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AIRCREW RADIATION EXPOSURE ESTIMATES AND THE EFFECT OF SOLAR FLARE ANISOTROPY

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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 particle events at aircraft altitudes. A comparison was made between the model predictions and actual flight measurements taken with various types of instruments during Ground Level Event 60. A computer-code has been developed to implement the model for routine analysis. Current research is focused on introducing a new anisotropy model that uses neutron monitor responses and pitch angle data to identify anisotropy and correct for it.

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. [4]

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.

An additional factor when analyzing SEPs is the effect of flare anisotropy. This refers to the way charged particles are transported through the earth's magnetosphere in an anisotropic fashion. Solar flares that are fairly isotropic produce a uniform radiation exposure for areas that have similar magnetic shielding, while highly anisotropic events produce variable exposures and are more difficult to model. Studies of neutron monitor (NM) count rates from detectors sharing similar magnetic shielding properties show a very different response during anisotropic events, leading to variations in aircrew radiation doses that may be significant for dose assessment.

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. A cut-off rigidity model accounts for the shielding effects of the Earth's magnetic field. The model has been tested against actual fight measurements. Current research aims at developing a model that can account for the flare anisotropy.

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%. Particle rigidity R (in MV) is related to its energy E (in MeV) by the relation:

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

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.

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 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. 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.

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 to predict the NM count rate ($\dot{C}$) 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.

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

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

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] :

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

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.

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.

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 1 shows an image of the user interface running in "Flight Information" mode.

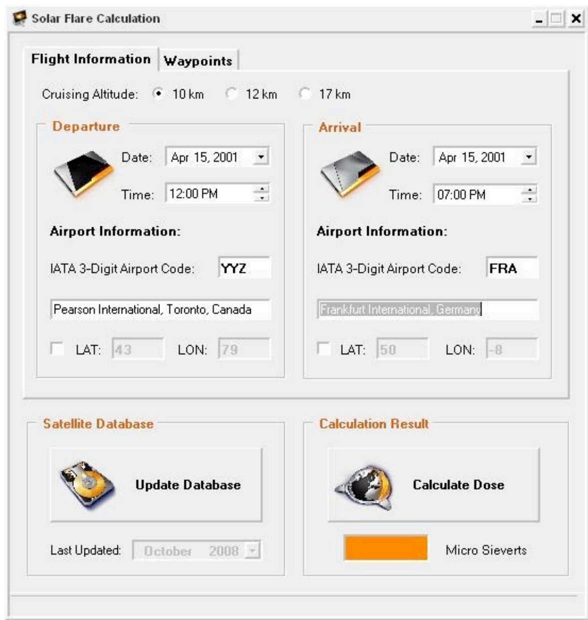

Figure 1 The graphical user interface used for implementing the solar flare calculation.

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) [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 2 and 3. 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.

