To my Dad
ACKNOWLEDGMENTS

I would like to thank my parents and my husband for their constant support and encouragement, without which I would never have had the courage to pursue my goals. I also need to thank the two most significant mentors in my academic career, Dr. Dugan and Dr. Baciak. Their wisdom and continued guidance, along with their reassurance and belief in me, set the stage for my success. Last, but not least, I want to thank all the wonderful people at Georgetown Rail Equipment Company, not only for their financial support, but also for the opportunity they awarded me to be a part of this truly incredible project.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>4</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>8</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>9</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>13</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>15</td>
</tr>
<tr>
<td>1.1 Research Motivation</td>
<td>15</td>
</tr>
<tr>
<td>1.2 Current Inspection Methods</td>
<td>18</td>
</tr>
<tr>
<td>1.3 Research Objectives</td>
<td>21</td>
</tr>
<tr>
<td>1.4 Overview of Relevant Work</td>
<td>23</td>
</tr>
<tr>
<td>1.4.1 Lateral Migration Radiography</td>
<td>28</td>
</tr>
<tr>
<td>1.4.2 Radiography by Selective Detection</td>
<td>29</td>
</tr>
<tr>
<td>1.4.3 Collimated Segmented Detector Scatter X-ray Imaging</td>
<td>31</td>
</tr>
<tr>
<td>1.5 Limitations and Improvements on Prior Work</td>
<td>33</td>
</tr>
<tr>
<td>1.6 Objective of Research</td>
<td>34</td>
</tr>
<tr>
<td>2 THEORY</td>
<td>36</td>
</tr>
<tr>
<td>2.1 Photon Interactions</td>
<td>36</td>
</tr>
<tr>
<td>2.1.1 Photoelectric Effect</td>
<td>36</td>
</tr>
<tr>
<td>2.1.2 Compton Scattering</td>
<td>37</td>
</tr>
<tr>
<td>2.2 The Backscatter Radiography Technique</td>
<td>43</td>
</tr>
<tr>
<td>3 EVALUATION OF IMAGING SYSTEMS</td>
<td>50</td>
</tr>
<tr>
<td>3.1 Linear Systems Theory</td>
<td>50</td>
</tr>
<tr>
<td>3.1.1 Fourier Transform</td>
<td>54</td>
</tr>
<tr>
<td>3.1.2 Sampled Signals</td>
<td>56</td>
</tr>
<tr>
<td>3.2 Image Quality Metrics</td>
<td>57</td>
</tr>
<tr>
<td>3.2.1 Spatial Resolution</td>
<td>57</td>
</tr>
<tr>
<td>3.2.2 Modulation Transfer Function</td>
<td>58</td>
</tr>
<tr>
<td>3.2.3 Presampled MTF</td>
<td>65</td>
</tr>
<tr>
<td>3.2.4 Noise</td>
<td>68</td>
</tr>
<tr>
<td>3.2.5 Detective Quantum Efficiency</td>
<td>73</td>
</tr>
<tr>
<td>4 OVERVIEW OF THE IMAGING SYSTEM</td>
<td>75</td>
</tr>
<tr>
<td>4.1 Design Criteria</td>
<td>75</td>
</tr>
</tbody>
</table>
4.2 Backscatter System Components ................................................................. 76
  4.2.1 Radiation Source .................................................................................. 76
  4.2.2 Source Collimator ............................................................................... 77
  4.2.3 Detector .............................................................................................. 80
  4.2.4 Detector Collimator ........................................................................... 81
  4.2.5 Image Acquisition Time ..................................................................... 84
  4.2.6 Noise .................................................................................................. 84
  4.2.7 Backscatter Imaging Technique ......................................................... 85
4.3 Prototype System Design .......................................................................... 86
  4.3.1 Radiation Source ............................................................................... 86
  4.3.2 Source Collimator ................................................................................ 87
  4.3.3 Detector ............................................................................................. 88
  4.3.4 Backscatter Imaging Technique ......................................................... 90
  4.3.5 Communication and Software ........................................................... 91
  4.3.6 Image Acquisition and Processing ..................................................... 92
  4.3.7 Initial Image Results and Limitations ............................................... 94
4.4 Optimization of System Design ................................................................. 101
  4.4.1 Radiation Source ............................................................................... 101
  4.4.2 Source Collimator ............................................................................... 102
  4.4.3 Detector ............................................................................................. 102
  4.4.4 Detector Collimator .......................................................................... 106
  4.4.5 Results of Optimized System ............................................................. 110
4.5 Final Design ............................................................................................... 113

5 RADIATION SHIELDING ............................................................................. 115
  5.1 Radiation Shielding Requirements ......................................................... 116
  5.2 Radiation Field Mapping ........................................................................ 118
  5.3 Preliminary Shielding Design and Analysis ............................................ 127
  5.4 Dynamic Testing .................................................................................... 130
  5.5 Final Shielding Design .......................................................................... 132

6 MODULATION TRANSFER FUNCTION ...................................................... 135
  6.1 Backscatter Radiography System MTF .................................................. 136
  6.2 Measurement of Backscatter System MTF ............................................ 139
    6.2.1 Bar Pattern Technique ..................................................................... 141
    6.2.2 Edge Method .................................................................................... 148
  6.3 MTF Results and Analysis .................................................................... 153
  6.4 Optimization of System Resolution ....................................................... 157
  6.5 Comparison of MTF Methods ................................................................. 162
  6.6 Limitations of Study ............................................................................... 165

7 DETECTIVE QUANTUM EFFICIENCY ...................................................... 167
  7.1 Methods Adapted for Backscatter Radiography ...................................... 168
    7.1.1 Uniformity Calibration ...................................................................... 168
7.1.2 System Response and Linearity ................................................................. 171
7.1.3 Presampled Modulation Transfer Function ............................................. 173
7.1.4 Noise Power Spectrum ............................................................................ 173
7.1.5 Detective Quantum Efficiency ................................................................. 176
7.2 Results and Analysis ................................................................................... 177
7.3 Considerations for Future Work ................................................................. 181
7.4 Limitations of Study .................................................................................... 182

8 CONCLUSIONS .............................................................................................. 184

8.1 Summary of Work ....................................................................................... 184
8.2 Concluding Remarks ................................................................................... 185
8.3 Recommendations for Future Work .......................................................... 187

LIST OF REFERENCES ....................................................................................... 191

BIOGRAPHICAL SKETCH .................................................................................. 198
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1</td>
<td>Scintillator material characteristics.</td>
<td>104</td>
</tr>
<tr>
<td>4-2</td>
<td>Dimensions of collimators tested for the linear detector array.</td>
<td>107</td>
</tr>
<tr>
<td>5-1</td>
<td>Measured exposure from a dynamic test of the shielded backscatter inspection vehicle and the estimated dose.</td>
<td>132</td>
</tr>
<tr>
<td>6-1</td>
<td>Limiting spatial resolution measured for the backscatter system.</td>
<td>157</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Major cause of railroad track accidents in 2015 by group.</td>
</tr>
<tr>
<td>1-2</td>
<td>Wood crosstie degradation caused by rot and fungus masked by a surface level appearing intact.</td>
</tr>
<tr>
<td>2-1</td>
<td>Compton scatter energy dependence on incident photon energy and scatter angles of 45°, 60°, 75°, 100°, and 180°.</td>
</tr>
<tr>
<td>2-2</td>
<td>Dependence of the Klein-Nishina cross-section on scattering angle for incident photon energies of 2.5 (outermost curve), 25, 50, 100, 250, 500, and 1000 keV (innermost curve).</td>
</tr>
<tr>
<td>2-3</td>
<td>Comparison of the scattering probability for the three common materials encountered in railroad track inspection.</td>
</tr>
<tr>
<td>2-4</td>
<td>Schematic of point-by-point scanning approach for Compton scatter imaging.</td>
</tr>
<tr>
<td>3-1</td>
<td>Four-bar binary pattern target constructed from line pairs of a fundamental spatial frequency.</td>
</tr>
<tr>
<td>4-1</td>
<td>Penumbra effect caused by finite source size F that results in a wider projected beam spot size $S_p$ on the target object surface.</td>
</tr>
<tr>
<td>4-2</td>
<td>Parallel hole detector collimator design for a pixelated linear array.</td>
</tr>
<tr>
<td>4-3</td>
<td>Prototype backscatter scanning system mounted to a hi-rail research cart.</td>
</tr>
<tr>
<td>4-4</td>
<td>Source collimator design.</td>
</tr>
<tr>
<td>4-5</td>
<td>X-Scan Imaging line scan detector array.</td>
</tr>
<tr>
<td>4-6</td>
<td>Linear detector array positioning that is offset from the fan beam source.</td>
</tr>
<tr>
<td>4-7</td>
<td>Pushbroom scanning method utilized by backscatter system on track.</td>
</tr>
<tr>
<td>4-8</td>
<td>Plywood calibration phantom used to correct for detector non-uniformity.</td>
</tr>
<tr>
<td>4-9</td>
<td>Position encoder attached to hi-rail wheel shaft.</td>
</tr>
<tr>
<td>4-10</td>
<td>Lead sheets placed on track to demonstrate scanning of high contrast materials.</td>
</tr>
<tr>
<td>4-11</td>
<td>Initial detector collimator composed of balsa wood and lead fins.</td>
</tr>
</tbody>
</table>
4-12 First backscatter image acquired with prototype system using a collimated detector, 450 kVp, and 3.3 mA. .......................................................... 98
4-13 Backscatter image acquired at 3.3 mA and different peak voltages. ............... 99
4-14 SNR corresponding to three different operating voltages: 225 kVp, 320 kVp, and 450 kVp. .......................................................... 99
4-15 SNR for various detector offset distances and nominal peak voltages. ........ 100
4-16 Optimal design for the radiation source beam forming collimator. ............ 102
4-17 Relative signals detected by the initial linear detector array composed of GOS crystals. .......................................................... 103
4-18 Full-length collimator attached to linear detector array. .......................... 107
4-19 Images acquired for different collimator designs. ............................... 108
4-20 Collimator design using air gaps between septa and minimal balsa wood. ..... 109
4-21 Backscatter image acquired with the optimal system parameters. .......... 110
4-22 Brand new wood tie installed in test track and used as calibration tie. ....... 111
4-23 Wood tie inspected in proof of concept test. .................................. 112
4-24 Image of the wood tie removed from the test track. ............................ 113
4-25 Final design of the backscatter inspection vehicle, Aurora X'. .................. 114
5-1 3D grid of measurement locations for radiation field map.......................... 119
5-2 Measured exposure rate for each grid location when operating the x-ray tube at 450 kVp and 3.3 mA. .......................................................... 121
5-3 Gap in the lead shielding to accommodate cables at x-ray tube housing ends. 122
5-4 Measurement of leakage radiation emitted through x-ray tube housing. ....... 124
5-5 Attenuation curve acquired from measuring leakage through x-ray tube housing while increasing the thickness of lead. ....................... 125
5-6 Attenuation curve acquired along the primary fan beam centerline. .............. 126
5-7 Configuration for initial shielding design. ........................................ 129
5-8 Surface plot of measured exposure rates for the shielded backscatter system scanning at the maximum tube operating parameters. .................. 130
6-19 MTF measured with the bar pattern target at different inspection speeds in the across-scan direction ................................................................. 160

7-1 Flat field calibration target used for the backscatter system constructed from plywood ................................................................. 170

7-2 Linearity test results showing exposure versus mean pixel value ....................... 177

7-3 NPS measured for the backscatter system at three detector exposure levels.. 178

7-4 DQE for the backscatter system obtained at three different exposure levels. .. 180
CHARACTERIZATION OF IMAGE QUALITY FOR AN X-RAY BACKSCATTER RADIOGRAHY SYSTEM USED IN THE INSPECTION OF RAIL TIES

By
Jessica Kelley

August 2016

Most railroad wood crossties degrade from the bottom upward, with surface levels often appearing intact and masking the true integrity of subsurface layers. Given that the primary inspection methods used today are based upon visual and laser profiling methods, these surface techniques often misjudge the true state of the tie, allowing their continued use in the railroad track until their eventual collapse results in train derailment. The objective of this work was to develop a mobile inspection system for grading the integrity of wood crossties, taking advantage of the ability of Compton backscatter to provide relative density indications from one side of the medium. In order for the inspection method to be viable on track, it must not disrupt normal rail traffic, requiring that the system be capable of scanning speeds of at least 10 miles per hour. Due to the inherently low probability for detecting backscattered photons, the requirement for fast image acquisition times often resulted in a tradeoff that had to be made between spatial resolution and detection efficiency.

Given the interrelatedness of several factors that can significantly affect overall performance in Compton backscatter imaging, a prototype system was constructed. The parameters that contribute to system performance include the radiation source,
detector, collimators, scanning technique, and geometrical layout. In order to understand the effect each system parameter has on performance, image quality tests were used to characterize spatial resolution, noise, and detection efficiency. Due to inherent differences that exist between transmission and backscatter radiography, each established method used to characterize image quality in conventional systems had to be specifically adapted to this novel backscatter method. By balancing the requirements for fast scanning and overall image quality, the optimal design was determined and a final system was constructed. Experiments verified the feasibility of the backscatter system and demonstrated that the method can detect voids in wood ties as small as 1.5 cm while scanning at 15 mph. Therefore, the one-sided backscatter imaging system is a viable method for detecting voids in the subsurface layers of wood crossties.
Research Motivation

One of the major problems that railroads have faced since their beginning is the prevention of service failures in track structural components. The basic railway track infrastructure components include the rails, spikes, tie-plates, crossties, ballast, and subgrade. As is the case with all modes of high-speed travel, failure of an essential component can have serious consequences. The U.S. Federal Railroad Administration (FRA) reported that train accidents attributable to track failures resulted in 486 derailments and over $87 million in reportable damage costs for 2015 [1]. Track defects are also the largest contributor of all accident causes, accounting for 37% as Fig. 1-1 demonstrates.

Figure 1-1. Major cause of railroad track accidents in 2015 by group.
North American freight operation has shown a dramatic increase in traffic levels over the past fifty years. Concurrent with this traffic growth is the move to heavier axial loads, increasing from 27 tons in 1960 to 36 tons today, as well as increased speeds. The implication of this trend is an increased rate of deterioration for certain track components and overall track condition. For example, the damaging effects caused by tie-plates and ballast, namely plate cutting and ballast abrasion, are accelerated with the use of faster and higher tonnage trains. This causes crossties to age prematurely and results in high crosstie replacement rates, with a growing importance placed on removing these poor ties earlier to avoid the risk of failure under traffic and derailment. In addition, the faster operating speeds dictate more stringent maintenance standards making accurate rail inspection more important today than it has ever been [2].

The reliable and efficient maintenance of railroad infrastructure require that maintenance personnel have accurate and reliable knowledge of the exact condition underlying the key structural components. However, while inspection techniques used in the measurement of rail and track geometry conditions have been around since the 1920s, only now are they evolving from a subjective activity to an objective technology. Out of all the major track component areas, the condition of the railroad crossties is one of the most critical issues for a railroad since their function is vitally important for overall track structure, they deteriorate relatively fast if not adequately cared for, and because there is such a large number of them that track owners must maintain.

Crossties perform three essential functions in the railroad track: (1) provide vertical support for the track by transmitting traffic loads to the ballast with diminished contact pressure, (2) restrain the track against lateral and longitudinal movements, and
maintain the proper distance between the rails, which is known as holding the rails in “gauge” [3]. Undoubtedly the most critical function is to maintain gauge, since wheels will leave the rail at any speed if distance exceeds limits, resulting in a derailment.

For the 170 plus years that railroads have operated in the U.S., the principal tie material has been wood, accounting for approximately 93% of track ties [4]. Their advantages include cost competiveness, light weight, ease of manufacture and installation, along with the fact that most current track maintenance equipment is set up and designed for operating with wood ties. Wood crossties exhibit some inherent disadvantages, however, being susceptible to mechanical degradation due to splitting, plate cutting, spike killing, and tamp killing. In addition, wood ties are subjected to harsh environmental conditions that lead to biological degradation such as rot and decay.

Depending on the regional climate and the type of wood used, wood ties will degrade and rot over time. The tie failure mechanism can be categorized into three different mechanism including mechanical wear, environmental conditions, and damage. Wood defects are going to have the greatest consequence in the rail-bearing area near the tie plates, however some are potentially so deleterious to strength that they are disastrous to ties regardless of degree or location. Mechanical wear includes failures such as those from plate cutting and worn ties. Environmental conditions can lead to split ties, decay, or the condition of a crushed rail seat which causes the tie to no longer be capable of supporting the load or holding a spike. Failed ties in the damage category include one that is broken, burned, or damaged which are the result of rough physical track conditions such as derailed wheels or dragging equipment.
Out of the 200,000 miles of active railroad track in the U.S., crossties represent a significant portion of their makeup, consisting of typically 3250 ties per mile [5]. Given that the six largest U.S. railroad companies own over 75% of the railroad track, each is responsible for maintaining between 18,000 and 38,000 miles of track. For example, a company owning 18,000 miles of track would have to maintain the infrastructure of about 60 million crossties. The inspection cycle for most ties is approximately every four to five years, resulting in an average of 12 to 15 million ties per year under the maintenance cycle. These average numbers demonstrate why railroad crossties represent the second largest capital expenditure of Class 1 freight railroads, accounting for between 20% and 40% of a railroad’s maintenance costs [6].

**Current Inspection Methods**

The railroad industry currently conducts regularly scheduled visual inspections. The traditional method of crosstie inspection involves a tie inspector walking the track, visually inspecting the condition of each tie and rating their integrity along a grading scale. The inspector assigns a grade along a rating scale from one to four, associated with the following conditions: Good, Marginal, Bad, and Failed. In addition to the visual inspection, a supplemental test often performed by the inspectors involve kicking the crossties or other structural components, watching for any movement or sounds that may demonstrate a hollow internal structure. The poorly graded ties are commonly counted through the use of simple mechanical counters that keep track of the number of bad ties per each mile investigated.

Visual inspectors are expected to look for all wood tie defects discussed previously, such as split ties or decay. Some of the defects they find, like excessively decayed ties, may be readily apparent even to a track inspection novice. On the other
hand, other track defects are subtler and require vigilance and proper training in order to
be detected. Some defects are only detected through indirect, visual cues.

Traditional grading methods suffer from several limitations, thereby limiting their
use and reliability. The labor-intensive process requires significant on-track time, with
inspectors typically inspecting only a few miles per day. Furthermore, the method is
highly subjective, varying with the large range of experience between inspectors that
are commonly encountered in the industry. Results can also vary based on which part
of the tie was struck, surface accessibility, and type of wood species used in the tie.

In the last decade, the increasing problem of limited maintenance budgets and
diminishing track access has led to the development of more innovative, cost-effective,
and efficient maintenance methods for wood crossties. In 2005, Georgetown Rail
Equipment Company (GREX) developed the Aurora tie inspection system, leveraging
machine vision technology to produce high-resolution surface images of the rail,
achieved in real-time processing [7]. Aurora utilizes high-speed cameras and lasers in
order to provide a 3D digital image of the track. The system then assigns one of four
grades to each wood tie, based upon more than 20 variables of tie degradation
including plate cut, surface roughness, decay, and cracks. Furthermore, it is capable of
operating speeds in excess of 40 miles per hour.

The advantages of Aurora include greater objectivity and consistency as
compared to manual inspection methods, all capable at higher inspection speeds, and
the ability to record and store large quantities of visual data in quantitative format. In
addition, data storage and identification with accurate GPS positioning allows an
analysis of the health of the track or vehicle components over both time and space,
used for historical trending, in tie replacement planning services, as well as more accurate tie marking.

While the Aurora automated technique provides several advantages, it is still limited to a surface scanning technique, leading to an incomplete grading assessment of wood tie integrity. The complication arises due to the deterioration process for wood having the ability to present itself visually through some defects, while others can remain masked, invisible to the naked eye. The visible worsening of wood conditions which include plate cutting, center binding, and splitting present themselves through visual traits, identifiable by the Aurora system and at times manual inspection. However, decay and wood rot commonly begins in the center of the tie or towards the bottom layers, eventually progressing towards the outer layers of wood some time later [8]. The subsurface decay mechanism is therefore often masked by the intact surface conditions of the tie, invisible to both the naked eye and Aurora. An example of a wood tie with severe internal rot and fungus deterioration that has been masked by an adequate surface level integrity is shown in Fig. 1-2.

![Figure 1-2. Wood crosstie degradation caused by rot and fungus masked by a surface level appearing intact.](image-url)
Research Objectives

Understanding the significance that subsurface defects can present to wood tie integrity, GREX endeavored to create a detection system capable of identifying subsurface flaws [9]. A variety of nondestructive techniques (NDT) developed for testing of sub-surface defects are commonly used for inspecting engineering materials, namely ultrasound, eddy current, radar, acoustic emission methods, and radiography. Each of these techniques has particular strengths and weaknesses that determine its suitability for specific applications. However, specific design criteria expected for the subsurface detection system resulted in eliminating many of these NDT methods as suitable options.

The end goal envisioned for this inspection system is to fully integrate it with the Aurora surface scanning results, providing an “all encompassing” tie inspection methodology. In order to achieve this efficiently and easily, the resolution and pixel spacing of this prototype system must be comparable to Aurora’s capabilities, which effectively eliminated solutions utilizing ground-penetrating radar. The criteria for integration also requires that the system obtain a minimum scanning speed of 10 mph, with the opportunity to increase it to match Aurora’s nominal inspection speed of 30 mph. The requirement for fast image acquisition times eliminated the use of ultrasound techniques.

The proposed technique must also comply with Plate C restrictions, achieved by maintaining a minimum standoff distance between all rigid components of the scanning platform and the rail [10]. Given that the current Aurora scanning platform is Plate C compliant, this operational parameter was labeled as one that could not be compromised, serving as the limiting factor for technology selection. This restriction
eliminated both electromagnetic acoustic transducer methods and ultrasonic techniques, which require close standoff distances to be effective inspection techniques.

The next criteria considered in the selection process concerns the depth of penetration necessary for the system to inspect. Given that most wood ties degrade from the bottom upward, it was necessary for the inspection method to reach the full depth of cross ties in the track. Given that the typical wood cross tie is about 18 cm deep, NDT methods capable of investigating the shallow or surface layers are thus eliminated, including eddy current methods.

Based on the established design criteria, it was proposed to employ an x-ray radiography technique that utilizes the penetrating power of radiation and unique properties of radiation with matter to image subsurface features. Traditional industrial radiography is an extremely important technology, with numerous advantages over other imaging methods. It has developed steadily for more than 25 years and a large variety of possible inspection techniques have become available. Conventional radiography utilizes those photons that pass through the target and are collected by the detector placed on the opposite side from the source. An image is created with areas of few x-ray interactions appearing bright and those where most of the x-rays are scattered or absorbed by the target appearing as dark.

While x-ray imaging traditionally had always been performed using transmission methods, the unique properties of Compton scattering have made it an invaluable addition to the arsenal of x-ray application techniques. Scatter imaging systems essentially do the opposite of their conventional counterpart, with areas that scatter a large fraction of x-rays appearing brighter than those materials that scatter less x-rays.
Scattering imaging methods are of particular interest in those cases where transmission measurements through the object are not possible, such as when the object dimensions are too large or the configuration is such that it cannot be accessed from both sides. The NDT inspection of wood ties presents one of these challenging inspection scenarios since detector placement below the railroad track is not possible. Therefore, scattering techniques are the only viable radiography solution to this complex diagnostic problem.

**Overview of Relevant Work**

Scatter imaging methods utilize the photons, which have Compton scattered off the inspection target in order to form an image, as opposed to conventional radiography methods that rely on transmitted photons. The most useful geometric configuration is often such that the radiation source and the detector are located on the same side of the inspected object. Methods, which utilize this geometry, are known as Compton backscatter imaging (CBI). This inspection approach is a viable alternative to transmission since Compton scattering is the predominant non-absorptive interaction for photons in the energy range of most commercial radiation sources (100 keV to 2 MeV).

The use of scattered radiation to inspect internal structures is not a new technique. Studies into the use of Compton scattering techniques have been conducted over a considerable span of time, being widely considered for use in many areas. The interest in this concept has remained vivid, enhanced by the fact that CBI has several characteristics that are not shared by conventional transmission radiography. First and foremost is the ability to place the source and detector on the same side of the inspected object. This unique imaging system trait opens the perspective for radiography of objects that would otherwise not be accessible to conventional x-ray
imaging, as in the case of inspecting aircraft frames, bridges, floors, layered structures, and most importantly railroad crossties. This is especially useful when an object with limited access points exists or when the interior of the object is complicated by overlaying details that transmission imaging systems are prone to miss due to the image’s complexity. Second, CBI has high contrast resolution in low atomic number materials that are impossible to image with conventional radiographic techniques. Third, no direct contact to the tested object is required. Fourth, more than one detector can be employed simultaneously and it can be inclined at different orientations with respect to the object. Lastly, CBI can provide quantitative information about the target material’s electron density.

The advantages afforded by CBI methods over their traditional counterpart have been exploited in order to solve several challenging diagnostic problems other methods have failed to do. A number of efforts have been made to apply backscatter imaging to applications ranging from medical diagnosis to industrial NDT. The first suggested use of a system utilizing x-ray backscatter technology to determine characteristics of a material was by Odeblad and Norhagen in 1956 [11]. The researchers demonstrated that the intensity of the detected scatter radiation for a fixed source energy and scattering angle depends on the electron density of the inspected target medium. Under conditions of a small volume element of uniform material composition, the electron density is proportional to the material density. The earliest CBI method utilized a collimated $^{60}$Co gamma-ray source and collimated scintillation detector in order to measure the relative electron densities of materials in the small voxel element defined
by the intersection of the source collimator’s field-of-view (FOV) and the detector’s acceptance angle.

CBI methods have a long tradition of use for probing the density of bulk homogenous materials, including soil [12], concrete [13], and even railroad wood crossties [14]. Although Compton scatter densitometry techniques were initially applied in the medical field to measure the density of bone [15, 16] and lung tissue [17], the non-contact, nondestructive nature of CBI is more appropriately suited for the industrial arena. These density probes rely on the same physics underlying the original CBI method proposed by Odeblad and Norhagen, monitoring the backscatter flux or intensity in order to provide information on the density and composition of the scattering medium.

Backscatter imaging has also gained interest in the application of food inspection [18]. In agriculture, the difference in the scattering properties of stones and potatoes has been validated [19]. CBI methods have been demonstrated in the monitoring of salt content in potato crisps [20] and the detection of voids in polystyrene samples [21]. Furthermore, backscatter imaging has been employed for foreign body detection in the food industry; effectively identifying high-density contaminants such as glass in various food materials [22] and near-surface bones in chicken meat samples [23].

Several commercial products have also been successfully developed based upon CBI methods. Adapting an apparatus designed originally for medical imaging, Philips developed the ComScan backscatter imaging system for NDT of aerospace components [24-28]. Employing an x-ray source collimated into a narrow pencil beam and a high-resolution detector array using slit collimators, the backscattered x-rays
reflected back from the inspected target object. ComScan is known as the plane-by-plane three-dimensional (3D) voxel based approach because it acquires data in sets of line voxels along the pencil beam. These planes are then reconstructed from the 3D data sets. In addition to the NDT of plastic and light alloy components for the aerospace industry, ComScan has founds uses in both the archeological and art history field, employed for the NDT of cultural artifacts such as mummies and fresco paintings [29, 30].

