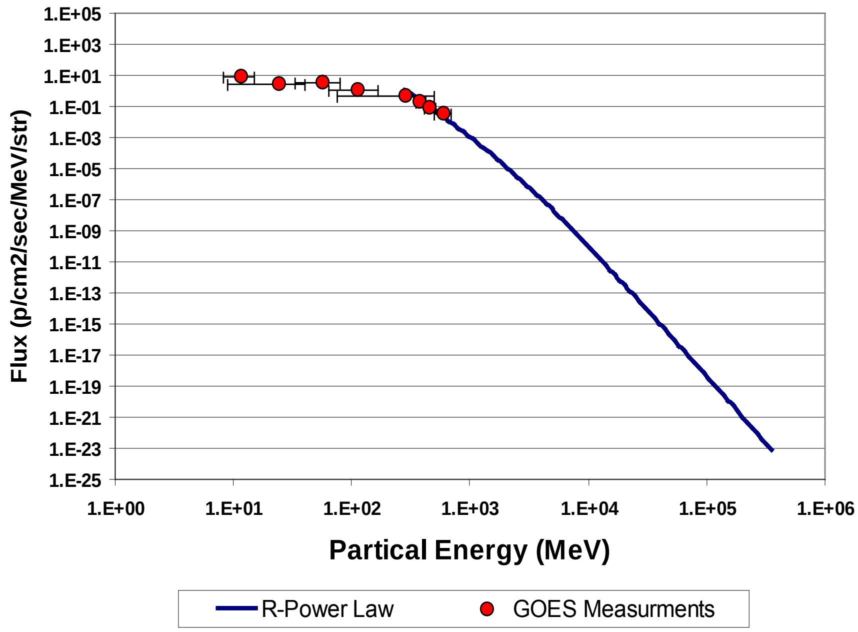


Figure 1 High-Energy extrapolation of differential proton energy data from the GOES satellite for GLE 60.

2.2 MCNPX Analysis

A Monte Carlo simulation refers to any simulation process in which there is a stochastic or random element, normally expressed in a simulation algorithm through the use of random numbers. Since particle physics models are very complex, it may be very difficult or even impossible to solve exactly for the properties of the system. A Monte Carlo simulation can be used for such models as a method for iteratively solving the problem of radiation transport.

Monte Carlo N-Particle eXtended code, MCNPX, is a 3-Dimensional Monte Carlo radiation transport code developed by the Los Alamos National Laboratory. The code is capable of tracking 34 particle types (nucleons and light ions) and 2000+ heavy ions at nearly all energies. It uses standard evaluated data libraries including physically-based models where data libraries are not yet available.

The MCNPX code (version 2.5) was used to determine the particle production and transport in the atmosphere. Although secondary particles are produced by interaction of primary cosmic ray particles with atmospheric nuclei, only the production of neutrons and protons were considered, as those particles are responsible for the majority of the radiation dose at high altitudes. The atmosphere was divided into 36 concentric shells using an average air density for a given shell thickness. Secondary particle energy spectra produced from an incident mono-energetic source particle were tracked in the analysis[5]. Combined particle spectra (at a given altitude) were therefore obtained by summing the secondary particle spectra derived from each mono-energetic primary particle based on the initial proton spectrum and helium spectrum. Dose conversion factors as well as neutron monitor response functions have been incorporated with the MCNPX results for a specific altitude[6].

As a preliminary test, the interstellar GCR spectrum was used to predict neutron and proton spectra on the ground and at an altitude of 17 km. These results were compared to those measured by Goldhagen and Gordon and were determined to be in reasonable agreement. [7-9] Further comparisons were made with measured neutron Bonner-sphere results for various altitudes and vertical cut-off rigidities (Figure 2).

