DEVELOPMENT OF 2D AND 3D FAN BEAM X-RAY SCATTER RADIOGRAPHY IMAGING METHODS FOR NON-DESTRUCTIVE EXAMINATION

By

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To Dr. Edward T Dugan
ACKNOWLEDGMENTS

I am grateful to Dr. James Baciak for accepting me as his student and serving as the chair of my Ph.D committee. This project would not have been successful without his realistic results-oriented leadership. He is one of the few academics which can bridge the gap between pure university research and commercialized advanced technology. Throughout this project he motivated me and guided me in the right direction.

Dr. Edward Dugan became my undergraduate advisor when I joined the Nuclear Engineering Sciences department in 2002. He is quiet, has a kind heart, a gentle selfless spirit, and nearly infinite patience. I took many classes taught by him including Radiation Interactions I to start my journey in nuclear engineering. Without his guidance I may not have graduated with my Bachelor of Science degree in 2006. Through his research and development of backscatter x-ray methods he motivated me to advance radiographic NDT methods instead of working for the nuclear power industry or the nuclear weapons programs of national labs. I joined him at Nucsafe in 2011 to contribute to the development of scatter x-ray imaging technology. Without his research and development of SXI methods this project would never have been possible. Dr. Dugan represents the type of engineer and person I aspire to become.

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Paul Ridgeway is the most skilled electrical engineer, mechanical engineer, and systems engineer to have ever created backscatter equipment. His creativity and attention to detail led to the success of x-ray backscatter inspection systems at Nucsafe and GREX's Aurora Xi.
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<td>As Low As Reasonably Achievable</td>
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<td>FOV</td>
<td>Field of View</td>
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<td>FRA</td>
<td>Federal Railroad Administration</td>
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<tr>
<td>GREX</td>
<td>Georgetown Rail Equipment Company</td>
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<tr>
<td>NRC</td>
<td>Nuclear Regulatory Commission</td>
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<tr>
<td>NDE</td>
<td>Non-Destructive Evaluation</td>
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By
Michael John Liesenfelt

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Chair: James Baciak
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In the United States, railroad infrastructure is critical for transporting goods which fuel our economy. Wood crossties support 93% of approximately 140,000 miles of class I railroad track in the US. The Georgetown Rail Equipment Company (GREX) began development of x-ray inspection technologies for both installed and newly fabricated crossties. The purpose of this research is to develop the methods necessary for both 2D and 3D fan beam scatter radiography.

Methods will be developed to produce high quality repeatable 2D x-ray backscatter images of installed crossties in excess of 20mph. Combinations of both MCNP modeling and experimental measurements will be used for prototype and production system designs. System design considerations include radiological safety, x-ray tube selection, x-ray fan beam formation, x-ray beam spectrum, backscatter field characterization, segmented collimator design, and detector design. The development of these 2D methods led to the creation of the Aurora Xi inspection system.

Newly fabricated wood crossties are not radiographically inspected for internal flaws and adequate penetration of degradation prevention treatments. Approximately $2.4B is spent on creating and installing 24,000,000 new wood crossties each year.
Building on the 2D backscatter technology, information about how radiation scatters within an object is valuable for 3D computed tomography inspection. A theoretical basis, system design, and methods for high-speed 3D fan beam transmission and scatter computed tomography will be proposed for development. Instead of applying traditional central axis of rotation computed tomography techniques, stationary fan-beam x-ray illumination sources will create unique transmission, forward scatter, side scatter, and backscatter radiography perspectives of a translating object. A new method of computed tomography which combines both transmission radiography and scatter radiography will be presented.
CHAPTER 1
INTRODUCTION

Problem Description and Motivation

In the United States, railroad infrastructure is critical for transporting goods which fuel our economy. In 2015 the 320 million people in the US transported approximately 13 billion tons of freight or approximately 40 tons per person per year. [1] As of 2011, Class I railroads have in total 140,000 miles (224,000km) of railroad track. Rail transportation has the largest share, nearly 40%, of all freight in the United States on a ton-mile basis. Rail is also an extremely efficient way to ship freight averaging 413 miles per ton per gallon of fuel in contrast to trucks which averages 110 miles per ton per gallon of fuel. [2] New and advanced technologies are being developed to maintain a safe and productive railroad infrastructure.

Railroad infrastructure can fail in a number of ways. Railroad track may have inadequate rock ballast or an unstable foundation. Rails can break due to loads, stresses, and temperature changes. Wood crossties can crack, split, rot, and/or lose structural integrity because of inadequate treatments, drainage, climate, and weather. [3] In 2013, track failures were responsible for 31% of all accidents. [1] When a track failure occurs, the consequences include possible injury or loss of life, hazardous material release, environmental damage, transportation delays, investigations, liability, and significant costs associated with each. In 2012, there were 2.47 million shipments of hazardous materials via railroad including flammable, corrosive, reactive, biohazard, toxic, radioactive, and explosive materials. [4] Preventative maintenance programs minimize accident risks by collecting data, monitoring track, repairing flaws, and preemptive replacement.
In the United States, 93% of all track miles are held together and supported by wood crossties. [5] Currently visual inspection methods are most commonly used to inspect wood ties for defects. For many a walking track inspector assigning qualitative grades for each tie was the only method of inspection. Walking inspectors are limited to approximately 2 to 3 miles per hour and the accuracy of each inspection can vary depending on the experience of the inspector and other human factors. In 2005, The Georgetown Rail Equipment Company (GREX) began developing the Aurora laser surface scanning track inspection system. Aurora can scan the surface of ties at speeds between 30mph and 45mph with a high degree of repeatability. Instead of an inspector’s qualitative assessment, Aurora processes the laser surface profile data with many algorithms to generate quantitative tie grades. All visual inspection methods, both with experienced track inspectors and automated scanning technologies, can only infer the internal structural integrity of a tie from its’ surface features. [6] Figure 1-2 shows a photograph of a destructively examined installed crosstie with a smooth surface but lacking structural integrity because the center is almost completely rotten.

Ultrasonic and ground penetrating radar systems have been developed in an attempt to directly inspect the internal features of a tie for structural integrity grading. Ultrasonic methods require direct contact with the crosstie at each point of inspection so at best it will not be faster than a walking track inspector. Ultrasonic inspection techniques works best on uniform homogeneous objects however wood has many grain boundaries, splits, knots, and internal features. Some railroad inspection companies have attempted to use ground penetrating radar to image the internal features of wood crossties, however when the wavelength and antenna size is many times larger than the
size of defect features, it will not be possible to detect or measure defects by this method. Also, ground penetrating radar data often has a very low signal to noise ratio which makes automated algorithmic analysis of the data very difficult or impossible. Unfortunately, neither of these methods are accurate enough to be combined with the Aurora laser scanning technology.

Radiography is one of the 5 main methods employed in Non-destructive Testing and Examination (NDT/NDE) methods. Most commonly, x-rays or gamma rays are passed through an object and detected on the opposite side to form an image of the interior. Transmission radiography images are formed from the inversion of how many photons are blocked between the source of radiation and the detector. However, when a detector or film cannot be placed on the opposite side of an object, scatter x-ray radiography is necessary. Scatter radiography is the opposite of transmission, forming an image from the photons scattered within an object, not by the amount of x-rays blocked by the object.

Applications of backscatter radiography have been principally in the aerospace and security markets. Backscatter radiography has been used to inspect the foam of the space shuttle fuel tanks and the re-entry heat shield of the Orion crew capsule. [7] Boeing has used backscatter radiography to inspect aircraft components to look for foreign objects, metal failures, and composite problems. American Science and Engineering uses backscatter radiography to inspect vehicles and cargo for homeland security applications. Because of the previous developments and application of backscatter radiography in other industries, x-ray backscatter radiography was selected as best technology see inside of railroad ties and add internal information to surface
scan inspections. An x-ray beam of sufficient energy can adequately penetrate through wood tie resulting in a clear scatter signal from the internal features of a wood tie.

GREX began development of an x-ray backscatter inspection technology to complement its’ laser surface scanning system in 2009. [6] Most importantly, this new inspection technology would have to ensure that no radiation areas above the Nuclear Regulatory Commission (NRC) regulatory limit of 0.02mSv/hr (2mrem/hr) would extend beyond the Federal Railroad Administration (FRA) boundary of the track area. Next, the x-ray system would have to operate at speeds in excess of 15mph such that laser and x-ray inspections could be performed simultaneously. Also, the x-ray system would have to produce accurate and reproducible results in both directions of travel. To produce accurate results, an x-ray spectrum of sufficient intensity and energy distribution would be necessary to produce high resolution images of the internal features within a crosstie.

The Physics of Photon Interactions

Radiographic inspections are performed using high energy x-ray or gamma ray sources. Gamma rays are emitted during the radioactive decay of unstable nuclei. The advantages of gamma ray sources include small size, no power or cooling requirements, higher energy photons, and discrete/predictable energy photons. Unfortunately, gamma ray sources and the radioactive decay process cannot be turned off for safety. X-rays are produced when the path of high energy electrons is changed by electronic or magnetic fields. This process is known as the bremsstrahlung effect. The main advantage of an x-ray sources is that the x-rays can be turned be turned off by removing power from the electron beam. However, x-ray sources are larger, require more equipment, and result in x-ray photons across a continuous spectra of energies.
Photons have a number of interaction mechanisms including photoelectric absorption, coherent scattering, incoherent Compton scattering, pair production, and photonuclear interactions. Each of these interactions depends on the atomic number(s) of the material and the energy of the photon. Figure 1-3 shows the wide range of scattering and absorption cross sections for Iron.

**Photoelectric Absorption**

Photoelectric absorption is the process of a photon transferring all of its energy to an electron. The cross section for the photoelectric effect is shown in Equation (1-1) where $E$ is the energy of the photon, $C$ is a proportionality constant, and $Z$ is the atomic number of the material. [8]

$$\sigma(E, Z) = C \frac{Z^{4.5}}{E^3}$$  \hspace{1cm} (1-1)

This relationship has a strong dependency on energy and the atomic number of the material. At lower energies and higher values of $Z$ it becomes very likely that a photon will be absorbed. High-Z, high density materials like Tungsten and Lead are optimal radiation shielding materials because the photoelectric absorption is exponentially higher than in low-Z materials like Beryllium or Aluminum.

**Incoherent Compton Scattering**

Incoherent Compton Scattering is the primary photon interaction used for scatter radiography. Compton scattering is the inelastic scattering of a photon by an electron. The transfer of energy to an electron results in a recoil electron and a reduced energy scattered photon. The relationship for the change in energy between the initial photon $E'$, scattered photon $E_0$, angle between their vectors $\theta$, and the electron rest mass energy $m_0c^2$ is shown in Equation (1-2).
Compton scattering can result in a photon with a reduced energy that may scatter at an angle between \((0, \pi)\). The most important aspect of this relationship is the likelihood that a photon can ‘backscatter’ at an angle between \((\frac{3\pi}{4}, \pi)\) towards the same side of the object that the photon source is located. These photons can be used to create a same-side backscatter image. Additionally, photons could potentially 'side scatter' at an angle between \((\frac{\pi}{4}, \frac{3\pi}{4})\) or ‘forward scatter’ at an angle between \((0, \frac{\pi}{4})\).

Because the change in angle has an accompanying change in energy, so the detectors used to form an image should be optimized for the scatter spectra, not the spectra of the beam. Additionally, because of the conservation of energy principle between \(E', E_0\), and \(\theta\) when two of these variables are known, the third can be determined. When combined with a fixed-energy gamma-ray source(s) this property can be valuable for 3D image reconstruction methods.

**Klein-Nishina Differential Scattering Cross Section**

Although a photon can scatter at many angles, the process is not isotropic. J.J Thompson developed the first relationship in Equation (1-3) for the differential scattering cross section per electron where \(\frac{d\sigma_e}{d\Omega_\theta}\) is the differential scattering cross section per solid angle in units of \(\text{cm}^2 \text{ sr}^{-1}\) where \(r_0\) is the classical electron radius, and \(\theta\) is the scattering angle of the photon.

\[
\frac{d\sigma_e}{d\Omega_\theta} = \frac{r_0^2}{2} (1 + \cos^2\theta) \tag{1-3}
\]
The differential Compton scattering cross section was developed with the assumption that each interaction occurs with unbound free electrons because binding energy of each electron is much less than the energy of the photon. This treatment allows the Compton scattering cross section to have no dependence on the average atomic number of the material. Building upon this relationship, Oscar Klein and Yoshio Nishina developed a quantum mechanical relationship for the differential Compton scatter cross section per electron given by Equation (1-4). [9]

\[
\frac{d\sigma_e}{d\Omega_\theta} = \frac{r_0^2}{2} \left( \frac{E'}{E_0} \right)^2 \left( \frac{E_0}{E'} + \frac{E'}{E_0} - 1 + \cos^2 \theta \right) \tag{1-4}
\]

When the change between the initial energy and scatter photon energy is very small, the differential Klein-Nishina relationship in Equation 4 reduces to the Thompson relationship in Equation (1-2). The total Compton scattering cross section in cm\(^2\)/atom in Equation (1-5) is computed by integrating the differential cross section between \((0, \pi)\) and multiplying by the number of electrons per atom, \(Z\).

\[
\sigma_{KN} = 2\pi \frac{N_A Z}{\rho} \int_0^\pi \frac{d\sigma_e}{d\Omega_\theta} \sin \theta \, d\theta \tag{1-5}
\]

Plotting the Klein-Nishina cross section at various energies per solid angle yields Figure 1-4. The Klein-Nishina cross section as a function of angle is much different than the distributions per solid angle. Figure 1-5 is a plot of the Klein-Nishina cross section at various energies as a function of angle. At a relatively low energy of 10keV, a Compton scattered photon has a similar likelihood of scattering into a solid angle between 0 and 20 degrees as backscattering into a solid angle between 160 and 180 degrees. However, as the photon energy increases, forward scatter becomes most likely and the total scatter likelihood decreases.
**Coherent Scattering**

Coherent Scattering or Rayleigh scattering is an elastic scatter of a photon. An elastically scattered photon travels in a new direction but has the same energy as the original photon. Figure 1-6 shows the ratio of incoherent to coherent scattering in carbon. At energies below 15keV coherent scattering is more likely than incoherent scattering and above 50keV incoherent scattering is an order of magnitude more likely than coherent scattering. Coherent scattering doesn't strongly influence scatter radiography methods because the cross sections are approximately 1 to 2 orders of magnitude less than photoelectric absorption and Compton scattering.

**Scatter to Absorption Ratio**

One of the most important considerations of scatter radiography methods is the ratio of scatter to absorption. This ratio directly effects the illumination time and the depth of penetration for an inspection. Figure 1-7 shows the scattering and absorption cross sections for 3 elements: Carbon (Z=6), Iron (Z=26), and Lead (Z=82).

The total cross sections effect the depth of penetration for a scatter radiography inspection and the ratio between the scatter to absorption cross sections will affect the amount of scatter signal and necessary illumination time. Figure 1-8 shows the ratio of scatter to absorption for the same elements. Scattering and absorption interactions depend on the atomic number(s) of the object and the energy of the photon. To optimize the depth of penetration and scatter signal an appropriate energy or energy distribution must be selected for the material composition and density being inspected. Scatter radiography methods depend on optimally applying the physics of photon interactions including the angularly dependent Klein-Nishina scattering cross section, the photoelectric absorption cross section, and the Compton backscatter spectra.
Mathematical Expression of Scatter Radiography

The first collision backscatter signal is the sum over all source energies of unattenuated photons from a source point(s) which travel within the fan beam to a point in the beam volume, scatter to a lower energy toward the detector volume, travel without attenuation to the detector, and are absorbed in the detector volume. The partial intensity, $I_{B \rightarrow S \rightarrow D}$ for a path originating from focal spot $B$, travelling along $r$ within beam volume $R$, scattering at location $S$ within the volume formed by the union of $R$ and $R'$ from energy $E \rightarrow E'$ and direction $\Omega_{B \rightarrow S} \rightarrow \Omega_{S \rightarrow D}$, travelling along return path $r'$ within volume $R'$, and reaching a detector at point $D$ is given by Equation (1-6) and shown in Figure 1-1.

$$I_{B \rightarrow S \rightarrow D} = \int_{E=0}^{E_{max}} \frac{E'}{2\pi(|B_i - S_r|)} \exp \left( \int_{r=B_i}^{S_r} -\frac{\mu}{\rho}(E)\rho(r)dr \right) \rho(S_r) \left( 2\pi \sin \theta \sigma_{KN}(r, E \rightarrow E', \Omega_{B \rightarrow S} \rightarrow \Omega_{S \rightarrow D}) \right)$$

$$\frac{1}{2\pi(|S_r - D_j|)} \exp \left( \int_{r' = S_r}^{D_j} -\frac{\mu}{\rho}(E')\rho(r')dr' \right) dE$$

Figure 1-1. Labeled diagram of scatter radiography.
\( \hat{I}_0(E') \) represents the normalized spectra of the illumination source and \( \sigma_{\text{Kn}}(r, E \rightarrow E', \hat{\Omega}_{B\rightarrow S} \rightarrow \hat{\Omega}_{S\rightarrow D}) \) is the Klein-Nishina scattering likelihood at point \( S \) of an x-ray scattering from energy \( E \) on the beam vector \( \hat{\Omega}_{B\rightarrow S} \) to energy \( E' \) on the return path vector \( \hat{\Omega}_{S\rightarrow D} \). The total scatter signal in Equation (1-7) is the integrated intensity of all contributing x-ray paths in the volume for all energies.

\[
Signal_D = \int_V I_{B\rightarrow S\rightarrow D}(r, E \rightarrow E', \hat{\Omega}_{B\rightarrow S} \rightarrow \hat{\Omega}_{S\rightarrow D}) \, dV
\]  

(1-7)

Figure 1-2. Destructively examined rotten crosstie, Gainesville, Florida, 2015. Photo courtesy of author. [10]
Figure 1-3. Interaction Cross Sections for Iron (Z=26). [11]
Figure 1-4. Klein-Nishina cross section per solid angle per electron.
Figure 1-5. Klein-Nishina cross section per angle per electron.
Figure 1-6. Incoherent to Coherent Scattering Ratio in Carbon. [11]
Figure 1-7. Scattering and Absorption cross sections for C, Fe, and Pb. [11]
Figure 1-8. Scatter to absorption ratio for C, Fe, and Pb. [11]
CHAPTER 2
REVIEW OF SCATTER X-RAY RADIOGRAPHY METHODS

Transmission and Backscatter Radiography

Transmission radiography forms images based on the quantity of radiation which passes through an object unchanged and is detected on the opposite side of the source. Backscatter radiography forms an image by detecting the photons which are Compton scattered backwards towards the photon source. Figure 2-1 shows the difference between transmission and backscatter radiography.

In Figure 2-1 on the left, transmission radiography acquires an image using film or a 2D detector array (green) from radiation which has passed through the object or region without being absorbed or scattered. In Figure 2-1 on the right, backscatter radiography forms images using radiation which has scattered off of an object 'backwards' to the same side of the object as the source. The illuminated volume is where the photon source is projecting radiation into (red) and the detector field of view is the volume that the detector can sense scatter radiation from (green). The union of these two volumes forms the inspection volume (green+red). Forming a backscatter radiography image is much more complicated than acquiring a transmission radiograph because extra degrees of freedom are introduced in the geometry and physics. Transmission radiography is preferred to backscatter radiography when access to every side of an object is available and practical, however some applications lack access to the opposite side of an object leaving backscatter methods as the only available option. Even with access to every side of an object is available, the scatter x-ray field can still provide valuable information about the internal composition of an object.
Uncollimated Techniques

In Figure 2-1 the inspection volume is relatively large because both the illumination field and the detector field of view is large. Uncollimated techniques rely on limiting and blocking the illumination field but leaving the detector uncollimated to detect any photon from a wide range of angles. A 2D image can then be created by translating or scanning the illumination beam through the object. As the beam is decreased in size the spatial resolution of the image can be increased however forming the image will take more time. The signal on the uncollimated detector will be the combination of both single-scattered and multiple-scattered photons. A significant fraction of the uncollimated backscatter signal originates from scattering events near the surface of an object. Photons which scatter near the surface are closer to the detector and are less likely to be absorbed by the object as they travel towards the detector. Figure 2-2 shows an example of a collimated x-ray illumination beam with an uncollimated detector.

Pencil Beam Raster Imaging

Pencil beam raster imaging uses a highly collimated illumination beam with a total cross sectional area and pixel size which is typically less than 4mm$^2$. One or more detectors are oriented symmetrically about the beam axis in order to sample the scatter field. A weighted combination of the signal from the detectors is used to generate a single 16 or 32 bit integer value pixel for a single point on the object. Then, the illumination beam and detectors are translated together on two axis to form a 2D image similar to Figure 2-3. Scanning systems typically are constantly moving so timed sequencing is used for integrating and separating signal into pixel values. Pencil beam raster imaging techniques have the advantage of being able to produce very high resolution images with a flat imaging perspective perpendicular to the beam lacking a
central focal spot, however the time necessary to form an image increases proportionally to the area being scanned.

**Pencil Beam Rotational Imaging**

An alternative to raster image formation using two dimensions of translating motion is to use a rotating collimator. A rotating collimator allows for improved speed because the system would translate in one direction over the object as narrow pencil beams sweep across the imaging plane. Although this method is much faster the resulting images have a cylindrical perspective instead of a flat perpendicular perspective. The time necessary to produce an image is proportional to the product of the sweep time of the pencil beam across the image and the translation speed. Multiple beam forming tubes can be used in a rotating collimator such that when one pencil beam tube is leaving the illuminated field, the next beam tube enters the illuminated field from the opposite side. Figure 2-4 shows an example of pencil beam paths sweeping through the imaging field as the illumination source is continually translated.

**Collimated Techniques**

Collimated techniques are configurations of absorbers placed on or near the detector(s) to selectively limit the detector(s) fields of view (FOV) by blocking some of the scattered x-rays. Collimating the detector reduces total signal and can increase image acquisition time, however it can significantly increase the image contrast and volumetric resolution. Contrast is increased because the fraction of multi-scatter photons which can be detected from a wide range of angles is reduced. By using appropriate collimation the scatter signal from a small 3D volume within an object can be measured. Figure 2-5 shows an example which includes both a narrow collimated x-
ray illumination beam and a collimated detector with a limited field of view for
backscattered photons.

**Radiography by Selective Detection**

Radiation by selective detection is a technique which uses collimation to detect
single and multi-scatter photons from specific segments of the detector’s field of view.
By placing the detector collimation in the proper orientation all single scatter photons
above a certain plane in an object can be blocked from reaching the detector. This
plane is referred to as the collimation plane. Collimation planes in the object have the
advantage of being able to improve the contrast of features deep within an object by
reducing or eliminating the contribution of surface scatter signals. Figure 2-6 shows the
geometry of the detector collimator, the detection field of view, and the collimation plane
(yellow dashed line). For some applications, the differences between collimated and
uncollimated detectors could be used to reduce noise and improve the contrast of
illuminated regions deep inside of an object.

Radiography by selective detection was successfully applied for many
applications. At the University of Florida, lead collimator fins were added to backscatter
detectors to selectively limit the backscatter field reaching each detector. Figure 2-7
shows the x-ray tube, beam forming collimator, detectors, and detector collimation
added to each detector. In this example, the collimation was used to inspect the bond of
a space shuttle heat tile to the structure. [7]

**Lateral Migration Radiography**

Lateral migration radiography is a backscatter imaging technique which
generates an image from x-rays which scatter more than once. Lateral migration
techniques use detector collimation to block photons which have only scattered once
from reaching the detector. This technique is best applied for the detection of voids in an object because x-rays which scatter more than once are likely to ‘migrate’ or travel across the void farther away from the illumination beam. [12] This technique was successfully applied to the detection of land mines. [13] In Figure 2-8 since there is no overlap of the beam illumination volume and the detector FOV so only x-rays which scatter at least twice can reach the detector.