Compton x-ray backscatter imaging has also been widely deployed in commercial systems for various Homeland Defense missions. These systems can quickly identify large organic threats such as explosives and also small metallic contraband [31]. CBI methods are also used for many kinds of inspection including screening of small to large packages, baggage, vehicles, and cargo containers [32, 33]. American Science and Engineering (AS&E) produced the Z Backscatter Van (ZBV) [34], a mobile backscatter imaging system, employed by the Department of Homeland Security in port and border security inspections for cargo and vehicles crossing national borders [35]. The technology is based on the flying-spot method, which utilizes a rotating chopper wheel and stationary slit that are used to for a thin pencil beam of x-rays that are used to raster scan the target. One or more large area detectors and fixed irradiation geometry record the backscattered x-rays. Most notably is the application of this flying-spot approach utilized in the high profile systems installed at public airports for the passenger screening of hidden contraband [36]. The Transportation Security Administration (TSA) contracted with Rapiscan Systems and utilized their Secure 1000 Series for security screening of individual personnel [37-39].
Despite its many advantages offered over conventional radiography, CBI systems suffer from several limitations, thereby limiting its applications in industry. The problem with detecting photons at such large scattering angles is that the probability for Compton scattering is very low, and consequently the signal-to-noise (SNR) ratio is inferior to traditional transmission techniques. Additionally, low x-ray tube output has been a major flaw in early CBI systems, leading to long image acquisition times and noisy images. The primary disadvantage of traditional CBI methods, however, is their reliance photons that have scattered from only one object to form an image. Object surface imperfections or unknown ridges, as well as the undesired detection of multiple-scatter photons, obstruct and degrade the image quality of these first-scatter dependent techniques, often requiring highly localized collimators on both the x-ray source and detector to extract useful subsurface structure information. The reduction in efficiency results in constraints on detector size, collimation, and mode of detector operation, often leading to high source strength and slow imaging system operation.

Given the limitations associated with conventional first-scatter CBI methods, there were several unique imaging challenges faced in the industrial field, which these methods couldn’t solve. These problems included the detection of buried plastic land mines, material flaws that lie close and parallel to a surface, and flaws embedded within extremely low density materials. Several variants of the CBI method have been developed which rely on the proper selection of x-ray field scatter components, including both single and multiple-scatter photons. These systems have shown significant improvements in image quality and contrast, so much so that in some cases objects that was not visible in conventional CBI become readily discernable.
Lateral Migration Radiography

The detection of nonmetallic antipersonnel (AP) landmines has presented a problem that numerous technologies have been unable to resolve. Even though most AP landmines do in fact contain some metallic components, the quantities are often too small to allow for the effective use of standard metal detection techniques. Several non-imaging backscatter x-ray applications for mine detection have been investigated [40-43]. However, these prior backscatter systems failed to provide a field able system, suffering from high false alarm rates due in part to their sensitivity to background clutter caused by the surrounding buried organic material and surface variations.

In order to solve the long-running and difficult problem of detecting nonmetallic buried land mines, several Compton backscatter imaging methods have been investigated [44, 45]. Lateral Migration Radiography (LMR), a variant of traditional CBI methods, was developed in order to reduce the high false alarm rate experienced with non-imaging methods. While traditional techniques only make use of the single scatter photons, LMR differed in respect to its utilization of both multiple- and single-scatter photons [46-55]. The difference in photon absorption and scattering properties of the irradiated targets were utilized to produce an image of the object.

The technique outputs are tomographic images of electron density and/or atomic number variations on planes perpendicular to the x-ray illumination direction at controllable depth from the surface. In order to achieve this optimal selection of the scatter field, two types of properly configured large-area detectors were used in the LMR system. The uncollimated detectors primarily record single-scattered photons, producing images that contain mostly surface or near-surface features. The collimated detectors generate images that contain both surface and subsurface contributions,
formed by detection of primarily multiple scatter photons. A rotating source collimator is used to sweep the x-ray beam across the surface of the soil. The use of two detector configurations and subsequently two image sets make LMR useful for imaging objects to depths of several photon mean free paths around 10 cm, even in the presence of surface clutter, where conventional techniques fail. The use of both detector types allows for the removal of the effects ground-surface variations.

The resulting images produced by the LMR system were extremely definitive in detail, as evidenced by their high contrast. Image intensity signals were in the range of 20 to 300 percent above the background soil image. The success of this technique is based on the impressive contrast generated by the alteration of migrating photons travelling lateral to the illuminating beam direction. The method is extremely sensitive to density and/or atomic number variations along the lateral migration path. The key aspect of the mines was the presence of the low-density interior air volumes, which are transparent to laterally migrating photons, resulting in their enhanced detection probability and thus high intensity signal. The land mine signatures were so unique, that not only can mine detection be achieved but also mine identification, therefore solving the difficult diagnostic problem of buried plastic landmine detection.

Radiography by Selective Detection

Following the successful work on landmine detection, it was proposed to exploit the impressive contrast of the LMR technique to the detection of a class of subsurface defects in materials and structures of industrial importance [56-59]. The detection of material flaws which lie close to, and parallel to, a surface represent a difficult diagnostic problem other inspection techniques have failed to solve. Image contrast is based on alterations to the photon lateral migration path relative to the illuminating beam
direction. This feature makes the technique sensitive to density and/or atomic number variations along the direction of laterally migrating photons. Thin, but large density variations caused by cracks and delamination, generate signal-to-noise background ratios sufficient to produce images of features that aren’t detectable in the usually interrogated thin dimension.

Modifications to the current LMR technique were necessary to scale the method from the centimeter resolution employed in landmine detection to the sub-millimeter resolution required in most NDT applications. The new technique was given the name Radiography by Selective Detection (RSD) [60, 61]. Although the two systems are similar, the LMR technique primarily counts multiple-collision backscattered photons that have laterally spread out from the primary x-ray beam entrance point whereas RSD techniques depend primarily on single-collision backscatter photons. Also, the addition of adjustable detector collimators allows for the preferential selection of which backscattered photons will be counted. Information relating to specific locations and properties of a target object can then be extracted.

A typical RSD system consists of adjustable collimators that limit the scatter acquisition to a depth at or below an imaginary plane, blocking the near surface scatter above the plane from being detected. A pencil beam of x-rays, located between the detectors, moves in a raster motion in order to build up the 2D images. The technique is considered unique because it collimates to a plane instead of a particular point as demonstrated by other pencil beam techniques. Collimating to a plane allows it to use a combination of single and multiple scatter events from various scan depths, which can be used to image a variety of defects, and scan for objects at different depths.
The images acquired by RSD systems demonstrate the capability of detecting and imaging subsurface material defects and geometrical structural changes on the inside of shell-like components with only single-sided access. The system was capable of detecting voids, delamination, relatively small composition changes, including corrosion on surfaces between layers of structural sheets, and subsurface flaws as small as 50 microns in height, 1 mm in width, and 1 cm long. A wide variety of materials have been imaged including aluminum, plastics, honeycomb structures, laminates, steel, reinforced carbon-carbon composites, concrete, and titanium.

RSD systems were also successfully applied to the inspection of the spray on foam insulation (SOFI) used on the external fuel tank of the space shuttle [62, 63]. The extremely low density (0.3 g/cm$^3$) of SOFI present a challenging diagnostic situation that other scatter imaging methods were unable to solve. However, the images produced by RSD scanning systems were able to resolve voids and delamination as small as 6 mm that were located below 50 to 100 mm of foam.

**Collimated Segmented Detector Scatter X-ray Imaging**

A significant downside to the RSD scanning techniques is the extremely long image acquisition times. The use of a narrow pencil beam requires shielding the majority of the photons exiting the x-ray tube in order to reduce beam dispersion. Since only a fraction of the photons produced by the tube are actually used, RSD systems spend a large amount of time on every pixel of the image in order to limit statistical uncertainties. Collimated Segmented Detector Scatter X-ray Imaging (CSD-SXI) systems were designed in an effort to reduce the acquisition times associated with RSD [64]. The method employs a fan beam source of x-rays, which provides a more efficient use of the photon source, resulting in many more photons per unit time than a pencil beam source.
A pixelated linear detector array is placed parallel to the widest dimension of the fan beam in order to simultaneously acquire one line of data. The scanning approach, known more generally as the line-by-line approach, is more efficient than the point-by-point method, utilized in RSD systems.

The original design utilized a fan beam source coupled to an uncollimated segmented one-dimensional detector array. The scan of a target object composed of both lead and nylon resulted in an image of very poor quality and minimal contrast. Given the highly absorbing material which results in a low count rate of scatter x-rays and the highly scattering nylon, a strong contrast should be visible between the two materials. However, the measured flux for pixels located over the nylon compared to those over the lead showed very little difference. The result was explained by the fact that each pixel can detect photons backscattered from any direction in the target object, and not exclusively those coming directly from below it. Consequently, each pixel will detect photons backscattered from both lead and nylon, resulting in an averaging of their signals, which causes the contrast to be greatly reduced. These results demonstrated that very little information could be obtained from the measured intensities for a fan beam coupled to an uncollimated pixel array.

A more suitable method for using a segmented detector and fan beam source would be to restrict each pixel to only detect backscatter photons that come from directly below it through mechanical collimation. By fitting a grid of highly absorbing material, such as lead or tungsten, onto the segmented detector, each pixel could only detect photons coming from within a limited solid angle. Repeating the scan of the lead and nylon target confirmed this assumption, resulting in images with comparable
contrast to those of the RSD technique. However, the addition of a collimator also resulted in the measured fluxes decreasing by two orders of magnitude relative to those measured in the uncollimated setup. Furthermore, the resolution was found to be inferior to the RSD system in the direction perpendicular to the segmented detector. The collimator and width of the fan beam was shown to determine the limiting spatial resolution. Although the image acquisition using the collimated system were a quarter of those used for an identical RSD scan, the contrast and resolution were visibly better in the RSD system for various materials tested.

**Limitations and Improvements on Prior Work**

The Compton scatter method has a genuine potential for solving difficult industrial problems, such as inspection of subsurface layers in wood ties. However, CBI techniques suffer from an inherent limitation: slow scanning speeds or very high-energy sources are necessary to achieve good spatial resolution. As a result, bulky shielding is required and mobile imaging systems become hard to construct. In addition, the design of Compton imaging systems is relatively problem-dependent so that it is difficult to produce a general-purpose device.

The principal difference between previous work in testing applications of Compton scattering and what is attempted in this research is the heavier importance placed on fast scanning speeds. The requirement for fast scanning speeds in the prototype system can only be achieved with the approach used in the CSD-SXI system, of a fan beam coupled to a collimated detector array. However, the CSD-SXI system suffered from several limitations that need substantial improvement in the aspects of efficiency, resolution, inspection speed, and geometrical layout. First, the resolution was different between the two orthogonal directions, or perpendicular and parallel to the
length of the segmented detector array. Furthermore, in the direction perpendicular to
the detector, resolution was inferior compared to that obtained with RSD techniques.
The collimator dimensions of the source and detector, as well as the standoff distance,
were found to have a large effect on the resolution, contrast, and count rates. In order to
solve this resolution dilemma, more work must be done to determine the effects both
detector and source beam size, as well as system geometry have on resolution.

The x-ray source used in the CSD-SXI system used very low energies requiring
small scanning speeds and very small relative distances between the detector, source,
and object. To scan an area of 4 cm x 4 cm, image acquisition times were around 3
minutes. The standoff distance between the detector and object was 3 cm, and the
array was placed 9 cm below the x-ray tube. Such small distances in the geometrical
layout are not practical for a large-scale railroad track scanning system. Since
improvements in resolution come at the expense of efficiency, an optimal solution for
these various system parameters must be experimentally determined in designing the
prototype system.

**Objective of Research**

In this work, the use of Compton backscatter of x-rays for flaw detection in wood
crossties is studied. The main aim of this research is three fold. First, the imaging
principle and underlying physics pertinent to CBI systems is presented. Second, the
mathematics and theory of characterizing imaging systems quality is described. The
design and construction of a novel CBI prototype system for NDT of rail ties is
discussed, along with the preliminary experimental x-ray backscatter imaging results.
Third, the dependence of image quality on system design parameters are investigated
and quantified through the construction and use of system-specific test tools, as well as
through the adaptation of established conventional radiography methods to this novel scanning technique.
CHAPTER 2
THEORY

Photon Interactions

A detailed understanding of Compton backscatter imaging as a NDT technique and the characteristics that contribute to its system performance, requires knowledge of the kinematics and probability of principle photon interactions occurring within the target material. At photon energies characteristic of x-ray machines and radioactive isotopes available for commercial use (100 keV and 2 MeV), three interaction processes are possible: photoelectric effect, Compton scattering, and pair production. The relative probabilities of their occurrence depend on the energy of the incident photon and the atomic number $Z$ of the absorbing medium. Pair production isn’t a dominant mode of interaction for low-$Z$ materials and photon energies below 10 MeV. Since commercially available isotopes do not emit gamma rays with energies greater than 2 MeV, and because x-ray tubes having energies above 1 MeV are too bulky and heavy for field use, only the photoelectric effect and Compton scatter interactions must be considered in CBI methods.

**Photoelectric Effect**

In the photoelectric event, the energy of the incident photon is fully transferred to a tightly bound atomic electron, subsequently ejecting the electron from the atom. A portion of the initial photon energy is used to overcome the small electron binding energy, transferring the majority of this remainder to the ejected electron and leaving a very small amount of recoil energy to the atom in order to conserve momentum. In order for the photoelectric effect to occur, the incident photon energy much exceeds the electron binding energy.
The probability of photoelectric absorption depends on the primary photon energy $E_0$, electron binding energy $E_b$, and the atomic number $Z$ of the absorbing medium. The photoelectric effect is the predominant mode of interaction for photons of relatively low energy ($<100$ keV) and is enhanced for absorber materials of high atomic number $Z$. Provided that the incident photon energy exceeds the electron binding energy, the closer $E_0$ is to $E_b$, the larger is the probability for the photoelectric effect to happen. The atomic cross-section as a function of energy exhibits a saw tooth pattern in which the sharp discontinuities, known as absorption edges, occur where the photon energy coincides with the binding energy of the atomic electron shell. The probability of photoelectric absorption per atom can be approximated using

$$\tau_a \approx k \frac{Z^n}{(E_0)^m}$$

where $k$ is a constant, the exponent $n$ is approximately 4 for low-energy photons (0.1 MeV), gradually rising to almost 5 for high-energy photons (3 MeV), and $m$ is approximately 3 for low-energy photons, gradually decreasing to about 1 at 5 MeV [65].

**Compton Scattering**

As the x-ray energy increases beyond the binding energy of the electron, photoelectric absorption decreases rapidly and the Compton scattering effect becomes more probable. Of all the photon interaction processes, Compton scattering is dominant for most materials over a wide range of industrial radiographic energies. For low-Z media, the region of Compton dominance is very broad, extending from approximately 20 keV to 30 MeV, with the effect gradually narrowing with increasing $Z$. The Compton mechanism occurs when an incident photon is scattered off an electron and the photon energy is considerably greater than the binding energy of the electron. The photon will
then transfer some of its energy to the electron as well as undergo an alteration in its initial trajectory. Using the conservation of energy and momentum laws, an expression relating the scattered photon energy $E_s$ to the photon scattering angle $\theta$ can be derived as

$$E_s = \frac{E_0}{1 + \frac{E_0}{m_0c^2}(1 - \cos \theta)}$$

(2.2)

where the rest mass energy of the electron is given by $m_0c^2$ (511 keV).

The incident photon can scatter in the range from $0^\circ$ to the maximum scattering angle $180^\circ$, referred to as forward and backscattering events, respectively. Plugging $\theta = 0^\circ$ into Equation 2.2 illustrates that some portion of the original energy is always retained by the incident photon and that the scattered energy will cover a range of values. For small scattering angles, very little energy is transferred, whereas in the other extreme case for backscattering events, these lead to the largest loss of photon energy. Plotting the scattered versus incident energy, shown in Fig. 2-1, demonstrates several important relationships evident in Compton scatter events. For angles greater than $0^\circ$, a saturation value is reached for the scattered energy no matter how high the incident photon energy. As the scattering angle increases, the saturation value decreases, approaching a minimum value of 255 keV for backscatter events. These results demonstrate for backscatter events, the scattered energy is lowest of all scattering angles and increasing incident photon energy beyond a certain point won’t achieve a scattering energy beyond 255 keV.

It is important to remember than none of the previous equations provide information about the probability of a photon or an electron being Compton-scattered in
any particular direction. When a photon interacts through the Compton effect, it can be scattered in all possible directions. Compton scattered photons have an angular distribution that depends on the incident photon energy, with the probability varying with scattering angles. The angular distribution of Compton scattered photons can be described by the well-known Klein-Nishina differential cross-section for scattering of photons by a single free electron:

\[
\frac{d_e \sigma_c}{d\Omega} = \frac{r_0^2}{2} \left(1 + \cos^2 \theta\right) \left\{ \frac{1}{1 + \alpha \left(1 - \cos \theta\right)} \right\}^2 \times \left\{ 1 + \frac{\alpha^2 \left(1 - \cos \theta\right)^2}{\left[1 + \alpha \left(1 - \cos \theta\right)\right]\left[1 + \cos \theta\right]} \right\}.
\] (2-3)

Equation 2-3 specifies the probability a photon will be scattered into a determined angle \(\theta\) per unit solid angle \(\Omega\) and per electron where \(\alpha\) is the dimensionless ratio \(E_0/m_0 c^2\) and \(r_0\) is the classical electron radius of \(2.82 \times 10^{-13}\) cm. Equation 2-3 assumes the electron
is initially free, which is only valid for if the energy transferred to the Compton electron is much greater than its binding energy. If this doesn’t hold, the binding energy of the electrons must be taken into account by applying a correction to the Klein-Nishina cross-section.

The implication of the Klein-Nishina formulation is best described using Fig. 2-2, which shows the probability of photon scattering in any direction for incident photon energies of 2.5 keV up to 1 MeV. At low energies (below 100 keV), the spatial distribution of the Compton intensity is generally isotropic, with the backscattered radiation being almost as strong as that in the forward direction. As the energy increases, the cross-section becomes increasingly forward peaked, with an incident energy of 500 keV or greater showing the largest predominance for forward scatter.

Figure 2-2. Dependence of the Klein-Nishina cross-section on scattering angle for incident photon energies of 2.5 (outermost curve), 25, 50, 100, 250, 500, and 1000 keV (innermost curve). Cross-section has been normalized to the squared electron radius $r_0^2$. 
Although Fig. 2-2 appears to imply that forward scatters into very small angles dominate the angular distribution, there is still sufficient intensity at all angles to permit the backscatter technique. Therefore, positioning the detector and source on the same side of the target object is still feasible even at higher photon energies.

The total Compton cross-section per electron for a photon of energy $E_0$ is obtained by first expressing the differential scattering cross-section in an alternative way, describing the probability of scattering into a solid angle defined by an annular ring of angular width $d\theta$ centered on angle $\theta$. However, for un-polarized photons, the scattering probability does not depend on the azimuthal scattering angle, and the following relationship between the two solid angles can be applied:

$$d\Omega = 2\pi \sin \theta \ d\theta.$$ (2-4)

Inserting Equation 2-4 into Equation 2-3 and integrating the differential cross-section over the entire angular range of 0 to $\pi$ for $\theta$ gives the electronic Compton cross-section

$$e\sigma_c = 2\pi r_0^2 \left\{ \frac{1 + \alpha}{\alpha^2} \left[ \frac{2(1 + \alpha)}{1 + 2\alpha} - \frac{\ln(1 + 2\alpha)}{\alpha} \right] + \frac{\ln(1 + 2\alpha)}{2\alpha} - \frac{1 + 3\alpha}{(1 + 2\alpha)^2} \right\}$$ (2-5)

in units of cm$^2$ per electron. Since the Compton effect is an interaction with a single electron, and the electron binding energy has been assumed to be zero, the Compton atomic cross-section is obtained by multiplying the electronic cross-section of Equation 2-5 by the atomic number $Z$ of the absorber

$$a\sigma_c = Z_e\sigma_c$$ (2-6)

which is given in units of cm$^2$ per atom. Equation 2-6 illustrates that the Compton atomic cross-section is therefore linearly proportional to $Z$.

The two major interaction processes, photoelectric absorption and Compton scattering are what give rise to contrast in Compton backscatter imaging techniques.
The contrast follows from the dependence of the various interactions processes with the atomic number $Z$ of the scattering material. However, their contribution modulates the detected flux intensity in opposing ways. While the photoelectric effect serves to reduce the scatter signal, Compton scatter interactions serve to increase it. At a given photon energy and $Z$, the relative probability of scattering is the ratio of the Compton linear attenuation coefficient $\sigma$ to the total attenuation coefficient $\mu$ of the absorber material.

$$P_s = \frac{\sigma}{\mu} \approx \frac{\sigma}{\sigma + \tau}$$

The atomic cross-sections given in Equations 2-1 and 2-6 are converted to their linear attenuation coefficients by multiplication with the number of atoms per unit volume of the absorber. In Equation 2-7, the total cross-section only included photoelectric and Compton events since most industrial radiation sources are less than the pair production threshold. The numerator of $P_s$ has a linear dependence on $Z$ as indicated by Equation 2-6, whereas the denominator has at least a $Z^n$ dependence, where $n$ is greater than 1 as shown in Equation 2-1. The implication is that $P_s$ is higher for low-$Z$ materials than for high-$Z$ materials.

An example of this behavior is shown in Fig. 2-3 which plots $P_s$ with incident photon energy for the typical materials encountered in the inspection of railroad wood crossties: wood ($Z = 6$), iron ($Z = 26$), and granite ($Z = 13$). It is clear that for the energy range between 10 and 250 keV, the $P_s$ value for the lowest $Z$ material, wood is more than that for granite or ballast. Beyond this energy range, the $P_s$ values for these two materials are very close because for energies greater than 250 keV, the absorption cross-sections for granite and wood are very close to each other and have a larger effect than the scattering cross-section. However, it is clear that the $P_s$ for iron is lower
than both wood and granite for the energy range between 10 and 300 keV. Based on the sensitivity of photon scatter to atomic number Z, many imaging applications of Compton scatter have been developed.

Figure 2-3. Comparison of the scattering probability for the three common materials encountered in railroad track inspection.

The Backscatter Radiography Technique

Compton scatter inspection techniques are based upon the detection of radiation scattered from the target object. Any two-dimensional (2D) image, whether it’s based upon conventional or scatter radiography techniques, represent the photon distribution mapped over space. Simply placing a position sensitive detector directly in front of the distributed photon source will not generate these images since the detected photons cannot be traced back to any specific part of the source. Put another way, detected photons do not give any spatial information on the nature of its source, making it
impossible to generate images from these indications. Any imaging system therefore must be able to link the photon detected to its place of emission.

The most common method of achieving spatial information is with mechanical collimators. Source collimation aims the incident photon beam in a particular direction and shape. Detector collimation focuses the detector FOV on a particular voxel along the incident photon beam. By constructing the lamellae out of a strongly absorbing material such as lead or tungsten, they are opaque to radiation, allowing the passage or detection of only those photons coming from a line perpendicular to the collimator axis. By establishing this one-to-one correspondence between the detector and object, images are the directly formed by recording this photon distribution as the detector and collimator are moved.

A variety of CBI system configurations have been proposed since its conception in 1956, using various arrangements for the primary and scatter beam geometries. These possibilities are categorized according to the number of scatter voxels that are simultaneously measured. Of historical importance is the point-by-point imaging scheme, originally conceptualized in one of the first Compton scatter imaging systems developed, yet still one of the most common techniques employed today [66]. The imaging approach, shown in Fig. 2-4, utilizes absorbing apertures to collimate the primary radiation source S into a narrow pencil beam, approximating a 1D line in the propagation direction of the x-ray beam. A single detector D is arranged to record the scatter signal through a collimator focused to a point P within the XZ plane. The intersection of the detector collimator’s FOV and pencil beam comprises the sensitive volume V, providing information for one pixel in the XZ plane. For each x-ray beam
position, the system measures sequentially the scatter from a series of points lying along the primary photon beam path, forming an intensity modulated line of x-ray data comprising different depths within the material. The entire 2D raster image can then be constructed by moving either the target object under inspection or both the source and detector combination in a direction perpendicular to the x-ray beam, along both the Z and Y direction.

Figure 2-4. Schematic of point-by-point scanning approach for Compton scatter imaging.

Compton scatter imaging is particularly attractive for inspecting objects made from uniform materials or well-defined structures. By probing an object, one can detect the presence of discontinuities, such as flaws or voided space, through the presence of abrupt changes in the profile of the scattering signals. Backscatter imaging systems are
possible because the number of x-ray photons scattered from a volume element within an object is a function of the voxel’s density. In order to understand the physical processes underlying the CBI technique, a simplified measurement model can be used to highlight the basic features contributing to and affecting the detected signal.

To model the scattering process, the empirical formulas are based upon the simple configuration previously discussed in Fig. 2-4. The source is collimated to a thin pencil beam directed perpendicular to the surface of the target under inspection, located a distance $D_{SP}$ from the collimator exit to the inspection point $P$. A detector $D$ is located on the same side of the source and has a collimator that subtends a solid angle $d\Omega$, located a distance $D_{PD}$ to the scattering site $P$. The intersection of the detector and source’s FOV forms the inspection volume $V$ from which scattered photons are detected.

Only single-scatter photons are considered in deriving this simple model, although both single and multiple scatter events contribute to the overall signal. Additional assumptions include an x-ray beam that is non-divergent, a radiation source that is mono-energetic, the detector efficiency is unity, coherent scattering is negligible, scattered photons along the incident and exit path do not significantly contribute to detector response, and the small attenuation by air between the object and backscatter system can be ignored.

The photon paths from source to detector can be divided into three primary stages, which determine their contribution to the measured signal. Consider the collimated photon source that generates a beam of incident photons having intensity $I_0$ (particles per unit time) and energy $E_0$. The number of incident photons directed
towards the scatter voxel is given by the beam flux $\Phi$, defined as the photon number incident on a unit area of the object per unit time. As the source radiation travels from the source S to point P, the intervening material of the target will attenuate the incident flux. If these photons travel a total distance $X_1$ within the target material before reaching some small volume V, the flux of photons reaching P is

$$\Phi_1 = \Phi_0 \exp \left[ - \int_{x_1} \mu(E_0, x) \, dx \right]$$

(2-8)

where $\mu$ is the linear attenuation coefficient evaluated at the incident photon energy $E_0$ for a given material located along $x$.

The second stage of the photon path involves the single Compton scatter events that take place at point P. Since radiation reaching the sensitive volume can scatter to any direction, only those scattering events directed towards the detector within its solid angle $d\Omega$ will be counted. However, within the voxel there are $\rho_e$ electrons per unit volume of the material. The flux of photons scattered at point P within $d\Omega$ is

$$\Phi_2 = \Phi_1 \rho_e V \int_{\theta_{\min}}^{\theta_{\max}} \frac{d_e \sigma_c}{d\Omega} \, d\Omega$$

(2-9)

where $\theta_{\min}$ to $\theta_{\max}$ represent the range of scatter angles accepted by the detector solid angle, $\rho_e$ is the average electron density of the material in voxel V, and $d_e \sigma_c / d\Omega$ is the differential Klein-Nishina cross-section given by Equation 2-3. The electron density is necessary to translate the electronic cross-section into the linear attenuation coefficient that has units of inverse length.
The third stage of the photon’s path involves their post-scatter attenuation to the detector. Radiation traveling from the scatter point P, along a distance $D_{PD}$ to reach the detector at D, will be attenuated. The flux of photons detected per unit area per unit time

$$\Phi_3 = \Phi_2 \exp \left[ - \int_{x_2} \mu \left( E_S, \frac{x}{\cos(\pi - \theta)} \right) dx \right] \quad (2-10)$$

where $\mu$ is the total linear attenuation coefficient of the target material located along the photon’s exit path $X_2$ and evaluated for the scattered photon energy $E_s$ calculated with Equation 2-2, and $\theta$ is the angle of Compton scatter at P.