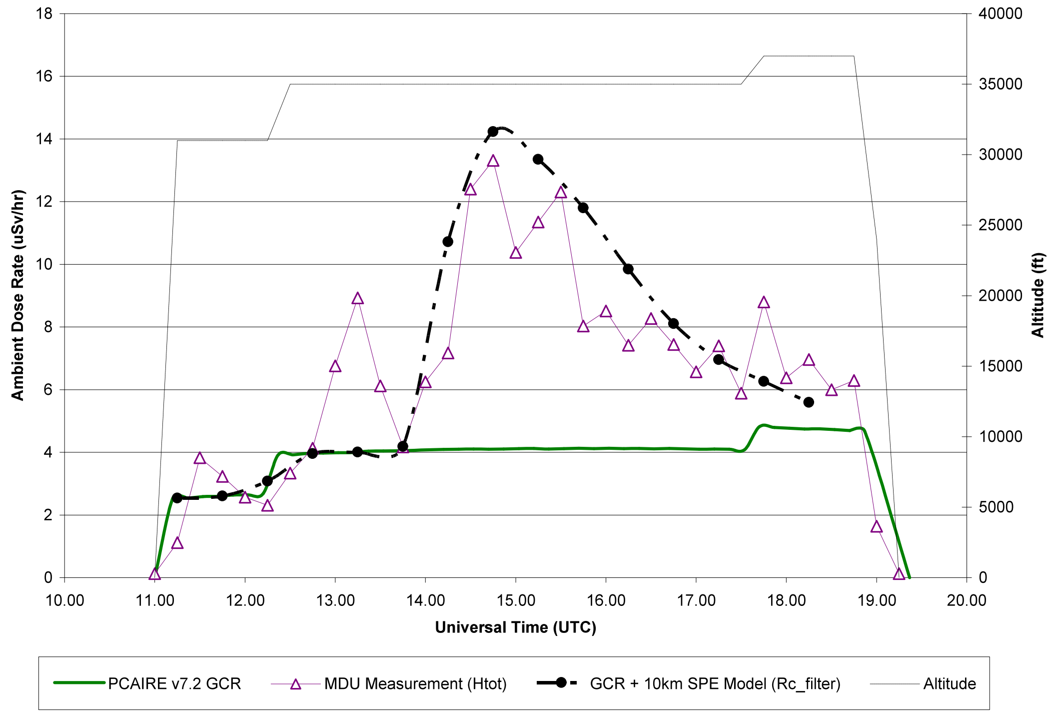

Figure 2 Comparison of calculations and measurements of the ambient dose equivalent rates during GLE 60 for PRG-JFK flight

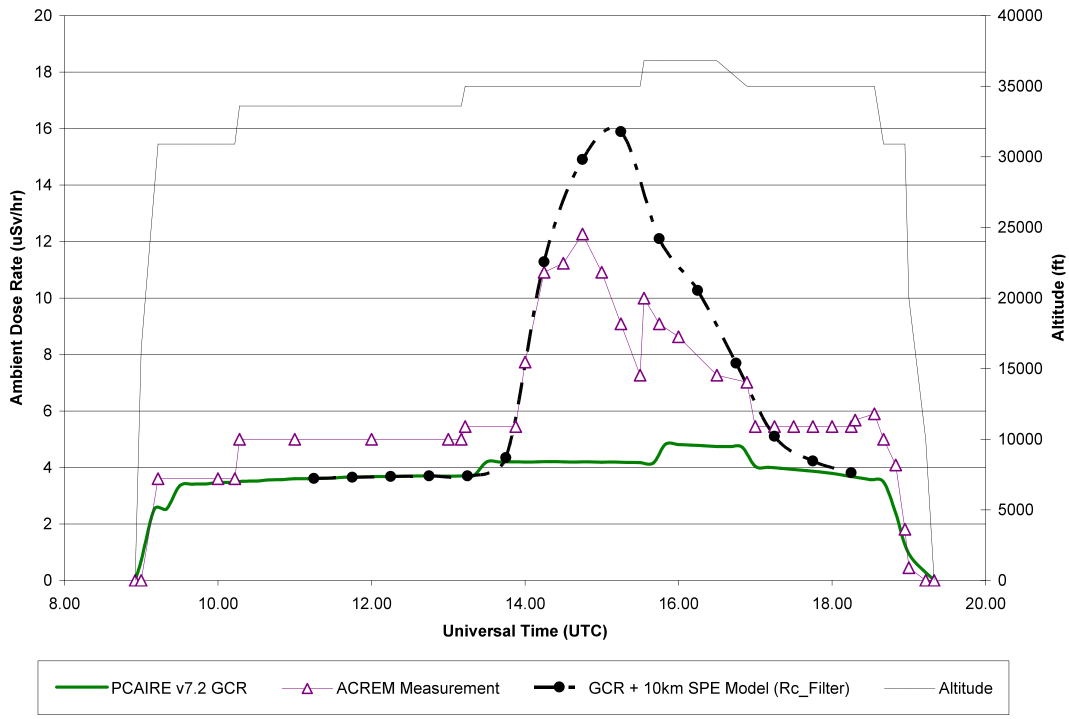

Figure 3 Comparison of calculations and measurements of the ambient dose equivalent rates during GLE 60 for FRA-DFW flight

5. Current Research

5.1 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 4.

