



**Multisource Direction Identification Using a
Rotating Scatter Mask**

THESIS

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AFIT-ENP-MS-18-M-073

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SCATTER MASK

THESIS

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Air Education and Training Command
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Degree of Master of Science in Nuclear Engineering

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Capt

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Abstract

The objective of this thesis was to develop the methodology and prove that the rotating scatter mask (RSM) can identify the direction of multiple gamma radiation sources. There exist various systems for the purpose of source imaging, but all are hindered by either a high cost, a large size, a narrow field of view, or a low geometric efficiency. The RSM mitigates those issues and provides an efficient means of determining the direction of a radioactive source. The RSM consists of a 3"x3" NaI(Tl) scintillating detector encompassed by a polymethacrylate scattering mask designed to predictably attenuate gamma rays traveling through it to the detector. Previous experimental and simulations proved the viability of using the variation of full energy counts as a function of the rotation angle of the mask to provide a detector response curve (DRC). Each position relative to the RSM assembly results in a unique DRC that can be used to identify the direction of a radioactive source. The results of this thesis proved that the RSM can also be used to simultaneously identify the direction of multiple gamma ray sources with distinguishable full energy peaks and with indistinguishable full energy peaks by using a deconvolution algorithm.

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List of Abbreviations

Abbreviation	Page
RSM	Rotating Scatter Mask 2
DHS	Department of Homeland Security 3
CBP	Customs and Border Protection 3
CdZnTe	cadmium-zinc-telluride 4
PMT	Photomultiplier Tube 4
DRC	Detector Response Curve 5
GEANT	GEometry ANd Tracking 6
MCNP	Monte Carlo N-Particle 6
FEP	Full Energy Peak 6
MCA	Multi-channel Analyzer 34
MAC	Modal Assurance Criterion 36

MULTISOURCE DIRECTION IDENTIFICATION USING A ROTATING SCATTER MASK

I. Introduction

1.1 Background

Radiation is ubiquitous. Without the proper laboratory equipment, it is normally not observable yet can have effects that do not manifest for years or even decades. While it can originate from sources as terrifying as a nuclear detonation or a star, it can also originate from less violent beginnings. Many elements have isotopes that emit radiation via a natural process. To the general population, the word radiation has a negative connotation and is typically associated with scenarios, such as Fukushima or Three Mile Island, that elicit negative emotions. Many less threatening scenarios, such as a chemotherapy session or a medical x-ray, show that radiation can be used to help people as well. Although radiation is commonly used for the benefit of patients, the negative effects of radiation are often topics of discussion.

In high school physics, three types of radiation are discussed: alpha particles, beta particles, and gamma rays. Usually, gamma rays are taught to be the most dangerous because they are able to penetrate deeply into matter. Gamma rays require several inches of lead to be stopped, while alpha particles can be stopped by a piece of paper and beta particles can be stopped by a piece of clothing [1]. The range of alpha particles in matter is approximately 10^{-5} meters and the range of beta particles in matter is approximately 10^{-3} meters [1]. Unfortunately, because alpha and beta particles can be stopped in such a short distance, using these particles to detect the

source of radiation becomes infeasible. Alpha and beta sources typically only become dangerous when ingested or when at a very high activity [1].

The third form of radiation is gamma radiation. Gamma radiation is a high energy form of electromagnetic radiation that originates from the decay of an excited state of the nucleus. Compared to visible light, gamma radiation is roughly five orders of magnitude more energetic [1]. This difference in energy is what determines the interactions that can occur between the radiation and the material through which it is passing. Visible light, which is relatively low energy, enables organisms to observe the world around them. Gamma radiation is energetic enough to penetrate deeply into matter or break down DNA leading to biological issues like cancer.

The threat of a nuclear weapon is ever present and a great amount of effort has been expended to ensure that the technology and ability to build and use nuclear weapons does not fall into the wrong hands. Part of this process is ensuring that the material used for manufacturing nuclear devices is accounted for at all times. In facilities that use or store nuclear material, radiation detectors are used to monitor the area to help ensure that all sources have been accounted for. An imaging systems like the H3D Polaris-H is an example of a device that has been developed for this purpose [2]. Radiation detection systems are also used to monitor imports into the United States for illicit radioactive material. The rotating scatter mask RSM project is an attempt to develop a radiation imaging system effectively and relatively cheaply.

1.2 Motivation

The needs for detectors that can identify and image the direction of an unknown radiation source abound. The ability to quickly locate orphan radiation sources serves myriad purposes, including locating a lost source in a lab and detecting radiological material smuggled across borders. Radiological terrorism is a very real threat to any

developed country in the world. Following the terrorist attacks on the World Trade Centers, the possibility of a smuggled nuclear device became a very large concern in the United States [3]. There are many methods of smuggling materials into the U.S., but perhaps one of the most vulnerable is through one of the large shipping ports [3]. Like most other countries, the United States' economy depends on the import and export of goods. In the U.S., there are five large shipping ports that provide a vulnerability to smuggling illicit nuclear material [4]. As of 2011, roughly 53% of U.S. imports and 38% of U.S. exports are through maritime vessels [4]. Any disruption caused by a detonation of a nuclear device in a major port would have far-spread damaging effects on the livelihoods of the citizens of the United States as well as the global economy at large.

In 2007, Congress directed the Department of Homeland Security (DHS) to utilize radiation detectors and imaging systems to scan every shipping container before it is loaded onto a U.S. bound ship [3]. With approximately 12 million shipping containers arriving through U.S. ports per year, this mandate is hardly trivial [3]. This law to scan all inbound containers before they are loaded onto U.S. bound ships exponentially increases the responsibility of the DHS. Currently, the Customs and Border Protection (CBP), an agency of the DHS, identifies approximately 5% of shipping containers as "high risk". These containers are then separated after arriving in the U.S. port and are scanned and imaged. Originally, the CBP was required to implement a method to follow this law by 2012. The scope and cost of this requirement has caused that deadline to be extended three times. The CBP now has until 2018 to meet this requirement, but will likely need another extension [3]. Scanning every single container is almost an unfathomable increase compared to the current capability of scanning only containers that are deemed "high risk". Having a low-cost, effective method for quickly scanning and imaging shipping containers for radioactive sources

could provide the capability to meet the requirements set forth by Congress.

1.3 Research Problem

Multiple detection systems have been developed to identify the direction and/or location of a gamma-ray radiation source. Current designs suffer from one or more of four main issues: multiple detectors required making them cost prohibitive, large detection system reducing portability, low geometric efficiency requiring long counting times, and limited field of view reducing the area a single system can cover [5]. Devices such as the large-area, coded-aperture, gamma-ray imager, which requires the use of fifty-seven individual detectors [6], or the H3D Polaris-H, which contains an array of eighteen cadmium-zinc-telluride (CdZnTe) crystals [2], require many expensive scintillating crystals. The large-area, coded-aperture, gamma-ray imager also requires multiple 45 kg blocks of lead to mask the signal from some of the detectors and requires a small truck to move it around [6]. These issues with cost and mobility prohibit their widespread availability and inhibit their use in situations such as an emergency response where the requirement is to get in quickly and save lives.

Rather than using an array of scintillating crystals, systems such as gamma cameras use an array of photomultiplier tubes (PMTs) behind a mechanical collimator [7]. Even though multiple PMTs are required, this array is less expensive because only one scintillating crystal is needed [7]. The issue with a design such as this is the presence of a collimator. The purpose of the collimator is to remove all gamma-rays that are not traveling perpendicular to the face of the detecting crystal [8]. The downside is that this process reduces the total number of gamma rays impinging on the imaging system, which lowers the efficiency of the detection system as a whole. The collimator is even referred to as the “weak link” for any imaging system [8].

The rotating scatter mask is designed to mitigate all of the above issues. It

required only a single sodium iodide thallium doped NaI(Tl) detector, which allows for a much lower cost and footprint than the other imaging systems. Because of their high intrinsic efficiency, NaI(Tl) detectors have been one of the most popular scintillating detectors for decades [9] [10]. Their ubiquitous use through industry means that many organizations will already have them or will be able to easily obtain them. Furthermore, the design of the RSM allows for a near- 4π steradian field-of-view for identification of a radiation source. The actual design of the RSM will be discussed in detail in Chapter III [5].

Through experiments and simulations, the RSM has already been shown to be able to identify the direction of a single Cs-137 gamma ray source. To increase the utility of the RSM, the capability to identify the direction of multiple gamma ray sources needed to be developed. Multiple sources with different energy emissions were used for simultaneous direction identification. An attempt at using the current RSM system for identification of multiple gamma sources with identical energy emissions to establish the response of the RSM in the presence of a distributed radiation source.

1.4 Previous Work

Previous RSM experimental and simulation work by Julie Logan, using the scatter mask assembled by Maj Christopher Charles based on the design by Fitzgerald [5], demonstrated the system's ability to identify the direction of a monoenergetic gamma source relative to the detector [11]. Specifically, Logan demonstrated that detector response curves (DRCs) developed from experimental data obtained from a Cs-137 source placed at various positions matched simulation predictions and allowed identification of radiation source directions relative to the detection system [11]. The development and theory of the DRCs will be described in Chapter II.

Logan's method of determining the direction of a radiation source was to develop a

library of DRCs for every possible source position, which could then be matched to the DRC of a source at an unknown position [11]. Each DRC in the library corresponded to a unique value of theta and phi, based on a spherical coordinate system. The DRC that matched the DRC of the source at the unknown position would give the direction of that source. This process will be described in better detail in Chapter III.

With help from Dr. Darrell Holland, Logan also developed a method of simulating the RSM assembly to prove that the system could be modeled accurately in a Monte Carlo simulation [11]. Two independent programs, GEANT-4 (GEometry ANd Tracking) and MCNP (Monte Carlo N-Particle), were used to run the Monte Carlo simulations of the RSM. Both methods gave the same results and also agreed with the experiment results. In this thesis, multiple libraries of DRCs were developed from different energy gamma rays and were compared with previous experimental and simulation DRCs.

1.5 Research Objectives

Each DRC describes the number of full energy peak FEP counts for a given energy as a function of mask rotation angle. Previous work demonstrated the ability to determine source direction for a single monoenergetic gamma source by matching experimentally obtained DRCs against a library of GEANT-4 simulated DRCs [11]. Before it can be further developed into a field-ready device, the RSM needs to be able to identify source direction in the presence of multiple sources. To determine the RSM's ability to simultaneously identify the directions of multiple gamma sources, the following research objectives were completed:

- Determined that the DRCs from different energy sources have the same general features and shape.
- Developed an experimental library of DRCs with multiple sources present and

verify that the resulting library matches with the libraries from Logan's research.

- Determined if the RSM can identify the direction of two different radioactive sources in the same location.
- Determined if the RSM can identify the direction of two different radioactive sources in different locations.
- Determined if the RSM can identify the direction of two identical radioactive sources in different locations.
- Determined if the RSM can identify the direction of three different radioactive sources in three different locations.

II. Theory and Literature Review

2.1 Radiation Interactions with Matter

For the current rotating scatter mask design, gamma rays in particular are the radiation type of interest. Gamma rays can originate from a nucleus deexciting from a long-lived, metastable state or from an excited state following an alpha or beta decay [12]. In both cases, the difference between the initial and final energy states of the nucleus is usually unique and results in gamma ray energies that can be used to identify the specific nucleide [1]. The typical energy range of gamma rays emitted in this manner is between 0.1 and 10 MeV [1].

Like other forms of neutrally-charged radiation, gamma rays can penetrate through a substantial distance through matter before interacting [1]. There are three processes through which gammas typically interact with matter: photoelectric absorption, Compton scattering, or pair production [1]. The probability of each interaction is dependent on physical properties of the matter as well as the energy of the gamma ray [1]. The quantity defined as the microscopic cross-section defines the probability of interaction based on atomic and nuclear qualities that are inherent to the material [9]. The quantity defined as the macroscopic cross-section defines the probability of interaction using information from the microscopic cross-section and physical properties like density and is given by the symbol μ [9]. In Equation 1, I_0 corresponds to the intensity of the original beam of gammas and I corresponds to the intensity of that beam after traveling some distance, x , through the material [9]. This distance at which the intensity of the beam has diminished by a factor of e is defined as the path length, L , of the material [9].

$$I = I_0 e^{-\mu x} \tag{1}$$

2.2 Types of Interactions

The likelihood of any of the three interactions, photoelectric absorption, Compton scattering, or pair production, occurring depends on two main factors: the energy of the incident gamma ray and the atomic number (Z) of the material [1]. Each of the modes of interactions will be described in some detail below.

Photoelectric Absorption

Photoelectric absorption is the primary photon interaction process at low energies, up to several hundred keV [1]. In the process of this interaction, the photon is completely absorbed by the atom and an energetic electron is emitted. The bulk of the photon's energy and momentum, except for a small amount of energy needed to overcome the electron's binding energy and miniscule atomic recoil, is transferred to the liberated electron. The mechanics of photoelectric absorption is shown in Figure 1. The probability of interaction increases rapidly with the atomic number of the material and decreases less rapidly with an increase in energy [1]. This dependence is shown in Equation 2.

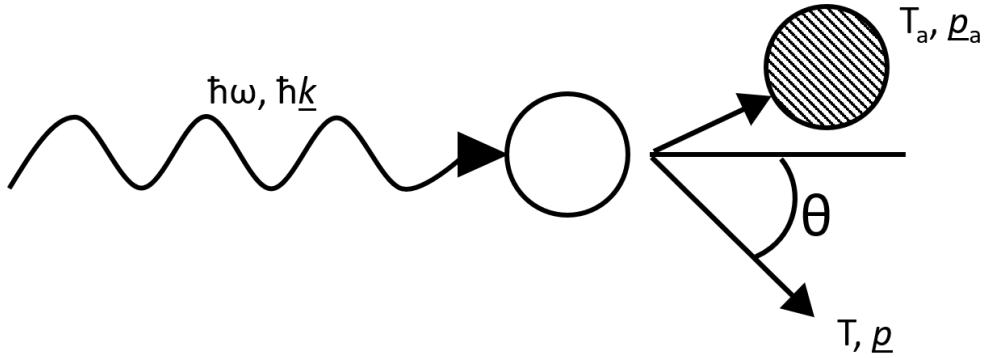


Figure 1. The kinematics for photoelectric absorption are shown in this figure. An incoming photon interacts with an electron bound to an atom. The result is that the electron is ejected and the atom recoils in such a way as to conserve momentum. [1]

$$\sigma_{\tau} \propto \frac{Z^5}{(\hbar\omega)^{\frac{7}{2}}} \quad (2)$$

Compton Scattering

The second method of gamma ray interaction, Compton scattering, occurs most often with photons that have an energy between several hundred keV and approximately a few MeV [1]. Compton scattering is defined as the interaction in which a photon imparts some of its energy to an atomic electron, but is not fully absorbed [1]. The result is that the electron and reduced energy photon escape from the atomic well in a direction that preserves the momentum of the incident photon [1]. The mechanics of this interaction are shown in Figure 2. The probability of this interaction occurring is proportional to the atomic number of the material and inversely proportional to the energy of the photon [1]. This dependence is shown in Equation 3.

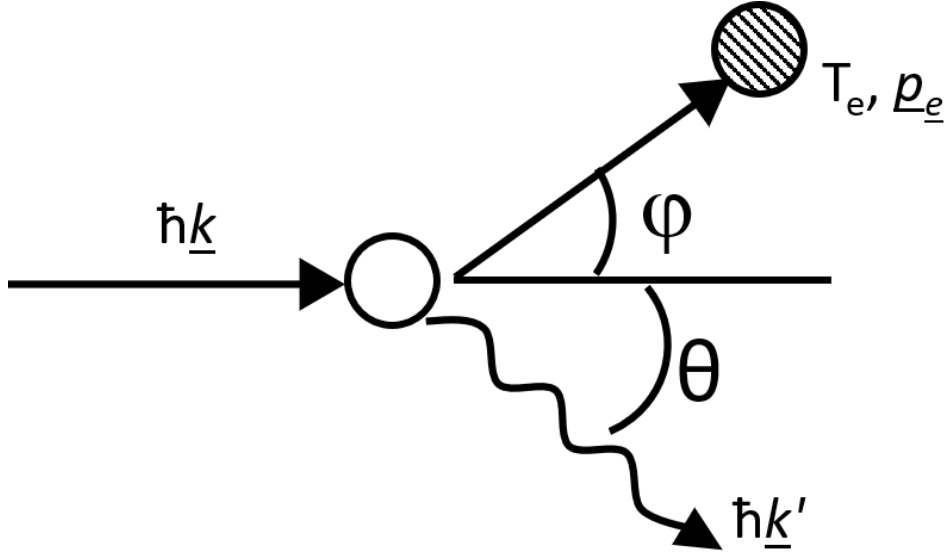


Figure 2. The kinematics for Compton scattering are shown in this figure. An incoming photon interacts with an electron and transfers some of its energy. The result is that the electron is ejected from the atom with a kinetic energy equal to the energy lost by the photon minus the electron binding energy. The photon recoils in such a way as to conserve momentum. [1]

$$\sigma_c \propto \frac{Z}{\hbar\omega} \quad (3)$$

Pair Production

Pair production, the last method of gamma ray interaction discussed in this thesis, does not begin to dominate the probability of interactions until the energy of the incident photon is above a few MeV [1]. In this interaction, the energy of the photon is converted into an electron and positron, which requires an energy of at least 1,022 keV [1]. To conserve momentum, pair production needs to be in the vicinity of another particle to occur [1]. The mechanics of this interaction are shown in Figure 3. As shown in Equation 4, the probability of pair production occurring increases with the atomic number of the material and with the energy of the photon.

