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# A Compton camera application for the GAMOS GEANT4-based framework

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ABSTRACT

Compton camera systems can be used to image sources of gamma radiation in a variety of applications such as nuclear medicine, homeland security and nuclear decommissioning. To locate gamma-ray sources, a Compton camera employs electronic collimation, utilising Compton kinematics to reconstruct the paths of gamma rays which interact within the detectors. The main benefit of this technique is the ability to accurately identify and locate sources of gamma radiation within a wide field of view, vastly improving the efficiency and specificity over existing devices. Potential advantages of this imaging technique, along with advances in detector technology, have brought about a rapidly expanding area of research into the optimisation of Compton camera systems, which relies on significant input from Monte-Carlo simulations. In this paper, the functionality of a Compton camera application that has been integrated into GAMOS, the GEANT4-based Architecture for Medicine-Oriented Simulations, is described. The application simplifies the use of GEANT4 for Monte-Carlo investigations by employing a script based language and plug-in technology. To demonstrate the use of the Compton camera application, simulated data have been generated using the GAMOS application and acquired through experiment for a preliminary validation, using a Compton camera configured with double sided high purity germanium strip detectors. Energy spectra and reconstructed images for the data sets are presented.

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## 1. Introduction

Compton imaging can be employed in a wide range of applications to locate sources of gamma radiation. Compton cameras were originally developed for high energy astrophysics research and have been successfully utilised in this field since the 1970s [1]. The potential advantages of these gamma-ray imaging systems have since stimulated significant interest from researchers aiming to utilise the concept in the fields of nuclear medicine [2], homeland security [3] and nuclear decommissioning [4].

The operation of a Compton camera relies on the ability to accurately reconstruct the paths of incident gamma rays using Compton kinematics. A typical system is composed of two energy and position sensitive detectors where the detector closest to the source of radiation is denoted the scatterer detector and the second is the absorber detector, although systems have been investigated which utilise only one detector [5] or several [6]. In a two-detector system, an incident gamma ray will ideally Compton scatter from an electron in the scatterer detector, transferring a fraction of its initial energy and then interact via photoelectric absorption in the absorber detector, depositing its remaining energy. The sum of the two recorded energies provides knowledge of the incident energy from the radiation source, if these are the only two interactions the gamma ray participates in. In reality, however, there are many combinations of interactions that the gamma ray can undergo within the system.

To reconstruct the gamma-ray path, the cone beam reconstruction method is employed. In this method, a measurement of the energies deposited by the gamma ray in the two interactions is used to calculate the Compton scattering angle $\theta$. Although the angle of scattering is calculated, it is not possible to know the direction in which the gamma ray has travelled without tracking the path of the recoil electron from which the gamma ray scatters. Therefore, in the absence of electron tracking, a cone of all possible directions is constructed for each gamma ray with apex angle $2\theta$. The cone axis is then formed using the vector difference between the interaction positions in the two detectors. The source is thus situated somewhere on the surface of the cone produced, as shown schematically in Fig. 1. By reconstructing many of these gamma-ray paths, the location of the source of radiation in 3D space can be

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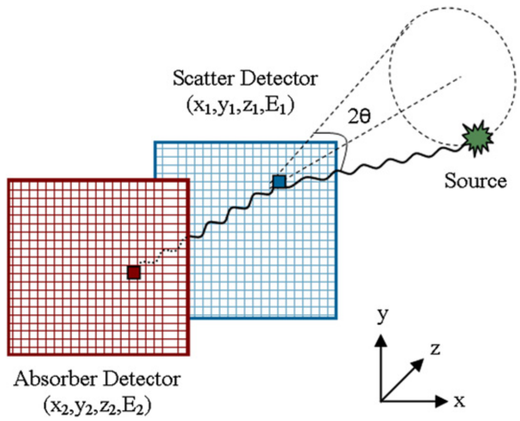


**Fig. 1.** A schematic diagram of a two detector Compton camera system showing the cone produced for one incident gamma ray which transfers energy $E_1$ to an electron via Compton scattering at position ($x_1$,$y_1$,$z_1$) in the scatterer detector and then deposits its remaining energy $E_2$ through photoelectric absorption at position ($x_2$,$y_2$,$z_2$) in the absorber detector.

found at the point at which there is maximum intersection of the cone surfaces.