Combining the contributions from all three stages of the photon path gives the flux of photons subjected to single-scattering events inside the sensitive volume V that reach the detector. In other words, the detected scatter signal originating from point P is

$$\Phi_{bs} = \Phi_0 \rho_e V \exp \left[ - \int_{x_1} \mu(E_0, x) dx \right] \int_{\theta_{\min}}^{\theta_{\max}} \frac{d\sigma_C}{d\Omega} d\Omega \times$$

$$\exp \left[ - \int_{x_2} \mu \left( E_S, \frac{x}{\cos(\pi - \theta)} \right) dx \right]. \quad (2-11)$$

From this equation, it is clear that the intensity of Compton scatter is directly proportional to the electron density of the scattering material. The electron density is related to the material density $\rho$ through the following equation:

$$\rho_e = \frac{\rho N_A Z}{A} \quad (2-12)$$

where $N_A$ is Avogadro’s number and A is the mass number. For most atoms, except hydrogen, the ratio of Z/A is approximately equal to $\frac{1}{2}$ so that it can be treated as a constant. Therefore, Equation 2-12 demonstrates that electron density is a direct
indicator of mass density in almost all materials (except hydrogen-rich materials). It is thus possible to distinguish between materials of different density by observing the change in magnitude of the photon scattering signal.
CHAPTER 3
EVALUATION OF IMAGING SYSTEMS

The ability to quantify imaging performance is essential to the development of any imaging system, particularly important in the early stages of system design. It provides a method for understanding the factors that limit image quality and also the means for optimizing system performance. Knowledge of image quality also allows one to compare various imaging system designs for a given technique, and to compare the information contained in the images acquired by the different setups. Furthermore, after the system is built and in use, the image quality is measured and tracked over time to ensure that the system continues to deliver the anticipated image quality and operates within the tolerance of the original requirements.

The performance of imaging equipment and the performance of its components can be assessed and specified in terms of just a few physical parameters. The principal components that are used to characterize image quality are contrast, spatial resolution, and noise. Objective image quality measurements such as the signal-to-noise ratio (SNR), the modulation transfer function (MTF), and the noise power spectrum (NPS) can evaluate these quality parameters. These factors all contribute to the measurement of the detective quantum efficiency (DQE), a metric established as the single most important parameter for describing the imaging performance of a system. Therefore, a complete characterization of the physical properties of the digital system requires the determination of the MTF, SNR, NPS, and DQE.

Linear Systems Theory

The relationship between the objects being imaged and the images produced are of fundamental importance in assessing the image quality. Linear system theory
provides a powerful tool for modeling and analyzing various imaging systems. The theory of linear systems can be used to determine the performance of an imaging system, without investigating in detail the various electro-optical parts that contribute to image formation. A system is broadly defined to be that which produces a set of output functions from a set of input functions. Any imaging device is a system, or black box, whose properties are defined by the way in which an input signal, or distribution is mapped to an output distribution, the image.

The most generalized mathematical description for an imaging system is to represent it by an operator $H\{\}$, which acts on the input function $f(x,y)$ to produce the corresponding output image $g(x,y)$. The following relation can describe the input-output relationship of any imaging system.

$$g(x, y) = H\{ f(x, y) \}$$

(3-1)

The operator $H$ is usually called the transfer function or system response function. $H\{f(x,y)\}$ should be interpreted to be the value at point $(x,y)$ of the signal obtained by applying the transformation $H$ on the entire input signal $f(x,y)$. It describes the imaging system and how this maps the object to a noise-free set of measurements. In a perfect imaging system, for all locations in space, $f(x,y) = g(x,y)$. However, almost no imaging system achieves this, and in general, it is necessary to conduct experiments to parameterize the relationship between the two functions.

The determination of the transfer function is rather complicated. It can be notably simplified when the imaging system can be described by two different properties: linear and shift invariant. Linear systems require both the property of scaling and that of superposition. The property of scaling exists when a scale factor $a$ applied to the input
f(x,y) of a system modeled by the operator H will result in the same scale factor resulting at the output g(x,y).

\[ g(x, y) = H\{af(x, y)\} = aH\{f(x, y)\} \tag{3-2} \]

The second property of linearity is that of superposition. Consider two separate inputs \( f_1(x, y) \) and \( f_2(x, y) \) to the imaging system \( H \), which demonstrates the superposition characteristic if the following is true:

\[ g(x, y) = H\{f_1(x, y) + f_2(x, y)\} = H\{f_1(x, y)\} + H\{f_2(x, y)\}. \tag{3-3} \]

The superposition property greatly simplifies the analysis of linear systems and most signal processing techniques are based upon this principle, which states that any signal can be decomposed into a group of simpler additive components. Then, each component is processed individually, and the results reunited. The superposition approach is powerful because a single complicated problem is broken down into many easy ones.

The fact that linearity is commutative is an important property demonstrated when two or more systems are combined. Consider when two systems are combined in a cascaded fashion, where the output of one system is the input to the next. If each system is linear, then the overall combination will also be linear. The commutative property states that the order of the systems in the cascade can be rearranged without affecting the characteristics of the overall combination.

In many linear systems, an additional simplification can be made by assuming that the response function is the same for all input points. In that case, the response function merely shifts its position for different input points, but doesn’t change its functional behavior. Such systems are said to be shift invariant. A system is shift
invariant if the output is independent of the location of the input. Therefore, for any spatial shift to points \((x_0, y_0)\), it follows that for a shift-invariant system the output response will be

\[
g(x, y) = H[f(x, y)] = H\{ f(x + x_0, y + y_0) \}. \tag{3-4}
\]

The implication is that a particular structure in the image will appear the same, regardless of where in the image it is placed.

Linear shift-invariant (LSI) systems form the basis of the equation used to describe an imaging system. If an input function to a system \(H\) is modeled by a delta function \(\delta\), then the output is given by

\[
h(x, y) = H[\delta(x, y)] \tag{3-5}
\]

where \(h(x,y)\) is known as the system impulse response function. The 2D delta function \(\delta(x,y)\) is characterized by infinite height, zero width, and is used to represent an ideal point input function. Since the output will never be an exact representation of the input for any real system, the output will be a blurred and broadened distribution, instead of an ideal delta function. The impulse response therefore characterizes the blurring properties of a system.

Using the linearity property given in Equation 3-3, the input consisting of a weighted summation (integral) of several signals will also yield an output that is a weighted summation of the response of the system to individual input signals. The output of a system \(g(x,y)\) to an input \(f(x,y)\) is therefore given by

\[
g(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y)h(x - x', y - y')dx \, dy. \tag{3-6}
\]
Equation 3-6 is the convolution of the output with the system’s impulse response, and is referred to as the convolution integral. The convolution integral is a fundamental equation in the imaging field because it describes mathematically what happens to the input signal physically.

The importance of the convolution integral originates from the fact that many situations involving the process of physical measurements with an imperfect system can be accurately described by convolution. If one knows the impulse response of the system, then the output can be calculated through Equation 3-6 for any given input function. The convolution integral is often expressed in shorthand notation as

$$g(x, y) = f(x, y) \ast h(x, y).$$  \hspace{1cm} (3-7)

**Fourier Transform**

There are two approaches to analyzing signals and systems: the spatial-domain approach and the frequency-domain approach. Although digital images are most commonly represented in the spatial domain, which exists in real space, they can also be represented in the frequency domain, which lies in abstract space. The two approaches are equivalent with both domains being connected by the common and invaluable mathematical tool known as the Fourier transform. The utility of Fourier theory lies in its ability to make the solution of otherwise difficult problems much easier.

The Fourier transform of an image is an exact representation of the image and no information is lost in the process of Fourier transformation. The choice of whether imaging problems are solved in the spatial or frequency domain is determined by which is easier, and it is often necessary to solve parts of a problem in one domain and the other parts in the conjugate domain. Often, more physical insight into a problem can be achieved in one domain over the other.
The computation in the spatial frequency domain is easier than in the spatial domain because multiplication is used instead of convolution, as demonstrated later with the Convolution Theorem. This is why the frequency domain representations are often applied in the analysis of a digital imaging system’s performance, using quantitative Fourier-based metrics such as the modulation transfer function (MTF), noise power spectrum (NPS), and detective quantum efficiency (DQE).

The Fourier transform expresses a function in terms of its complex sinusoidal-basis components. The spatial domain signal can be represented in frequency space by applying the Fourier transform equation

$$\mathcal{F}\{f(x,y)\} = F(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \exp[-i2\pi(ux + vy)] dxdy$$  \hspace{1cm} (3-8)

where $\mathcal{F}$ is the Fourier transform operator, and $u$ and $v$ are spatial frequencies corresponding to the Cartesian coordinates $x$ and $y$. In this case, spatial frequency is an inverse or reciprocal index of space or distance, commonly expressed in units of mm$^{-1}$ or cycles/mm. For example, a 3 mm wide object along with 3 mm of air or free space will be represented by a spatial frequency of 1/6 mm$^{-1}$.

One of the most significant applications of Fourier transforms in imaging applications is the calculation of convolutions. The process of convolving two functions in the spatial domain is a rather messy integral, which can be equivalently carried out by a simple and convenient form in the frequency domain; this is provided by the convolution theorem. Consider the system input signal and impulse response represented by the two functions $f(x,y)$ and $h(x,y)$, having Fourier transforms respectively denoted by $F(u,v)$ and $H(u,v)$. The convolution theorem states that the
Fourier transform of the convolution of two functions is equal to the product of the individual transforms.

\[
\mathcal{F}\{f(x,y) * h(x,y)\} = F(u,v)H(u,v)
\]  (3-9)

Thus the process of convolving two functions in the spatial domain can be equivalently carried out by simple multiplication of their transforms in the frequency domain. The convolution theorem forms the essential basis for the powerful methods of frequency-domain filtering.

**Sampled Signals**

In order to process the continuous analog signals produced by the imaging system, they must be sampled periodically and converted into a digital representation. In general, sampling is the process of measuring the value of a continuous signal at regular time or space intervals. The time that separates the sampling points \(T_s\) is called the sampling interval and its reciprocal the sampling frequency or rate \(f_s\). By appropriately choosing the sampling rate, these discrete values can represent the original signal sufficiently. Clearly, the sampling interval must be small enough so that the signal variations occurring between samples are not lost. However, sampling at too small a size becomes impractical from the standpoint of storage.

In order to determine the optimal sampling for a given system, the Shannon sampling theorem is applied. The theorem states that an accurate representation of a continuous signal by its spatial samples must meet two conditions. The first assumes that the signal is bandlimited, defined by a frequency spectrum limited to contain frequencies up to some maximum \(f_{\text{max}}\) and none beyond that. The second condition is that the sampling frequency \(f_s\) must be selected to be at least twice \(f_{\text{max}}\). The frequency
at which this second condition is met is referred to specifically as the Nyquist frequency limit of the sampled signal.

If the imaging signal contains high frequency components that exceed the Nyquist limit, they still appear in the sampled signal, however at a lower spatial frequency. When this occurs, it’s referred to as aliasing because it incorrectly portrays high frequency information present in the object as lower frequency and it degrades the image quality. Aliasing can be avoided by requiring the Nyquist frequency to be greater than or equal to $f_{\text{max}}$ in the image prior to sampling.

**Image Quality Metrics**

Quantifying the image quality is the fundamental measure of system performance, especially important in the design phase of an imaging system since it enables the comparison of competing factors. The three most commonly cited image quality metrics are the spatial resolution, contrast, and noise. The goal of every imaging system is to produce images of high resolution and contrast, and low noise. However, several components along the imaging chain can counteract these goals, requiring a fundamental understanding of their underlying factors in order to construct the most optimal system.

**Spatial Resolution**

The traditional notion of spatial resolution is the ability of an imaging system to distinctly depict two objects as they become smaller and closer together. The closer they are, with the image still representing them as two separate objects, the better the spatial resolution. However, this definition of resolution isn’t very practical because it depends to some degree on the shape of the objects used to define it.
A more informative descriptor is the shape of the system’s response to a sharp impulse function, known as the Point Spread Function (PSF). The PSF describes how well a single point in an object is reproduced in an image. The PSF can be used directly as an indicator of resolution by measuring its full-width-at-half-maximum (FWHM). The PSF is important in imaging because it completely describes the imaging properties of the system and is a spatial domain representation of the resolving power of an imaging detector. Mathematically, if the input point can be described by a delta function, then the output will be the system PSF.

\[
PSF(x, y) = g(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \delta(x, y) f(x, y) \, dx \, dy
\]  

(3-10)

An ideal imaging system would have a PSF exactly equal to the Dirac delta function for all combinations of the input and output coordinates. The system would map each infinitesimal point in the input distribution to a corresponding infinitesimal point in the image output, and no blurring would exist, creating a ‘perfect’ image. In reality, the fundamental physics of electromagnetic diffraction dictates that such an ideal system can never be achieved in practice.

**Modulation Transfer Function**

Although the concepts of spatial resolution can be represented in the spatial domain, it’s incomplete and limited in further analysis. Rather than attempt to define spatial resolution with a single minimum object size parameter, it is better to fully describe the way inherent contrast of an imaged object is lost in the imaging system as spatial frequencies increase. A description of the spatial resolution in the frequency domain is best characterized by the modulation transfer function (MTF). Mathematically, the MTF is the Fourier amplitude of the PSF.
When analyzing an x-ray system in the frequency domain, the imaging of sine wave inputs is considered rather than point objects. If the system is LSI, the response of the detector to a sinusoidal beam input profile would produce an approximately sinusoidal in shape output with the same spatial frequency as the object distribution. The optical imperfections of the system, however, will cause the amplitude of the intensity distribution to be reduced, indicating a loss of resolution in the system. It is customary to describe the sinusoidal distribution in terms of its modulation value \( M \), or amplitude of the modulation response, rather than its amplitude,

\[
M(f) = \frac{I_{\text{Max}}(f) - I_{\text{Min}}(f)}{I_{\text{Max}}(f) + I_{\text{Min}}(f)}
\]

where \( I_{\text{max}} \) and \( I_{\text{min}} \) are the local maximum and minimum intensities, respectively, for a given discrete spatial frequency \( f \) associated with the sine wave pattern of the incident modulation. The finite response of the system’s impulse response reduces the intensity peaks and fills in the valleys of the output sine wave. The effect of this is to decrease the modulation depth in the image relative to that in the object.

A more attractive definition that conceptually describes the MTF is to represent it as the fraction of an object’s contrast reported as a function of the size of the object, relating the frequency domain to the imaging system resolution.

\[
MTF(f) = \frac{M_{\text{image}}(f)}{M_{\text{object}}(f)}
\]

\( M_{\text{image}} \) is the input signal modulation or inherent contrast in the imaged object, and \( M_{\text{object}} \) is the output signal modulation or image contrast. The MTF curve is always
normalized so that the value at zero spatial frequency is unity. The ideal imaging system has a constant value of 1.0 in the entire range of spatial frequencies. In real systems, blurring and un-sharpness introduced by the imaging system affect the higher spatial frequencies, so that only the lower frequencies are well reproduced. As a result, the MTF progressively decreases with increasing spatial frequencies. The fall of the MTF means that smaller details have low contrast. When the MTF reaches zero, the resolution limit of the system is determined.

In the analysis of an imaging system, the resolution is a characteristic of the whole imaging system and only needs to be evaluated once. Therefore, the measured MTF represents the signal transfer over the entire imaging chain. The overall MTF of a system consisting of several components in the imaging chain takes into account each of the individual component MTFs. Because the response of these individual components to any input signal are linear and shift-invariant, the MTF of the system can therefore be described as the product of the individual component MTFs

\[
MTF_{\text{system}} = MTF_1 MTF_2 MTF_3 \ldots
\]  

(3-14)

where \(MTF_1\), \(MTF_2\), and \(MTF_3\) are the MTFs associated with each blurring component. Because each component contributes to the blurring, the overall system MTF is subsequently worse than each individual factor. Furthermore, the weakest transfer element in the chain, or weakest link, dominates the MTF of the entire system and therefore the image quality.

Different measurement techniques can be used to assess the resolving capability and overall MTF of an imaging system. They are based on measuring the response of the detector to simple, known objects to obtain the system response function. As
previously mentioned, the shape of the PSF provides a great and complete measure of spatial resolution from which the MTF can be derived. In radiography systems, the PSF can be obtained experimentally by imaging a small hole bored into a lead sheet. In order to approximate the input source with a delta function, the size of the hole must be small compared to that of the PSF. According to the mathematical definition, the image of a delta function input is exactly the system PSF. However, the construction of a target, which meets this requirement, is extremely difficult to achieve in practice. Furthermore, these very small objects will only transmit a small number of photons, making it difficult to distinguish them from their surroundings.

A different form of sensor stimulus that is easier to apply in practice is to image a narrow slit formed between two lead sheets. The detector's response is the line-spread function (LSF), derived from the one-dimensional profile through the exposure distribution in the direction perpendicular to the length of the slit. The image of the line source is blurred, with the amount of blurring reflecting the resolving power of the imaging system. The LSF is an accurate determination of the PSF. Similar to the PSF; the shape of the LSF provides full information about the spatial resolution characteristics of the imaging system.

From a mathematical point of view, the line-source object input is a delta function in x and a constant in y. The LSF is simply the 2D convolution of the line source object with the impulse response of the imaging system. In other words, the LSF is defined as the one-dimensional integral of the PSF along a given direction, where the details of the response in the orthogonal direction have been integrated out.
Each point in the line source produces a PSF in the image plane. These displaced PSFs overlap in the vertical direction and their sum forms the LSF. Essentially the LSF can be viewed as several PSFs closely spaced along this line.

Measuring the LSF will determine the MTF in the direction that is perpendicular to the axis of the slit. The MTF can be calculated by taking the magnitude of the Fourier transform of the LSF.

\[ MTF(u) = |\mathcal{F}\{LSF(x)\}| = \int_{-\infty}^{\infty} LSF(x)e^{-j2\pi ux} \, dx \quad (3-16) \]

Since this method only provides a one-dimensional MTF, other profiles of the transfer function are obtained by rotating the line source.

The issue with an MTF method that is based upon a slit is the difficulty in directly obtaining the LSF. The edge response method avoids this difficulty by using an indirect form of obtaining the LSF. Instead of using two attenuating blocks, only one such metal collimator is placed in the beam path so that the beam profile incident on the detector resembles a gradient or step profile. The resulting imaging response profile is known as the edge spread function (ESF).

The ESF can be represented by the system response for an input given by the step function. Mathematically, the ESF is the 2D convolution of the PSF with the unit-step function.

\[ ESF(x) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(x', y') step \,(x - x') \, dx' \, dy' \quad (3-17) \]
The y convolution of the PSF with a constant produces a LSF, and the x convolution with the step function produces a cumulative integration. The ESF is a cumulative, monotonically increasing function.

The ESF can be described in terms of the superposition of LSFs. Each vertical strip in the open part of the aperture produces a LSF at its corresponding location in the image plane. The displaced LSFs overlap in the horizontal direction and sum to form the ESF. Taking the limit to smaller and smaller displacements, the summation turns into an integral as shown in the simple relationship equating the two parameters.

\[ ESF(x) = \int_{-\infty}^{\infty} LSF(x')dx' \]  

(3-18)

To convert the ESF to the MTF, the derivative of the ESF must be obtained to invert the integral given in Equation 3-18.

\[ LSF(x) = \frac{d}{dx} \{ ESF(x) \} \]  

(3-19)

Through the use of Equation 3-16, the MTF can then be determined from the ESF data.

An alternative method for measuring the MTF relies upon measuring the system response to an input of sinusoidal variations in x-ray intensity. The incident profile can be provided in practice by imaging an attenuating object whose thickness varies as a sine wave of a particular discrete spatial frequency. However, this approach is not generally used because constructing a sinusoidal pattern from a suitable attenuator would be expensive and the accuracy of the sine wave output would be highly dependent on the x-ray beam quality used. The more commonly applied approach uses square wave patterns that are much easier to fabricate. The square waves are represented by three-bar or four-bar binary patterns, illustrated in Fig. 3-1.
Figure 3-1. Four-bar binary pattern target constructed from line pairs of a fundamental spatial frequency.

For an x-ray imaging system, line pair tools are constructed from bars made of a highly absorbing material such as lead, with an x-ray transparent material between them. One line pair is defined as the attenuating bar width (black) $w$ plus the spacing (white) between bars $w$, shown in Fig. 3-1. Typically, the widths of the lines and the spaces are equal. The line pairs are described in units of line pairs per mm (lp/mm), specified by the fundamental discrete spatial frequency $f$,

$$f \ (lp/mm) = \frac{1}{2w} \quad (3-20)$$

where $w$ is the width of the attenuating bar and the spacing between them. The entire target is composed of four-bar line pairs, which generally have spacing that decreases towards one end of the tool, representing higher spatial frequencies.

The analysis and theory presented over the years have confirmed that for the same imaging system, the bar target derived spatial frequency response and the sine wave target MTF are not equal to one another, but can be related through a mathematical relationship. The spatial frequency response obtained from a bar pattern
target is known as the contrast transfer function (CTF) or square wave response. The Coltman approximation converts the square wave CTF to its equivalent MTF, by correcting for the presence of harmonic contributions in the modulation values and using the Fourier decomposition of the square waves [67].

\[ MTF(f) = \frac{\pi}{4} \left[ CTF(f) + \frac{CTF(3f)}{3} - \frac{CTF(5f)}{5} + \frac{CTF(7f)}{7} + \frac{CTF(11f)}{11} + \ldots \right] \]  \hspace{1cm} (3-21)

The CTF is calculated for each square wave using Equations 3-12 and 3-13, evaluated for the discrete spatial frequency \( f \) associated with the bar pattern width.

For each frequency, a CTF measurement must be made at a series of frequencies that are harmonically related to the desired frequency of the MTF. The fact that the frequency of evaluation increases with each successive term in the expansion indicates that for evaluation at higher and higher frequencies, fewer and fewer terms are used because no modulation values are available above the cut-off frequency. For evaluation frequencies greater than \( 1/3 \) of the cut-off frequency, only the first term exists, resulting in a simplified expression given by:

\[ MTF(f) \approx \frac{\pi}{4} CTF(f) \]  \hspace{1cm} (3-22)

where \( f_{\text{cut-off}} \) is simply the Nyquist limit of the system [68].

**Presampled MTF**

A complication in applying the MTF concept to digital detectors results from the fact that these systems perform discrete sampling over a finite area. Undersampling in digital systems occurs when the image is not finely sampled enough to record all spatial frequencies without aliasing. Almost all digital detectors are undersampled to some degree, due to tradeoffs that must be faced in designing a suitable system. Although
possible to sample finely enough so that no aliasing takes place, such an image would contain a large volume of data that would strain the storage technology.

The issue presented by undersampling is that aliasing results in a non-linear imaging system. Digital systems with discrete sampling are actually space variant; the response of digital detectors to an MTF target object will depend on where on the array the target falls. If for example the target is aligned within a single pixel so that most image intensity falls completely on the single-detector element, then the signal produced is spatially compact. However, if the target falls between two adjacent pixels, most of the flux is split between the two, which results in further spillover to adjacent pixels thus producing a broader response or PSF. Therefore, although identical sources are imaged in both scenarios, significant differences are seen in the sampled images because of the different spatial phase of each source relative to the sampling grid.

Aliasing has the potential to cause significant errors in transfer function analysis, particularly in the case of MTF measurements. In the context of the sine wave target, the space variance means that the phase between this target and the scanner’s detector array plays a role in the actual MTF achieved. Phase is the location of the detector’s pixel within a sine wave period at the time the pixel is collecting light energy. As the target-detector phase changes, the system MTF can change. Computing the MTF for this sampled system would thereby lead to a Fourier transform that depends on the alignment of the target with respect to the detector, with the best alignment giving the broadest MTF. Visually this translates to an image appearing degraded as the sampling grid is moved across the object.
Various techniques exist for correcting and overcoming this issue of undersampled system, requiring major modifications to the MTF methodologies used to obtain slit, edge, and modulation response profiles. The fundamental concept used by all is to have the MTF test target located with different phasing with respect to the sampling grid. Therefore, the target is intentionally oriented so that its boundary does not match the pixel axis of the sensor but is tilted at a slight angle. The angle of the median axis $\theta$ of the edge effectively displaces successive rows of pixels by a very small sub-pixel distance given by

$$\Delta x = p \tan \theta$$  \hspace{1cm} (3-23)

where $p$ is the pixel size in the detector. By using this process, the data are rearranged and the distances between each point decrease, resulting in a sampling frequency increase [69]. For example, if the rotation is $15^\circ$ then the spacing of the samples will be a little less than one-fourth the pixel pitch, giving an effective resolution of about four times that which could be given by the detector array in normal use.

The increase in sampling frequency is achieved by using a group of $N$ consecutive rows to construct an oversampled edge or line response function. In the ideal case, the number of rows $N$ should be selected so that the edge line just passes through one column of pixels

$$N = \text{round} \left( \frac{1}{\tan \theta} \right)$$  \hspace{1cm} (3-24)

where the tangent value of the angle is utilized.

An important fact to note is that the MTF measured by these angulation techniques does not represent the entire system MTF. Since such un-aliased MTF spectra represent the spatial resolution of imagers prior to sampling effects, they are
referred to as presampled MTF. The total MTF of a digital detector includes both the presampling and the digital component. In digital systems with no aliasing due to oversampling, the digital MTF and the presampling MTF are the same.

**Noise**

The sensitivity and accuracy of any detection system is limited not only by blurring caused by transfer characteristics, but also by random fluctuations that always accompany the measurement. These stochastic fluctuations in the acquired signals are known as noise. In digital imaging systems, image noise is an important measure of the image quality and its existence can be attributed to many different processes, including the generation of the signal carriers, propagation or transformation of these carriers through the imaging process, and the addition of extraneous noise from various sources such as the imaging electronics.

The total noise in a digital sensor is the result of three primary noise sources, described by the following equation

\[
\sigma_{Total} = \sqrt{\sigma_{Elec}^2 + \sigma_{Quant}^2 + \sigma_{FP}^2}
\]  

(3-25)

where \(\sigma_{Elec}\) is the electronic read noise, \(\sigma_{Quant}\) is the photon statistics limited quantum noise, and \(\sigma_{FP}\) is the fixed pattern structured noise. The ideal sensor response would demonstrate that each noise source is dominant at different signal levels. Additive electronic noise is introduced by electronic components in the system, such as read noise and dark current that are present even in the complete absence of external signal. Read noise is mainly due to on-chip transistors and amplifier noises, but can also include any other noise sources independent of signal level. Dark current corresponds to thermally generated charge carriers inside the photodiode, created even in the
absence of external signal and caused by thermally excited electrons. The dark current builds up a dark signal over time, and random fluctuations in this signal are called dark noise.