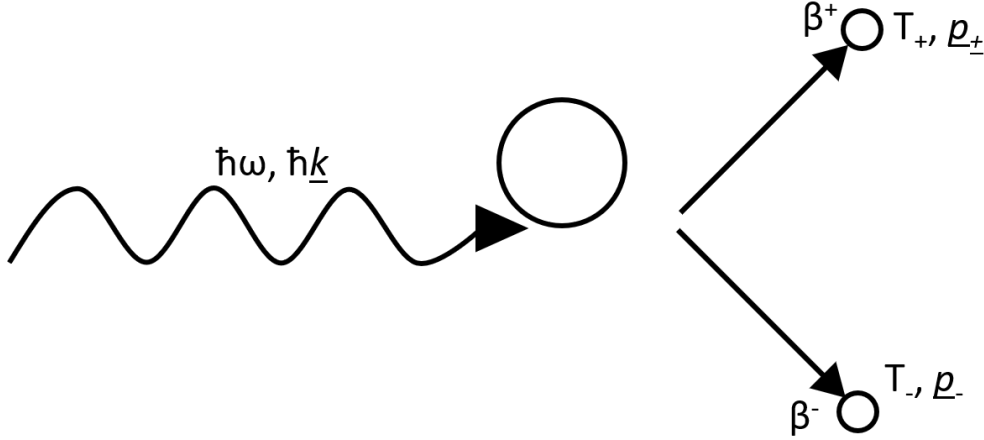


Figure 3. The kinematics for pair production are shown in this figure. An incoming photon with an energy of at least 1,022 keV (twice the rest mass of an electron) has a chance of undergoing pair production in the vicinity of another particle. After the interaction, the gamma photon is converted to an electron and positron with combined kinetic energies of the photon minus 1,022 keV. [1]

$$\sigma_\kappa \propto Z^2 \ln \left(\frac{\hbar\omega}{2m_e c^2} \right) \quad (4)$$

Figure 4 shows the probabilities of interaction for each of the three interactions as functions of atomic number and photon energy. As shown in the figure, the dominant interaction at low energies is photoelectric absorption and at high energies is pair production. In between the two is Compton scattering.

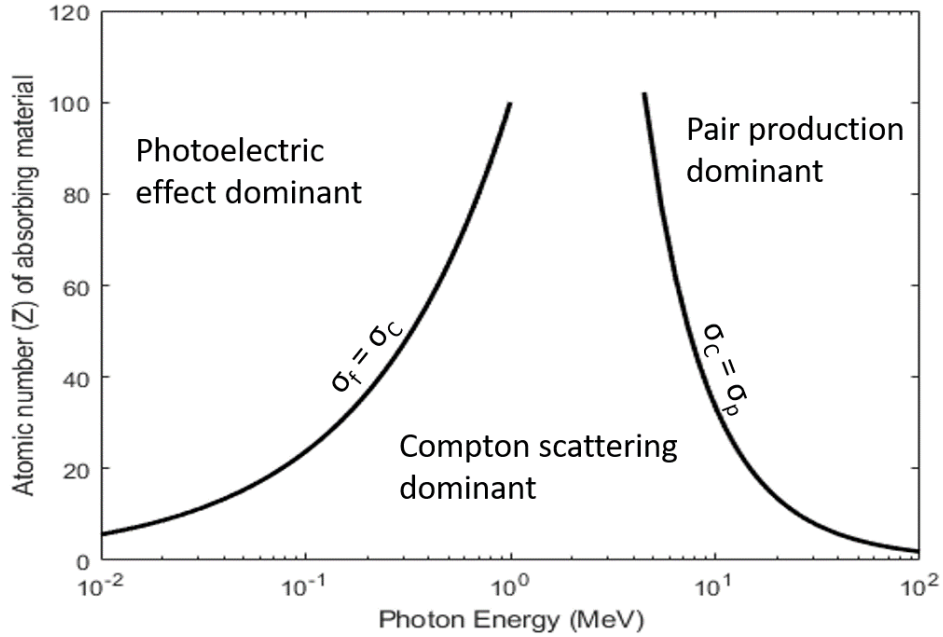


Figure 4. The photon interaction probabilities are shown in this figure. The photoelectric effect dominates at lower energies and pair production dominates at higher energies. The Compton effect dominates at the energies in between the two. [13]

2.3 Photon Detection

The radiation sources used for this thesis emit gamma rays in the energy range where photoelectric absorption and Compton scattering are the dominant interactions. To detect and record information about a photon, one of the possible interactions needs to occur in a medium in which it can be observed.

The two interactions, photoelectric absorption and Compton scattering impart either all or some, respectively, of the energy of the gamma ray to an atomic electron

[12]. The probability the photon will interact depends on the photon energy and the material properties (density and atomic number) of the medium through which it is travelling [1]. For example, air, which is made up of mostly nitrogen and oxygen, has a low density and low atomic number. Using the equations for interaction probabilities given in Section 2.2, a very low cross-section could be expected. Figure 5 shows the total and component microscopic interaction cross sections for air as a function of photon energy. The path length, as described in Section 2.1, in air is approximately 130 meters for a 1 MeV gamma ray [14].

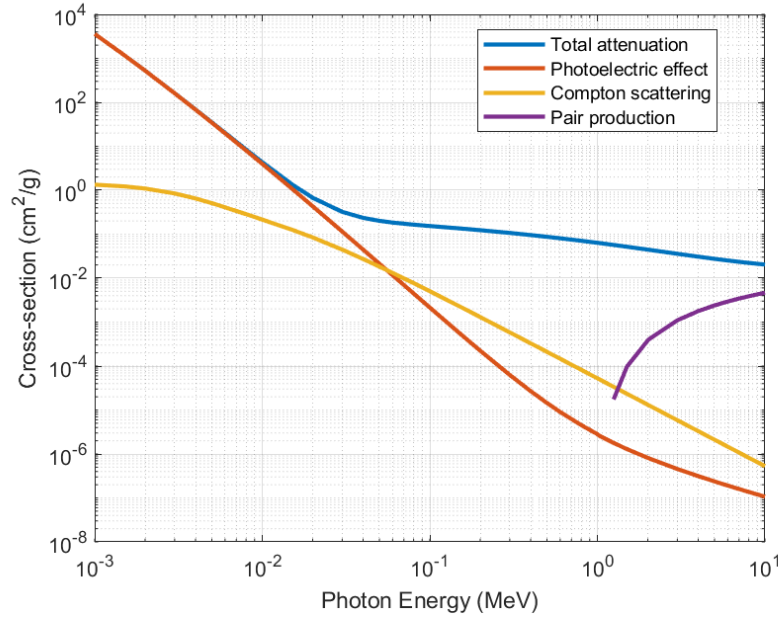


Figure 5. The microscopic cross-sections for the different photon interactions in air, as a function of photon energy, are shown in this figure. The legend depicts which line represents total attenuation, photoelectric effect, Compton effect, and pair production. [14]

The materials of scintillation detectors are chosen based on myriad requirements for efficient photon detection [10] Some of the desired properties are:

- High density
- High atomic number

- Mechanically durable
- Hardened to radiation
- Short decay times
- Transparent to its emitted photons
- Photon emission in the energy range of a photomultiplier tube
- Low cost
- Linear response over a wide energy range

For decades, a material of choice has been a crystal of sodium iodide doped with thallium, NaI(Tl) [10]. The path length in this material is approximately 2 centimeters for a 1 MeV gamma ray [14]. In this thesis, a 3"x3" cylindrical NaI(Tl) scintillating crystal was exclusively used.

The interaction of a gamma ray with the NaI(Tl) material, either by photoelectric absorption or Compton scattering, will free an electron bound to an atom, which will then interact with the thallium to produce scintillation photons proportional to the energy of the incident gamma ray [12]. These photons are converted to photoelectrons by a photomultiplier tube that is attached to the crystal. This PMT uses an electric field to multiply the signal of the electron until it is strong enough to be read by the laboratory electronics as an electric pulse [12]. The pulse height, measured in volts, is directly related to the energy of the original free electron [12]. Thus, a record of the pulse heights from multiple detections can be used to form a spectrum in which the horizontal axis is the energy of detection and the vertical axis is the number of counts at that energy. An example energy spectrum is shown in Figure 7.

Figure 7 shows the raw spectrum captured during a Cs-137 experimental run. The decay of Cs-137 produces a 662 keV gamma ray, which shows in the spectrum

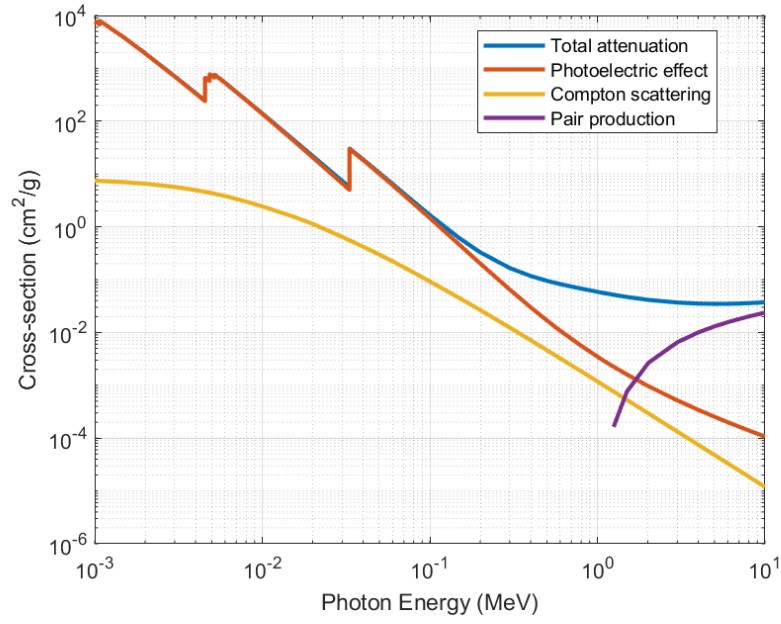


Figure 6. The microscopic cross-sections for the different photon interactions in an NaI scintillating crystal, as a function of photon energy, are shown in this figure. The legend depicts which line represents total attenuation, photoelectric effect, Compton effect, and pair production. The sharp peaks in the total and photoelectric interaction lines correspond to resonance energies for electrons bound to the iodine atoms. [10] [14]

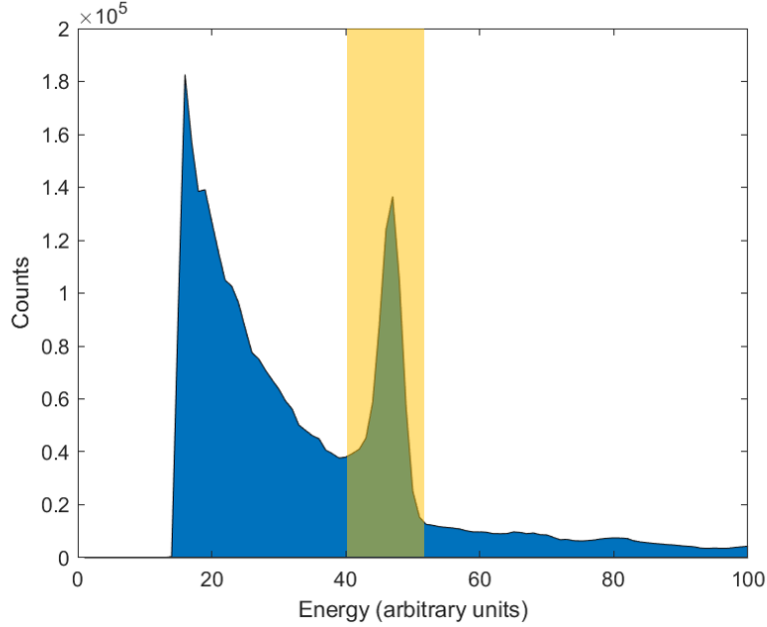


Figure 7. Energy spectrum of with a Cs-137 source. The peak highlighted in orange is the Cs-137 peak.

as a characteristic full energy peak (highlighted from 40-50 arbitrary units). The FEP corresponds to a detection of an electron that absorbed all of the energy of the incident gamma ray through any number of Compton scatters followed by a photoelectric absorption. The counts for other energies of the spectrum are either from Compton scatters, which results in a detection with less than 662 keV of energy, or from noise from the background or other sources in the vicinity. In the presence of very active sources, a second gamma ray can interact with the detector before the scintillation response from the first has completed. This results in pulse pile up which manifests as a higher energy detection. The placement and activity of the sources used in this thesis allowed for negligible pulse pile up effects.

2.4 Source Location

In Chapter I, different attempts at developing a method of source location were mentioned. To reiterate some of the downfalls of these methods that this thesis is attempting to mitigate, the other methods suffered from one of four main issues: multiple detectors required (expensive), large footprint (not portable), low efficiency (long counting times), and low field of view [5]. The work presented in this thesis is a further development of an idea to take a single NaI(Tl) detector, which is relatively cheap and small, and place it inside a scatter mask for the purpose of modulating the number of full energy gamma rays interacting with the detector.

The basic idea of a rotating modulation collimator system was first put forth by Ben Kowash who was attempting to develop a method of identifying the location of the radiation source [15]. In this system, the collimator was used to remove gamma rays that were not incident perpendicular to the face of the detecting crystal. The side effects were a substantial reduction of the field of view to around 17° and a significant reduction in count rate [15]. A later researcher, Jack Fitzgerald, developed a design for the rotating scatter mask as an improvement on the design put forth by Benjamin Kowash. Fitzgerald's RSM design provided an almost 4π steradian field of view, limited mostly by the electronics and hardware to the rear of the detector. The actual design of the RSM will be described in Chapter III.

Maj Christopher Charles 3D printed Fitzgerald's design to begin testing the theory that it could be used to identify the direction of a radiation source. Julie Logan developed a Monte Carlo simulation of the RSM detection system in GEANT-4 and conducted validation and verification of the detection system [11]. She also performed experimental runs to the same end. Both experimental and simulation results agreed and provided the ability to identify the direction of a single source of radiation [11]. In this thesis, the RSM will be tested on its ability to locate multiple energy radiation

sources. The following configurations were used to study the RSM detection system's source direction identification capabilities:

- Two different energy sources in the same location
- Two different energy sources in different locations
- Two identical energy sources in different locations
- Three different energy sources each in a different location

III. Methods

3.1 Introduction

The full rotating scatter mask assembly was developed and assembled by Maj Christopher Charles. The experimental setup for the RSM is fairly simple in that few electronics are needed. The detector is a Saint Gobain 3"x3" NaI(Tl) scintillating crystal hermetically sealed with a photomultiplier tube [10]. The rotating scatter mask is made of polymethacrylate (also known as Plexiglass) which encases the detector to provide the gamma modulation that allows for direction identification. The detector is powered by an ORTEC 556 High Voltage supply. The output of the PMT is passed through an ORTEC 142 Preamplifier and an ORTEC 460 Delay Line Amplifier to shape the signal. A simple stepping motor drives two belts that rotate the mask. An encoder ring rotates along with the RSM and records the angle of the rotation of the mask. The RSM with housing surrounding the detector and NIMBox with modules are shown in Figures 8 and 9.

The output of the amplifiers is passed into a NIMBox NDA8 Data Acquisition Module, which takes the analog electric signal and converts it to a digital signal. This process begins when the electric signal reaches a threshold limit, which was set to reduce background noise below approximately 50 keV. The NIMBox digitizes the signal into a waveform with eighty total points after reaching an electronic trigger of approximately 0.2 volts. The waveform is then sent through the LabVIEW program to be recorded. The maximum energy of the detection is the only required data point, so the program records only the maximum value of the digitized waveform. At the same time, LabVIEW queries the encoder ring to record the rotation angle of the RSM. These two data points per detection, after post-processing, allow for the identification of the direction of the radiation source.

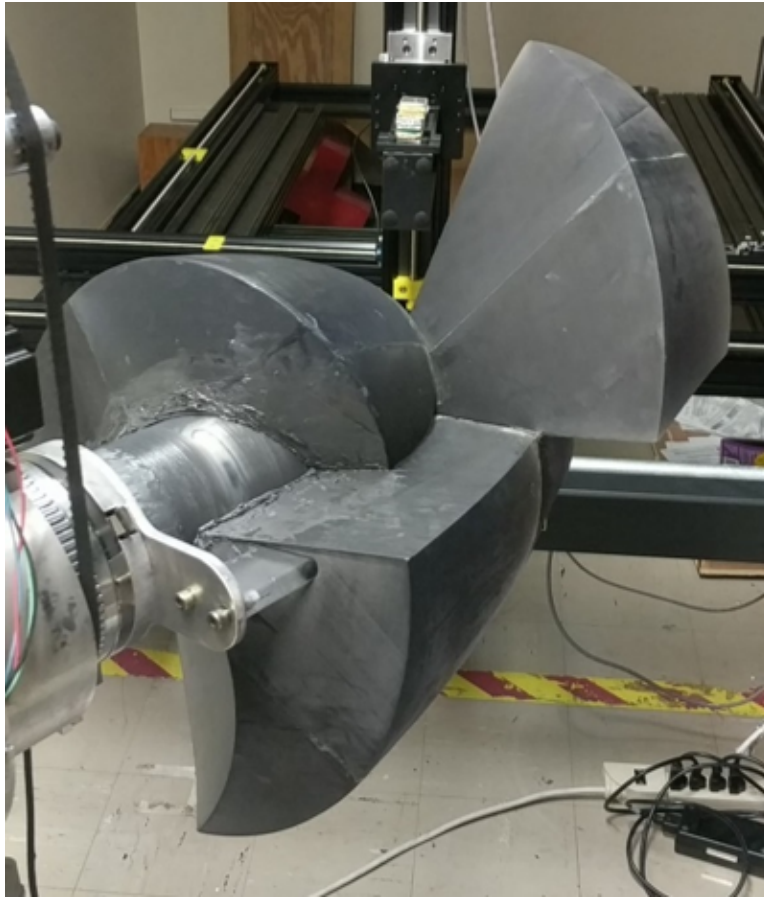


Figure 8. In this figure is the rotating scatter mask (in the foreground) and two radioactive sources on the source arm used to position the sources (in the background).

