ROYAL AEROSPACE ESTABLISHMENT

PARTICLE TRANSPORT SIMULATION FOR SPACEDRONE,
NaI GAMMA-RAY SPECTROMETERS

by

C. S. Dyer
P. R. Truscott
A. J. Sims
C. Comber
N. D. A. Hammond

RELEASED UNDER AGREEMENT

November 1986

Procurement Executive, Ministry of Defence
Farnborough, Hants

UNLIMITED
PARTICLE TRANSPORT SIMULATION FOR SPACEBORNE,
NaI GAMMA-RAY SPECTROMETERS

by
C. S. Dyer
P. R. Truscott
A. J. Sims
C. Comber
N. D. A. Hammond

SUMMARY

Radioactivity induced in detectors by protons and secondary neutrons limits the sensitivity of spaceborne gamma-ray spectrometers. Three dimensional Monte Carlo transport codes have been employed to simulate particle transport of cosmic rays and inner-belt protons in various representations of the Gamma Ray Observatory Spacecraft and the Oriented Scintillation Spectrometer Experiment. Results are used to accurately quantify the contributions to the radioactive background, assess shielding options and examine the effect of detector and spacecraft orientation in anisotropic trapped proton fluxes.
PARTICLE TRANSPORT SIMULATION FOR SPACEBORNE, NaI GAMMA-RAY SPECTROMETERS

Dr C S Dyer, P R Truscott, A J Sims
†Dr C Comber, Dr N D A Hammond

Abstract

Radioactivity induced in detectors by protons and secondary neutrons limits the sensitivity of spaceborne gamma-ray spectrometers. Three dimensional Monte Carlo transport codes have been employed to simulate particle transport of cosmic rays and inner-belt protons in various representations of the Gamma Ray Observatory Spacecraft and the Oriented Scintillation Spectrometer Experiment. Results are used to accurately quantify the contributions to the radioactive background, assess shielding options and examine the effect of detector and spacecraft orientation in anisotropic trapped proton fluxes.

Introduction

Radioactivity induced in scintillation detectors by cosmic rays, trapped protons and secondary neutrons produces an important source of background in spaceborne gamma-ray spectrometers. For the early detectors, which employed relatively lightweight crystals of NaI and CsI (a few pounds) on modestly sized spacecraft (a few hundred pounds), typical particle pathlengths through the spacecraft and detector material were significantly less than the nuclear interaction length and the direct spallation interactions of primary particles sufficed to explain the observed radioactivity. For the next generation of instruments to be carried on the Gamma Ray Observatory individual detector masses of order 2 tons are to be carried on a 15 ton spacecraft. Typical particle pathlengths exceed the nuclear interaction length and the consequent importance of secondary particles requires the application of particle transport codes. In a previous paper 1-D transport calculations, which employed the ANISN neutron code in spherical geometry, were used to assess the importance of secondary neutron capture on NaI and explore the efficacy of LiH shield layers around the central NaI elements. Such layers were in fact shown to be counterproductive and this result was confirmed by preliminary results from a 3-D simulation of trapped proton transport in a more representative geometry. In the current paper the full 3-D simulation is applied to a number of detector and spacecraft configurations in order to assess the dependence of the various background components on spacecraft and detector geometries and particle anisotropies.

Components of the Calculation

The Transport Suite

The codes used in this study all employ Monte Carlo techniques and include the High Energy Transport Code (HETC) for protons and energetic hadrons and the MORSE code for neutrons of less than 15 MeV. HETC is a nucleon/meson transport code which uses an intranuclear cascade and evaporation model to simulate the...
nuclear interactions. MORSE is a coupled neutron/gamma ray code which
utilises multigroup scattering and absorption cross-section data. It is
used here to transport neutrons over the energy range from 15 MeV down to
thermal energies using the neutron source generated by HETC. These codes
share a common combinatorial geometry package. Other codes used to predict
spallation product yields, time variations in induced radioactivity and energy-
loss spectra for decay products are as discussed in Ref 1.

