In-Field Examination of
Root-Microbial Interactions using
SPECT Imaging

Honours Thesis
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List of Abbreviations

- **GAGG** - Gadolinium Aluminium Gallium Garnet
- **HVL** - half-value layer
- **PET** - positron emission tomography
- **PMT** - Photomultiplier Tube
- **SPECT** - single-photon emission computed tomography
Abstract

A Compton camera SPECT imager was simulated using GEANT4 to determine its feasibility for imaging roots and microbes within soil. The simulated detector was composed of a polystyrene scatter detector (as an approximation of plastic scintillator) and a GAGG scintillator crystal absorber detector. Various detector configurations were explored.

It was found that the detector has reasonable efficiency up to depths of 15 cm to 35 cm depending on the saturation of the soil for 511 keV photons. The optimal spacing between the scatter and absorber detectors was found to be 5 cm or less. It was also found that a scatter detector thickness of 5 cm will have a higher efficiency (by around 0.6%) than a thickness of 2 cm, but a thicker scatter detector will make the detector less portable and will also deteriorate the resolution of the detector.

The calculated scattering angles using the energy deposited within the detector were compared to the truth angles that were calculated using initial momentum and scattered direction. The reconstructed angles from energy deposition appear to be similar to the true values. The energies of the scattered photons and scattered electrons for different scattering angles also appear to match the expected values quite closely.

The Compton camera method appears to be quite promising for imaging near surface in-field roots and microbes within soil.
1 Introduction

Research is being conducted at the University of Saskatchewan to develop and test a phosphorous-rich material that, when added to soil, can help improve the consumption of hydrocarbon pollutants by microbes (i.e. bacteria and fungi) [1]. The testing of this substance requires an in-depth understanding of the motion of these microbes within the soil. It may be possible to image the migration of the microbial clusters using single-photon emission computed tomography (SPECT) imaging by introducing a radioactively tagged nutrient for the microbes to consume. The development of a SPECT detector for the investigation of the microbe clusters could also be beneficial in other areas of biology, such as imaging plant roots in-field as well as the interactions between roots and microbes.

The goal of this project is to simulate a potential method of SPECT detection and determine its feasibility for imaging microbes within soil. This feasibility will depend on depth at which the detector will be effective, the resolution and geometrical arrangement of the detector, as well as the efficiency of photon detection.

2 Background and Research

SPECT detection was chosen for this project as a positron emission tomography (PET) plant detector requires an accurate coincidence setup in order to detect the two photons emitted with 180° separation due to electron-positron annihilation. Therefore, a PET detector is not viable for imaging within a large field, as the detector must be able to wrap around all angles of the entire sample being imaged. In addition to a more appropriate setup, SPECT has the advantage of having a wider variety of radiation sources available for tagging nutrients (as both positron emitting sources as well as photon emitting sources can be used).

Two different techniques of SPECT imaging were considered for the creation of the detector: 1. SPECT Laminography and 2. Compton Camera.

SPECT Laminography is a method of reconstructing an image by isolating photons
that come from specific directions through mechanical collimation. Laminography refers to reconstructing 3-dimensional images through the process of stacking 2-dimensional image planes of differential depths. These 2-dimensional images are formed by sweeping the detector over a range of angles and reconstructing the layer where the photon trajectories cross.

The collimation of the photons is typically done using a parallel-hole or a multi-pinhole collimator. These collimators consist of a series of thin holes cut into a piece of attenuating metal (typically lead) so that the trajectory of the photons can be narrowed down based on which holes the photons pass through. Parallel-hole collimators have straight cut holes that will isolate photons that come from directly below the collimator (within a range depending on the thickness of the holes). Pinhole collimators consist of a single hole that will accept a cone of photon trajectories and magnifies the image, and multi-pinhole collimators consist of multiple pinholes. The collimation of the photons provides a high spatial resolution, the thinner the holes the higher the resolution, but also results in a low efficiency of the detector. Typically, due to the reduced field of view by cutting out most angles of photon trajectory, the efficiency of these detectors is in the range of 0.01% to 0.1% [5].