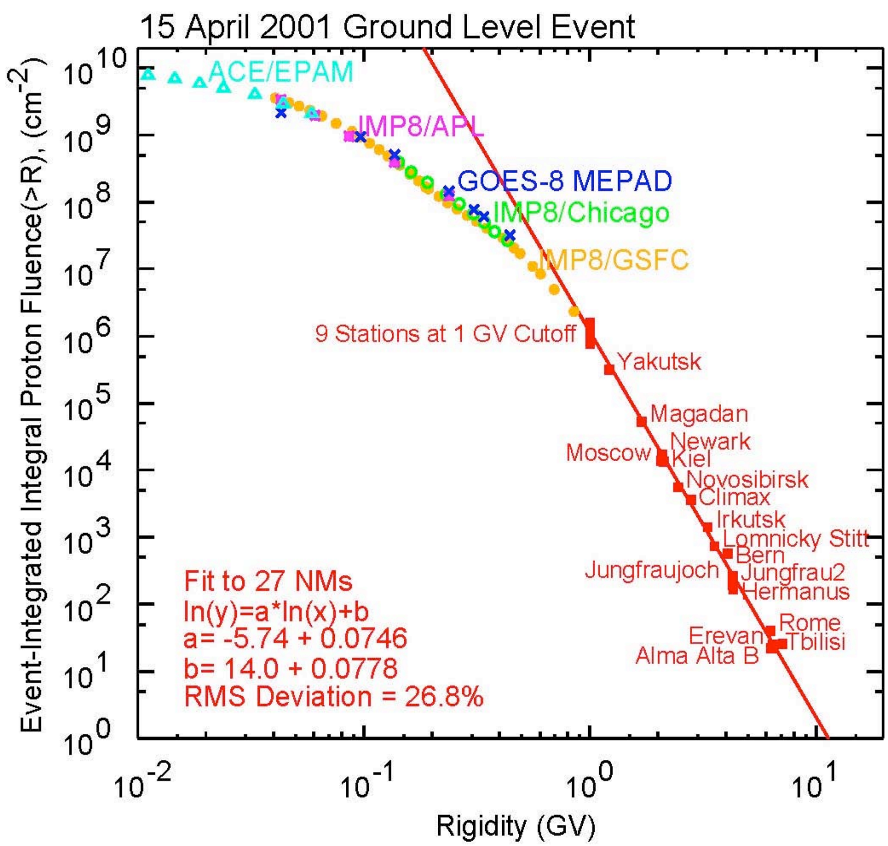

Figure 4 Particle spectrum obtained using the model proposed by Tylka *et al*.

5.2 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. This is evident in Figure 5, showing large variations in NM count rate data for different neutron monitors with similar cut-off rigidities during the event on December 13, 2006.