Detector and Spacecraft Geometry

The detectors and spacecraft under study are representations of the Oriented
Scintillation Spectrometer Experiment (OSSE) to be carried on the Gamma Ray
Observatory. The OSSE detector employs four identical telescopes, each of
which comprise a 13 inch diameter central NaI/CsI phoswich (a phosphor sandwich
with a 4 inch thickness of NaI plus 3 inches of CsI and utilising the different
pulse shapes in the two materials to veto events arriving from the rear),
provided with an active NaI shield of about 3 inch thickness and a passive
slat collimator of tungsten to give an opening angle of 5° x 11°. The
telemicroscopes are orientable through about 192° in pairs. The combinatorial
geometry representation is illustrated in Figure 1. For simplicity the tungsten
collimator is represented by a diffuse mass of lower density having the same
total mass as the actual slat arrangement. The 6LiF layer around the inner
phoswich was given a thickness of 0.3 cm to represent the 6Li impregnated
silicone actually incorporated in the instrument. This material was incorporated
in order to reduce the influence of thermal neutrons arising from hydrazine
tanks and plastic scintillators carried on the spacecraft. In certain simulations
this thickness has been increased up to 5 cm to investigate the efficacy in
reducing the more energetic neutrons from the spacecraft and outer NaI shield.
Such increased thicknesses proved to be counterproductive in this case. For
certain simulations adjacent spacecraft material was represented by 10 cm of
aluminium on two sides as in Figure 1. In other cases an isolated telescope
was studied and in further cases a diffuse aluminium model of the spacecraft
was employed (Figure 2). Intercomparison of these cases enables consideration
of the relative importance of secondaries arising from the detector, local
material and spacecraft.

Proton Fluxes

The incident trapped proton and cosmic ray fluxes and their spectra are those
predicted for a 28.5°, 450 km orbit in 1991. As discussed in Ref 4, trapped
protons have a characteristic energy of 100 MeV and probably do not exceed
600 MeV, while the majority of cosmic ray interactions arise from protons in
the energy range from 6 to 30 GeV. The exact flux of trapped protons
experienced in the South Atlantic Anomaly remains in some doubt, in part due
to uncertainties in the models and in part due to debate as to the correct
procedures for incorporating the influence of the time varying geomagnetic
field. In the light of this debate Stassinopoulos' has recently revised the
GRO proton fluence estimates and uses two alternative approaches to arrive at
integral daily fluences in excess of 100 MeV of 3.6 x 10^5 and 7.1 x 10^5 cm^-2.
In this paper we therefore use a value of 5 x 10^5 with an uncertainty factor of
two. This fluence is a factor of three lower than the value used in Ref 4.
For simplicity isotropic incidence has been used in most cases. However use
of these 3-D codes enables the influence of alternative distributions to be
studied. Such effects are likely to be more important for trapped protons as
they are highly anisotropic and also less penetrating than cosmic rays. Recent
studies of Space Station shielding have led to reconsideration of the spatial
distribution of South Atlantic Anomaly protons. Using this work proton
distributions have been generated as in Figure 3, which shows that,
in the SAA, protons are close to their mirror point and have pitch angles close
to 90°. There is a further East-West anisotropy which increases with energy and
is due to the removal of particles by the atmosphere.
Results

Sample results obtained to date are presented in Tables 1 and 2 for isotropic trapped protons and cosmic rays respectively for the geometries discussed above. The 1-D case is that studied in Refs 2 and 4 but using the revised trapped proton estimate, and in all cases the nominal shielding thickness of 0.3 cm of LiH is used. It can be seen that results are in generally good agreement between the 1-D studies and the 3-D study on the isolated detector, the latter case tending to be higher by up to a factor of 2. This is presumably due to the more accurate treatment of the cascades to include tertiary and higher order products. Analysis shows that the production of particle cascades enhances the spallation background over that due to primaries by up to a factor of 3 for trapped protons and up to a factor of 13 for cosmic rays. The additional production of $^{129}$I increases the overall background enhancement factors to 4.7 and 19.0 respectively. Comparison of the rates between the various geometries indicates that the presence of other detectors and spacecraft material has a net shielding benefit for trapped protons but has a deleterious effect for cosmic rays. This is due to the greater penetration and higher multiplicities for the production of secondaries of the more energetic cosmic rays.