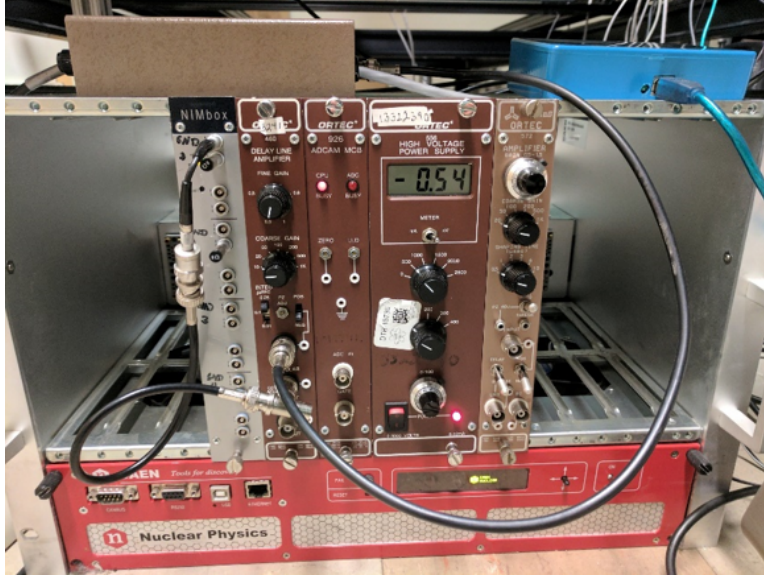


Figure 9. The electronics for the RSM experiment. From left to right: NIMBox Data Acquisition Module, ORTEC 460 Delay Line Amplifier, ORTEC 926 ADCAM MCB (not used), and an ORTEC 556 High Voltage Power Supply. In the upper left is an ORTEC 142 Preamplifier and in the upper right is part of the encoder ring electronics.

The main sources used in the experiments, their energies, and activities are given in Table 1.

Table 1. The sources used in this thesis along with their emitted energies and activities.

Source	Emitted Energy (keV)	Current Activity (μCi)
Cs-137	662	6.7
Co-60	1,173	2.6
	1,332	2.6
Na-22	511	8.9 (x2)
	1,273	8.9

3.2 Design Efficiency

The end goal of developing an RSM assembly is to create a portable device that can operate in near-real time to locate a radiation source. The size, and subsequently the efficiency, of the assembly is one limiting factor to meeting this goal. Other factors

such as characteristics of the source like energy emission and activity or characteristics of the environment like materials present or background radiation will affect the ability to detect a radiation source. The following paragraphs provide an overview of various phenomena affecting RSM detection system efficiency.

The first efficiency to consider is the geometric efficiency [12]. In most cases, the emission of radiation from a source is isotropic [1]. In other words, there is an equal chance that it can be emitted in any direction. A typical radiation source in the laboratory is placed inside a planchet, meaning it has measurable thickness in all three dimensions. At close range, this can affect the probability of the emission in certain directions, based on its shape. At far enough range, on the order of centimeters, the sources used in these experiments can be treated as a point source [12]. Within that range, the RSM might not be necessary to locate the source. Outside that range, any dependency of the radiation flux on the angle is negligible. Rather, assuming there are no interfering materials between the source and detector, only the distance from the source is needed to calculate the radiation flux.

A radiation source will have a certain activity based on the amounts and types of radioactive material present. The radiation flux through a given area from the source can be approximated by dividing the given area by the area of a sphere with a radius equal to the distance to the source. For isotropic sources, the geometric efficiency decreases rapidly with the inverse square of the radius. The ratio of the activity at the detector to the, A_d , to the source activity, A_s , is related to the ratio of the diameter of the cylindrical detector, d_c , to the distance from the detector to the source d_s (see Equation 5).

$$\frac{A_d}{A_s} = \frac{\frac{1}{4}\pi d_c^2}{\pi d_s^2} \quad (5)$$

The second efficiency is the detector absorption efficiency which is based on the

detector material. Typically, this information is given by the company that provides the crystal. At higher energies, the absorption efficiency begins to decrease [16]. The behavior of a 3 inch NaI(Tl) crystal, like the one used in experiments, is shown in Figure 10 [16].

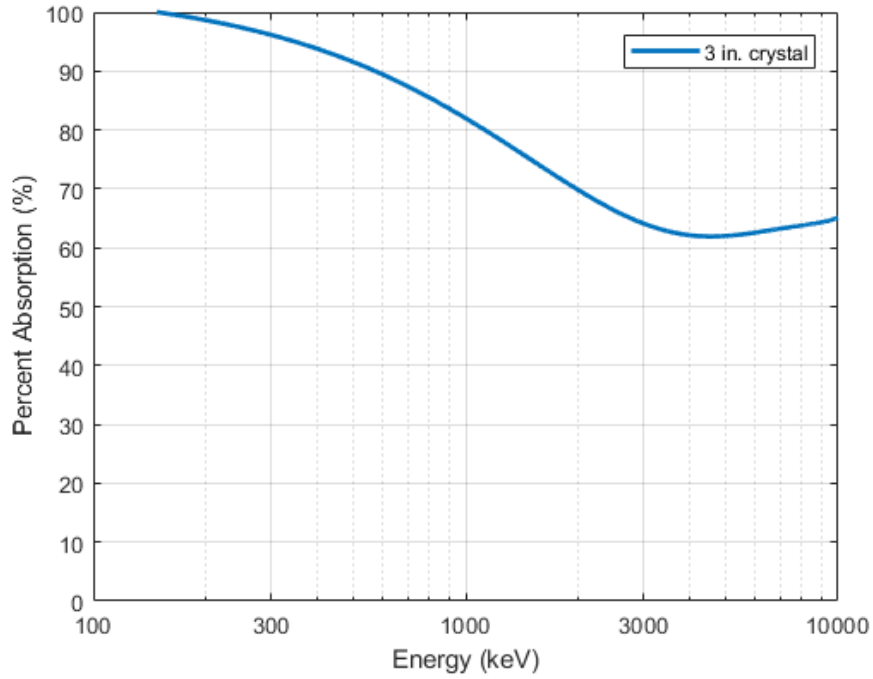


Figure 10. Absorption efficiency of a 3 inch cylindrical sodium iodide scintillating crystal. The percent absorption is based on the difference between $I_o - I$ where I_o is the initial photon intensity and I is the intensity after the beam of photons passes through the detector. The percentage is normalized by dividing by the initial intensity, $(I_o - I)/I_o$. [16]

Although the absorption efficiency provides information about the chance of any particular interaction occurring, the last efficiency, called the peak-to-total efficiency, gives the probability of that interaction depositing the full energy of the gamma ray. The peak-to-total efficiency is defined as the number of detections with the full energy in a certain time divided by the total detections at all energies in the same time. The peak-to-total efficiency for the 3 inch NaI(Tl) crystal is given in Figure 11.

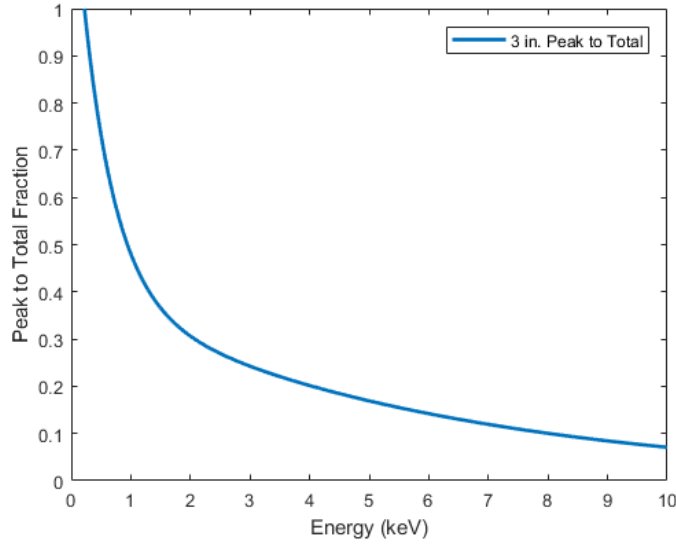


Figure 11. Peak-to-total efficiency for a 3 inch NaI(Tl) crystal. The peak-to-total is defined as the ratio of the number of counts in the full energy peak to the total number of detections at all energies. [16]

3.3 Mask Geometry and Effects

Typically, the above three efficiencies are enough to describe a whole detector assembly, but this is not the case with the RSM. By virtue of its purpose, the rotating scatter mask was created to scatter gamma rays, which reduces the overall efficiency since those gammas will not be detected at their full energy. As mentioned in Chapter I, the RSM produces a detector response curve that is unique for every possible source position. By utilizing spherical coordinates, as pictured in Figure 12, the location of any radioactive source can be defined relative to the center of the detector. The RSM rotates about the z-axis, the angle of which is measured by θ . The angle from the z-axis is measured by the angle ϕ .

The method of producing the mask design, as presented by Fitzgerald [5], is to create a matrix where the rows correspond to the angle in ϕ , the columns correspond to the angle in θ , and the number in each box corresponds to the mask thickness (see Figure 13). A computer render of the geometry can be seen in Figure 14. Also

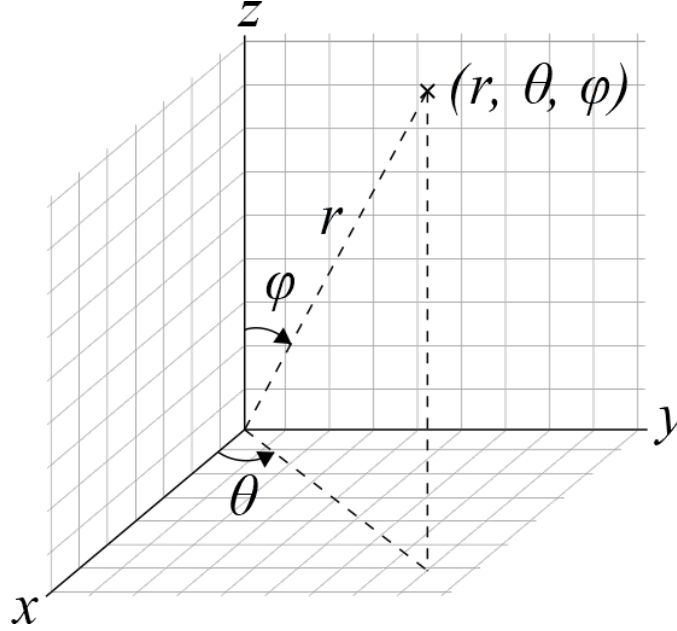


Figure 12. Spherical coordinates system as used to define how to measure the angles from the mask. The axis of rotation of the mask is along the z-axis shown in this picture. [17]

included in the design is a hollow cylinder at the face corresponding to $\phi = 180^\circ$ to accommodate the detector and support the mask.

To produce distinct DRCs for each source location, the design of the mask incorporates a unique shape. The mask features several discontinuities in thickness as measured radially from the center. The variation in thickness causes a predictable and consistent variation in the total number of full energy gamma rays that make it to the detector as the mask rotates in θ .

Because of its high ratio of gamma scattering to gamma attenuation, polymethacrylate was chosen as the material for the mask. The mask was designed with the following constraints:

- The maximum thickness of the mask is approximately 20 centimeters
- The average thickness of the mask over a full rotation in theta is the same for every angle in ϕ

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	26	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	31	30	29						
	27	27	28	29	30	31	1	2	3	4	5	6	7	8	9	10	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	31	30	29					
	28	28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	31	30	29				
	29	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	31	30	29			
	30	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	31	30	29		
	31	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	31	30	29	

Figure 13. This figure shows the matrix used to define the design of the mask. The rows correspond to the mask along the z-axis and the columns correspond to the mask about the axis of rotation. The values and colors in each cell correspond to the thickness of the mask at that point. [11]

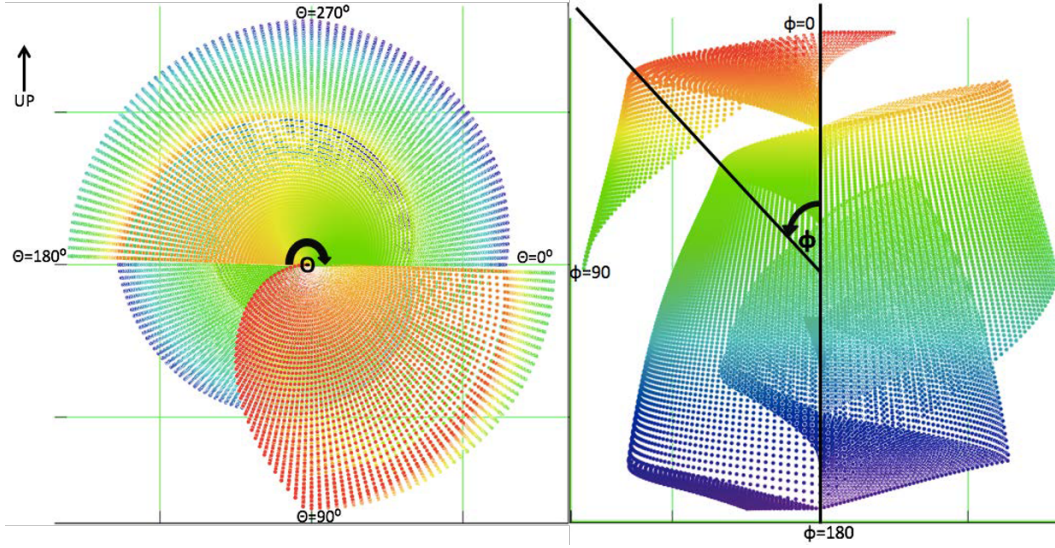


Figure 14. Computer render of the mask itself. The view on the left is from the top looking down the axis of rotation. The view on the right is from $\phi = 90^\circ$ with the axis of rotation highlighted as a vertical line in the center. This unique geometry is what allows for the generation of detector response curves and gives the ability to identify source direction. [11]

The total and component microscopic interaction cross sections for each kind of photon interaction in polymethacrylate, as a function of photon energy, are shown in Figure 15. Using Figure 15 and a density of $1.18 \frac{g}{cm^3}$, the mean free path of a 1 MeV gamma is approximately 12.34 cm [10].

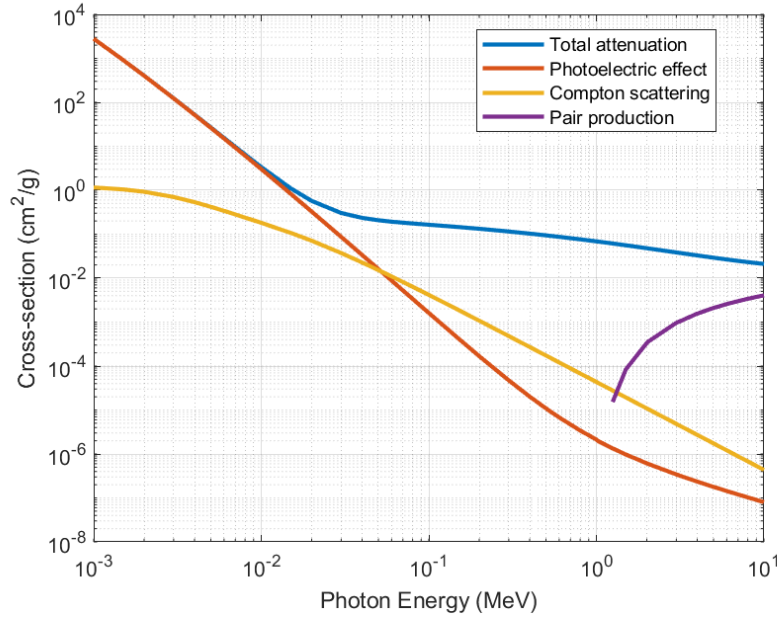


Figure 15. The probabilities of photon interactions in polymethacrylate are shown in this figure. The legend depicts which line represents total attenuation, photoelectric effect, Compton effect, and pair production. [14]

3.4 Data Post Processing

As mentioned in a Section 3.1, the NIMBox digitizes the electric pulse from the NaI(Tl) detector into eighty points. Each of these points are represented by a channel number between 0 and 16,383, which is native to the NIMBox. An example of this digitized waveform is in Figure 16.

Also mentioned in Section 3.1, the LabVIEW program records the maximum of that waveform. The resulting file after an experiment was a list of numbers between 500, a threshold set to reduce background noise, and 16,383. These values corre-

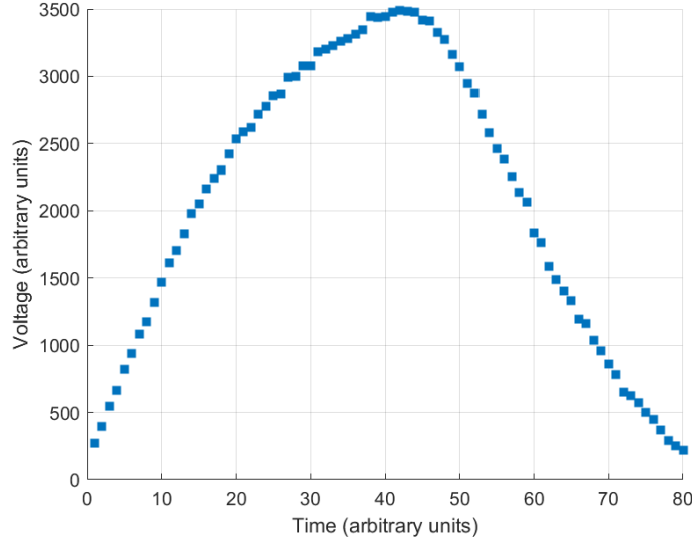


Figure 16. Example of a digitized waveform. The maximum of the waveform would be recorded and, once calibrated, the energy of the incident gamma ray could be determined based off the maximum.

sponded to the maximum voltage of each detection. To generate the spectrum, a bin size of approximately 32 channels (arbitrary NIMBox units) was chosen. This resulted in a total of 512 bins, which was recommended as a rule of thumb for recording gamma energies up to 2 MeV [18]. An example of an uncalibrated spectrum is shown in Figure 17.

