Coded Aperture Imaging Application in One-sided Imaging of Visually Obscured Objects

by

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Abstract

The physical properties of visible light and its interaction with matter create obstructions the human eye cannot explore. High energy radiation has been used as an alternative to visible light to penetrate these concealed regions and reveal their contents. However, traditional imaging techniques require a two-sided apparatus with a radiation source and a detector on opposite sides of the concealed object.

One-sided imaging of concealed objects is made possible by a technique called backscatter imaging, utilizing high energy radiation. However, the signal produced by backscatter imaging is inherently weak, which makes interpretation difficult. One of the most promising techniques for recovering the weak signal is the coding and decoding provided by Coded Aperture Imaging (CAI).

The purpose of this study was to create and test a coded aperture imaging system using backscattered x-rays. This would enable one-sided imaging of concealed objects and demonstrate whether a portable imaging system was feasible. The results obtained from conducting a computer simulation, visible light experiments, and x-ray experiments proved that the process works, however, the x-ray flux levels required were too high for a portable system, based upon the current equipment available at UOIT.
Acknowledgements

Thanks to Dr. Waller and Dr. Nokleby for your mentorship over the past few years. I especially appreciate your patience in catering to my “unique” style of learning. Some things come naturally, this project was a struggle almost all of the way. Most things didn’t work as expected, but most things did work eventually. You both were available to help when I was really stuck, but let me struggle on my own, which helped me learn a lot.

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I started this degree thinking I could finish in two years while working. Of all the things I learned during the course of the past three and a half years, the one I notice most is the value of time. I feel relieved (almost shocked) that I’m finally finished and looking forward to choosing how to spend the newfound hours in the day.
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Abbreviations

ATRS  Automatic Target Recognition System
AUC   Area Under Curve
AXGAM  All-sky X-ray & Gamma ray Astronomy Monitor
BAT   Burst Alert Telescope
CAL-  Coded Aperture Laminography
CAFNA  Coded Aperture Fast Neutron Analysis
CAT-  Coded Aperture Tomography
CMGVC  Coded Mask Gamma Vision Camera
CT-   computed tomography
EDX-  Energy Dispersive X-Ray Spectrometry
EMBD  expectation maximized blind deconvolution
EXITE Energetic X-Ray Imaging Telescope
GRB   Gamma Ray Bursts
GRIS  Gamma Ray Imaging System
GVC   Gamma Vision Camera
HERV  high energy radiation visualizer
LEHR  low energy high resolution
MCAT- Modular Coded Aperture Technology
MLE   Maximum Likelihood Estimator
MOCAI- Moving Object Coded Aperture Imaging
MSE   Mean Square Error
MURA  Modified Uniformly Redundant Arrays
PIXE-  Proton-Induced X-Ray Emission
PFNA  Pulsed Fast Neutron Analysis
PSF   Point Spread Function
PS-PMT Position Sensitive Photo Multiplier Tube
RMC-  Rotation Modulation Collimator
ROC-  Receiver Operating Characteristics
SOR  Successive Over-Relaxation
SPECT  Single Photon Emission Computed Tomography
SPSF  System Point Spread Function
URA  Uniformly Redundant Array
WDS - Wavelength Dispersive Spectrometry
XRF - X-ray fluorescence
Chapter 1

Introduction

Traditional radiography depends on the transmission of radiation through an object and the casting of its shadow onto a detector on the far side. This requires access to both sides of the object being imaged. However, access to both sides is not always possible. In this case, backscatter imaging offers an elegant alternative where the object is illuminated by the source and an image formed from the scattered flux focused on the detector. The same material density indications are produced as with transmission, the only difference being that the object is illuminated in this case and not shadowed [1].

The complication with backscatter is the small amount of signal scattering in the direction of the detector, making the process inefficient. A number of methods have been developed to address the low signal gathering efficiency [2, 3]. Low signal to noise ratios were also a problem encountered
in astronomy work in the 1980s, prompting the development of techniques to encode and decode the signal [4]. Similar techniques have been adapted to medical imaging [5], contraband detection [6], landmine detection [7, 12, 25] and gamma-ray observations [8, 13].

Prior to experimental application, a simulation was performed to demonstrate the feasibility of the geometry and the reconstruction code. This simulation was coded in MATLAB and MCNPX (Monte Carlo N-Particle eXtended). Following the simulation, an experiment was designed to test the simulated scenario using a portable x-ray machine as the source, an aluminum letter F as the object, and a digital x-ray detector to form the image. Since the initial x-ray system operated at such a low flux level, an analogous apparatus was created using light and a digital camera to test the same reconstruction algorithm on a saturated target. Once this was successful, the same parameters were tested again on the low power, portable x-ray system and finally on a high power, stationary x-ray system, with both sets of results presented here.

1.1 Coded Aperture Imaging

Coded apertures were originally developed to improve the capabilities of gamma ray astronomy imaging [22]. Dicke and Ables are credited with in-
dependently suggesting an array of pinholes arranged on an opaque screen [9]. Uniformly Redundant Arrays (URA) were the first type of apertures used more than 30 years ago [22, 26]. The first terrestrial versions of coded apertures, for use in arms inspections, were reported in the 1980s [10, 22]. Numerous improvements have been made since then, while the principle remains the same.