Using the rates from the last rows of each table the best estimate of the spectra of the radioactive background components has been revised and results are presented in figures 4 and 5. The lower estimate for the SAA proton fluence and the higher multiplicities for cosmic ray effects raise the relative importance of the cosmic ray components compared with the estimates of Ref 2.

It can be seen that the production of $^{129}$I by neutron capture provides a significant component of the background. Use of Monte Carlo codes enables neutron tagging to ascertain the origin of the neutrons which eventually capture in the central NaI element. Results are presented in Table 3 and confirm that the majority of captures in fact arise from neutrons originating in the same detector. Furthermore, within a detector the majority of captures in the central NaI are due to neutrons generated in the surrounding materials, primarily the massive NaI shield. This implies that any neutron shieldings strategy must aim to shield the central NaI from the remainder of the detector structure. However attempts to use thermalising absorbers have appeared counterproductive. This is confirmed in Figure 6 which presents the influence of varying the amount of LiH shielding upon $^{129}$I production rates in the central NaI crystal for the trapped proton case for all the simulations and geometries. The deleterious influence of thermalising absorber on the $^{129}$I component is confirmed. This is more marked when there is a large source of neutrons as is the case for both the 1-D study, when the detector was allowed to grow with increased LiH thickness, and the full spacecraft simulation. The effect of an alternative neutron shield location has also been examined. Naively it might be supposed that positioning an LiH shield midway in the outer NaI shield could provide some advantage as it could then thermalise and absorb neutrons from the outermost annulus of NaI while the thermalised neutrons escaping would in part be removed by the inner annulus before entering the central NaI. Such a design would be more likely to be effective for the trapped proton source as in this case the neutron production is more biased towards the outside. Hence a simulation has been performed incorporating a 2 cm LiH layer at the expense of the central 2 cm of the outer NaI shield. Results for neutron capture and spallation are in fact not significantly different (7% enhanced) from the case for zero neutron shield. Thus use of LiH shielding is not a promising approach for current sizes of detector. However it should be noted that the spacecraft model contained no thermalising materials. If the external neutron source has a thermal component it is possible that small thicknesses could have a net benefit against this component of the background.
Preliminary investigations have been made of the influence of detector orientation and particle anisotropies. Reorientation of the detectors with respect to the spacecraft within an isotropic flux gives variations which are currently not statistically significant and at present can be sized at less than 15%. However use of the trapped proton anisotropies of Fig 3 as input to the simulations indicates that activation of the central crystal can vary by about a factor of 2.3 between what are presumed to be the best (spacecraft to the West of the detectors) and worst (spacecraft to the South of the detectors, detectors pointing West) cases (Fig 7). Activation of the tungsten collimator is a factor of 4 higher for the worst case. Hence trapped proton effects could be diminished somewhat by appropriate orientation during South Atlantic Anomaly traversals. Further studies are needed using a more accurate representation of the collimator and covering a wider range of orientations while taking account of the mission constraints in order to determine the exact improvement that is possible.

Acknowledgements

This work has benefited from collaboration with Dr J Kurfess and other members of the GRO/OSSE team at the Naval Research Laboratory, Washington DC.

References

3 W W Engle, Jr, ORNL-RSIC,CCC-254 (1973)
5 K C Chandler and T W Armstrong, ORNL-4744 (1972)
6 M B Emmett, ORNL-4972 (1983)
9 E G Stassinopoulos, J W Barth, R L Smith, NASA/GSFC X-600-87-9/10 (1987)
### TABLE 1
**TRAPPED PROTON EFFECTS**

Daily trapped proton fluence $= 5.0 \times 10^5$ cm$^{-2}$, $E_p > 100$ MeV

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mean Production Rates s$^{-1}$ in Central NaI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutrons</td>
</tr>
<tr>
<td>1-D isolated</td>
<td>1119</td>
</tr>
<tr>
<td>3-D isolated</td>
<td>2033</td>
</tr>
<tr>
<td>3-D 4 detectors + 10 cm Al</td>
<td>1235</td>
</tr>
<tr>
<td>3-D 4 detectors + spacecraft</td>
<td>1038</td>
</tr>
</tbody>
</table>

