The GEANT Simulation Package and its use in Compton Telescope Design

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The Role of Simulation in Design

Prototypes, Balloons, etc. + Simulations, Models, etc. = Scientific Mission

MEGA Prototype

MEGA Prototype Simulation Model

MEGA Flight Concept

+ Realistic component performance
- Expensive and time consuming
- Inflexible configuration
- Unrealistic environment

+ Inexpensive and comparatively rapid
+ Flexible configuration
+ Flexible environment
+ Must model the component performance

- Successful flight experiment, where:
  - Realistic estimates of performance help “sell” the mission
  - Instrument design is optimized for scientific mission and environment
Simulating Compton Telescopes

- Analytical modeling of Compton imager physical response is impractical due to complexities of geometry, scattering, and secondary production

- The most viable approach is Monte Carlo radiation transport simulation — probabilistic tracking individual “test particles”

- Other simulations important to instrument design: mechanical, thermal, electronics, etc.
**Instrument Simulation Framework**

Credible Simulation Requires Credible Inputs at All Levels
Monte Carlo Radiation Transport Packages

Requirements for Compton Telescope simulations:

- Detailed electromagnetic physics for direct telescope response (~1 keV – 100 MeV)
- Competent hadronic cascade physics for simulation of prompt cosmic-ray–induced background
- Isotope excitation and radioactive decay for simulations of delayed activation-induced background
- Convenient and flexible handling of complex geometry and materials for rapid design studies
- Modern, modular architecture that allows customization

The particle and nuclear physics communities have developed several “general-purpose” Monte Carlo transport packages, including:

- EGS
- FLUKA
- HETC/MORSE/MICAP
- CALOR
- MCNP/MCNPX
- GEANT
Capabilities of GEANT4

GEANT := GEometry And Tracking

Complex 3D geometry, materials, MC transport, and visualization in one package

Developed & maintained by CERN + large collaboration

Modern, object-oriented (C++) “toolkit” architecture

Comprehensive (nearly) suite of EM and hadronic physics

Straightforward installation and use on many platforms
  - Wintel, Sun, HP, Linux, Darwin

ESA Space Specific Modules

General Source Particle Module
  - Toolkit for input spatial/spectral sampling

Radioactive Decay Module
  - Provides the capability to model activation-induced background in orbit
  - Uses detailed Evaluated Nuclear Structure Data Files

Low-energy EM physics
  - Uses detailed cross sections from LLNL Evaluated Photon/Electron/Atomic Data Libraries
  - Applicable above ~250 eV
  - Ties X-ray and Gamma-ray applications

geant4.web.cern.ch

www.space.qinetiq.com
Effects of Atomic Electron Binding

\[
\left( \frac{d^2 \sigma}{d\Omega dk} \right)_i = \frac{r_o^2}{4} \left( \frac{k_f k}{k_o^2} \right) \left( \frac{k_f}{k_o} + \frac{k_o}{k_f} - \sin^2 \varphi \right) \frac{dp_z}{dk} J_i(p_z)
\]

- Suppresses forward scattering, particularly at low energies
- Suppresses total scattering probability at low energies

**GEANT4 Low-energy Compton process includes these effects**
Doppler Broadening Physics & Effects

For free electron: \( p_z = 0; \ E_o = m_o c^2 \)
\[
k_{\text{free}} = k_o - \frac{k_o k}{m_o c^2} (1 - \cos \varphi)
\]

For bound atomic electron:
\[
k = k_o - \frac{k_o k}{E_o} (1 - \cos \varphi) - p_z |k_o - k|
\]

Doppler broadening error:
\[
\Delta k = k - k_{\text{free}}; \quad \Delta \varphi = \varphi - \varphi_{\text{free}}
\]
GLECS & G4LECS

- GLECS = GEANT Low-Energy Compton Scattering
  - Thanks to Doug Swartz (USRA, Huntsville) for early help

- Incorporates Doppler broadening into GEANT & GEANT4

- Algorithm based closely on EGS Implementation
  - Relativistic impulse approximation (ignore atomic electron interactions)
  - Uses EPDL for total cross sections
  - Uses EPDL differential cross sections (scattering form factors)
  - Uses shellwise Compton profiles (Biggs, Mendlesohn, & Mann 1975) to sample Doppler broadened scattered photon energies
  - Also fixes Rayleigh (coherent) scattering physics with EPDL data
  - Computing performance within 5% of G4LowEnergy classes

- Soon to come: combined polarization and Doppler broadening
Verification of G4LECS

- G4LECS compared to synchrotron beam experiment

Experiment (Polarized Beam)

Simulation (Unpolarized Beam)
Test Results

- Good agreement in Compton and Rayleigh peaks (and Ge-K escape)
- Some differences in multi-Compton continuum probably due to approximated geometry
Application to Compton Telescope Design

Doppler Limit Angular Resolution


![Graph showing FWHM of ARM for different materials and nuclear charge Z.](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>Ge</th>
<th>CdTe</th>
<th>Xe</th>
<th>CsI</th>
<th>NaI</th>
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</thead>
<tbody>
<tr>
<td>FWHM at 200 keV [°]</td>
<td>2.85</td>
<td>3.50</td>
<td>3.30</td>
<td>2.95</td>
<td>3.00</td>
</tr>
<tr>
<td>FWHM at 500 keV [°]</td>
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<td>1.55</td>
<td>1.45</td>
<td>1.25</td>
<td>1.40</td>
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<tr>
<td>FWHM at 1000 keV [°]</td>
<td>0.65</td>
<td>0.85</td>
<td>0.80</td>
<td>0.75</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Telescope Design Study Example

Si + CZT multi-scatter Design

Angular Res. (FWHM, deg)

Energy (keV)

$E^2 \cdot$ Sensitivity (keV·cm$^{-2}$·s$^{-1}$)

Energy (keV)

$100 \times 100$ cm$^2$

No Doppler

BATSE

COMPTEL

New Design

1 Msec

100 cm

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