**Shadow Aperture Backscatter Radiography**

Shadow Aperture Backscatter Radiography (SABR) is a backscatter radiography method in which a planar aperture is used to block most of an illumination field. [14] A film or detector is located between the aperture plane and the object to generate an image from the areas which are shadowed from the illumination field. Some of the illumination field scatters in the object and leaves an image on the detector. The areas of the film which are not blocked by the aperture become saturated leaving unresolved gaps in the image. Figure 2-9 illustrates the shadow aperture backscatter radiography method.

In Figure 2-9, the red triangle represents the x-ray illumination field, the black segments represent the aperture, the green and white checkerboard represents the film, the solid red arrows represent the illumination vectors passing through the aperture, the grey region is the object being inspected, and the dashed red arrows represent backscatter x-rays. A backscatter image representing the combination of the local scattering and absorption likelihoods of the object is cast onto the film to form a partial image. Figure 2-10 is a picture of a SABR aperture made of lead squares. Figure 2-11 is a picture of sample objects on nylon. Figure 2-12 is the resultant SABR image on the film.
In Figure 2-12, the backscatter image is projected onto the film and resolvable in the regions in which the x-ray illumination field was blocked by the aperture grid. This method requires the object to be relatively thin, approximately one mean free path thick, and with a minimal object to film distance. An advantage of this method is a portion of a large field area can be collected simultaneously without scanning but with the disadvantage of needing a second exposure with an offset the aperture pattern and to create a processed complete image. This method is also better at lower x-ray energies to minimize the thickness of the aperture. [14]

**Segmented Collimator Linear Detector Array**

The first demonstration of fan beam illumination combined with a segmented collimator linear detector array was conducted by Olivier Bougeant for his master’s thesis. The proof of concept experiment used an x-ray tube collimated into a fan beam shown in Figure 2-14, a segment collimated linear detector array shown in Figure 2-13, and a strongly contrasting object made of lead and polyethylene. It was demonstrated that 2D images could be formed by translating the system in one direction and using an appropriate segmented collimator on the linear detector array. Without detector collimation, the x-ray scatter field from every point illuminated by the fan beam blurred the image as shown in Figure 2-15. However, with the segmented collimator on the linear detector array, each detector element in the linear detector array had a limited field of view eliminating the cross-scatter to form an accurate image as shown in Figure 2-14. [15]
Figure 2-1. Radiography methods. A) Transmission. B) Backscatter.

Figure 2-2. Uncollimated backscatter radiography.

Figure 2-3. Raster image formation pattern.
Figure 2-4. Rotating collimator image formation pattern.

Figure 2-5. Collimated backscatter radiography.

Figure 2-6. Radiography by selective detection.
Figure 2-7. Radiography by selective detection system picture, Gainesville, Florida, 2007. Photo courtesy of Daniel Shedlock. [7]

Figure 2-8. Lateral migration radiography.
Figure 2-9. Shadow aperture backscatter radiography geometry.

Figure 2-10. Picture of SABR aperture, Gainesville, Florida, 2007. Photo courtesy of Daniel Shedlock. [7]
Figure 2-11. Picture of SABR objects, Gainesville, Florida, 2007. Photo courtesy of Daniel Shedlock. [7]

Figure 2-12. Resultant SABR image, Gainesville, Florida, 2007. Photo courtesy of Daniel Shedlock. [7]
Figure 2-13. Segmented collimator, Gainesville, Florida, 2009. Photo courtesy of Olivier Bougeant. [15]

Figure 2-14. The first fan beam and segmented collimator array, Gainesville, Florida, 2009. Photo courtesy of Olivier Bougeant. [15]
Figure 2-15. Uncollimated fan beam image, Gainesville, Florida, 2009. Photo courtesy of Olivier Bougeant. [15]

Figure 2-16. The first collimated fan beam image, Gainesville, Florida, 2009. Photo courtesy of Olivier Bougeant. [15]
CHAPTER 3
2D FAN BEAM SYSTEM DESIGN

Design Requirements and Technology Selection

The 5 major American Society of Non-destructive Testing techniques include dye penetrant testing (PT), magnetic particle testing (MT), ultrasonic testing (UT), eddy current testing (ET), and radiographic testing (RT). Dye penetrant testing, magnetic particle testing, and eddy current testing cannot be applied to organic non-conductive porous pre-treated wood crossties. Ultrasonic testing methods would require direct contact with every crosstie in multiple locations and would not create a 2D image. Additionally, each species of wood would have different acoustical properties. Ground Penetrating Radar (GPR) was considered but the signal return for wood is low and it isn't possible to achieve a resolution smaller than the GPR wavelength, transmitter(s) size, or receiver(s) size. Backscatter radiographic inspection techniques were selected as the only method capable of accurately inspecting the internal features of wood crossties. Each scatter radiography method, geometric configuration, and technique has advantages and disadvantages. For railroad crosstie inspection speed, resolution, and stand-off distance are the most difficult requirements to meet.

Plate-C Compliance

Federal Railroad Administration regulations mandate that anything traveling on the rails fit within an envelope called Plate-C shown in Figure 3-1. This ensures that a vehicle will not damage the railroad or any equipment installed on the railroad, and installed railroad equipment will not impact or damage any vehicle traveling on the rails. The distance between the top of the rail and the bottom of the Plate-C envelope is 7cm and the top of the rail can be 25cm. The potential stand-off distance between the bottom
of the Plate-C envelope and the top of the crosstie surface is at least 32cm. This standoff distance is too large for the SABR method to be applied. Also, since the tops of the crossties being inspected are usually always exposed and laser surface scans are available, RSD techniques are not necessary for improving contrast when a crosstie is partly covered.

**Radiological Safety**

Safety and compliance with all state and federal radiological, environmental, health, and safety regulations is the most important factor. This project would not be possible without adhering to a strong safety culture based upon As Low As Reasonably Achievable (ALARA) principles. The spectra, size, intensity, placement, and use of the x-ray fan beam system were all influenced by complying with regulatory limits, minimizing the radiation fields, minimizing operator exposure, and minimizing exposure to members of the general public. The system was designed such that no radiation fields exceeding the 0.02mSv/hr (2.0mrem/hr) definition of a radiation area would extend beyond the Federal Railroad Administration’s defined track fouling plane boundary 4 feet from the nearest running rail. Early testing indicated that the thick steel rails are essential for blocking scatter x-rays and reducing the field intensity at the FRA boundary. Therefore, the crossties would only be illuminated and inspected between the crossties.

Although mono-energetic gamma ray sources of sufficient energy and intensity were considered for this system because of their use in other industrial applications, radioisotope sources cannot be turned off and could potentially be lost or stolen. A mono-energetic gamma ray source would allow for the collection of 3D information and the rejection of multi-scatter photons improving both signal to noise and image contrast.
Since safety is the most important consideration for railroad work, an x-ray source was selected instead of a radioisotope source because x-ray sources produce no radiation when the power is turned off and there is no possibility of residual radiation. Initial testing indicated that a primary beam peak energy between 225kV and 450kV would be required to adequately penetrate through an 8” thick crosstie. Minimizing the peak energy of the x-ray spectra also reduces the amount of safety shielding necessary to ensure that radiation levels at the operating boundary of the inspection system are below the regulatory definition of a radiation area.

The fan beam will only illuminate the crossties between the rails because the rails are very effective at shielding the lower average energy spectra of the x-ray scatter field. To comply with the Plate-C envelope and remain within regulatory limits it would not be practical to illuminate outside of the rails and shield the lateral scatter field. Both rigid and flexible shielding was used to block the backscatter field. Lead in the form of solid plates or small spheres of lead shot filling a cavity were used within the Plate-C envelope. Flexible Silflex shielding was added to the system to block more of the scatter field in locations which would be outside of the Plate-C envelope.

**Resolution and Image Quality**

Speed and resolution are often directly competing requirements. Generally, a slower system can produce images with a higher resolution and a system can gain speed by sacrificing resolution. It was required that this scanning system operate at no less than 10mph and potentially up to 42mph to match the maximum speed of the Aurora laser surface scanning. At 42mph with a pixel size of 0.5” in the travel direction data would have to be acquired at a frequency of 1478 lines per second. Forming an image by translating/rastering the x-ray source is far too slow and is entirely impractical.
Although a flying spot or rotating collimator beam forming method could be applied a large, heavy, balanced high speed x-ray absorber would be required. A large spinning mass would pose many significant mechanical, structural, and safety challenges.

From these considerations, an entirely new backscatter method was required to meet the system goals. The only way to reach both the speed and resolution goals was to simultaneously illuminate a line between the rails and collect the scatter x-ray signal in segments as the entire system moved at a high rate of speed. For this system, it would be necessary to collimate the x-ray source to create a fan beam and collimate a linear detector array into segmented fields of view.

**Creating the X-ray Fan Beam**

X-rays are created by the Bremsstrahlung process as high energy electrons deflect in the electric field around the nuclei of a target material. The loss of kinetic energy of the electron is converted into an x-ray photon satisfying the conservation of energy. Typically x-rays are created by evacuated vacuum tubes which contain a heated filament for the creation of electrons by thermionic emission and the acceleration of those electrons by a large electric field potential. Also, the beam of electrons can be magnetically steered or focused into a higher intensity beam directed at the target material.

**X-ray Tube Selection**

The first step in creating a fan beam is selecting an optimal x-ray tube based on the system considerations. First, the x-ray tube would need to produce an x-ray spectra with a maximum energy of up to 450keV. At this potential the tube would need to be able to continuously operate at a high continuous power level between 1kW and 5kW. The electron beam target within the x-ray tube should be angled and geometrically
oriented such that x-ray field is as uniform as possible and is wide enough to illuminate a line between the rails. This will ensure that the narrow fan beam created by collimating the x-ray field penetrates and scatters within the object similarly. The x-ray tube should be as close as possible to the crosstie for maximum illumination intensity. This requires an x-ray tube with a wide illumination field.

Since crossties are thick, the spectra of the x-ray tube should have as high of an average energy as possible or be as ‘hard’ as possible without sacrificing fan beam illumination intensity and speed. This is accomplished by selecting a tube with Iron and Copper windows instead of Beryllium or Aluminum windows because the higher atomic number materials will absorb most of the low energy x-rays. This spectral characteristic reduces the amount of low energy x-rays scattering near the surface of the object and improves the backscatter signal fraction from deep within the crosstie.

The Comet MXR-452/Y x-ray tube weighs 100kg, has a maximum potential of 450kV, maximum power of 4500W, a target made of Tungsten 0.5mm thick on a Copper heat sink at angle of 30 degrees, a focal spot size of 5.5mm, a 90x20° degree emission field, and 2.3mm Fe + 1.0mm of Cu inherit filtration. Figure 3-2 is the product image of the MXR-452Y x-ray tube, Figure 3-3 shows the relative emission field, and Figure 3-4 shows the tube internal construction and materials.

The focal spot is the area on the anode target within the x-ray tube where the accelerated electron beam strikes to create x-rays. Figure 3-5 shows the small and large focal spot pictures of the MXR-452Y x-ray tube. Focal spots are not circulate or uniform because the accelerated electron beam isn’t emitted from a point source or perfectly focused onto the target. To make a narrow fan beam it is necessary to select a
tube with an appropriately narrow focal spot. Relative to the resolution goal for wood
crosstie inspection, both the small focal spot and the large focal spot are small enough.
However, overall x-ray tube life is reduced when the focal spot power density is
increased and the small focal spot is used instead of the large focal spot. Knowing the
size and distribution of the focal spot is important for designing an optimal beam forming
collimator.

**Beam Forming Collimator**

The fan beam is created by utilizing the full 90° degree radial field of view and
restricting the 20° degree axial field of view. Lead and/or Tungsten is used as a beam
forming collimator to reduce the 20° field to less than 1°. This aperture controls the width
of the fan beam, the width of the illumination spot on the object, and also
resolvability/resolution perpendicular to the plane of the fan beam. It is difficult to
resolve features in objects which are smaller than the illumination spot size. The
aperture of the beam forming collimator should be sized such that it is approximately the
same size as the focal spot of the x-ray tube. If the aperture is smaller than the focal
spot, the aperture will reduce the beam intensity and potential backscatter signal. If the
aperture is larger than the focal spot, the beam will have more intensity, a larger
illumination spot, and be less able to resolve object features. Figure 3-6 shows
examples of a lower intensity higher resolution beam forming collimator, an ideal beam
forming collimator, and a higher intensity lower resolution beam forming collimator.

The focal spot of the x-ray tube can typically be between 1mm and 6mm in size.
The collimator is sized to be thick enough that it can entirely block the highest energy
photons of the x-ray spectra. Figure 3-7 shows the measured signal intensity of the fan
beam as sheets of lead were used to attenuate it. The measured half value layer
thickness of lead for the MXR-452Y x-ray tube at 450kV is 0.484cm. The length of the beam forming collimator aperture/slot was selected to provide the desired illumination spot size on the surface of the object. For wood crosstie inspection applications a beam width of 0.5in (12.7mm) at the crosstie surface was selected as the imaging resolution.

**Crosstie Illumination Characteristics**

The fan beam created by the beam forming collimator has a number of unique illumination characteristics. Although the x-ray tube emissions are fairly radially symmetric within the 90° degree field of view, when illuminating a planar target like a crosstie the edges of the fan beam are farther away from the focal spot of the x-ray tube. This property results in the center of the crosstie being illuminated more than the edges of the crosstie. Also, the edges of the fan beam are not entering the crosstie perpendicular but instead at a 45° degree angle from the normal to the crosstie surface plane. For minimizing the x-ray scatter field at the track fouling boundary the edges of the fan beam would illuminate part of the tie plates but not any part of the rail itself.

In the direction of travel the fan beam is a narrow curtain of x-rays which has a Gaussian profile. The Gaussian profile develops because the focal spot is an area, not a point, and the beam forming collimator has a finite length. Since crossties have vertical boundaries between the wood and the ballast it was important to ensure that the fan beam was exactly perpendicular to the crosstie surface so that the leading and trailing edge of each tie could be identified. In the direction of travel if the fan beam was not normal to the surface the boundaries between ballast and wood would be difficult to resolve.
Detecting the Scatter X-ray Field

The fan beam illumination between the rails results in an x-ray field scattering from within the wood crosstie. A 1D profile could be created by using a single detector with one large detector element to sample the x-ray backscatter field. In order to create a 2D image a detector with a linear array of detection elements parallel to but offset from the x-ray fan beam must be used. The detector type, design, geometry, placement, and collimation are the most critical aspects of forming high quality images at high speeds using fan beam illumination.

Detector Type and Position

The detector selected for this application is made by X-scan Imaging Corporation as a custom adaptation of their transmission radiography linear detector arrays. The linear detector array is 1.477m long and contains 864 CsI:Tl crystals which are 1.6mm long, 11mm wide, and 4.5mm thick arranged in 27 modules of 32 detector elements. A thickness of 4.5mm was selected to absorb a significant fraction of the backscatter spectra. For optimal light collection the sensor area should match the area of the crystal. The total length spans the rail gauge and allows for the sampling of the x-ray backscatter field. Figure 3-8 is a cross section of the detector with the scintillator crystal array and FOV highlighted. Future iterations of the detector will be designed to optimize the x-ray backscatter field collection and maximize the signal to noise ratio.

Although the detector could be placed at many locations relative to the beam and track, the optimal location is as close to the fan beam as possible. The Klein-Nishina scattering cross section becomes larger as the detector is closer to normal to the crosstie surface. As the angle formed between the fan beam and detector field of view becomes larger resolving vertical features such as tie boundaries becomes difficult.
However, since it is impossible to place a detector within the fan beam, any image formed from a single detector will have a slight imaging angle. One way to correct for this is to add the signal from second detector at a symmetric location on the opposite side of the beam. The total signal available for image formation scales linearly with the number of detectors sampling the backscatter field.

**Segmented Collimation**

Each detector has a unique field of view or perspective of the backscatter field. Without collimation each detector of the linear detector array would detect x-rays scattered from any point within the crosstie. To form a 2D image collimation must be added to each detector element such that only x-rays originating from directly in front of each detector element are measured. To accomplish this a linear array of collimator fins must be added to the front face of the detector. The length and pitch of the fins create a solid angle which when projected onto the crosstie surface approximate the resolution of the system perpendicular to the direction of travel.

The detector collimator fins must be thick enough to eliminate cross scatter, and with the correct length/pitch geometry relative to the detector crystals to produce images of the appropriate resolution. The fins are made of attenuating elements such as Lead or Tungsten maximize the absorption of scatter from outside of the detector element’s FOV while minimizing the fraction of the front face of the detector which is blocked. Figure 3-9 shows which scattered x-rays can reach the detector without collimation fins, with collimation fins, the FOV, and the resulting virtual focal spot. Given a fin to detector element length $l$, a detector element pitch $p$, and a collimator to object distance of $d$, the approximate resolution at the object surface is given by $R$. 

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The system scan speed is determined by the available signal, detector acquisition rate, and resolution requirement in the direction of travel. The signal integration time is inversely proportional to the number of lines acquired per second. The detector can operate at line acquisition rates up to 8000 lines per second. The detector operates in current mode so the accumulated signal will increase or decrease proportional to integration time. For this system a line rate was selected based on the desired resolution and maximum scan speed. The goal is to ensure that at least one line will be acquired for each segment of the track travelled. Since the desired resolution is approximately 0.5" (12.7mm) and the maximum speed of the system is limited to 25mph by the FRA for the selected vehicle platform a minimum line rate of 808Hz is necessary. Table 3-1 contains a set of desired resolutions, scan speeds, and required line rates (in Hz). Without an adequate line rate small segments of the scan will be missing or under-sampled. For the desired combination of speed and resolution the detector is operated at 1000Hz to over-sample the track.

Table 3-1. Detector Acquisition Rates.

<table>
<thead>
<tr>
<th>Scan Speed (mph)</th>
<th>Scan Rate (Hz) vs Resolution (in)</th>
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<tbody>
<tr>
<td></td>
<td>0.25&quot;</td>
</tr>
<tr>
<td>1</td>
<td>70</td>
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<tr>
<td>5</td>
<td>352</td>
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<td>10</td>
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<td>1408</td>
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<td>25</td>
<td>1760</td>
</tr>
<tr>
<td>30</td>
<td>2112</td>
</tr>
</tbody>
</table>
Figure 3-1. AAR Railroad Plate-C envelope. [2]
Figure 3-2. Picture of the MXR-452/Y, Photo courtesy of Comet X-ray Group, http://www.comet-xray.com/Products/X-Ray-Tubes/MXR-452-Y. [16]
Figure 3-3. MXR-452Y 90x20° field, Photo courtesy of Comet X-ray Group, http://www.comet-xray.com/Products/X-Ray-Tubes/MXR-452-Y. [16]
Figure 3-4. Tube materials for modeling and simulation, Image courtesy of Comet X-ray Group, http://www.comet-xray.com/Products/X-Ray-Tubes/MXR-452-Y. [16]

Figure 3-5. Focal spot pictures of the MXR-452/Y, Photo courtesy of author. [16, 17]
Figure 3.6. Beam forming collimators.

Figure 3.7. Measured attenuation of 450kV spectra by lead.
Figure 3-8. Scintillator crystal location and FOV, Image courtesy of X-scan Imaging Corporation. [18]
Figure 3-9. Scatter Detector Segmented Collimation.
CHAPTER 4
2D FAN BEAM SYSTEM DEVELOPMENT

In the development of the 2D fan beam system simulations were valuable for guiding design decisions. A simplified system model was created using MCNP to simulate the x-ray backscatter radiography process and study imaging performance. MCNP simulations allow for the rapid testing of system variations without the need to physically build multiple prototypes. Simulations are necessary for some regions including the primary fan beam because radiation intensity is too high to safely or directly measure. The information learned from simulations can guide design decisions while reduce prototyping costs and time.

**MCNP Simulation Model**

The MCNP 2D fan beam imaging model consists of an x-ray tube, beam forming collimator, railroad track segment, linear detector array, detector collimation, scatter field shielding, and the tallying necessary for scatter field measurements. The MCNP geometry model contained many important simplifications of the geometry which would optimize simulation speed without impacting accuracy.

**Railroad Track Geometry**

Railroad tracks are made by placing two rails set 4’ 8.5” apart on top of steel tie plates. The steel tie plates are fastened to wood crossties using steel spikes. The crossties are placed on top of ballast and surrounded by ballast but not covered by ballast. The MCNP model attempts to accurately simulate real track geometry in the simplest way possible. Instead of modeling the curves and contours of the rail, each rail was modeled as a stack of three solid rectangular volumes representing the rail base, rail stem, and rail head. The rail stem was modeled to be as thick as the thinnest portion
of a real rail stem. The tie plates were modeled as a single rectangular plate without spike holes or surface slopes. The tie plate and rail volumes were filled with Iron at a density of 7.8g/cc. Instead of using a computationally complex randomly generated set of volumes representing each rock, ballast was modeled as a uniform material but the density was reduced proportional to the ballast packing fraction. For accurate estimates of scatter streaming under the rails, the model includes an air gap between the ballast surface and rail base between crossties. The crossties are modeled as standard 7” tall 9” wide 9’ long homogeneous wood material with an average density of 0.7g/cc. Figure 4-1 shows a side view of the rail, tie plate, crosstie, and ballast volumes in the geometry model.

**Crosstie Flaw Geometry**

Within selected crossties voids were inserted to simulate void defects. These flaws represented a range of sizes, depths, and positions. In the MCNP simulation, three crossties included voids which were 0.75”, 1.5”, and 2.25” in height at a variety of depths. The probability of detecting flaws as a function of depth can be determined from the signal change of void regions. The approximate resolution of the system can be determined from the edges between void and solid regions. By changing the maximum energy and filtering of the x-ray tube an optimal x-ray spectra can be selected. By changing the segmented collimator thickness, length, and pitch an adequate resolution can be achieved without over-collimating the backscatter field. Figure 4-2 shows a cross section of the flaws modeled within three crossties. In the first crosstie there are seven 0.75” voids each at a different depth. The second crosstie contains six voids which are 1.5” in height at overlapping depths. The third crosstie contains five 2.25” tall voids at overlapping depths.
The dimensions and positions of these void patterns were selected because they could also be fabricated into real wood particleboard targets. Direct comparisons between MCNP simulations and proof-of-concept measurements can be made by using the same void defect patterns and the same crosstie material density. Figure 4-3 is a picture of MCNP simulated void patterns fabricated into calibration target crossties.

**X-ray Tube and Beam Forming Collimator Geometry**

The x-ray tube would be one of the most complicated components to completely model but fortunately only the target, target angle, cylindrical window/filter materials, and beam forming collimator are critical for an accurate simulation. Figure 4-4 shows a picture of the x-ray tube and beam forming collimator used for the prototype 2D fan beam x-ray backscatter system. The beam forming collimator was made using two blocks of lead with a smooth flat face supported by steel. Each half of the collimator was attached with threaded rod for adjusting the beam forming collimator gap.

Within the x-ray tube, the target is made of Tungsten at a 30° angle. It was modeled as a solid cylinder with its center at the focal spot location. The window of the x-ray tube is a 1.0mm thick cylinder of Copper inside of a 2.3mm thick cylinder of Iron. The windows must be modeled as cylinders to avoid significantly changing the beam path length through the windows, beam intensity, and beam spectra at the edges of the fan beam. Since the x-ray tube was shielded to conservatively meet radiation safety regulations, the x-ray tube boundaries modeled as void volumes of 0 photon importance. Within MCNP, any particle which encounters the surface of a volume with 0 importance is terminated. This practice minimizes the amount of computational time spent tracking photons through thick shielding materials. The beam forming collimator was created as a perfect absorbing void region with a gap equal to the focal spot width.
Figure 4-5 shows side views of the x-ray tube model, filters, and beam forming collimator.

The x-ray tube model was elevated such that the edges of the fan beam would only slightly intersect the inner edges of the rail base. This allowed for the tube to be placed as close as possible to the crosstie by using the full 90° illumination field. An x-ray tube with a smaller illumination field would have to be located farther from the crosstie surface and would result in less illumination intensity. Figure 4-6 shows the fan beam illumination field area between the rails.