For low signals, the system is dominated by electronic contributions because this source represents the random noise measured under totally dark conditions. There is no change in noise as the signal intensity increases because electronic noise is independent of signal level. At higher signal levels, it has an almost negligible effect as the quantum noise becomes increasingly important.

Photon noise arises from the quantized nature of light, seen by the variation in the number of photons arriving at the detector and demonstrating a Poisson distribution in the number of x-ray photons absorbed by the detector material. Due to the Poisson statistics, quantum noise is given by the square root of the input signal, represented by the number of x-ray photons incident on the detector. At long exposure times and high enough flux, the photon noise will become dominating and other sources of noise may be neglected. The system is then defined as quantum-noise limited, with the photon noise setting the ultimate limit to the minimum detectable signal.

Static noise, or fixed pattern noise (FPN) describes the spatially fixed variations in gain across the detector, related to pixel-to-pixel and column-to-column non-uniformities, due to differences in sensitivity and the transistor’s gain inside each pixel and differences in the gain of columns amplifiers, respectively. Sources of structure noise include damage on the scintillator or a variation of gain between different pixels in the sensor. This noise is static and can be completely removed by making a flat-field correction to remove the fixed spatial pattern evident from frame to frame. The
magnitude of the FPN is assumed to be proportional to the signal level. It is dominant for high signal levels, beyond those associated with quantum-limited systems.

The amount of noise present in detector pixels will affect the visibility of the image. In cases where the noise is large with respect to the signal, the image will be impossible to interpret even if the resolution is high. Therefore, it’s often desirable to reduce it to as much as possible through system design and operation. This is only possible with an accurate and detailed understanding of the system’s noise transfer characteristics must be known.

In addition to measuring the absolute level of noise in a sensor pixel, it’s also important to evaluate whether noise components are correlated over a number of pixels. Correlation drastically enhances the visibility of noise due to the spatial integration performed by the visual system of the human observer. Image noise is said to be uncorrelated if the value of each pixel is independent of the values in other neighboring pixels. If this is true, then the complete characterization of the system noise is simply obtained by calculating the variance of the image on a per pixel basis. Uncorrelated noise, known as white noise, has all spatial frequencies represented in equal amounts. All x-ray noise in images begins as white noise since the production of x-ray quanta at any point in time and any particular direction doesn’t depend on the previous quanta that was created, or any subsequent quanta to follow. Thus, the production of x-ray quanta is described as an uncorrelated process in both time and space.

However, the difficulty in imaging systems is that most resultant images are uncorrelated in space since each x-ray will create multiple secondary carriers that are necessarily correlated, with each carrier then diffusing from a single point of creation.
The subsequent signal recorded from a singular x-ray is often spread among several pixels, leading to the reduction in pixel variation and neighboring pixel values that are correlated. In order to properly describe the noise characteristics of these systems, a more complete and accurate metric than the spatial domain variance is the noise power spectrum (NPS) in the frequency domain. The NPS provides an estimation of the spatial frequency dependence of the pixel-to-pixel fluctuation presented in the image.

In order to apply these Fourier-based descriptions of image noise, two important assumptions must be made. The first is that the processes responsible for noise both in the input signal and within the imaging chain be wide-sense stationary (WSS). A random process such as noise fluctuations in an image is considered WSS if its autocorrelation function is independent of the particular data sample (e.g. the particular location in the image) used to obtain it. The autocorrelation function is a measure of the spatial correlation of noise patterns within an image. The second assumption is that the system be ergodic. Noise in an image is defined as ergodic if expectation values obtained from data samples at various locations in the image are equivalent to ensemble averages obtained from many repeated measurements under identical conditions at a single location.

If the system meets both conditions of ergodicity and WSS, then the NPS completely describes the noise properties of the system. In mathematical terms, the NPS of a finite area measurement is the ensemble average of the square of the Fourier transform of the spatial density fluctuations

\[
NPS(u, v) = \lim_{N_x,N_y,M \to \infty} \frac{\Delta x \Delta y}{M N_x N_y} \sum_{m=1}^{M} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \left| I(x_i, y_i) - \bar{I}(x_i, y_i) \right|^2 e^{-j2\pi(u_n x_i + v_n y_i)}
\]
where \( I(x_i,y_i) \) is the image intensity at the pixel location \((x_i,y_i)\) in a uniformly exposed open field image, \( \bar{I}(x_i,y_i) \) is the mean intensity in each sub region, \( u \) and \( v \) are the spatial frequency conjugates of \( x \) and \( y \), \( N_x \) and \( N_y \) are the number of pixels in the \( x \) and \( y \) directions of the digital image, \( M \) is the number of regions used for the analysis of the ensemble average, and \( \Delta x \) and \( \Delta y \) are the pixel spacing’s in the \( x \) and \( y \) directions [70].

Conceptually the NPS is easier to grasp than the mathematical one just presented. The NPS is also the Fourier transform of the autocorrelation function. A highly uncorrelated noise pattern will render a sharply peak autocorrelation function and a broad NPS, while correlated noise will have a broader autocorrelation function and a narrow NPS. The NPS can also represent the spatial pattern of noise, in addition to its magnitude. The lower the NPS, the better or lower is the noise within the image.

The NPS is measured experimentally by recording an image without an object between the source and detector or using a uniform object to obtain flat-field images at the desired beam qualities and exposures. The resulting image will have variations due to detector non-uniformity and inherent statistical fluctuations in the x-ray source beam. The noise is the uncertainty with which a signal is reproduced, and it can be characterized by the standard deviation of the intensity measurement obtained at the imaging detector.

The NPS spectrum obtained from the equation above is a 2D spectrum of the imaging system variance, and it is often desirable to extract 1D NPS components along individual axes. The acquisition of 1D NPS spectra is also necessary to conform to the MTF measurements that are obtained along individual coordinate axes for further characterization of imaging performance. One-dimensional traces through the two-
dimensional NPS are obtained by orthogonal, diagonal, or radial band averaging of the two-dimensional spectrum.

**Detective Quantum Efficiency**

The most commonly used parameter for characterizing the effectiveness and overall performance of imaging systems is the detective quantum efficiency (DQE). DQE is a useful descriptor of image detector performance because it takes into account detection efficiency, spatial resolution, and noise. The x-ray detection system is an integral component of any imaging system. In order to obtain the maximum system performance, and hence optimize image quality, information through the form of signal and noise, must be transferred as efficiently as possible from input to output in the system.

The DQE describes the relative efficiency in maintaining the SNR level available in the imaging process. It can be conceptually represented by

\[
DQE(u) = \frac{SNR_{in}^2(u)}{SNR_{out}^2(u)}
\]  

where \(SNR_{in}^2\) represents the signal-to-noise ratio of the incident radiation and it equals the incident number of quanta per unit area according to the Poisson distribution of x-ray photons. \(SNR_{out}^2\) is the signal-to-noise ratio in the output image.

The ideal scenario represents a detector that preserves the input SNR. However, the reality is that various physical processes within the detector will further degrade the SNR. The detector component within an imaging system chain can be viewed as having its own underlying sub processes, including x-ray physics, secondary quanta physics, and digital sampling effects. Efficient SNR transfer is important because the detection performance of both humans and ideal observers improves with increasing SNR.
The DQE expresses the fraction of input x-ray quanta used to create an image at each spatial frequency. Practically, the DQE is calculated from the following formula

\[ DQE(u) = \frac{S^2 MTF^2(u)}{q NPS(u)} \]  

(3-28)

where \( q \) is the mean number of x-ray quanta per unit area incident on the detector, MTF is the presampling version, and \( S \) is the large area signal, which is the average pixel value of the output images when a uniform beam irradiates the detector [70].

DQE is often plotted against the spatial frequency, having a value between one and zero. A DQE of unity corresponds to an ideal detector with perfect modulation, a perfectly absorbing material, and only photon noise. In other words, all radiation energy is absorbed and converted into image information. Since the MTF will always be unity at the zero frequency, the DQE at this point will directly give the absorption efficiency of the detector material. However, additional noise sources and decreasing spatial resolution in real detectors reduces the efficiency at higher spatial frequencies, causing the DQE to decrease with increasing spatial frequency.
CHAPTER 4
OVERVIEW OF THE IMAGING SYSTEM

When employing a backscatter inspection system, the system principal parameters and environmental factors will directly affect the system performance. The chapter describes the efforts to develop a prototype Compton backscatter imaging (CBI) system. The objective of this work is to seek an optimal combination of system parameters so that the proposed system can reach its maximum performance. Since CBI methods are highly application-specific, the criterion that the system must meet is presented first. Next, a general overview of the major system components used in scatter imaging methods and the effect they have on system performance is described. Next, the technical details of the prototype imaging system design and the initial experimental results are discussed. Lastly, through selection of the optimal parameters and initial results, the observed improvements and final system design are described.

**Design Criteria**

In order to meet the needs of a subsurface imaging system used for the NDT of wood crossties, the x-ray backscatter inspection prototype was designed and specific technology was selected to meet the following goals:

1. Provide high quality information about the density and subsurface composition of the crosstie, with a resolution on track of at least 3 cm.

2. Produce images with a pixel pitch similar to the currently used technology of 2 mm, enabling the data from the two systems to be easily aligned and integrated with one another.

3. Image at high inspection speeds, capable of scanning at a minimum of 10 mph, with the potential to match the typical scanning speeds on track of 30 mph.

4. Penetrate the entire thickness of the wood tie, which are typically 18 cm deep, with a conservative depth of penetration aimed at 20 cm.
5. Plate C compliant for rigid system components, meeting the minimum required vertical standoff distance of 7.6 cm above the rail.

6. Safe operation, meeting all rules and regulations of the Federal Railroad Administration, individual railroad customers, State, and Federal agencies.

**Backscatter System Components**

When employing CBI systems, several principal parameters and environmental factors are interrelated and can severely limit the system performance if not optimized for. The SNR may be limited by counting statistics, which are largely dependent on the photon source strength, background noise, scatter volume, detector sensitivity, and the duration of the scan. The spatial resolution, however, may be limited by the size of the scatter voxel, the primary photon beam dimensions, and the size of the detector aperture. Therefore, the most important controllable system components, which must be considered in the design stage, are the photon source, the detector, the collimators, system geometry and scanning configuration. The principal environmental factors include the target material type, flaw/defect type (size, material composition, shape), depth of flaw within the target, and surrounding materials. Since many of these factors are interconnected, a tradeoff must often be made between competing goals in order to achieve the specifications listed in the design criteria.

**Radiation Source**

When selecting a radiation source, the important characteristics are its energy, intensity of the flux, beam spot size, and collimation. The source energy should be selected based upon the kind of objects to be inspected and the degree of penetration required. Due to the competition that exists between the attenuation and scatter probability, generally, a higher energy will increase the contribution of Compton scattering and provide greater depths of penetration due to the reduction in attenuation.
that occurs along photon travel paths. However, there is an upper limit to the source energy since CBI systems have an effective inspection depth limit. This is caused by the fact that photons must travel into the material, undergo a scatter event, and return back out in order to be recorded by the detector. Regardless of the incident photon energy, Eq. (2-2) illustrates that backscattered photons have a maximum energy limit of 255.5 keV. Even if the high-energy incident photons can reach deep into the material, the scattered photons will be absorbed on their way back because of their downgrade to relatively low energy. Therefore, the imaging depth of CBI systems is bounded to the maximum range of 255.5 keV-backscattered photons in the material being inspected.

Another important source selection parameter is its intensity, or number of photons emitted per second. A major determinant of the image quality in CBI is the number of photons used to create each pixel; the fewer the photons forming each pixel, the larger the statistical variations visible in the signals from one pixel to the next. Images that are produced with higher flux sources, or using longer periods of time to accumulate more photons, will have better image quality than ones produced with short acquisition times or lower flux sources. The intensity therefore governs the imaging acquisition time required to collect a statistically acceptable scatter signal.

Source Collimator

The size of the radiation field at the target object should also be a consideration when selecting the radiation source. In the absence of reflection and refraction phenomenon, a measurement of the spatial distribution of scatter radiation can only be performed using some kind of mechanical collimation. In scatter imaging techniques, one must know which part of the target has scattered the photon. The isotropic emission of radiation and beam divergence requires that the radiation source be confined into a
beam to localize the object’s exposure. Source collimation also enables the direction of the radiation into the required area of inspection within the target object. The collimator design has a significant impact on image quality because it affects spatial resolution, field size, and intensity. Even though collimation has the added benefit of localizing the source, it comes at the expense of reduced source utilization since absorptive collimators result in photons being removed from the beam.

The dimensions of the beam spot where it intersects the target object under investigation is important since it typically dictates the limiting spatial resolution in scatter imaging systems. Beam size is determined by the configuration of the source size $F$, collimator aperture $W$, and distance to the object $D$ (Fig. 4-1). In x-ray tubes, the

![Figure 4-1. Penumbra effect caused by finite source size F that results in a wider projected beam spot size $S_p$ on the target object surface.](image)

source size $F$ is the physical size of the target bombarded by accelerated electrons in the tube housing, known as the focal spot. The finite size of the focal spot causes a
penumbra effect such that the beam spot size is determined not only by the collimator aperture position and size, but also by the relative sizes of the focal spot and aperture. The resulting beam spot size is substantially larger than the field that would result if the focal spot were a point source. Using the geometry of Fig. 4-1, the width of the source beam $S$ and that of the penumbral region $S_p$ projected on the surface of the target can be calculated by:

$$S = W + DW - F \frac{W - F}{M + L}, \quad \text{and}$$

$$S_p - S = \frac{2FD}{M + L}.$$  

Equation 4-2 illustrates that a smaller focal spot leads to a smaller penumbra. In systems with a fixed source size $F$, the penumbra can be reduced by moving the object closer to the collimator’s exit aperture (decreasing $D$), increasing the collimator’s length $L$, and/or by increasing the distance from the source to the collimator entrance $M$.

The required coverage of the radiation field for a given application depends directly on the collimator aperture $W$ as demonstrated in Equation 4-1. Reducing $L$ and/or $M$ and increasing $D$ can increase the field. If the source size is large, spatial resolution can be improved by confining the size of the field that reaches the object to a small area. Reducing the size of the collimator aperture $W$ or increasing the length $L$ will achieve a smaller field size, as Equation 4-1 indicates. However, decreasing $W$ will result in a reduction in the fraction of source particles utilized in collimation, whereas increasing the length will result in a decreased intensity. When using scatter imaging, it’s important to remember that the probability of detection is much smaller than
transmission. Therefore, this improvement in spatial resolution through smaller apertures will come at the expense of detection efficiency.

**Detector**

Several properties of the detector must be considered when designing the optimal system arrangement including the radiation energy, detector type, its geometry (shape and size), and its collimator (width, length, thickness). Furthermore, practical specifications such as ruggedness can be equally as important when applied in the industrial radiography arena. Of the three primary detector types commonly used, scintillators serve the best purpose for this application given the high energy x-rays that are being detected. The scintillator material is used to absorb the incident x-rays and convert them into visible light photons, with a number created proportional to the amount of energy deposited in the crystal. They serve as the front end of the x-ray detectors.

With CBI systems, the probability of photons reaching the detector is very low. It is therefore very important to develop a highly efficient detection system. The efficiency of absorption is dependent on the characteristics of the detector material, as well as the energy of the emitted radiation and the scanning configuration. The composition of the scintillator, including its atomic number and density, will dictate its absorption properties for a given x-ray energy. Several other important properties of the scintillator determine its performance, including light output, decay time, and spectral emission, as will be discussed later in the chapter.

The relative position of the detector to the source and object also should be considered as it directly affects performance. The geometrical layout of the detection system includes its distance from the primary source beam and from the target object,
with both factors affecting the detector’s solid angle. Increasing the distance of the
detector from the target surface will widen the FOV, which will in turn change the
detector counts. Most importantly, the relative position determines the range of
Compton scatter angles that can be effectively detected.

**Detector Collimator**

In CBI methods, spatial mapping can be achieved by correlating the detector
signal with the x-ray beam’s known point of intersection in the target. This can be
achieved by attaching a grid, made from highly absorbing material, onto the pixelated
detector array, resulting in the pixels being separated from each other at regular
intervals. Collimating the pixel allows only photons scattering from a limited solid angle
to be detected, effectively recording only those originating within the pixel’s line of sight.
Detector collimation also defines the desired view into the volume irradiated by the
source. The intersection of the source and detector FOV determines the sensitive
volume from which scattered photons are detected.

As with the radiation source, collimator design has a significant effect on the
detector and overall system performance. Collimator performance is characterized by its
cross-sectional hole shape, hole dimensions (length and diameter), septal thickness,
and collimator material as shown in Fig. 4-2. Two main measures of collimator
performance, geometric efficiency and collimator resolution, are determined by these
adjustable hole dimensions.

The majority of photons not traveling in the proper direction, or outside the
collimator FOV, are absorbed by the thin septa. However, some may penetrate the
collimator septa or be scattered and enter the detector pixel. Collimator geometric
efficiency is defined as the fraction of photons passing through the collimator per
Figure 4-2. Parallel hole detector collimator design for a pixelated linear array.

An x-ray photon emitted by the source. For a collimator with square aperture holes, the efficiency is described by

\[ g_{\text{square}} = \frac{1}{4\pi l_e^2} \frac{W_d^4}{(W_D + t)^2} \]  

(4-3)

where \( W_d \) is the collimator hole width, \( t \) is the septal thickness [71], and the effective hole length \( l_e \) is used to describe the length dimension, given by

\[ l_e = 1 - \frac{2}{\mu} \]  

(4-4)

The linear attenuation coefficient for the collimator material at the energy of photons being detected is given by \( \mu \) in Equation 4-4. The resulting \( l_e \) is somewhat smaller than the collimator fin’s actual length due to septal penetration.

The two parameters that decide the acceptance angle of the detector are the collimator length and diameter. The larger the acceptance angle, the more scattering photons are recorded. Altering the collimator length will have a direct effect on the count
rate seen by the detection system. As the collimation length is extended, count rate is expected to decline due to additional shielding volume available for the absorption of both multiple- and single-scatter photons from angles other than that of interest. On the contrary, increasing the collimator width will increase the count rate due to the larger acceptance angles each pixel sees.

According to Equation 4-3, collimator efficiency is maximized by the thinnest possible septa so they obstruct only a small area of detector surface. However, thin septa allow a larger fraction of photons to penetrate the collimator walls. Increasing septa wall thickness is necessary to control unwanted photon penetration. Therefore, a primary consideration in collimator design is to ensure that septal penetration by scattered x-rays crossing from one collimator hole to the next is negligibly small.

The dimensions of the aperture and length, as well as the distance of the target from the collimator determine the resolution of the collimator. The equation describing the resolution of parallel hole collimators is well established in the literature [72]. However, for the specific CBI method used in this prototype system, a fan beam source is utilized which relies on a different equation given by the intercept theorem

\[
R = W_D \frac{(D - L/2)}{(L/2)^2}
\]  

(4-5)

where D is the distance between the target object and the detector, W_D is the width of the collimator aperture, and L is the collimator length [64]. The equation demonstrates that resolution improves as the collimator length increases, pixel size decreases, or distance between target and detector decreases. The improvement in resolution is the result of inspecting a smaller sensitive volume.
Image Acquisition Time

The acquisition period is governed by the time required to collect data that will provide statistically significant information. The variables, which dictate counting periods, are the radiation source intensity, collimators, detector efficiency, resolution, and measurement geometry. The detector counts per unit time is directly proportional to the radiation intensity of the source, therefore, increasing the intensity reduces the required counting time. When using an x-ray tube for the source, both the peak voltage and tube current will affect the fluence. In addition, source collimation will also affect the emitted intensity and thus image acquisition time. Detector collimation will also have an effect on the acquisition time. Highly collimated systems (small aperture and long collimator) will greatly increase counting time due to a loss of a large fraction of photons in the collimation.

The scanning speed is also determined by the speed at which the detector can gather a single line of data. In order to reduce the effects image distortion, the optimal parameters are designed such that the target’s horizontal motion relative to the beam during this single line scan time is small. Ideally, this is less than a pixel or so from the top to the bottom of the FOV. However, detectors have an upper limit on the maximum line rate at which they can operate, effectively putting an upper limit on the highest scan speed achievable with a given detector system.

Noise

In a CBI scanning method, the number of photons in each image pixel is dependent on how long the incident beam dwells on that element. Often the approach in CBI systems is to count for a certain amount of time necessary to achieve the desired error of detection the investigator is willing to accept. However, in fast scanning
systems, achieving short dwell times are placed at a higher priority than achieving statistically significant counts. Thus, one of the largest concerns when using fast scan times is that the noise component will have a greater influence on the results since photon statistics will be poor due to the very short beam dwell time. The number of detected events in CBI is dependent on several factors including intensity of the incident photon beam flux, which as previously mentioned depends on the source collimator aperture and its geometrical positioning relative to the object and detector. One solution is to increase the flux from the photon source, permitting higher quality fast CBI images. The result demonstrates one of the main tradeoffs in all imaging systems: image noise can be reduced at the expense of resolution or scanning times.

**Backscatter Imaging Technique**

One of the most commonly used scanning approaches, point-by-point, was discussed in the previous chapter. While the point-by-point method is able to provide a high-resolution 3D image of the sample, the tight collimation makes poor use of the radiation source. The result is a low detection efficiency which can only be improved with increased scanning times and higher intensity photon sources.

Alternatively, the line-by-line approach, also known as a pushbroom system, uses a source collimator, which projects a thin line of the radiation source, rather than a point, across the object [30]. A slit collimator attached to the front of the radiation source forms a fan beam that illuminates an entire line of the target object simultaneously. The width of the projected fan should span the inspected object over one of its dimensions. A pixelated linear detector array is placed parallel to the fan beam with the collimating element composed of a series of plane lamella made from an absorbing material. The detector collimator forces each pixel to view its own region of the primary fan beam,
thereby limiting the collection of only scattered photons originating from directly below it. A 2D image is then constructed by sweeping the source-detector arrangement over the target object in a direction perpendicular to the fan beam. Because the source collimation is opened up to a line, rather than a point, the utilization efficiency of the radiation source is enhanced and sampling time is subsequently reduced. However, the resolution is often worse than that achieved with the point-by-point approach.

**Prototype System Design**

A 50-foot ballasted railroad test track was constructed at the University of Florida in order to carry out all initial experiments with the prototype backscatter system. The track consisted of wood ties in both new and deteriorated condition, as well as composite ties in new condition. The track was installed on a one-foot thick layer of ballast. The first prototype CBI scanning system consisted of the following major components: the x-ray tube, high-voltage generator, linear detector array with its associated electronics and collimation system, and a laptop computer to control data acquisition and image generation. All of these components were mounted to a hi-rail research cart, as shown in Fig. 4-3 that was designed to provide the ability to test and verify various configurations of the x-ray components and relevant system.

**Radiation Source**

The requirement for fast scanning time demands that the intensity be high in order to reduce the image acquisition times. In order to meet these needs, the photon source selected for the prototype system was an x-ray tube due to the advantage of increased incident beam intensity over radioactive sources. Given the inherent slowness of the traditional point-by-point imaging method, the line-by-line or pushbroom approach is more appropriate for the given application.
Another consideration in the selection of an appropriate x-ray tube concerns the beam energy. Results of previous research demonstrated that x-rays with energies of 450 keV are more than adequate to penetrate the entire wood tie. Based upon this, a Comet MXR-451HP/11 bipolar oil-cooled x-ray tube was selected for the initial prototype radiation source. The tube has a nominal voltage of 450 kV and effective focal spots of 1 mm (large focal spot) and 0.4 mm (small focal spot), respectively. Only the large focal spot was utilized in the prototype testing. The inherent filtration is 5 mm of beryllium. The angle of the tungsten target is 11°. The emission cone of the x-ray source is 40° x 30° where the larger angle corresponds to the axis along the most uniform portion of the cone, i.e. not along the direction of the anode heel effect.

Source Collimator

An additional consideration in the design of this prototype unit, which has significant implications on the overall system performance, was the dimensions of the photon source beam. In order to produce an illumination line necessary to sample the object one line at a time, a narrow fan beam was formed. Adjustable lead collimators
attached below the tube exit window produce a rectangular aperture. The radiation beam is well collimated in one direction (the width of the fan beam or narrow slit between lead plates), while the length must span the entire object’s FOV in the other dimension. The beam-forming collimator was constructed from a 1.4 mm x 200 mm rectangular slit with a lead thickness of 38 mm, shown in Fig. 4-4. Penumbra and geometric divergence result in the illumination beam size measured on track to have dimensions of 2.54 cm x 123.6 cm.

Figure 4-4. Source collimator design. A) View from below the x-ray tube exit window. B) View from the transverse axis of the fan beam.

Detector

Since the fan beam illuminates an entire line of the target object between the rails, the most efficient use of this source would couple it to a pixelated linear detector array. For the initial phase of system design, the off-the-shelf model selected was an X-Scan Imaging Corporation XH8816 line scan camera shown in Fig. 4-5, configured parallel to the illumination line. The linear array consisted of terbium-doped gadolinium oxysulfide (Gd$_2$O$_2$S:Tb, GOS) scintillator pixels. The 30.5 cm long active volume was comprised of
192 pixels, each 1.6 mm x 2.2 mm in size. The detector is housed within heavy tungsten shielding which protects the diode arrays and sensitive internal electronics. X-rays are allowed to enter through a narrow 9.5 mm collimation slit in the tungsten shielding, thereby striking the scintillation crystal. Fiber optics conveys the created scintillation photons to a shielded semiconductor device, which converts the visible photons into an electric signal. Specifically utilized by this detector is complementary metal oxide semiconductor (CMOS) silicon linear diode arrays which make it possible to integrate the whole functionality of a camera onto a single chip, including the analog/digital converter and digital output.

Figure 4-5. X-Scan Imaging line scan detector.

The linear detector array is positioned below and offset from the x-ray fan beam, shown in Fig. 4-6. The detector’s collimation slit is focused onto the track and angled slightly so that it intersects the fan beam projection on the surface of the track. As the cart is moved across the test track, detector data is sampled at approximately 1000 lines per second, although the array is capable of acquiring line rates up 9000 Hz. The detector is operated in current mode, where pulses are collected and integrated over a
period of time known as the integration response time. An analog-to-digital converter is used to sample and quantize the image data into discrete integer (gray-scale) values, with the range of values determined by 16 bits.

Figure 4-6. Linear detector array position is offset from the fan beam source.

**Backscatter Imaging Technique**

In the pushbroom approach illustrated by Fig. 4-7, an entire line of the target object is interrogated by scanning the fan beam of x-rays along one dimension of the object. The prototype system mechanically scanned the object by pulling the hi-rail cart between opposite ends of the track. For each position of the scanning fan beam, one line of scattered x-rays is collected by the linear detector array placed parallel to the beam width. Since translation of the detector over the target object is necessary to produce 2D images, synchronization of the movement between the object and the detector is required to ensure a constant aspect ratio. A position encoder is mounted to the hi-rail wheel so that it can mechanically couple the encoder shaft directly to a part of
the drive system. By coupling the encoder signal to the detector, an association between the detected signal and fan beam position was made. By stacking the collected lines of scatter data and correcting for the speed of the cart, as well as detector line dimensions, a continuous 2D image was formed.

Figure 4-7. Pushbroom scanning method utilized by backscatter system on track.