The Compton Camera method, on the other hand, has a higher efficiency, typically closer to 1%, but tends to have a lower resolution [6]. Unlike SPECT Laminography, the Compton Camera method does not require a mechanical collimator. This method uses kinematics of Compton scattering to reconstruct initial energy and direction of the detected photons. The lack of mechanical collimation tends to result in a lighter, more portable detector.

The choice in detector method will rely heavily on the efficiency required for practical detection of the photons, and as the focus of this project is specifically for imaging within soil, the attenuation of photons within a typical soil sample must be considered. Kucuk et al. measured the mass attenuation coefficient of five different soil samples in energies ranging from 661.6 keV to 1332.5 keV, which were found to be in the range of 0.06 – 0.08 cm²/g. The density of the soil was then calculated using the most common elemental components of soil obtained from a thorough study conducted in the United States in 1984 [7]. The average percentage of common elements found in soil are shown in table [1].
<table>
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<tr>
<td>Titanium</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Table 1: Average percentage of elements found in soil samples \[7\]

The average percentage of elements constitute \(\sim 43\%\) of the soil volume as a rough estimate, leaving \(\sim 57\%\) of pore space. The effective density of soil was then approximated using these percentages of elements for completely dry (pore space completely filled with air) and completely saturated (pore space completely filled with water) to range from \(\rho_{eff} = 1.082 \text{ g/cm}^3\) (dry) to \(\rho_{eff} = 1.652 \text{ g/cm}^3\) (saturated). The half-value layer (HVL, equation [1] where \(\mu_l\) is the linear attenuation coefficient) for soil, which is the distance required to reduce the flux of photons in half, was then estimated using the mass attenuation plot from Kucuk et al. for energies of around 350 \(keV\) to 1.5 \(MeV\) and found to be within the range of 4.2 \(cm\) (saturated soil, low energy) to 10.7 \(cm\) (dry soil, high energy). It should be noted that these values are only a rough estimate based on approximated values, and certain soil samples may not fall within this range.

\[
HVL = \frac{-\ln(\frac{1}{2})}{\mu_l}
\]  

Since it would be ideal to observe the microbial clusters as deep into the soil as possible, and the photon flux will be reduced by half at best every 10 \(cm\) or so with \(\sim 1.5 \text{ MeV}\) energy photons and will be an even shorter distance with the lower energy of common nutrient tags, the efficiency of less than 0.1% of typical mechanically collimated SPECT detectors would be impractical. Therefore, the Compton Camera method was explored for this project.
2.1 Compton Camera

The idea of using Compton scattering kinematics for collimation of photons in SPECT imaging was first proposed in 1974 by Todd et al. \cite{12} for use in nuclear medicine. The first working prototype was created and analyzed in the early 1980s by Singh and Doria \cite{13,14}, and since then many Compton camera designs have been presented.

Compton Cameras are made up of two planar detectors operating in coincidence: a scatter detector in which the photon undergoes Compton scattering and an absorber detector, in which the scattered photon is completely absorbed. Some configurations of Compton Cameras have two or more scatter detectors before the absorber detector; these are used primarily for higher energy detection and will not be necessary for this project. The preliminary Compton Camera designs used high purity germanium or silicon for the scatter detector coupled with scintillating detectors for the absorber detector. However, the portability of such detectors is limited due to the need for either large volume PMTs or the need for cryogenic cooling (semiconductor detectors). \cite{10}

More portable Compton Camera detectors have been designed by taking advantage of advances in semiconductor technology. These detectors tend to use silicon arrays as the scatter detector and a semiconductor detector that is operational at room temperature for the absorber detector, such as cadmium telluride (CdTe), cadmium zinc telluride (CdZnTe), and mercury di-iodide (HgI\(_2\)). \cite{6} \cite{9}