**Detector Array and Segmented Collimator Geometry**

The detector array and segmented collimator are located as close to the crosstie surface as possible without causing the collimator to violate the Plate-C physical boundaries. The backscatter field intensity is highest closest to the illuminated crosstie. The detector was placed as close to the fan beam plane as possible without blocking the fan beam to provide a near-vertical perspective to discern vertical features such as tie boundaries. As the scatter perspective increases in angle relative to the fan beam plane the vertical crosstie edges would be blurred. To reduce angular scatter perspective two linear detector arrays can be symmetrically located on both sides of the fan beam. A weighted combination of these two perspectives can result in a 2D images which appear to be from the same plane as the illumination fan beam. Figure 4-7 shows the detector array region centered above the Plate-C boundary and below the beam forming collimator.

The segmented collimator for the linear detector array was modeled as an alternating set of shielding and air volumes. Shielding materials modeled include Lead, Tungsten, and a perfect absorbing void. The 2D imaging resolution was investigated by
changing the segmented collimator array material, length, thickness, and pitch. Figure 4-8 shows an example model of the segmented collimator array inside of the detector enclosure above the Plate-C boundary above the rail.

The prototype collimator was constructed from balsa wood and thin lead sheets. Balsa wood was selected because it’s low density, low average atomic number, and relative transparency to scattered x-rays. The collimator was 2.5” tall, 3.0” wide, and 60” long. The collimator was filled with lead fins which were 3/64” thick and separated by 1/8” air gaps created by balsa wood spacers. Figure 4-9 shows how the lead fins were stacked within the box to form the full-length prototype segmented collimator array. Figure 4-10 is a picture of the completed collimator.

**Mesh Tallies of the Simulation Geometry**

In the MCNP simulation, tallies are a method of recording information about the simulation. A single tally can be used to record information about the particles which are traveling through a surface or volume. When recording information about a single surface or volume isn’t adequate a mesh tally can be used. A mesh tally superimposes a single or multi-dimensional grid onto the simulation space and records this information into an output file. To simulate the x-ray fan beam backscatter imaging process combinations of 1D, 2D, and 3D mesh tallies were applied to regions of the simulation model.

Two types of mesh tallies were used to measure aspects of the fan beam. The first mesh tally measures the total energy of all particles crossing through each mesh of a 2D array. Each volume in the mesh is 2cm long, 1cm wide, and 1cm high. The 2D set of $1\text{cm}^2$ measurements was used to make a 2D image of the radiation intensity in the fan beam plane. From this tally the intensity variation at the surface, the penetration of
the fan beam, and the scatter field were simulated. The second mesh tally is a 2D counting array at the opening of the beam forming collimator. The first dimension of this array is a set of 1D tallying volumes along the beam forming collimator. The second dimension is 450 groups of energy information where each group is used to record spectral information for 1keV ranges. This tally is primarily used to generate normalized x-ray fan beam spectra. Figure 4-11 shows the location of the fan beam tally at the opening of the beam forming collimator.

An additional two mesh tallies are used to measure aspects of the scatter field. The first scatter field tally is a full 3D volumetric tally with 1cm³ voxels throughout the entire volume. This tally allows for the measurement and visualization of the scatter x-ray field in all possible directions to the boundaries of the simulation. The second mesh tally is a 1D array of volumes at the same location as the CsI scintillation crystals within the LDA. This mesh is separated into 864 volumes with 1, 2, and 4 energy groups. This tally is used to simulate the ideal signal measured by the X-scan LDA. Figure 4-12 shows the mesh location within the detector case.

**Source Definition**

Every MCNP simulation uses a radiation source definition to initialize the position, direction, energy, and type of each particle of the simulation. Although many reference spectra are available for medical and industrial sources between 20keV and 225keV there was no reliable x-ray spectra previously published or from the manufacturer at the higher energies and larger target angle. To generate an accurate x-ray spectra MCNP simulations were created with an electron beam disk source 1cm in front of the target directed at the angled target surface. Figure 4-13 is an example
image of the x-ray field resulting from an electron beam directed at the target within the x-ray tube.

By tallying the photons which reach the opening of the beam forming collimator in Figure 4-11 using an energy mesh with 1keV wide bins accurate spectra was computed. Computing each spectra is very computationally expensive because electron transport requires many thousands of interactions for each source particle. During this step to improve the computational efficiency of the spectra generation x-ray tube window materials were omitted.

Next, the resulting x-ray spectra was attenuated by the x-ray tube window materials. The Cu+Fe window materials were included in the simulation and the source definition was changed to an x-ray source with the previously computed spectra originating isotopically from a disk centered at the x-ray tube focal spot, with a diameter of the x-ray tube focal spot, and offset 0.001cm from the surface of the angled x-ray tube target. By setting the source disk close to but not touching the target surface MCNP particle creation and tracking problems were avoided. By tallying the photons which reach the opening of the beam forming collimator into 1keV wide energy bins accurate filtered spectra were obtained.

Although an isotropic photon source is much more computationally efficient than an electron beam source, a vast majority of the photons created on the focal spot will terminate within the x-ray tube box and never exit the beam forming collimator. Therefore, the isotropic focal spot source was replaced with a fan beam source definition. The fan beam source definition creates x-rays at positions randomly sampled on the focal spot disk but limits the angular distribution about a beam vector directed at
the beam forming collimator opening. This results in a computationally efficient and accurate MCNP 90° x-ray fan beam source in \( \frac{90°}{360°} (2\pi) \) circular geometry not \((4\pi)\) spherical geometry. Figure 4-15 shows an example image of a directed x-ray source originating at the focal spot directed towards the beam forming collimator gap.

Figure 4-16 shows the resulting filtered x-ray spectra at the opening of the beam forming collimator for a range of potentials. As the energy of the electron beam is increased the average x-ray energy, peak x-ray energy, and the total number of x-rays which have penetrated the windows increases. Because of the attenuation by the Copper and Iron windows the minimum energy of each distribution is approximately 50keV independent of the maximum x-ray energy. Variations in each spectra are due to random variations in the tallying statistics from the Monte Carlo simulation.

**Source Spectra Validation**

Because the x-ray fan beam is a very intense source of radiation it is difficult to directly measure the x-ray spectra to verify simulation results. Instead, the penetration characteristics of the spectra can be measured to determine the accuracy of the MCNP generated spectra. To measure the penetration characteristics of 450kVp and 300kVp spectra 1/16" sheets of strongly attenuating lead were placed between the x-ray source and a detector. The peak intensity of the x-ray fan beam was recorded as sheets of lead were stacked to block the x-ray fan beam. The predicted attenuation was computed by integrating the individually attenuated energies of the entire spectra using energy dependent lead attenuation cross sections from NIST XCOM. [11] Figure 4-17 is a photograph showing how the primary beam profile and intensity changed as lead sheets were used to attenuate the beam. Figure 4-19 shows the measured vs predicted
normalized signal intensity as a function of lead shield thickness for a 450kVp and 300kVp spectra.

Within the sampling error of the transmission linear detector array, the predicted x-ray attenuation characteristics of the MCNP generated spectra match the measured attenuation characteristics from the x-ray tube spectra at 300kVp and 450kVp. This agreement indicates that the simulated x-ray spectra are accurate representations of the actual x-ray spectra produced by the MXR-452Y tube at more than one peak energy.

**Backscatter Spectra**

Determining the backscatter x-ray spectra from a solid wood crosstie is important for optimizing the scintillator material and thickness of the linear detector array. Since it is difficult to obtain a spectra from a very high radiation area an MCNP simulation can be used instead. The fan beam should be illuminating the center of a wood crosstie to maximize the backscatter field intensity. Figure 4-19 shows the normalized x-ray spectra and predicted backscatter spectra at the linear detector array of a 300kVp illumination fan beam.

The backscatter spectra ranges between 25keV and 155keV. The detector has a 1mm thick Aluminum window which attenuates most of the scattered photons below 25keV in energy. Higher energy photons between 75keV and 155keV are very likely to have only scattered once within the object and are most important for maximizing the resolution of the backscatter system. Photons between 25keV and 75keV are much more likely to have scattered more than once losing correlation to the location of the first Compton scatter event. Because it’s not possible to track the exact path of multi-scatter
low energy photons, they are less important for image quality and reduce the effective system resolution by contributing to blurring within the image.

As the length of the scintillator crystals are increased, the area sampling the backscatter field and the resulting signal intensity is proportionally increased. The length of the crystals should be maximized within manufacturing capabilities. Based on manufacturing limitations, the crystals were 10.5mm long presenting a detection area of 16mm$^2$ per crystal. In total, 864 detector elements had a total detection area of 138.2cm$^2$. Figure 4-20 shows the beam and backscatter spectra on a per-source-particle absolute scale. Backscatter radiography at a large standoff distance is an extremely inefficient process with an average backscatter signal intensity which is 5 to 6 orders of magnitude less than the illumination intensity. In this geometry, for every 1,000,000 photons in the x-ray fan beam, between 9 and 10 will reach the small sampling area of the linear detector array.

Based on the backscatter spectra, the scintillator crystals should be sized to maximize the absorption of the highest energy backscatter photons. A 4.5mm thick CsI:Tl scintillator crystal will absorb approximately 70% of the highest energy 160keV backscatter photons. The same crystal will absorb approximately 98% of backscatter photons at 100keV. Figure 4-21 shows the fraction of photons which would be absorbed by various thicknesses of CsI scintillator crystals.

**Automation for Simulated Image Formation**

The x-ray tube, beam forming collimator, and detector can form a 1D profile of the object illuminated by the fan beam. To simulate the formation of a 2D many MCNP simulations in the travel direction of the scanning system are necessary. Manually creating each input file is not practical so each MCNP input file is generated by a single
python script. The python script increments the position of the x-ray tube, focal spot, source definition, beam forming collimator, and detector while leaving the crossties, ballast, rails, and tie plates stationary. The python script also needs to ensure each MCNP simulation is seeded with a unique pseudo-random number generation seed. For each MCNP input file generated a corresponding cluster job submission script was also written. Once the simulations were complete additional python scripts were used to collect the results from each meshtally file and assemble each 1D meshtally result into a 2D image. Figure 4-22 is an example of a simulated scan of 8 crossties created from 380 MCNP simulations using between 5B and 10B particles per simulation spaced 0.5” apart representing 190.0” of scan length. The unique random number seed ensures that horizontal streaking artifacts aren’t created in the simulated image.

Each crosstie can be easily identified because the strongly absorbing steel tie plates at each end of the crosstie. The first through fifth crossties have wood densities of 100%, 75%, 50%, 25% and 0% respectively. Although the first crosstie has the highest signal return, the influence of the angled scatter detector perspective can be seen in the darker leading edge, the brighter trailing edge, and slight gradient within the crosstie. Three sets of four lead line pair strips of 1.0”, 0.5”, and 0.25” width and 1/8” thickness were placed on the third ballast region and third crosstie. From these line pairs the segmented collimator allows for the resolution of 1.0” line pairs and 0.5” line pairs but field of view of each detector element is not limited enough to resolve the 0.25” line pairs. Also, the third crosstie at approximately 50% theoretical wood density or 0.35g/cc results in a backscatter signal approximately equal to the ballast. The fifth crosstie is essentially a hole where x-rays are only scattering off of the ballast rock.
approximately 7” below the crosstie surface. In part of this area where the return path of
the scattered x-rays is attenuated by ballast the scatter signal is less than that of steel.
When ballast doesn’t attenuate the return path to the detector more signal will reach the
detector from the ballast beneath the crosstie than from the steel tie plates.

The final three crossties, numbers six, seven, and eight contain the void patterns from Figure 4-2. These crossties allow for an estimated probability of detection of void flaws as a function of size and depth. In crosstie six a 0.75” void can be visually
detected within the image at a depth of 3.0”. In crosstie seven a 1.5” void can be
visually detected at a depth of 3.75”. In crosstie seven a 2.25” void can be visually
detected at a depth of 4.5”. Automating the creation of MCNP input files using python
scripting is essential simulating a translating system for scatter radiation imaging
methods.

**Collimator Geometry and Image Quality**

**Simulated Image Features**

In each simulated image of crosstie flaws the collimator fin length, thickness, and
material composition directly affect image quality and the probability of detecting
features within each image. X-ray spectra peak energy is the primary factor contributing
to depth of penetration into a crosstie and the ability to resolve flaws in the bottom half
of a crosstie. The x-ray fan beam width directly effects the resolution of the system in
the direction of travel. The geometry and composition of the segmented collimator linear
detector array directly affect the spatial resolution of the system perpendicular to the
direction of travel. The sample rate of the detector and the efficiency of the linear
detector array for a given collimator geometry directly affect the maximum speed of the
inspection.
**Varying Collimator Length**

The length of the segmented collimator array affects two aspects of image formation. As the fin length is increased the effective field of view of each detector element is reduced. A reduced field of view increases the resolution of the system perpendicular to the direction of travel. Additionally, longer fins increase the probability of blocking scattered x-rays from outside of the field of view effectively reducing the blurring effect perpendicular to the direction of travel. However, by gaining resolution and reducing blurring more x-rays are absorbed, less x-rays reach each detector element, and the amount of signal detected is reduced. To isolate just the detector collimator fin length effects on image quality each collimator fin is composed of a perfect absorber to block all photons of any energy which touch the fin surface. Figure 4-23 is a combination of 3 image formation simulations using one MCNP simulation per line in each image. Each image was formed by combining 130 MCNP simulations which used an x-ray spectra with a peak energy of 325keV to inspect 3 crossties with 0.75”, 1.5”, and 2.25” void patterns.

When all 3 image formation simulations are combined on the same scale the reduction in total signal intensity with longer fin lengths is apparent. 1” collimator fins result in a much higher signal by reducing feature resolvability. 2” and 3” long collimator fins create smaller fields of view which block more x-rays to improve resolution. Figure 4-24 shows a histogram of the images in Figure 4-23.

In Figure 4-24 the 1” long collimator fins result in a distribution of values between 2.75e-8 and 3.75e-8. The peak at 3.0e-8 corresponds to the signal return of the ballast and the signal return at 3.5e-8 corresponds to the increased signal return of solid wood. The grading region for wood crossties occurs between the signal return of solid wood
crossties and the signal return of ballast material. The 2" long collimator fins result in approximately half the signal of 1" long collimator fins. The 3” long collimator fins result in approximately one third of the signal return compared to the 1” long collimator fins. In each of these distributions the crosstie to ballast signal ratio is approximately the same just scaled to lower signal levels as collimator fin length increases. Figure 4-26 shows the resulting images of each collimator fin length scaled relative to its grading region.

When each image is individually scaled the voids in each crosstie, the boundaries of each void in the perpendicular direction, and the steel tie plate boundaries are much more resolvable. In all three images the 2.25” thick voids are visible and detectable. The longer 2” and 3” collimation fins were necessary to resolve smallest 0.75” thick voids at the deepest parts of the crosstie. Figure 4-25 shows the scaled crosstie profile of the smallest 0.75” thick void flaws.

The 0.75” thick void patterns represent the most difficult to resolve voids within a crosstie. For a 7.0” thick crosstie a 0.75” void represents an 11% density loss. When the void is near the surface at crosstie position 45.0” the measured drop in signal is approximately 13%. When the void is 5.5” deep in the wood the 0.75” void only results in approximately a 4% signal reduction. Because the 1” long collimator fins result in more blurring the 0.75” void flaws are less resolvable from the neighboring solid wood crosstie segments. The profiles of the 0.75” void flaws from the 2” and 3” collimator fin lengths are nearly identical which indicate that for crosstie scanning applications collimator fins longer than 2” will only result in a reduction of signal without significantly increasing resolution.
Varying Collimator Material

The segmented collimator array material affects the likelihood of blocking scattered x-rays from outside each field of view. Materials which strongly absorb scattered x-rays improve the resolution of the array by reducing the blurring effect perpendicular to the direction of travel. If low attenuating materials are used for collimation fins the amount of scattered x-ray energy is higher, however less of that signal originates exclusively from within the desired field of view. If strongly attenuating materials are used for collimation fins the detected signal is reduced but a higher fraction of the detected signal originates from within the field of view. To isolate just the detector collimator fin material effects on image quality the collimator fin length was fixed at 2” long and the fin width was fixed at 30% of the collimator fin pitch. Collimator fins composed of Iron, Lead, Tungsten, and perfect attenuating void were used in the image formation simulations shown in Figure 4-28. Each image was formed by combining 130 MCNP simulations which used an x-ray spectra with a peak energy of 325keV to inspect 3 crossties with 0.75”, 1.5”, and 2.25” void patterns.

Because iron has a much lower cross section and absorption likelihood the total signal is much higher, however the blurring effect significantly reduces image resolution. In Figure 4-28 the lead, tungsten, and void collimator fins have nearly identical imaging performance because each is a strong attenuator for a wood backscatter spectra. Figure 4-27 shows the images formed by only the strongly attenuating collimator fins excluding iron.

The line profiles of the 0.75” void flaws within the first crosstie of each segment further verify that the strong absorbers are nearly identical but a lighter lower-Z element like Iron results in poor imaging performance. Figure 4-29 shows the normalized 0.75”
void patterns for iron, lead, tungsten, and ideal perfect absorbing segmented collimator fins.

**Varying Collimator Thickness**

The collimator thickness affects the total detector area and the likelihood of blocking scattered x-rays from outside of each field of view. For strongly absorbing collimator fin material the optimal resolution when the collimator fin thickness is able to block more than 90% of scattered x-rays from outside the field of view. However, beyond this point further increasing the thickness of each collimator fin will reduce scatter signal without significantly improving imaging performance. Using lead collimator fins and a 320kVp x-ray fan beam spectra 3 collimator fin thicknesses were modeled representing 3 coverage fractions. Figure 4-30 shows an image of crosstie flaws generated from lead collimator fins which are sized to be 10%, 30%, and 50% of the collimator fin pitch.

Because lead is a strongly absorbing material and the backscatter spectra is relatively low in energy fins which are 10% of the collimator pitch in thickness adequately block a majority of the scatter signal from outside each detector element field of view. Further increases in the collimator fin thickness reduce the backscatter signal without significantly increasing the system imaging performance. Figure 4-30 shows a histogram of Figure 4-31.

In Figure 4-31 the three distributions correspond to each of the three fin thicknesses. The 10% pitch fin thickness has the highest signal because it covers the smallest fraction of the detector area. Collimator fins which are 30% of the fin pitch have approximately 25% lower signal but the same high quality imaging performance. Collimator fins which are 50% of the pitch have approximately 40% less signal without...
any noticeable gain in imaging performance. Although thicker fins reduce the signal, each image has a high quality and adequate contrast between ballast signal and wood crosstie signal. From this investigation it can be concluded that fin thickness should be approximately 10% of the detector element pitch. Collimation fins should be made as thin as possible while still ensuring that a vast majority of scattered x-rays originating from outside of each field of view are attenuated.

**Proof-of-Concept System**

Modeling and simulation methods are a critical first step to drive proof of concept system development. Using the principles of 2D fan beam backscatter radiography a proof of concept test track and prototype system was constructed. Two segments of test track were constructed which included new solid wood crossties, removed from service degraded crossties, composite crossties, concrete crossties, and concrete slabtrack. These test tracks allowed for controlled full scale testing of fan beam illumination and segmented collimator testing. Full scale testing was also critical to measure scatter radiation field intensities and to verify safety shielding configurations exceeded regulatory limits and reached ALARA goals. Figure 4-32 shows a picture of the test tracks.

The proof of concept system was built onto a trailer cart which also had retractable hi-rail wheels. A configurable gantry space in the center of the cart allowed for dynamically positioning the x-ray tube at any point between the rails and at many heights. The research cart also contained the high voltage generators and x-ray tube cooling equipment. Figure 4-34 shows the research cart with the x-ray tube, linear detector array, power systems, and cooling system. The x-ray tube is contained and
shielded within the blue box and the linear detector array and segmented collimator was located as close as possible to the crossties while maintaining Plate-C compliance.

Testing confirmed that these 2D methods could produce images of internal features within crossties. Figure 4-33 shows a sample image of three crossties in the test track segment. The third crosstie is mostly solid except for a small crack. The first crosstie shows significant segregation and material loss. The first crosstie was selected for destructive examination to verify the proof of concept system was accurate. Figure 1-2 is an image of that destructively examined crosstie. These proof of concept investigations applied the modeling and simulation efforts confirming the 2D fan beam methods could be brought to production.

**Aurora Xi Production System**

Information learned from the proof of concept research cart system and test track studies were applied to the development of the Aurora Xi system. Aurora Xi combined the Aurora laser surface scanning system with 2D fan beam and segmented collimator x-ray backscatter methods. Figure 4-35 shows an image of the completed Aurora Xi production system. The system was designed to deploy out of the back of a Hi-Rail equipped vehicle and operate at speeds up to the FRA vehicle platform limit of 25mph. x-ray tube and scatter radiation shielding was included in the system design to ensure regulatory compliance for all radiation fields.

Figure 4-36 shows a closer view of the Aurora Xi system including the shielded 2D fan beam backscatter system and laser surface scanners. The x-ray tube is contained within the shielded cylinder centered between the rails and the segmented collimator linear detector array is contained within the scatter field shielding enclosure.
The white enclosure contains solid radiation shielding and the black flaps contain flexible radiation shielding materials.

Figure 4-1. Railroad model side view.

Figure 4-2. Void patterns within three crossties. A) Seven 0.75" thick voids. B) Six 1.5" thick voids. C) Five 2.25" thick voids.
Figure 4-3. Fabricated crosstie void patterns, Georgetown, Texas, 2015. Photo courtesy of author. [17]

Figure 4-4. Photograph of x-ray tube and beam forming collimator, Gainesville, Florida, 2014. Photo courtesy of author. [10]
Figure 4-5. X-ray fan beam source model. A) X-ray source above the crossties. B) X-ray target and beam forming collimator.

Figure 4-6. Fan beam illumination within the rail gauge.
Figure 4-7. Segmented collimator detector position.

Figure 4-8. Segmented collimator fins and LDA near the rail.
Figure 4-9. Prototype segmented collimator construction method, Georgetown, Texas, 2015. Photo courtesy of author. [17]

Figure 4-10. Completed prototype collimator, Georgetown, Texas, 2015. Photo courtesy of author. [17]
Figure 4-11. Fan beam tally location inside the beam forming collimator.

Figure 4-12. Tallying array at the CsI scintillator inside the LDA.
Figure 4-13. Example of using an electron beam for x-ray production.

Figure 4-14. Example of an isotropic x-ray source originating at the focal spot.
Figure 4-15. Example of a circular x-ray source originating at the focal spot.
Figure 4-16. Filtered x-ray spectra between 225kV and 425kV
Figure 4-17. Measuring primary beam attenuation through lead sheets, Georgetown, Texas, 2015. Photo courtesy of author. [17]
Figure 4-18. Predicted versus Measured attenuation curves in lead for 450kVp and 300kVp spectra.
Figure 4-19. Normalized 300kVp beam spectra and wood crosstie backscatter spectra.
Figure 4-20. Absolute 300kVp beam spectra and wood crosstie backscatter spectra.
Figure 4-21. Fraction of backscattered photons absorbed by CsI:TI scintillators.
Figure 4-22. Simulated image formation.

Figure 4-23. Crosstie flaws with A) 1”, B) 2”, and C) 3” long collimator fins.
Figure 4-24. Histogram of the images formed by 1”, 2”, and 3” long collimator fins.

Figure 4-25. Normalized crosstie signal profiles of 0.75” voids.
Figure 4-26. Scaled images of crosstie flaws. A) with 1” collimator fins. B) with 2” collimator fins. C) with 3” collimator fins.

Figure 4-27. Crosstie flaws with A) lead, B) tungsten, C) and void collimator fins.
Figure 4-28. Crosstie flaws with A) iron, B) lead, C) tungsten, and D) void collimator fins.