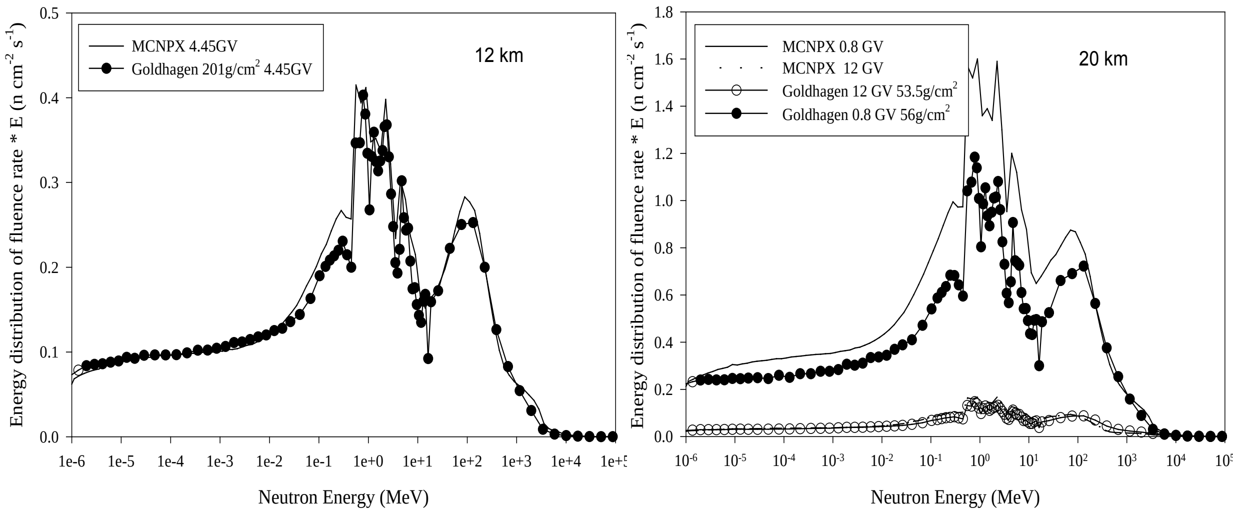


Figure 2 Comparison of predicted and measured neutron spectra at various altitudes and vertical cut-off rigidities.

Based on this agreement, the MCNPX analysis was applied to the SEP particle spectrum. For the GCR spectrum, a spherical geometry was used, since galactic rays are assumed to be isotropic, arriving from any direction. For the solar flare code, a planer source geometry was used. Figure 3 illustrates both geometries for transporting particles through the Earth's atmosphere.

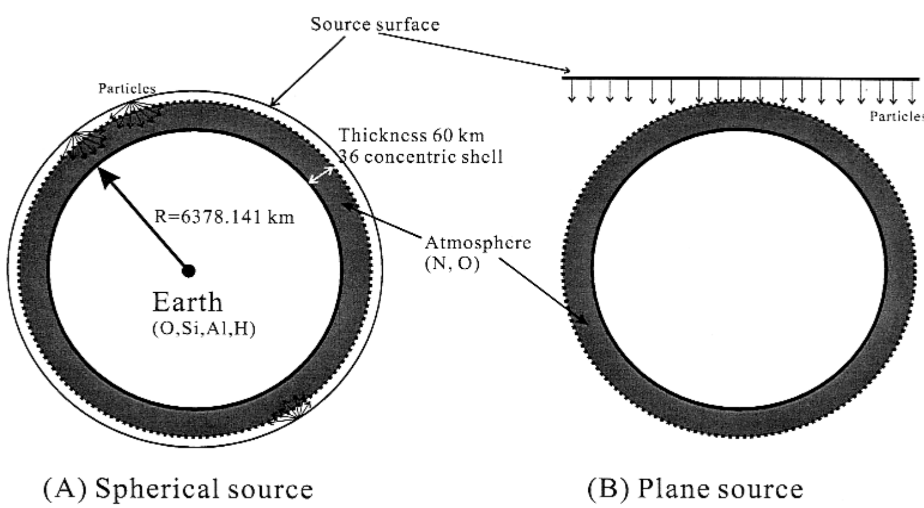


Figure 3 Spherical and planer geometry for MCNPX transport code

The coefficients obtained from the MCNPX analysis, P_{ij}, are combined with dose conversion coefficients, K_j, and NM response functions, R_j, using Equations **(3)** and **(4)**. Different coefficients are used for ambient dose equivalent rate ($\dot{H}$) and effective dose rate ($\dot{E}$) for equation **(3)**, while different NM detector type response functions are used in Equation **(4)**. A complete list of tabulated P_A and P_{NM} coefficients are given in Reference 6. The coefficient c accounts for the source detector geometry.