The image reconstruction of Compton cameras relies on the position and energy deposited in both the scatter and absorber detector for each photon detected. The angle of the photon can be determined via equation \ref{eq:compton_angle}, where \(E_\gamma\) is the total energy of the photon before scattering (which is equal to the sum of energy deposited within the scatter and absorber detectors) and \(E_{\text{scatter}}\) is the energy deposited in the scatter detector. The value for total photon energy can also be written as \(E_\gamma = E_{\text{scatter}} + E_{\text{absorber}}\). The Compton angle extracted from equation \ref{eq:compton_angle} is an approximation as it is assumed that the scatter electron was at rest when the Compton interaction occurred.
\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_\gamma - E_{\text{scatter}}} - \frac{1}{E_\gamma} \right) \]  \hspace{1cm} (2)

From the Compton angle \( \theta \) and the hit positions of the scatter and absorber detectors a cone can be constructed that describes all of the possible points of emission of the initial photon that could have occurred. This concept is illustrated in figure 1 where the cone with angle spread \( \theta \) from the axial vector is reconstructed along the line connecting the scatter and absorber hits.

![Figure 1: Depiction of Compton cone reconstructed from scattering event in a Compton Camera.](image)

When there are multiple events, the point of emission of the photon can be reconstructed as the point in which multiple cones cross. A common algorithm for reconstructing the initial position of the photons is the Two Cone Backprojection method. [15]

The first step in this method is to project the cones onto 2-dimensional planes defining angles in x- and y- directions. Angle space is used because the Compton cone cross-sections are likely ellipses in real space (due to the angle of trajectory), but circles in angle space. The use of circular cross-sections simplifies the algorithm for determining the intercept positions. The calculated quantities for the algorithm are shown in Figure 2, which shows the intersections between two cone cross-sections in angle space.
Figure 2: Illustration of two cone back projection algorithm.

The algorithm then finds the center of two event cones, $\vec{c}_a$ and $\vec{c}_b$ with cone angles $\theta_a$ and $\theta_b$ respectively. The distance between the two centers $\Delta \vec{c}$ is then determined by subtracting vectors $\vec{c}_a$ and $\vec{c}_b$, and the angle $\gamma$ between $\Delta \vec{c}$ and the vector from the center of the first cone to the intersection ($\vec{\theta}_a$) can be determined via equation (3).

$$\gamma = \cos^{-1}\left[\frac{\theta_a^2 + |\Delta \vec{c}|^2 - \theta_b^2}{2\theta_a |\Delta \vec{c}|}\right]$$  (3)

The vector $\vec{\theta}_a$ is then simply the rotation of $\Delta \vec{c}$ by the angle $\gamma$ with $|\vec{\theta}_a| = \theta_a$. Rotating $\Delta \vec{c}$ in both the positive and negative direction will give the two intercepts of the two cones. These intersections can be calculated for each unique pair of cones. The intersections are then plotted on a histogram to determine the most likely photon emission point.

However, since the electron in the Compton interaction will have its own momentum, there is error in equation (2) for determining the Compton angle, called the Doppler broadening effect. This effect results in a smearing of the detector resolution. This inherent smearing in the design of Compton cameras means that the angular resolution will tend to be worse than mechanically collimated SPECT detectors. It is important then to come up with a detector configuration that will minimize the detector’s resolution.

The setup of the detector must be optimized to find the best configuration for both efficiency and resolution. The distance between the scatter and absorber detectors as well
as the pixel resolution of both detectors are the main factors which affect the efficacy of the detector.

Section 11.5.2 in Radiation Detectors for Medical Imaging outlines the effects of different thicknesses of the scatter (Si) detector and the absorber (CdTe) detector for different isotopes, as well as the effect of spacing between the two detectors for isotopes of fluorine-18 and technetium-99m [6]. It was found in this study that a thickness of 2 cm for the Si scatter detector, thickness of 4 cm for the CdTe absorber detector, and a spacing of 10 cm between the two was the optimal geometry for the detector.