The performance of a Compton camera is assessed by its ability to identify and locate the radionuclide. When determining which Compton camera configuration is optimum for a specific application, it is therefore useful to examine the efficiency of various geometrical configurations and the contribution of detector characteristics to image quality. The most common technique to perform such an investigation is through the use of Monte-Carlo simulations. An open-software package which is designed specifically for the simulation of Compton cameras would therefore be an ideal tool to aid in system design and optimisation. Such software should facilitate the investigation of Compton camera systems with varying detector geometries and materials, with attributable characteristics such as energy resolution, position resolution and dead time. As Compton imaging is used in many different applications, the software would also have to be flexible enough to allow the user to investigate various types of gamma-ray source distributions, including phantoms. In addition, the software should provide tools which allow the user to easily extract and analyse the simulated data.

GEANT4 [7,8] is a widely used Monte-Carlo toolkit, originally developed for high energy physics research, which simulates the interaction of particles in matter. Such a toolkit provides excellent flexibility, functionality and a highly validated response [9] for those users who have the required knowledge of C++ and who can manipulate the complex architecture. However, GEANT4 is increasingly being used by researchers in many fields who may not have significant C++ experience, or a knowledge of the GEANT4 toolkit. GAMOS [10], the GEANT4-based Architecture for Medicine-Oriented Simulations, provides a scripting language based on GEANT4 to facilitate the development of Monte-Carlo applications without the C++ programming prerequisite. An application to model Compton camera systems in the GAMOS framework is presented in this work.

To our knowledge, the GAMOS application is the only publicly available open-source software specifically designed to simulate Compton camera systems for medical imaging, although other software packages based on the GEANT4 toolkit exist, such as CIS [11], SWORD [12], MEGAlib [13] and GATE [14]. CIS has been developed to simulate Compton camera data by integrating GEANT4 and MATLAB, however it is not entirely open-source. SWORD is based on MCNPX and GEANT4 and is targeted towards the use of Compton cameras and coded aperture systems in homeland security applications, in particular with the examination of Special Nuclear Material (SNM) targets and industrial backgrounds. Similarly, MEGAlib provides a suite of tools for astrophysicists to simulate and reconstruct GEANT4 data for Compton telescopes. GATE is a GEANT4-based platform developed for the simulation of the nuclear medical imaging techniques Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT). GATE would allow the user to extract Compton camera data however it is not ideal if the user wishes to have a deeper understanding of the simulation, or to examine a novel primary generator position distribution. The GAMOS Compton camera application will facilitate the investigation of new Compton imaging devices without the requirement for each research group to develop their own Monte-Carlo simulation. The application benefits from excellent flexibility and an array of existing GAMOS functionalities, to be described in Section 3.

## 2. Compton camera optimisation

The requirements of an imaging system for nuclear medicine, homeland security and nuclear decommissioning vary significantly and thus there is no unique Compton camera configuration which is suitable for all applications. A system for nuclear medicine requires a device which can deliver high quality images in real time to aid clinical diagnosis whilst exhibiting high efficiency in the energy range of medical radionuclides (typically 141–511 keV), to maximise the utilisation of radiation administered to the patient. In contrast, a system designed for homeland security should provide an excellent field of view and provide good efficiency across a wide energy range, to allow the identification of a wide variety of radionuclides. Such a system should ideally give real-time images and demonstrate excellent specificity in the identification of unknown radionuclides by utilising detectors with excellent energy resolution. A device for nuclear decommissioning should be portable and robust, to allow transport onto and around nuclear sites. These types of systems should also be able to identify and locate radionuclides above an increased level of background radiation.

There have been many publications which describe the use of Monte-Carlo techniques to optimise Compton camera systems for specific applications [15–17]. The process of designing a new system can be time-consuming due to the large number of parameters to be investigated during optimisation. There are a number of quantities which characterise the performance of a Compton camera system for a specific application and those commonly selected for optimisation purposes are efficiency and image resolution. Contributing factors to these quantities can be modelled and examined using Monte-Carlo techniques, such as GAMOS, to determine the optimum Compton camera configuration.

### 2.1. Efficiency

The efficiency of a Compton camera can be described in terms of the number of detected events of a particular type, $N_{detected}$, and the number of gamma rays incident on the scatterer detector, $N_{incident}$,

$$\epsilon_{system} = \frac{N_{detected}}{N_{incident}}. \quad (1)$$

The detected events are categorised by type according to their efficacy in the imaging process, as the number of events used in the reconstruction algorithm is typically less than the total number of events detected by the system. The minimum requirement for reconstruction of a gamma-ray path is that it interacts once via Compton scattering and is fully absorbed in the system. However, other gamma rays which interact multiple times

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