$$\begin{aligned}\dot{\mathrm{E}}, \dot{H}\,(\mathrm{Sv\,h^{-1}}) &= \sum_{i=1}^{m}\left[\sum_{j=1}^{n}\left\{c\cdot\Delta E_{i,i+1}\cdot K_j\cdot P_{ij}\cdot\left(\frac{3600\,\mathrm{s}}{\mathrm{h}}\right)\right\}\dot{\Phi}_{E,\Omega_i}^{prim}\right] \\ &= \sum_{i=1}^{m} P_A(E_i)\dot{\Phi}_{E,\Omega}^{prim}(E_i)\end{aligned} \quad \textbf{(3)}$$

$$\begin{aligned}\dot{C}\,(\mathrm{count\,h^{-1}}) &= \sum_{i=1}^{m}\left[\sum_{j=1}^{n}\left\{c\cdot\Delta E_{i,i+1}\cdot R_j\cdot P_{ij}\cdot\left(\frac{3600s}{h}\right)\right\}\dot{\Phi}_{E,\Omega_i}^{prim}\right] \\ &= \sum_{i=1}^{m} P_{NM}(E_i)\dot{\Phi}_{E,\Omega}^{prim}(E_i)\end{aligned} \quad \textbf{(4)}$$

2.3 Vertical Cut-off Rigidity

The Earth's magnetic field acts as a shield to incoming particles and radiation. Particles that do not have sufficient energy to penetrate the Earth's field are reflected back into space. Therefore, a model of the cutoff rigidity has to take into account the properties of the Earth's magnetic field as well as geographical position.

During an SPE, the Earth is bombarded with energetic particles causing major disturbances in the field. Not only do the particles contribute largely to the already-existing radiation (due to GCR), the solar wind during a geomagnetic storm can perturb the Earth's magnetic field thus lowering the cutoff rigidity.

The cut-off rigidity model used in this analysis is a value obtained by averaging a quiet sun model, R_U, and a noisy sun model, R_L. The quiet sun model uses the vertical cut-off rigidity, R_C (in GV) obtained from standard International Geomagnetic Reference Field (IGRF) maps (1995 model), while the noisy sun model is calculated using[10] :

$$R_L(GV) = \{1 - 0.54\exp(-R_c(GV)/2.9)\} \quad \textbf{(5)}$$

The effect of the cutoff rigidity is taken into consideration in the calculation by summing up only those particles with energies greater than the corresponding energy for a given vertical cutoff rigidity, R_c (using Eq. 2). A low pass energy filter was applied to match the NM data where primary protons with energy less than 430 MeV were ignored in the summation. This filter was chosen by matching predicted results to observed ground-level NM data. This filter accounts for the ability of lower energy particles to reach the neutron monitor at ground level.

Figure 4 illustrates the prediction of the model using various cutoff filters, leading to the final choice of 1 GV. Figure 5 shows a comparison between the predicted NM count rates against data from NM stations around the world for Ground Level Event (GLE) 60.

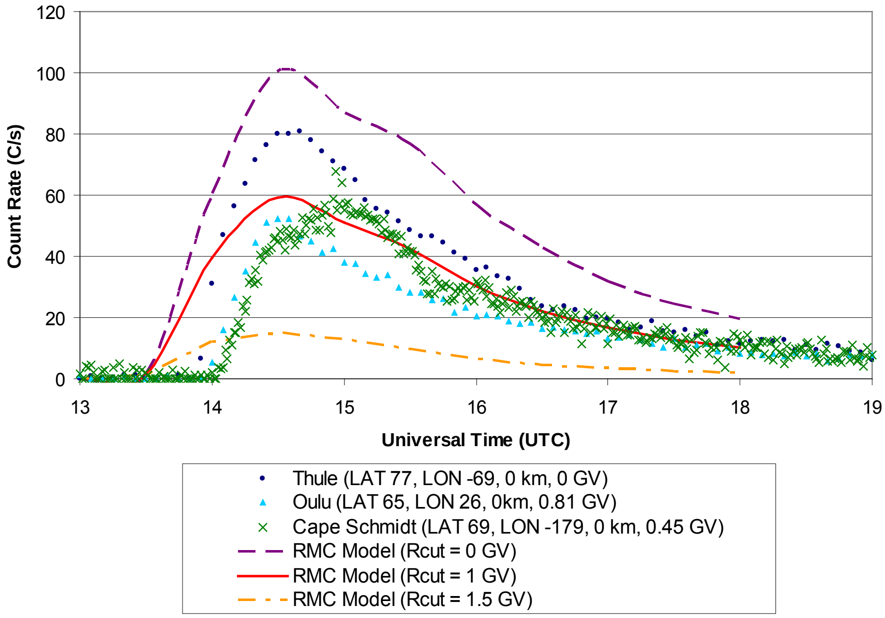


Figure 4 Observed count rate history (minus background GCR) versus model predictions for GLE 60 (April 15th, 2001)