Figure 4-29. Scaled 0.75" thick void patterns with iron, lead, tungsten, and void collimator fins.
Figure 4-30. Cross-tie flaws with lead fins which are A) 10%, B) 30%, and C) 50% of the detector array pitch.

Figure 4-31. Histogram of the image formed fins which are 10%, 30%, and 50% of the collimator pitch.
Figure 4-32. University of Florida test track segments, Gainesville, Florida, 2014. Photo courtesy of author. [10]

Figure 4-33. Sample image and line profile created by the research cart system.
Figure 4-34. Research cart proof-of-concept system, Gainesville, Florida, 2014. Photo courtesy of author. [10]

Figure 4-35. Aurora Xi production vehicle, Georgetown, Texas, 2015. Photo courtesy of the Georgetown Rail Equipment Company. [19]
Figure 4-36. Aurora Xi production system, Georgetown, Texas, 2015. Photo courtesy of the Georgetown Rail Equipment Company. [19]
Maximizing Fan Beam Intensity

One of the most important aspects of 2D fan beam image formation is the method used to align the focal spot and the beam forming collimator. Adequate illumination intensity is important for creating an image. This process is difficult because the exact focal spot is optically blocked by the x-ray tube window and the exact location is not marked on the x-ray tube. Furthermore, even for x-ray tubes of the same model the position of the focal spot within may vary up to 10mm relative to the housing. If the beam forming collimator is misaligned by more than the focal spot size the entire beam will be blocked. The beam forming collimator gap and alignment must be within 0.5mm of the focal spot size and position. An optimal alignment is necessary for maximizing the intensity and symmetry of the illumination fan beam.

The method for focal spot alignment is a multi-step process. First, the x-ray tube and beam collimator are mounted together. A linear detector array is oriented in the center of and perpendicular to the fan beam. The symmetry of the fan beam profile can be more accurately measured as the distance between the focal spot and LDA is increased. Figure 5-1 shows a picture of the beam forming collimator alignment method. Without moving the linear detector array the x-ray tube and beam forming collimator are moved in 0.5mm increments relative to each other. At each position an averaged line profile is recorded using a low-power fan beam with a max energy of 150keV and a maximum current of 2mA. The optimal alignment position will result in an illumination profile with the most symmetry and maximum integrated intensity. Figure 5-2 contains the fan beam illumination profiles at various offset positions.
The slopes of the leading and trailing edges of the fan beam are a strong indicator of beam symmetry and focal spot alignment. Figure 5-3 shows the integrated intensity of each profile relative to the optimal profile. A misalignment of 1.0mm could result in a reduction of the fan beam intensity by between 3% and 11% depending on offset direction. This asymmetry is caused by the non-uniform distribution of the focal spot. Figure 3-5 shows an example of the non-uniform creation of x-rays at the focal spot on the target and the measured offset of each focal spot within the expected target area.

**Electronic Background Subtraction**

The raw x-ray data cannot be viewed directly and must be processed into images which can be viewed or analyzed. Forming viewable images is a 5 step process. Since the acquired data is the combination of both the electronic background signal and the scatter x-ray signal, the first step is to subtract the electronic background. The electronic background of each detector in the array is acquired by averaging a large number of samples when the x-rays are off. The standard deviation of the of the electronic background was also determined. The electronic background signal of the detector and it’s standard deviation is shown in Figure 5-4.

The electronic background signal of the detector can vary between 4700 and 6500 units of a 16-bit range. Along the array the electronic background signal varies for each set of 32 pixels and 27 total modules. Differences in the shape profile of each module are caused by the circuit board layout of each module, variance in the quality of the electrical components of each module, and optical coupling between each sensor and scintillator. A histogram of the electronic background signal is shown in Figure 5-5.
Because backscatter radiography often has a very small amount of signal, the recorded signal may be much less than the electronic background for a pixel.

Normalizing Illumination Intensity

Because the radial fan beam illuminates a flat crosstie a geometric scaling factor is also applied after the electronic background is removed. The crosstie surface at the edges of the fan beam are farther from the focal spot than the crosstie surface in the center of the fan beam. A scaling factor is necessary to scale the illumination intensity of the radial fan beam scanning geometry. For a 90° fan beam, a rail gauge of 143.5cm (4’8.5”), and a focal spot height of 71.8cm, Figure 5-7 shows the applied scaling factor as a function of distance from the fan beam centerline.

After the electronic background signal is subtracted and the geometric scaling factors have been applied the average brightness of the ballast and the crossties in the center of the image and at near the rail will be similar. Figure 5-8 shows an example of the resulting image. The resulting image still contains streaks which must be removed by calibration and/or correction methods.

Streak Correction

After applying the previous steps there will still be strong streak artifacts in the image. This streaking is the result of the intrinsic efficiency variation of each pixel and collimator fin alignment variation. Streaking can be corrected by using a combination of static calibration and dynamic correction methods. The fundamental assumption of the static correction method is that a perfectly uniform object should have a uniform signal response. Calibration factors are generated by taking images of uniform density highly scattering materials at a range of energies. For railroad inspection blocks of wood
particle board with a very small particle size or polyethylene block were used as uniform scattering materials.

Dynamic correction methods use features within the image to correct for streaking. Over time, the electronic background of a detector can vary as a function of temperature or collimation fins can become damaged. Dynamic correction methods are important for correcting image streaks from these sources. The fundamental assumption of the dynamic streak correction method is that for a sufficiently long segment of railroad track the highest backscatter signals measured by each detector element should approach the same value. The dynamic correction factors can become less accurate for segments of track which are less than a mile long or do not include sufficient amounts of ballast.

**Histogram Creation**

To generate streak correction factors, a statistically significant scan length is used to create histograms of signal responses for each element in the linear detector array. For railroad inspection peaks will appear in the histograms corresponding to bridge gaps, steel crosstie plates, ballast, and wood crossties. Because of statistical variance in the signal, the histograms are smoothed by using a simple moving average. Figure 5-9 is an example of the streak correction histogram for detector element 462. Detector element 462 was selected because it is in the very center of the 864 element linear detector array.

**Cumulative Density Function**

Next, the simple moving average of each histogram is used to create a cumulative density function (CDF). The signal intensity corresponding to the 95th percentile of the normalized CDF is determined for each detector element. Figure 5-10
shows the CDF for the moving average in Figure 5-9. The 95\textsuperscript{th} percentile of the CDF of pixel 462 is 2090 units of signal intensity.

By using a CDF abnormal objects in the inspection area with lower signal responses such as mud, steel spikes, displaced plates, switches, crossings, and bridge gaps will not bias the streak correction method. The average 95\textsuperscript{th} percentile signal intensity of the middle 80\% of the LDA is also computed. Figure 5-11 shows the 95\textsuperscript{th} percentile signal intensity of each detector element and the average 95\textsuperscript{th} percentile signal intensity across the middle of the array. The brightest part of each CDF drops near the edges of the LDA because the fan beam illumination strip is slightly less than the length of the LDA.

**Streak Correction Factors**

The streak correction factor for a detector element is computed by dividing the average 95\textsuperscript{th} percentile signal intensity by the 95\textsuperscript{th} percentile signal intensity for each detector element. Figure 5-12 shows the streak correction factor required to scale the 95\textsuperscript{th} percentile signal intensity to the average 95\textsuperscript{th} percentile signal intensity. Pixel 462 has a scaling factor of 0.70517. Even with good detector elements these streak correction factors can vary widely because of electronic background signal drift, variance in detector element gain, collimator fin alignment, and fabrication quality. In each LDA there is a high likelihood of bad detector elements or misaligned collimator fins.

**Dark and Dead Pixel Correction**

When computing streak correction factors between 0\% and 5\% of the detector elements in a linear detector array have an abnormally low signal response. Low signal response pixels can be caused by bent collimator fins, bad electronics, or reduced
illumination near the edges of the fan beam. A low response pixel is defined by streak correction factors which are greater than 1.5. Before any other image formation methods are applied these pixels need to be identified and corrected. Replacing the data for a pixel with an average of adequate signal neighboring pixels is the best correction method. Correcting these pixels before the raw data is formed into images improves image quality. Figure 5-13 shows an example image after electronic background subtraction, dark pixel correction, and application of streak correction factors.

**Time to Space Domain Image Formation**

The final step in forming an image is to form an image in the spatial domain from the continuously acquired time domain detector data. The 864x1.6mm wide array of pixels can be collected into square aspect ratio pixels of a configurable size. Continuously acquired samples from the detector are accumulated and averaged for each segment or slice of the scan using the wheel encoder. Figure 5-14 shows an example of the 2D fan beam image formation method including focal spot alignment, electronic background subtraction, image normalization, dark pixel correction, streak removal, and finally time domain to space domain image formation.

Based on the requirements of scanning wood crossties, it was determined that any features smaller than 12.7mm (0.5") would not significantly affect crosstie integrity. Figure 5-15 shows a final image formed with 6.35mm (0.25") pixels and 12.7mm (0.5") pixels. The image formation process ensures that an image of the same resolution can be formed even if the track segment is scanned at different or changing speeds. Additionally, in the spatial domain these images can be aligned and correlated with laser surface profile scanning methods.
**Crosstie, Ballast, and Plate Detection**

The resulting images can then be algorithmically processed to detect crossties, flaws within crossties, ballast, and steel tie plates. The first step to detect these features is to create a ‘tie mask’ image. Portions of the image which have a signal 30% greater than the ballast signal average are marked as wood. Portions of the image which have a signal 30% less than the ballast signal average are marked as steel tie plates.

Because Iron has a higher atomic number and density than ballast, steel tie plates strongly absorb x-rays and result in very little backscatter signal. Crossties can then be found by using a set of many simple moving averages at different skew angles. Once the center of the crosstie and its skew angle is determined the width of each crosstie can be determined. Figure 5-16 shows an example of an image tie mask which includes crosstie and tie plate detection.

Using information about the location and geometry of each crosstie, the pixels within tie regions are copied to a new workspace for further analysis and processing. Individual crosstie parameters such as average density, percent material loss, density variance, and entropy can be computed. The crosstie-only image can be used to generate density line graphs both perpendicular and parallel to the rails. A gradient image can be generated for edge and flaw detection from the crosstie-only image data. Finally, once regions of interest are identified, the x-ray data can be combined with the laser surface profile for tie grading algorithms. Figure 5-17 shows an example of the crosstie detection and plate detection mask, an image gradient view, a greyscale image, colorized crosstie regions, and a crosstie average density profile.
Figure 5-1. Focal spot alignment, Georgetown, Texas, 2015. Photo courtesy of author. [17]
Figure 5-2. Beam forming collimator alignment profiles.
Figure 5-3. Beam forming collimator alignment relative intensity.

Figure 5-4. Detector electronic background signal and standard deviation.
Figure 5-5. Electronic background histogram.

Figure 5-6. Image before electronic background subtraction.
Figure 5-7. Fan beam geometric scaling factor.

Figure 5-8. Raw data with electronic background removed.
Figure 5-9. Streak correction histogram.

Figure 5-10. Streak correction cumulative density function.
Figure 5-11. 95th percentiles of each detector element.

Figure 5-12. Streak correction factors of each detector element.
Figure 5-13. Image streak removal and dark pixel correction.

Figure 5-15. Forming images of different resolution. A) Image with 0.25” pixels. B) Image with 0.5” pixels.
Figure 5-16. Tie mask creation. A) Original image. B) Tie mask (green) and plate mask (red) from original image.
3D Motivation: In-Plant Inspection

To maintain and ensure safe railroad operations new technologies must be developed for wood crosstie inspection before and after installation. The Railway Tie Association forecasts $2.4B will be spent to purchase approximately 23,700,000 new crossties in 2017. A new wood crosstie costs approximately $100 per tie installed with approximately $35 of material cost, $35 of treatment cost, and $30 of installation cost. After new crossties are purchased they are stacked for drying at tie treatment facilities to reduce the water content. Figure 6-1 shows an image of how crossties are stacked before treatment.

New crossties are expected to last between 10 and 25 years depending on regional environmental conditions. Inspecting wood crossties at the plant could be used to reject ties which have internal damage or defects before they are treated, sort treated ties into multiple quality grades, measure the treatment penetration into the tie, and begin individually tracking the integrity of each tie throughout its lifecycle. For composite ties impurity inclusions, air bubbles, non-uniformly mixed materials, and regions with a lack of fusion could be detected. Figure 1-2 is an example of a crosstie which failed prematurely because the rot prevention treatment penetrated only the outer 2.0cm to 4.0cm of the crosstie. The untreated wood in the center of the crosstie was left unprotected and the degradation was only detected after destructively examined. Figure 6-2 shows an image of how the dried crossties are bundled and rolled into a tank for treatment.
Newly fabricated crossties are not radiographically inspected and there is a market need for a 3D radiographic inspection of newly fabricated railroad crossties. Sawmills don’t radiographically inspect crossties to minimize production costs and tie treatment facilities don’t radiographically inspect after treatment to maximize throughput. Tie treatment facilities make the assumption that the amount of treatment missing from an entire batch is a good estimate of how much treatment each tie contains individually. Currently the most widespread method for the 3D inspection of an object is transmission radiography based computed tomography (CT). Transmission CT uses 2D transmission radiography images from many perspectives about a central axis of rotation to generate a 3D reconstruction. Backprojection, filtered backprojection, Fourier transforms, and radon transform methods are used to create a 3D reconstruction from many 2D perspectives. These mathematically based methods have been improved by incorporating physics treatments and computational optimizations.

Each crosstie is 8’6” long and if a tie plant produces 10,000 ties in a 12 hour shift the scanning speed necessary would be 70cm/s. Spiral scan CT with cone beam illumination would have to operate at a high rotational speed to ensure each segment of the object remains within the cone beam for one complete rotation. Spiral scan computed tomography (CT) systems are not designed for the 50cm/s to 200cm/s speed of a wood crosstie production line. Although traditional CT techniques are very effective at low linear scanning speeds, they are not be fast enough to scan all the ties produced by a tie plant each day. The railroad industry has a need for a new high-speed non-rotational 3D CT radiography method for inspecting newly fabricated railroad crossties.
Aurora Xi can operate at speeds exceeding 25mph using 2D fan beam illumination, backscattered x-rays, and segmented collimator linear detector arrays. Building on this technology, information about how radiation scatters within an object in addition to how radiation is absorbed is valuable for 3D computed tomography. Transmission radiography methods are based on only the line attenuation between two points. Scatter radiography methods are the product of illumination beam attenuation, total scatter signal from the intersection of the illumination beam and detector field of view, and the attenuation of scattered radiation. A new 3D, high-speed, in-plant conveyer belt system is proposed which combines both scatter and transmission radiography methods without rotating the crossties or system about a central axis.

**System Design Characteristics**

System performance goals for the inspection of railroad crossties drive design decisions. Scanning speed is the most important goal of this system design. To scan objects at speeds between 50cm/s and 500cm/s with a resolution goal of 1.0cm³ a spiral CT scanning system with a 5cm wide detector would have to rotate at a frequency of 10Hz to 50Hz. Those rotational speeds currently aren't feasible in medical spiral scan CT technologies. The fastest CT systems rotate at approximately 1Hz to 4Hz. Rotational systems have two degrees of freedom in the motion. To reach scanning speed goals the system is designed to remove one of those degrees of freedom by only translating the object while the illumination sources and detectors remain stationary. System complexity is greatly reduced by eliminating continuous rotational motion. In a system where the illumination sources and detectors are stationary the object translation is the only degree of freedom of motion.
Radiological safety considerations are also critical system design considerations. In medical CT applications patient dose should be minimized however for wood crosstie inspection there is no dose limit for wood or risk of residual radioactivity. Because scatter radiography is a very inefficient process a high intensity source can be used to create a significant scatter field. Each fan beam and associated scatter field can be adequately shielded in every direction with adequate thicknesses of steel and lead. For the inspection of wood crossties at a tie production facility the power-off safety of x-ray sources is more important than the enhanced reconstruction capabilities from continuously emitting predictable source energy gamma ray emitting radioisotopes.

Without being able to rotate x-ray sources and detectors around an object to gather many 2D transmission radiography perspectives, the system is designed to collect combinations of transmission perspectives and scatter field perspectives. Each fan beam illumination source will result in a single 1D transmission perspective and a scatter field on every side of the object. To gather as much information as possible the system is designed to collect forward scatter, side scatter, and backscatter perspectives of the scatter field on each side of the illumination fan beam from each source. Also, if the detectors could measure the energy of each scattered x-ray, that information would be helpful to filter low energy x-rays which have scattered more than once and increase the importance of higher energy x-rays in the reconstruction algorithm. The system design does not require a cylindrical inspection region or central axis of rotational symmetry in the object region for the transmission perspective and scatter perspectives. System scanning speed would be limited only by the illumination intensity of the source(s) and detector sample rates.
The system is designed to collect multiple 1D transmission perspectives of the translating crosstie using two or more x-ray fan beams. To allow each illumination fan beam to create an independent scatter field the x-ray fan beam sources must be offset from each other along the translation path of the crosstie. To take advantage of geometric magnification in the 1D transmission perspectives x-ray tubes with a wide illumination field will be selected so each focal spot can be as close to the object as possible while the transmission detectors can be distanced from the object. The offset fan beams will illuminate the object from two or more orthogonal sides of the crosstie to maximizing the overall illumination orthogonality. Figure 6-3 shows the system design including two orthogonally oriented illumination perspectives, transmission detectors, scatter detector locations, and a set of laser or optical surface scanners.

In Figure 6-3, a surface profile of the object is acquired by laser/optical scanners (in purple) for determining which voxels in the reconstruction region are always treated as air. The illumination field of each x-ray tube is collimated to create a fan beam for object illumination (in red). On the opposite side of the object a linear detector array samples the transmission perspective of each fan beam (in green). Many scatter detectors (in blue) are statically arranged around the object but slightly offset from the fan beam. These detectors are used to selectively detect the back scatter, side scatter, and forward scatter perspectives of the object. The scatter detectors can be 1D arrays of segmented collimators or 2D arrays of individually collimated detector elements.

3D Surface Scan

As the object translates through the scanning system the first step is to obtain a surface scan of the object. A surface scan using laser or optical method provides information about which voxels in the reconstruction volume contain the object and
which voxels are air. By applying the knowledge of which voxels surrounding the object are air and will always be air a number of computational benefits are gained. First, this information can be used to initialize the object within reconstruction volume. A voxel which is known to be air from the 3D surface scan will always be treated as air and reconstruction artifacts will never be introduced into the reconstruction volume surrounding the object. By reducing the reconstruction work space the reconstruction algorithm will spend more computational time on estimating the voxel composition within the object. A laser or optical surface scan is a cost effective method for initializing the reconstruction volume, eliminating artifact creation surrounding the object, and optimizing the fraction of computational time spent on the object volume. For inspecting newly fabricated wood crossties only 2 to 3 laser or optical surface scanners would be necessary.

**Transmission Perspectives**

Transmission perspectives provide information about how x-rays are absorbed by the object. To collect transmission perspectives a 1D linear detector array is placed within the illumination fan beam on the opposite side of the object from the illumination source. The illumination orthogonality of a voxel is the sum of the angles between every illumination direction. Ideally, each voxel within the object should be illuminated from at least 2 perspectives with the highest degree of orthogonality possible. The number of illumination sources can be odd or even.

The illumination sources can be at any position around the object. Even or odd numbers of sources can be used but the optimal positioning will maximize the degree of orthogonality for every voxel in the reconstruction. Each source can be a different distance from the center of the object and the center of each fan beam is not required to
be directed at the center of the object. If the object with known boundaries like a wood crosstie is being inspected, illumination sources could be aligned with the edges of the object. To maximize the illumination intensity each illumination source should be placed as close to the object as possible. Figure 6-4 shows an example of two orthogonal illumination source positions around a simulated crosstie with a grid of void defects.

In Figure 6-4 the rotational reference is defined to be directly above the crosstie. For crosstie inspection the center of each illumination vector does not have to be perpendicular to a crosstie surface. Figure 6-5 shows an example of three illumination positions which are rotated 120 degrees from each other relative to the center of the crosstie.

Each element of the transmission detector does not have to be equidistant to the illumination source. To maximize geometric magnification the transmission detector could be placed farther away from the illumination source. Transmission detectors on the opposite side of each illumination source could be linear, curved, or angled as long as the location of each detector element is known in 3D.

Two different types of transmission detector arrays could be used to collect transmission perspectives. Transmission detectors can be made of stacked detector elements or filtered single elements. Figure 6-6 shows an example of a transmission detector with 8 stacked detector elements for each position along the array and two arrays of single detector elements with different filter thicknesses.

A stack of detector elements can provide information about the energy distribution of x-rays penetrating through the object. The differences in signal between each stacked detector element and the attenuation properties of the detector element
can be used to compute an approximate multi-group transmission spectra. Each detector element in the stack would add a spectral perspective to the reconstruction method.

Single transmission detector elements integrate the energies of all absorbed x-rays which penetrate the object and detector case material. Detectors will use thin aluminum or plastic to minimize absorption of x-rays. A second linear array of detectors with a thicker denser filter material can be placed adjacent to the first detector array but also within the illumination fan beam. The average energy of the x-ray distribution penetrating the object can be determined using knowledge of the filter material, density, thickness, and the signal difference between detector elements.

**1D Scatter Perspectives**

The same 1D linear detector arrays of scatter detector elements can be used to collect information for a 3D reconstruction. A limited size scatter detector element should be as close as possible to the object to capture more scattered x-rays. For railroad crosstie inspection the collimator fins do not have to be arranged in a circle around the object and can instead be oriented perpendicular to the surface of the object. Figure 6-7 shows an image of perpendicularly oriented 1D segmented collimator arrays surrounding a crosstie with 9 cylindrical voids.

When an array of 1D collimator fins is used to limit the fields of view of each detector element the signal will originate from an elongated volume within the object. These volumes are as wide as the fan beam illumination field, as long as the width of the object, and approximately as high as the collimator pitch. 1D scatter detector arrays provide information about a segment of the volume which is much larger than an
individual voxel. Figure 6-8 shows the collimated scatter field from a solid uniform cross section of wood crosstie slightly offset from the fan beam.

In Figure 6-8 it can be seen that the magnitude of the forward scatter field is larger than the magnitude of the backscatter field. Also, the side scatter field has the highest intensity at the top of the crosstie which is illuminated by the fan beam. As the fan beam is attenuated by the object fewer x-rays are side scattered from deeper within the object. Additionally, in the backscatter and forward scatter fields there is a slight curvature where the scatter field intensity is slightly higher in the middle of the object compared to the edges of the object. This is because of higher order scatter contributions. Near the edge of the crosstie there is half as much material for photons to scatter more than once in to contribute to the measured intensity. When voids are introduced into the crosstie the collimated scatter fields surrounding the crosstie change. Figure 6-9 shows the scatter field intensity when 9 voids are introduced into the crosstie.

The collimated scatter field intensity of the crosstie segment in Figure 6-9 is significantly different than the collimated scatter field intensity of a solid uniform crosstie. The differences in the scatter field intensity prove that a collimated scatter field contains some information about the material properties of the object within each detector element field of view. Reductions in the backscatter, side scatter, and forward scatter field intensities correspond to the locations of the voids introduced into the tie. Figure 6-10 shows the change in the collimated scatter field intensity when voids are introduced into the wood. Reductions of the scatter field are shown in red and increases in the scatter field are shown in green.
Voids and other density variations cause changes in the scatter field which can be used in a reconstruction method. In each of the surrounding perspectives voids reduce the scatter field intensity. Also, when voids are present the illumination fan beam penetrates deeper into portions of the crosstie resulting in an increase of the side scatter field from deep within the crosstie. Additionally, depending on the geometric arrangement of the voids and the illumination direction of the fan beam the forward scatter perspective may contain both reductions and increases in the scatter field intensity. These changes are helpful for determining the edges of voids within an object. When a high signal to noise ratio scatter perspectives are collected smaller differences in object density can be resolved by using only the scatter perspectives.