**Communication and Software**

The computer hardware consisted of a data acquisition laptop PC that was directly connected to the x-ray generator by GigE standard high-speed serial interface. The x-ray console was operated through the Spellman High Voltage Electronics Digital Interface program installed on the laptop. In order to transfer the digital image data acquired by the detector to the computer, a connection to the detector via a GigE standard high-speed serial interface was used. Detector data was acquired one line at a time and output to the tab separate ASCII text for processing through the use of a
simple line grabber code provided by X-Scan Imaging. The 1D detector signal is in the form of 16 bit integer values.

**Image Acquisition and Processing**

CBI data can be directly displayed without reconstruction. However, it usually benefits from processing to correct and enhance the image. An image data file output by the detector simply consists of an array of integers in counts per pixel. The range of integers is then linearly scaled to a 16-bit range (0 to 65,535) where the lowest count is mapped to zero and the highest count scaled to 16-bits minus one. First, the electronic background noise of the detector must be corrected for by subtracting its contribution from the raw acquired data. The background noise is found by taking several hundred lines with the detector when the x-ray tube is turned off. These lines are then averaged and subtracted from the raw signal.

The second step involves correcting for signal background due to attenuation, geometry, and efficiency variations that occur among detector channels. Ideally, when a fixed uniform radiation field falls on the pixels of a linear detector array, each pixel should give the same output signal. However, due to factors such as differences in the pixel area or the thickness of the surface layers, this does not happen and instead the response will vary from pixel to pixel. Photons can also be preferentially absorbed in regions that are most attenuating, causing a non-uniform response. Larger deviations can be produced in some pixels by spurious deposits formed during manufacture or by dust either on the surface of the array or on the window. In order to adjust for the non-uniformity of different pixels, correction factors were acquired from calibration scans of a standard material averaged to reduce noise. In the specific application of this prototype, a calibration phantom was made of uniform plywood as shown in Fig. 4-8. In linear
detector arrays, this non-uniformity results in streaking, which is visible in the image as channels of dark versus light lines. In pushbroom systems, the channels are always aligned with the direction of scanning or motion.

Figure 4-8. Plywood calibration phantom used to correct for detector non-uniformity.

The last processing step must correct the detector data feed according to changing vehicle speeds as the system translates the track, by scaling the detector’s time-valued data according to the position encoder’s space-valued data. The speed of the research cart is monitored by the position encoder, shown in Fig. 4-9, and then related to the detector data by averaging detector lines for each spatial segment of the scan. Also, the 192 pixels that are 1.6 mm wide are then reduced to form 0.5-inch square pixels in the final image. The background subtracted and gain offset data is then imported into Image J where they can be displayed as 2D images or 1D plots of the signal density acquired per pixel.
Figure 4-9. Position encoder attached to hi-rail wheel shaft.

**Initial Image Results and Limitations**

In order to determine the necessity of a detector collimator, an experiment was repeated twice, either with or without the use of a detector collimator. Lead sheets 1.6 mm thick was placed over several of the ties in order to provide contrast between this attenuating material and the highly scattering ties. The layout on track, as well as the corresponding uncollimated image of these lead strips is shown in Fig. 4-10. The lighter segments correspond to the wood ties; the darker segments are the ballast. An uncollimated detector essentially creates a 1D density blur such that the highly absorbing lead strips are indistinguishable in the image, smeared over both the lighter and darker ballast/wood tie segments. The reason is because without a collimator, scattered x-rays coming from a point on the track can hit any one of the 192 pixels present in the linear detector array, essentially losing all spatial information.

In order to determine the direction of incoming x-rays, a mechanical multi-hole collimator was constructed. The cross-sectional shape and width of the collimator hole
must be selected to optimize system performance. Traditional systems use a collimation aperture that does not match the structure of the pixilation in the detector; the hole shapes differ from the detector element shape and the holes of the collimator are offset with respect to the detector elements. This mismatch in shape and alignment are less than optimal for detectors having a square pixelated structure, as the linear detector array in this CBI system uses. This is the result of pixelated detectors having reduced sensitivity and increased boundary effects at borders between adjacent detector elements.

The new design for the prototype detector used a registered collimator in order to strike a balance between sensitivity, resolution, and noise. The cross-sectional collimator hole shape was matched to the detector pixels in the array. The matched design increases the utilization of the detector element, resulting in improved resolution and sensitivity. This effectively causes the detector and collimator hole to act as a single

Figure 4-10. Lead sheets placed on track to demonstrate scanning of high contrast materials. A) Photograph. B) Uncollimated backscatter detector image. C) Collimated detector image.
radiation detector. Thus, the collimator resolution determines the system resolution. In addition, another potential advantage of using a matched collimator with a pixelated system is that the small inactive portions at the edge of the detector element are covered by collimator septa rather than being exposed in the area of the holes, allowing an increase in geometric efficiency [71].

To achieve the maximum collimator efficiency, materials of high atomic number Z, high density, and large linear attenuation coefficients are selected to minimize septal thickness. Lead was selected for its high atomic number (Z = 8), density (11.34 g/cm³), low cost, and its soft nature, which makes it easy to cut and shape. Although tungsten is the more absorptive material due to a density 50% larger than that of lead (19.25 g/cm³), it’s expensive and very difficult to machine [73].

Lead fins were 1.2 mm thick, based upon the initial assumption that this thickness will provide sufficient attenuation. The width of these septa must cover the entire collimation slot machined into the detector in order to provide adequate collimation, resulting in fins 51 mm wide. The initial length was constructed to be 51 mm, with the goal of optimizing the dimensions in subsequent tests.

An issue with constructing thin septa walls from lead is that it lacks the necessary rigidity to maintain its shape. The septa were easily bent when handled; requiring some form of structural support placed between the septa walls in order to maintain the alignment and straightness of the aperture holes. Balsa wood was the selected material to serve as these spacers due to its low density (0.18 g/cm³) presenting very low attenuation to scattered x-rays. Since the ideal design would consist of parallel holes aligned exactly with individual detector pixels, a spacer thickness of 1.6 mm balsa wood
was selected to match the 1.6 mm detector pixel width. Figure 4-11 illustrates the initial collimator design.

![Collimator Design](image1.png)

Figure 4-11. Initial detector collimator composed of balsa wood and lead fins.

The collimator was attached flush to the detector array, aligned with the detector's tungsten collimation slot. The lead sheets were placed on the track and the scanning repeated for the collimated detector, with the image shown in Fig. 4-10. These results indicate that a collimated grid is necessary for a linear pixelated array if a 2D image depicting shapes and details is desired.

An image of the test track was acquired with the system operated at 450 kVp, 3.3 mA, using the collimated detector array. Figure 4-12 displays the scatter image, along with a line profile plot obtained by drawing a region-of-interest (ROI) in Image J around the entire width of the image. The grey scale values located along a column of the ROI are averaged and collapsed into a single value representing one point along the x-axis. The darker regions in the image represent ballast, having lower signal values ranging between 80 and 90 in the line profile. The wood ties appear lighter than ballast,
indicating higher grey scale intensities between 110 and 140. Differences in the signal intensities between different ties indicate a higher density versus lower density tie. Also

![Graph showing grey scale values](image)

Figure 4-12. First backscatter image acquired with prototype system using a collimated detector, 450 kVp, and 3.3 mA.

evident in the figure is the incorrect scaling of the position encoder. While stationary on ballast, several lines of detector data are acquired which incorrectly appears as if a large region were scanned. Also, slower scan speeds show up incorrectly as a wider tie in the x-direction in comparison to the other tie widths.

In order to evaluate the effect source energy and intensity had on the system, measurements were taken with all parameters constant except the x-ray tube peak voltage. Three different operating peak voltages were tested using a tube current of 3.3 mA: 225 kVp, 325 kVp, and 450 kVp. Figures 4-13 and 4-14 display the images and their associated SNR. As evidenced by the images, the brightest signal occurs for the highest voltage of 450 kVp and also has the sharpest details. At 225 kVp, however, the
Figure 4-13. Backscatter image acquired at 3.3 mA and different peak voltages. A) 225 kVp. B) 325 kVp. C) 450 kVp.

Figure 4-14. SNR corresponding to three different operating voltages: 225 kVp, 320 kVp, and 450 kVp.

The signal is extremely low with a loss of detail and contrast illustrated by the dark mask over the entire image. Although the signal is lower for 325 kVp than 450 kVp, details of the tie are still visible, representing a tradeoff between energy and resolution. If lower energies are necessary from a radiation safety standpoint, then 325 kVp could be the
optimal choice selected for the operating voltage. The next set of measurements was performed to test the effect of the offset distance between the detector and primary source beam. Spacer bars were utilized that altered the distance of the offset from the parallel array to the fan beam. When no spacer was attached, the detector offset from the beam was 46 cm. The smallest offset distance possible with the hi-rail cart setup, i.e. the closest the detector could be placed to the beam, was 5 cm. Figure 4-15 displays the SNR obtained with three operating voltages and the two extreme offsets of closest and furthest from the primary beam. The figure illustrates that the closer the detector is to the beam, the larger the SNR. The reasoning behind this is based on the Klein-Nishina differential scattering cross-section. Recall Fig. 2-2 illustrated the increasing probability as the scatter angle increases from 150° to 180°, with the largest cross-section for any backscatter direction occurring at 180°. Therefore, as the detector
is moved closer to the primary beam, the scatter angle that falls within the detector FOV is effectively increased, as well. However, the detector cannot be placed any closer than the 5 cm offset since it would begin to interfere with the primary beam, potentially causing the fan beam to scatter off the detector before reaching the track.

**Optimization of System Design**

Based on the initial testing and theoretical evaluation of system performance under different operating parameters, the limitations of the current system and its detrimental effects on overall imaging performance were evident. In order to provide the optimal prototype design, several components were reconfigured to obtain the best possible imaging performance within the practical constraints.

**Radiation Source**

Both the x-ray tube and the source collimator were optimized following the initial results. When considering an x-ray tube for any specific application, the issue of coverage must be considered. Because of the line focus principle used in angled anode target designs, the field coverage is determined by the radiation emission angle and distance from the source to the target using simple geometric relationships. Due to the low signals detected in the prototype design, it was desirable to increase signal by bringing the source closer to the target. The small emission angle used in this tube, though, would result in the inadequate coverage of the target if the tube was brought much closer to the track. Therefore, a more optimal tube was one with a larger emission angle in the direction spanning the distance between the rails. The x-ray tube selected for the second phase of the prototype testing was a Comet MXR-452/Y which had a 90° coverage angle along the dimension between the rails. The tube had a nominal voltage of 450 keV and tungsten target. Inherent filtration consisted of 2.3 mm iron followed by
1.0 mm copper. The small focal spot was 2.5 mm and large focal spot, 5.5 mm. The use of an iron and copper filter also served to harden the spectrum, producing higher energy x-rays in the primary beam.

**Source Collimator**

The new x-ray tube differed in its beam form and shape, requiring a new collimation system to be designed. Furthermore, the initial beam forming collimation system was limited in its use since the collimation slit was not easily adjustable. The second beam-forming collimator employed a larger dimension for the length of the fan beam slit in order to match the wider coverage angle of the new tube. It was composed of lead blocks with dimensions of 6.9 mm x 38.7 mm x 9.5 mm, as shown in Fig. 4-16.

![Figure 4-16. Optimal design for the radiation source beam forming collimator.](image)

**Detector**

The original detector used for the experiments was not sensitive enough for the energy range of backscattered x-rays coming from the track. One of the biggest limitations of the prototype system design was the detector’s low scatter signal and high background. This is evident in Fig. 4-17, which compares various signals acquired with
the GOS scintillator. The detector operates in 16-bit mode, resulting in a maximum possible signal value of 65,536, which is displayed on the chart for relative comparison. When the x-ray tube is turned off, an average background signal around 7,700 is recorded. However, an uncollimated detector corrected for background has an average signal around 220 for the brightest wood tie in the track. Furthermore, the collimated signal shows a significant reduction in gray scale values, having an average of only 15 for the brightest wood tie.

![Graph](image)

**Figure 4-17.** Relative signals detected by the initial linear detector array composed of GOS crystals.

Collimation of the initial and scattered radiation allows the detection of relatively few scattered photons, and this is one of the predominant reasons why the statistics relative to this process are very poor. However, since collimation is necessary for spatial localization, it can be optimized to improve the signal but its effect will never be
eliminated completely. Therefore, the remaining parameter, which is easiest to alter, would be the detector in order to improve its sensitivity and efficiency. Considerations for the optimal detector design include its overall dimensions, scintillator material, and the size of the pixels. However, the most important determinant of efficiency will be the scintillator material and thus a careful selection of it is required to optimize detector performance.

The primary considerations when selecting a scintillator is its attenuation for x-rays, inherent blurring within the crystal, spectral matching between the scintillator emission spectrum and photodiode, light yield, chemical stability, radiation resistance, and decay time. The attenuation coefficient of a given thickness of a material depends on its density and effective atomic number $Z_{\text{eff}}$. Considering only the photoelectric absorption interaction, the x-ray attenuation coefficient appears proportional to $Z_{\text{eff}}^{-3.5}$ as discussed in Chapter 2.

The three scintillator materials offered by X-Scan Imaging for the detector design are: terbium doped gadolinium oxysulfide (GOS), thallium doped cesium iodide (CsI:Tl), and cadmium tungstate (CWO). Important characteristics for the scintillator materials are shown in Table 4-1 [74]. CsI:Tl was selected over CWO and the currently employed GOS material, due to several of its attractive properties. CsI:Tl has the largest light yield of all three scintillators and its light emission is at a wavelength that is well suited for

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm$^3$)</th>
<th>Effective Z</th>
<th>Light yield (photons/MeV)</th>
<th>Hygroscopic?</th>
<th>Optical transparency</th>
<th>Decay time (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOS</td>
<td>7.34</td>
<td>64</td>
<td>60,000</td>
<td>No</td>
<td>Low</td>
<td>$6 \times 10^5$</td>
</tr>
<tr>
<td>CsI:Tl</td>
<td>4.52</td>
<td>54</td>
<td>66,000</td>
<td>Slightly</td>
<td>High</td>
<td>$6 \times 10^3$</td>
</tr>
<tr>
<td>CWO</td>
<td>6.12</td>
<td>64</td>
<td>15,000</td>
<td>No</td>
<td>High</td>
<td>800</td>
</tr>
</tbody>
</table>
photodiodes. It provides the highest x-ray sensitivity of the three materials due to its relatively high density and high Z$_{\text{eff}}$. Another attractive property of CsI is its optical clarity compared to the currently employed GOS. Light produced in response to radiation interactions can exit the detector more efficiently and with minimal blurring since the clear crystal provides excellent optical coupling to the subsequent light sensor. These detectors are quite rugged, as they can withstand severe shocks, acceleration, and vibration, as well as large temperature gradients and sudden temperature changes. These properties make the scintillator especially well-suited for crosstie inspection under the harsh industrial conditions it will be exposed to on track. Although slightly hygroscopic, it performs better than the extremely hygroscopic sodium iodide.

In addition to the new scintillator material, the length of the first line scan detector was only 30.5 cm. However, the FOV parallel to the detector is the width between the tracks, approximately 120 cm. This resulted in the detector losing a large portion of signal to its collimator since scattered photons from the outer edges of track were well outside of the pixel’s FOV. Therefore, a more efficient design was a linear array that matched the dimension of the track.

The new detector selected for the prototype system was a custom built X-Scan Imaging Corporation linear detector array, which had a 137 cm active length. X-rays are allowed to enter through a 9.5 mm wide collimated slot and strike the CsI:Tl scintillator. The visible light produced is then guided via fiber optics to a CMOS silicon imaging diode active pixel sensor array. The detector is composed of 864 pixels with dimensions of 1.6 mm x 11 mm x 4.5 mm. The detector is mounted parallel to the widest dimension of the fan beam, positioned 71 cm below the x-ray tube exit window and offset from the
fan beam by 5.1 cm. The tight collimation slot requires the detector to be angled towards the fan beam source so it will intersect the fan on the surface of the track.

**Detector Collimator**

Another significant factor contributing to system performance was the detector collimator. The noisy images and large reduction in signal associated with the prototype collimator indicate a much more optimal design is possible. Furthermore, the new linear detector array had different pixel dimensions, requiring a new collimator be designed to match this system. Since the collimation is a significant determinant of image quality, the effect it has on system performance was studied by comparing different collimation designs. One drawback to using a matched collimator design is that the requirements for high resolution cause low sensitivity, possibly causing sub-optimal image quality due to low photon detection counts. If the sensitivity is too low, the spatial resolution may be improved but this occurs at the expense of scan time. Consequently, the tradeoff between sensitivity and spatial resolution remains an important consideration when choosing between different collimator designs.

In the multi-hole collimator design, the size of the detector elements dictates the width of the collimator aperture or pitch. However, the inner dimensions of the pixels and their associated grouping into modules was unknown requiring that several arrangements be tested to identify where the optimal matching occurred. The collimator length, septal thickness, and aperture width were varied in order to adjust the tradeoff between resolution and sensitivity. The design that maximizes sensitivity without exceeding the required collimator resolution was identified and selected as the design for the final collimator.
Six different configurations of pixel-matched collimators were designed for the new detector array, with their characteristics shown in Table 4-2. All collimators were built to span the detector’s entire 137 cm active length and 7.6 cm width as illustrated in Fig.4-18. Performance of the collimators was evaluated based on noise, resolution, and contrast visible in the output images. The image obtained with the worst performing collimator is shown in Fig. 4-19. The worst collimator design was found to be Collimator

Table 4-2. Dimensions of collimators tested for the linear detector array.

<table>
<thead>
<tr>
<th>Collimator model</th>
<th>Length (cm)</th>
<th>Septum thickness (mm)</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.3</td>
<td>1.2</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>1.2</td>
<td>4.8</td>
</tr>
<tr>
<td>3</td>
<td>5.1</td>
<td>1.2</td>
<td>3.2</td>
</tr>
<tr>
<td>4</td>
<td>5.1</td>
<td>1.2</td>
<td>4.8</td>
</tr>
<tr>
<td>5</td>
<td>5.1</td>
<td>1.2</td>
<td>6.4</td>
</tr>
<tr>
<td>6</td>
<td>5.1</td>
<td>2.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Figure 4-18. Full-length collimator attached to linear detector array.
#6, visible by the extremely noisy images attributable to a low detected scatter signal. The design was constructed of lead fins 5.1 cm long and 2.4 mm thick, spaced by 3.2 mm of balsa wood. The poor performance was most likely the result of an over-attenuated signal due to the thickness of lead septa, thereby blocking a large portion of the pixel area and absorbing a large fraction of scattered x-rays originating outside the collimator FOV. Furthermore, the spacing of balsa resulted in large collimator apertures, thereby limiting the resolution.

Figure 4-19. Images acquired for different collimator designs. A) Collimator #6. B) Collimator #3.

The optimal design was Collimator #3, and the image obtained with it is shown in Fig.4-19. The dimensions of the lead fins were 5.1 cm long and 1.2 mm thick, spaced by
1.6 mm of balsa wood. The major difference between the optimal and poor performing collimator was the thickness and spacing of lead septa. A larger signal is obtained with the smaller septa, indicating that this attenuates the appropriate portion of scattered x-rays originating outside the FOV. Furthermore, the spacing of 1.6 mm provides a better match between the collimator holes and detector pixel width of 1.6 mm.

One of the limitations associated with all collimator designs were the spacers fabricated from balsa wood. Although a low-density material, the average energy of scattered x-rays impinging the detector array was determined through MCNP simulations to be between 25 and 45 keV. These low-energy x-rays will subsequently be affected by the presence of the balsa wood spacers, thereby attenuating and lowering the detected scatter signal. In order to correct for this limitation, a new design was constructed for the collimator that utilized air gaps between the lead septa for a better signal. Balsa wood spacers were reduced to only cover the outer edge of the fins, as shown in Fig. 4-20. Images with the new design were found to have a higher resolution than the same design that didn’t use air gaps between the septa.

Figure 4-20. Collimator design using air gaps between septa and minimal balsa wood.
Results of Optimized System

Images of the test track were acquired using the optimal arrangement of system parameters. The x-ray tube was operated at 450 kVp, 3.3 mA and the new linear array was collimated with the air gap design. The approximate scanning speed was 1 mph on the test track. The resulting backscatter image is significantly improved using the optimal system parameters as shown in Fig. 4-21 Details of wood tie flaws are evident in several of the ties, shown by the darker gray stripes through their center. Furthermore, the average signal for a wood tie is approximately 950 with the new detector, in comparison to the old detector's average signal between 50 and 100. Resolution also improved substantially since fine details are now evident in the images, such as the lead letters shown in the left side of the track image.

![Figure 4-21. Backscatter image acquired with the optimal system parameters.](image)

The CBI system was ultimately designed to distinguish between damaged wood ties and sound ties based on density variations across its volume. Compton scattering reveals the presence of a defect by a change in the scattered photon intensity, or detector counts, as a result of the density variation in the scattering medium. By monitoring the count rate, the simple presence of a defect should be indicated quickly by the change in counts detected. Wood ties are indicated as damaged, or of poor
grade, when the intensity of the backscattered x-rays is low compared with that for a sound wood tie. In order to establish baseline density levels of a sound tie, a new wood, never before used in track, was installed as a part of the test track. The image of this healthy wood tie and its corresponding line plot is shown in the Fig. 4-22. In the density profile, a healthy tie had gray scale values that ranged from 900 to 1000. Ballast is typically shown as a darker intensity due to its lower scattering probability, with lower gray scale values between 400 and 500. The lower signal visible to the right of the wood tie in the line profile is due to the lead letters placed on track. The wood tie beneath the lead causes the signal peaks visible on the left and right of the lead signal.

Figure 4-22. Brand new wood tie installed in test track and used as calibration tie. A) Backscatter image. B) Line plot for the associated calibration tie.

Proof of concept for the viability of this technique was performed by comparing the new technology to the current and most established visual inspection method. A visual inspector that has worked in the field for over 30 years was asked to visit the test track and give a grade to each of the wood ties. His grades were then compared to the
backscatter inspection vehicle’s signal for each tie. The wood tie shown in the photograph of Fig. 4-23A was given a passing grade by the inspector, based on visual and sound testing. However, the backscatter image in Fig. 4-23B demonstrated this wood tie had several low density cracks running vertically through the image illustrated by dark gray scale values. Furthermore, the line profile plot drawn through the backscatter image in Fig. 4-23C also suggested the tie had one of the lowest relative
density values in comparison to the calibration tie, showing gray scale signals between 650 and 800 versus the calibration signal range of 900 to 1000.

Next, the tie was physically removed from the test track. A chain saw was used to split the tie in half in order to visualize its internal conditions, shown in Fig. 4-24. The internal condition of the tie had a significant amount of decay and rot lying below its surface. Furthermore, a large void measured to be at least 3 feet long spanned the length of the wood tie. This test demonstrated the success of this prototype system and its viability as a wood tie inspection method. It also illustrated how inaccurate visual inspection could be when the surface layers are in adequate condition, all the while masking a significantly degraded internal condition of the tie.

![Figure 4-24. Image of the wood tie removed from the test track. A) Sawed in half. B) Ruler inserted through the center, indicating a void 91 cm long.](image)

**Final Design**

Following the prototype testing, the system was transferred to a hi-rail truck capable of pulling the system and its associated components. The truck also provides power to the x-ray generator and detector electronics. In addition to the backscatter inspection system, the vehicle contained the Aurora scanning system, thereby coupling
the two inspection methods as originally planned. Patent applications were filed in 2012 and the final system, called Aurora X, is illustrated in Fig. 4-25 [78].

Figure 4-25. Final design of the backscatter inspection vehicle, Aurora X.
CHAPTER 5
RADIATION SHIELDING

One of the most important criteria necessary for the successful design of this prototype backscatter scanning system that mounted a powerful x-ray source integrated into a mobile hi-rail truck platform was that of safety. The final design parameter specifically required that this system be able to safely operate within all rules and regulations of the Federal Railroad Administration, railroad customers, State, and Federal Agencies. Given that this system is entirely new, several unique radiation shielding and licensing challenges had to be addressed for the first time in order to meet these goals.

Typically, industrial radiography is performed in remote areas, where the source is well shielded and access is tightly controlled. A restricted area surrounding the source is barricaded and serves to protect the public from receiving undue exposure to radiation. In order to achieve high productivity in the inspection of railroads, the backscatter unit must use an x-ray source that is exposed continuously and concurrently with the mobile system. On average, the backscatter unit will inspect approximately 40 miles of railroad track daily. Furthermore, this system will be operated in populated areas such as railroad crossings, bridges, and urban areas around members of the general public. Therefore, it’s not practical to barricade a restricted area around the railroad track as is commonly done in industrial radiography.

Even though the regulatory guidelines provide clear dose limits for radiation emitted by x-ray machines, they don’t specifically address where these limits must be met, i.e., at what distance from the radiation source. Typically, it is the restricted area established by operators of industrial radiography sources that dictate this distance.
Since barricades are impractical to implement for our system, a major challenge in shielding design was establishing at what distance the public dose rate limit must be met.

Complicating radiation-safety related matters further was the fact that this system was the first-of-its kind. No prior work has been done on characterizing the backscatter radiation field surrounding rail structural components. The use of a fan beam projection produces a much larger radiation field than that of the commonly used pencil beam, which in turn produces a much larger scatter component. Further adding to this is the fact that a large majority of rail infrastructure has a high scattering probability, including the concrete-based ballast, concrete ties, and wood ties. These effects, along with the continuous operation of the x-ray tube, must be assessed in order to properly design the necessary radiation shielding.

In addition to the radiation-safety related concerns, there also existed issues brought forth by operating this system on railroad tracks in North America. More specifically, the safe design must also abide by the FRA’s. Furthermore, since Class 1 railroad track is privately owned, each company has their own set of rules for operating on their property.

**Radiation Shielding Requirements**

All regulations relevant to the protection of humans from radiation can be found in Title 10, Chapter 1 Part 20 Code of Federal Regulations (10 CFR 20). The document establishes maximum dose limits for individuals depending on whether they are classified as members of the general public or occupational workers. As previously addressed, it is impractical to barricade the large area of railroad track scanned daily by the system. Therefore, the shielding must be more conservative and designed to
operate around members of the general public. 10 CFR 20 requires that the total effective dose equivalent to individual members of the public does not exceed 100 mrem (1 mSv) in one year. A more relevant parameter for establishing limits, which the shielding design must meet, is the dose rate since a continuous-exposure x-ray tube is used in the system. 10 CFR 20 establishes the limit on dose in any unrestricted area cannot exceed 2 mrem (0.02 mSv) in any one hour.

In order to determine the required shielding necessary to meet this 2 mrem/hr dose rate limit, it must first be determined at what distance from the backscatter system this limit would be met. Since a physical barrier was impractical for this system, the solution was to establish a ‘virtual barrier’ based upon railroad-specific regulations. Each private railroad company establishes their own guidelines for operating trains on their track. However, common to all companies is a violation known as ‘fouling the track.’ The restriction states that an individual or item of equipment must maintain a distance of at least four feet from the field side of the near running rail; otherwise they are fouling the track [76]. This creates a virtual barrier of 4 feet on either side of the track which the system can operate in. Therefore, the shielding must be designed so that the dose rates at any distance further than 4 feet from the rail will be below 2 mR/hr.