The coded aperture is modeled after the pinhole camera, with the addition of multiple pinholes. In this manner, images can be formed from sources other than visible light, such as high energy ionizing radiation. This is what makes coded apertures such an attractive solution for imaging concealed objects. When x-ray or gamma radiation is projected at an object it will produce a detector response which can be reconstructed to reveal the original object [29]. Since the numerous pinholes in the aperture create a convoluted projection, computer decoding is required to reconstruct the image. A pictorial summary of this process is shown in Figure 1.1.

The main advantage of Coded Aperture Imaging (CAI) is the increased light gathering efficiency over other imaging techniques, due to the multiple pinholes. Multiple pinholes increase the amount of power entering the detector resulting in a stronger image, albeit, a convoluted one. The clarity is then recovered by the decoding process which restores image quality with the increased signal strength of multiple holes and the addition of some noise. As
long as the aperture and decoding aperture are matched, the original image should be clearly reproduced.

With any form of imaging, increasing the source flux will increase the signal reaching the detector. In addition to the desired signal, unwanted noise levels are also increased. This creates a balance between amplifying the signal and ruining the clarity with background noise. Noise can come from a variety of sources including: x-rays passing straight through, or scattering within, the solid portion of the mask, and physically in the detector or signal wires.

In this case, low flux was the main difficulty affecting image quality and increasing the source strength was beneficial up to image saturation. This happens when the maximum detectable value is reached and any additional signal is not recorded. The problem with increasing the source flux in this application is the exposure consideration associated with ionizing radiation.
and consequential negative health effects. An important focus of this re-
search is to keep the dose fields as low as reasonably achievable (ALARA) and this means minimizing the source flux. In order to achieve discernible image quality, a coding and decoding mask pattern must utilize the entire available signal.

1.2 Purpose

The purpose of this research was to investigate whether a coded aperture imaging technique could be implemented in a system such that real-time, one-sided x-ray imaging could be performed from a portable platform.

1.3 Objectives

1. The first objective was to reproduce the reconstruction algorithm published in R. Accorsi’s PhD thesis, to enable image resolution [18].
2. Once the code worked, an experimental setup was required to demonstrate the benefits and limitations of the system deployed in the physical environment.
3. Testing and optimization was required on a portable platform to assess feasibility as a real-time imaging system.
1.4 Hypothesis

Since the reconstruction code has been well documented and the results shown [18], the process is expected to work; however, the limitation will be in using a small x-ray source to generate the flux. Especially in a portable system, the dose to humans should be kept to ALARA levels and the greatest challenge will be in optimizing the system to work with such a low flux. The images should be captured on the detector, even with a weak signal, but the signal to noise ratio will make the object difficult to discern and this may be the defining characteristic of the system. A real-time system requires significant optimization of the time involved in system alignment, image acquisition and the reconstruction algorithm which may not be possible.

1.5 Outline

The outline for the remaining chapters is as follows:

Chapter 2 presents the background information and basic aperture theory.
Chapter 3 discusses the computer simulations and initial x-ray experiments.
Chapter 4 explains the light experiments.
Chapter 5 demonstrates the high flux experiments.
Chapter 6 finishes with conclusions and future work.
Additional mathematics is included in Appendix A.
Relevant computer code is attached in Appendix B.
Chapter 2

Background

The principle behind digital cameras has evolved very quickly, however, they are still limited to the properties of visible light. Since light waves cannot bend around corners or travel through opaque walls, digital cameras cannot take pictures of visually obscured objects. This presents a challenge because there are many cases where this ability would be helpful. These include: helping police recover evidence, finding humans trapped in collapsed buildings, searching for cracks in pipes, locating structural defects, and imaging in locations with limited human access, such as features inside of a nuclear reactor. In order to address these challenges, a number of one-sided imaging techniques are employed.
2.1 Methods of One-Sided Imaging

There are two main distinctions in methods of one sided imaging: non-ionizing and ionizing radiation. Non-ionizing techniques use a variety of ultrasound waves and electro-magnetic wave frequencies, namely microwaves and millimetre waves to detect changes in material density. The ionizing techniques make use of ionizing radiation. Ionizing radiation is used for its greater penetration depth, often requiring shielding to be considered.

2.1.1 Non-Ionizing Radiation

Non-ionizing waves have the potential to excel in many applications, however, waves with the necessary frequency to reflect off an object and generate an image have a limited penetration depth. This leaves them at a great disadvantage when it comes to objects obscured by walls, or a strong contrast in material density.

Millimetre Waves

Millimetre waves are good at penetrating materials which have low electron densities and are readily absorbed by materials with higher electron densities. This makes them reasonable candidates for scanning of soft tissues and also in determining relative densities. This factor can be used in discriminating
between materials of differing electron densities. Millimetre waves also have
challenges with noise discrimination.

Ultrasound

An ultrasound machine emits high-frequency sound waves in the MHz range.
The sound waves transmitted into the material are reflected at a boundary,
where the density of material changes, and while some waves are reflected
back toward the machine, the rest travel farther until they reach another
boundary and are similarly reflected. The reflected waves are registered in
the machine and the distance to the reflection boundary is calculated by us-
ing the time between pulses and the speed of sound in the material. A graph
of distances and intensities is displayed on a monitor almost instantaneously.
Ultrasound works well in imaging a human fetus in the womb because of
the consistency in tissue densities and the understanding of the properties of
sound in these materials. Petroleum jelly is used to remove the air gap which
affects signal response. With no air gap, the sound waves are transmitted
much more efficiently.