To reduce the sensitive volume formed by the illumination beam and detector field of view two system modifications can be applied. First, the illumination volume could be reduced by using a pencil beam instead of a fan beam however this would significantly reduce scanning speed by adding another dimension of translation or rotation to the illumination source. Alternatively, multiple 1D segmented scatter detector arrays can be oriented in parallel to sample scattered x-rays from different depths within the object by adding collimation perpendicular to the fin direction to further limit each field of view. For example, two 1D arrays on the same side of the object can divide the field of view volume in half. To further enhance volumetric sensitivity many 1D scatter detector arrays can be combined into 2D stacked arrays.

2D Scatter Perspectives

In scatter x-ray imaging 2D arrays of individually collimated elements increase the spatial importance of the scatter signal at the cost of collectable signal. Arrays of scatter detector elements can be oriented on planes or on the surface of an ellipse.
surrounding the object. The collimation of detector elements can be a rectangular grid, a grid of cylinders, and/or a grid of hexagons. Figure 6-11 shows two rectangular collimator grids and two 2D scatter detector arrays oriented to measure the scatter field from side scatter perspectives of a crosstie.

In Figure 6-11 B the red line represents the fan beam illumination of the object and the green lines represent the location of 2D detector elements within the rectangular collimation grids. Figure 6-11 A shows grids on the side scatter perspectives and Figure 6-11 B shows fan beam illumination plane and the planar scatter detector elements within the collimation grids. Although two planar scatter detector arrays are shown in Figure 6-11 B the ideal configuration of scatter detector elements would surround the illumination plane on all sides of the object. Figure 6-12 shows a partial 2D array of scatter detector elements sampling the scatter field from a corresponding set of illuminated voxels within the object. Also, Figure 6-12 shows 8 orthogonally aligned positions that the scatter field of a single voxel within the object can be sampled from.

By observing the scatter signal of each voxel from multiple perspectives another unique scatter reconstruction optimization method can be applied. After accounting for the angular scattering probability the differences in scatter signals are entirely the result of unique attenuation of the scattered radiation towards each scatter detector element. These differences can be used to adjust the density of the scattering voxel and the densities of each voxel between the scattering voxel and scatter detector element. To take advantage of this property, the number of scatter detector elements for each voxel should be maximized. These scatter detector elements can be oriented at any position around the object arranged in rectangular grids, elliptical curves, or other mesh
geometries. Figure 6-13 shows an example of the relative signal intensity of two 2D detector side scatter detector arrays offset from the fan beam. The intensity of scattered x-rays is greatest from sides of the object which are closer to the x-ray source and closer to the scatter detector array. In this example four voids were placed within the crosstie at the x-ray fan beam illumination plane. The resulting scatter field was measured using two 2D detectors with collimation grids. Figure 6-13 also shows that 2D images of the scatter field can be gathered from many locations surrounding the object. Although this example is planar in nature, the fundamental methods are not limited to planar orthogonal geometries for detector placement so collimated scatter detector elements could be arranged on the surface of an ellipse or sphere surrounding the object.

Figure 6-1. German stacked crossties, Sutten, West Virginia, 2011. Photo courtesy of Andy Andrekovich. [20]
Figure 6-2. Dried crossties bundled for treatment, Springfield, Missouri, 2011. Photo courtesy Bill Moss. [21]

Figure 6-3. 3D In-plant crosstie inspection system design concept.
Figure 6-4. Two fan beam x-ray sources illuminating a crosstie from A) directly above the crosstie and B) rotated 90 degrees.

Figure 6-5. Three fan beam x-ray sources illuminating a crosstie maximizing orthogonality from A) 120 degrees, B) 000 degrees, and C) 240 degrees.

Figure 6-6. Two types of transmission detector arrays.
Figure 6-7. Four 1D collimator arrays around a crosstie with nine voids.
Figure 6-8. Collimated scatter field of a solid wood crosstie.
Figure 6-9. Collimated scatter field of nine voids in a crosstie.
Figure 6-10. Changes in the collimated scatter field intensity.
Figure 6-11. Collimation grids for 2D scatter perspectives showing A) an axial slice and B) a horizontal slice.

Figure 6-12. 3D positioning of scatter detector arrays.
Figure 6-13. Two 2D scatter detector array signal responses.
CHAPTER 7
3D SCATTER AND TRANSMISSION COMPUTED TOMOGRAPHY

Review of Computed Tomography Methods

The development of 3D scatter and transmission computed tomography methods are based on the advancements of many previous computed tomographic approaches. Modern computed tomography methods are based on line attenuation transmission radiography about a central axis of rotation. In transmission radiography scattered x-rays are treated as noise because they blur the reconstruction. There is no previously developed computed tomography method which can combine transmission and scatter radiography methods.

Transmission-Based Central Axis Computed Tomography

The first proof of concept Computed Tomography system used an x-ray source collimated into a narrow pencil beam. A single scintillator and photomultiplier detector was placed on the opposite side of an object. The x-ray source and detector were translated along the object to make a 1D parallel perspectives. The object was then rotated within the scanner and additional 1D parallel perspectives were taken. This resulted in many 1D parallel perspectives of a 2D slice within the object. To generate a 3D image the object was raised or lowered to a new vertical position within the scanner. The first CT systems were very slow because they required the X-ray source to both translate and rotate about the object. To create a 3D reconstruction the radon transform and algebraic reconstruction techniques were applied to solve for each slice of the object. The Radon Transform is based on the principle that an object can be reconstructed with a large number of projections. This method requires the object to be
imaged about a central axis of rotation. The first CT methods didn’t include full spectra physics treatments.

The next major advancement in CT system design was achieved by increasing the illumination field and the number of simultaneously acquired slices. Illumination beams changed from a pencil beam to a fan beam and linear detector arrays were used instead of a single detector. Because this design change eliminated the need to translate the X-ray tube when acquiring each perspective, the scanning speed was only limited by the rotational time per slice and the number of slices in the reconstruction. The change in illumination geometry also changed the reconstruction method from radon transform based simultaneous algebraic reconstruction to filtered backprojection. Backprojection techniques project the measured signal from each detector element along a ray through the object to the fan beam focal spot.

The third major advancement in CT system design was achieved by increasing the number of slices and continually translating along the central axis of rotation in a ‘helical’ or ‘spiral’ scanning pattern. The system could scan at speeds proportional to twice the detector array width per revolution. Advances in computational capability combined with increasing numbers of slices and detector elements per slices significantly improved the resolution of transmission based central axis of rotation computed tomography systems. The need to increase scanning speed and minimize exposure was realized by increasing the rotational speeds and sampling frequencies at the expense of signal to noise ratio. More advanced filtering methods and iteratively convergent successive approximations to the reconstruction were applied to maintain reconstruction quality.
As the length and width of the arrays of detectors increases the scanning geometry becomes best represented by cone beam illumination. Cone beam computed tomography systems collect sets of 2D perspectives around an object and can be used in partial angle applications like dental scanning or in high speed helical scanning. Because of the increased illumination field, the amount of scatter radiation from the object reaching the 2D detector array is increased which results in increased noise and a reduced signal to noise ratio of the image. Cone beam reconstruction methods have the highest computational requirements based on doing true 3D projections instead of 2D slice reconstruction.

**Scatter Computed Tomography: Mono-energetic Compton Imaging**

Computed Tomography by using the Compton scatter process can be accomplished using a monoenergetic gamma ray source and energy sensitive detectors. The Compton scattering relationship in Equation (1-2) correlates the initial energy, scattered energy, and scattering angle. When two of these three factors are known the third can be computed. This property can be used for computed tomography with both collimated pencil beams and wide illumination fields. When a highly collimated pencil beam is used the scattering point along the illumination ray can be determined by computing the scattering angle using the initial gamma ray energy, scattered gamma ray energy, vector of the gamma ray pencil beam, and position of the detector. The pencil beam can then be translated or swept through the object until every voxel in the reconstruction is adequately illuminated and sampled. The reconstruction accuracy can be improved by weighting each event based on the beam path attenuation and scatter path attenuation.
When a gamma ray source is collimated into a wide cone beam for illumination a slightly different reconstruction approach is necessary. By knowing the geometry of the system and the change in energy of the scattered gamma ray the scattering angle can be computed. With a wide illumination field the gamma ray could scatter from any position along an arc within the illumination field at the computed angle towards the detector. Every voxel which the arc intersects in the illumination field would be given a signal contribution weighted by the partial path length of the arc, the beam path attenuation, and the scatter path attenuation. Although these methods can be used for scatter CT, gamma ray sources have lower intensities, would require long scan times, and cannot be turned off for safety.

**Scatter Computed Tomography: Faysal El Khettabi and Esam Hussein**

Determining the density of an object using only Compton scattered photons has been explored by Faysal El Khettabi and Esam Hussein at the University of New Brunswick. They developed a system and associated methods for volumetric reconstruction by using an x-ray source collimated into a pencil beam to raster scan an object. A transmission detector was placed in the pencil beam on the opposite side of the object to measure the amount of transmitted x-rays and 1D arrays of collimated scatter detectors were configured to measure the orthogonal side scatter from the pencil beam illumination path. Figure 7-1 shows an image of the scanning concept including the beam vector, transmission detector location, and two 1D scatter detector arrays.

The reconstruction method assumed that all beam vectors and scatter vectors would be orthogonal to the surfaces of every voxel. The method assumed that the entire x-ray spectra would be represented by a single effective energy and the scattered
spectra would also be represented by a single effective energy. By making these assumptions a single beam attenuation coefficient and a single scatter attenuation coefficient were applied to an algebraic image reconstruction technique. The single energy approximations and alignment to a 3D cubic grid were made to accommodate limitations of the reconstruction method.

**Scatter Computed Tomography: Paul Jacob Arsenault and Esam Hussein**

Building on the previous work, Paul Jacob Arsenault and Esam Hussein developed another system and method for scatter CT. Design and method changes were made to allow for single-side scanning and 3D reconstruction. The system design consists of two highly collimated x-ray cone beams and a 1D array of highly collimated scatter detectors. The x-ray illumination beams and the scatter detector array are configured to be coplanar. Each scatter detector element has a narrow cone beam field of view directly orthogonal to a line of voxels within the object. The x-ray cone beams sweep through the object such that each voxel in the plane is illuminated by both cone beams simultaneously. The amount of scattered radiation is measured by the 1D array and a 2D image is reconstructed by balancing the discrepancies between the detector responses. The system is then designed to change the imaging plane within the object and acquire the scatter data to reconstruct another 2D image. The set of 2D images represents a 3D reconstruction of the object. Figure 7-2 shows the system concept developed by Arsenault and Hussein.

Similar to the previous work Arsenault and Hussein made a number of assumptions about the physics. The reconstruction method assumes that the x-ray spectra and scatter spectra can be collapsed into a single equivalent energy. This method is a 2D slice based reconstruction method which generates 3D information by
stacking many 2D slices and isn’t a full 3D method like cone beam computed
tomography. The system requires sweeping or rotating two x-ray sources and
translating the x-ray sources in two dimensions. The degrees of freedom in the
scanning motion would limit the scanning speed if a prototype of the system was built
and tested.

Information Theory: Input vs Output Units.

To create a reconstruction the density of each voxel must be determined from a
number of measurements. The ratio between the amount of information contained in the
reconstruction and the amount of information measured to create that reconstruction
leads to the reconstruction determination ratio. A determination ratio of less than one
isn’t adequate for creating a reconstruction because there are more voxels than
measurements. As more information about the object is obtained the determination ratio
increases and more accurate reconstructions can be made. If the resolution of the
system is increased the determination ratio of the reconstruction is decreased.
Additionally, for penetrating radiation reconstructions become more accurate when each
voxel in the reconstruction is sampled from many different perspectives in 3D. These
perspectives contain more valuable information for reconstruction if they originate from
a number of perspectives which are not coplanar on the same slice through an object.

Well determined systems have many measurements of information for each
voxel in the reconstruction. In traditional medical CT machines the ratio of transmission
signal measurements to reconstruction voxels ranges between 5 and 25. This high ratio
is achieved by using geometric magnification, a transmission radiography linear
detector array with more detector elements than voxels in a single dimension of the
reconstruction, and between 360 and 1080 perspectives equally distributed around the
object. All slice-based CT systems sample each voxel in the object on a 2D planes. Cone beam CT systems can sample each voxel in an object from a slightly wider range of perspectives in 3D. One of the goals and unique features of combining scatter and transmission radiography methods is that information about an object can be collected from more perspectives around an object.

**Transmission and Scatter Reconstruction Principles**

To combine transmission and scatter radiography in a computed tomographic reconstruction method the physics of each process must be properly modeled. Transmission radiography is governed by the energy dependent photoelectric absorption of photons along rays passing through an object. Scatter radiography is governed by the initial photon energy and the angularly dependent Compton scattering cross section between illumination rays and scattered rays. The parameter which unifies both transmission physics and scattering physics is the density and composition of the material.

To hybridize both transmission and scatter radiography a number of principles should be followed. Previously developed line attenuation based reconstruction methods should not be applied to rays which scatter or change direction. Although many rotational based CT methods have been developed in the past to incorporate scattering physics a new method is required. Additionally, to combine these radiography methods careful attention on the geometric degrees of freedom including illumination fields and scatter detector fields of view are critical. To create reconstructions from both transmission and scatter information the following principles are applied:

1. Single Compton scatter photons contribute to signal while higher order scatter is noise.
2. Traditional CT methods based on line attenuation, central slice theorem, averaged energies, and a central axis of rotation should not be used because scattered x-rays change direction and energy.

3. Full spectra physics is used along each ray and no average energy approximations are used.

4. The angular and energy dependent differential scattering cross section and Compton scatter change of energy must be determined for the beam vector and scatter vector from every voxel.

5. A surface scan optimizes computational effort by initializing the object region with a density approximation and permanently treating voxels surrounding the object as air.

6. Collimation should be used on scatter detector elements to selectively limit each field of view.

7. Filters and/or calibration should be used to increase the importance of single scatter x-rays.

The reconstruction method iteratively converges the density, not the attenuation coefficient, of each voxel in the object region by comparing the predicted signal and the measured signal. Ranges of densities are correlated with the scatter and absorption cross sections of known materials such as air, wood, water, and iron. Within each iteration, differences from both the transmission and scatter perspectives are combined to successively estimate voxel densities to minimize the difference between predicted and measured signal intensity.

By applying these principles the reconstruction method gains additional capabilities. Small angle forward scatter signals can be used to remove forward scatter noise on transmission detector elements. From the same source two adjacent transmission detectors with different filter thicknesses could be used for dual spectra or dual energy estimation of the transmission attenuation coefficients. Similarly, adjacent scatter detector elements with nearly identical fields of view could have different filters
to estimate the scatter spectra. Because these methods are all based on vectors in a 3D coordinate system and no central axis of rotation is necessary symmetry between the sources and detectors of different perspectives isn’t required. Additionally, each illumination source can use a different spectra of penetrating radiation.

**Flow Chart of the Reconstruction Method**

The order of operations for this reconstruction method is based on the reconstruction principles. Figure 7-3 shows the flow chart of how each algorithm combines to create a reconstruction. First, the reconstruction program initializes itself, allocates memory, and reads input data. The laser surface scan of the crosstie or object is then used to permanently mark voxels surrounding the object as air and create the object volume. Then the object volume is initialized by using a uniform density estimate or density estimates from the transmission perspectives. Once the reconstruction has initialized the object with an initial density estimate the iterative method begins.

Within each iteration the reconstruction method predicts the density of each voxel using all of the scatter perspectives. Next the method predicts the density of each voxel using all of the transmission perspectives. These predictions are combined and used to update the voxel densities within the reconstruction. After every voxel has a new density but before the end of the iteration the transmission perspectives are used to guarantee that the new estimated density values of each voxel remain convergent before the end of the iteration. Then, the reconstruction method can begin the next iteration or perform checks on the convergence of the reconstruction.

**Transmission Reconstruction Method**

Transmission radiography methods are based on only the full spectra line attenuation along a ray between the x-ray source focal spot and each detector element.
The transmission method requires knowledge of the entire x-ray spectral distribution, not just a single average energy value of the x-ray spectra. Because the x-ray source is collimated into a fan beam, the geometric attenuation of the source is modeled as a circle in $2\pi r$ geometry, not as an isotropic source in $4\pi r^2$ geometry. Using an initial normalized x-ray beam spectra of $\hat{I}_0(E)$ and a transmission constant $C_T$, the predicted transmission signal $T_{B_i\rightarrow D_j}$ between any focal spot location $B_i$ and detector location $D_j$ is computed using Equation (7-1). The transmission constant $C_T$ includes the conversion factors between detector signal units and keV. The line attenuation along each ray $r$ at energy $E$ is computed from the product of the density at each position, $\rho(r)$, and it’s associated mass attenuation coefficient $-\mu/\rho(E)$. This transmission method does not assume an average or equivalent value of the x-ray beam spectra to compute a single attenuation coefficient $\mu_{B_i\rightarrow D_j}$ between the source and detector. To implement this method properly the energy dependent terms $\hat{I}_0(E)$ and $-\mu/\rho(E)$ must be implemented as continuous functions or lookup-tables.

$$T_{B_i\rightarrow D_j} = C_T \int_{E=0}^{E_{\text{max}}} \frac{E \hat{I}_0(E)}{2\pi(|B_i - D_j|)} \exp \left( \int_{r=B_i}^{D_j} -\mu/\rho(E) \rho(r) dr \right) dE$$ (7-1)

The signal difference, $\Delta T_n$, between the predicted signal $T_{B_i\rightarrow D_j}$ and the measured signal $M_{B_i\rightarrow D_j}$ for each voxel along ray $B_i \rightarrow D_j$ is given in Equation (7-2).

$$\Delta T_n = \frac{T_{B_i\rightarrow D_j} - M_{B_i\rightarrow D_j}}{M_{B_i\rightarrow D_j}}$$ (7-2)

The attenuation of the spectra along each ray can be accurately computed in two different ways. The first method assumed that the object will be composed of a single material. Using this assumption the energy dependent mass attenuation coefficients will
be obtained from a single set of piecewise continuous coefficients or a lookup-table. The second method assumes that the object can be composed of many different materials each with unique attenuation properties. When many different materials can compose the object ranges of density can be correlated with the average attenuation properties of the most likely materials. For example, it is most likely that a density of 1.0g/cc will correspond to water, a density of approximately 2.0g/cc to 3.0g/cc will correspond to ballast, and a density of 7.8g/cc will correspond to Iron. For wood crosstie inspection, densities in a range between 0.1g/cc and 0.9g/cc can be assumed to correspond to the mass attenuation coefficients for wood.

The line integral along the beam ray $r$ can be evaluated computationally in two ways. Both methods rely on ray tracing in a 3D space. The first ray tracing method advances the ray position a fixed distance and samples the density at the end of each fixed differential length. This method approximates the continuous integral

$$\int_{r=B_i}^{D_j} -\mu/\rho(E)\rho(r)dr$$

as the sum of many segments $\sum_{r=B_i}^{D_j} -\mu/\rho(E)\rho(r)|\Delta r|$. The length of the fixed distance ray trace $|\Delta r|$ is selected to be a reasonable fraction of the voxel pitch. The second ray tracing method computes the path length of the ray within each voxel and then advances the ray into subsequent voxels. When a surface profile of the object is used to determine the boundary of the object an additional optimization can be applied to rays exiting the object. The surface profile allows the ray tracing method to know that all of the voxels along the entire path $l = |r - D_j|$ between the edge of the object at $r$ and the detector are composed of air. Therefore, this can be accurately modeled by computing $-\mu/\rho_{air}(E)\rho_{air}l$ across many air voxels avoiding the previous ray tracing methods through every single voxel intersected by the ray.
To refine the initial density estimate for every voxel, Equation (7-3) estimates the next voxel density \( \rho(V_r)^{k+1} \) using the previous voxel density, \( \rho(V_r)^k \), a convergence constant \( \gamma_t \), and the average of signal differences of a subset of all rays \( A \) which intersect voxel \( V_r \). This is a first order successive approximation technique which could be enhanced by selecting optimal values of the convergence constant \( \gamma_t \), using spatially dependent convergence factors, or using higher order approximations if many previous iterations of the reconstruction can be stored.

\[
\rho(V_r)^{k+1} = \rho(V_r)^k \left( 1 + \frac{\gamma_t}{A} \sum_{A} \Delta r_a \right)
\]  

(7-3)

**Scatter Reconstruction Method**

Scatter radiography methods depend on Compton scattering physics where the photon would change direction and energy. To apply this physical process to a reconstruction method accurate predictions of the energy and angularly dependent scatter fields must be computed. The scattering field from each voxel in a reconstruction is dependent on how the x-ray fan beam is attenuated by the object before reaching the scattering voxel, the angular and energy dependent scattering likelihood into a solid angle towards a scatter detector from the material within the voxel, the change in x-ray energy, and how the scattered x-rays are attenuated by the object before reaching the detector.

The partial predicted scatter signal \( S_{B_i \rightarrow V_r \rightarrow D_j} \), from a focal spot location \( B_i \) to a single voxel \( V_r \) is given by Equation (7-4). In Equation (7-4), \( C_s \) is the scatter constant, \( \hat{I}_0(E) \) is the normalized X-ray beam spectra, \( \sigma_{KN} \) is the Klein-Nishina scattering cross section into a solid angle formed by \( \hat{\Omega} \rightarrow \hat{\Omega}' \), \( \theta \) is the angle between vectors \( \hat{\Omega} \rightarrow \hat{\Omega}' \), and
$E \rightarrow E'$ is the Compton scatter change of energy from Equation (1-2). In Equation (7-4) the partial energy contribution to the scatter detector element is dependent on the scattered energy $E'$, not the initial energy $E$.

$$S_{B_i \rightarrow V_r \rightarrow D_j} = C_S \int_{E=0}^{E_{\text{max}}} \frac{E' \tilde{I}_0(E)}{2\pi(|B_i - V_r|)} \exp \left( \int_{r=B_i}^{V_r} -\mu / \rho(E) \rho(r) dr \right)$$

$$\rho(V_r) \sigma_{KN}(r, E \rightarrow E', \hat{\Omega} \rightarrow \hat{\Omega}') \frac{2\pi \sin \theta}{2\pi(|V_r - D_j|)} \exp \left( \int_{r'=V_r}^{D_j} -\mu / \rho(E') \rho(r') dr' \right) dE$$

Equation (7-5) is the sum of all partial scatter signals from all voxels $V_r$ within the intersection of the illumination volume and the scatter detector element FOV, $V_R$, scaled by the fraction of photons which have only scattered once, $F(O_1)$. The fraction of single scattered photons can be computed by calibration to known uniform-density object or by tracking photon scatter order in an MCNP simulation of a uniform object.

$$S_{B_i \rightarrow D_j} = F(O_1) \sum_{V_r} S_{B_i \rightarrow V_r \rightarrow D_j}$$

The difference, $\Delta s_m$, between the predicted signal $S_{B_i \rightarrow D_j}$ and the measured signal $M_{B_i \rightarrow D_j}$ for all illuminated voxels $V_r$ within detector element FOV is given in Equation (7-6). Equation (7-6) estimates the next voxel density $\rho(V_r)^{k+1}$ using the previous voxel density $\rho(V_r)^k$, a scatter convergence constant $\gamma_s$, and the average signal differences of the set $B$, where $B$ is composed of all scatter detector elements with an intersecting FOV.
\[ \Delta_{Sm} = \frac{S_{B_i \rightarrow D_j} - M_{B_i \rightarrow D_j}}{M_{B_i \rightarrow D_j}} \]  

(7-6)

To refine the initial density estimate for every voxel, Equation (7-7) estimates the next voxel density \( \rho(V_r)^{k+1} \) using the previous voxel density, \( \rho(V_r)^k \), a convergence constant \( \gamma_s \), and the average of signal differences of a subset of all rays \( B \) which intersect voxel \( V_r \). This is a first order successive approximation technique which could be enhanced by selecting optimal values of the convergence constant \( \gamma_s \), using spatially dependent convergence factors, or using higher order approximations if many previous iterations of the reconstruction can be stored.

\[ \rho(V_r)^{k+1} = \rho(V_r)^k \left( 1 - \frac{\gamma_s}{B} \sum_{B} \Delta_{S_b} \right) \]  

(7-7)

**Combining Transmission and Scatter Methods**

Since the transmission method and scatter method are both based only upon successive estimations on the density Equations (7-3) and (7-7) can be combined into Equation (7-8). Equation (7-8) assumes that the subsequent density estimations from transmission information and scatter information are of equal importance at any spatial location around the object. Elements within the set of density estimations from transmission information \( A \) and the set of density estimations from scatter information \( B \) can be assigned weights based on their location in the reconstruction.

\[ \rho(V_r)^{k+1} = \rho(V_r)^k \left( 1 + \frac{1}{A + B} \left( \sum_{A} \gamma_t \Delta_{T_a} - \sum_{B} \gamma_s \Delta_{S_b} \right) \right) \]  

(7-8)

To ensure that the reconstruction remains bounded after the densities of each voxel are corrected with the combined method in (7-8) at the end of each iteration a transmission-only correction of the density can be applied. Additionally this method
bounds the density of each voxel between the density of Air and the density of Lead so negative densities or high densities are not numerically permitted. This ensures that along each transmission ray through the object there is always an appropriate amount of material, although the distribution of that material along each ray may vary.