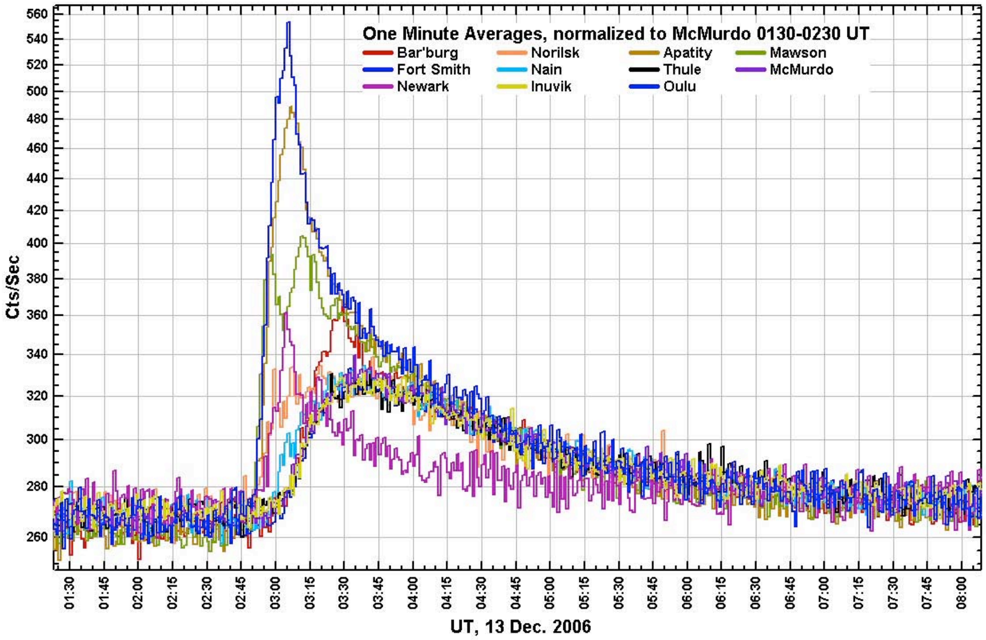

Figure 5 Observations of GLE 70 recorded by a variety of Neutron Monitors

An important concept when analyzing flare anisotropy is the asymptotic viewing direction. This viewing cone is defined as the set of all allowed trajectories from a given latitude/longitude. For an energetic particle to be detected at the viewing location, its trajectory must go through this cone. These viewing cones vary depending on the earth's magnetic field conditions along with solar storm effects. As a result, these viewing cones are unique for each event.

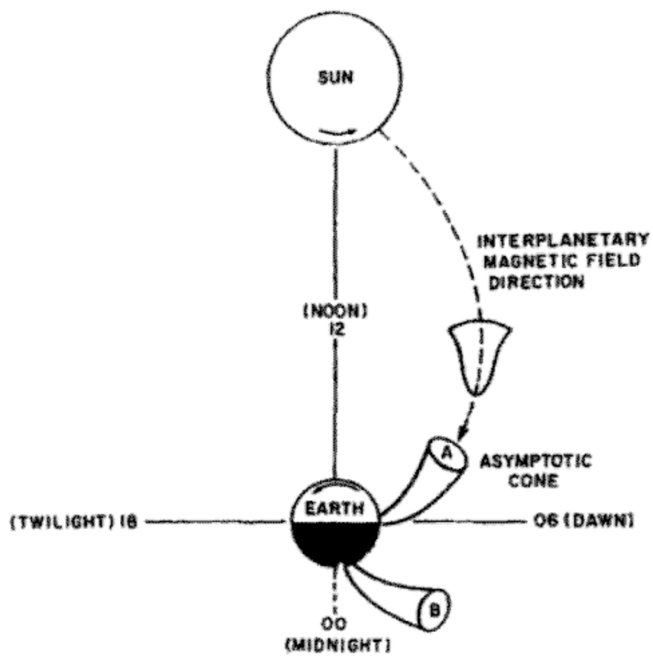

Figure 6 An illustration of asymptotic viewing directions and the trajectory required by solar particles to be detected at the viewing location [13]

During isotropic events, the charged particles ejected from the sun diffuse through the earth's magnetic sphere in a symmetrical fashion. However, during highly anisotropic events, the maximum particle flux is along the interplanetary magnetic field (IMF) direction at earth. This can be confirmed by plotting the peak increase in neutron monitor counts on an asymptotic directions map.

During a typical GLE, the maximum response for a sea-level neutron monitor is produced by the 2.2 GV particles. Thus, on an asymptotic map, the NM count rates are plotted at the latitude and longitude where the 2.2 GV particles enter the magnetopause, where the earth's magnetic field and the solar wind meet, not where the monitor is physically located. The IMF data can be obtained from special magnetometers onboard satellites such as the IMP-8.