The operation of this backscatter system on railroad track also requires that it abide by any FRA-related regulations. The Association of American Railroads (AAR) has established a loading gauge that defines the maximum height and width for all railway vehicles in order to ensure safe passage through bridges, tunnels, and other structures [10]. The most widespread standard is termed AAR Plate C, which does not
allow any item on the track vehicle (other than hi-rail wheels) to be closer than 3 inches from the rail. What this leads to is a 3-inch gap in the shielding which must be accounted for in the scatter off low-lying rail structure.

**Radiation Field Mapping**

The first step in developing the shielding plan was to determine the baseline radiation levels emitted by the preliminary shielded backscatter system. The radiation field was mapped by laying out a grid of 33 points located at various off track locations where measurements would be acquired, as shown in Fig. 5-1. A grid was only established for one side of the railroad track since symmetry of the emitted radiation levels was assumed for opposite sides of the tube. The x-axis was aligned parallel to the steel rail with the origin at the x-ray tube exit window where the fan beam centerline is projected onto the track. The y-axis is the perpendicular distance away from track, with the origin at the steel rail and the 4-foot y-axis location corresponds to the fouling line where the virtual barrier ends, i.e. the distance of closest approach for any individual to the system. All grid points are located four feet from each other in both the x and y-dimensions. The z-axis is the height at which the ion chamber actually acquired its measurements, with the origin beginning at the top surface of the wood crossties. For each x-y coordinate in this grid that are demonstrated by blue crosses in the figure, a total of 3 measured exposure rates were taken at vertical heights of 1 foot, 3 feet, and 6 feet. These multiple-height measurements were acquired by using steel stakes that were driven into the ground at each x-y location. Three survey meters were then attached to each stake at the corresponding heights above the tie. Overall, the 33 coordinates shown in the figure resulted in a total of 99 measurements, producing a 3D field map around the backscatter system.
Figure 5-1. 3D grid of measurement locations for radiation field map. A) Illustration of grid locations. B) Photograph of grid measurement technique using stakes and three different vertical heights.

In order to provide the most conservative shielding design, the backscatter system was stationary during these measurements and placed in the middle of the 50-foot ballasted track segment, even though normal operation will consist of the system scanning at speeds at least 10 mph or greater. Furthermore, the x-ray tube was operated continuously at the maximum power level of 450 kVp and 3.3 mA. The measurements were performed using nine Thermo Scientific RadEye G Gamma Survey Meters that are capable of recording the maximum exposure rate in units of mR/hr. They hold the maximum exposure rate until a manual reset is done on the system, which was performed after each measurement.

In addition to simply mapping the baseline radiation values, knowledge of where the radiation originates from is also necessary because this will determine where the shielding should physically be placed around different components of the backscatter system. If the radiation source is caused by scatter components from the primary fan beam, this indicates that more shielding should be added around areas where the
centerline of the beam is emitted. However, if radiation levels are high because of scatter off rail infrastructure components, additional shielding may be necessary around various part of the system where these increased levels are measured. Lastly, if the source of high levels were due to leakage from the x-ray tube housing, this would indicate that more shielding must be placed inside the x-ray tube housing.

The most important finding from mapping the radiation field was that for all three vertical heights, the exposure rates far exceeded the 2 mR/hr limit at the 4 foot distance, indicating that shielding is absolutely necessary for the system's safe and licensed operation. The measured exposure rates for the initially unshielded system are displayed through Matlab 3D surface plots given in Fig. 5-2. These plots show the field map from a bird's eye view, i.e. looking down on the track. Displaying the exposure rate field map in this manner allows one to ascertain information regarding the spatial relationship and trends of emitted radiation levels. The different colors of the plot correspond to different exposure rates, with warmer colors shown for higher rates and cooler tones reserved for the lower values. The x = 0 line is centrally located as opposed to the far left as is common in most plots, and it corresponds to the location of the fan beam centerline, i.e. the location of the primary beam. The y-axis is defined at the top of the figure and corresponds to the beginning of the virtual barrier, or 4 ft. from the rail. Moving from the top of the plot, vertically downward, corresponds to farther distances from the x-ray tube. Each plot corresponds to measurements taken at a vertical height above the tie surface, specifically 1 foot, 3 feet, and 6 feet.

The most notable trend identified by comparing the three surface plots is that the exposure rate or radiation field is height-dependent. Specifically, the maximum
Figure 5-2. Measured exposure rate for when operating the x-ray tube at 450 kVp and 3.3 mA. A) 1 foot. B) 3 feet. C) 6 feet.

exposure increased from 10 mR/hr at 1-foot levels, to 26 and 41 mR/hr at 3 and 6-feet, respectively. The decreased exposure at ground level is believed to be the result of shielding provided by the 7 inch tall highly absorbing steel rail, which serves to greatly attenuate the scattered x-rays. The location of the fan beam is evident in the plots by the maximum exposure rates measured along the $x = 0$ line that decrease in value for increasing values of the y-axis, or at further distances away from the x-ray tube. These
results agree with the theory of the diverging nature of radiation and inverse fall-off; the intensity of the backscatter field increases in value, or the measured exposure rates in this case, closer to the plane of the x-ray beam centerline. The areas of high exposure to the left and right of the primary beam located at x-axis values of 8 feet and extend vertically downward through the entire plot suggest there is significant leakage through the tube ends. This is the result of gaps in the tube housing that exist in order to accommodate the electrical cables, as shown in Fig. 5-3.

![Figure 5-3. Gap in the lead shielding to accommodate cables at x-ray tube housing ends.](image)

An additional significant finding regarding the spatial distribution of radiation was the large exposure rates measured for the 4-foot fouling line at x-axis values of 12 feet on either side of the fan beam. Given the existence of high exposure rates far from the centerline suggests they are the combined result of both tube leakage and scatter off track structural components. These results suggest the need for a low-lying shield to help reduce the scatter components from track structure. Moreover, results
demonstrating the height-dependent exposure rate caused by the self-shielding of the rail further serve to indicate that a low hanging shield near the rail could further reduce radiation levels. The reason for the appearance of cold spots at x-axis values between 8 and 10 feet on both sides of the fan beam centerline and for y-axis values near 4 feet are due to the layout of structures on the hi-rail cart and its electrical components. On the left side of the tube (negative x-values), a large toolbox blocks the scatter moving from the track to the measurement location; on the right side the identical situation occurs due to the large generator.

The next step in shielding design was to determine how much of the high exposure rates measured are actually attributable to the primary fan beam, the leakage from the tube, or scatter off track components. In order to determine their individual contributions, it was necessary to isolate either the primary fan beam or the leakage one and measure the resulting radiation levels. The leakage contribution was measured by plugging the exit window of the x-ray tube in order to eliminate any portion of the primary beam from escaping. This was achieved by bringing together the two lead collimation plates of the beam forming collimator within the housing. Additional lead was placed over the slit to ensure no x-rays leaked through the lead closure. These measurements were performed using a Fluke Biomedical 451 portable ion chamber. The tube was operated at 0.5 mA and 450 kVp in order to enable direct placement of the survey meter on the outside of the tube housing. The measured exposure rates were then linearly scaled from 0.5 mA to the maximum tube current 3.3 mA.

Exposure rates for various locations around the tube housing were recorded. The maximum value of 145 mR/hr was measured on the center of the housing, where the
target is most likely located in the tube. This indicates that the largest source of escaping radiation contributing to the leakage component is due to inadequate shielding within the tube housing. The exposure rate recorded from the left and right tube ends where the cables required a gap in shielding was 33 and 17 mR/hr.

The thickness of lead necessary to shield this central portion of the tube leakage was determined by performing an attenuation experiment. As shown in Fig. 5-4, an

Figure 5-4. Measurement of leakage radiation emitted through x-ray tube housing.

increasing thickness of lead sheets were placed in between the tube housing and the ion chamber while exposure rates were recorded. The attenuation curve acquired from this experiment is shown in the Fig. 5-5. These results suggest that approximately 0.65 inch thick lead is necessary to reduce the 145 mR/hr exposure rate to less than 1 mR/hr. However, this is an overestimation since there is over 6 feet between the tube's housing and the fouling line, which allows for the inverse fall-off of radiation.
Next, the fan beam contribution was measured by placing several sheets of lead around the tube ends and tube box in order to essentially remove all emitted radiation that is the result of tube leakage. The entire radiation field map was measured for the 2D grid points again in order to assess how much of the exposure rates measured outside of the fan beam centerline were caused by scatter from track structure components versus the primary beam. The same exposure rate trend of hot spots at the fouling line and x-axis values of 12 ft. on either side of the beam were recorded in this experiment, suggesting their origin is from scatter off track structural components and not leakage as originally hypothesized.

In order to determine the lead thickness necessary to shield the scattered components originating from the primary fan beam along its centerline, an attenuation experiment was performed. Measurements were acquired with the ion chamber held at
the fan beam centerline approximately 2 feet above the rail. The x-ray tube was operated at 450 kVp and 0.5 mA for radiation protection purposes, and the results linearly scaled up to 3.3 mA. An increasing number of lead sheets were then placed between the tube and survey meter as exposure rates were recorded. Each lead sheet was approximately 2 ft. wide and 4 ft. long, with a thickness of 1/16-in.

The resulting attenuation curve is shown in Fig. 5-6, demonstrating an exponential reduction in exposure with thickness of lead. The maximum exposure rate was measured to at 1650 mR/hr. The curve suggested that a lead thickness of 0.2 in. was required to shield the primary fan beam scatter components in order to reduce the exposure rate to less than 2 mR/hr.

Figure 5-6. Attenuation curve acquired along the primary fan beam centerline.
Preliminary Shielding Design and Analysis

The results from the radiation field map suggested several different areas are necessary in the shield design. First, additional lead shielding is necessary within the x-ray tube housing in order to reduce leakage out the tube ends and through the tube box. Second, a low-hanging lead curtain must be draped around the rail cart in order to reduce the large amount of scatter that originates from the fan beam’s interaction with track structural components. The thickness of the shielding was determined from the attenuation curves, and the size and positioning ascertained from the original field mapping.

The amount of lead added to the inner housing of the tube and the ends were approximately 0.5 inch thick. The results from radiation field mapping indicated the need for a low-lying shield, demonstrable as a skirt. Since the exposure rates over 2 mR/hr were measured for x-axis locations as far as 20 feet away, it was determined that the size of the shielding curtain had to span the entire bottom edge of the cart. The thickness of the lead was determined by the attenuation curve measurements, which indicated a value of 0.3 inches is required to reduce the exposure rate to 1 mR/hr at the centerline directly over the rail.

Mathematical modeling of the radiation confirmed a similar value with the experimental measurements, as well. MCNP simulations estimated at the surface of the wood tie between the rails in the center of the fan beam, i.e. the central axis of the fan beam centerline had an exposure rate of approximately 1,240 R/hr [77]. Simulations showed a 3/8-in. thick sheet of lead would reduce the backscatter field from 1.2 R/hr to 2 mR/hr on the outside surface of the lead shield directly above the rail. At the fouling
line, simulations estimated the exposure rate to drop to 0.8 mR/hr from this lead sheet, indicating the conservative thickness of the shield.

Furthermore, since any x-rays scattering off the track that have a direct line of sight to the measurement point will contribute to the measured radiation level, and because all heights showed higher than acceptable exposure rates, the shielding curtain must be able to cover the entire vertical distance from the tube box to the rail. The primary difficulty in employing the lead curtain near the rail was its interference with Plate C regulations set forth by the railroad track. Since Plate C doesn’t allow any rigid item on the track vehicle (other than hi-rail wheels) to be closer than 3 in. from the rail, a 3-inch gap in the shielding must be designed or accounted for.

The lead curtain was designed with all these specifications and the initial configuration is shown in Fig. 5-7. Figure 5-7A displays both lead curtain and the shield covering the x-ray tube housing. In Fig. 5-7B, lead sheets were added to cover the gap between the tube housing and the hanging skirt. When measurements were acquired prior to the laying these additional sheets, high exposure values were recorded for the 6-foot height because scattered x-rays reflected off the track could escape through this gap. Figure 5-7C shows the hanging lead curtain to block the scattered x-rays from the primary beam that were able to exposure off-axis values around 12 ft. on either side of the beam.

The radiation field map for this prototype shield design was measured again using the maximum tube operating parameters and Thermo Scientific RadEye G Gamma Survey meters. These measurements were also verified with the 451 Biomedical Fluke ion chamber, as well. The associated 3D surface plots for the shielded
Figure 5-7. Configuration for initial shielding design. A) Lead curtain and tube housing shield. B) Additional shield covering the gap between tube and curtain. C) Low-hanging shield to block scattered x-rays from track components.

system are shown in Fig. 5-8. The most significant result was that all recorded values fell below the 2 mR/hr rule at the fouling line, indicating the system’s ability to safely operate around general members of the public. Two hot spots are visible within the 6-foot height, located at $x = 4$ feet from the fan beam centerline and extending from the fouling line down to $y = 8$ feet from the rail. These are most likely the result of the gap in the shielding between the tube and the curtain. This can easily be corrected in the final shield design by building a lead dome around the tube and fan beam formed from a solid piece of lead.
Figure 5-8. Surface plot of measured exposure rates for the shielded backscatter system scanning at the maximum tube operating parameters. A) 1 foot. B) 3 feet. C) 6 feet.

**Dynamic Testing**

All of the previous measurements were carried out under the initial assumption that the backscatter system was operating in a stationary position, i.e. fixed on one location of the track. However, this doesn’t represent the normal interaction of the inspection vehicle with members of the general public. In order to obtain a more realistic analysis of the backscatter unit’s shielding design, a different set of measurements were
conducted with a dynamic system. These are meant to represent the more applicable scenario where a fixed individual is located beside the track, while the inspection system drives past them at speeds between 10 and 20 mph.

In order to test this scenario, the RadEye Gamma survey meters were placed at the 4-foot fouling line for all three vertical heights of 1, 3, and 6-feet above the tie surface. Each survey meter was set to record the overall integrated exposure (in units of mR) received during the given test. Specifically, the three meters were placed on the 2D coordinate grid location along the fan beam centerline or \( x = 0 \) axis in an attempt to acquire the most conservative measurement possible. Each measurement was recorded as the research cart was pulled from the far ends of the 50-foot ballasted track. This provided the longest beam-on time, as well as the distance between the start and end to the meters fell outside the meter's sensitive range due to the inverse fall off of radiation. All measurements were acquired using the same shielding design described in the prior section and the x-ray tube was operated at maximum parameters of 450 kVp and 3.3 mA.

These measurements were recorded as the research cart was pulled from the left side of the track to the right, with the hi-rail cart covering a distance of 28 feet. The time it took to travel this distance and the x-ray tube beam-on time was 20 seconds, resulting in the cart traveling at approximately 0.95 miles per hour. Even though the survey meters read out the integrated exposure in air, the absorbed dose to tissue is a more relevant parameter when dealing with radiation protection. The absorbed dose to a medium other than air can be calculated from the exposure using the F-factor.
The F-factor depends on the energy for all media other than air and the material of exposure. A constant F factor of 0.96 was assumed for all dose calculations analyzed for muscle at the maximum x-ray tube energy of 450 keV. [78].

Since the maximum speed of the research cart on the test track is 1 mph, scanning doesn’t represent the normal operating scenario in the field which will be at least the minimum speed of 10 mph. In order to approximate the most realistic scenario of the backscatter unit’s operation, all recorded results for the dose measurements were linearly scaled to speeds of 10 miles per hour. The results are also given in Table 5-1 for all three vertical heights.

### Table 5-1. Measured exposure from a dynamic test of the shielded backscatter inspection vehicle and the estimated dose.

<table>
<thead>
<tr>
<th>Measurement height (ft)</th>
<th>1 mph exposure (mR)</th>
<th>1 mph dose (μSv)</th>
<th>10 mph exposure (mR)</th>
<th>10 mph dose (μSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>1.7</td>
<td>0.002</td>
<td>0.17</td>
</tr>
<tr>
<td>3</td>
<td>0.03</td>
<td>2.5</td>
<td>0.003</td>
<td>0.25</td>
</tr>
<tr>
<td>6</td>
<td>0.04</td>
<td>3.4</td>
<td>0.004</td>
<td>0.34</td>
</tr>
</tbody>
</table>

**Final Shielding Design**

Given the requirement to conform to Plate C regulations, coupled with the need for a low-lying shield to absorb scattered x-rays from the track, a modification was made to the original lead skirt design. The issue with having rigid components, such as lead, hanging near the rail is due to the rough conditions experienced on track. Items laying on the track could bump the easily deformable lead skirt and possibly tear it off. Not only would this lead to the possibility of radiation emitted over public dose limits, but also the toxicity of lead in the environment would be a concern. Furthermore, the harsh
environmental conditions on track such as extreme heat or high humidity could further reduce the integrity and durability of a lead curtain.

In order to correct for these limitations associated with lead, a new type of shielding material was utilized for the lead skirt made by the American Ceramic Technology, Inc. and called Silflex. The material is non-toxic and engineered to provide superior radiation shielding. It’s composed of silicone and a propriety mixture of radiation shielding material that gives it a half-value-layer (HVL) of 0.5 inch. Silflex provides exceptional stability at high temperatures and in moist conditions. Most importantly is the excellent ruggedness it maintains, being highly resistant to physical abuse, including puncture and tear-resistance. Furthermore, it’s the lightest shielding available, weighing in at 4.5 pounds per square foot in comparison to lead wool that is 10 pounds per square foot.

The Silflex material used for the skirt was in the form of rectangular strips 1 foot high and 4 inches wide. Each strip has one grommet drilled into the top allowing them to be attached to the base of the lead shield. Strips of Silflex, illustrated in Fig. 5-10, demonstrate its ability to maintain a close distance to the rail to provide superior radiation shielding of scatter off the track while easily conforming to the rigid dimensions of the rail. The photograph in Fig. 5-10A is a view from the back of the inspection vehicle shielding, where Silflex strips hang low between the rails in order to maintain a close distance to the track surface under normal scanning conditions. Figure 5-10B displays the side view of the inspection vehicle shielding design, where the Silflex strips hang over the outside of the rail edge in order to block scattered x-rays coming from the track structural components.
The results of the shielding design measurements illustrate the inherent safety of this novel backscatter scanning unit used for wood cross tie inspection. All exposure rates were within regulatory requirements of the State and railroad community, and its operation has proven to be safe around general members of the public. In 2014, the backscatter system was issued an operating license by the Texas Department of State Health Services Radiation Control Program. It has subsequently been licensed to operate in 32 other states following its initial registration in Texas.
CHAPTER 6
MODULATION TRANSFER FUNCTION

The modulation transfer function is an important tool used to evaluate imaging systems. It provides a means of expressing image quality of optical systems both objectively and quantitatively. In medical imaging systems, the MTF is regarded as one of the best descriptors of overall image quality and its routine measurement is often required as a means of tracking the system performance over time.

The first goal in this research is to adapt the well-known MTF measurement techniques specifically to this Compton backscatter system. While several well-documented methods exist for MTF techniques in a transmission x-ray system, very little data exists on how to carry these methods out on a scatter system. Since the detected backscatter signal requires photons to both traverse and escape the target material, the geometry of the measurement volume, including its size, shape, and position within the sample, play a significant role. The output contrast will therefore be dependent on both the electron density of the material and the geometrical setup of the system. As a result, the accuracy of MTF measurements is highly dependent on the appropriate target material and thickness, along with their orientation and relationship to surrounding materials.

The principal challenge with scatter imaging, as demonstrated in previous chapters, is to be able to record a detectable signal with moderate source strength and within a reasonable exposure time. The spatial resolution of this system is basically dominated by the width of the source beam and by the step increment employed in the scanning process. The width of the fan beam determines the geometric efficiency of the x-ray source, which in turn affects the minimum source strength need for successful
applications. In addition, the step increment determines the total measurement time required in an inspection process. Therefore, for a given source strength, the spatial resolution is compromised by available image acquisition time. In other words, the inspection speed must be traded off against the required spatial resolution. Thus, the results from the MTF measurements were then utilized to quantitatively compare different system parameters and determine which lead to the optimal system performance. Specifically, the focus was quantifying the spatial resolution degradation as the source motion was increased, thereby characterizing the tradeoff between resolution limits and system speed. The results were then used to optimize the speed of the imaging system while maintaining the minimum spatial resolution of 2.5 cm required for the detection of subsurface flaws.

Another significant aim of the MTF research was to extend the use of linear systems metrics that are typically only associated with imaging research, to the fully operational CBI scanning system as part of routine quality assurance (QA). Routine QA measurements of MTF provide an effective method to quantify any loss in image quality that may be induced during everyday field use like mechanical damage, misalignments, inappropriate calibrations, or radiation damage to peripheral electronics. Given the rough terrain conditions of railroad scanning and the limited track time for performing quality assurance monitoring, these developed image quality protocol methods are designed to be a quick and easy method for carrying out routine QA on the system.

**Backscatter Radiography System MTF**

In order to characterize the MTF for the prototype system, it’s helpful to understand which components contribute to blurring as the object is moved through the imaging chain. Similar to traditional radiography systems, the principal components that
degrade resolution are those associated with the focal spot, detector, and electronics. However, an additional factor which must be considered for the CBI system is the blurring effects caused by the continuous motion of the system necessary to obtain images. Assuming all the processes of the imaging system are separable, the system MTF is given by their individual multiplication.

\[
MTF_{\text{system}} = MTF_{\text{optics}} MTF_{\text{det}} MTF_{\text{motion}} MTF_{\text{electronics}}
\] (6-1)

The finite size of the x-ray tube focal spot, as well as the distance between the source to object and object to detector, cause a penumbra effect. The optical MTF includes the effect of the geometric un-sharpness caused by the finite size and shape of the focal spot, as well as the magnification factor used. The MTF associated with the optical components due to the focal spot and the geometry of the exposure setup can be represented by

\[
MTF_{\text{geom}}(u) = \left| \frac{\sin \pi u S_p}{\pi u S_p} \right|
\] (6-2)

where \(S_p\) is the width of the penumbra given by Equation 4-2.

The finite size of the detector aperture and its sampling interval contribute an additional component of blur. The detector MTF is caused by the spatial integration that occurs over the detector active area once a scatter signal falls on it. For the CBI linear detector array, the pixels are rectangular in shape causing different active widths along the x and y dimension. The two dimensional MTF for the rectangular detector blurring is

\[
MTF_{\text{aperture}}(u, v) = \left| \frac{\sin (\pi u w_x)}{\pi u w_x} \right| \left| \frac{\sin (\pi v w_y)}{\pi v w_y} \right|
\] (6-3)

where \(w_x\) and \(w_y\) are the active widths of the rectangular pixels in the x and y dimension. The MTF is written as a product of the two 1D MTFs because it was assumed the
impulse response is separable. The equation shows that the smaller the pixel dimension is, the better the MTF will be.

The discrete sampling of a digital detector array leads to spatial averaging over the samples acquired. For a two-dimensional rectangular sampling grid, the impulse response is a rect function whose widths are equal to the sampling intervals in each direction. In the backscatter system, sampling along the length of the detector is fixed by the pixel aperture widths. However, sampling along the direction of motion can be altered and is determined by the detector line rate. The sampling MTF for both directions is given by

$$MTF_{\text{sampling}}(u, v) = \left| \frac{\sin(\pi u x_{\text{samp}})}{\pi u x_{\text{samp}}} \right| \left| \frac{\sin(\pi v y_{\text{samp}})}{\pi v y_{\text{samp}}} \right|$$ (6-4)

where $x_{\text{samp}}$ and $y_{\text{samp}}$ are the distance between sampling intervals in the spatial domain.

The formation of 2D images in CBI systems always require some kind of mechanical scanning of the detector-source conveyer system over the target object. Another factor that must be considered in the detector sampling process is the time interval over which the sensor is integrating the flux. Because the detector is moving across the object during this process, there is additional blurring in the direction of linear motion. The blur is directional and will affect the image differently based on the direction. The impulse response can be represented in the form of a rect function whose base is as long as the distance the detector moves during the integration time.

Assume the motion is in the direction of the y-axis and the detector moves with a constant velocity $v_{\text{sensor}}$. Over the time interval of exposure $t$, the detector travels a distance during the detector integration $S$. $S$ is the spatial distance traveled by the detector as projected to the ground during integration, and is simply the product of
platform velocity $v_{\text{sensor}}$ and detector integration time $t$. The one-dimensional blur caused by linear motion in the direction of travel is thus represented by

$$
MTF_{\text{along-motion}}(u) = \left| \frac{\sin(\pi uv_{\text{sensor}}t)}{(\pi uv_{\text{sensor}}t)} \right|
$$

where the equation demonstrates linear motion is direction dependent. The extent of the blur depends on how far the detector moves while the signal is being integrated by the electronic circuitry. Typically, the detector array on the focal plane has an integration time in which to capture the incident radiance, thus causing the incident blur. The image blurring is in addition to the spatial integration of the detector itself.

**Measurement of Backscatter System MTF**

The physical structure of the linear detector array utilized in this CBI system is different between the two orthogonal directions. The sensitive cells of the detector pixels are rectangular in shape, having an aperture pixel size of 1.6 mm and thickness of 11 mm. For this reason, the MTF cannot be assumed as rotationally symmetric and thus it must be evaluated along both directions for any MTF measurement method. In order to accomplish this, separate measurements were carried out with the test tools aligned along the direction of system motion (called along-scan direction or x-axis) or across it (called across-scan direction or y-axis) as illustrated in Fig. 6-1. The across-scan axis is aligned parallel to the length of the 1D array whereas the along-scan direction is perpendicular to the detector, shown by Fig. 6-2.

All MTF techniques were evaluated using the same operating conditions, both in terms of x-ray energy and intensity, as well as in terms of geometric configuration. The system was evaluated using the standard operating parameters used on track: 325 kVp, source to object distance of 122 cm, detector to object distance of 46 cm, large focal
spot, and tube current of 3.3 mA. For the initial development of the MTF methods, the inspection speed was 2 mph.

Figure 6-1. Axis naming convention for orthogonal scanning directions in MTF measurements on track.

Figure 6-2. Across-scan axis aligned parallel to the largest length of the linear detector array.
Bar Pattern Technique

In order to measure the MTF using the bar pattern method, a custom-designed target was constructed for the prototype scanning system. The line pairs were constructed from 1.2 mm thick lead bars and placed on top of a 1.9 cm plywood board, as illustrated in Fig. 6-3. The use of a plywood board was focused on emulating the typical scanning parameters for the CBI system. The line pairs were 5 cm tall and had widths corresponding to 10 different spatial frequencies in line pairs per cm (lp/cm): 0.17, 0.2, 0.25, 0.33, 0.4, 0.5, 0.67, 1.0, 2.0, and 5.0. The MTF target contains four lead bars (line pairs) for each spatial frequency tested in order to ensure good statistics in the results.

Figure 6-3. Bar pattern target constructed from lead and plywood.

The setup for measuring the MTF with the bar pattern method is shown in Fig. 6-4. The tool is placed in the center of the track, oriented either perpendicular or parallel to the wood tie for the along-scan and across-scan MTF, respectively. The target was scanned with the backscatter system and the images transferred to the computer for processing. Intensity profiles were obtained by drawing a rectangular ROI over
Figure 6-4. Bar pattern tool alignment procedure. A) Along-scan direction, B) Across-scan direction.

the line pairs in the acquired backscatter image, and creating a surface profile plot in Image J, shown in Fig. 6-5.

Figure 6-5. Intensity profile plot for the bar pattern target ROI.