The basis for this project is to create a simulation using GEANT4 of a Compton camera detector to explore different detector configurations and determine optimal geometries for imaging soil. The simulation was used to test the depths at which the detector could penetrate field soil, as well as exploring the efficiency of the detector with different absorber and scatter detector spacings and thicknesses.

3 Methodology

GEANT4 is an open source Monte Carlo software created at CERN that can accurately simulate the passage of particles through matter. [11] The different processes of particle interaction in matter and probabilities of those processes occurring can be built in to the simulation to observe what will occur in a certain detector setup. This software package was used to simulate a Compton Camera detector for imaging radiation within soil.

3.1 Simulated Detector Setup

The first step in the creation of this simulation was to define the detector geometry. In a real world situation, a Compton Camera detector would be of a finite size and would be pointed at the image target at a variety of angles to produce a three-dimensional image.
For the sake of having an efficient simulation, the step of rotating the detector was skipped by defining the detector layers (absorber and scatterer) as semi-spherical shells. This creates a dome like structure around the surface of the simulated soil which samples a variety of angles simultaneously. The soil sample was chosen to be a 1-meter-long cube, which would provide sufficient room for testing various depths of radiation within the soil. The radius of the scatter detector was set to be 50 cm so that the entirety of the scatter dome would be directly on top of soil as it would in a field environment. The scatter detector was initially given a thickness of 2 cm, as suggested in section 11.5.2 of Radiation Detectors for Medical Imaging. The absorber detector was then given a thickness of 5 cm as an overestimate to ensure the majority of photons would be completely absorbed within the absorber detector, and was given an inner radius that was the sum of the scatter radius plus the scatter thickness plus the spacing between absorber and scatter detector. This spacing was initially set to 10 cm, again based on the recommendations from Radiation Detectors for Medical Imaging. The geometry of the detector is shown in figure 3 below, where the absorber detector layer is shown in blue, the scatter layer is shown in green, and the soil is shown in yellow.

![Simulated detector setup](image)

Figure 3: Simulated detector setup (left) with 10 example 511 keV photon tracks, one scattering off of scatter detector. Blue: absorber, green: scatterer, yellow: soil, lime: photon tracks.

The detector materials were chosen based on what materials are available in the plant imaging lab at the University of Regina. The scatter detector is simulated to be polystyrene, which has roughly the same density and chemical components of a plastic scintillator, and the absorber detector is simulated to be made of Gadolinium Aluminium Gallium Garnet (GAGG) scintillator crystal. The soil sample is a 1 m × 1 m cube, and the material simulated for the soil is based off of the average chemical makeup of soil from the 1984 study described in section 2. Both the extremes of completely dry soil and completely saturated soil were simulated in this
study. For the purposes of this study the soil was simulated to be of a homogeneous material as an approximation, whereas a real soil sample would be a heterogeneous mixture with water content varying with depth.

The radiation source for the simulation is set up to be a point emission with fixed energy set to 0.511 $MeV$, to simulate the energy of photons originating from a positron source. This energy was chosen since a common radioactive tracer used of PET imaging of plants is fluorine-18 (half-life 110 minutes) which can be added to glucose compounds which are taken up by the plants and microbes as nutrients. However, other potential isotopes should be explored in future simulations, as higher energy sources will improve the resolution of Compton cameras \[18\]. This can be seen below in equation 4 which is the propagation of uncertainty in the scattering angle that can be derived from equation 2. The squared energy term in the denominator indicates that the uncertainty in scattering angle decreases rapidly for higher initial photon energies.

\[
\Delta \theta = \frac{m_e c^2}{\sin \theta (E_\gamma - E_{\text{scatter}})^2} \Delta E
\]

The 0.511 $MeV$ point source is given an initial direction which is distributed outward at any angle (in spherical coordinates of $\phi_s$ ranging from 0 to $2\pi$ and $\theta_s$ ranging from 0 to $\pi$). Figure 3 shows simulated photon tracks for 10 initial events. It can be seen in this figure that the majority of photon events will attenuate and scatter within the soil sample at this energy, with only one of the 10 in that figure reaching the scatter detector and scattering off of it.