Examples of this process are shown in Figures 7 and 8. For the GLE 38 event (7 DEC 1982), the IMF was at geographic latitude 44°, longitude 85°. For the GLE 44 event (22 OCT 1989), the IMF was geographic latitude -48°, longitude -146°. Both examples show that for highly anisotropic events, the maximum increase in neutron monitor count rates occurs at stations near the direction of the IMF at the time of the event.

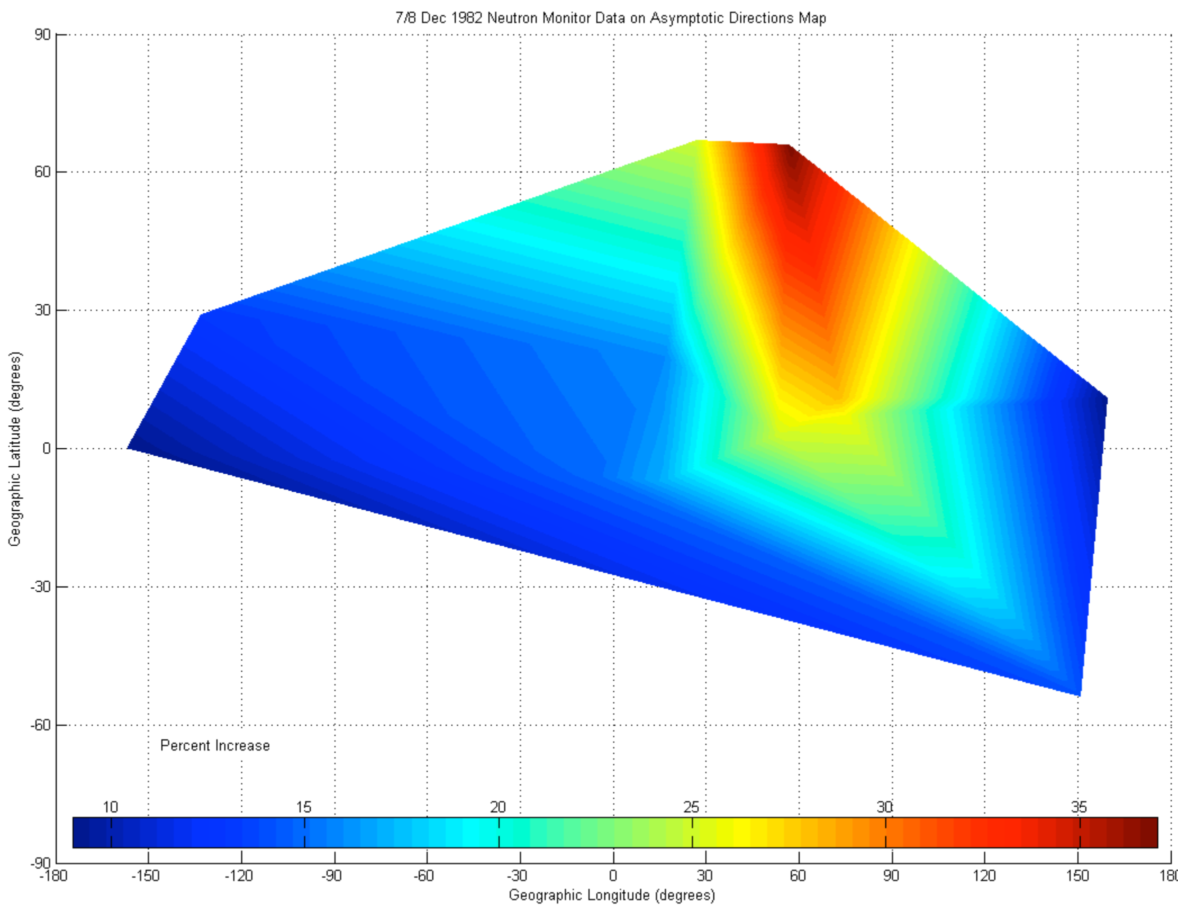

Figure 7 Neutron monitor peak increase during GLE 38 on an asymptotic directions map