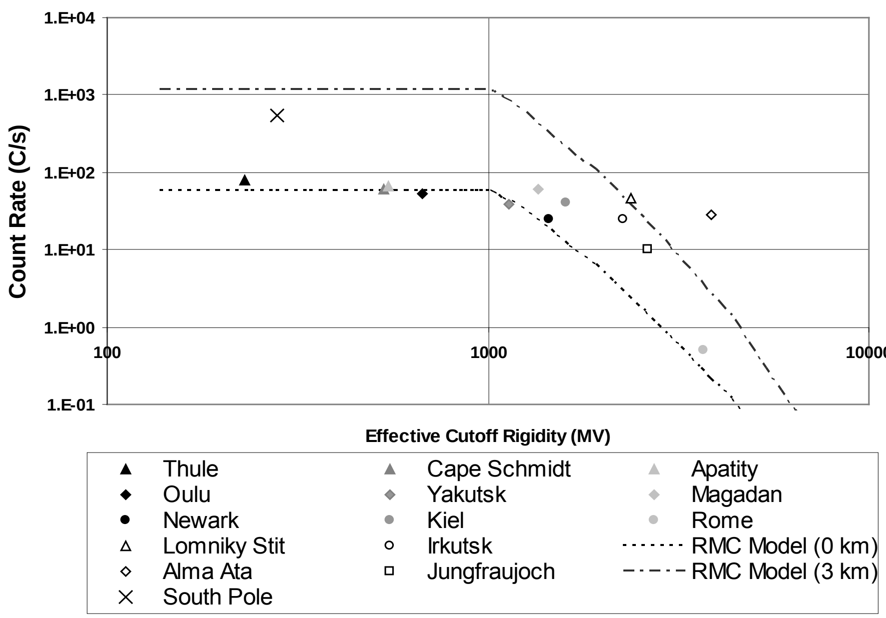


Figure 5 Comparison of the model calculations to the observed peak count rates for various NMs located around the world during GLE 60. (Hollow shapes represent NMs at an altitude of 3 km and solids represent NMs at an altitude of 0 km)

3. Software Development

To perform the calculation on a routine basis, a computer code was developed using C++. The code, compiled as a Dynamically Linked Library (DLL), includes several modules that perform all the necessary input data acquisition and great circle route calculations, as well as the analysis required for estimating the radiation dose absorbed by aircrew at a given altitude.

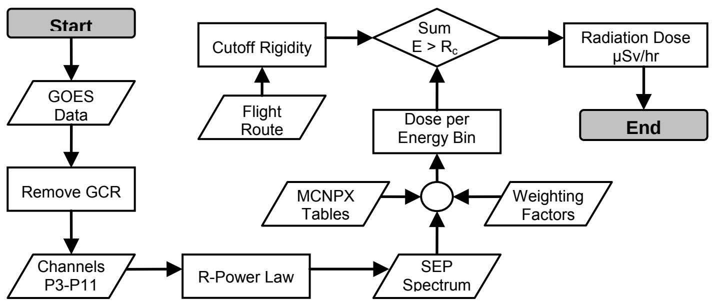


Figure 6 Flowchart describing the general methodology for calculating the radiation dose.

To simplify the end-user experience, a Graphical User Interface (GUI) was developed using Visual Basic that calls the DLL calculation routine. The GUI allows the user to enter flight data either in "Flight Information" mode or in "Waypoint" mode. In the former, the user provides the departure and arrival airports, and a great circle route calculator estimates the flight route. In the latter, the user provides a list of waypoints each containing latitude, longitude, and altitude information for the actual flight route. Figure 7 shows an image of the user interface running in "Flight Information" mode.