While the response time is advantageous, the limited penetration depth is a
problem in this application. Ultrasound does well imaging the surface and
contents of a wall, and has more difficulty imaging objects beyond.
Nuclear Magnetic Resonance Imaging

Another proven imaging technique is the use of nuclear magnetic resonance imaging (NMRI). NMRI excels in medical scanning, where the object to be scanned is surrounded in a massive magnet. This is not a problem for most medical imaging applications, but it makes one-sided imaging impossible for NMRI, so magnetic resonances will not be suitable for this application.

2.1.2 Ionizing Radiation

Most of the ionizing radiation techniques make use of the Compton scattering principle. Compton scattering is a type of inelastic collision between x-rays or gamma rays and electrons in the matter they collide with. The collision leaves the scattered x-ray with less than its incident energy, transferring the difference to the electron.

X-Ray Fluorescence

X-Ray fluorescence (XRF) is the emission of characteristic fluorescent X-rays from a material that has been previously excited by high-energy X-rays or gamma rays. Each atom has characteristic emission lines which can be detected, identified, and linked to the specific atom. As the composition of elements in the sample varies, so do the line intensities. Although this is an
excellent tool for chemical and elemental composition analysis, the obscured objects will remain so because of the difficulty in measuring the small number of x-rays emitted from the object, which then pass through the obstruction.

**Single-Photon Emission Computed Tomography**

Current single-photon emission computed tomography (SPECT) experiments are being conducted on small lab animals and show promise for use in larger scale applications [16]. SPECT, with its semiconductor detectors, performs well in the laboratory setting with close distances between source and detector [17]. While the semiconductor detectors are an improvement, others could certainly be made. Radiotracer imaging in lab animals has become an important research tool for the study of human disease and its treatment. Due to the larger distances being studied in this experiment, SPECT techniques are less than ideal.

### 2.2 Coded Aperture Imaging

The most promising imaging method for this application is photon scattering with coded aperture imaging (CAI). The flux can be generated either by an isotopic gamma source or an x-ray source. An isotopic gamma source has the disadvantages of always being on, requiring shielding even when not
in use and constantly decaying. An x-ray source has the advantages of an on / off switch and the control of an adjustable output. In this case, an x-ray source is scattered off an object, projected through a coded aperture, and the resultant image recorded. Since the aperture creates a convolution, computer decoding is required to reconstruct the image. Since the user can choose the source strength, aperture design and decoding process, the coded aperture has the potential to image a variety of objects in visually obscured environments.

2.3 Basic Aperture Theory

What began as a means of improving x-ray imaging of distant stars, has now, with the increase in computer processor power, become a feasible technique for imaging near-field objects on Earth [12]. The imaging of stars was possible first because at very large distances, the incoming rays are essentially parallel [19], so they produce a projection through the aperture with minimal overlap of images. In the more recent near-field applications, because the source is much closer to the aperture, the projected images from each hole overlap, creating a convoluted image. This convolution is composed of a faint image from each hole in the aperture all blurred together. The reason for using a coded aperture is that each faint image can be associated with the hole it came from, providing the aperture and decoding aperture are of
a matched set. This is the main principle behind coded apertures. Using a
computer to perform the calculations, a convoluted projection can be recon-
structed mathematically to reveal the original image.

Prior to discussing coded aperture theory, an overview of simple aper-
tures is required. The pinhole camera is a classic example of the application
of a single-hole aperture. Composed of a box, sealed at the edges, with a
single pinhole in the centre of one side, early photographs were produced by
this simple design. The light enters the box through the pinhole and the
image appears on the film on the far side of the box, inverted. The image is
inverted because of the path of the light rays, as shown in Figure 2.1.

![Pinhole ray diagram](image)

**Figure 2.1: Pinhole ray diagram**

Although this single aperture process is simple; the pinhole only allows a
small amount of light to enter, producing a very faint image or requiring an
extremely long exposure time. In order to produce a recognizable image, the
amount of light detected must be increased. Increasing the exposure time
will improve light intensity, while any movement during this time will tend to blur the image. A larger pinhole will improve light intensity by allowing more light to enter in a given time, but at the cost of image resolution. A unique property of the pinhole camera is that the size of the pinhole dictates the size of the smallest element which can be resolved. This means that a larger pinhole will produce a brighter image, with lower resolution.

To solve this problem, photographers began using lenses to focus more light onto the film, producing brighter and clearer images. This works well for visible light, but high energy radiation is not focused by glass or plastic lenses. Since traditional camera lenses do not work with x-rays, the other way to increase the light intensity is with multiple pinholes, which is the essence of coded apertures. The light intensity is increased not by larger holes, but by many small ones.

The multiple pinholes produce an image which is convoluted. The key factor in coded aperture imaging system design is the aperture mask pattern, chosen specifically, so the image can be reconstructed mathematically. The aperture is accompanied by a complementary decoding aperture, represented digitally in the reconstruction code, which is used in conjunction with the detector response to reconstruct the image [15]. Where traditional cameras use photographic film to collect the light and produce the image, a photon detector is used in x-ray CAI. This can take the form of an electronic or
radiographic film type imaging system. Where camera lenses have a focal length based on their curvature, the focal length of a coded aperture system can be varied in the reconstruction algorithm.