### TABLE 2
**COSMIC RAY EFFECTS**

Average Cosmic ray flux $= 0.16$ cm$^{-2}$ s$^{-1}$, $E_p > 100$ MeV

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mean Production Rates s$^{-1}$ in Central NaI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutrons</td>
</tr>
<tr>
<td>1-D isolated</td>
<td>1421</td>
</tr>
<tr>
<td>3-D isolated</td>
<td>1409</td>
</tr>
<tr>
<td>3-D 4 detectors + spacecraft</td>
<td>1690</td>
</tr>
</tbody>
</table>

### TABLE 3
**ORIGIN OF CAPTURED NEUTRONS**

<table>
<thead>
<tr>
<th>Proton Source</th>
<th>Fraction of Total Captures in Single Detector by Neutrons from:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Same Detector</td>
</tr>
<tr>
<td>Inner Belt</td>
<td>0.73</td>
</tr>
<tr>
<td>Cosmic Rays</td>
<td>0.81</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proton Source</th>
<th>For '1' above Fraction of Captures in Central NaI by Neutrons from:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Central NaI</td>
</tr>
<tr>
<td>Inner Belt</td>
<td>0.16</td>
</tr>
<tr>
<td>Cosmic Ray</td>
<td>0.37</td>
</tr>
</tbody>
</table>
Fig. 3 Proton directional flux distributions for the SAA show a narrow Gaussian in cosθ, where θ is the pitch angle, and a preferential flux of protons travelling geomagnetically eastwards (θ = 90°), particularly at high energies.
COSMIC RAY ACTIVATION AT 9 DAYS

SAA ACTIVATION AT 1 HOUR AFTER LAST PASS ON DAY 10

Fig. 4 Energy-loss spectra are compared for radioactivity induced by spallation and neutron capture in the central NaI crystal due to interactions with cosmic rays for 9 days in orbit at 450 km, 28.5. Results are from the full 3-D spacecraft plus detector simulation.

Fig. 5 A comparison similar to Fig. 4 is made for radioactivity induced by inner-belt protons, taking levels appropriate to 1 hour after the last significant SAA pass on day 10. Full 3-D simulation of spacecraft plus detector is used with isotropic trapped proton fluxes at the revised intensity.
NEUTRON CAPTURES ON IODINE IN INNER SODIUM IODIDE ZONE
COMPARISON OF THE FOUR ILLUSTRATED GEOMETRIES; TRAPPED PROTON SOURCE

Neutron captures in inner zone per second

- Full spacecraft geometry
- Isolated detector
- 4 detectors and 10cm Al plate
- ANISN

LiH shielding thickness (cm)

Fig. 6

BEST CASE

Magnetic Field Direction

Maximum Flux

ORIENTATION OF OSSW WITH RESPECT TO THE MAGNETIC FIELD AND DIRECTION OF MAXIMUM FLUX

WORST CASE

Magnetic Field Direction

Maximum Flux

ORIENTATION OF OSSW WITH RESPECT TO THE MAGNETIC FIELD AND DIRECTION OF MAXIMUM FLUX

Fig 7 Supposed best and worst case orientations with respect to the geomagnetic field and the direction of maximum trapped proton fluxes.
Particle transport simulation for spaceborne, NaI gamma-ray spectrometers

IEEE Nuclear and Space Radiation Effects Conference, Portland, Oregon, USA, 11-15 July, 1988

C.S. Truscott, P.R. Sims, A.J., Comber, C. Hammond, N.D.A.

RAE TN Space 365

Abstract

Radioactivity induced in detectors by protons and secondary neutrons limits the sensitivity of spaceborne gamma-ray spectrometers. Three dimensional Monte Carlo transport codes have been employed to simulate particle transport of cosmic rays and inner-belt protons in various representations of the Gamma Ray Observatory Spacecraft and the Oriented Scintillation Spectrometer Experiment. Results are used to accurately quantify the contributions to the radioactive background, discuss shielding options and examine the effect of detector and spacecraft orientation in anisotropic trapped proton fluxes.