3.5 Calibration

The calibration of the system was based off two easily distinguished peaks in a multinuclide spectrum. The energies and activities of the isotopes present in the multinuclide are given in Appendix B. In a paper written by Akkurt et al., the response of a 3"x3" NaI(Tl) detector for a Cs-137 and Co-60 sources was observed to be linear [19]. A spectrum was developed using a multinuclide source (shown in Figure 18). Using that spectrum to identify the peak corresponding to the isotopes in the source, a calibration equation was developed to verify that all of the peaks in

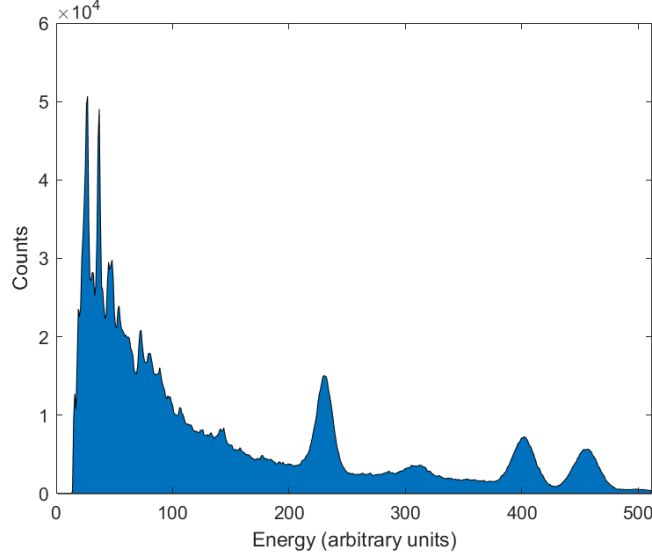


Figure 17. This figure shows an uncalibrated spectrum taken with a multinuclide source present. There are various peaks in the spectrum from the multiple isotopes in the source. Calibration in the next section reveals the isotope that resulted in each peak.

the spectrum corresponded to those in the source. Equation 6, where E is the energy in keV and x is the energy bin before calibration, shows the linear equation used for the response of the NaI detector. A plot (Figure 19) for this equation shows that the response of the crystal is indeed very nearly linear.

$$E(keV) = 3.02x - 26.28 \quad (6)$$

3.6 Detector Response Curve Development

The number of FEP counts for a given energy and rotation angle of the mask were used to construct the detector response curves. Each point represents the FEP counts at a given energy for the corresponding mask rotation angle. To construct the DRCs, first all full energy peaks were identified (see Figure 18). Next, all FEP counts were summed for each θ bin. A five degree bin size, yielding seventy two bins for a

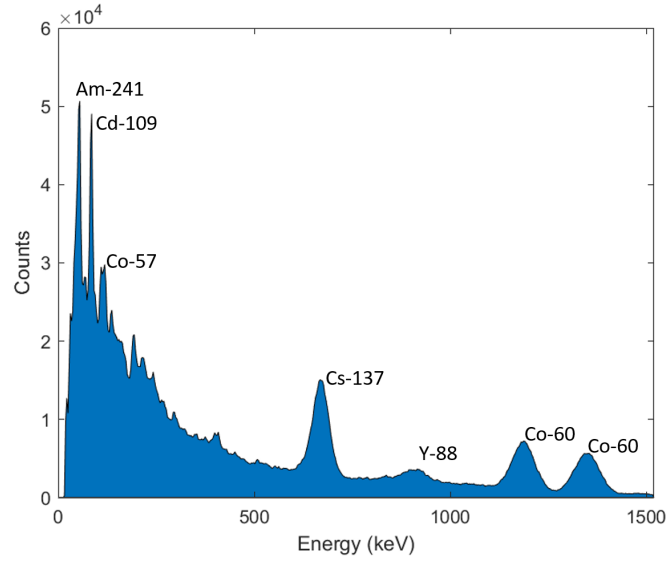


Figure 18. This figure shows a calibrated spectrum with the observable peaks from a multinuclide source labeled. The Cs-137 and Co-60 peaks were used in calibration and the Am-241, Cd-109, Co-57, and Y-88 peaks were identified using the calibration equation obtained. A linear fit of the calibration is given in Figure 19.

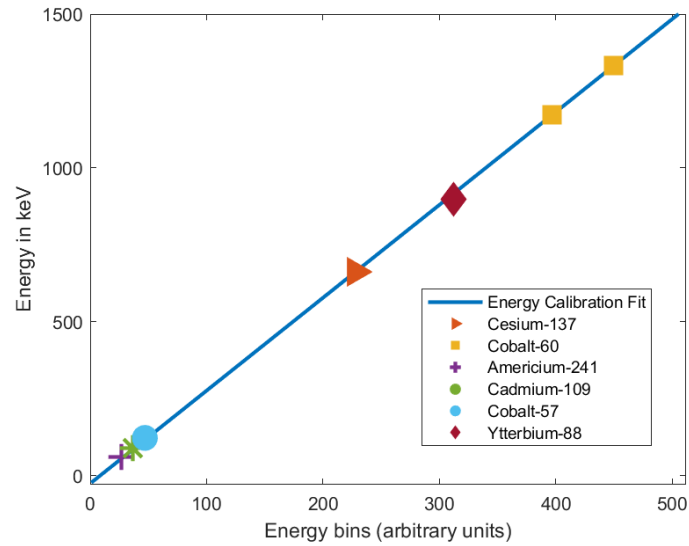


Figure 19. This figure shows the linear fit that represents the energy calibration for the NaI crystal. The legend identifies the isotope that corresponds to each point. The equation for the calibration is shown in Equation 6

full 360° rotation, was used for consistency with previous research [11].

As expected, the general shape of any DRC for a given theta-phi combination roughly corresponds to an inverse of the thickness of the mask at an angle ϕ over a full rotation in θ . The thickest portions, where more photons interact with the mask, correspond to minimums in the DRC and the thinnest portions, where fewer photons interact with the mask, correspond to the maximums in the DRC. An example DRC is given in Figure 20.

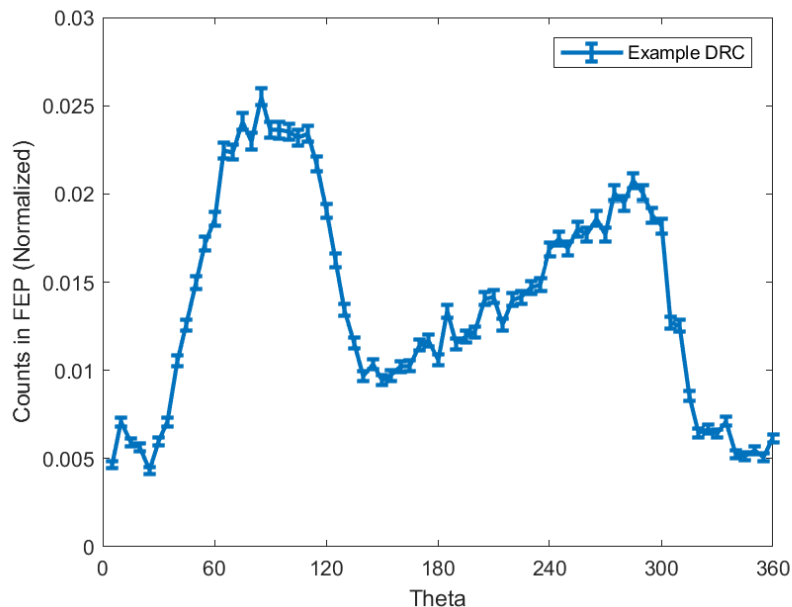


Figure 20. Sample DRC. This DRC corresponds to a Cs-137 source at $\phi = 105^\circ$ and $\theta = 0^\circ$. The error bars are the standard error based on the number of counts before normalization.

3.7 Normalization

In order to compare any two DRCs, the data within the DRCs need to be normalized. Before normalization, each data point in the DRC corresponds to the number of counts in the full energy peak at that angle. Each DRC was normalized to the total number of counts in that DRC so that any two can be compared regardless of

the collection time. To normalize a DRC each point in the DRC was then divided by the total number of counts in all channels of the DRC. Figure 20 shows a normalized DRC with error bars.

3.8 Library of Curves

With this mask design, a library of detector response curves was required in the process of determining the direction of an unknown source. Before describing the library of curves, the bin size and, subsequently, the directional resolution of the mask was defined. As mentioned in Section 3.6, the θ bin size was five degrees which resulted in seventy-two bins for a full rotation of 360° . The ϕ bin size was chosen to be ten degrees. Because the dimensions of the mask do not vary significantly close to $\phi = 0^\circ$, the ϕ bin values start at five degrees. This results in a total of eighteen total bins in ϕ . The resolution of the mask with these bin sizes allowed for 1,296 unique possible directions that it can attribute to a source.

The previous student, Julie Logan, ran simulations to get a DRC for each angle bin in ϕ . All eighteen DRCs from simulations can be seen in Figure 21 [11]. Each of these DRCs corresponds to a θ of zero degrees and would only be useful to locate a source at $\theta = 0^\circ$. To obtain the DRC for any other θ , that DRC need only be circularly shifted. For example, to get a library DRC defined by $\phi = 65^\circ$ and $\theta = 30^\circ$, one only needs to take the DRC for $\phi = 65^\circ$ and shift the data points by six data points. The difference between the shifted and unshifted DRC can be seen in Figure 22.

Using the above algorithm to get a library DRC for any ϕ and θ , the direction of any source can now be determined. To do this, the DRC for data taken in the presence of a source needs to be generated. That DRC is then compared to each library DRC at every shift in theta for a total of 1,296 comparisons. The closest

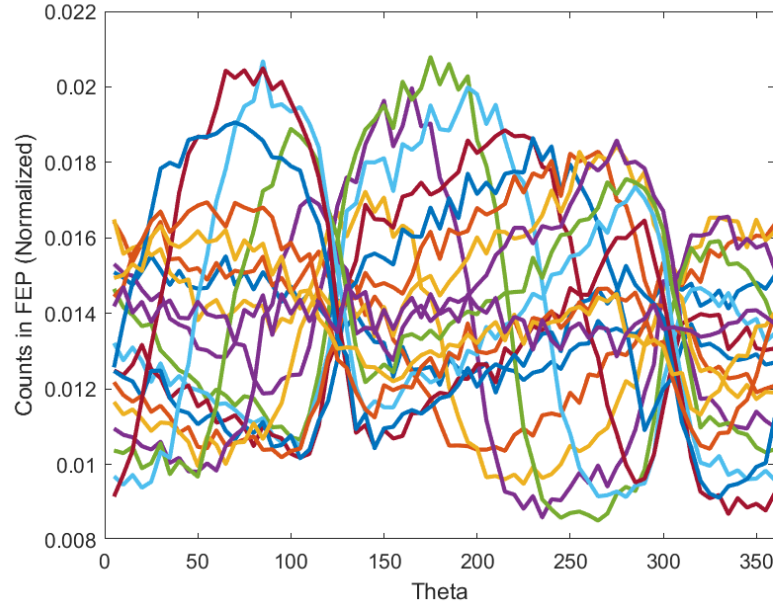


Figure 21. All DRCs in the library for the 662 keV full energy peak. There is no legend or error bars to reduce the number of items in the already cluttered figure. Each of the DRCs are unique, which allows for identification of the direction of the source.

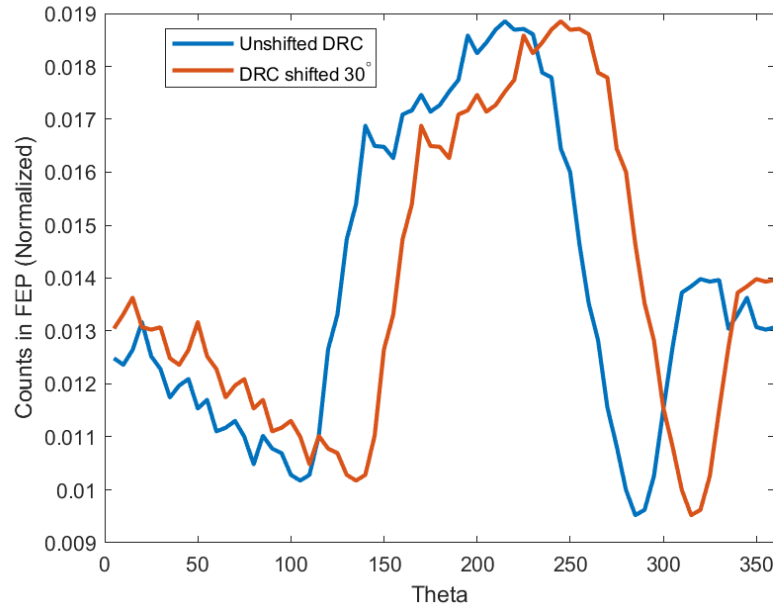


Figure 22. Example of shifting a DRC by 30 degrees. The DRC in blue is unshifted and corresponds to $\phi = 65^\circ$ and $\theta = 0^\circ$. The DRC in orange is shifted and corresponds to $\phi = 65^\circ$ and $\theta = 30^\circ$

match will give the ϕ and θ that corresponds to the direction of the source. The method of determining the closest match will be described in Chapter IV.

3.9 Trapezoid Background Subtraction

When generating the DRC from a spectrum with only one full energy peak, the background noise was originally ignored. There was no correction to the number of counts in the full energy peak. Unfortunately, with the introduction of multiple sources, the higher energy gamma rays can downscatter and add counts to and around the full energy peaks of lower energy gamma rays. There are a few methods of correcting for background noise, but for this thesis, the trapezoid subtraction method was most viable. A method known as matrix deconvolution, which is described in Appendix C, may provide better information, but is reserved for a future recommendation of research.

Although simple and less robust than other methods, such as the deconvolution method, the trapezoid method is useful enough to be employed by Canberra in their multi-channel analyzers (MCAs) and analysis software packages [20]. The method is visualized in Figure 23. To subtract the background, a trapezoid is created under the full energy peak using the data points at which the peak meets the background noise. If the background is approximated to change linearly, then the two points can be joined by a line, thereby creating a trapezoid. The number of counts between the two chosen points minus the counts in the trapezoid is a better representation of the actual number of full energy gamma rays that were detected.

To assure a better fit to the actual background, an average of five channels both before and after the full energy peak was used. This ensured that random fluctuations in the noise cause less variation when subtracting from the full energy peak. This method, with averaging before and after the peak, was used in processing all of the

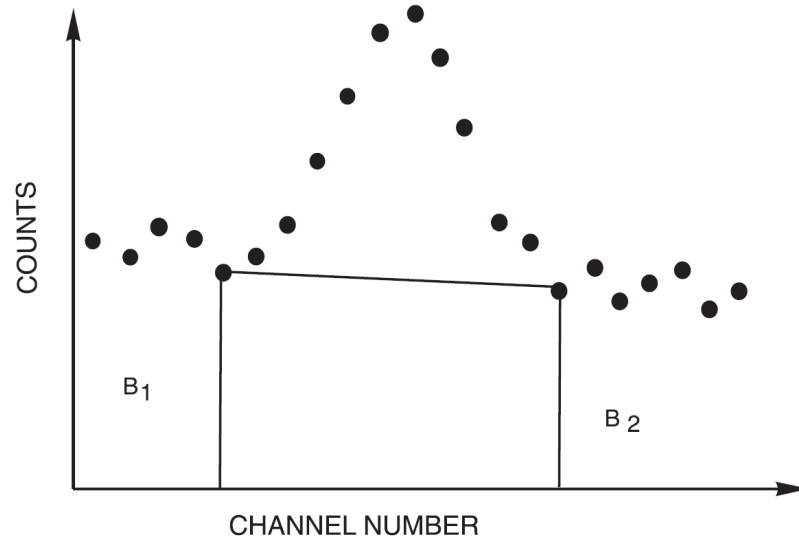


Figure 23. Example of a trapezoid subtraction. The area under the trapezoid can be assumed to be the background underneath the full energy peak. The total area underneath the full energy peak subtracted by the area of the trapezoid is the number of full energy counts. [20]

data for this thesis.

IV. Results and Analysis

4.1 Introduction

In Logan's simulations and experiments, a Cs-137 662 keV source was used to develop a library of DRCs for source direction identification [11]. To develop the ability to identify the direction of different energy sources, the difference between DRCs from different energy FEPs was studied. Furthermore, the Modal Assurance Criterion (MAC), which was the method DRC comparison for direction identification in Logan's paper, was chosen as the method of comparison for this thesis.

The development of the library of DRCs used in this thesis served two purposes. The first purpose was to prove that the presence of two radiation sources did not hinder the ability to develop the correct DRC for any particular source location. The second was to ensure that the DRCs developed for the new library were still comparable to the old simulation and experimental library. The last sections of this chapter show that the RSM was able to use the new library to correctly identify the location of multiple radiation sources simultaneously.

4.2 Different Energy Hypothesis

The method of determining the direction of a source is by comparing the detector response curve of the source to all of the detector response curves in the library. Before explaining the methods of source direction identification, one of the hypotheses stated at the beginning of this thesis needs to be addressed. Past experiments and simulations showed that the DRCs from a Cs-137 source are consistent among the various methods of generating them. DRCs for other energy gamma sources were not yet developed.