A simple and effective aperture design is the Modified Uniformly Redundant Array (MURA) [30]. Each aperture has a corresponding decoding aperture, which, represented digitally in the reconstruction code, restores the image quality sufficiently enough to recognize the original object. In the case of MURAs, the apertures are square and have a unique property that their anti-mask aperture is a 90 degree rotation of the original aperture [14]. The anti-mask is the exact opposite of the mask, that is, the solid elements and holes are reversed. This should not be confused with the digital decoding mask. The digital decoding mask is a matrix used in the reconstruction code.

Since this reconstruction technique creates undesired artifacts due to the particular pattern of holes, some image clarity will be lost, as compared to the original object. One method of artifact cancellation utilizes one image through the mask, summed with a second image through the anti-mask. This is used to cancel the artifacts attributed to the mask pattern, while enhancing the signal. The fact that the mask and anti-mask can be interchanged by a simple rotation means that only one mask requires machining. The difficulty with this method of artifact cancellation is registration of the two masks. If the centres of each image are not aligned correctly the images will
not properly overlap and consequently the artifacts will not be cancelled. In either case, depending on the thickness of the mask, an x-ray transparent backing may be required to support the mask elements.

The improvements in sensitivity of coded apertures over a single pinhole of the same hole size is theoretically proportional to the square root of the number of holes in the aperture, where the holes do not occupy more than 50% of the surface of the aperture [14, 30]. More simply, for a mask of a fixed area, a more detailed coded aperture mask results in a higher signal gathering efficiency. The most promising apertures, at the moment, come from cyclic difference sets [11, 14]. Providing the decoding matrix is appropriately matched, the system point spread function will be a delta function, which can be manipulated mathematically [11]. The point spread function and Dirac delta function are defined as follows:

"The point spread function (PSF) describes the response of an imaging system to a point source or point object. A more general term for the PSF is a system’s impulse response, the PSF being the impulse response of a focused optical system" [32].

"The Dirac delta function, or delta function, is (informally) a generalized function depending on a real parameter such that it is zero for all values of the parameter except when the parameter is zero, and its integral over the
parameter from $-\infty$ to $\infty$ is equal to one” [33].

2.4 Mask Considerations

Once x-rays and coded apertures were chosen, there are a multitude of design options when deciding upon an experimental model. The first of which is the type of shielding material used in the masks. Lead was used to fabricate the masks because it was readily available, workable, and a reasonable shielding material. The four most commonly used materials are compared in Table 2.1 [14].

Table 2.1: X-ray Attenuation Coefficients at 50 KeV

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm$^3$)</th>
<th>Mass Attenuation Coefficient (cm$^2$/g)</th>
<th>Linear Attenuation Coefficient (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>11.36</td>
<td>8.041</td>
<td>91.35</td>
</tr>
<tr>
<td>Tungsten</td>
<td>19.25</td>
<td>5.949</td>
<td>114.52</td>
</tr>
<tr>
<td>Gold</td>
<td>19.32</td>
<td>7.256</td>
<td>140.19</td>
</tr>
<tr>
<td>Uranium</td>
<td>19.05</td>
<td>11.21</td>
<td>213.55</td>
</tr>
</tbody>
</table>

In terms of the linear attenuation coefficient, lead has the least attenuating power, per cm, because it permits a larger percentage of particles through the solid part of the mask. Lead, however, is reasonably cheap and easy to work with. Gold is more expensive to purchase, very soft, and difficult to machine, but very good at shielding. Uranium is the best in terms of shielding, but is also difficult to obtain and machine. Tungsten is better
than lead at shielding, quite difficult to machine, more expensive than lead, and a commonly used material for this application.

Mask thickness was an important consideration, partly driven by the material choice. In order to attenuate the same percentage of x-rays as tungsten, the lead must be thicker due to its attenuating properties. From Table 2.1, the ratio of linear attenuation coefficients between lead and tungsten is 

\[
\frac{114.52}{91.35} \approx 1.25
\]

meaning the lead sheet must be 1.25 times thicker than the tungsten to achieve the same attenuation. This additional thickness introduces edge effects. Edge effects occur when the x-rays, instead of passing completely through a hole, are blocked by either the leading or trailing edge of the mask. These x-rays should have contributed to the detector image, but instead they were altered on the way and have now changed the final image, possibly compromising its clarity, to some extent. Due to the availability and workability of lead, it was the best choice for these experiments.

The geometrical setup also contains a great deal of flexibility in this project. Ideally, it should maximize the amount of scattered radiation which reaches the detector, while minimizing the complications of image reconstruction. The significant design features related to the geometrical setup include the object to mask distance, the mask to detector distance, and the angles between the source, object, and detector. The distance between the object and the mask, as well as the distance between the mask and the detector
will affect the properties of the image and the way that the reconstruction is performed. To minimize the complications of scaling factors, the distance between the object and the mask and the distance between the mask and the detector were initially kept equal. This would result in an image whose size is identical to the size of the object, simply removing a source of variance from the experiments.
2.5 Main Advantages of CAI

The main advantages of a CAI system are:

- Well validated technique
- Good signal gain over pinhole design
- Testability of the same mask with both visible light and high energy radiation
- Flexibility in mask pattern and material
- Mask fabrication is possible with available resources
- Many areas for optimization

For this project, imaging at distances of over 1 m, with targets between 10 cm and 30 cm and on the far side of a solid wall, CAI was the best available option. The unique properties of coded apertures give them the potential to be very useful in detecting visually obscured objects. Once the technology is refined, it can be applied to a range of applications.