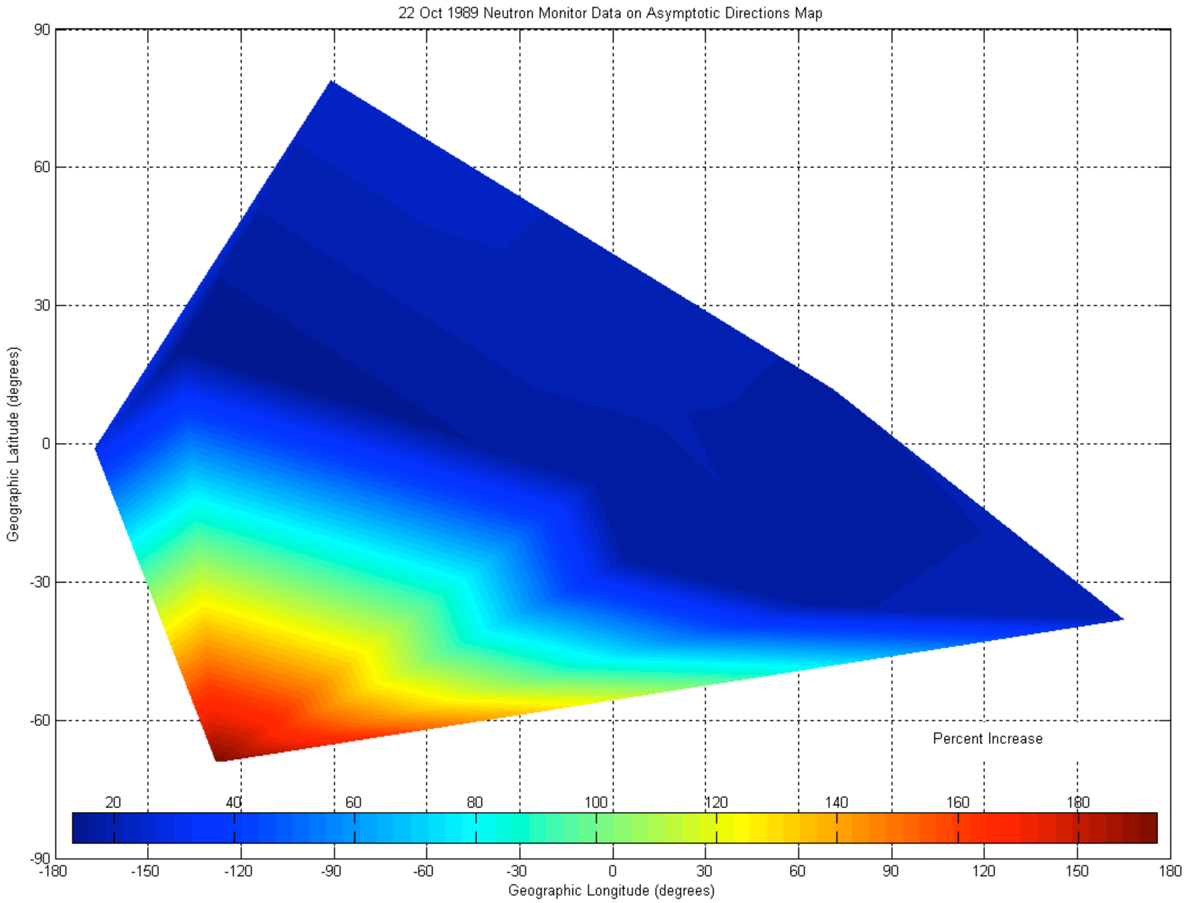

Figure 8 Neutron monitor peak increase during GLE 44 on an asymptotic directions map

To properly account for anisotropy, a study was done to predict neutron monitor responses based on an anisotropic behaviour. This is accomplished by fitting a response function 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). [14]

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

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 9.