### 3.2 Simulation Output

Simulations provide the opportunity to observe the truth values as well as the detected values. In order to analyze the detector setup and its ability to detect and reconstruct photons, it is necessary to first output information about the initial photon. The primary photon information is stored in a class called EventPrimary which is written as an array to a ROOT\[1\] file for analysis. The EventPrimary class stores the track ID of the particle (which for the primary

\[1\] ROOT Data Analysis FrameWork \[16\]
photon is always 1), the particle ID (always photon), the vertex position (set by user), the initial momentum (direction randomly generated), and the total energy of the particle (which in this case is always 0.511 MeV).

A class called scatterHit then stores information about particles that enter the scatter detector. For any track generated by the simulation that starts in the world volume and ends in the scatter detector, the value of kinetic energy is stored as the kinetic energy entering the scatter detector. Any time a track originates within the scatter detector, the vertex kinetic energy, track ID, parent ID (which is track ID of parent particle), global time, local time, energy deposited within the volume, particle ID (type, such as photon or electron), and vertex position are stored within the scatterHits array. In addition, if the track particle is not the primary photon, the process that created the secondary particle is stored. If the end step of the track that originates in the scatter detector is in the world volume, meaning the particle left the scatter detector, the particle’s kinetic energy is stored as kinetic energy leaving the detector.

A similar class to scatterHit, called absorberHit, is used to store information about the particles entering the absorber detector. The same logic is used for getting the values of kinetic energy entering and kinetic energy leaving the detector. Particle track ID, particle ID, process of particle creation, global time, local time, energy deposited, vertex kinetic energy and vertex position are also stored.

3.3 Analysis

The raw simulation data files must then be analyzed to gain information about the detector setup. The first step is to eliminate undesired events. These are events that either do not reach the absorber or scatter detector, events that do not scatter (deposit energy) within the scatter detector, events that are not absorbed within the absorber detector, or events in which a significant portion of energy was lost but not deposited within either the scatter or absorber detectors.
In order to remove unwanted events in the simulated data, the analysis program loops through each event stored in the ROOT tree. For each event there is an array of scatter hits with the information described in section 3.2. All tracks entered in the scatter hits array are checked for each event and the event is flagged as a good event if the following conditions are true:

1. Particle entering the scatter detector is the primary photon thrown (track ID equals 1).

2. The energy reaching the scatter detector is within 10 keV of the initial 511 keV (to ensure that most of the energy was not attenuated due to scattering within the soil).

3. The difference in kinetic energy of the photon passing through the scatter detector is at least 10 keV to ensure the photon is interacting with the scatter detector.

If the event meets the above criteria, then a variable is stored that contains the track ID of the lowest valued (and therefore first occurring) secondary particle (which is confirmed to be an electron resulting from Compton scattering). The vertex position of the scattered electron is stored as the scatter hit position, and the energy deposited by that secondary particle is stored. Another variable is used to store the energy deposited by any additional secondary particles that may have been produced (either by the primary photon or by the scattered electron). The event is flagged if multiple secondary particles are created.

After the good events have been determined from the scatter hits, the analysis program loops through the events in the absorber hit array. If the track ID of the absorber hit is equal to 1 (primary photon) and the event is flagged as a good event, then the vertex position as well as the kinetic energy entering and exiting the absorber detector are saved. The energy deposited in the absorber detector is also summed for all tracks in the array.

The Compton angle is calculated for the events using equation 2 where $E_\gamma$ is the sum of energy deposited within the scatter and absorber detectors, and $E_\gamma - E_{\text{scatter}}$ is the energy deposited in the absorber detector.