2.6 Mathematics

The mathematics involved in coded aperture mask design, including the optimal size and pattern, is well documented in published papers [21, 28]. The
particular design chosen for this experiment was the 19 x 19 MURA, see Figure 2.2. To make the physical mask shown in Figure 2.2, the lead pieces are arranged with white representing lead and black representing the holes. This view is from the detector plane, flipped left to right as seen by the object plane.

MURA masks are generated by a particular pattern which enhances the signal gathering efficiency over a mask of the same size and open fraction, with randomly spaced holes [18]. The number and size of individual mask elements are both variables, chosen in this case to be a square of 19 x 19 elements, 2 mm square each, for a total mask size of 38 mm high x 38 mm wide.

This could be fabricated with the tools available and still allow enough signal through to demonstrate the reconstruction process. The process of generating a MURA mask pattern is calculated by the logic: where A represents the mask, calculated by Equation 2.1, and G is the decoding array, calculated by Equation 2.3. To create the mask pattern (A) for example, an array of 19 x 19 elements is populated with either a 1 or 0 depending on the logic shown in Equation 2.1 and 2.2. The matrix produced is shown in Table 2.2. In the matrix shown in Table 2.2, 1 represents a hole and 0 represents lead. The MATLAB code used to generate the mask and decoding patterns is called Makemask.m, included in Appendix B.
Figure 2.2: 19 x 19 MURA mask pattern (from object plane)
|   | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |

Table 2.2: Mask Array, (A)
\[ A_{ij} = \begin{cases} 
0 & \text{if } i=0 \\
1 & \text{if } j=0, i \neq 0 \\
1 & \text{if } c_p(i) \cdot c_p(j) = 1 \\
0 & \text{otherwise} 
\end{cases} \quad (2.1) \]

\[ c_p(i) = \begin{cases} 
1 & \text{if there exists an integer } x, 1 \leq x < p \\
such that \ i = \text{mod}_p x^2 \\
-1 & \text{otherwise} 
\end{cases} \quad (2.2) \]

\[ G_{ij} = \begin{cases} 
1 & \text{if } i \oplus j = 0 \\
1 & \text{if } A_{ij} = 1, i \oplus j \neq 0 \\
0 & \text{if } A_{ij} = 0, i \oplus j \neq 0 
\end{cases} \quad (2.3) \]

Where: \( i \) and \( j \) are integers, representing position in the array, \( A \) is the MURA mask, \( G \) is the decoding mask, \( \oplus \) is a periodic summation, i.e. the
modulus of $i$ and $j$, the remainder after division, and $p$ is the mask side length [18].

The images produced by MURAs are encoded and a number of methods have been explored to decode the signal. The decoding process primarily consists of a method of correlating the signal received by the detector to the particular hole in the mask which produced it. The two main mathematical methods of this are balanced correlation [22] and odd-periodic correlation [27]. See Appendix A for a discussion of the mathematics. Rather than trying to calculate each x-ray’s original vector based on its position relative to the centre of the mask, Fast Fourier Transforms (FFTs) are used, making the process much faster.

The image reconstruction code is described by the following process:

1. Capture the signal (R) on the detector
2. Multiply the conjugate of the FFT of the detector signal (R) and the FFT of the decoding array (G)
3. Take the inverse FFT of the result
4. Circularly shift the first element in the array to the centre and rotate 180 degrees
There are also magnification considerations for each scenario, which, along with the reconstruction process, are covered in far more detail in numerous published papers [14, 15, 20, 23, 24]. For more explanation of the mathematics involved, refer to Appendix A. The reconstruction code is included in Appendix B.
Chapter 3

Low Flux X-Ray Experiments

Before imaging with a Coded Aperture Imaging (CAI) system, a Monte Carlo radiation transport simulation was created to determine feasibility. The simulation indicated that the reconstruction process works as outlined in [18], given a perfect geometry. The challenge was to recreate a near-perfect geometry in the lab.

3.1 MCNPX Simulations

In order to prove the concept that backscattered x-rays can be used to form an image, a radiation transport code, Monte Carlo N-Particle eXtended (MCNPX) [34, 35] was used to model the experiment. MCNPX is used for modeling the interaction of radiation with matter. It has the capability to model
most particles, nearly all energies, in almost all applications without an additional computational time penalty. MCNPX modelling is three-dimensional and time dependent. It utilizes the latest nuclear cross section libraries and physics models for particle types and energies where tabular data are not available. Applications of MCNPX range from outer space to deep underground, nuclear medicine to nuclear safeguards [34].

First an example in transmission was modelled. A screenshot of the transmission geometry is shown in Figure 3.1.