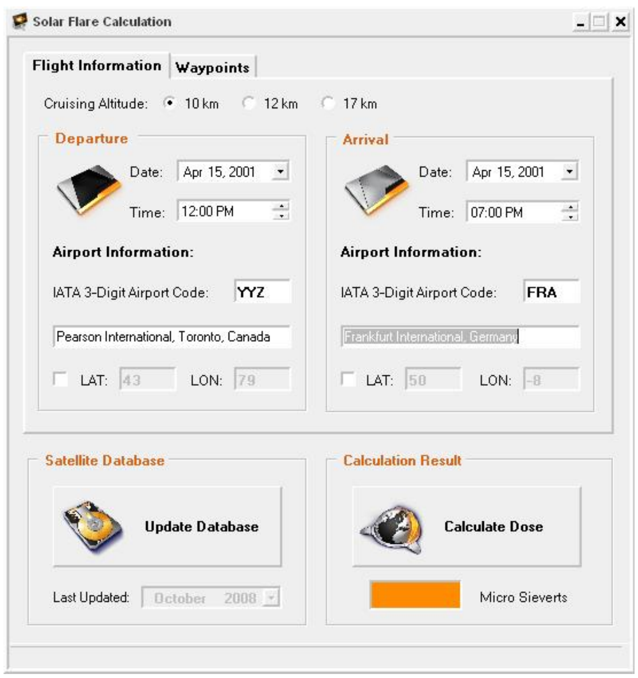


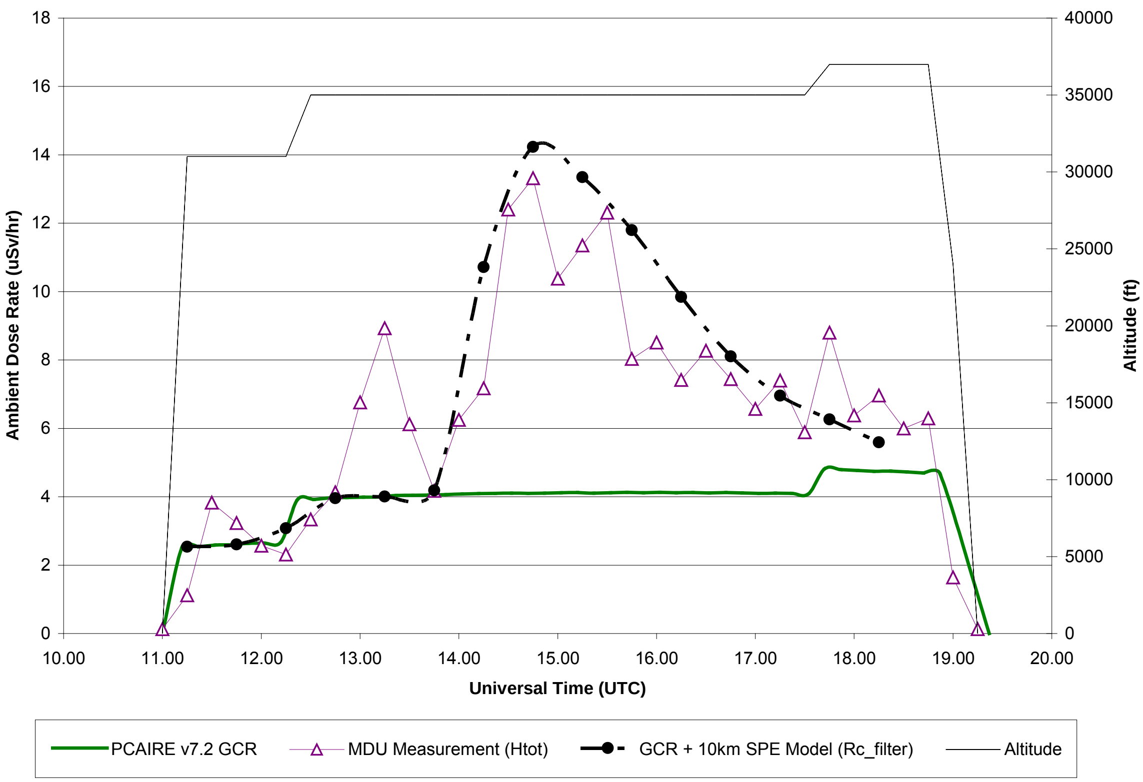
Figure 7 The graphical user interface used for implementing the solar flare calculation.

