MONTE CARLO CALIBRATION OF THE SMM GAMMA RAY SPECTROMETER FOR HIGH ENERGY GAMMA RAYS AND NEUTRONS

J. F. Cooper and C. Reppin
Max Planck Institute for Extraterrestrial Physics
D-8046 Garching, F.R.G.

D. J. Forrest and E. L. Chupp
University of New Hampshire, Durham, N.H. 03824, U.S.A.

G. H. Share and R. L. Kinzer
Naval Research Laboratory, Washington, D.C. 20375, U.S.A.

1. Introduction. The Gamma Ray Spectrometer /1/ on the Solar Maximum Mission spacecraft was primarily designed and calibrated for nuclear gamma ray line measurements, but also has a high energy mode which allows the detection of gamma rays at energies above 10 MeV and solar neutrons above 20 MeV. The GRS response has been extrapolated until now for high energy gamma rays from an early design study /2/ employing Monte Carlo calculations. The response to 50-600 MeV solar neutrons was estimated from a simple model which did not consider secondary charged particles escaping into the veto shields /3/. In view of numerous detections by the GRS of solar flares emitting high energy gamma rays /4/, including at least two emitting directly detectable neutrons /3,5,6/, the calibration of the high energy mode in the flight model has been recalculated by the use of more sophisticated Monte Carlo computer codes described in Section 2. New results presented in Section 3 show that the GRS response to gamma rays above 20 MeV and to neutrons above 100 MeV is significantly lower than the earlier estimates.

2. Monte Carlo Simulation of the GRS. The simulation of GRS response in the high energy mode has required several stages of software development: (1) representation of the principal materials and structures, both active and passive, by combinatorial geometry routines, (2) propagation of primary photons, and their secondary interaction products, through the GRS with the Electron-Gamma Shower Code (EGS) /7/, (3) propagation of neutrons and their secondary products with the High Energy Transport Code (HETC) /8/ and with EGS, (4) calculation of charged particle scintillation efficiencies /9/, and (5) the final selection of events satisfying pulse height logic criteria.

The combinatorial geometry routines give an accurate representation of the GRS flight model /1/, consisting of seven (7.6-cm x 7.6-cm) NaI detectors in an upper array and a large (24.2-cm x 7.6-cm) CsI detector, located 18 cm below the upper array. These detectors are surrounded by an array of plastic and CsI veto shields to reject charged particle events.

In the calculations the flight model is represented by fifty active scintillator or passive structure elements. These volume elements are defined in terms of intersections or unions of solid cylinders, cylindrical shells, hemispherical shells, and planar boundaries, in order to represent the upper NaI and lower CsI detector crystals, photomultiplier tube assemblies between the upper and lower detectors, the plastic and CsI shields, and the principal supporting structures, including the metal housings for the active detectors and shields. A significant improvement over the previous study /2/ is in the treatment of empty interstitial spaces between the material volumes. Tracking of Monte Carlo particles through all of these volumes and boundaries is accomplished with common geometry routines in EGS and HETC.

The compatibility of the tracking routines is particularly useful for the simulation of neutron interactions, which produce secondary products requiring two-stage tracking, first by HETC for nucleons and pions, and then by EGS for secondary gamma rays from pion decay or the de-excitation of nuclei excited by collisions. Interactions of nucleons and pions with target nuclei, and the residual excitation energy emitted as gamma rays, are simulated with the two-stage intranuclear-cascade and nuclear evaporation routines in HETC. A low energy cutoff of 15 MeV is used for the propagation of nucleons and pions in HETC, although the intranuclear cascade model, decomposing interactions with nuclei into individual collisions with the constituent nucleons, is not valid for collision energies below 100 MeV. EGS uses cross sections derived from analytical formulae or experimental data to simulate the interactions of gamma rays above 100 KeV and electrons above 500 KeV. Cumulative errors due to Monte Carlo statistics and the accuracy of the interaction cross sections used in both HETC and EGS are about 10-20 percent.