The initial results obtained with the bar pattern target were poor, suggesting a more optimal design was necessary. Several limitations associated with the original design were evident when analyzing the output profiles. The first issue was the
presence of noise and low contrast in the modulations, which masked the identification of any separate peaks or valleys in the output profile for all spatial frequencies tested. Other possible reasons for this effect is shadowing, or minimal attenuation provided by the 11.2 mm thick lead. The second drawback is due to the off-axis effects visible at the 0.17 lp/cm peak, resulting in a reduced contrast for this small spatial frequency when in reality the signal should be the greatest since it corresponds to the largest bar pattern width. These off-axis effects are caused by the decreasing strength of the fan beam at the edges due to the longer distance radiation must travel to the outer edges versus those in the central axis. Also, there should be a modulation in the signal amplitude as the spatial frequency increases along the x-axis in Fig. 6-5, yet the signal amplitude is relatively constant for the 0.2, 0.25, and 0.33 lp/cm frequency peaks.

Based on the preliminary results, an improved bar pattern target was constructed for the backscatter system. The first alteration was to utilize the higher quality, more uniform wood for the scattering medium. Medium density fiberboard (MDF) was employed instead of plywood, since plywood suffers from knots and imperfections while MDF has a more consistent density. The second variation used thicker lead bars (6.4 mm) in order to improve the contrast signal between the wood and lead. A router was used remove an equivalent depth and size matching that of the bars so that the lead was placed flush within the MDF board. The widths of the line pairs were also increased in order to include smaller spatial frequencies since the previous tool used spatial frequencies well below the resolution limit of the system. In the second bar-pattern target shown in Fig. 6-6, a total of ten discrete spatial frequencies in line-pairs per
centimeter (lp/cm) were generated: 0.10, 0.11, 0.13, 0.14, 0.17, 0.20, 0.25, 0.33, 0.50, and 1.0.

Figure 6-6. Improved bar pattern target for MTF measurement of backscatter system.

Another limitation associated with the prototype bar pattern was its layout and size. The initial bar pattern modulations measured were most likely affected by geometric artifacts due to beam divergence. Since all of the frequencies were placed on one board, line pairs located on the outer edge of the tool were positioned significantly off-axis from the central beam. Due to the diverging nature of the beam and the inverse square fall off, the measured intensities for off-axis line pairs was much lower than their centrally located counterparts even though they had larger spatial widths. The improved target was designed so that one discrete spatial frequency, represented by four line pairs, was placed per MDF board as shown in Fig. 6-7.
Figure 6-7. Improved bar pattern target for one discrete spatial frequency placed per MDF board section.

For the measurements, each individual board was placed on top of the wood ties, taking extreme care to overlap the ballast as little as possible as shown in Fig. 6-8. It's believed that the thinness of the wood tool allows scatter interactions to occur below it, possibly complicating the signal. Another difference is that the tools were centrally located between the rails, such that the central axis of the beam intersected the center
of the board, illustrated by Fig. 6-9. This placement was done to ensure beam divergence effects at off-axis locations near the rail would not complicate the measurements. Lastly, the target was angulated approximately 45° with respect to the imaging axis to ensure that the MTF does not depend on the coincidence between bar centers and detector pixels. Placing the bars at an angle helps to average these sampling phase effects out.

Figure 6-9. Bar pattern test tools placed centrally between the rail for testing the along-scan direction.

In order to accurately describe the variance associated with each spatial frequency, the ROIs were selected to cover a major portion of the line-pair modulations for each spatial frequency. However, the peripheral regions of the line-pairs were avoided since they included scatter from regions outside the bar pairs, including the contribution from ballast, which could lead to an underestimation of the modulation
contrast value. The ROIs were selected with top and bottom margins of one-third the height of the bars each shown in Fig. 6-10. The right and left margins differed depending on which direction the tool was oriented. If the test was for the across-scan direction, the bar pattern was placed directly along the wood tie and scatter from under the tool is not a concern. These ROIs were selected with left and right margins of one and a half bar widths each. If the test is for the along-scan direction, a portion of the lead bars might overlap onto ballast sections of track. The ROIs were selected with left and right margins to match as closely to those used for the across-scan direction. If this margin resulted in a region of ballast underneath, the ROI width was minimized in order to avoid the inclusion of lower signal resulting from the minimal scatter off the ballast.

![Image](image_url)

**Figure 6-10.** ROI selected around the bar pattern image.

Each ROI produced an output grey-level profile composed of three peaks and four valleys for each discrete spatial frequency, illustrated by Fig. 6-11. The maximum and minimum intensities were measured and the results averaged over the four lead bars and three wood regions. These intensities were then used to calculate the modulation depth from Equation 3-12 and then the CTF from Equation 3-13. Multiple ROIs were analyzed for each frequency and their results averaged to obtain the final
CTF. The MTF was then calculated by using the Coltman approximation in Equation 3-21.

![Intensity profile plot for extracted ROI in bar pattern target image.](image)

**Figure 6-11.** Intensity profile plot for extracted ROI in bar pattern target image.

**Edge Method**

In order to avoid aliasing effects from regular pixel sampling, the edge response is oversampled by extracting the ESF profiles at sub-pixel intervals using a special reconstruction technique. The presampled MTF of the system was measured using a variation of the edge slant method [79]. In transmission radiography, the measurement would consist of placing a slightly angled lead sheet directly atop the linear array, thereby hiding a portion of the pixels. However, this is not possible with a system using backscatter geometry and a line scan camera. Instead, an arrangement of the edge on track that essentially creates this same scenario as would be seen from the detectors point of view must be carried out.
A fully absorbing edge target was constructed from a 0.64-cm thick lead sheet. The wood crosstie served as the high intensity side of the edge. The lead sheet was placed on top of a wood crosstie for all tests, aligned differently depending upon which orthogonal direction was being measured. The configuration for measuring the MTF along the direction of motion is shown in Fig. 6-12, with the rectangle drawn around the edge boundary to be measured in the image ROI. The edge boundary was aligned parallel to the longest dimension of the wood tie, such that the central axis of the x-ray beam matched the center of the edge. The edge was also placed such that half of the tie was exposed and the other half was lead. This was done to reduce the effects of any scatter from ballast contributing to the measured edge response. The configuration for

Figure 6-12. Slanted edge target for measuring the along-scan direction MTF.
measuring the MTF in the across-scan direction is similar to that shown in Fig. 6-12, except the ROI would be drawn on the right edge of the target. The edge was aligned perpendicular to the wood tie, and aligned with the central axis of the x-ray beam. In order to oversample the digital detector, the edge target was then given a slight angle between 1-3° with respect to the imaging coordinate axis for which the 1D MTF is desired.

A total of three images were taken for each measurement: one edge image, one flat field image, and one dark image. The dark image was measured by acquiring lines of data from the linear detector while the x-ray tube was turned off. The flat field image was acquired by scanning a calibration wood target of uniform density. The edge images were measured with the same operating parameters discussed previously.

After the image of the edge device is acquired, the digital image data is transferred to a computer and processed to obtain the presampled MTF. A well-established processing method was used for the individual edge images at each angle, with slight variations to account for the differences caused by backscatter systems. The processing includes one pre-processing step followed by three processing steps, including the angle determination, re-projection, and ESF to MTF transformation. All processing routines were carried out in Matlab.

The pre-processing step dealt with the gain and offset correction necessary for the detector array. The dark image was subtracted from both the edge image and the flat field image in order to remove dark signal, and remove baseline offset added in software. Next, the edge image was divided by the flat field image in order to remove non-uniformities that may be present in the CMOS, scintillator, or x-ray beam, giving a
pre-processed image. An ROI was then selected around most of the edge boundary as shown in Fig. 6-13.

![ROI selection](image)

Figure 6-13. Selection of the ROI extracted from edge images in order to produce the oversampled ESF.

In the first processing step, the position and orientation of the edge line in the image are estimated in order to calculate the angle of the edge profile needed for sampling the oversampled ESF. The angle of the edge is found by applying a Hough transform which first requires a binary line image as the input. Otsu thresholding is used to create an 8-bit binary image from the gray-scale image by supplying a binary threshold value computed as the average of the signals from the two sides of the edge image.

Next, edge detection is performed in the binary image by the Canny method, selected since it’s generally acknowledged as the best all-around edge detection method. The first step of the Canny method is to smooth the image using a Gaussian kernel since gradient operators are sensitive to noise. The gradient of the image is the
computed with Sobel operators in order to acquire the binary line image of the pre-processed ROI extracted above.

The angle and position of the edge transition is found with the aid of the Hough transformation, which is a common technique for detection of lines in images. Each non-zero point in the binary image is transformed to a curve in polar coordinate space. The curves associated with collinear data points intersect at a point in the polar coordinate corresponding to the angle and position of the line with respect to a reference point in the image. From this, the coordinates of the peak value in the Hough transform gave the angle and slope intercept of the edge line.

In the second processing step, an oversampled ESF is produced from N consecutive rows. Using Equation 3-24, the number of rows necessary to oversample the ESF is calculated using the line angle obtained by the Hough transform. For each of the N rows, the gray level data are projected along the direction of the estimated edge onto the horizontal axis, forming a one-dimensional array of the profiles aligned according to their sub-pixel edge locations.

In general, the angle of the edge with respect to the sampling grid does not produce uniformly distributed data points along the perpendicular to the edge. Also with longer edges, many data points may be located in close proximity to one another. The ESF data must be resampled and collected into uniformly spaced bins with a sub-pixel spatial width selected relative to the pixel dimensions. In order to accumulate a sufficiently large number of pixels within each bin while still providing a good frequency response, it's reported that the bin width should be equal to 10% of the pixel width. Interpolation was used to fill in any missing data points within the uniform spacing and
then values of the pixels collected in each bin were averaged, generating a one-dimensional profile with 10 times the oversampling multiple.

Once the edge profiles have been aligned, it is necessary to smooth the data because of random noise introduced by the detector or target heterogeneity. The ESF array is smoothed with a fourth-order Gaussian weighted, moving polynomial fit. The use of this local smoothing doesn’t confine the ESF to a particular mathematical form. For each element in the ESF array, a polynomial function is fit using adjacent elements and the initial element value is replaced with the value predicted by the fit.

In the third processing step, the smoothed ESF array was processed to obtain the presampled MTF. First, the array was numerically differentiated with a standard first-order central difference algorithm to obtain the LSF. A moving Gaussian weighted polynomial window was fit to the smoothed LSF because differentiation led to a reduction in the SNR. The presampled MTF was obtained by taking the magnitude of the fast Fourier transform of the LSF. It was then normalized by its first coefficient value.

**MTF Results and Analysis**

The resulting MTF curves obtained from the bar pattern method for the along and across-scan direction is shown in Fig. 6-14. As expected, the across-scan direction has a higher MTF curve than the along-scan. The additional blurring component caused by linear motion causes degradation in resolution for only the along-scan direction. The spatial frequency where the MTF is 10%, also known as the limiting spatial resolution, is 0.34 lp/cm for the across-scan, whereas it’s 0.33 lp/cm for the along-scan direction, representing only a 3% difference.

Differing results than those obtained with the bar pattern method are the MTF curves for the edge method, shown in Fig. 6-15. The edge method demonstrates near
Figure 6-14. MTF curves for the along-scan and across-scan directions measured with the bar pattern target.

Figure 6-15. MTF curves for the along-scan and across-scan directions measured with the edge method.

identical curves for both directions across the entire frequency range. In order to determine which method is in error, a comparison between the edge and bar pattern results for the along-scan direction is illustrated in Fig. 6-16. The edge method gives a
higher MTF for the low-frequency range from 0 to about 0.17 lp/cm and the high frequency range spanning 0.3 lp/cm and higher. The reason for the low-frequency range disparity is the result of two effects. The first cause is due to the coarse nature of bar pattern MTF measurement methods. Since only a discrete number of frequencies can be modeled in the bar target (10 in this target), then measurements exists only for these values and anything in between is interpolated by the graph. The smallest spatial frequency in the bar target was 0.1 lp/cm, whereas the edge method is sampled continuously over the entire frequency range. Thus, no measurements exist for any frequency higher than 0.1 lp/cm where the two curves have the greatest difference. The same disparity at high resolutions is most likely attributed to this effect, as well. It’s possible that modulation is visible in frequencies smaller than 0.35, but lower than the next discrete frequency in the target of 0.25 lp/cm but this sample is lost in the coarse measurement.

![MTF curves for the along-scan direction measured with the edge and bar pattern method.](image)

Figure 6-16. MTF curves for the along-scan direction measured with the edge and bar pattern method.
The second factor leading to the edge method having a higher MTF in the along-scan direction is attributed to how the measurements were carried out on the railroad track. When measuring the edge ROI for this direction, its width could only be drawn to cover lead regions as wide as ½ the wood tie in this direction. When the ROI covered regions of ballast located below the lead, the signal was very noisy and inaccurate. It’s been established that the edge width in the ROI has a significant effect on the results and it must be large enough to suppress high frequency noise. Therefore, due to scatter from structures below the lead target, the edge width was not long enough to give accurate results. Furthermore, the differentiation of the LSF increases the high frequency noise, resulting in the method lacking accuracy in higher frequency ranges as is evident in this MTF curve.

The MTF curves for the across-scan direction are compared between the two methods and shown in Fig. 6-17. Again, the low frequency and high frequency regions
are lower for the bar pattern method, but to a much smaller extent than visible in the along-scan direction results. These disparities in this case are most likely the result of only the bar pattern coarse measurements, which don’t sample low or high enough frequencies. The edge method in this direction is accurate since a long enough ROI could be accurately assessed across the entire wood length, therefore suppressing noisy signals.

An additional measure of image quality that is commonly used to compare imaging systems is the limiting spatial resolution. It is often quoted as the spatial frequency at which the MTF falls to 10% since this corresponds to the limit of the human eye. The limiting spatial resolution is calculated for both directions and methods, shown in Table 6-1. The table demonstrates the accuracy of these results, with the largest difference of 3% caused by the edge method’s inability to provide an ROI unaffected by structure and scatter below the target. Furthermore, the number of bars visible in the actual images agrees with these results since 1.5 cm bars were the smallest width resolvable.

<table>
<thead>
<tr>
<th>MTF measurement technique</th>
<th>Along-scan limiting spatial resolution (lp/cm)</th>
<th>Across-scan limiting spatial resolution (lp/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge method</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>Bar pattern method</td>
<td>0.30</td>
<td>0.31</td>
</tr>
</tbody>
</table>

**Optimization of System Resolution**

The ultimate goal of establishing MTF methods for the backscatter system was to determine the optimal balance between imaging parameters necessary to achieve the required performance. As previously discussed, resolution and image acquisition time are competing factors in this backscatter system. Linear motion of the system causes
an additional blurring component in the along-scan direction that must be accounted for, which worsens with longer detector integration times.

Design criteria established a minimum scan speed of 10 mph and resolution capable of detecting voids at least 2.5 cm small in wood ties. In order to understand how much scanning speed degrades resolution, MTF measurements were carried out at four different inspection speeds and their results compared. The maximum speed at which the limiting spatial resolution was 2.5 cm was identified by both visual image interpretation and the MTF value at 10%. The bar pattern and edge method described above were repeated for the scanning system using four inspection speeds: 2, 5, 10, and 15 mph.

The MTFs calculated for the along-scan and across-scan directions with the bar pattern target is shown in Fig. 6-18. Visible in all the curves is the degradation of the MTF curve at all spatial frequencies for increasing scan speeds. These results agree with theory in that the linear motion introduces an additional component of blur in the along-scan direction. However, the differences are only slight, with the greatest disparity being 3% between different speeds. The reason that these higher speeds do not show a larger reduction in resolution suggests that the line detector sampling rates are large enough to offset the effects of linear motion. Typically, the detector acquires lines at 1000 Hz, or 0.001 seconds per line, which is far more rapid than the translational speed of the inspection system. For example, at 2 mph and 1000 Hz detector line rates, the translational motion is only 0.89 mm. At the highest speed of 15 mph and 1000 HZ, the inspection unit covers 6.7 mm. As a result, image distortion due to the linear motion is not that significant of an effect, thus MTF does not degrade a lot with speed.
The resulting limiting spatial resolutions show differences of 11, 3, and 6% between the four increasing vehicle inspection speeds. The most significant finding, however, is that the limiting spatial resolution for the fastest scan speed is 0.31 lp/cm, corresponding to a resolvable width of 1.6 cm. This result exceeds the required minimum resolvable void width of 2.5 cm; thereby implying that the fastest scanning speed of 15 mph can be used to inspect wood ties in the CBI system.

The MTFs calculated for the across-scan directions with the bar pattern target is shown in Fig. 6-19. Agreeing with the previous results, the resolution in this direction is not affected by scanning speed or linear motion. Therefore, the curves agree relatively well with one another for all four scanning speeds. These MTF measurements include the contribution from the finite size of the detector aperture and electronic blurring, but they don’t include linear motion. Because the electronic system utilized by the system is
highly advanced, its contribution to blurring is expected to be negligible. Therefore, the overall system MTF in this direction is dominated not by the system speed or finite focal spot width, but rather by the finite width of the detector and its collimation grid.

![Figure 6-19. MTF measured with the bar pattern target at different inspection speeds in the across-scan direction.](image)

The results confirm the notion that the effect of source motion is one-dimensional blurring evident only along the scan direction. At the slowest speed of 2 mph, the extent of blur is minimal and resolution is best, indicated by the highest MTF values of all speeds tested and for every spatial frequency. As the system motion is increased, the resolution suffers only slightly, resulting in a lower MTF curve across the range of spatial frequencies. However, these results suggest that the weakest link in the imaging chain for the along-scan direction is not linear motion as was originally expected. The limiting resolution is instead believed to be the result of the finite width of the fan beam projected on the railroad track. This conclusion is based upon the rect functions which
were used to derive the individual frequency-domain MTF equations given in Equations 6-3 and 6-5. As discussed in the linear systems review, a wider rect function will translate into a narrower sinc function (or an MTF curve which falls off faster with spatial frequency). Therefore, the limiting resolution is caused by the geometrical aperture MTF (fan beam width) whose rect has a width projected on track of 1 in., much larger than the 6.7 mm (linear motion rect function width) traversed by the imaging system at 15 mph and detector sampling rate of 1000 Hz.

Based upon these MTF results, improvements in spatial resolution could be achieved in the along-scan direction by using a narrower fan beam width. The ideal width would equal that of the focal spot along this axis. However, reducing the collimator slit will also have a drastic effect on the fraction of x-rays efficiently utilized by the system. Unless a longer image acquisition time is employed, reducing the number of emitted source x-rays would subsequently result in a lower detected scatter intensity and higher noise.

Another way to offset the reduced signal caused by a narrower fan beam would be through alterations to the geometrical layout of the system. If the x-ray source to target distance were reduced, such that the tube is now closer to the track, less divergence of the beam would occur and thus less blurring associated with a smaller beam width projected on track. However, the harsh conditions and physical layout of the system components require a minimum distance be maintained between the source and track. Placing the x-ray tube closer than this could damage the system components if the inspection vehicle encountered large debris on track or excessive bumps during scanning.
In the across-scan direction, the results suggested that the limiting MTF contribution is due to the finite width of the detector aperture. Since a collimation grid is employed in order to separate the scatter response of each detector pixel, its presumed that the collimator dimensions will have a significant effect on the resolution. As discussed in the previous chapter, collimator length, septa thickness, and pitch will all affect the spatial resolution. Improvements in resolution for the across-scan direction could be achieved by designing a more optimal collimator with a pitch whose width aligns exactly to that of the individual pixel spacing. Constructing a collimator whose fins are longer and or thicker in order to narrow the detector pixel acceptance angle could also enhance the resolution. However, this improved resolution will come at the cost of decreased detection efficiency and increased noise that can only be offset by employing a longer acquisition time.

**Comparison of MTF Methods**

Theoretically, the bar pattern and edge methods for measuring the MTF should lead to identical results. However, in practice, since the ideal edge or sinusoidal stimulus is physically impossible, and only their approximate versions are used, the obtained responses of the system to these unrefined stimuli are not exactly the same. As a result, the obtained MTFs with the different stimuli are not identical as was demonstrated in this study.

The bar pattern method for MTF measurement provides a practical solution to implement linear systems metrics for CBI systems due to its bases on phantom imaging that can be done quickly and easily without the need for a complex imaging setup. The fundamental advantages of this method are its simplicity relative to the edge technique, as well as the fact that it produces a direct visualization of image spatial resolution.
through the acquired images of line-pairs. The ease of simply placing the target on the track and imaging it implies that routine quality assurance with this method is simple and quick.

Limitations in applying the Coltman approximation to derive a sine wave MTF from a square wave CTF include two conditional assumptions which don’t apply in practice for modern digital imaging systems. The first condition is that the Coltman approximation inherently assumes an infinite number of bars in the target, i.e. the bar target is a true square wave of infinite extent. Second, the approximation is fundamentally derived for an analog, continuous imaging system that doesn’t accurately model the discrete area sampling of a sampled imaging system.

Additional issues with the bar pattern method include the difficulty in determining the correct amplitude from the digital image of the bar pattern. In a noisy image, the edges of the bars appear rounded and are difficult to find the amplitude. Furthermore, bar patterns commonly only test a handful of discrete spatial frequencies, causing a very coarse estimate of the system’s frequency response.

The MTF values calculated for almost all the measurements with the bar pattern showed MTF values lower than the edge method in the very low and very high frequency range. The trend for the low spatial frequencies could be the limitation in applying the Coltman approximation. The equation is best applied when there are an infinite number of square waves, and it fails at values below 1/3 of the cut-off frequency, or in this case 0.10 lp/cm. More accurate results could be obtained by carrying out the higher harmonic terms for low spatial frequencies. In the high frequency region, the
disparity is attributable to the coarse sampling of discrete spatial frequencies constructed in only ten bar widths.

There are several advantages to using the edge response for measuring the MTF. First, the measurement is in the same form as the image information is encoded. The main reason to investigate the resolution of a system is to determine how the edges in the image are blurred. Second, it is simple to measure because edges are easy to generate in images. The third advantage is that the MTF can be obtained directly by taking the Fourier transform of the LSF.

A significant disadvantage of the edge method is that the characteristics of the target affect the accuracy of MTF results. The contrast, homogeneity, random noise, incline angle, and size of target have to be strictly defined to minimize their influences. To restrain the influence of random noise, the high reflectance side should ideally approach the dynamic range of the sensor, and the low reflectance side should be as low as possible, yet coordinated with the surrounding background. Furthermore, the size of the target must ensure that the number of sample points for the ESF be large enough to suppress the effect of random noise [69].

A very important parameter for the edge detection method is the length of the edge profile. It should be long enough for reliably estimating the ESF, but not too much longer to avoid the possibility of introducing image noise effects. The minimum length is determined by the incline angle, because it requires the edge should cross at least one pixel. In addition, extreme care must be taken in aligning the edge with respect to the beam axis.
A second disadvantage arises because the procedure for determining the edge function involves differentiation, which makes it very sensitive to any noise in the measured edge function. In particular, it amplifies the noise at the high frequency end of the MTF curve making the method inaccurate at higher spatial frequencies.

The disadvantages associated with the edge method were possibly evident in many of the measurements acquired. The dynamic range of the sensor was not approached for either the high reflectance or low reflectance side of the edge target. This limitation most likely caused the disparity at higher frequencies for several of the MTF curves used in comparison to the bar pattern method.

**Limitations of Study**

The fundamental limitation of both MTF measurement techniques applied in this research is the lack of statistical confidence in the results. Given the limited time available on track to carry out these measurements, each test was performed only a handful of times. If any disparity existed between measurements, their effects were extremely apparent since they could not be averaged out, as would be the case with good statistical data.

Another area of improvement would be a more optimal design for the edge tool, using a machined target for more accurate and precise results. The edge target has a significant effect on the measurements and this tool was machined by hand. The edge boundary was not exactly straight along the entire line, and this probably affected the results, as well. The wood tie in the track provided the high reflectance region in this test. However, this railroad track was in very poor condition with several degraded and low-density ties. Their scatter signal was most likely lower than would be measured for a high quality tie or even specially designed thick wood test tool.
The lead portion of the edge target should also be optimized in its dimensions. It's suggested that the low reflectance side be in the dynamic range of the system and also match the background area. Neither of these requirements were met in this study. When dealing with backscatter systems, scatter off surrounding materials can have a significant effect on the overall signal. Thus, the ballast section underneath the edge target in the along-scan direction contributed to noisy measurements and less than optimal sampling points for the ESF. Furthermore, accurate alignment of the x-ray beam with the edge was only estimated with a plum-bob tool. Laser alignment lights would provide a more accurate procedure.
CHAPTER 7
DETECTIVE QUANTUM EFFICIENCY

Detection efficiency, noise, and spatial resolution are parameters on which the detection of x-rays depends critically. Spatial resolution, as characterized by the MTF, is an important image quality metric widely implemented in radiography systems. However, optimization of the MTF fails to account for the contribution of noise to imaging performance. In comparing signal and noise properties of imaging systems, it is therefore useful to analyze the noise versus spatial frequency. Also, the MTF doesn't describe the sharpness in the final image since imaging processing can alter the resolution. The DQE is regarded as one of the best metrics in order to characterize the overall quality of an imaging detector. It combines the signal-to-noise, resolution, and sensitivity properties of an imaging system.

Experimental determination of detector DQE is well established and practiced regularly to evaluate performance of imaging systems [80]. However, the popularity of these standardized protocols are primarily focused in the medical imaging community for transmission radiography. Due to the inherent differences in image formation between a backscatter and conventional radiography system, these methods cannot be directly or easily applied to this novel prototype inspection unit. One primary difference is encountered when acquiring flat field images which are necessary to measure the noise power spectrum. Uniform flat field images are relatively simple to obtain in transmission units, often achieved by exposing an open-air field. In backscatter, however, an object must be placed between the detector and source in order to scatter the photons and acquire a signal. Furthermore, the unique system in this research utilizes a linear detector array, only enabling the acquisition of lines of data versus a
two-dimensional grid of values achieved in transmission systems. Given that the accuracy of NPS measurements depend highly on the amount of data used in the average flat field images, these limitations associated with linear arrays will most likely affect the uncertainty achievable in backscatter systems analysis. The goal of this research is to develop a similar protocol adapted specifically to measure the imaging performance in Compton backscatter imaging systems.

**Methods Adapted for Backscatter Radiography**

**Uniformity Calibration**

Artifacts associated with scintillation images typically result from local imperfections in pixel response, or from dead pixels. The detector readout electronics may not be exactly the same, or the amount deposited of the x-ray sensitive layer may vary. The result is that the gain of individual pixels may vary from location to location. Correction for these variations is possible through gain and offset procedures. The process is also referred to as dark image subtraction and flat-field correction.

X-ray based imaging systems under the condition of no incident x-ray exposure to the detector exhibit thermionic charge generation, resulting in a dark signal. This dark signal is integrated along with the charges generated during exposure, resulting in increased amplitude. Therefore, the acquired images need to be corrected for this increase achieved by an offset correction that removes the noise contributions associated with the amplifier and with dark currents. In addition, there may be a pixel-to-pixel variation in gain, corrected by normalizing the linear non-uniform response of each pixel and its associated electronics. The offset correction is typically achieved by subtracting a dark image from each subsequent exposure image. Gain calibration is achieved by the process of flat-field exposures of intensity in the normal operating
dynamic range of the system. Ideally, multiple gain calibrations are averaged so the gain map correction will only contain fixed pattern limited noise. When this condition holds, application of a gain correction will not increase the overall noise.