4. Results and Analysis

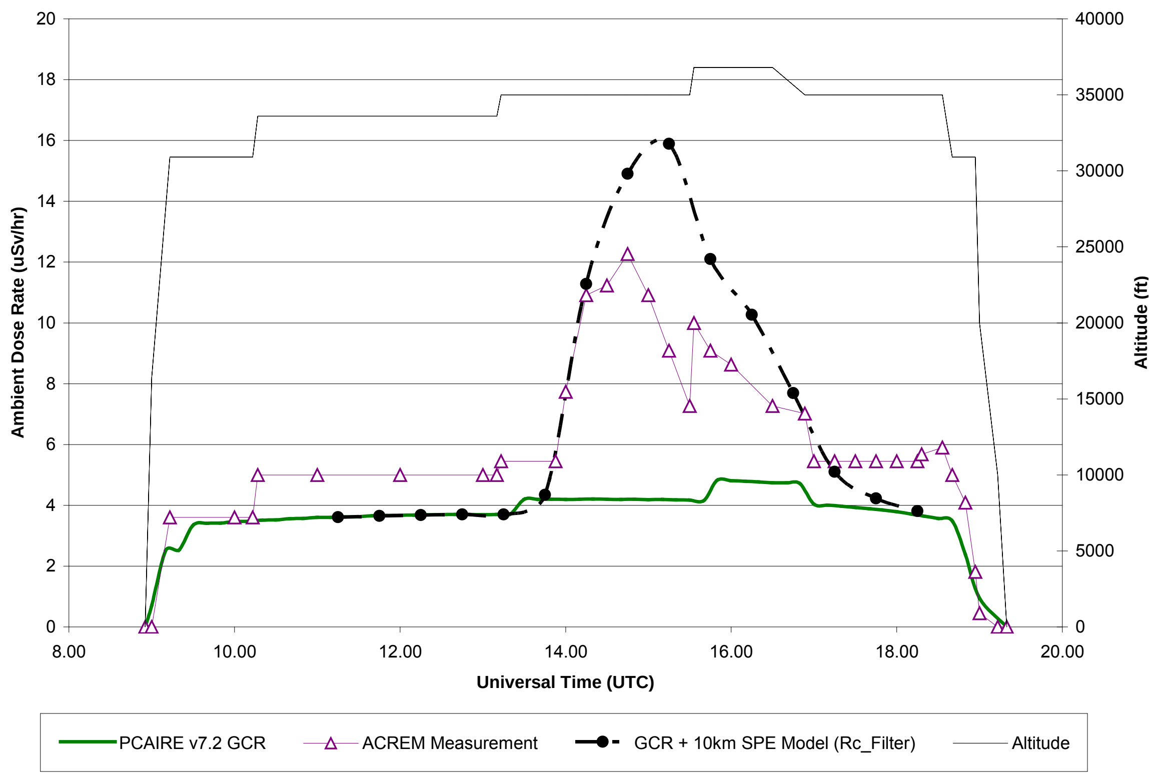
To test the validity of the model, it was necessary to perform the solar flare calculation on GLEs where actual flight measurements exist, allowing direct comparison. One such event is GLE 60, where flight measurements were taken as part of the EU DOSMAX (Dosimetry of Aircrew Exposure during Solar Maximum) project. One flight from Prague to New York (PRG-JFK) employed a MDU-Liulin device[11], whereas a second flight from Frankfurt to Dallas Fort Worth (FRA-DFW) used an ACREM monitor (scaled GM tube measurements) for radiation monitoring[12].

To calculate the SEP exposure, the initial proton fluence rates were first obtained by subtracting the GCR component from the GOES measurement. Here, the GCR component was obtained from spectra that were averaged prior to the event. The GCR exposure was estimated from the PCAire code and summed with the SEP estimate to obtain a total determination of the aircrew exposure.

The results are illustrated in Figures 8 and 9. Good agreement is observed with a discrepancy between the model and measurements of typically less than ±25%. As seen in the figure, the solar flare contributed 45% to the total cumulative dose of 54 μSv for the PRG-JFK route.



Figures 8 Comparison of calculations and measurements of the ambient dose equivalent rates during GLE 60 for PRG-JFK flight



Figures 9 Comparison of calculations and measurements of the ambient dose equivalent rates during GLE 60 for FRA-DFW flight

6. Current Research

6.1 MCNPX Analysis

The MCNPX analysis only considers the production of secondary neutrons due to incoming protons. A review of this approach that involves transporting additional particles may lead to improvement in the model. Since neutrons are one of many secondary particles that can be found at high altitudes, new runs of MCNPX that account for other reactions and other particles may be necessary.

6.2 Solar Flare Particle Spectrum

Current research on this project aims at improving various aspects of the model. The current model extrapolates limited satellite data to high-energies to obtain the initial particle spectrum. Improvement to the model can be achieved by combining neutron monitor data, which provide better information of the particle spectrum at high energies, with the satellite data. Collaboration with the US Naval Research Lab is currently under way to implement an improved particle spectrum model. An example of the proposed particle spectrum is shown in Figure 10.