**Initializing the Reconstruction Volume**

A surface scan of the object can be very valuable to the reconstruction method for a number of reasons. A surface scan can be used to pre-condition the reconstruction space by determining which voxels are filled with air and which voxels must be occupied by the object. Because there are a limited number of transmission perspectives, transmission radiography alone cannot be relied upon to be able to determine the boundaries of an object within the inspection region. By knowing which voxels are air the method can avoid artificially introducing artifacts into the air surrounding the object and the object itself. Then, of the set of voxels within the object an initial density approximation can be applied to decrease the iterative reconstruction time and improve reconstruction accuracy. Ultimately, avoiding the introducing of artifacts and conditioning the reconstruction volume improve the computational performance of the reconstruction.

**Cross Section Treatments**

This transmission method depends on using the appropriate energy dependent cross sections for the materials in the reconstruction. For wood with a density between 0.1g/cc and 0.9g/cc with a composition of roughly 50% carbon, 42% oxygen, 6% hydrogen, 1% nitrogen, and 1% other trace elements by mass the energy dependent wood attenuation including absorption, scattering, and pair production is shown in Figure 7-4. [11]
When implementing a transmission radiography method it’s important to accurately model the highly nonlinear material cross sections. To accurately represent the cross sections of wood four relationships are necessary. The mass attenuation coefficients for wood between 1keV and 1000keV can be determined using Equation (7-9).

\[-\mu/\rho_{\text{wood}}(E) = \begin{cases} 
3303.2E^{-2.9235}, & 1\text{keV} \leq E < 15\text{keV} \\
221.4E^{-1.9375}, & 15\text{keV} \leq E < 30\text{keV} \\
5.073E^{-0.8217}, & 30\text{keV} \leq E < 50\text{keV} \\
0.8591E^{-0.3614}, & 50\text{keV} \leq E < 1000\text{keV} 
\end{cases}\]  

(7-9)

Frequently evaluating the exponential relationship \(-\mu/\rho(E) = C_1E^{C_2}\) is computationally expensive. The cross sections for every material can be computed once and stored in lookup tables with an energy resolution of 1keV. Pre-computing 1000 64-bit numbers for a 1keV to 1000keV energy range and reserving 8kByte per material is a classic example of a computational time optimization by space utilization tradeoff. Casting a floating point number representing the energy of an x-ray into an integer which can directly reference the memory location of the mass attenuation coefficient is very computationally efficient. Modern processors have on the order of many Megabytes of L2 cache available for storing frequently used values. Additionally the table of mass attenuation coefficients can be populated directly from interpolated tabular data read from a database or file instead of computed from piecewise best-fit relationships.

**Scatter Cross Section Treatments**

The terms in Equation (7-4) for modelling the probability of an x-ray scattering at a voxel \(V_r\) towards a detector element at \(D_j\) are expanded in Equation (7-10). The scattering likelihood is dependent on the density of the voxel \(\rho(V_r)\), the total scattering
cross section at $V_r$, $\sigma_{total}(V_r, E)$ and the normalized Klein-Nishina differential scattering likelihood $\hat{\sigma}_{KN}(E \rightarrow E', \Omega \rightarrow \Omega')$. Because the scatter detector element occupies only a small segment of the circular scattering solid angle, the factor $2\pi \sin \theta$ is necessary where $\theta$ is the angle formed by scattering from $\Omega \rightarrow \Omega'$.

\[
P(B_i \rightarrow V_r \rightarrow D_j) = \rho(V_r) \left(2\pi \sin \theta\right)\sigma_{KN}(r, E \rightarrow E', \hat{\Omega} \rightarrow \hat{\Omega}')
\]

\[
P(B_i \rightarrow V_r \rightarrow D_j) = \rho(V_r) \left(2\pi \sin \theta\right)\left(\sigma_{total}(V_r, E) \hat{\sigma}_{KN}(E \rightarrow E', \Omega \rightarrow \Omega')\right)
\]  

(7-10)

Computationally the total scatter cross section $\sigma_{total}(V_r, E)$ for each material is also implemented as a look-up table similar to the total absorption cross section in Equation (7-9). The total scattering cross section can be generated from best-fit relationships for each material or read from a database or input file. The normalized angularly dependent Klein-Nishina differential scattering cross section $\hat{\sigma}_{KN}(E \rightarrow E', \hat{\Omega} \rightarrow \hat{\Omega}')$ is implemented as a static 2D lookup table independent of each material as a function of both energy and scattering angle.

**Smoothing Method**

During iterative reconstruction methods the surface profile and transmission perspectives ensure that the density values within the reconstruction remain bounded and will converge, however within small local regions of the reconstruction neighboring density values can diverge from each other. This can be referred to as higher order iterative ‘noise’. This type of noise is also exhibited in reconstruction methods which probabilistically estimate the voxel properties. Smoothing methods can be applied after each iteration or after multiple iterations. The smoothing method implemented performs a simple average of the densities of the current and adjacent voxels. The smoothing method is shown in Equation (7-11).
\[ \rho(V_{x,y,z})^{k+1} = \frac{1}{(|i| + |j| + |k|)} \sum_{i=-a}^{a} \sum_{j=-b}^{b} \sum_{k=-c}^{c} \rho(V_{x+i,y+j,z+k})^k \] (7-11)

Ray Tracing Considerations

This reconstruction method uses ray tracing in 3D to predict signal contributions. To properly compute the attenuation of x-rays as they pass through voxels the density and cross sections of the material each ray passes through must be sampled. Sampling can occur by using a variable path length estimator or a fixed path length estimator. The variable path length estimator will compute the exact path length to the boundary of the next voxel in the ray path and sample the density of the voxel it’s travelling through. The fixed length estimator will advance a pre-set distance and sample the density of the voxel at the new point. Figure 7-5 shows an example of the variable path length estimator and fixed path length estimator through a voxel set.

Computationally, the variable path length estimator scales proportionally to the number of voxels the ray traverses through. The fixed path length estimator will always scale proportionally to the distance between the focal spot and detector element. For parallel computation, the variable path length estimator may result in a more variation in the ray tracing computational time than fixed path length estimator. Ray tracing is a problem which is best solved using modern graphics processing units (GPU's). In a GPU the fixed path length estimator allows many rays to perform the same tasks without individual rays terminating early resulting in thread branching.

Asymmetric Focal Spot Considerations

When the focal spot or the detector element is wider than the voxel pitch multiple ray traces can be used instead of a single ray trace. In Figure 1-1, the diagram shows that a focal spot and detector element can both be represented as areas, not just points.
Rays can be started from multiple locations within the focal spot and weighted proportionally to the x-ray luminosity of each segment of the focal spot. Ray traces from each point of the focal spot can be transported to different parts or edges of each detector element. Figure 7-6 shows an example of a focal spot divided into 9 regions allowing each to be a source of multiple rays which are transported to the edges of each detector element. The weighting factors for the focal spot region must be determined using a geometrically magnified pinhole image of the focal spot. Although this increases the computational time for the reconstruction, by properly modeling the x-ray physics voxel sizes which are smaller than the focal spot may be accurately converged for higher resolution reconstructions.

**Reconstruction Method Advantages and Disadvantages**

This reconstruction method has a number of unique advantages and also corresponding disadvantages. They key differentiation of this method is that it is based on the physics of photon production, scattering, and absorption rather than a mathematical method. The radon transform and filtered back projection are examples of mathematical reconstruction methods. The mathematical algorithms perform volumetric reconstruction using transmission X-ray images but lack consideration of the X-ray spectra distribution. Additionally, the mathematical reconstruction methods don’t take advantage of knowing the highly non-linear nature of cross sections as a function of energy. This physics based method requires knowledge of the x-ray spectra distribution and material attenuation properties. The real physics of x-ray imaging is multi-spectral and this method removes average approximations of the x-ray source energy and averaged material cross section properties.
By performing physics-based methods in a 3D volume space this method allows for unique geometric configurations and speeds. Mathematically based reconstruction methods require central axis of rotational symmetry and require rotational motion. By eliminating the physical design constraint inherited from the mathematics, this method allows for higher linear scanning speeds compared to rotational systems. The linear scanning speed of the system would be limited by properties of the detector performance including the signal to noise ratio as a function of sample rate. However, this property also has the disadvantage of requiring many perspectives of both transmission and scatter x-ray fields to gather sufficient information for accurate reconstructions.

This physics based method can combine both x-ray sources and gamma ray sources in the same scanning system. Although this can be a unique advantage, many applications require that the production of radiation can be stopped by removing power from the system for safety considerations and regulatory compliance. If gamma ray illumination sources were used the computational effort required for reconstruction becomes significantly reduced by potentially two orders of magnitude because gamma ray sources emit at predictable energies with predictable yields.

Finally, although accurately modelling the physics of an inspection system can have significant benefits, the main drawback is the computational complexity. Properly estimating the physics of photon interactions across many dozens or hundreds of energy groups becomes more computationally expensive than current filtered back projection methods. However, as computational capabilities develop including parallel computing methods, cluster computing methods, and graphics processing computations
can be performed today which wouldn’t have been possible 5 years ago. As long as these reconstruction methods are properly implemented for highly parallel processing systems physics based reconstruction methods will improve at a rate proportional to the performance gains of future computational hardware.

Figure 7-1. Khettabi and Hussein pencil beam system concept. [23]
Figure 7-2. Arsenault and Hussein dual illumination system concept. [24]

Figure 7-3. Reconstruction method flow chart.
Figure 7-4. Wood attenuation cross sections and best-fit expressions. [11]

Figure 7-5. Ray tracing attenuation estimators.
Figure 7-6. Ray traces to model focal spot sizes.
CHAPTER 8
3D SCATTER AND TRANSMISSION IMAGE RECONSTRUCTION

MCNP Model Development

The first step in reducing the combined scatter and transmission reconstruction method to practice is the simulation of the scanning system. By using Monte Carlo simulations to predict how x-rays would be absorbed and scattered by wood crossties simulated detector data can be generated. This simulated transmission and scatter x-ray data is used as an input to the reconstruction method. The MCNP models consist of a fan beam x-ray source created from a focal spot area with accurate spectra. The wood crosstie is simulated as a solid rectangle region with air cylinder patterns embedded inside. 1D collimator fin arrays modeled as thin voids surrounded the crosstie on every side slightly offset from the x-ray fan beam plane. Simulated detector data was collected using two different mesh tally arrays. The first 2D mesh tally was located directly in the x-ray fan beam. The second 2D mesh tally was placed offset from the x-ray fan beam including the 1D collimator fin arrays. The simulated transmission detector data was acquired from a single line of the 2D fan beam plane on the opposite side of the object. The simulated scatter detector data was acquired from 4 segments within collimated fin arrays surrounding the 4 sides of the crosstie. A set of MCNP models were created using a python script to simulate the crosstie translating through the fan beam. Figure 8-1 shows the tallying locations used to generate the simulated transmission detector data and the simulated scatter detector data.

From these locations in the mesh tallies the signal intensities are converted into a 4D data format composed of the 3D position each the detector element and the signal value. The transmission field is sampled far away from the object in order to take
advantage of geometric magnification. The scatter fields are sampled within the collimator fin arrays as close to the crosstie as possible without creating significantly large fields of view. The MCNP models generate two full 2D mesh tally fields to allow for simulating detectors in multiple positions without needing to repeat the entire set of MCNP simulations.

**Hole Patterns in Wood Crossties**

Within the crosstie various hole patterns were simulated to test reconstruction performance and accuracy. Within the 18cm by 22cm cross section of a crosstie 2cm diameter voids were in various patterns at 9 positions aligned to a 3x3 grid within the crosstie. Figure 8-2 shows the potential locations of the voids within the rectangular crosstie from the MCNP plot window.

By simulating air in the cylindrical regions the density would vary between 0.7g/cc and nearly 0.0g/cc. To reconstruct smaller density differences like the difference between treated and untreated regions of a crosstie the same reconstruction method is applied to detector data with an adequate signal to noise ratio to discern subtle density differences. The pattern of voids used in the 9 locations on a 3x3 grid can be represented in shorthand using binary matrix notation. The matrix \[
\begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1 \\
\end{bmatrix}
\]
represents voids at every one of the nine locations and the matrix \[
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\]
represents solid wood at every location simulating a uniform density crosstie. Typical patterns modeled in each simulation included every location, no locations, near row \[
\begin{bmatrix}
1 & 1 & 1 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\]
, far row \[
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
1 & 1 & 1 \\
\end{bmatrix}
\]
, one column \[
\begin{bmatrix}
1 & 0 & 0 \\
1 & 0 & 0 \\
1 & 0 & 0 \\
\end{bmatrix}
\]
, ‘T’ pattern \[
\begin{bmatrix}
1 & 1 & 1 \\
0 & 1 & 0 \\
0 & 1 & 0 \\
\end{bmatrix}
\]
, inverted ‘L’ pattern \[
\begin{bmatrix}
1 & 1 & 1 \\
1 & 0 & 0 \\
1 & 0 & 0 \\
\end{bmatrix}
\]
, diagonal pattern
Selected to test the performance of the reconstruction methods

**Transmission-Only Reconstructions**

Computed tomography reconstructions using only transmission radiography methods rely on the geometric projection. The proposed method uses a combination of ray tracing, a surface scan of the object, and multi-group physics treatments. Figure 8-3 is a single transmission x-ray image of a crosstie with various void patterns when illuminated from above with a 325keV spectra.

The greyscale within Figure 8-3 is windowed for maximum contrast over in the signal range between full illumination and maximum attenuation by the thickest segments of crosstie. The brightest portion of the image occurs where x-rays are crossing just above the corners of the crosstie eliminating attention by the object and minimizing the path length between the focal spot and detector element. The darkest portion of the image occurs where rays must travel the maximum path length through the object exiting at the corners on the opposite side. These two signal extremes define the sensitivity range of the transmission perspective. Within Figure 8-3 the ‘T’ pattern with five voids is the third row from the bottom. Figure 8-4 shows a plot of the signal across the ‘T’ pattern of voids.

Because more x-rays penetrate through smaller path lengths of material, the largest signal values were obtained from rays which penetrated only the corners of the crosstie and the smallest signal values were obtained from rays which penetrated through the thickest non-void segments of the simulated crosstie. Figure 8-5 is a representative example of backprojecting a single perspective transmission x-ray signal.
intensity values similar to Figure 8-4 into the crosstie area without any physics-based corrections.

In Figure 8-5 the x-ray signal intensity of each detector element is backprojected to every non-air voxel along each ray from the detector element position to the focal spot position. The voxels filled by air are shown in blue surrounding the crosstie. The uniform density of the crosstie can be properly predicted by accurately using multi-group physics and the signal differences obtained from both short and long path lengths ray traced through the crosstie. Figure 8-6 shows the same 5 hole ‘T’ pattern reconstructed from a single transmission perspective using the multi-group transmission method in Equations (7-1), (7-2), and (7-3).

In Figure 8-6 the wood crosstie region is surrounded by air and includes five 2.0cm diameter voids. Since only one transmission perspective the reconstruction method uniformly distributes the density loss of the void(s) along each ray. Most importantly, the surface scan combined with the multi-group transmission physics method accurately predicts the density of the wood as 0.7g/cc from x-ray signals which penetrate through thick or thin segments of the crosstie. As more transmission perspectives are added from unique directions the transmission method can better reconstruct the void pattern. Figure 8-7 shows the resulting reconstruction slice using two orthogonal transmission perspectives.

Using only two transmission perspectives the ‘T’ pattern of voids appears with other artifacts created from an underdetermined system. At each of the four corners where illumination rays travel along very short paths lengths within the crosstie the reconstruction the density of the crosstie is accurately predicted to be approximately
0.7g/cc. This confirms that knowing where the object surface is in 3D space is very valuable for this reconstruction technique. Two perspectives also result in low density artifacts at locations \([\begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 1 \end{bmatrix}]\) within the crosstie. As the number of perspectives is increased and the system is better determined artifacts created by the reconstruction process are reduced. Another beneficial property of this reconstruction method is that the transmission reconstruction method is self-converging. The self-converging property results from accurately applying multigroup cross sections for the entire x-ray spectra. Verifying this property is accomplished by creating a reconstruction uniform solid wood at 0.7g/cc. Figure 8-8 shows the resulting reconstruction with a high contrast greyscale using two transmission perspectives.

In Figure 8-8 the reconstruction of solid wood shows a few artifacts which are the result of the fixed path length ray tracing physics method. The upper right corner of the crosstie which is closest to both of the focal spot positions has a slightly overestimated density of 0.718g/cc. This represents an overestimation of the density by approximately 2.5%. Within the object there two darker streaks originating from each focal spot location which result from the fixed path length ray tracing method. Additionally, in the lower right corner and the upper left corner the density is slightly overestimated because each perspective is traversing through very different path lengths of crosstie. Overall, the reconstruction is very accurate and a histogram of the density values from this solid wood slice are shown in Figure 8-9.

The histogram in Figure 8-9 shows that the average density of the uniform 0.7g/cc crosstie is predicted to be 0.6985g/cc. The reconstruction method under-predicts the density by 0.21%. Although this result is extremely accurate, the distribution
which deviates from 0.7g/cc can be attributed to the statistical variation of the MCNP tallies combined with the inaccuracy of the fixed distance ray tracing method at the voxels on the boundary of the object. To eliminate this the fixed distance ray tracing method can be replaced by the variable distance ray tracing method to the exact boundary of each voxel within and at the surface boundaries of the object.

**Scatter-Only Reconstructions**

The first step in completing a scatter only reconstruction is evaluating what each scatter perspective looks like individually. The 1D forward scatter, side scatter, and backscatter fields can be collected into multiple 2D images as the simulated crosstie is translated through the fan beam. Figure 8-10 shows scatter images of the backscatter, side scatter, and forward scatter 2D perspectives. The 4 scatter perspectives were generated by combining 50 individual MCNP simulations of the crosstie translating through the fan beam.

In Figure 8-10 each greyscale image is individually windowed for each simulated signal range. Figure 6-8 and Figure 6-9 are simulated 2D images of the scatter x-ray field orthogonal to the images in Figure 8-10 at the first set of voids and within a solid segment of the crosstie. Each of the scatter perspectives contains information about the hole patterns within the crosstie. In Figure 8-10 A the backscatter field is most sensitive to the voids closer to the x-ray tube. In Figure 8-10 B the forward scatter field is most sensitive to voids farther away from the x-ray tube. Additionally, voids closer to the x-ray tube result in more forward scatter signal. In Figure 8-10 B and C the side scatter field has a gradient between side of the crosstie closest to the x-ray tube and deep within the crosstie. This gradient is caused by the attenuation of the x-ray beam as it penetrates into the object. The largest side scatter signal is measured close to the top of the
crosstie and the lowest side scatter signal is measured from the bottom of the crosstie. The shape of this gradient provides information for the distribution of density within the crosstie.

**Reconstruction of Solid Wood**

Creating a reconstruction of a uniform solid wood tie using only the scatter perspectives is the first benchmark of the scatter reconstruction method. To reconstruct a single slice of solid wood two illumination directions with four scatter perspectives were used. Figure 8-11 shows a high contrast greyscale image reconstruction of uniform 0.7g/cc wood.

In Figure 8-11 the simulated signals of every detector element in each of the four 1D scatter perspectives surrounding the crosstie are used in Equation (7-4), Equation (7-5), and Equation (7-6) to estimate the density of each voxel in the slice. The reconstruction of 0.7g/cc solid wood is expected to be approximately 0.7g/cc with some variance introduced by the stochastic nature of the MCNP. The values range between 0.662g/cc and 0.726g/cc with an average of 0.697g/cc and a standard deviation of 0.009g/cc. A histogram of the reconstructed density values is shown in Figure 8-12.

The distribution in estimated densities is due to the variance of each MCNP tally and the amount of information used to reconstruct the voxels within the solid slice. Within the slice there are 1584 voxels however the four 1D collimated scatter perspectives contain only 160 samples of the scatter field. This means that the scatter reconstruction is poorly conditioned. By using 2D scatter detector arrays it is possible to make more measurements than the number of voxels illuminated by the fan beam. Because each MCNP simulation results in tallies which inherently statistically vary, these variations are magnified in reconstructions with low conditioning ratios. In Figure
8-11 variances between the predicted and measured scatter signals result in streaks which are most prominent in the voxels nearest to the scatter detector element. This result also indicates that the scatter reconstruction method will distribute the density loss of a void to all of the voxels within the scatter detector element field of view. The accuracy of the scatter reconstruction method was investigated by reconstructing the ‘T’ hole pattern and the 9 hole void pattern.

**Reconstruction of ‘T’ Hole Pattern**

In Figure 8-7 the T-pattern was reconstructed using only two orthogonal transmission perspectives. Figure 8-13 was reconstructed using the eight corresponding scatter perspectives. Each illumination fan beam resulted in a 1D perspective of the forward scatter field, the backscatter field, and two side scatter field perspectives.

In Figure 8-13 various combinations of the scatter perspective localize the density loss on planes parallel to the 1D collimator fin arrays. The dual perspective scatter information starts to localize density loss near the actual positions of the voids. Each 1D scatter array enhances the reconstruction of voxels nearest to the detector element position. This reconstruction confirms that information from the scatter fields can be valuable for determining the internal density distributions of an object.

**Reconstruction of 9 Hole Pattern**

A reconstruction of the 9 hole pattern was created using the eight 1D scatter perspectives of the two fan beam illumination directions. Figure 8-14 shows that the grid of voids is resolved by using only the scatter signals. The density and signal loss contributed by each void is distributed to voxels parallel with each scatter perspective. This reconstruction slice confirms that the method is accurately estimating densities.
from scatter field signals which both increase and decrease. Figure 6-10 shows field changes which are used as the basis for this reconstruction.

**Combined Reconstructions of Hole Patterns**

By combining both scatter and transmission radiography methods the accuracy of reconstructions can be improved compared to transmission only CT methods. To show these improvements single and dual fan beam reconstructions were compared with and without the scatter reconstruction information.