Further selection is performed before filling histograms with data from the good events.
First, the event must be flagged as a good event. Second, there must be at least one secondary produced within the scatter detector. The summation of energy deposited in scatter and absorber detector must be within a window of the initial energy of the photon. This window was initially set to 150 keV. There is also a minimum requirement for energy deposited within the scatter detector.

This minimum arises from the method of calculating the Compton angle. If it is assumed that all energy is detected of the initial photon ($E_\gamma = 0.511 \text{ MeV}$), then the value of $m_e c^2 \left( \frac{1}{E_\gamma - E_{\text{scatter}}} - \frac{1}{E_\gamma} \right)$ will be greater than 1 and will therefore produce an unphysical value for $cos\theta$ if the absorber energy is less than 170 keV. Therefore it is also required that the energy deposited within the absorber detector be greater than 170 keV. This minimum energy limit can also be seen in figure 4, where the minimum possible energy of a scattered photon from an initial 0.511 MeV source is 0.170 MeV at 180° scattering angle.

Figure 4: Energies of the photon and electron undergoing Compton scattering at various angles $\theta$ with initial photon energy of 0.511 MeV.
4 Results and Discussion

One of the main goals of this project was to determine how deep within the soil the detector can reasonably image. In order to determine the maximum depth at which the Compton camera could achieve the efficiency of detecting photons at different source depths was examined. Using the above event selection criteria, the absolute efficiency of the detector was defined as the total number of accepted events divided by the number of initial photons generated. Source depths ranging from 5 to 50 cm within the soil were simulated for both completely dry and completely saturated soil samples.

Figure 5: Absolute efficiency of Compton camera at various depths for both completely dry and completely saturated soil. Detector spacing 10 cm, Scatter thickness 2 cm.

The absolute efficiencies for these depths can be seen in figure 5. This figure shows that the absolute efficiency is in the order of 1% for 5 cm depth, but drops off fairly rapidly. For very wet soils, imaging would likely only be effective up to around 15 cm deep, and for very dry soils it could be effective up to around 35 cm deep, for source energies of 511 keV.
The depth efficiencies were also determined for a higher energy source. The simulation was set to produce a point source of photons with energy 1173.2 keV (the lowest of the two gammas emitted by Cobalt-60). These efficiencies for various soil depth are shown in figure 6. In this case the event selection was changed slightly to have energies deposited within 10 keV of 1.1732 MeV instead of 0.511 MeV, along with several other similar changes.

Figure 6: Comparison of absolute efficiencies for various depths for photon energies 1173.2 keV and 511 keV, both completely dry and completely saturated soil.

For the higher photon energy of 1173.2 keV, the efficiencies appear to be smaller for the low depths (5 cm for both wet and dry soil, and 10 cm for dry soil) and then get larger than 511 keV efficiencies at greater depths. This means that for the lower depths the higher energy photons likely pass through the detector without depositing energy, but for greater depths more photons are passing through the soil without too much attenuation.

It should be noted that figures 5 and 6 account for many different angles as the detector is in the form of a dome, and the efficiency of a finite sized detector that does not surround the
target would be smaller than the above values. However, not all angles that the dome detector is sensitive to would provide many events. The number of events per x-y coordinate was used to provide an illustration of where the accepted events were occurring.

Figure 7: Number of accepted events per area on x-y plane tangent to the apex of absorber detector. The x and y coordinates range from -200 cm to 200 cm away from the initial photon x-y coordinate. Conditions: dry soil, soil depth 10 cm, spacing between absorber and scatterer 10 cm, absorber thickness 5 cm, scatter thickness 2 cm.