The hypothesis postulated that, assuming the source location remained the same,

the detector response curve for different gamma ray energies would have the same shape (ie. the same θ location for the peaks and minimums), but the ratio between the minimum and maximum would be smaller for higher energy gammas. As can be seen in Figure 15, the mean free path of gamma rays increases with energy. This results in less attenuation overall through the mask, especially through the thickest portions of the mask. At 662 keV, the mean free path is approximately 9.74 cm. At 1,332 keV, the mean free path is approximately 16.9 cm. The thinnest portion of the mask is approximately 10 cm and the thickest portion of the mask is approximately 20 cm. The number of mean free paths traveled by both gamma energies are summarized in Table 2. At the bottom of the table, the ratio of the mean free paths at each thickness for each gamma are given. This ratio approximately matches the ratios seen in the DRCs at different energies. Any variation is due to noise and other background detections that interfere with any particular full energy peak.

Table 2. This table shows that the ratio of the number of mean free paths through the thickest portion of the mask to the thinnest portion of the mask should correspond to the ratio between the number of counts in the maximum and minimum of each DRC.

Gamma Energy (keV)	# of MFPs (min)	# of MFPs (max)	Ratio
662	1.03	2.05	2.0
1,332	0.59	1.18	2.0

In the same way that the mask has a varying cross-section of interaction with gamma ray energy, so does the scintillating NaI(Tl) crystal. This change in cross-section does not have an appreciable effect on the DRC. The crystal itself is rotationally symmetric and the rotation will not affect the number of gamma rays that are absorbed. The efficiency of the crystal, as seen in Figure 10, decreases by approximately 30% over the range of energies used in this thesis [10]. The result of this is fewer counts from high energy sources when compared to a similar activity, lower energy source.

The two gamma energies above were chosen because they are the gamma emissions of Cs-137 and Co-60, respectively. Because the main focus of this thesis is to determine if the direction of two gamma ray sources can be simultaneously determined, experimental DRCs were generated with both sources present and in the same location. As can be seen in Figure 24, the maximum for the 662 keV DRC is higher than the maximum for the 1,332 keV DRCs and, conversely, the minimum for the 662 keV DRC is lower than the minimum for the 1,332 keV DRC. The ratio between the maximum and minimum for the 662 keV DRC was calculated to be 1.98 and the ratio between the maximum and the minimum for the 1,332 keV DRC was calculated to be 1.83.

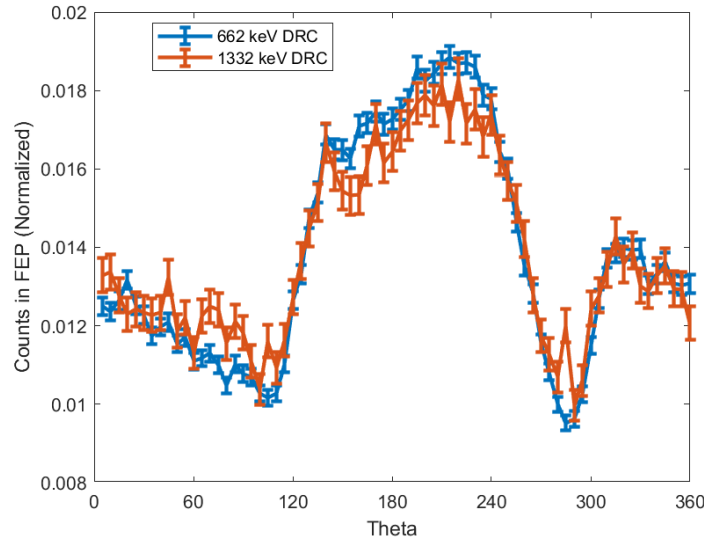


Figure 24. This figure shows the DRCs from two different energy FEPs. In blue is the DRC for the 662 keV FEP and in orange is the DRC for the 1,332 keV DRC. Both DRCs are at the same ϕ and θ . The ratio of the maximum and minimum of the 662 keV DRC is 1.98 and the ratio of the maximum and minimum of the 1,332 keV DRC is 1.83.

4.3 Previous Library and Modal Assurance Criterion

The previous students, Julie Logan and Christopher Charles, developed both a simulation and an experimental library of DRCs for gamma rays from a Cs-137 source [11]. The method used by Logan to compare her simulation curves to the experimental curves was the Modal Assurance Criterion [11]. This method compares two curves, each represented by a one-dimensional array, to determine the level of linear dependence. A value closer to one means that the curves are linear dependent (ie. more similar) and a value closer to zero means the curves are linearly independent (ie. less similar). The equation to determine the MAC number, which ranges from zero to one, is shown in Equation 7 [21].

$$MAC(LibDRC, TestDRC) = \frac{|LibDRC^T \cdot TestDRC|^2}{(LibDRC^T \cdot LibDRC)(TestDRC^T \cdot TestDRC)} \quad (7)$$

An example is given in Figure 25. The two curves in the picture on the left are very similar and the MAC number is close to one. The two curves in the picture to the right are dissimilar and the resulting MAC number is close to zero. This is the method of curve comparison chosen for this thesis. In determining the library curve that best matched an experimental curve, the MAC number was calculated for each combination of the experimental curve and library curve. The result would be a 72x18 matrix of MAC numbers. The highest number would correspond to the curve that gave the direction of the experimental source. An example of the 72x18 matrix is in Figure 26. The legend to the right shows the meaning of the colors in the heat map and the highest number identifies the direction of the source.

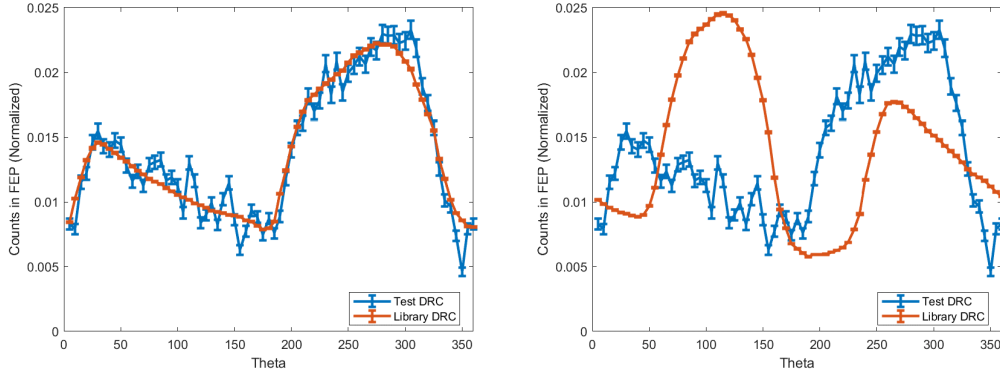


Figure 25. The picture on the left shows the test DRC (in blue) and the closest matching library DRC (in orange). The location of the source was determined to be at $\phi = 65^\circ$ and $\theta = 295^\circ$ with a MAC value of 0.9383. The picture on the right shows the test DRC (in blue) and the least matched library DRC (in orange). The MAC value for these two curves is 3.76×10^{-7} .

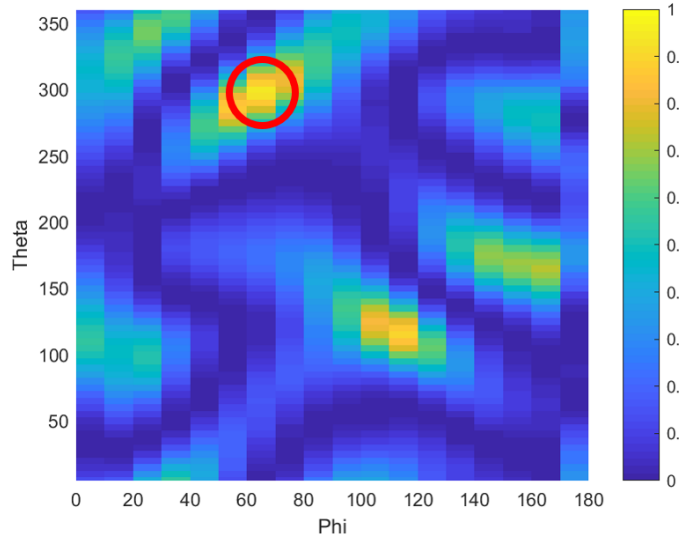


Figure 26. The algorithm to determine the closest matching library DRC computes the MAC value for every possible source location in the library with the test DRC. It then finds the maximum value (highlighted in the red circle) and determines the phi and theta value of the matched curve to give the direction of the source, which in this case was $\phi = 65^\circ$ and $\theta = 295^\circ$.

4.4 Library Development

Because the past methods of generating a library of DRCs only used one source, a new library of DRCs needed to be developed with multiple sources present to ensure the RSM still worked properly. The two sources used in the development of this library were Cs-137 and Co-60. Both were sources readily available that had a high enough activity to provide good statistics. The two gamma ray emissions from the Co-60 allowed for a total of three libraries to be generated with only two sources present.

The method of recording data was very similar to the method chosen by Charles and Logan. The two sources were placed in the same location and data was recorded for a total of twenty-three hours. A total of eighteen data sets were taken, starting at $\phi = 5^\circ$ and increasing ϕ by 10° each run. The resulting eighteen DRCs for each energy are shown in Figures 27 (662 keV), 28 (1,173 keV), and 29 (1,332 keV). The relative θ of the sources was not varied through the development of this library. To be able to identify gamma sources using this library, this θ position was set to be zero.

Each of the DRCs in the library at 662 keV can be compared to both the experimental and simulation libraries of the previous students. In a similar fashion, using the MAC number, the linear dependence of each DRC can be compared to each DRC for both libraries. Figure 30 shows a MAC number comparison between the current DRC library for 662 keV detections with the previous experimental (left picture) and simulation (right picture) libraries. This similarity among all the libraries confirms that the RSM system will identify the same direction for a radiation source regardless of the library used.

In addition to old libraries, a concurrent student, Robert Olesen, working on optimizing the mask design, was able to provide simulation DRC libraries from gamma

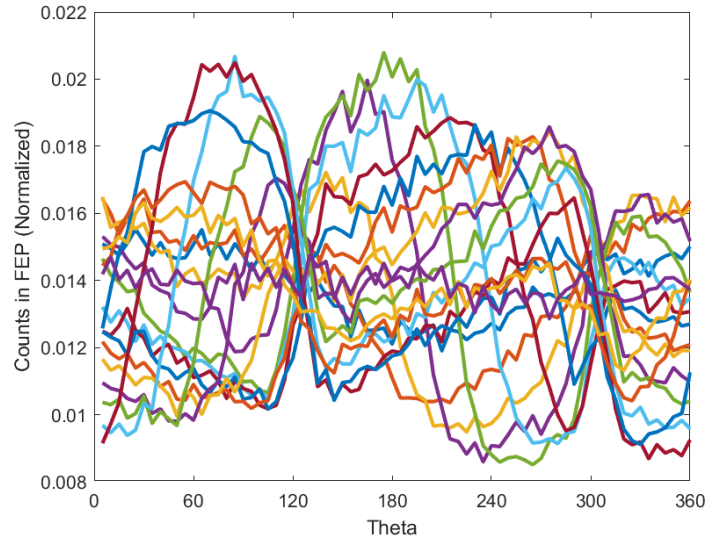


Figure 27. Full library of curves for the 662 keV full energy peak as developed from experimental runs.

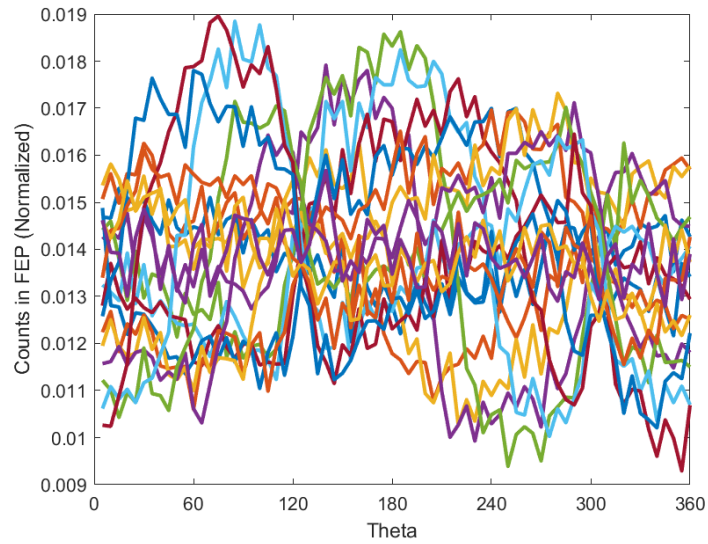


Figure 28. Full library of curves for the 1,173 keV full energy peak as developed from experimental runs.

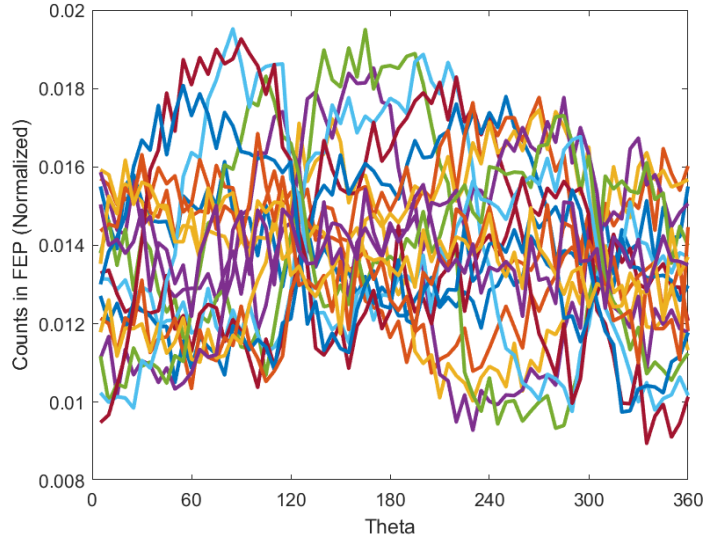


Figure 29. Full library of curves for the 1,332 keV full energy peak as developed from experimental runs.

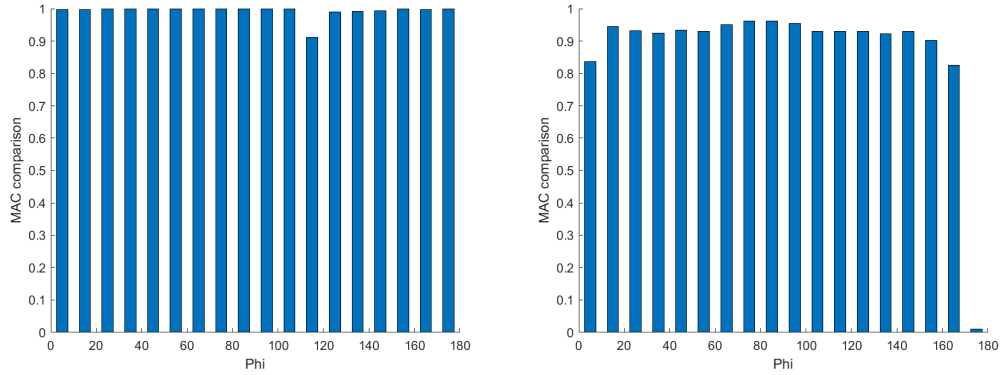


Figure 30. This figure shows comparisons between the library developed in this thesis and the previous experimental library and simulations. In the picture on the left, a MAC value comparison of equivalent DRCs in the current experimental library and previous experimental library is shown. All DRCs match very closely except at $\phi = 115^\circ$ (the reasons for which are discussed in Logan's thesis). In the picture on the right, a MAC value comparison of equivalent DRCs in the current experimental and previous simulation library is shown. These do not match as nicely to the previous experimental because the simulations did not include the support equipment of the RSM. A large amount of this equipment is at $\phi = 175^\circ$, which partially accounts for the large discrepancy in the two libraries at that point.

rays with energies matching Cs-137 and Co-60 sources. Figures 31, 32, and 33 show the full simulation library (left on each) and how well it compares to the experimental library (right). The MAC comparison, especially for $\phi = 175^\circ$, matches more closely for all DRCs with these comparisons than the MAC comparison with the simulation library provided by Logan. This is most likely due to the difference in simulation packages used. Logan used GEANT-4 to simulate the RSM while Olesen used MCNP6 [11].

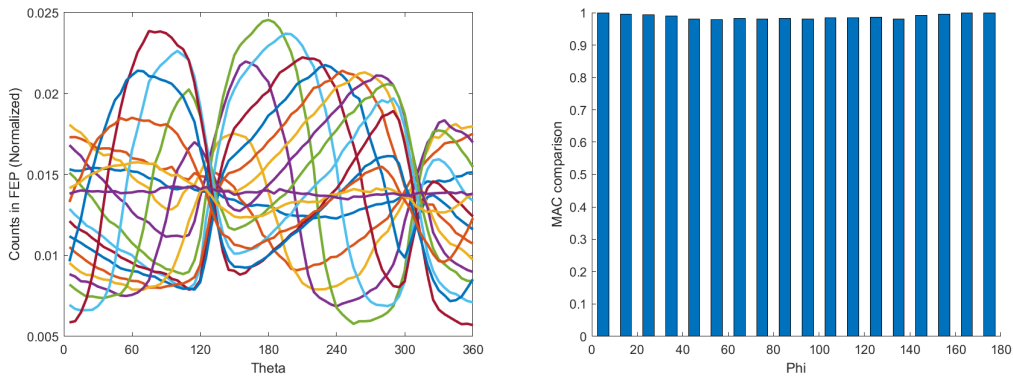


Figure 31. This figure compares the experimental library of 662 keV DRCs recorded and development in this thesis to the library of 662 keV DRCs developed through simulation by Robert Olesen. In the left picture, the library of curves developed by Olesen is shown and in the right picture, the MAC comparison between each DRC in the experimental library with the corresponding curve in the simulation library is shown.