The present calculations use only a rough approximation procedure for energy deposition in the detectors by secondary neutrons produced at energies below 15 MeV. The neutron response calculations have been run for two cases: (1) the low energy neutrons produced below 15 MeV deposit their full energy locally via nuclear recoil or inelastic interactions, or (2) these neutrons escape from the GRS without any further interaction. The final neutron responses are the average of the results from these two cases, significantly different for 50-100 MeV neutrons but much less so for higher energies.

The pulse height logic criteria for gamma ray or neutron events in the high energy mode are the following: (1) 10-100 MeV electron-equivalent energy deposited in either the upper NaI detector assembly or the lower CsI detector, or in both, (2) no deposits greater than about 3 MeV in the annular CsI side shields, and (3) no deposits greater than about 500 KeV in either the

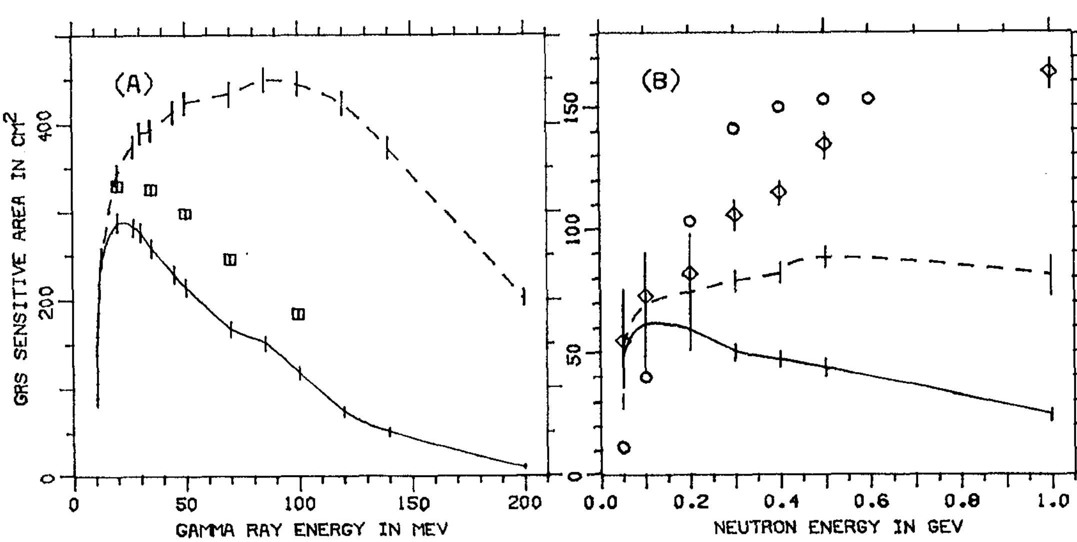

Figure 1: (A) 10-140 MeV gamma ray response. (B) 50-1000 MeV neutron response. Nominal high energy matrix response with (solid curves) and without (dashed curves) shield veto. Gamma ray response from /2/ with corrections for the GRS flight model (boxes). Neutron response without shield veto and 100-MeV cutoff from present work (diamonds) and /3/ (circles).

front or back plastic shields. Energy deposits in the upper and lower detector arrays are pulse-height analysed separately with four channels below 100 MeV, while deposits above 100 MeV in either array are not recorded due to preset electronics limitations. The four channels correspond to electron-equivalent energy deposits of 10-25, 25-40, 40-65, and 65-100 MeV. The GRS event logic also records a two-dimensional high energy matrix which includes "mixed" events triggering both the upper and lower detectors, as the result of secondary charged particle and photon showers, and depositing total energies up to 140 MeV. The total energy deposited in the matrix gives at least a minimum measure of the incident particle's energy, while the fraction of mixed events allows some discrimination between gamma rays and neutrons.

3. High Energy Gamma Ray and Neutron Response. Calculated results for the total GRS responses to gamma rays and neutrons as functions of incidence energy are shown respectively in Figures 1(A) and 1(B). The incident photons or neutrons are perpendicularly incident onto the front surface of the GRS, as would be the case for radiation of solar origin. The GRS response to high energy gamma rays from off-axis sources has also been calculated and used for in-orbit calibration and cosmic burst studies, the response being nearly constant up to 30 degrees off-axis at all energies and falling off by up to a factor of three at 90 degrees and 20 MeV.