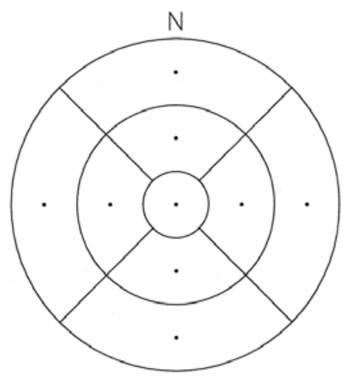

Figure 9 The segments above a neutron monitor. Viewing directions are calculated for each of the directions marked with dots (zenith angles 0°, 16°, 32° for azimuths 0°, 90°, 180°, and 270°).

The full anisotropy model is currently being developed provide the 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 one to compute the propagation of charged cosmic rays through different magnetic field models of the earth's magnetosphere. It also allows the computation of cut-off rigidities and asymptotic directions of particle incidence. An example of the MAGNETOCOSMICS' output can be seen in Figure 10.

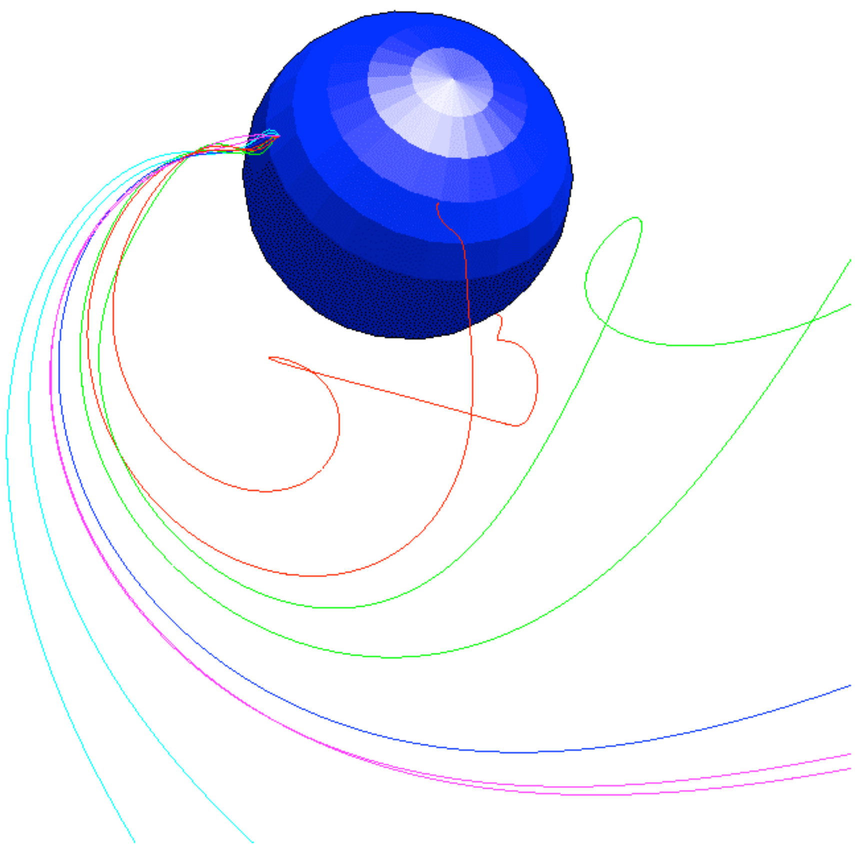

Figure 10 Visualization of MAGNETOCOSMICS' particle tracing. Particles with different energies are traced backwards from a given viewing location.

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 the development of a more sophisticated model to account for solar flare anisotropy effects which uses neutron monitor responses and pitch angle data .

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