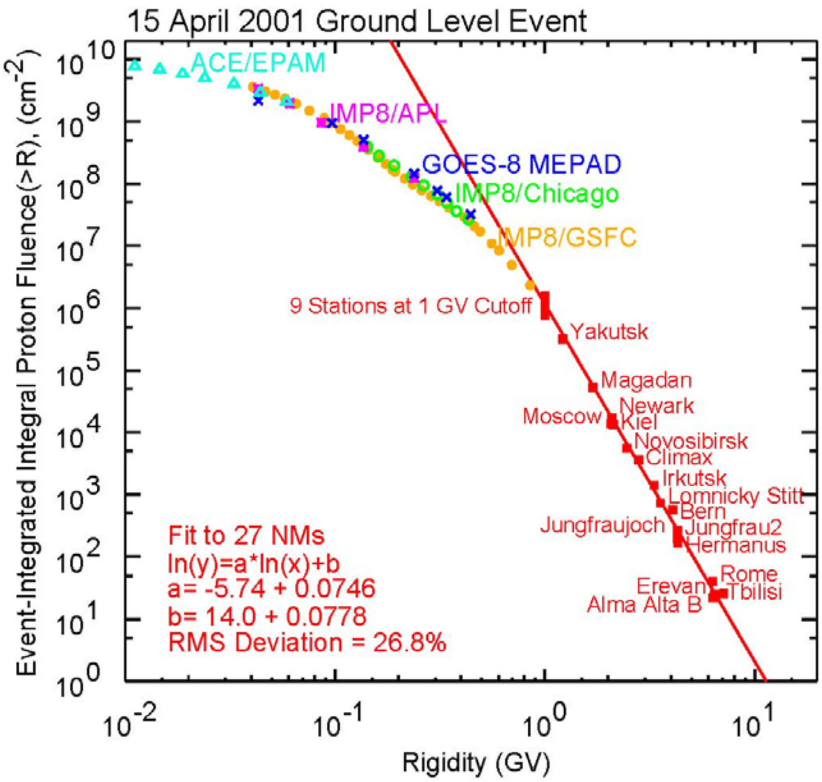


Figure 10 Particle spectrum obtained using the model proposed by Tylka *et al*.

6.3 Particle Anisotropy

The current model assumes a homogenous distribution of the incoming solar particles through the atmosphere without accounting for particle anisotropy. In reality, the particle distribution may be highly anisotropic, with certain regions receiving a significantly larger dose than other regions with the same cut-off rigidity.

To properly account for anisotropy, a study was done to predict neutron monitor responses based on an anisotropic behavior. This is accomplished by fitting an equation to neutron monitor data over a wide range of rigidities. This fitting process allows the derivation of the parameters needed for calculating the pitch angle distribution (PAD), which is a measure of the solar flare anisotropy. Once the PAD is derived, neutron monitor responses can be predicted and compared with actual measurements to determine how accurate the fit is. This allows the prediction of areas showing a higher response than other areas with the same cut-off rigidity.

The anisotropy analysis technique includes a least squares fitting procedure which allows the selection of an optimum solution for each of the time intervals considered during the event. For this technique to be successful, data must be selected from many neutron monitor stations that are widely separated in longitude and latitude. The responses of NM stations over a wide range of rigidities are required to determine the particle anisotropy and its axis of symmetry. This technique assumes that the response of neutron monitors to solar protons takes the form shown in equation (6). [13]

$$\frac{\Delta N}{N} = \frac{1}{9} \sum_{(\theta,\phi)=1}^{9} \frac{\sum_{P_{\min}}^{P_{\max}} Q_{(\theta,\phi)}(P) J(P) S(P) G(\alpha) \Delta P}{\sum_{P_{\min}}^{\infty} Q_{(\theta,\phi)}(P) J_o(P) S(P) \Delta P} \tag{6}$$

where
- ΔN absolute count rate increase due to solar protons
- N pre-event baseline count rate due to galactic cosmic rays
- P particle rigidity (GV)
- P_{min} lowest rigidity of particles considered in the analysis
- P_{max} maximum rigidity considered
- (θ,Φ) zenith and azimuth coordinates of incident protons arrival at the top of the atmosphere above the NM
- Q 1 for accessible directions of arrival and 0 otherwise
- J differential solar proton flux
- J_o interplanetary differential flux adjusted for the level of solar cycle modulation
- S neutron monitor yield function
- G pitch angle distribution of the arriving solar protons

The analysis divides the area above a neutron monitor into nine segments, each contributing an equal amount to the overall count rate response. This is the reason for the factor of 1/9th in front of the summation. The nine segments are illustrated in Figure 11.