The high energy matrix response for solar gamma rays, shown by the solid curve in Figure 1(A), is heavily attenuated above 15 MeV by the vetoing of events which produce shower electrons escaping through the active shields, where these electrons trigger the side and bottom shields at about the same rates. The new responses are ten percent below the earlier ones /2/ at 20 MeV, but the differences increase to thirty percent at higher energies. These differences arise from the use of different instrument models and shield veto criteria which produce increasingly divergent results above 20 MeV.

The strong forward showering of secondary photons and electrons produces a characteristic response in the GRS to solar gamma rays above 20 MeV, where these events contribute mixed events to the high energy matrix. At increasing energies the mixed events increase in significance but are also associated with high veto rates and low total response. The calculated ratios of mixed and total matrix events are 0.01, 0.2, 0.6, and 0.4 at 30, 70, 140, and 200 MeV respectively, decreasing above 140 MeV due to matrix energy limits.

In Figure 1(B) the solid curve shows the large cumulative effect on the neutron response from shield vetoes and the 100-MeV cutoff, without which the present and earlier /3/ calculations converge above 500 MeV. The relative significance of shield vetoing alone is illustrated by the increasing difference between the solid and dashed curves at higher energy. The large error bars for the response to neutrons at 50-100 MeV arise from the low energy neutron approximation discussed in Section 2. The neutron response is characterized by a relatively negligible fraction (less than 0.03) of mixed events, arising from the physical separation of the upper and lower GRS detectors, and from the relatively isotropic scattering of neutron interaction products.

4. Discussion. The new Monte Carlo calibration gives a significant improvement of the earlier results /2/ for higher energy gamma rays producing mixed events, the difference between the two calculations at 20 MeV being relatively negligible. Since average gamma ray energies in the high energy GRS flares /4/ were less than 25 MeV in the impulsive phase, the integral fluences for those flares do not require revision. Analyses of flares emitting higher energy gamma rays from pion decay /10/ are highly dependent

on the measured fraction of mixed matrix events and require the new calibration.

Aside from residual uncertainties regarding the newly calculated GRS response to solar neutrons below a few hundred MeV, the important effects of shield vetoing, the 100-MeV high energy mode cutoff, and details of the secondary interaction product distributions, have otherwise been accurately modeled for the first time. The earlier estimates /3/ of GRS response to neutrons, derived from simple cross section arguments without consideration of these effects, greatly exceed the new ones at neutron energies above 100 MeV. At 20-100 MeV the earlier estimates should be used, since neutron cross sections in the new HETC calculations have probably been overestimated at those energies. The total matrix responses of the GRS with shield vetoing to neutrons at 50, 100, 200, 300, 400, 500, and 1000 MeV are then 11, 40, 59, 50, 47, 44, and 24 cm^2 respectively, and the corresponding ratios of the new and old responses are 1.0, 1.0, 0.57, 0.36, 0.31, and 0.28 up to 500 MeV.

The in-flight GRS data provide some confirmation that the current calibration of the high energy mode is reasonably accurate. In-flight calibration data have confirmed the stability of energy deposit thresholds for the shields, although thresholds at 10 MeV and above for the high energy matrix are still uncertain by a few MeV. The gamma ray calibration has been checked at 30-200 MeV by measurements of atmospheric gamma rays, as the GRS points toward the earth's horizon during the night portion of its orbit, which agree within 20-30 percent with comparable SAS-2 data /11/. For a check of the neutron response, delayed neutrons from the June 21, 1980 solar flare /3/ provide a relatively "clean" neutron source, uncontaminated by high energy gamma rays emitted only in the initial impulsive phase. These neutrons produced a very small fraction of mixed events in the high energy matrix after background subtraction /6/, thereby confirming the predicted response from these calculations.

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