![Figure 3.1: MCNPX simulated experimental setup, transmission](image)

The backscatter geometry was modeled next with the source and detector at right angles to each other and the object rotated 45 degrees to either
axis. To replicate the existing x-ray source, a mono-energetic beam of 60 KVP (mean energy) x-rays with a 40 degree opening angle was simulated. A pinhole mask was used to focus the image produced by a million counts. The simulated experimental setup is shown in Figure 3.2 and Figure 3.3, where the source is a cone, the object is a sphere on the far side of a wood wall, and both the mask and detector are squares.

![Simulated experimental setup, isometric view](image)

Figure 3.2: Simulated experimental setup, isometric view

The sphere was difficult to discern in backscatter from the source itself, prompting the need for a new object. For ease of identification, the letters F and L were chosen for their lack of rotational symmetry. Figure 3.4 and Figure 3.5 are the projections produced by MCNPX. The letters in these two figures are slightly distorted because of the angle between the object and detector plane. This is essentially the letter projected at a 45 degree angle.
onto a plane.

The MCNPX simulation proved the concept that backscattered x-rays and CAI can be used to obtain an image.

3.2 X-Ray Setup

The initial experimental setup was simplified for the purposes of first proving the concept. To reduce the complexities of additional scattering, the object was not concealed by a wall. This way, the x-rays interacted directly with the object of interest, while still demonstrating one-sided imaging. Another simplification was to begin with a pinhole mask and progress towards more
Figure 3.4: The letter F through a pinhole using MCNPX
Figure 3.5: The letter L through a pinhole using MCNPX
complex coded aperture masks.

The experimental apparatus was constructed using aluminum rails, which gave the necessary strength and the freedom to easily change the configuration. The x-ray machine used was a Golden Engineering RTR-4 XR200, pulse type, 150 kVP energy output, in 60 ns pulses. It was mounted on a tower which was directly connected to the rest of the apparatus, to define the reference geometry. The x-ray machine was fixed on a specially machined aluminum block, which also accommodated a lead collimator. The x-ray machine is shown in Figure 3.6, the mounting tower in Figure 3.7, the x-ray collimator in Figure 3.8, and the aluminum rails in Figure 3.9.

Figure 3.6: RTR-4 XR200 X-ray machine
Figure 3.7: X-ray mounting tower

Figure 3.8: X-ray collimator (10 degrees)
A thin wood structure was used to mount the objects and frame the pinhole mask. The detector was mounted on a wood stand, which gave it the necessary height and was made adjustable using bolts. The object, the mask, and the detector ran along the aluminum track with bolts that kept everything square and could be tightened down to fix the final position. The test object is shown in Figure 3.10, the detector stand in Figure 3.11, the pinhole mask in Figure 3.12, and the experimental geometry in Figure 3.13. Figure 3.14 shows a lead shield which was placed behind the x-ray machine to provide shielding for any x-rays which could come out of the back of the machine and towards the operator location.

The operator controlled the x-ray machine with a laptop computer from
Figure 3.10: Test object; the letter F

Figure 3.11: Detector stand
Figure 3.12: Lead pinhole mask

Figure 3.13: Experimental geometry
the control station located 6 m behind the x-ray machine, shown in Figure 3.15. At a distance of 6 m from the x-ray machine, the radiation field was negligible and one could safely stand unshielded at that line. In the interest of ALARA, the operator shield was added.

3.3 Masks

Before any experiments could be performed with x-rays, a suitable mask was required. This presented a number of challenges as the mask needed to be of a particular pattern, material, and thickness that would sufficiently block x-rays while being relatively easy to produce. The stages in design and testing of both pinhole and CAI masks are described below.

Figure 3.14: X-ray Shield
3.3.1 Design Process

The first step in the design process of mask fabrication was to gather information on available techniques and their applicability to the design criteria. The two main methods of constructing masks from thin metal are cutting the pieces to size or melting the metal into a mold. Ideally, tungsten would be the material of choice because of its excellent x-ray attenuating properties. Lead is a good second choice due to its availability, malleability, and relatively good attenuating properties. Tungsten is brittle and extremely difficult to work with. For this reason, most tungsten masks are photo-etched or cut with a laser to achieve a high level of precision. Due to the small

Figure 3.15: Laptop console
pieces required, on the order of 2 to 4 mm square, and the thickness of the
mask, on the order of 1.5 to 2 mm, the precision of cutting techniques was
of utmost importance. This was demonstrated to be effective with lead.

3.3.2 Design Criteria

The two main design considerations for this mask design are: (i) enough holes
to create a useful signal gathering efficiency and (ii) individual elements small
enough to image in reasonable detail. One documented mask design is the 79
x 79 MURA mask, 2 mm thick, measuring 158 mm square [18]. Ideally this
would be photo etched from a single tungsten sheet in order to preserve the
tight tolerances, and the pieces would be attached to a relatively transparent
x-ray backing. The backing is necessary because unless an extremely precise
method of fabrication such as laser cutting is used, and the corners rounded
slightly, the solid pieces of the mask will not be connected. Figure 3.16 shows
a 79 x 79 MURA where the black shapes are holes and the white shapes are
metal. Any of the simpler MURA masks would also work well, such as 19 x
19 elements, and with fewer pieces they are easier to fabricate.
Figure 3.16: 79 x 79 MURA pattern
3.3.3 Construction

In order to test the severity of the edge effects in lead and also to experiment with lead working techniques, a pinhole mask was made first. This was made from 1.1 mm thick lead and covered with hardboard for support. This mask is shown in Figure 3.17. Since the pinhole was such a small area compared to the total area of the mask, not many x-rays passed through, making the detector images very faint. This was one noticeable difference between the simulation, which suffered no edge effects, and the real world experiments. This mask worked well as a first test, but showed many areas for improvement.