Figure 7 shows the number of accepted events per area for a depth of 10 cm within dry soil resulting from 10 million generated initial photons. The x-y coordinate for each event is a projection of the scattered photon trajectory (line connecting the scatter detector position to absorber detector position) onto the plane tangent to the absorber detector’s apex. The majority of events are occurring directly above the photon source, with a uniform decrease in events moving radially outward, as expected. Because the absorber detector has an outer radius of 67 cm with this spacing and thickness configuration, the area of high concentration (roughly greater than 50 counts per 16 cm² area) falls within the x-y coordinates of the detector. The events lying outside this region would be caused by events near the outer edges of the dome.

It is also important to note that the efficiencies in figures 5 and 6 were produced using the
configuration of 10 cm spacing between absorber and scatter detector with 2 cm thick scatter detector and 5 cm thick absorber detector. The efficiency could potentially be improved with different detector geometry.

Different spacings between the scatter and absorber detectors were explored to determine the impact of the distance between the detectors on the efficiency of detection.

![Figure 8: Absolute efficiency of Compton camera for different scatter detector to absorber detector spacings. Conditions: dry soil, soil depth 10 cm, absorber thickness 5 cm, scatter thickness 2 cm](image)

Figure 8 shows the absolute efficiency of the detector for scatter to absorber spacings ranging from 2 cm to 15 cm. The efficiency appears to have a level maximum for small spacings up to about 5 cm, which decreases slightly as the detectors are spaced farther apart. The difference between 5 cm spacing and 10 cm spacing is only around 0.02% and would not have a significant impact on the depth efficiencies shown in figure 5. However, the mean values in this plot seem to indicate that the optimal spacing for the absorber and scatter detectors is within 5 cm. This optimization of closer spacing coincides with detector spacing used by the
The thickness of the scatter detector was also varied to determine its effect on efficiency. Figure 9 shows the absolute efficiencies for scatter detector thicknesses of 5 \text{mm} to 50 \text{mm}. It is clear from this figure that a thicker scatter detector will improve efficiency quite significantly, as the change from 2 \text{cm} to 5 \text{cm} increases the efficiency by nearly 70\%. It is likely that the absolute efficiency of the detector will peak within a centimeter or two greater than 5 \text{cm}. However, a thicker scatterer will result in a bulkier detector, which will decrease the portability of the Compton camera. More importantly, a thicker detector will worsen the resolution of the detector. The trade-off between efficiency and resolution and portability must be considered in the implementation of such a detector.

![Figure 9: Absolute efficiencies for different scatter detector thicknesses. Conditions: dry soil, soil depth 10 cm, scatter to absorber spacing 4 cm.](image)

It is necessary to determine if the accepted events give reasonable values for energies, Compton angles, and positions, to make sure the detector works as expected. To investigate
the properties of the detector, several histograms were produced to observe various quantities, including:

- the energy deposited within the scatter detector
- the kinetic energy of the scattered electron
- the difference between kinetic energy lost in the scatter detector and the energy deposited within the scatter detector
- energy deposited within the absorber detector
- the Compton angle calculated using energies deposited within the absorber and scatter detector
- the actual angle between initial photon momentum and line connecting scatter and absorber hit positions

The plot of energy deposited within the scatter detector was found to be nearly identical to the kinetic energy of the scattered electron, as shown in figure 10. This adds confidence that the Compton process was handled correctly in the simulation.

Figure 10: Comparison of energy deposited in scatter detector by scattered electron compared to scattered electron kinetic energy.
Figure 10 also shows there is a maximum energy around 0.340 MeV. This corresponds well to the expected energy values for gammas of 511 keV, which were shown in figure 4.

The Compton angles calculated via equation 2 were also compared to the angle calculated between the direction of initial momentum of the photon and the line connecting the hit positions in the scatter and absorber detectors. This comparison can be seen in figure 11.

![Figure 11: Comparison of the Compton angle calculated using energy deposited in detector (blue) and the calculated truth value of the scattering angle using initial momentum direction and scattered direction (red).](image)

The above plot shows that there is a fairly close match between the actual scattered angle of the photon and the calculated angle based on energy deposited within the detector. There is a discrepancy, however, in which the true scatter angle is 180° but was calculated by energy deposition to be smaller. This could be due to some energy being deposited within the detectors during backscatter events. Further investigation is required to determine if that is the case, or if something else is happening in the selected events to produce the peak.