4.5 Two Different Sources, Same Location Direction Identification

Now that the library of DRCs has been developed and verified, the ability to identify the location of two sources simultaneously can be tested. The first step is to collect data on two sources, Cs-137 and Co-60, in the same location. From this data, three DRCs will be generated. Although this is very similar to the method of generating the library of curves, the theta position of the sources was changed to determine and verify that shifting the library DRCs is a valid method of identifying

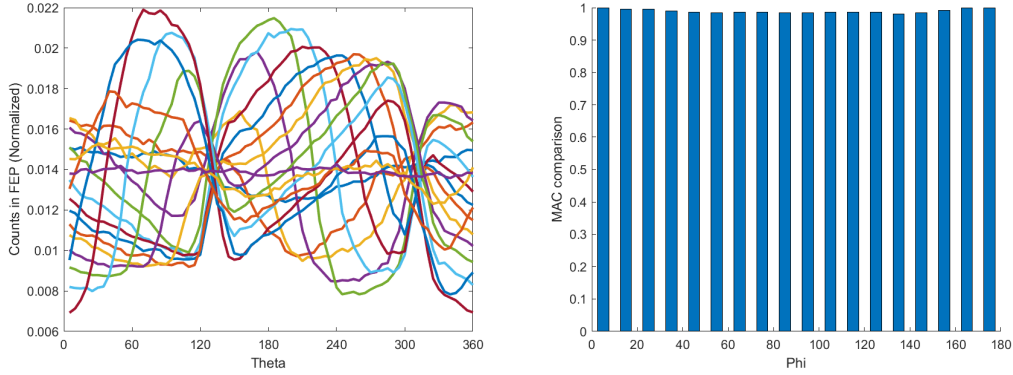


Figure 32. This figure compares the experimental library of 1,173 keV DRCs recorded and development in this thesis to the library of 1,173 keV DRCs developed through simulation by Robert Olesen. In the left picture, the library of curves developed by Olesen is shown and in the right picture, the MAC comparison between each DRC in the experimental library with the corresponding curve in the simulation library is shown.

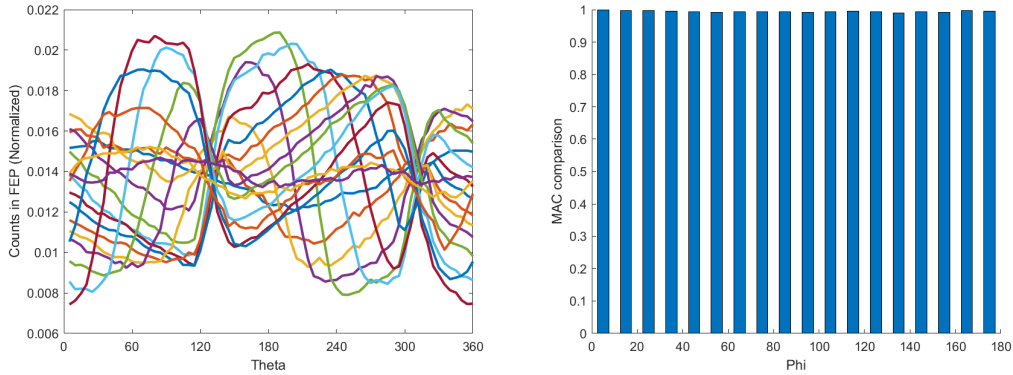


Figure 33. This figure compares the experimental library of 1,332 keV DRCs recorded and development in this thesis to the library of 1,332 keV DRCs developed through simulation by Robert Olesen. In the left picture, the library of curves developed by Olesen is shown and in the right picture, the MAC comparison between each DRC in the experimental library with the corresponding curve in the simulation library is shown.

the source direction.

Both sources were placed on the source arm and positioned at approximately $\phi = 35^\circ$ and approximately $\theta = 0^\circ$. Therefore, no shifting of the library would be needed to determine the direction of the sources. The DRCs resulting from the recorded data with the matched library DRCs are shown in Figures 34, 35, and 36.

Table 3. Direction identification results for two different sources in the same location. The FEPs from 662 keV, 1,173 keV, and 1,332 keV emissions were used to generate the DRCs. The RSM was able to correctly identify the direction of the sources based on these three DRCs.

Source	Energy (keV)	Placement	Calculated Direction	MAC
Cs-137	662	$\phi = 35^\circ, \theta = 0^\circ$	$\phi = 35^\circ, \theta = 5^\circ$	0.9483
Co-60	1,173	$\phi = 35^\circ, \theta = 0^\circ$	$\phi = 35^\circ, \theta = 0^\circ$	0.7858
Co-60	1,332	$\phi = 35^\circ, \theta = 0^\circ$	$\phi = 35^\circ, \theta = 5^\circ$	0.8740

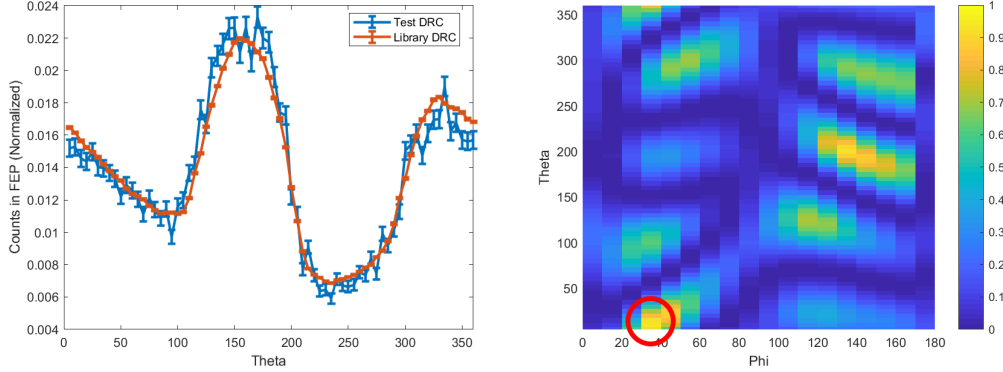


Figure 34. This figure shows the matched DRC for the Cs-137 662 keV DRC. The source was placed at approximately $\phi = 35^\circ, \theta = 0^\circ$ and the RSM identified the direction of the source as $\phi = 35^\circ, \theta = 5^\circ$. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

From Table 3 and Figures 34, 35, and 36, the RSM was able to identify the direction of both sources simultaneously almost exactly. The slight difference in the theta location is largely due to the fact that there will always be slight random variations in each DRC developed experimentally when compared to the library DRC.

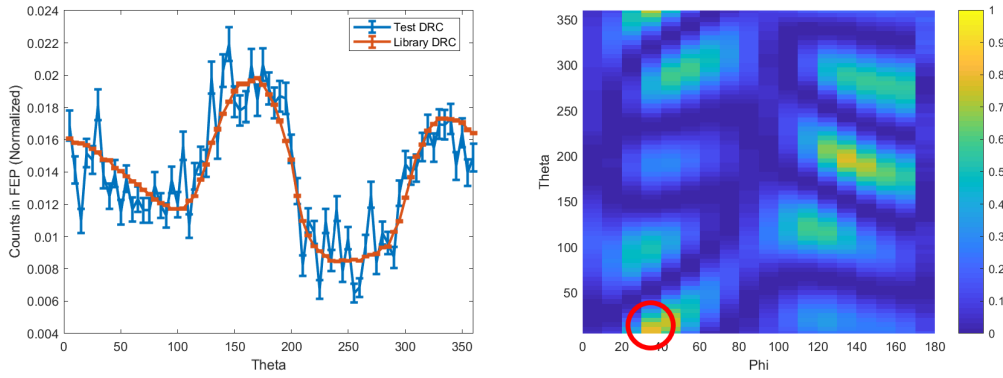


Figure 35. This figure shows the matched DRC for the Co-60 1,173 keV DRC. The source was placed at approximately $\phi = 35^\circ$, $\theta = 0^\circ$ and the RSM identified the direction of the source as $\phi = 35^\circ$, $\theta = 0^\circ$. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

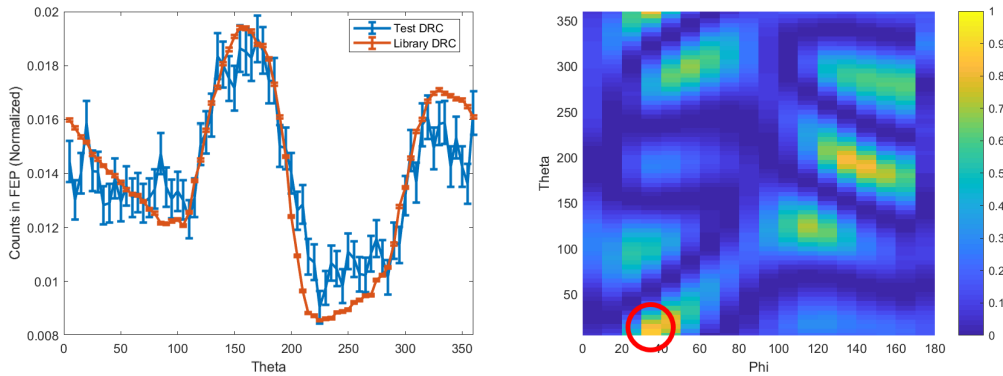


Figure 36. This figure shows the matched DRC for the Co-60 1,332 keV DRC. The source was placed at approximately $\phi = 35^\circ$, $\theta = 0^\circ$ and the RSM identified the direction of the source as $\phi = 35^\circ$, $\theta = 5^\circ$. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

4.6 Two Different Sources in Different Locations Direction Identification

A much more interesting problem is being able to identify the direction of two sources in different locations. Using the same methods as described above, the DRCs were generated using data from two sources, a Cs-137 source and a Co-60 source. This time, the sources were placed in different locations. The Cs-137 source was placed at approximately $\phi = 65^\circ$ and $\theta = 335^\circ$ and the Co-60 source was placed at approximately $\phi = 65^\circ$ and $\theta = 45^\circ$.

The DRCs from the FEPs for each gamma was compared to the library for that energy. The matching curve can be seen in Figures 37, 38, and 39. To the right of each curve is a matrix showing a heat map of the MAC numbers for each test DRC with each DRC from the entire library. The results are that the RSM was able to provide the direction of each of the sources.

Table 4. Direction identification results for two different sources in different locations. The FEPs from 662 keV, 1,173 keV, and 1,332 keV emissions were used to generate the DRCs. The RSM was able to correctly identify the direction of the sources based on these three DRCs.

Source	Energy (keV)	Placement	Calculated Direction	MAC
Cs-137	662	$\phi = 65^\circ, \theta = 335^\circ$	$\phi = 75^\circ, \theta = 340^\circ$	0.9469
Co-60	1,173	$\phi = 65^\circ, \theta = 45^\circ$	$\phi = 65^\circ, \theta = 45^\circ$	0.9338
Co-60	1,332	$\phi = 65^\circ, \theta = 45^\circ$	$\phi = 65^\circ, \theta = 45^\circ$	0.8387

From Table 4 and Figures 37, 38, and 39, the RSM was able to identify the direction of both sources in different locations simultaneously. The direction of the Co-60 was identified exactly, but the direction of the Cs-137 source was off slightly. Although the DRCs for $\phi = 65^\circ$ and $\phi = 75^\circ$ are similar (the MAC value for those two library curves is 0.7902), the random statistical variations are the most likely cause for the incorrect identification.

To ensure the validity of direction identification, a second test was performed but with the sources in different locations than the first test. The Cs-137 source was

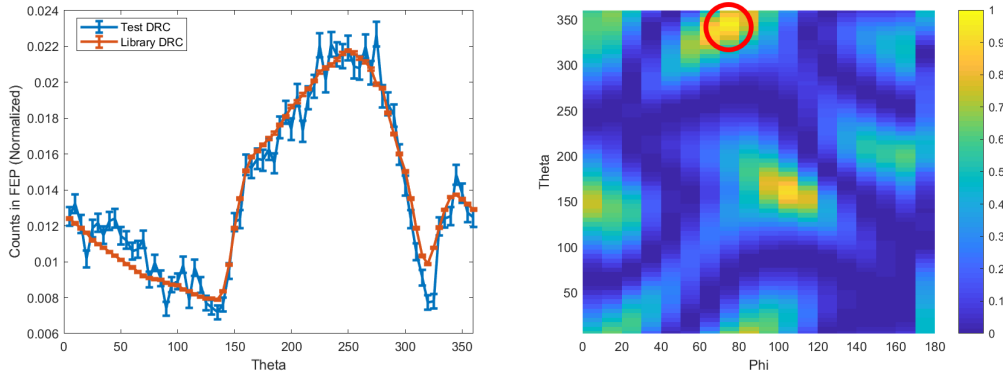


Figure 37. This figure shows the matched DRC for the Cs-137 662 keV DRC. The source was placed at approximately $\phi = 65^\circ$, $\theta = 335^\circ$ and the RSM identified the direction of the source as $\phi = 75^\circ$, $\theta = 340^\circ$. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

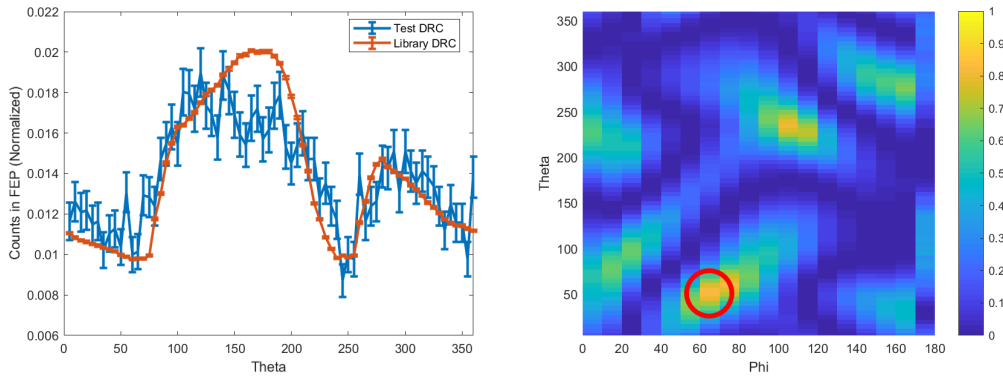


Figure 38. This figure shows the matched DRC for the Co-60 1,173 keV DRC. The source was placed at approximately $\phi = 65^\circ$, $\theta = 45^\circ$ and the RSM identified the direction of the source as $\phi = 65^\circ$, $\theta = 45^\circ$. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

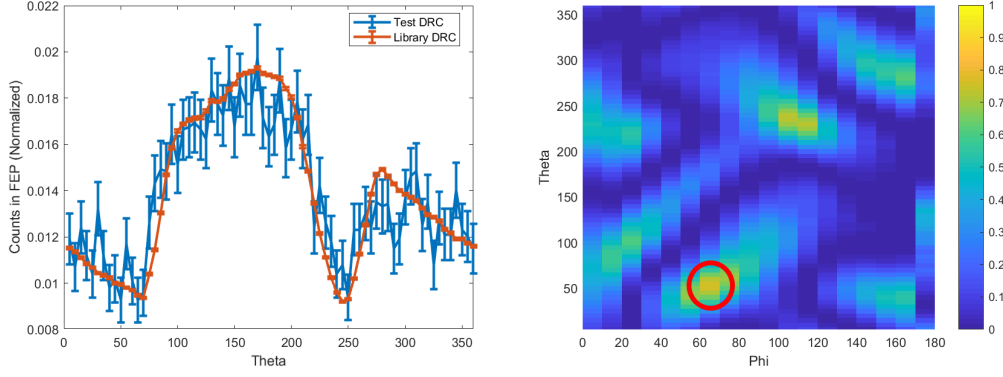


Figure 39. This figure shows the matched DRC for the Co-60 1,332 keV DRC. The source was placed at approximately $\phi = 65^\circ$, $\theta = 45^\circ$ and the RSM identified the direction of the source as $\phi = 65^\circ$, $\theta = 45^\circ$. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

placed at approximately $\phi = 135^\circ$ and $\theta = 335^\circ$ and the Co-60 source was placed at approximately $\phi = 65^\circ$ and $\theta = 335^\circ$. The matched directions for the Cs-137 are $\phi = 125^\circ$ and $\theta = 345^\circ$ and for the Co-60 are $\phi = 65^\circ$ and $\theta = 345^\circ$. Again, the RSM was able to very nearly identify the exact source direction.

4.7 Two Sources, Same Energy, Different Locations Direction Identification

When two or more sources emitting the same energy are present, more sophisticated methods of identifying the location of the source are needed. The full energy peaks from both sources are not resolvable unless more complicated data processing techniques are used. To determine if the RSM can be used to identify the location of multiple, similar emission sources, two Cs-137 sources were placed at approximately $\phi = 65^\circ$, $\theta = 335^\circ$ and $\phi = 135^\circ$, $\theta = 335^\circ$. A DRC was developed using the full energy peak from both sources. The DRC should be a combination of the DRCs relating to the source directions and weighted based on each source's activity.

To identify both source locations, an algorithm was developed to make every pos-

sible weighted combination of library curves using weights between 0 and 1 with increments of 0.01. This resulted in a total of $1,296 * 1,296 * 101 = 1.7 * 10^8$ combined library curves that were tested. This method of comparison was very computationally expensive and future methods of direction identification could help reduce the computation time.

Using the activities given in Appendix B and the distance of each respective source, the correct combination of curves are given in Table 5. The corresponding DRCs are shown in Figure 40 and combination of library curves with the test DRC from the experiment are shown in Figure 41.

Table 5. The correct weighted combination of curves for the directions of two Cs-137 sources. This was calculated based on the source activity, given in Appendix B, and the distance to the detector. The DRCs for each source are shown in Figure 40 and the test DRC matched with this is shown in Figure 41. The MAC value for this combination of curves and the test DRC is given in the far right column.