Figure 3.17: Pinhole mask, 4 mm hole, 1.1 mm thickness

In order to increase the image intensity on the detector, a larger open
area, or open fraction, was required. Since this can be done in one of two ways, (i) a single larger hole, or (ii) many smaller ones, a single 6 mm hole was drilled in a 6.35 mm thick lead sheet for comparison. Although this mask did let more signal through, no image was produced. The larger hole-size would have reduced the resolution of the image, while the additional mask thickness would block a higher percentage of x-rays interacting with the solid portion of the mask. The other option was to use many smaller holes, which has the effect of producing a faint image through each of the small holes, all superimposed on top of each other.

For simplicity, a 5 x 5 element mask was created first, primarily to see how easily lead could be cut with a sharp knife. Each element was chosen to be 10 mm square, in order to increase the amount of light through the mask and to show that the transmission ratio was large enough to resolve an image. This mask design resulted in a large open fraction; large enough to see some signal in the detector, but not enough to reconstruct an image. The 5 x 5 mask is shown in Figure 3.18.

In order to improve upon the mask shown in Figure 3.18, another 5 x 5 mask, the same pattern as the one described above, was cut from 1.6 mm thick lead sheet with a purity of 99.99%; this time with 2 mm square elements, instead of 10 mm. This 5 x 5 mask was made to fit in a 38 mm by 38 mm hole milled in a 6.35 mm thick lead sheet for additional shielding.
This allowed different mask patterns to be inserted into the milled hole to provide good shielding characteristics without creating the edge effects of a full thickness sheet. This mask is shown in Figure 3.19 and the shield in Figure 3.20.

Since this 5 x 5 mask now has even smaller elements, the transmission will be less than the first 5 x 5 mask, but its main purpose was to demonstrate the construction techniques and determine if this shielding configuration was adequate.

The lead cutting techniques worked very well and the shielding seemed to improve, so a 2 mm square pinhole mask was made to fit the 38 mm milled

![Figure 3.18: 5 x 5 MURA mask, 10 mm holes, 1.6 mm thickness](image)

Figure 3.18: 5 x 5 MURA mask, 10 mm holes, 1.6 mm thickness
Figure 3.19: 5 x 5 lead mask, 2 mm holes, 1.6 mm thickness

Figure 3.20: Lead shield, 38 mm hole, 6.35 mm thickness
opening to compare to the original pinhole images and provide some measure of background noise. This pinhole mask is shown in Figure 3.21.

Figure 3.21: Pinhole mask insert, 2 mm hole, 1.6 mm thickness

In order to compare the detector response of each of these new masks to something with an open fraction close to 50%, a mask with more elements was required. The masks with more than 5 x 5 elements were no longer self supporting, so the fabrication techniques were slightly different. This meant cutting the small pieces by hand and gluing them to a relatively x-ray transparent backing to achieve the desired pattern. The next reasonable size MURA to attempt construction consisted of 19 x 19 elements. If the smallest
of these elements was taken to be 2 mm x 2 mm, the total mask size became 38 mm x 38 mm and consisted of 50 pieces cut and glued to an overhead transparency, as a plastic backing. This process was very time consuming, but proved to be worthwhile as the finished product was made to very high tolerances. A template of the mask is shown in Figure 3.22 and the actual mask is shown in Figure 3.23. Figure 3.24 shows the mask inserted in the lead shield.

Figure 3.22: 19 x 19 MURA mask pattern
Figure 3.23: 19 x 19 MURA mask insert, 1.6 mm thickness (shadows are contact cement)

Figure 3.24: 19 x 19 MURA mask in lead shield
3.3.4 Mask Fabrication Techniques

A number of useful techniques were discovered relating to the mask fabrication process. All of the techniques discussed below relate to lead: melting, cutting, and gluing.

Lead Casting

One idea for making a lead mask was to first build a mold out of plastic or wood and pour molten lead into the cavity to produce the desired mask shape. This is difficult for a number of reasons.

First of all, most metals, including lead, shrink when they cool, making the size of the holes in the mold larger than the cooled finished product. While this helps to extract the cooled lead, it creates a problem when the final pieces are not the desired size, but smaller by the shrinking factor. If this shrinking factor can be quantified, and the mold size increased by this factor, then in principle, the cooled lead elements will be the desired size. In addition to this, each lead piece would have a meniscus of lead on the top surface, where the lead settles and this would not be flush with the mold, creating an uneven thickness. This does not account for irregularities in the mold, metal, or uneven cooling, all of which result in undesired shapes.

Another complication is that as lead cools, bubbles will form on the bot-
tom, due to moisture and air impurities. These bubbles will be trapped at the bottom if the mold is not agitated as it cools. Agitation would allow the bubbles to rise to the surface and leave the mixture. Furthermore, if the mold material, wood or plastic, contains any moisture, this will create more bubbles in the lead and some may remain trapped in the metal until the piece is fully cooled.