**Single Fan Beam Reconstructions**

Figure 8-15 shows a side-by-side comparison between a reconstruction created with only a single transmission perspective and a reconstruction made including four 1D scatter perspectives. With only a single transmission perspective a reconstruction method cannot determine how variations in density are distributed within the object. Figure 8-15 A shows that a single transmission perspective is limited to predicting the average material density along each ray through the object. Figure 8-15 B shows that the scatter signals provide information on how density is distributed within the object. The ratio of the forward scatter to the backscatter signal intensities can be used to determine if density is distributed closer to the x-ray source, or farther from the x-ray source. The distribution of side scatter signal provides information about the density distribution along each ray from a nearly orthogonal perspectives. The relative importance of the backscatter perspective and forward scatter perspective is greatly reduced when there is a low degree of orthogonality with the transmission perspective. However, the side scatter perspectives are nearly orthogonal to the transmission perspective and therefore provide a better perspective of how density is distributed along each ray.
Dual Fan Beam Reconstructions

A second fan beam illumination perspective contributes a second orthogonal transmission perspective with a corresponding set of scatter perspectives. Although the scatter information is localized to a linear array of voxels instead of one voxel, the scatter information improves the transmission-only reconstruction by estimating a solid wood density near each surface and between the void holes. Figure 8-16 A shows the resulting reconstruction with only two transmission perspectives and Figure 8-16 B shows the reconstruction resulting from two transmission perspectives and eight scatter perspectives.

One of the important features of Figure 8-16 B is that backscatter and forward scatter perspectives which have a low degree of orthogonality and are nearly parallel to the transmission perspective do not contribute high importance unique information to the reconstruction. Multiple scatter or transmission perspectives from nearly the same direction are not as important for an accurate reconstruction. Just as traditional CT methods use many different equidistant uniformly offset perspectives, hybrid methods combining both transmission and scatter perspectives improve reconstruction accuracy when a diverse unique perspectives are available. This principle extends and applies to 2D collimated scatter detector arrays, because each detector element has a high importance for a small volumetric region of the object.

Iterative Convergence Stability

Iterative convergence stability is an important property of successive approximation reconstruction methods. Because these reconstruction methods are based on the successive approximation of density using a transmission method, a
scatter method, and both methods simultaneously the convergence characteristics of each method and their combination were investigated.

**Transmission-Only Convergence Stability**

The transmission method has unique convergence properties because it is implemented using the full x-ray source spectra and energy dependent cross section properties of the material. When the predicted signal of each transmission ray through the object is more than the measured signal the density of the voxels intersected by that ray are proportionally reduced for the next iteration. When predicting the transmission signal in the next iteration the attenuation characteristics of x-rays in every group of the source spectra is different. By applying full spectra physics the transmission reconstruction becomes inherently self-converging. The only way to reduce the predicted signal is to increase the density of the voxels intersected by the transmission ray and the only way to increase predicted signal is to decrease the density of the voxels intersected by the transmission ray. Figure 8-17 shows a reconstruction of a solid slice of a crosstie after 10 iterations. When the density of the material results in the predicted signal nearly matching the measured signal the densities are only slightly adjusted. The transmission perspectives contribute to convergence stability even at high iteration counts.

**Scatter-Only Convergence Stability**

The convergence stability of the scatter reconstruction method alone is very different than the transmission convergence stability because of the physics involved. Estimating the density of a voxel using scatter information is dependent on the attenuation of illumination fan beam, the density of the scattering voxel, the angle and energy of the scattered x-rays, and the attenuation of the scatter spectra. The
convergence stability of the scatter reconstruction method depends on these 3 factors whereas the convergence stability of the transmission method only depends on 1 factor. It’s not easy to determine if the density of the voxels in the beam path, the return path, or the scattering voxel itself should be changed to make the predicted scatter signal an measured scatter signal converge. The scatter method attempts to reduce the degrees of freedom of the scatter reconstruction method by only altering the density of the scattering voxel while leaving the density of the voxels in the beam path and return path unchanged. Therefore, the scatter convergence method alone is not self-stable at high iteration counts.

Figure 8-18 shows a reconstruction of a solid wood slice of a crosstie after 10 iterations of only the scatter convergence method. Figure 8-19 shows a histogram of the density values displayed in Figure 8-18. In Figure 8-18 the density of the crosstie farthest from each of the fan beam illumination sources in regions of the crosstie where the illumination beams are most attenuated is overestimated. Simultaneously the density of the crosstie closest to the fan beam sources becomes underestimated. In this case a lower amount of beam attenuation combined with an increase in the return path attenuation can result in the same predicted signal level. The only way to improve the convergence of the scatter method is to decrease the field of view of each scatter detector element by using 2D collimated detector arrays and/or by using detectors which provide information about the energy distribution of the scatter spectra.

**Combined Convergence Stability**

Within each iteration the new density estimates for each voxel are composed of the signal differences from both the transmission and scatter methods. Although the scatter signal information can be used to improve the reconstruction, the transmission
perspectives are necessary to ensure a convergent iterative reconstruction. To guarantee the reconstruction will converge a density approximation using only the transmission perspectives can be performed at the end of each iteration or after a few combined iterations.

**Smoothing Method**

Although a reconstruction may converge globally, an iterative method may diverge within small local regions of the reconstruction. These local variances are often referred to as a reconstruction noise. This noise is also created by the Maximum Likelihood Expectation Maximization (MLEM) algorithms used in traditional CT. To eliminate this noise in combined scatter and transmission reconstructions the smoothing method in Equation (7-11) is used to correct every local volume of the reconstruction at the end of each iteration. Figure 8-20 shows a combined reconstruction after 40 iterations and the without the smoothing method. Figure 8-21 shows a combined reconstruction after 40 iterations with the smoothing method applied at the end of each iteration. Figure 8-20 shows that after 40 iterations the noisy variations in local density are significant and these variations are eliminated in Figure 8-21.

**Convergence Stability Varying the Initial Density Estimate**

The initial density estimation is an important part of the reconstruction method. For wood crossties which can range in density between 0.5g/cc and 0.9g/cc a reasonable initial density estimate is 0.7g/cc. To demonstrate convergence of the reconstruction method Figure 8-22 shows a fully converged 40 iteration reconstruction using an initial density estimate of 0.3g/cc and Figure 8-23 shows a fully converged 40 iteration reconstruction using an initial density estimate of 1.0g/cc. Both reconstructions are fairly accurate however the limited number of perspectives and under conditioned
nature of these reconstructions lead to a slight gradient artifact perpendicular to each x-ray source within the reconstruction. The effect of these reconstruction artifacts can be minimized by collecting an adequate number of unique transmission and scatter perspectives.

Figure 8-1. Simulated transmission and scatter fields A) within the fan beam plane and B) within the scatter field collimation fins.

Figure 8-2. Potential void locations within the MCNP model.
Figure 8-3. Transmission x-ray image of a crosstie with void patterns.

Figure 8-4. Signal profile across the ‘T’ pattern of voids.
Figure 8-5. One perspective backprojection without reconstruction physics.

Figure 8-6. One perspective reconstruction using physics considerations.
Figure 8-7. Two perspective reconstruction using physics considerations.

Figure 8-8. Two perspective reconstruction of solid wood.
Figure 8-9. Two perspective reconstruction density histogram.

Figure 8-10. 2D scatter perspectives of A) the backscatter field, B) the forward scatter field, C) side scatter from the left face of the crosstie, and C) side scatter from the right face of the crosstie.
Figure 8-11. Scatter-only reconstruction of a solid crosstie slice in A) full color range and B) high contrast greyscale.

Figure 8-12. Histogram of a scatter-only reconstruction of solid wood.
Figure 8-13. Scatter reconstruction of the ‘T’ hole pattern.

Figure 8-14. Scatter reconstruction of the 9 hole pattern.
Figure 8-15. Single fan beam reconstruction of A) transmission information and B) combining transmission and scatter information.

Figure 8-16. Dual fan beam reconstruction of A) transmission information and B) combining transmission and scatter information.

Figure 8-17. Convergence stability of transmission perspectives after 10 iterations.
Figure 8-18. Convergence stability of scatter perspectives after 10 iterations.

Figure 8-19. Histogram of the scatter reconstruction after 10 iterations.
Figure 8-20. 40 Iteration reconstruction without the smoothing method.

Figure 8-21. 40 Iteration reconstruction with the smoothing method.
Figure 8-22. 40 Iteration reconstruction with an initial 0.3g/cc density estimate.

Figure 8-23. 40 Iteration reconstruction with an initial 1.0g/cc density estimate.
CHAPTER 9
3D PROOF OF CONCEPT SYSTEM DEVELOPMENT

Proof of Concept System Construction

To test the scatter and transmission 3D reconstruction principles a proof-of-concept system was developed, constructed, and used to collect experimental data. The system was designed to collect both transmission and scatter data from a single crosstie while minimizing research costs and utilizing available equipment. The system features a single shielded x-ray tube positioned above a translating crosstie. The crosstie translates under the x-ray tube and through the fan beam on v-track.

Gathering Perspectives of the Crosstie

To create a reconstruction of a crosstie multiple transmission and scatter perspectives of a translating are required. To accomplish this goal multiple x-ray tubes could surround the crosstie, a single x-ray tube could be moved to multiple sides of the crosstie, or the crosstie could be rotated under a single stationary x-ray tube. Rotating the crosstie and using multiple passes through the fan beam is the simplest solution to gather perspectives. To support the x-ray tube, rolling crosstie, and radiological shielding a gantry structure was made from Unistrut framing. Figure 9-1 shows this gantry structure under construction after the x-ray tube shielded box was placed in the center of the gantry. Figure 9-2 shows the x-ray tube box and rolling crosstie from above one of the v-track rails. The proof of concept system was designed to allow a full-length crosstie to translate through the x-ray fan beam.

In order to simulate illuminating the crosstie from multiple perspectives ½” holes were drilled into each end of the crosstie and ½” diameter 8” long bolts were used to mount the crosstie. Figure 9-3 is a picture of how the crosstie mounts created an axis of
rotation. To simulate illuminating the crosstie from multiple perspectives an angular alignment plate was attached to one end of the crosstie. Figure 9-4 shows a picture of the angular alignment plate. The alignment plate contains 72 holes evenly spaced every 5 degrees. These holes allow the proof of concept to simulate an x-ray fan beam illuminating the crosstie from any of the 72 positions. These holes will allow for inspections to be made with two illumination perspectives with 90 degrees of separation and three illumination perspectives with 120 degrees of separation with various angular offsets from the vertical direction.

**Radiological Safety and Shielding**

Radiation shielding is necessary for operating x-ray equipment safely and within regulatory limitations. To meet radiation safety goals a combination of lead shielding and operational limits were used. Shielding was placed around the x-ray tube box, under the primary fan beam, and surrounding the entire system. The proof-of-concept system was never operated near full potential or power in order to keep all radiation fields as low as possible. The x-ray tube is rated for up to 450kV potentials and 4500W of power, but for the proof-of-concept investigation of crossties a maximum potential of 225kV and 225W of total power was necessary. The transmission and scatter detectors were set to use longer sample times instead of increasing the system power, potential, and scatter radiation fields. At the edges of the hanging scatter shields a maximum scatter field intensity of 0.3mR/hr was measured.

The x-ray tube was placed on secured mounts within the x-ray tube box. Figure 9-5 shows the beam forming collimator and x-ray tube mounts in the bottom center of the x-ray tube box. Five 0.25" thick lead plates were used to shield x-rays scattering horizontally out of the sides of the box from the inner surfaces of the beam forming
collimator. Figure 9-6 shows the x-ray tube mounted in the box on top of foam blocks. These foam blocks are nearly transparent to x-rays which will form the fan beam but will displace additional lead shielding. Within the tube box two different types of shielding were used around the x-ray tube. Lead wool fibers were used to shield each end and the top of the x-ray tube. Figure 9-7 shows how 50lb blocks of lead wool were distributed around each end of the x-ray tube to shield the leakage radiation. Lead shot was used near the center of the x-ray tube because of the high primary and scatter radiation fields around the tube window and beam forming collimator. Figure 9-8 shows how the lead shot filled all of the spaces near the opening of the x-ray tube. Figure 9-9 shows a picture of both the lead shot and lead wool before the x-ray tube was completely covered by a layer of lead wool.

After the x-ray tube was completely shielded the next source of radiation to shield was the scatter fields from the crosstie and detector. Figure 9-10 shows how overlapping 3/32" thick lead sheets were hung the entire length of the scanning system on both sides to block scattered radiation. Because the radiation detectors used are very sensitive, 1/2" lead strips were used to protect the detector and create a narrow detection aperture. To effectively absorb the primary beam instead of letting it create a backscatter field off of the concrete floor a beam trap was made with 3/8" thick lead sheets. Figure 9-11 shows the lead beam traps and transmission detector shielding.

**X-ray Fan Beam Creation**

The x-ray fan beam was created using two thick parallel blocks of lead mounted on steel for support. Figure 9-5 shows an image of the two collimator blocks placed under the x-ray tube. Each block measures 3.5" thick, 16" long, and 4" wide. The gap between the collimator blocks was made using three 1/16" thick lead sheets. The lead
sheets results in a gap approximately the same as the x-ray tube focal spot while also being able to absorb side scatter radiation. The fan beam collimator was securely attached to the bottom of the x-ray tube box. To align the focal spot with the beam forming collimators threaded rods were used to attach each end of the x-ray tube to its’ enclosure. Figure 9-12 shows an image of which includes two threaded rods, coupling nuts, and screws used for x-ray tube alignment. The high voltage generators, x-ray tube chiller, electronics box, and safety interlock box are shown in Figure 9-13.

**Dual-Detector Imaging**

To use both transmission and scatter radiographic methods at least two detectors are necessary. The transmission detector must be located within the fan beam on the opposite side of the object. The scatter detector needs to be collimated and offset from the fan beam while being as close as possible to the object. Because of the intensity of the primary x-ray beam it is necessary to create a narrow aperture to protect the detector electronics and prevent the detector from being saturated. Figure 9-14 shows how two sheets of 1/2" thick lead were used to create a transmission detector aperture with a 1/16" gap. Because these two lead sheets were not perfectly straight, the aperture width and amount of x-rays reaching the detector vary and must be properly calibrated. Figure 9-15 shows how the narrow aperture of the transmission detector was centered within the fan beam.

The second detector used in the proof-of-concept system was the same size and type used as the transmission detector. Because of its’ length it was oriented vertically, orthogonal to the transmission detector perspective. Figure 9-16 shows how the hanging detector was placed just to the left of the fan beam. Figure 9-17 shows the scatter detector and attached collimator for creating a side-scatter perspective as the
crosstie passes through the fan beam. The inside of the detector collimator is shown in Figure 9-18.

Each detector was operated at different sample rates to ensure that adequate signal above background was measured during each integration period. In order to align the perspectives of each detector and convert the acquired data from the frequency domain to the spatial domain a position encoder was necessary. The encoder signal was equally split to each detector and both detectors were set to start at the same encoder position. Figure 9-19 shows how the encoder wheel was placed directly on the v-track to record the position, speed, and acceleration of the crosstie as it passed through the fan beam.

Proof of Concept System Results

Transmission Detector Calibration Method

To create transmission images and transmission data suitable for 3D reconstruction a number of processing steps and a modification of the reconstruction method is necessary. The method in Equation (7-1) assumes that 100% of the x-rays are measured which pass through the mesh tally volume representing a detector element. However, using a real detector some of the higher energy x-rays may penetrate through the detector element without contributing to the detector signal. This requires Equation (7-1) to properly account for the absorption of x-rays within the CsI detector elements. Equation (9-1) is the modified version of Equation (7-1) where 

\[
\frac{\mu}{\rho}(E)_{\text{CsI}}
\]

is the cross section for CsI, \(l\) is the path length of the transmission ray through the detector element, and \(\rho_{\text{CsI}}\) is the density of CsI.
\[ T_{B_i \rightarrow D_j} = C_T \int_{E=0}^{E_{\text{max}}} \frac{E \hat{I}_0(E)}{2\pi(B_i - D_j)} \exp \left( \int_{r=B_i}^{D_j} -\mu / \rho(E) \rho(r) dr \right) \]

\[
\left( 1 - \exp \left( -\frac{\mu}{\rho} (E) C_{\text{Sl}} \rho_{\text{CSl}} l \right) \right) dE
\]

To create 2D transmission images and 3D transmission input data a multi-step process similar to the 2D backscatter image formation method is necessary. The process includes the following steps:

1. Acquisition of an electronic background signal with no x-ray illumination.
2. Data acquisition of a crosstie passing through the fan beam.
3. Conversion of the time domain detector stream into spatial domain square pixels.
4. Geometric correction to scale detector signals to be equidistant to the focal spot.
5. Streak correction to remove the variations contributed by both the transmission detector aperture and manufacturing differences between detector modules.
6. Geometric inversion back to a linear detector array.

In step 1 the electronic background signal of the detector was acquired without any x-ray illumination. The resulting time domain image and electronic background profile is shown in Figure 9-20. This data is used to determine the signal changes as the crosstie is rolled through the energized fan beam. The uneven transmission detector aperture perturbs the expected signal distribution which would peak in the center of the detector array closest to the focal spot of the x-ray tube. Figure 9-21 shows the time domain signal data before electronic background subtraction. Figure 9-22 shows the time domain transmission detector profile after electronic background subtraction. In this data there is a wide scale across the 16-bit, 65535 unit, data range representing a very
high signal to noise ratio because the standard deviation of the electronic background signal of each detector element is less than 50 units.

In step 4 the background subtracted signal values were scaled so that they are equidistant from the focal spot. After this transformation a streak correction method was applied to each column of the data in step 5 relying on the assumption that the transmission signal through air should be the same to all detector elements equidistant from the focal spot. After streak correction factors were computed and applied to the data, Figure 9-23 shows the resulting profile and image after streak correction. Figure 9-23 shows the curved profile expected because the edges of the linear detector array are farther away from the focal spot.

**Transmission Perspectives**

Transmission perspectives of the crosstie were acquired every 10 degrees around the center of the crosstie at a rate of 1000Hz using a 225kV spectra with a tube current of 0.5mA. After the transmission detector calibration method was applied to the data high resolution images with a square pixel pitch of 1.661mm were created. Because the distances between the detector array, crosstie center, and focal spot the crossties were imaged with a geometric magnification factor of 1.64. Figure 9-24 shows four resulting transmission perspectives of the crosstie illuminated at -50, 00, 50, and 90 degrees. The high contrast look-up table and histogram of an image is shown in Figure 9-25.

The transmission perspectives in Figure 9-24 reveal many features of interest. Within the crosstie there are eight spike holes in two sets of four. Steel spikes occupy three of the four holes in one group. On one end of the crosstie 3/32” thick lead sheets were taped to the crosstie. On one face of the crosstie three lead sheets were taped in
a stair-step pattern to block the side scatter signal. Another four lead sheets were bent around each of the four corners of the crosstie for edge detection and alignment purposes. The steel spikes and lead sheets are strong attenuators which block most of the x-rays penetrating through them. Figure 9-26 shows the penetration of the spikes from 90 degrees. In contrast to the strong absorbers, certain regions of the crosstie are nearly transparent to x-rays because they are near the corners of the crosstie or there are air holes. Also visible are regions of the wood crosstie which have variations in density because of the natural variation in the wood growth. Figure 9-27 shows densification of the wood near the spike holes because spikes displace wood as they are driven into the crosstie. A 225kV spectra adequately penetrates the crosstie resulting in a high signal to noise ratio and visual contrast for inspection purposes.

**Transmission Signal vs X-ray Beam Spectra**

Changing the maximum potential of the high voltage generators will result in a fan beam with different spectral distributions. Spectra with maximum energies of 160kV, 225kV, 320kV, and 450kV were used to create images of the crosstie through 7” of wood directly above the crosstie and through 9” of wood at an offset angle of 90 degrees. In order to keep signal levels within the detectors sensitivity range 1.0mA of current was used at 160kV, 0.5mA of current was used at 225kV, and 0.2mA of current was used for both 320kV and 450kV. The power use for each illumination was 160W, 113W, 64W, and 90W respectively. At lower energies fewer x-rays penetrate the 2.3mm Fe and 1.0mm Cu x-ray tube window and at higher energies the 4.5mm thick CsI scintillator crystals are not thick enough to measure all of the highest energy x-rays.

Figure 9-28 and Figure 9-29 shows normalized images of the same transmission perspectives using a variety of x-ray spectra. As the peak x-ray energy is increased the
spectra more effectively penetrates the crosstie. The 90 degree perspective through the 9" width of the crosstie attenuates the fan beam more than the 7" height at 0 degrees. Figure 9-30 shows the normalized signal profiles at 90 degrees through 9" of wood using various spectra. By comparing the signal level exceeding the electronic background level for every detector element to the noise of each detector element the signal to noise profiles for each spectra can be determined. Figure 9-31 shows the resulting signal to noise profiles for each spectra. These images and profiles confirm that there is adequate penetration and signal to noise margin using each of these spectra. Additionally, lower power x-ray sources are easier to cool and can provide smaller focal spot sizes for better feature resolvability.

**Proof-of-Concept Resolution**

Measuring the resolution of the proof-of-concept system is also important for image characterization. The resolution of the system was measured in both the travel direction and transverse direction using the edge response method. Within the images there are steel spikes embedded within the crosstie which are strong absorbers resulting in large contrast differences. Additionally, the crosstie spikes have square cross sections that are aligned with the direction of travel. Figure 9-32 shows an image of the crosstie spike region used to calculate the resolution. In the travel direction the average signal value of the steel spike was subtracted from the spike profile. The 90% to 10% change in the signal was used to compute the resolution in the travel and transverse directions. Equation (9-2) determines the resolution in the travel direction and Equation (9-3) determines the resolution in the transverse direction. Figure 9-33 shows an example of the signal change at the transverse edge of the spike.
Resolution in the travel direction was 1.82 lp/cm and the resolution in the transverse direction was 1.00 lp/cm. The resolution in the travel direction was better than the transverse resolution because the lead aperture on protecting the transmission detector was smaller than the focal spot size. The resolution in the transverse direction after correcting for the geometric magnification makes the resolution very similar to the focal spot size. The focal spot size will always be a limiting factor for the resolution of an imaging system.

**Conversion to 3D vector input.**

To create a 3D reconstruction from a 1D or 2D detector array additional information about the system configuration is required. A traditional 2D image is suitable for displaying information onto a 2D screen but those formats lack the information necessary to create 3D reconstructions. Traditional central axis of rotation CT methods including fan beam, cone beam, and spiral scan using sets of 1D and 2D detector array responses \( \{ R_i, R_{i,j} \} \), the pixel pitch of each detector element \( p \), an angle about a central axis of rotation \( \theta \), a distance between the detector and central axis \( d_1 \), a distance between the focal spot and central axis of rotation \( d_2 \), and a displacement along that central axis of rotation \( z \). The sets of information necessary for traditional CT reconstruction are shown in Equation (9-4).
Because this reconstruction method does not require a central axis of rotation, a different set of information is required to create reconstructions. The reconstruction method requires correlated sets of the focal spot location $S_{x,y,z}$, detector location $D_{x,y,z}$, detector element size $p$, and detected signal $R$ to create a ray through space. Additionally, the ordered set $\langle E, \phi \rangle$ representing the x-ray energy distribution is necessary to properly predict total x-ray signal along each ray through the object. The scatter detector elements also require information about the direction of the field of view after collimation $\Omega$. Equation (9-5) shows the data format used for converting the 2D transmission and scatter information into a 3D stream of vector information. This data format allows for different size detector elements, movable detector elements, movable x-ray sources, and scanning configurations which do not require a central axis of rotation.

\begin{align}
\text{Transmission: } & \{S_{x,y,z}, D_{x,y,z}, p, R\}_{n=0}^N; \langle E, \phi \rangle \\
\text{Scatter: } & \{S_{x,y,z}, D_{x,y,z}, p, R, \Omega\}_{n=0}^N; \langle E, \phi \rangle
\end{align}

**Dual ‘Stereoscopic’ Transmission Perspectives**

After the 2D data was converted into the 3D vector input format reconstructions were created using two transmission perspectives. To maximize orthogonality and provide unique perspectives the two perspectives selected were offset by approximately 90 degrees. The stereoscopic reconstruction selected perspectives that were perpendicular to the surfaces of the crosstie at 0 degrees and 90 degrees.
Figure 9-34 shows an image of the stereoscopic reconstruction perpendicular to the crosstie surfaces. The reconstruction was created with cubic voxels measuring 0.25mm on each side for a volume of 0.015625mm³ per voxel. Figure 9-34 shows a set of slices of the same reconstruction at various positions along the crosstie. The reconstruction uses a color scale to show variations in wood density between 0.3g/cc and 1.0g/cc. Because the reconstruction area is slightly larger than the actual wood crosstie the edge densities become slightly inaccurate. Using an actual laser scan of the crosstie surfaces would fix these reconstruction artifacts. Within the various slices features such as higher density wood, lower density wood, cracks, wood holes, spike holes, wood densification around spike holes, and high density steel spikes can be resolved. Also, artifacts from the steel mounting bolt can be seen on the left side of the reconstructions and artifacts from the lead sheets used for detecting the 4 edges of the crosstie in 2D images can be seen on the right side of the crosstie. Because of the limited perspectives the signal change resulting from the highly absorbing crosstie spikes are spread throughout the crosstie. This reconstruction shows that even with limited perspectives a reconstruction can be created with takes into account the x-ray spectra, varying x-ray beam path lengths through the crosstie, and the attenuation properties of different density materials. Although rotating the crosstie was easier than repositioning an x-ray tube and shielding, all of the rays were traced in a 3D space not dependent on a central axis of rotation.