The linear detector array utilized in the prototype system suffers from non-uniformity in its pixel response when exposed to a uniform object. As a result, images acquired through a pushbroom scanning method typically suffer from streaking artifacts, caused by the response non-uniformity for separate pixels. As the linear array collects multiple lines, these defective pixels create channels of signal variation in the image. Therefore, prior to use, gain and offset calibrations were performed for the line camera as part of a pre-processing step.

The flat field calibration step includes a per-pixel compensation to correct for differences in the amplifier gains and offsets, and for beam in-homogeneities (heel effect, collimator grid non-uniformity). The goal of this compensation is to produce an image of uniformly constant value. In traditional imaging systems, these flat field images can be acquired with nothing in the beam. However, for a backscatter system, a uniform target must be placed in the beam in order to provide the scattering signal.

All flat field images were acquired using the 17 cm-thick calibration target composed of particleboard, and discussed in previous chapters. The tool had dimensions of 122 cm x 244 cm, such that it spanned the entire width between the rails. Particleboard was selected for its uniform material properties, lacking any knots or cracks, and having a density (0.722 g/cm³) similar to that of oak (0.75 g/cm³), the material composition scanned by the system under routine use. The thickness was selected to provide sufficient attenuation of the incident beam so that scattering from
materials below the board did not obscure the measurements. Acquisition of a typical flat field calibration image for the backscatter system is demonstrated in Fig. 7-1.

Figure 7-1. Flat field calibration target used for the backscatter system constructed from plywood.

In medical imaging, the gain and offset procedure is provided by the detector manufacturer since the accuracy of detection relies heavily on this correction routine. Industrial radiography is limited in this respect, however, with no guidance provided for the proper flat field correction of the linear detector array. A standard gain and offset correction formula was applied to the backscatter system to remove structured noise:

\[
I_C(x, y) = \frac{I(x, y) - \bar{I}_D(x, y)}{\bar{I}_G(x, y) - \bar{I}_D(x, y)} \max[\bar{I}_G - \bar{I}_D].
\]  

(7-1)
The flat field correction of a raw image $I(x,y)$ acquired by scanning the calibration phantom begins by first removing the offset signal by subtraction of the average dark current images $I_D(x,y)$ acquired at the same exposure time. $I_G(x,y)$ is the average flat field image under the same irradiation conditions and integration time. All images are averaged over 20 frames to reduce the random noise components. The scaling of Equation 7-1 by the max of average of dark-corrected uniform images preserves the range of the corrected image pixel values.

**System Response and Linearity**

For digital systems, the output of the detector should be linear with the input radiation. The beam spectrum to be employed in the field should be used if it’s desired to have a quantitative characteristic curve relating image pixel value to absolute exposure. For each beam spectrum tested, multiple uniform images should be acquired at different exposure levels. The experimental imaging geometry is not highly crucial unless the pixel value response versus absolute exposure is desired. The imaging technique should be selected that minimizes confounding factors that might bias the true system response. An example is the requirement to turn off all image processing, examining only the raw data acquired. The only exception to this is that any pixel-by-pixel correction in the device should still be applied. These corrections adjust for gain and offset of individual pixels, interpolating across bad pixels.

The range of exposure values to be analyzed depends on the expected range of the system response. At the very least, measurements every tenfold variation in exposure should be used, covering the majority of the usable range of field exposures to be encountered. Ideally, more exposures values should be examined when the very lowest exposure values can be obtained through variation of mA, time, and source to
detector distance all whist maintaining the same beam spectrum. The increment between exposure values was selected to adequately fit a curve to the data on a linear curve, with 10 data points generally being sufficient.

The large area transfer response characteristics of the CBI system and the linearity of the detector were assessed. Imaging parameters in this case were 300 kVp and a source to image distance of 24 cm. For the tested beam spectrum, multiple uniform images were acquired using a range of exposures. Exposure intensity was varied by changing the time which the x-ray beam was exposing the ion chamber. Each exposure was taken over a 30 second exposure to ensure the maximum power was reached during the 10-second ramp-up time associated with the system generator.

Exposure values were measured with the Rad Eye Gamma Survey meter with the detector array removed from its normal operating position. For the exposure measurements, linearity was tested without the detector collimation grid attached per the suggestion of the IEC protocol. This ensures that any deformations in the collimator do not affect the measurement. Furthermore, it allows comparison between different detectors since collimators will not be identical between different systems.

Flat field images were acquired with the MDF calibration phantom. The only image processing performed on the images was to remove the fixed pattern noise that exists with the scintillator array, using the gain and offset correction described in the previous section. For each gain and offset corrected image, ROIs 100 x 100 pixels in size were extracted from the central region of the image to avoid edge effects. The mean pixel value associated with each ROI was then determined and plotted against
exposure level. A linear fit was applied to the data in order to estimate exposure in the flat field images used for the NPS calculation and demonstrate detector linearity.

**Presampled Modulation Transfer Function**

The presampled modulation transfer function of the system was measured using the edge method established in the previous chapter. The edge method was selected over the bar pattern given the higher accuracy associated with a continuous range of frequency data provided by edges. The results of this test give MTF data in one dimension. Thus, the MTF measurements were provided for both the along-scan and across-scan direction.

**Noise Power Spectrum**

In addition to the absolute level of noise present in each detector pixel, it is also important to evaluate whether noise components are correlated over a number of pixels, since this correlation drastically enhances the visibility of noise due to the spatial integration performed by the visual system of the human observer. In real imaging systems, correlations in the data generally exist, thus requiring that the NPS be utilized in order to describe both the magnitude and spatial relationship of noise.

One of the fundamental difficulties faced in determining the NPS is that there is only a limited amount of data available for analysis, yet the discrete Fourier transform and ensemble averages in Equation 3-26 required evaluation over an infinite extent. Thus, some compromises must be made in order to arrive at the best estimate of the NPS. For 2D image data, the compromise involves a tradeoff between the size N and number M of the ROIs used for analysis. The best practical value of N depends on the approximate shape of the NPS spectrum. The size of the ROIs should be selected to contain enough pixels to adequately illustrate the structure in the NPS curve. If the NPS
is smoothly varying with frequency, then only a small ROI must be used. However, if there are spikes in the power spectrum, then a larger number of pixels will be required to maintain the shape of a more sharply peaked NPS. The size of the ROIs governs the frequency resolution of the NPS; small sizes will tend to underestimate low frequency components of the NPS. The NPS region size $M$ is the size of the sub image extracted out of the original raw uniform image, from which the NPS ROIs are taken. Caution should be used when large NPS region sizes are employed, since the image statistics may not be shift invariant over large areas. Using a larger NPS region will increase the number of ROIs in the NPS ensemble for a fixed ROI size, and this reduces the statistical uncertainty on the NPS estimate.

The standard procedure to determine the NPS of an x-ray detector is documented by the International Electrotechnical Commission (IEC). In this protocol, capturing a series of flat field images and evaluating the central region measure the NPS. Several images must be exposed to provide at least four million independent image pixels for the evaluation, resulting in an accuracy of 5% for the NPS. A series of 200 repeated exposures of 300 kVp, 3 mA, and 10 s were acquired. The exposure technique was within the detector's linear range as established in the linearity test. A gain and offset correction is applied to the extracted region to remove the dark offset and minimize gain variations between different pixels. Since the structure or fixed pattern noise is correlated noise, it needs to be removed to improve the SNR of the detector.

Following the correction of the raw flat images, the NPS was calculated by applying an algorithm to the corrected flat field image. The image data was cropped to
512 x 512 pixels to reduce edge effects such that data only came from the center of the detector. This pixel sub-image region corresponded to physical dimensions of 82 cm. Trend removal was performed by subtracting from each ROI its mean value. This removes the influence of low frequency non-uniformities or artifacts on the NPS.

The analysis region was broken up into half overlapping ROIs of 256 x 256 pixels, such that the overlapping region was 128 x 128 pixels. The ROIs are taken from the same location (centered) from the 200 images. The squared modulus of the 2D FT was calculated for each ROI sub region. The 2D transforms from each sub region were averaged to give the 2D NPS ensemble. The normalized noise power spectrum is obtained by dividing the NPS by the square of the large area signal.

The NPS is displayed as a 1D signal in each orthogonal direction. However, the extreme susceptibility of the NPS to low frequency baseline artifacts make it impractical to extract 1D NPS components from the axial vectors of NPS. A more sophisticated method is to sample the NPS (u,v) along the elements immediately adjacent to the axes. This is performed by acquiring 1D profiles of the 2D NPS (u,v) parallel to the u and v axes that are commonly 3 to 4 elements thick. The axis is omitted itself because they’re susceptible to any remnant column or row wise fixed pattern noise on the flat field images. In other words, in the presence of horizontal or vertical structure noise, the NPS has an unusually large value along the u and v axis, which is not representative of stochastic noise. Each data point was associated with a specific spatial frequency by means of the formula

\[ f = \sqrt{u^2 + v^2} \] (7-2)
in order to determine the 1D NPS along the central, vertical, and horizontal axes. The average from 14 rows of the 2D NPS was computed, (7 on each side of the axis), excluding the axes themselves.

**Detective Quantum Efficiency**

In order to calculate the DQE, the ideal SNR must be determined. This is the SNR of the x-ray beam incident upon the image receptor, or the incident number of x-ray quanta. To calculate this, the x-ray spectrum of the imaging system must be calculated or estimated from a table of values. The incident number of photons per pixel was determined through the measurement of exposure level and the incident spectrum used in the NPS measurement. The exposure level of the incident x-ray during each shot of the NPS measurements were measured with a Gamma Rad Eye ion chamber.

The incident spectrum was determined through the use of an x-ray spectrum software calculator SpekCalc [81, 82]. Input parameters for the software were filter material and thickness, kVp, and emission angles for the radiation field. The readout from SpekCalc provides the spectrum in units of photons/keV cm² mAs at one meter in air. Through the mass absorption coefficient and conversion from dose to exposure, the spectrum can be converted to units of photon counts per unit exposure [83]. By integrating the energy-dependent photons counts per unit exposure over all energy bins, the ideal signal to noise ratio squared, or incident photon fluence per unit exposure (Φ/X) is determined. The number of photons per mm² per mR was then calculated with the following formula,

\[ q = \frac{\Phi}{X} \Delta x^2 \]  

(7-3)
where the exposure level measured for the NPS flat field images in mR is $X$ and the area of the detector pixel is $\Delta x^2$. The equation gives $q$ in units of photons per pixel.

The DQE was determined using the one-dimensional NPS, the MTF, and the x-ray photon fluence through the use of Equation 3-27. The MTF data used for the measurement of the DQE were provided by linear interpolation of the experimental data provided in Chapter 6.

**Results and Analysis**

The average of the pixel values in ROIs from uniform flat field images are recorded and plotted as a function of exposure, illustrated in Fig. 7-2. For the 300-kVp spectrum, the linear regression for system response to exposure $X$ without the detector collimator was determined to be

$$\text{pixel value} = 310.04 X (mR) - 940 \quad (7-4)$$

![Figure 7-2. Linearity test results showing exposure versus mean pixel value.](image)
where exposure is in units of mR and pixel value is the 16 bit integer output from the detector. A calculated correlation coefficient for the regression demonstrated an excellent fit. The detector meets the IEC linearity requirement, which states that $R^2$ must be greater than or equal to 0.99. The detector was found to have a linear response covering the whole exposure range, with the linear regression giving a correlation coefficient ($R^2$) greater than 0.99 for the CsI:Tl detector.

The NPS is shown in Fig. 7-3 for the Compton backscatter system, acquired at three different exposure levels. The NPS curves all decrease in magnitude with increasing spatial frequency, indicating that correlations exist in the data. If strong correlations were absent, the NPS would fall off in a relatively gradual manner across the entire frequency range. For example, the NPS of white, or uncorrelated noise is relatively horizontal in shape across the entire frequency range.

![Figure 7-3. NPS measured for the backscatter system at three detector exposure levels.](image)
The declining NPS in the low frequency range is most likely attributable to the pre-processing flat field correction, applied in order to reduce the structured noise in each image. In the medium to high-energy frequency range, the noise levels of the image are related to the MTF of the system. In this frequency range, the MTF curve experiences a sharp decline in magnitude.

For the linear detector array, the shape of the NPS is relatively independent of exposure, but tends to have higher slopes at higher exposures. This could be due to less added electronic noise and/or some low frequency structure noise at high exposures. The NPS curves decrease in magnitude with exposure, as expected. However, the spacing between the three exposure levels does not correspond to the equal difference between sequential exposures (40 mR each). The reduced spacing between NPS curves is most evident in the low to mid-spatial frequencies, suggesting a higher level of FPN with increasing exposures. This could be the result of non-stochastic noise in the detector that is not corrected by the gain map.

The DQE is displayed in Fig. 7-4 for the backscatter system measured at three different exposure levels. The DQE decreases with increased exposure, possibly due to incomplete non-uniformity corrections. A quantum noise limited system is one that is dominated by x-ray quanta noise, and the DQE is independent of exposure. That is, the DQE does not change by increasing the exposure and the system noise changes with the square root of the signal. If the DQE doesn’t show a significant difference with exposure, this indicates that the noise in the system is predominantly photon noise. It also indicates that increasing the signal level will not provide further improvements in image quality. At this signal level, an optimum DQE is reached for the imaging system.
Figure 7-4. DQE for the backscatter system obtained at three different exposure levels.

Structure noise is a multiplicative noise source (multiplied by the x-ray signal), which becomes progressively more important as the exposure increases. The DQE will reduce as the exposure is increased due to the growing influence of structured noise on DQE, demonstrating a linear relationship with signal level. At very low exposures, the DQE is expected to be strongly dependent upon incident exposure, since the additive electronic noise component is of the same order as (or much larger than) the incident x-ray fluence. For these low signal levels, DQE is expected to increase with exposure due to a relatively high contribution of added electronic noise that eventually becomes similar in magnitude to the quantum noise contribution that grows with signal. A further increase in exposure leads to a reduction in DQE due to the growing contribution of FPN resulting from detector non-uniformity and variations in pixel sensitivities. This reduction in DQE is only evident in systems that don’t properly correct for non-uniformity through their gain and offset calibrations. In this study, the exposures were not low
enough to observe the electronic noise limited operational range where DQE should grow with signal. But the latter effect of decreasing DQE with signal was evident, suggesting that a portion of FPN remains within the images.

**Considerations for Future Work**

Non-stochastic noise patterns are reduced or eliminated by the application of a flat field correction algorithm. Only images corrected for the defects, offset, and gain can be used for DQE measurements since it is not possible to distinguish noise from offset or gain variations in a raw image. Even a very small number of defective pixels would completely change the noise spectrum. Consequently, the useful DQE of a detector is partly determined by the corrections applied. Errors in the dark and flat field images will translate into excess noise in the current image, in turn reducing the DQE.

System performance is optimized when the correction image is free of statistical variations. However, as these results have demonstrated, the stationary noise patterns are not effectively removed for flat field images acquired at a relatively low exposure. Furthermore, when the flat field correction image and the raw image are acquired with a widely different incident exposure, the stationary noise pattern might not be entirely canceled. Under such conditions, a reduction in image quality will occur in the corrected image due the increase in noise attributed to the non-canceled stationary noise. The incomplete removal of FPN also resulted in a loss of DQE.

A more robust flat field correction methodology should be developed for the linear detector array. The perfect gain calibration is one where the noise is fixed pattern limited, resulting in the best correction covering the broad range of all system conditions. Since one needs to average multiple gain calibrations to achieve a correction map that contains only fixed pattern limited noise, a more robust method
would average a greater number of frames in Equation 7-1. The noise using a single flat field image at any exposure to create a gain map is considerably more than that of the FPN. For each additional frame that is averaged in the correction, a subsequent reduction in noise will take place. Since the number of frames used in the average affects the SNR, it also disturbs the measured DQE, decreasing its value when less frames are averaged. The optimal number of frames should also be determined, indicated by the point beyond which additional averaging provides no significant reduction in noise. At this point, most noise measured will be FPN, indicating the ideal gain calibration region.

Most importantly, however, is the exposure-dependent DQE and flat field correction. A broader range of exposures should be assessed for the flat field corrections, specifically evaluating low signal levels. Lower exposures increase the amount of quantum noise relative to FPN, reducing the effectiveness of flat field corrections. At lower exposures, it will also require more averages for the images to be fixed pattern noise-limited. At low exposures, therefore, the stationary noise present in the image will not be effectively removed.

Limitations of Study

One of the biggest determinants of the uncertainty in DQE measurements come from the MTF results due to its squared dependency. Including this is the number of photons per unit area calculated from the spectrum. The MTF measurements were measured at the center of the image, however it’s not certain that the blurring will be constant across the detector. When MTF are no longer isotropic for a detector, differences in NPS are expected where spectra are not isotropic, but show a far steeper decline in one direction. In addition to the MTF uncertainty, the use of a software
program to calculate the x-ray spectrum has its own uncertainty associated with it that should be corrected for. The ideal scenario would be to measure the photon fluence for the tube spectrum in use, as opposed to estimating it from software.

When estimating both the NPS and DQE, various assumptions are made based on linear systems theory and Fourier concepts. As such, the DQE analysis assumes a linear and shift invariant system. For digital imaging systems, it is often assumed that the random processes generating the variance is wide sense stationary, meaning the expected value and autocorrelation of the noise realized in the image are both stationary, i.e. they are independent of position in the image and that these statistics do not change between two positions separated by an integer multiple of sample spacing. The process of flat field correcting and using the same ROI from multiple images for NPS analysis allows for the reasonable assumption of shift invariant properties of the detector system even though it might not be the case. However, given that the NPS and DQE results indicated a correlated noise process most likely attributable to fixed pattern noise, it’s suggested that a better flat field correction should be applied. Therefore, the assumption of shift invariance could be inaccurate in the dynamic range of the detector, which was tested in this study.
Summary of Work

The objective of this work was to develop a method for measuring the relative density of wood crossties installed in railroad track. In order to enable density measurements from one side of the target, Compton backscattering of x-rays were employed to produce images of the track. Although several variants of CBI systems have been employed successfully in the NDT of various industrial materials, they all suffered from the limitation of slow scanning speeds. One of the principal requirements for this imaging system to be a viable solution to automated crosstie inspection; it had to be capable of scanning the track at least 10 mph.

The new imaging modality represents an advance over previous CBI scanners that are limited in their image acquisition times through the selection of the optimal system components that maximize performance. Given the application specific nature of CBI methods, a prototype system was constructed in order to conduct experiments, which tested various configurations of each major system component. The main parameters studies with the prototype system were the characteristics of the radiation source and its collimators, detection system and its collimator, relative geometrical layout, and scanning approach. However, due to the interrelated nature of these system components and their significant effect on resolution and overall performance, test tools and methods were established to quantify the image quality obtained with each configuration. Specifically, measures such as the modulation transfer function and detective quantum efficiency were adapted to this novel inspection system in order to determine which combination yielded the maximum system performance. Based on
these measurements and results, a final design of components, specifications, and layout of the scanning system was constructed.

**Concluding Remarks**

The experiments concluded that an x-ray source with a high energy and small radiation emission angle, coupled to a narrow fan beam collimator is the optimal source design for detected wood voids buried within 8 inches of the tie. The detector should consist of a scintillator with high detection efficiency and high sensitivity for the given backscatter x-ray energy range of interest. It should be positioned as close as possible to the source, in terms of both standoff from the primary beam and target. A parallel grid of thin lead septa should be fitted to the front of the linear array, with dimensions selected to match the detector pixel widths. Although it was noted that an uncollimated detector achieved a much higher count than that acquired with a collimator, the images produced lacked any contrast or spatial information necessary to determine relative density variations in wood ties.

Experiments verified the safety of using this inspection system around members of the general public, achieved by an understanding of the backscatter field and through the selection of the appropriate shielding design. Radiation field mapping and attenuation curves determined the thickness of lead necessary to shield the system, as well as the geometrical layout required to reduce the component of scatter coming from track structural components. Construction of a 0.3-inch thick lead curtain reduced the emitted exposure rates below the 2 mR/hr limit at 4 feet from the rail. However, through the use of a flexible shielding material known as Silflex, the system met the Plate C requirement and avoided the use of toxic lead material on track. The system was capable of meeting all Federal, State, and FRA regulatory guidelines, enabling its
successful licensing and registration awarded to the final unit in 32 different states. The most significant finding was the extremely low effective doses an individual would receive when the inspection vehicle drove past them on the track.

Results concluded the maximum scanning speed at which the required resolvability for voids in crossties could still be met. By constructing and establishing methods to characterize the modulation transfer function, it was determined that scanning speed did not have a significant impact on system resolution. Furthermore, a bar pattern test tool was designed that was capable of performing routine quality assurance measurements in order to quickly and accurately measure the spatial resolution of the backscatter system. Through these experiments, it was determined that a scanning speed of 15 mph could be used which was capable of resolving voids 1.5 cm in width.

In order to optimize the detection system efficiency, DQE methods were established and measured for the backscatter system. As a part of this experiment, the NPS was characterized for the linear detector array which discovered its degradation with spatial frequency and improvement with signal level. These measurements established that a better correction for pixel non-uniformity should be applied to the linear array since the NPS results demonstrated a correlated noise component, indicating the flat field correction has not adequately removed all FPN present. The DQE also showed a dependence on signal level, illustrating that the system is not quantum noise limited. Since the DQE decreased with exposure level, the FPN component has become dominant due to its linear dependence on signal and inadequate flat field correction.
In summary, it can be concluded that the proposed Compton imaging method and designed inspection system serves as a viable scanning approach for detecting relative density changes in wood crossties in railroad track. The system met all design criteria established in the prototype phase, including but not limited to, Plate C compliance, integration with Aurora’s resolution, inspection speeds greater than 10 mph, resolvability for at least 2.5 cm in size, as well as the safe operation around general members of the public and railroad track operators.

**Recommendations for Future Work**

Although the inspection system was capable of meeting the design criteria established at the outset of this work, through a better understanding of system parameters and their interrelated nature, performance could be improved further. In order to achieve the optimal resolution capability of the system, additional MTF measurements should be carried out on the backscatter unit. Future experiments should first employ more accurately designed edge and bar pattern test tools. An edge target should be constructed from material that provides the maximum and minimum dynamic range of the detector. In an effort to carry out MTF measurements with materials that most closely represent those actually being scanned by the system, wood crossties were utilized as the highly scattering or “translucent” side of the edge. However, because each tie’s density will vary, the calculated MTF curves using this edge target will also differ. A more optimal solution would construct an edge target from a uniform piece of MDF which is thick enough to provide sufficient attenuation to the primary fan beam such that scatter off structures below it are negligible. Furthermore, since the contrast between intensity levels of the two edge materials will alter the measured MTF curve, efforts to improve the difference in signal should be made by employing a
material that scatters the x-ray spectrum more than the currently used material wood. Given the low atomic number of plastic, its scattering probability is expected to be larger than wood. Therefore, an additional edge target should consider plastic-based materials for the highly scattering edge portion, thereby providing a higher contrast.

Additional improvements in the edge target design would focus on the dimensions of the two materials and their geometric layout in relation to one another. Given that the edge method is highly dependent on the length and width of the boundary, additional testing should be carried out to evaluate the optimal dimensions. Also, the prototype edge target was constructed from the lead sheet placed on top of the wood tie. However, the MTF calculated from the edge function includes the effect of a geometric edge. Since the lead was set higher than the wood, geometric lead shielding on the edges of the wood piece are most likely enhanced. Different designs should evaluate wood edges placed higher than and equal to the lead boundary in order to determine the optimal edge spread function.

Future work should also focus on enhancing the design of the bar pattern target. A line pair tool should be machined to test more than the ten discrete spatial frequencies tested by the improved prototype tool, with finer sampling of frequencies placed between the original ten. Also, thicker MDF should be evaluated in order to ensure negligible attenuation of the primary beam since the ballast underneath the target most likely altered the measured signal modulations.

Another consideration for future work would be to test the relationship between resolution and inspection depth. All MTF measurements took place at the surface of the track. However, given the primary goal of this inspection system is to evaluate the
subsurface tie conditions, the resolution should be quantified for various depths within the 7-inch thick wood tie. A simple determination of this would simply bury the MTF tools under some given thickness of wood, measuring the MTF as it changes with depth of burial. A more detailed examination would construct a completely different target consisting of air voids that have different sizes and are located at incrementally deeper depths within the tie. These measurements would thereby characterize the resolution versus the thickness of wood covering the flaw. Experiments should also be carried out which serve to determine how the material around and within the flaw affects the resolution of the system. For example, different moisture levels within the tie should be examined in order to emulate severely rotted and decayed wood.

All CBI methods are limited in their detection efficiency, and this system was no different. Therefore, the detector system could benefit from a more thorough characterization of its abilities and factors that determine its performance. The NPS and DQE experiments were performed for a single x-ray beam spectrum. Since the nominal peak voltage can have a drastic effect on several parameters, steps should be taken to understand how it governs efficiency and noise of the detector system. Also, the accuracy of DQE calculations relies heavily on the accuracy with which the x-ray beam spectrum was measured. In this research, a computer program was employed to approximate the beam spectrum. However, the maximum kVp that could be simulated was 300 kVp, whereas the nominal operating voltage is 325 kVp. The x-ray tube is also capable of a maximum 450 kVp, which future work should evaluate.

Given the significant amount of FPN associated with linear detector arrays that use the pushbroom scanning method, pixel non-uniformity corrections are not only
necessary but have a significant effect on overall image quality of the backscatter system. Since the manufacturers do not provide a flat field correction technique for the linear array, it was initially unknown whether an adequate correction algorithm was developed or not. However, the DQE and NPS results demonstrated that there exists a large amount of FPN present in the images, even after the flat field correction is applied, indicating the limitations of the current algorithm. The amount of frames used in the flat field average, the size of the ROI extracted, and the magnitude and range of exposure levels should be varied in order to understand their effect on the flat field correction, as well as the measured NPS. Given the persistence of dead and hot pixels in the flat field image, it would also be worthwhile to examine the effect a nearest neighbor smoothing filter has on the flat field algorithm.

Testing the DQE over a wider range of exposure levels will also serve to determine the point at which the backscatter system becomes quantum noise limited. The DQE demonstrated a decrease with increasing exposure for the levels evaluated, indicating that possibly a higher than necessary signal is being used. Since the DQE of a quantum noise limited system is constant with increasing signal, the ideal operating point is not currently being employed in this backscatter system.

Lastly, DQE and NPS tests should be evaluated for competing detector materials and designs in order to determine the most efficient system. Given the low sensitivity experienced with the initial GOS design, it’s possible that significant improvements in performance could be obtained with a more optimal signal level or pixel size, both of which can be analyzed and compared through the established backscatter DQE methods.
LIST OF REFERENCES


2. ZETA-TECH Report to the Railway Tie Association, “Validation of the Traditional USDA Forest Products Laboratory Tie Life Curve Using Recent Data from US Class 1 Railroads,” (September 2008).


BIOGRAPHICAL SKETCH

Jessica Kelley completed a Bachelor of Science in Nuclear Engineering from University of Florida in 2009. She obtained her Master of Science in Medical Physics from Duke University in 2011 and then moved to California where she worked as a diagnostic imaging medical physics consultant for two years. In the summer of 2016, she received her Doctorate of Philosophy, as well as her Master of Business Administration from the University of Florida. After graduating, she joined the Radiation Oncology department at New York University as a clinical medical physics resident and researcher in the summer of 2016.