It is expected, as seen in figure 4, that as the scatter angle increases the photon energy will decrease and the energy of the scattered electron will increase. In order to confirm that this is in fact what is being seen in the simulation, histograms were plotted with narrow ranges on the Compton scattering angles. Angle ranges of $15 \pm 2.5^\circ$, $30 \pm 2.5^\circ$, $45 \pm 2.5^\circ$, $60 \pm 2.5^\circ$, and $90 \pm 2.5^\circ$ were used and the mean energies of the scattered photon and scattered electron were...
extracted from the resulting histograms, an example of the $\theta = 45 \pm 2.5^\circ$ histograms shown below, the rest can be found in Appendix A.

![Histograms](image)

Figure 12: Scattered electron kinetic energy (left) and scattered photon kinetic energy (right) for Compton angle $\theta = 45 \pm 2.5^\circ$.

These mean energies were then plotted against the Compton angle and overlaid on the plot shown in figure 4. The results are shown in figure 13, where the error bars are equal to the standard deviation of the energy histograms.

![Comparison of simulated and theoretical scattered electron and photon energies](image)

Figure 13: Comparison of simulated and theoretical scattered electron and photon energies per Compton angle.
The electron energies appear to match nearly perfectly, whereas there is slight deviation of the photon energy from the expected values. This is due to the secondary peak that can be seen in figure 15 in Appendix A at low energies. Further investigation is required to determine the cause of this secondary peak. It is likely that this peak is caused by unwanted events that are making it past the selection criteria.

The simulation was also run with vacuum in the surrounding volumes, replacing both the soil and the air in the world volume. This was done to observe the effects the soil had on the distributions. A qualitative analysis was conducted and there appeared to be similar energy spectra and Compton angle distribution. The number of accepted events for the vacuum simulation appears to be approximately 5 times the number of events within dry soil for a depth of 10 cm.

5 Conclusions

This analysis is meant to be a first step in putting together a Compton camera SPECT detector for in-field examination of roots and microbes. The simulation is still in its early phases of development, but gives promising results in terms of efficiency for the detector.

It was found in this analysis that the efficiency of detection is improved by a scatter to absorber detector spacing less than 5 cm and a thicker scatter detector. However the resolution of different configurations has not yet been explored enough to conclusively determine the optimal arrangement. It was also found that for the extreme case of completely dry soil the detector will likely be reasonably effective up to a depth of around 35 − 40 cm for a positron source. The depth at which the detector will be effective can be improved upon by using higher energy gamma sources.

The angles being calculated by the energy deposited within the detector appear to match reasonably well with the true scattered angles of the photons. The event selection can be further improved upon by future simulations, which may improve agreement with simulated data to expected values.
The next steps in this development of a Compton camera detector are to build a proto-
type detector for data collection, as well as writing code to for image reconstruction. Further
simulations can also be conducted to study the detector resolution and to improve upon the
event selection criteria.

It can be concluded that the Compton camera method has some potential of being a
viable candidate for imaging near-surface roots and microbes within soil.

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Appendices

A Appendix A

Figure 14: Scattered electron kinetic energy (left) and scattered photon kinetic energy (right) for Compton angle $\theta = 15 \pm 2.5^\circ$

Figure 15: Scattered electron kinetic energy (left) and scattered photon kinetic energy (right) for Compton angle $\theta = 30 \pm 2.5^\circ$
Figure 16: Scattered electron kinetic energy (left) and scattered photon kinetic energy (right) for Compton angle $\theta = 60 \pm 2.5^\circ$.

Figure 17: Scattered electron kinetic energy (left) and scattered photon kinetic energy (right) for Compton angle $\theta = 90 \pm 2.5^\circ$. 
References