Three Transmission Perspectives

After completing stereoscopic reconstructions a reconstruction using three transmission perspectives was completed. In order to maximize the orthogonality between perspectives and provide unique perspectives of the crosstie the center of
each fan beam was rotated 120 degrees from the other perspectives relative to the crosstie. One perspective was directed at the top surface of the crosstie and the other perspectives were directed at the bottom corners. The reconstruction was created with cubic voxels measuring 0.25mm on each side for a volume of 0.015625mm$^3$ per voxel.

Figure 9-35 shows a reconstruction created by using three transmission perspectives. Similar variations in density, features within the wood, and absorbing materials can be seen in this reconstruction. By using three perspectives it can be seen that the mounting bolt on the left side of the crosstie wasn’t perfectly orthogonal to the end of the crosstie. The three of the reconstruction artifacts caused by the mounting bolt do not perfectly intersect. This results in a slight misalignment as the crosstie is rotated to different angles. The solution to this problem is to create a different crosstie mount which would grip onto the end of the crosstie instead of penetrate into the crosstie. The reconstruction does show that the methods accurately predict the density of wood within various parts of the crosstie producing reconstructions suitable for automated analysis methods.

**Every Transmission Perspective**

A total of 36 transmission perspectives were collected each offset 10 degrees from each other. A reconstruction of the crosstie was created using 36 transmission perspectives around the crosstie. Figure 9-36 shows the reconstruction resulting from every transmission perspective. Because of the misalignment shown in Figure 9-35 the reconstruction isn’t perfect and has some blurring, however even with the misalignment Figure 9-36 is a validation that this method can create reconstructions in a similar way to traditional CT methods.
On the left side of the image the reconstruction determines that a steel tie plate was attached to the end of the crosstie but is smaller than the crosstie cross section. Within the crosstie the lower density holes and higher density knots are clearly visible. The empty spike holes are well defined and the spikes are reconstructed as high density materials. The reconstruction shows the depth of penetration of the crack in the top of the tie, the warping of the crosstie within the reconstruction region, and the misaligned mounting bolt. The large number of perspectives allows the reconstruction to determine that the lead alignment sheets were placed on the surfaces and corners of the crosstie and that there is a low density hole within 1” of one of the lead sheets. The reconstruction also estimates that the density of the voxel on the very corner of the crosstie where the lead sheets are located is between 10g/cc and 11g/cc, which would causes the reconstruction method to use cross section values for lead to successfully approximate the signal drop of the short path length rays crossing those corners. The highly attenuating crosstie spikes block the x-ray illumination beam but still result in reconstruction artifacts in their vicinity because the forward scatter field from neighboring voxels is the primary contributor to measured signal. Properly using forward scatter approximations from a neighborhood of voxels about the beam ray to correct for the scatter contribution would correct these artifacts at the expense of increased computational time for transmission perspective computations. Even though this data was acquired with an imperfect proof-of-concept system this reconstruction validates the transmission reconstruction methods. Without changing the methods a reconstruction of much greater accuracy could be created by acquiring data from a scanning system with mechanical and geometric tolerances less than 1mm.
Side-Scatter Perspectives

Side-scatter perspectives of the crosstie were acquired orthogonal to the 0 degree illumination direction at a variety of energies. Figure 9-37 shows raw side-scatter images at 225kV, 320kV, and 450kV using an integration time of 20Hz, 50 times slower than the transmission perspective. The longer integration time is necessary because the scatter signal is much less than the primary beam signal. Although there is less side scatter signal from deeper in the crosstie and the image should appear darker, the image was normalized to result in a flat 2D image. This was done to show the variations in the scatter field more prominently than the gradient of the scatter field.

Many features of interest are visible in Figure 9-37. Three lead sheets were placed on the face of the crosstie at various heights. These lead sheets are visible at their respective heights in the images. There is blurring at the edges of the crosstie and at the edges of the lead sheets which is caused by a combination of the collimator geometry, distance between the crosstie and detector, collimated field of view of the side scatter detector elements, and the higher order scatter components from within the crosstie. The scatter perspectives also show the degree to which the crosstie is bowing. The steel spike closest to the scatter detector results in a large drop in the side scatter signal by blocking both the illumination beam and scattered x-rays. The spike holes also cause a drop in the side scatter signal. The gradient on the bottom of the crossties is caused by the steel tie plate blocking scattered x-rays from reaching the detector. The gradients within the crosstie volume are caused by variations in density of the crosstie. Higher energy beam spectra result in deeper side scatter perspectives of the object and lower energy beam spectra reveal crosstie features which are closest to the scatter.
detector. The higher energy beam spectra ensures that on average a first scatter photon has sufficient energy to penetrate more wood.

**A Side-Scatter and Transmission Reconstruction**

A reconstruction was created using a single transmission perspective and a single orthogonal side scatter perspective. The transmission perspective was acquired at a frequency of 1000Hz and the size scatter perspective was acquired at a frequency of 20Hz. This reconstruction uses the same two perspectives that were used to generate Figure 8-15, however the 3D vector input was created using data acquired from two real detectors instead of two simulated MCNP meshtallies. Figure 9-38 contains an image of only the transmission perspective, only the side scatter perspective, a combination of both perspectives, and various slices of the crosstie which show the scatter information altering the density distribution perpendicular to the transmission perspective.

Figure 9-38 is the first most basic demonstration of the transmission and scatter signal prediction methods being applied to proof-of-concept data. This data is not well conditioned and it would likely take many more perspectives of both transmission and scatter information to make a well-conditioned reconstruction. Additionally, the fields of view of each collimator are slices through the entire crosstie and aren’t localized. This reconstruction demonstrates that with the right methods, physics approximations, detectors, data, and geometry the combined method isn’t impossible. Just as these methods were applied to simulation data, the same methods will be able to reconstruct both scatter and transmission perspectives.
Figure 9-1. Gantry frame under construction side view, Georgetown, Texas, 2016. Photo courtesy of author. [17]

Figure 9-2. Gantry frame under construction front view, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-3. Crosstie mounting bolt for rotating the crosstie, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-4. Crosstie angular alignment plate, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-5. Beam forming collimator and x-ray tube mount, Georgetown, Texas, 2016. Photo courtesy of author. [17]

Figure 9-6. X-ray tube mounted on foam, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-7. Blocks of lead wool being added to shield the x-ray tube, Georgetown, Texas, 2016. Photo courtesy of author. [17]

Figure 9-8. Lead shot filling in all the space around the center of the x-ray tube, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-9. Lead shot and lead wool shielding from above, Georgetown, Texas, 2016. Photo courtesy of author. [17]

Figure 9-10. Hanging scatter shielding around the proof-of-concept system, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-11. Lead shields to protect the detector and absorb the primary beam, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-12. Threaded rod to align the x-ray tube, Georgetown, Texas, 2016. Photo courtesy of author. [17]

Figure 9-13. X-ray power and cooling systems, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-14. Transmission detector aperture, Georgetown, Texas, 2016. Photo courtesy of author. [17]

Figure 9-15. Transmission detector alignment, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-16. Scatter detector placement side view, Georgetown, Texas, 2016. Photo courtesy of author. [17]

Figure 9-17. Scatter detector placement end view, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-18. Scatter detector collimator, Georgetown, Texas, 2016. Photo courtesy of author. [17]

Figure 9-19. Motion encoder, Georgetown, Texas, 2016. Photo courtesy of author. [17]
Figure 9-20. Electronic background signal of the transmission detector.

Figure 9-21. Signal profile before electronic background subtraction.
Figure 9-22. Signal profile after electronic background subtraction.

Figure 9-23. Signal profile after streak correction.
Figure 9.24. Transmission perspectives at A) -50 degrees, B) 00 degrees, C) 50 degrees, and D) 90 degrees.
Figure 9-25. Histogram of transmission image and the enhanced contrast lookup table.

Figure 9-26. Steel spikes within the crosstie from the 90 degree perspective.
Figure 9-27. Densification of the wood around spike holes and lead alignment sheets.
Figure 9-28. Transmission perspectives at 0 degrees using A) 160kV, B) 225kV, C) 320kV, and D) 450kV spectra.
Figure 9-29. Transmission perspectives at 90 degrees using A) 160kV, B) 225kV, C) 320kV, and D) 450kV spectra.
Figure 9-30. Normalized signal profiles through 9" of wood at 90 degrees.

Figure 9-31. Signal to noise ratios through 9" of wood at 90 degrees.
Figure 9-32. Crosstie spikes used for edge method resolution determination.
Figure 9-33. Edge method resolution determination.
Figure 9-34. Views of a dual perspective crosstie reconstruction.
Figure 9-35. Views of a three perspective crosstie reconstruction.
Figure 9-36. Views of a 36 perspective crosstie reconstruction.
Figure 9-37. Flattened 2D side scatter images acquired at A) 225kV 0.5mA, B) 320kV 0.2mA, C) 450kV 0.2mA and D) the look-up table.
Figure 9-38. Views of a reconstruction created from a transmission perspective and an orthogonal side scatter perspective.
CHAPTER 10
CONCLUSIONS

Summary of 2D Work

In the US approximately 400M wood crossties support approximately 140,000 miles of Class I railroad. Improving railroad safety, replacement planning, and capital allocation required a novel NDT method to accurately inspect the internal features of crossties at a high rate of speed. NDT methods including acoustical, visual, eddy current, ground penetrating radar, and transmission radiography couldn't successfully inspect crossties at a high rate of speed. It was necessary to develop new systems and methods for backscatter x-ray inspection using 2D fan beam illumination and segmented collimator detection. The critical design goals were a scanning speed in excess of 20mph, penetration through 8” of wood, imaging resolution of less than 1”, all while ensuring radiation fields were significantly below state and federal regulatory limits. The development of the 2D system and methods required significant simulation using MCNP and full scale testing.

Reaching the depth of penetration goals required selecting the optimal x-ray tube geometry and detector characteristics. The research determined that a filtered x-ray spectra with a peak energy of 300keV would penetrate through 8” of wood and create measurable backscatter signal. By placing the x-ray tube in the center of the track a wide fan beam would simultaneously illuminate the entire area within the rail gauge. By using a narrow fan beam which was perpendicular to the crosstie surface the system would be capable of accurately imaging the vertical edges of the crossties.

The speed goal was the most difficult design parameters to meet. To scan at a high speed high speed data acquisition with a high signal to noise margin was
necessary. Simultaneous fan beam illumination of the crossties was the only practical method because rotating, sweeping, translating, or pulsed illumination wouldn't be fast enough. High speed motion required a high speed detector capable of acquiring hundreds of samples of the x-ray backscatter field per second. The detector was designed to maximize the size of the scintillator crystals collecting as much signal as possible while minimizing the blurring from scintillator afterglow. The x-ray tube was operated at a very high power and illumination intensity to create the largest possible backscatter field for the detector. Finally, the amount of collimation on the detector was minimized to maximize signal while preserving imaging quality. The final system was capable of creating high quality images at speeds exceeding 25mph, however the Federal Railroad Administration speed limit for the production vehicle platform was set at 25mph.

To reach the imaging goals new system designs and methods were necessary. The width of the fan beam was minimized to accurately resolve the vertical boundaries of wood crossties. Methods for aligning the x-ray tube focal spot to the beam forming collimator with high precision were developed to maximize fan beam intensity and symmetry. To detect the signal change from material loss on the bottom of a crosstie an optimal x-ray spectra to maximize backscatter intensity and signal to noise ratio was investigated with simulation, tested at full scale, and verified. Segmented collimator designs for the detector were simulated, constructed, and tested optimizing the fin length to pitch ratio to meet the image quality goals using highly attenuating materials to minimizing blurring, maximizing signal to noise, and minimizing collimator fin thickness. After collecting the raw data, a new method of image formation was developed to
produce high quality images suitable for machine vision algorithms and automated grading methods. To create high quality images the electronic background signal was removed, variance of each detector element determined, geometric distance from the focal spot was scaled, malfunctioning detector elements were corrected, streaks caused by variations in detector nonuniformity were removed, and the constant frequency time domain data was collected into a spatial domain data using an encoder stream.

Many design considerations were made in order to conservatively meet state and federal limits for system radiological safety. The system was designed to illuminate the crosstie between the rails so the thick iron rails would significantly block and decrease the scatter field intensity at the FRA defined railroad boundary. A custom designed beam forming collimator was invented which can rotate 90 degrees to entirely block the illumination fan beam. This collimator design innovation functioned as a safety interlock and critical aspect of the imaging system. Simulation and experiments determined the amount of shielding necessary to ensure all external surfaces of the x-ray system was less than 2.0mR/hr on contact. Lead shot was used to surround the curved x-ray tube, cable ends, and beam forming collimator occupying all of the space to its maximum packing fraction to prevent radiation leakage. Combinations of rigid lead shielding and flexible Silflex containing bismuth was used to encase the fan beam and detector and block the backscatter field. Additional Silflex shielding was added to the operator compartment to further increase the ALARA factor for operators. All radiation areas surrounding the system at or in excess of 2.0mR/hr were well within the FRA railway fouling boundary 4’ from the nearest running rail. The Texas department of health radiation licensing board evaluated and granted an operating license.
At the completion of this thesis four Aurora Xi vehicles are licensed for operations in 40 states and have scanned a total of 25,000 miles in the last 2 years. More vehicles are planned. Aurora Xi has become recognized as a proven industry-leading wood crosstie inspection technology.

Summary of 3D Work

In addition to inspecting wood crossties after installation there is a market opportunity for inspecting wood crossties as they are being fabricated before installation. Inspection before installation could improve the overall safety, quality, and longevity of railroad crossties. The development of 3D methods to inspect crossties before installation is the motivation for the development of a new system and methods.

Inspecting crossties before installation is much more difficult because crossties must be examined and graded immediately at a rate matching the wood crosstie production line. Because of the nature of wood a 3D method is necessary to examine the circular structures, linear cracks, and non-uniform treatment penetration. Traditional CT methods which rotate around the object cannot rotate at the speeds necessary to keep up with a conveyor belt of new crossties. A new type of iterative CT method based on ray tracing, knowledge of the x-ray spectral distribution, multi-group scattering and attenuation physics along each ray, and the convergence of predicted signals to measured signals by varying voxel densities within an object. This new system and method doesn’t require symmetric rotation about a central axis but does require modern computational capability for x-ray scattering and absorption physics along ray traces through a volume.

To create this method a significant amount of MCNP simulations were run on the UF high performance computing cluster to simulate transmission and scattering fields.
The tally results of the MCNP simulation outputs were converted into a 3D vector format suitable for the new reconstruction method. The reconstruction method was programmed in C for performance reasons avoiding inefficient automated memory management and utilized OpenMP for multi-processing. Computational optimizations such as pre-computed look-up tables for material absorption cross sections, scattering cross sections, and Klein-Nishina scattering probabilities were implemented. A cubic lattice of voxels was mapped into a linear memory space for quickly determining the density of a voxel at any point of the reconstruction while optimizing the processor cache hit ratio. A hierarchy of memory structures was created so that every parallel processor could collaboratively work as a team without disrupting each other. This method benefits greatly from parallel processing across many CPU cores or GPU blocks.

A proof-of-concept system was built to collect real data instead of using MCNP simulations for 3D input. A testing gantry large enough to inspect a full length crosstie was constructed. Significant effort was put into radiation safety shielding of the x-ray tube enclosure, fan beam collimator, transmission detector, fan beam trap, and scatter field shields. More than a ton of lead was used for radiation shielding in the construction of the in-plant proof-of-concept system. The methods used to create flattened streak-free 2D backscatter images were adapted to create 2D transmission and scatter images of the crosstie. A variety of spectra were used to acquire images through the crosstie which will lead to an optimized design for a production in-plant scanner.

The same reconstruction methods applied to the MCNP generated crosstie were successfully applied to x-ray data acquired with the proof-of-concept gantry. The
methods were slightly adapted to account for the difference between real detection efficiencies and the perfect mathematical tallying of a simulated detector element. Reconstructions using 2, 3, and 36 perspectives were created which predict the crosstie density. The proof-of-concept transmission data and reconstructions validated the MCNP simulated data and reconstructions. Although the proof-of-concept scatter perspective data does not have the signal quality and perfect collimated fields-of-view from the MCNP scatter field simulations, the data confirms that the reconstruction method combining both transmission and scatter information is valid. A reconstruction method which uses information about the x-ray beam spectra, material attenuation properties, material scattering properties, and detector properties can create accurate reconstructions.

The various perspectives of data acquired will lead to an optimal illumination configuration for a production in-plant inspection system. The low scatter radiation levels measured surrounding the proof-of-concept system confirm that a production in-plant inspection system can meet all regulations for a self-contained cabinet inspection system. Finally, the high signal to noise levels at very low illumination intensities combined with the fast sampling rates of the detectors confirm that an in-plant inspection system will be able to successfully acquire data at speeds exceeding anything used within a crosstie production facility.

**Concluding Remarks**

This research has been a phenomenal opportunity for personal and professional development effort over the last 4 years at UF/GREX. The CT methods pioneered by Hounsfield at EMI for the first medical CT scanner took decades of incremental optimization to reach modern capabilities. His work was based on the idea that
transmission x-ray perspectives could be combined to create images of slices through an object. This research and development of 2D and 3D fan beam methods is based on the idea that both transmission and scattering physics can be used to create images of an object.

Traditional CT inspection developed through multiple generations of technological advancement. The first generation was based on slice reconstruction using a translate-rotate single detector scanner. The second generation employed fan beam illumination and linear detector arrays to acquire data one slice at a time. The third generation employed cone beam illumination and 2D detector arrays in both slice and spiral reconstruction configurations. The systems and methods in this work are the first generation of a different type of CT. The reconstruction methods, computational efficiency, and scatter detector technologies have the most future development potential.

**Future Work**

This research has revealed that there are many ways this work can be adapted, improved, and advanced in the future. First, these ray tracing physics based reconstruction methods should be implemented on graphics processing hardware instead of on general purpose computing cores. Graphics processors are optimized for multi-dimensional vector computations by using many tiny computational units which simultaneously perform the same operation. For this type of application graphics processors are conservatively 100 times faster at computed tomography compared to general purpose processors.

Additionally, there are potential enhancements to the physics methods used in this work. Most conventional CT uses mathematical filtering methods to correct for
scattered radiation from the object in transmission perspectives of the object. It is possible to use the scatter methods to approximate the amount of scatter signal on each transmission detector element contributed from the small angle forward scatter from a number of voxels surrounding the path of the transmission ray. Additionally, for reconstructions using a lower energy illumination source the coherent scattering contributions can be computed and incorporated into the predicted scatter signal.

There have been countless methods for improving the convergence properties of traditional CT methods. There will be countless ways of optimizing the convergence of these methods for different materials, inspections, and system configurations. Convergence methods and sensitivity analysis are areas of future work which will take significant effort and would evolve as these methods evolve. Additionally, as these methods are implemented for different inspection goals on different computational hardware many unique convergence optimizations and heuristics will be necessary.

Although this research investigated wood crossties, the inspection capabilities for composite crossties should also be investigated. The fabrication methods used to make composite crossties can create unique flaws or defects which should be identified before installation. Composite ties are only slightly higher in density so a wood crosstie scanning system would also be able to scan composite ties. Additionally, composite ties would create a slightly higher field of scatter x-rays surrounding the fan beam illumination plane.

Scanning concrete crossties before installation would require an entirely different inspection system. Concrete and the steel reinforcements throughout have a much higher average density than wood or composite crossties. High sensitivity high
efficiency detectors would need to be paired with a high-energy high-power fan beam. The x-ray spectra necessary to penetrate a concrete crosstie would likely exceed 400kV. Additionally, because of strongly attenuating nature of concrete and steel compared to wood the system would not be able to scan as fast as wood or composite crosstie scanning systems. Although a higher energy would be required and the inspection is more difficult, it is possible to create a system to inspect concrete crossties with fan beam methods.

Many optimizations can be investigated for the transmission detectors. To prevent the saturation of the transmission detector it is possible to use filtering materials such as iron, copper, and tin or use a variable width aperture. The methods in this work can properly predict the amount of x-ray signal which would penetrate iron, copper, or tin filters. Although a detector may be physically constructed with identical detector elements, a variable width aperture can be accounted for by varying the detector size parameter in the 3D vector input stream. Finally, just as this reconstruction method can properly account for the attenuation of filtering materials in front of the detector, the signal contribution to a stack of detector elements with different thicknesses and material compositions can also be predicted. Stacked detector elements can add extra spectral perspectives of the same spatial perspective of the object.

Many optimizations can be investigated for scatter detectors. As previously mentioned using 2D arrays of 2D collimated scatter detector elements would significantly increase the amount of information gathered about the scatter fields from and object while simultaneously increasing the spatial importance of each scatter detector element. Filters could be added to the scatter detector elements to block a
higher fraction of lower energy multi-scatter photons increasing the fractional contribution from single Compton scatter photons. Finally, detector arrays which can provide information about the energy of each scatter event would simultaneously add an incredible amount of information to a scatter reconstruction and necessitate more advanced single photon scatter reconstruction methods.

A number of unique inspection system configurations could be investigated in the future. Currently rail cargo is only scanned with a single high energy transmission perspective. Nobody has or wants to build a high energy rotational CT scanner large enough to roll an entire train though. It may be possible to build a scanner which would use multiple stationary offset illumination sources, transmission detectors, backscatter, side scatter, and forward scatter 2D detector arrays surrounding a railroad track to scan an entire train with double stacked shipping containers as it rolls through.

These methods aren’t limited to just fan beam spectra from x-ray and accelerator sources. These methods could be applied to transmission and scatter data collected with pencil beam illumination system with a raster or rotating collimator. These methods can also be applied to radioactive isotope illumination sources which create gamma rays at discrete energies. The reconstruction speed significantly increases by computing 1 or 2 energy groups instead of 450 energy groups. By limiting the illumination field to a 1D pencil beam and eliminating the detector collimation it may be possible to use low-intensity low-energy gamma ray sources combined with energy sensitive uncollimated scatter detector arrays for a single-side no-contact 3D mammogram. There are many avenues of future research and development for 2D and 3D scatter radiographic methods.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Michael Liesenfelt completed a Bachelor of Science in nuclear engineering from the University of Florida in 2006 and a Master of Science in nuclear engineering sciences from the University of Florida in 2009. After graduating he improved nuclear reactor core simulation speed and accuracy for AREVA NP in Lynchburg, Virginia. In 2011 he accepted a position at Nucsafe in Oak Ridge, Tennessee to work as a scatter x-ray imaging engineer under Dr. Edward Dugan and Dr. Daniel Shedlock. He followed Dr. Dugan back to the University of Florida in the spring of 2013 to develop new 2D and 3D fan beam scatter radiography methods. In the fall of 2016 he earned his Doctor of Philosophy in nuclear engineering sciences from the University of Florida and accepted a position at the Georgetown Rail Equipment Company.