Source	Energy (keV)	Placement	Correct Weight	MAC
Cs-137	662	$\phi = 65^\circ, \theta = 335^\circ$	0.67	0.8157
Cs-137	662	$\phi = 135^\circ, \theta = 335^\circ$	0.33	

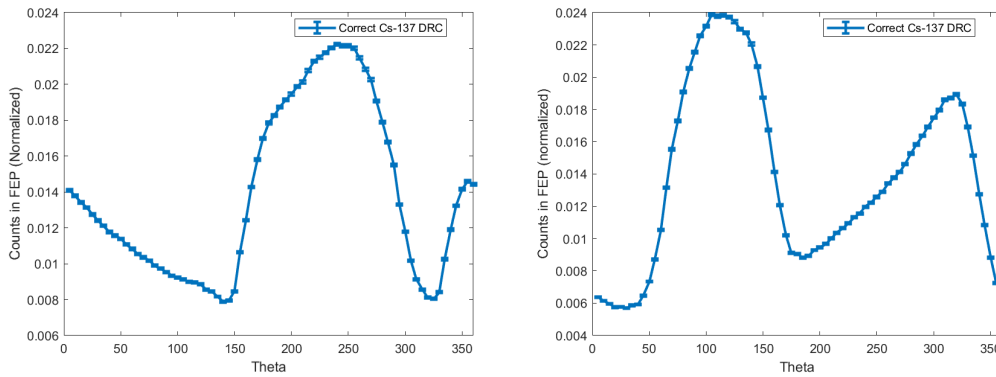


Figure 40. The correct DRCs for the two Cs-137 sources based on the placement of the sources. One Cs-137 source was placed at $\phi = 65^\circ, \theta = 335^\circ$ and the other was placed at $\phi = 135^\circ, \theta = 335^\circ$.

The results of the algorithm to determine the weighting on each library curve that most closely fits the test DRC are shown in Table 6. The DRCs that combined

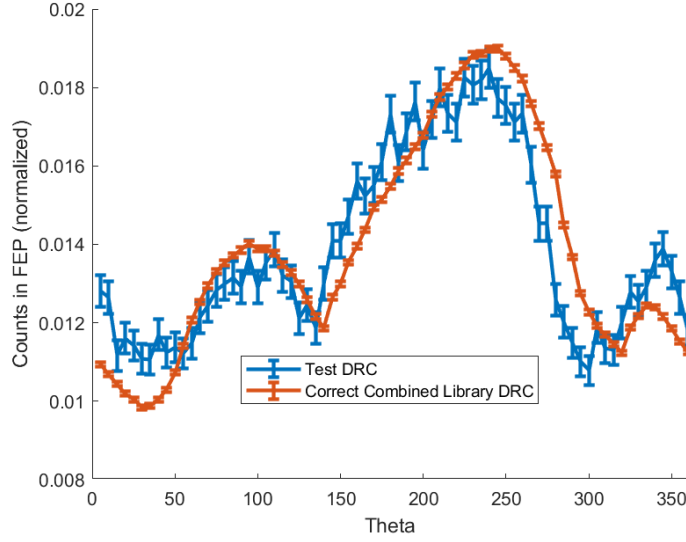


Figure 41. The combined library DRCs with weights as given in Table 5 and the test DRC generated from the combined FEP from both Cs-137 sources. These two curves had a MAC value of 0.8157.

to most closely match the test DRC are shown in Figure 42 and the test DRC and combined library DRC are shown in Figure 43.

Table 6. The combination of weights and library curves as a result of the algorithm written to determine which combination of library curves matched the test DRC most closely. The matched DRCs for each source are shown in Figure 42 and the combination of library curves that matched most closely with the test DRC are shown in Figure 43. The MAC value for this combination of curves and the test DRC is given in the far right column.

Source	Energy (keV)	Calculated Direction	Calculated Weight	MAC
Cs-137	662	$\phi = 65^\circ, \theta = 5^\circ$	0.74	0.934
Cs-137	662	$\phi = 125^\circ, \theta = 350^\circ$	0.26	

The current RSM was not designed to be able to identify the direction of two nearly identical sources because it required distinct FEPs. This method of combining library DRCs has shown that the RSM can in fact closely identify the direction of the two sources. The resolution of the detector and noise from multiple sources present led to a the difference from calculated direction to the actual direction. Also, the

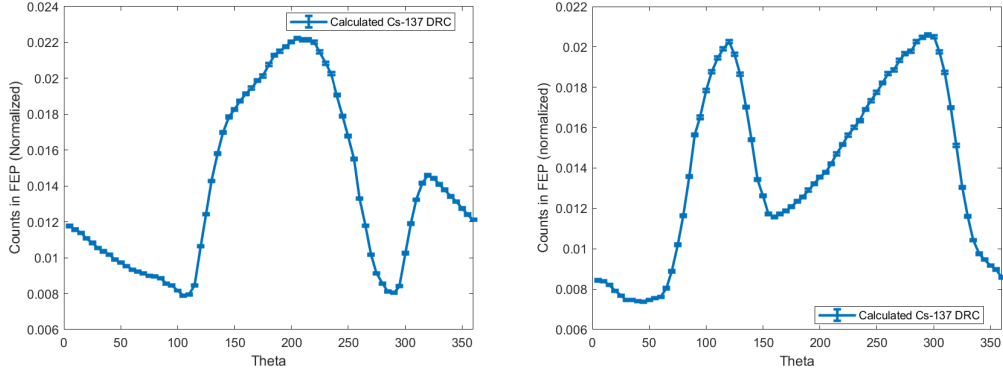


Figure 42. The calculated DRCs for the two Cs-137 sources using the algorithm that varied the weight and combination of library curves to match the test DRC. The left picture is the DRC for $\phi = 65^\circ$, $\theta = 5^\circ$ and the right picture is the DRC for $\phi = 125^\circ$, $\theta = 350^\circ$.

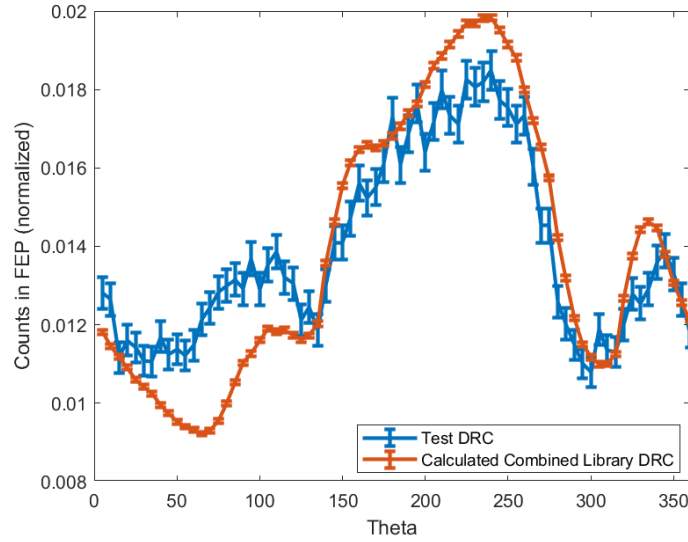


Figure 43. The combined library DRCs with weights as determined with the algorithm and shown in Table 6 and the test DRC generated from the combined FEP from both Cs-137 sources. These two curves had a MAC value of 0.934.

trapezoid method of background subtraction is an imperfect method of identifying just counts in the FEP and was partially the cause of the variation. Future RSM designs and methods of data processing will make this method of identifying similar, or even distributed sources, more reliable.

4.8 Three Different Sources, Different Locations Direction Identification

A natural shift from being able to identify the direction of two sources is to develop the ability to identify the direction of three sources. The extra challenge that this caused was to collect three sources, that were available in the lab, which would result in full energy peaks that were distinguishable. In the end, a compromise had to be made with some additional data processing to be able to identify three sources. The three sources used for this data set were Cs-137, Co-60, and Na-22.

The Na-22 source has two gamma rays in its decay scheme, which can be seen in Figure 44. It can decay by positron emission, which results in two 511 keV photons when it annihilates with an electron. The daughter product also decays 90% of the time by emitting a 1,274 keV photon. The FEP from the 511 keV gamma was distinguishable as a separate peak, but the FEP from the 1,274 keV gamma interfered with the FEP from the 1,332 keV gamma from Co-60. With the current mask design and data processing, it is not possible to distinguish between the two high energy peaks. The spectrum from this data is shown in Figure 45. Each peak is identified with the corresponding radioactive isotope.

First, the distinguishable FEPs were used to develop DRCs to determine the location of each of the three sources. The same background subtraction technique was used to develop these DRCs. The results of the direction identification algorithm are listed in Table 7. The matched library curve for each DRC are shown in Figures 46 (511 keV), 47 (662 keV), and 48 (1,173 keV).

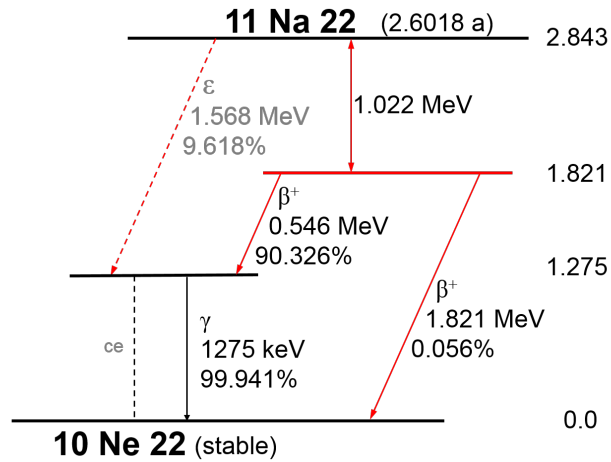


Figure 44. Decay scheme for Na-22. Approximately 10% of the time, Na-22 decays by electron capture and subsequently decays by a 1,274 keV gamma emission. The rest of the time, Na-22 decays by positron emission which is almost always followed by a 1,274 keV gamma emission as well. Only 0.056% of the time that Na-22 decays will there be no 1,274 keV gamma emission.

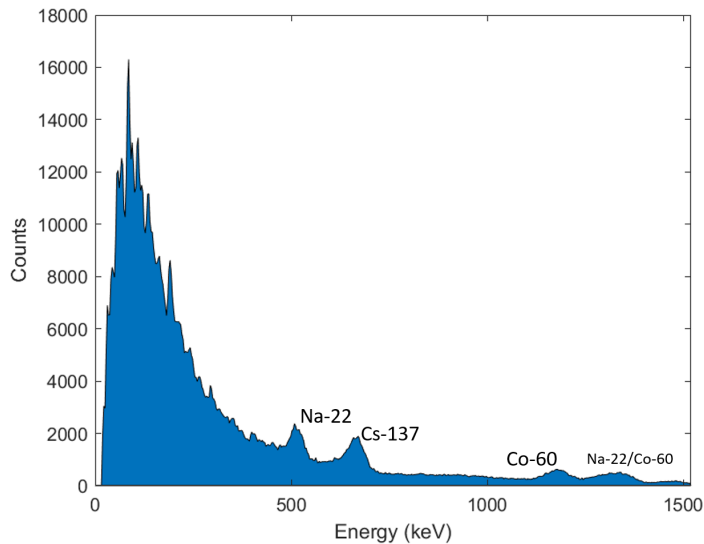


Figure 45. The spectrum for three sources is shown in this figure. The isotope that matches with each peak is label above the respective peak. On the far right of the spectrum, the combination of the Na-22 1,273 keV and Co-60 1,332 keV peaks can be seen.

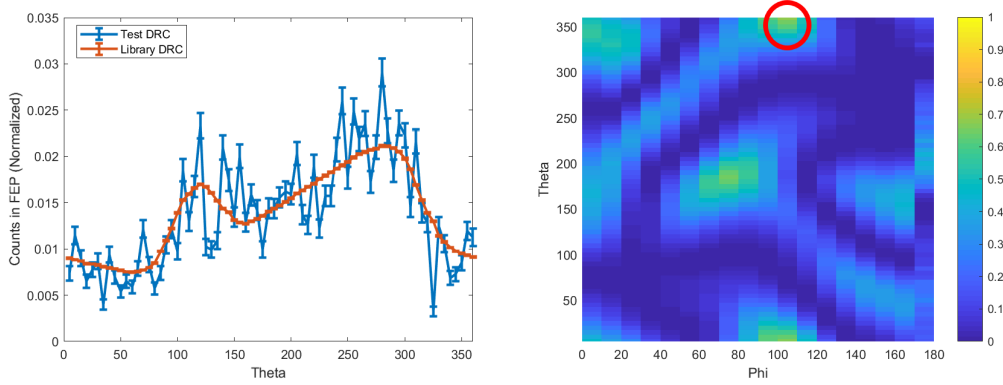


Figure 46. This figure shows the matched DRC for the Na-22 511 keV DRC. The source was placed at approximately $\phi = 105^\circ$, $\theta = 350^\circ$ and the RSM identified the direction of the source as $\phi = 105^\circ$, $\theta = 355^\circ$. The MAC value for this identification was 0.6751. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

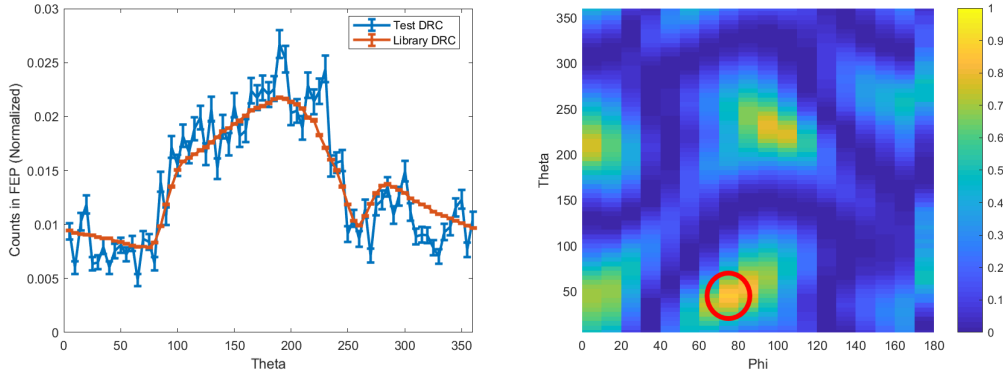


Figure 47. This figure shows the matched DRC for the Cs-137 662 keV DRC. The source was placed at approximately $\phi = 75^\circ$, $\theta = 45^\circ$ and the RSM identified the direction of the source as $\phi = 75^\circ$, $\theta = 40^\circ$. The MAC value for this identification was 0.860. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

Table 7. Source direction identification for three sources in three different locations. Only the FEPs for 511 keV, 662 keV, and 1,173 keV were used in generating these DRCs. The RSM was able to correctly identify the direction of the sources based on these three DRCs.

Source	Energy (keV)	Placement	Calculated Direction	MAC
Na-22	511	$\phi = 105^\circ, \theta = 350^\circ$	$\phi = 105^\circ, \theta = 355^\circ$	0.6751
Cs-137	662	$\phi = 75^\circ, \theta = 45^\circ$	$\phi = 75^\circ, \theta = 40^\circ$	0.8600
Co-60	1,173	$\phi = 125^\circ, \theta = 335^\circ$	$\phi = 135^\circ, \theta = 335^\circ$	0.6878

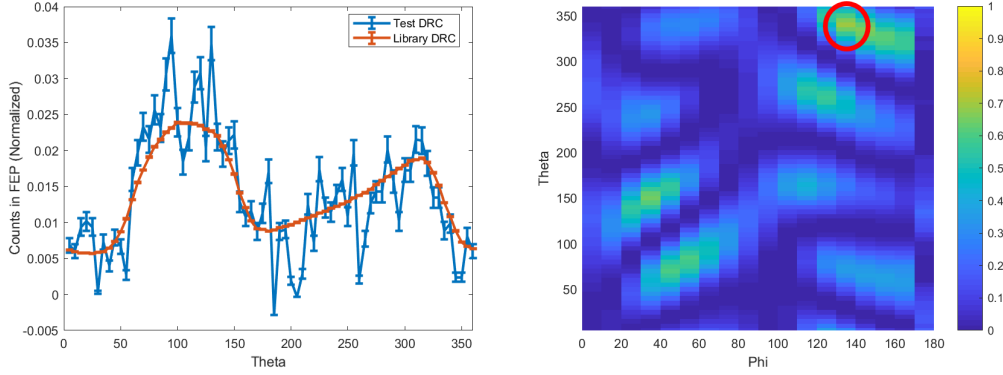


Figure 48. This figure shows the matched DRC for the Co-60 1,173 keV DRC. The source was placed at approximately $\phi = 125^\circ, \theta = 335^\circ$ and the RSM identified the direction of the source as $\phi = 135^\circ, \theta = 335^\circ$. The MAC value for this identification was 0.6878. The heatmap on the right shows the values for all MAC values when the test DRC was compared to the library.

The data from the combined 1,274 and 1,332 keV peak was then processed and analyzed in a similar method to the double Cs-137 FEP from Section 4.7. The same method of combining library curves with different weights was used to match the combined-source DRC. Table 8 shows the correct weighting and direction corresponding to each source location. The expected DRCs, based on source activity and distance, are shown in Figure 49. The test DRC with the correct combination of library DRCs are shown in Figure 50.

The results of the algorithm to determine the which weighting on each library curve that most closely fits the combined peak DRC are shown in Table 9. The DRCs that combined to most closely match the test DRC are shown in Figure 51 and

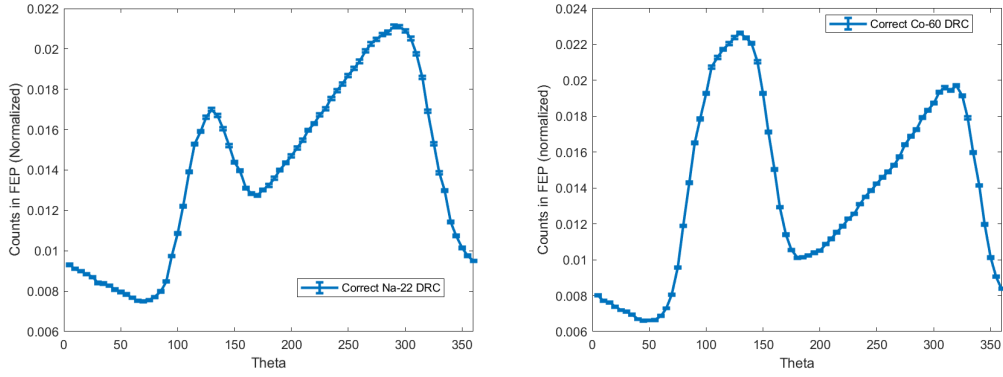


Figure 49. The correct DRCs for combined peak from the Na-22 and Co-60 sources based on the placement of the sources. The Na-22 source was placed at $\phi = 105^\circ$, $\theta = 350^\circ$ and the Co-60 source was placed at $\phi = 125^\circ$, $\theta = 335^\circ$.