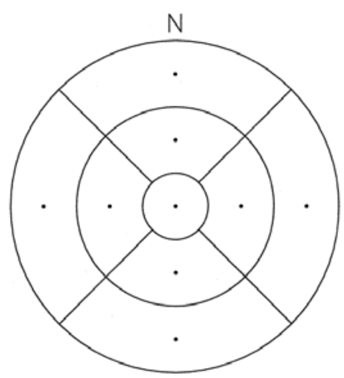


Figure 11 The segments above a neutron monitor. Viewing directions are calculated for each of the directions marked with dots (zenith angles 0°, 16°, 32° for azimuths 0°, 90°, 180°, and 270°).

While the full anisotropy model has yet to be developed, a great amount of work was put in to understand the problem of pitch angle distribution. The calculation used to derive the fitting parameters is computing intensive, and requires a fair amount of data processing. The first step involves calculating asymptotic viewing directions for every node on the earth's latitude/longitude grid. Asymptotic directions of arriving protons are calculated by tracing the trajectories of negative particles of the same rigidities moving away from the earth. The set of asymptotic directions of all allowed trajectories constitutes the asymptotic cone of acceptance for a particular latitude/longitude.

This process is done using MAGNETOCOSMICS, a code developed at the University of Bern, Germany. The code allows us to compute the propagation of charged cosmic rays through different magnetic field models of the earth's magnetosphere. It also allows us to compute cut-off rigidities and asymptotic directions of particle incidence. An example of MAGNETOCOSMICS' output can be seen in Figures 12.

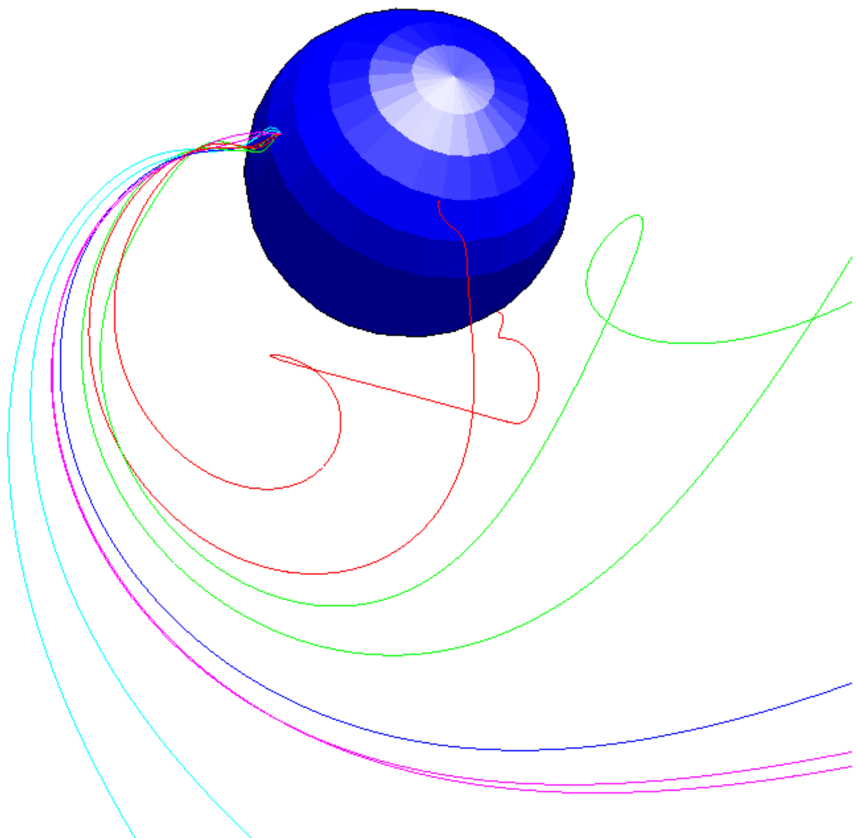


Figure 12 Visualization of MAGNETOCOSMICS' particle tracing. Particles with different energies are traced backwards from a given viewing location.

6. Summary and Conclusions

A transport code analysis with MCNPX is used to propagate an extrapolated particle spectrum based on satellite measurements through the atmosphere in order to estimate additional aircrew exposure from the SEP event. The transport code calculation is benchmarked against actual neutron spectra measured at high altitudes and on the ground. A routine methodology has been developed to estimate the aircrew exposure for the SEP contribution. These computations are compared with count rate data observed at various NMs on the ground as well as ambient dose equivalent rate measurements made on-board jet aircraft during GLE 60. Current research is focused on improving the solar particle spectrum, as well as introducing a new anisotropy model that uses neutron monitor responses and pitch angle data to identify anisotropy and correct for it.

7. References

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