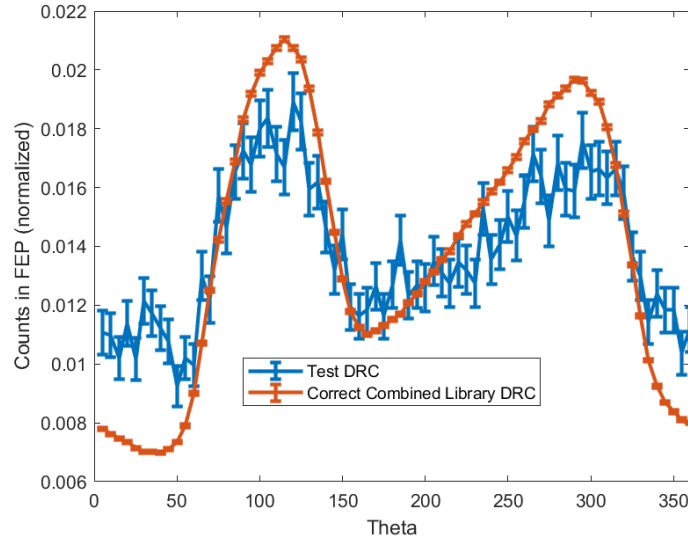


Figure 50. The combined library DRCs with weights as given in Table 8 and the test DRC generated from the combined FEP from the Na-22 and Co-60 sources. These two curves had a MAC value of 0.8670.

Table 8. The correct weighted combination of curves for the directions of the Na-22 and Co-60 sources. This was calculated based on the source activity, given in Appendix B, and the distance to the detector. The DRCs for each source are shown in Figure 49 and the test DRC matched with this is shown in Figure 50. The MAC value for this combination of curves and the test DRC is given in the far right column.

Source	Energy (keV)	Placement	Correct Weight	MAC
Na-22	1,274	$\phi = 105^\circ, \theta = 350^\circ$	0.27	0.8670
Co-60	1,332	$\phi = 125^\circ, \theta = 335^\circ$	0.73	

the test DRC and combined library DRC are shown in Figure 52.

Table 9. The combination of weights and library curves as a result of the algorithm written to determine which combination of library curves matched the test DRC most closely. The matched DRCs for each source are shown in Figure 51 and the combination of library curves that matched most closely with the test DRC are shown in Figure 52. The MAC value for this combination of curves and the test DRC is given in the far right column.

Source	Energy (keV)	Calculated Direction	Calculated Weight	MAC
Na-22	1,274	$\phi = 115^\circ, \theta = 345^\circ$	0.15	0.8897
Co-60	1,332	$\phi = 125^\circ, \theta = 5^\circ$	0.85	

Although the presence of three sources caused higher noise for lower energy FEPs, the RSM was still able to identify the direction of the three sources using the distinguishable FEPs. The average MAC numbers were lower for these matches compared to previous experimental results. This was a direct result of the higher noise causing random variations in each DRC. The combined peak from the 1,274 keV emission from Na-22 and the 1,332 keV emission from Co-60 were able to be used for direction identification as well using the method of library DRC combination discussed in the previous section. Higher resolution detectors will help reduce the effect of combined peaks and improve RSM capability in the future.

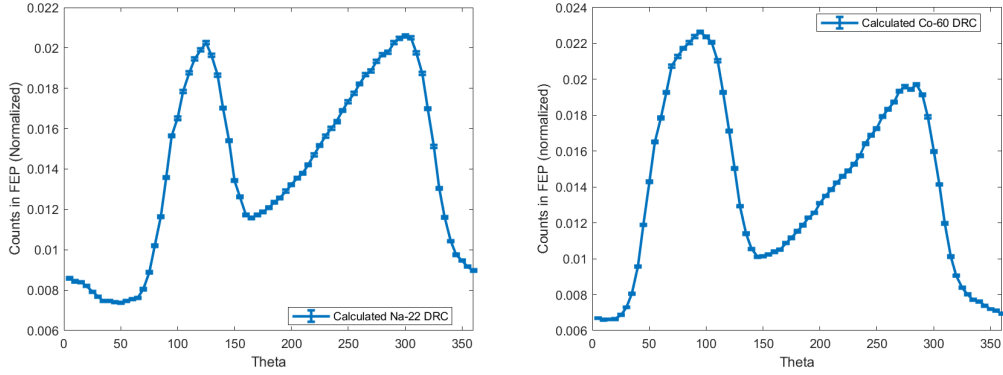


Figure 51. The calculated DRCs for the Na-22 and Co-60 sources using the algorithm that varied the weight and combination of library curves to match the test DRC. The left picture is the DRC for $\phi = 115^\circ$, $\theta = 345^\circ$ and the right picture is the DRC for $\phi = 125^\circ$, $\theta = 5^\circ$.

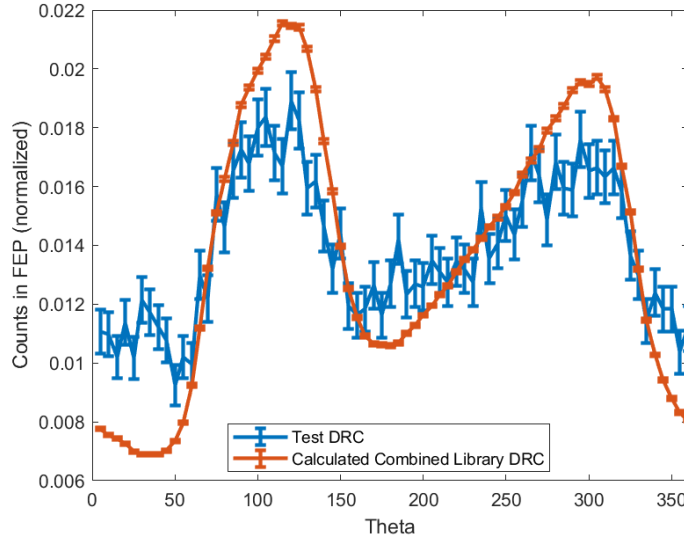


Figure 52. The combined library DRCs with weights as determined with the algorithm and shown in Table 9 and the test DRC generated from the combined FEP from the higher energy emissions from Na-22 and Co-60. These two curves had a MAC value of 0.8897.

V. Conclusions

5.1 Summary

While the idea of developing a system to identify source location or direction is not a novel idea, the development of the RSM is a vast improvement over past attempts. Previous methods have relied on either many scintillating crystals, large lead blocks, or efficiency reducing collimators to provide the ability to identify the direction of a source. These methods are either very expensive, not portable, or too inefficient for many scenarios. The rotating scatter mask provides the same capability with little of the drawbacks.

Logan's experimental and simulation research has proven the efficacy of the RSM to identify the direction of a single radiation source. This research has proven that the RSM is able to identify the direction of any number of radiation sources, provided the full energy peaks from the gamma emissions are distinguishable in the energy spectrum. The use of trapezoidal background reduction provides a method of reducing the error in the data and allows for more accurate direction identification. Although there was a difference in the DRC generated from different FEPs, the general shape of the curve was the same and could be used for identification of radiation sources at different energies.

5.2 Research Objectives Results

The further development of the RSM was the purpose of this thesis. To accomplish this, six research objectives were set and tested through experimentation. The following is a summary of the results of those objectives:

- The DRCs that were generated from different energy sources had the same general shape. There was a difference in the maximum-to-minimum ratios as a

function of the energy of the gamma ray in the FEP. A higher energy gamma ray resulted in a DRC with a lower maximum-to-minimum ratio when compared to the DRC from a lower energy gamma ray.

- A library of curves was developed from a 662 keV FEP, a 1,173 keV FEP, and a 1,332 keV FEP. The library from the 662 keV FEP matched very well with previous libraries developed from both experimental and simulation results. This along with the previous research objective was enough to show that the RSM performed as expected for different energy sources.
- The RSM was able to identify the direction of two different radioactive sources in the same location. Slight discrepancies existed from the actual direction and the measured direction of the sources, but this was due to either the random fluctuations in data collected or trapezoidal subtraction as a method of noise reduction.
- The RSM was able to identify the direction of two different radioactive sources in different locations. The two FEPs were clearly distinguishable and the DRCs matched the correct library DRC very well.
- The current RSM design could determine the direction of two identical-emission radioactive sources using a method of combining library curves to match the DRC from the mutli-source FEP. This method only works if it is known that two sources are present. Future designs developed by Olesen should be able to correctly identify a similar situation more readily.
- The RSM was able to identify the direction of three different radioactive sources in three different locations. Two of the FEPs from the sources overlapped, but the DRC generated from the combined FEP was matched to a combination of library curves similar to the identical-energy multiple-source problem. The

remaining three FEPs provided the ability to identify the direction of the Na-22, Cs-137, and Co-60 sources.

5.3 Applicability for Real World Source Direction Identification

Currently, the RSM assembly can only be used as a stationary radiation detector that can identify the direction of sources in the near vicinity. While this would be suitable for a purpose like a radiation portal monitor, the setup used in this thesis is unable to be moved by one person. It is conceivable that the RSM can be developed into a handheld device that could be brought out into the field. The mask used in this thesis needs to be handled carefully with two hands because the connectors to the gear that rotates it are fragile. Similar mask designs are smaller and have been used with 1"x1" crystals. The disadvantage to reducing the size of the mask is the ability to attenuate incoming gamma rays decreases with the size. Olesen's work on developing a different mask design would help mitigate this problem. A more efficient mask could be scaled and allow for a smaller detector, which would make the system more portable.

While the current RSM design works very well for its intended purpose, it is not yet ready for full scale deployment. More efficient designs can be developed to enable better precision when identifying the direction of a source. Once proven and fully developed, the RSM could be used in scenarios such as a radiation portal monitor to aid in border control with respect to radiation sources. If the RSM were developed to process data in near real-time, it is possible that the RSM could provide a source direction with decreasing uncertainty as the system records more data and develops better statistics.

5.4 Limitations

The current mask design of the RSM is not optimal. Concurrent research by another student, Robert Olesen, attempted and succeeded in identifying more efficient designs for the scatter mask. The designs that were developed focused on reducing the similarities among the DRCs which subsequently reduces the error in direction identification. These better designs can more directly lead to the ability to perform near real-time identification of source location by providing higher efficiency and better counting statistics.

The current experimental setup also suffers from an issue that is not related to the efficiency of radiation detection. The digitizer in the experimental setup used for this thesis records data by sending a single data packet to the USB port of the laptop for every detection. The data then sat in the buffer of that port. The Windows operating system on the laptop only checks the data in the port when there is available processing power, which ends up being a longer time than the time between detections. This resulted in an overall loss of some signals, but since this happened randomly over all rotation angles of the mask, the overall result was just a minor efficiency loss.

5.5 Future Research

The current RSM assembly has many aspects that can be improved upon. As mentioned in Section 5.4, Olesen was working on optimizing the design of the mask itself. The future work that is recommended is listed below.

- The mask design developed by Robert Olesen are superior in almost all aspects of source direction identification. Future research should definitely focus on developing the optimized mask from his results into a physical mask. This research validated the use of the RSM to identify source direction of multiple

sources. The new design will not need to reprove this idea, but could rather be used to develop the RSM to a more final product.

- A method of reducing the background noise known as matrix deconvolution would greatly help in improving the ability of the RSM to identify the source direction. This method is explained in some detail in Appendix C.
- One of the first steps to developing a final RSM assembly is to find a method to process the data recorded by the RSM in near real-time. The serial bus issue could be mitigated by possibly finding a data acquisition platform that can record waveforms to an internal hard drive, then send larger data chunks to the laptop in intervals that are longer than the Windows' USB latency. This method would have to incorporate a way of still recording the rotation angle of the mask for every detection, which was controlled by the LabVIEW software.
- To develop the RSM into an even more useful tool, a method of detecting neutrons would allow for a much more versatile capability to identify source location. Saint-Gobain makes detectors that can detect both gamma rays and neutrons. This requires more data processing to separate the signals, but could be done.

MULTISOURCE DIRECTION IDENTIFICATION USING A ROTATING SCATTER MASK

A. Setup

The detector chosen for this thesis was a SCIONIX HOLLAND 3" x 3" NaI(Tl) detector. A CAEN Model NIM8304 housed the ORTEC 556 High Voltage Power Supply used to power the detector, the ORTEC 460 Delay Line Amplifier, and the NIMBox NDA8 DAC. An ORTEC 142 preamplifier was used to shape the signal from the detector to send to the delay line amplifier. Figures 8 and 9 show the full set up. In the top right corner of Figure 9, a blue box that contains custom electronics to control the encoder ring that records the angle of the mask. This box connects directly to a USB port on the laptop. The settings for each of the modules are given below:

- ORTEC 556 High Voltage Power Supply
 - Output: Negative
 - Voltage: -540 Volts
- ORTEC 142 Preamplifier
 - Input Capacitance: $0\mu\text{F}$
- ORTEC 460 Delay Line Amplifier
 - Fine Gain: 0.3
 - Course Gain: 10

- Integration Time: $0.25\ \mu s$
- Input Polarity: Negative

B. Sources Used

Table 10. This table shows all of the sources used in this experiment, their original activities and the activities at the time of experimentation.

Isotope	Source ID#	Emission	Half-life	Age	Current Activity
Cs-137	644-69	662 keV	30.17 yrs	17.4 yrs	6.707 μ Ci
Cs-137	00173	662 keV	30.17 yrs	49.8 yrs	3.241 μ Ci
Co-60	T-124	1173 keV	5.272 yrs	10.3 yrs	2.643 μ Ci
Co-60	T-124	1332 keV	5.272 yrs	10.3 yrs	2.643 μ Ci
Na-22	T-129	511 keV	950.8 days	3410 days	8.908 μ Ci
Na-22	T-129	1273 keV	950.8 days	3410 days	8.908 μ Ci
Eu-152*	T-110	[multiple]	4933 days	4780 days	5.180 μ Ci
Mn-54*	T-064	83 keV	312.3 days	8371 days	7.363 e-7 μ Ci
Am-241**	T-175	60 keV	432.17 yrs	1.13 yrs	0.02941 μ Ci
Cd-109**	T-175	88 keV	462.6 days	413 days	0.1458 μ Ci
Co-57**	T-175	122 keV	271.8 days	413 days	0.0036 μ Ci
Te-123m**	T-175	159 keV	119.7 days	413 days	0.0013 μ Ci
Cr-51**	T-175	320 keV	27.70 days	413 days	1.10 e-5 μ Ci
Sn-113**	T-175	392 keV	115.1 days	413 days	0.0042 μ Ci
Sr-85**	T-175	514 keV	64.85 days	413 days	7.47 e-4 μ Ci
Cs-137**	T-175	662 keV	30.17 yrs	1.13 yrs	0.0421 μ Ci
Y-88**	T-175	898 keV	106.6 days	413 days	0.0066 μ Ci
Co-60**	T-175	1173 keV	5.272 yrs	1.13 yrs	0.0440 μ Ci
Co-60**	T-175	1332 keV	5.272 yrs	1.13 yrs	0.0440 μ Ci
Y-88**	T-175	1836 keV	106.6 days	413 days	0.0066 μ Ci

* isotopes that were attempted to be used in data collection, but either emitted at too many different energies (Eu-152) or had their activity incorrectly calculated when first used (Mn-54).

**isotopes that were part of the multinuclide used for calibration

C. Matrix Deconvolution

A more robust background correction method is a process called matrix deconvolution. The method deconvolutes the spectrum via matrix inversion [22]. Although it is very straightforward, it requires a Monte Carlo simulation of the experimental setup followed by Gaussian broadening of the simulated spectrum [22]. The general idea behind this method is to envision the emitted spectrum from the source as a one-dimensional array that is all zeroes except at the energy of the emission. The observed spectrum can also be envisioned as a one-dimensional array. To transform from one to the other, a two-dimensional square matrix can be developed to act on the emitted spectrum and result in the observed spectrum (see Equation 8).

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 11 \\ 17 \\ 50 \\ 18 \\ 9 \\ 0 \end{bmatrix} = M \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 100 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

In Equation 8, the array on the right side of the equation is an example of an emitted spectrum with 100 hypothetical gamma ray counts in the seventh energy bin. The array on the left side is the observed spectrum after the gamma rays have interacted with the detector and electronics. Some variance in energy and background radiation is observed.

The square matrix, M , that acts on the emitted spectrum is called the response matrix. Ideally, this response matrix would contain the information that fully characterizes the laboratory setup, including the detector response, electronic noise, backscatters from nearby structures, etc. If the response matrix were known and invertible, then the observed spectrum could be multiplied by the inverted response matrix to give the emitted spectrum. Developing this method would result in a great reduction in the background noise, which the scatter mask is adept at producing, as well as increased source identification if the emitted spectrum was precisely known.

Finding the response matrix requires a Monte Carlo simulation with as much of the experimental setup as possible recreated in the simulation [22]. Unfortunately, for the RSM assembly, this would need to be done at every possible ϕ and θ rotation. With the current design, this would require at least 1,296 simulations to fully develop the response matrix. One of Olesen's designs could prove to be a better candidate for a study such as this in future research.

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