Lead melts at 327 C (621 F) which is easily attainable with a blow torch or a stove top element but is also high enough to char or burn a wood mold or melt a plastic one. This constrained the mold material to something which could be machined accurately and also withstand the temperature of molten lead. All of these considerations could be dealt with if the end product would be of high quality. A few test samples were made, each in the shape of a rectangular prism. A blowtorch was used to melt the lead and drip it into an aluminum mold, which had already been heated, so the lead would not cool on contact. This allowed the lead to cool slowly and gave the bubbles time to rise to the surface. By the time the lead cooled, it had shrunk enough to easily come out of the mold and was relatively smooth on all sides except the bottom. There were still bubbles trapped on the bottom which gave it a rougher surface than the other sides. The uneven shrinking as it cooled was apparent. For something as small and precise as the 2 mm square mask elements, the required precision would be difficult to obtain.
The real problem was that the desired MURA masks were not self-supporting, meaning no mold could produce these masks as one piece. All the small elements must be made separately and then glued onto a relatively transparent x-ray backing in the correct configuration. In this case, all the work of casting the pieces in a mold would still be dependent on the gluing process for the desired pattern. For this reason, an alternative to the casting process was required and lead cutting was investigated.

**Lead Cutting**

Tough metals can be cut by water-saws, lasers, and hot-wire. Softer metals can be cut by pinching, scoring, or something similar to a guillotine. Lead can be cut with a sharp knife. The main problem with cutting is that as the sharp point of an ordinary knife cuts deeper into the material, the relief is to both sides and the material spreads in a V-shape. This is fine for most cutting tasks, but for this mask, straight, square sides were important. This meant, simple cutting or scoring would not have produced acceptable results. For this project, a knife was required which had one sharp flat side and one tapered side for the relief. In this manner, by flipping the knife around, all sides could be made straight. Since the thickness of the lead was about 1.6 mm, a set of sharp X-Acto knives worked very well.

Freehand cutting was the first approach and this demonstrated that the
lead could be cut relatively easily and within reasonable tolerances. The mask shown in Figure 3.18 was cut freehand. To refine the cutting and make an even more precise mask, a set of straightedges was used. This did not work as well as originally thought, because it was difficult to keep the straightedge in the same place with respect to the lead. The lead was so soft, that the knife could push under the straightedge if pressure was applied unevenly. The lead also moved considerably as it was cut, with the relief edge elongating the lead piece perpendicular to the cut.

All of these problems were magnified by the fact that a 5 x 5 mask cut from a large sheet of lead left no room for the relief. These factors caused the lead to either pile up or push out, elongating the entire sheet. One solution to this problem was to drill small holes in the middle of the square to be removed, to provide somewhere for the relief lead to go.

The above problem can be minimized by cutting out individual pieces, measuring after each cut, and gluing them to a backing, because each piece can be trimmed to size. This was the best method and the one used in the final mask fabrication. In addition, a small vice, calipers, and squares were used as quality controls to ensure the final product was as close as possible to the desired size. Since the cutting technique seemed to work well enough, a procedure refined by iteration and a series of controls was designed to bring the tolerances of each piece to about 1 % or 0.02 mm.
This was the procedure followed in the construction of the 19 x 19 MURA mask shown in Figure 3.23. As seen in the figure, there was more adhesive than necessary on the plastic transparency. This was mainly due to the nature of the contact cement adhesive, which was very tacky and difficult to sparingly apply. Since the contact cement was not a good x-ray attenuator, this was not a major problem from an imaging perspective, and it was not observed to be a problem in the detector images.

3.4 Results

3.4.1 Initial Experiments

In order to verify that all of the equipment functioned correctly and to compare results with the simulation, a series of experiments were conducted in a transmission configuration. The expected results for tests in transmission consisted of a shadow of the object on the detector. For the initial experiments, the object was the letter F and was chosen specifically because of its lack of rotational symmetry. This permitted a clear identification of the orientation of the object on the detector. The results of this simple experiment confirmed that both the simulation and the equipment were working.

Different shielding configurations were investigated and the thickness of
lead was varied to measure shielding effectiveness. For example, the black rectangle in Figure 3.26 was the pinhole mask made of 1.1 mm thick lead sheet and was held in place in a wooden frame. In front of the mask was a thick cylinder of lead used to show the difference in ability to shield x-rays between the two different thicknesses of lead. By examining Figure 3.26 it appears as though the 1.1 mm thick mask was capable of providing sufficient shielding, since the lead cylinder was barely visible and there was sufficient contrast between the shielded and non-shielded areas. In backscatter, however, there was no visible distinction between x-rays that passed through the pinhole and x-rays that passed through the solid area of the mask.

Once an acceptable level of shielding was established for the purpose of the backscatter experiments, multiple tests were conducted to establish a baseline of the scattering geometry in a backscatter configuration as seen in Figure 3.27. The dimensions in this setup were a distance from source to object of about 1 m, with the object to mask distance (a) and the mask to detector distance (b) equal, at about 40 cm. The object was rotated 45 degrees from parallel away from the mask. It was important to find a configuration of the experimental apparatus such that a high concentration of the x-rays scattering off the object would be centered on the detector. This would help the image observed to encompass the entire object in the center of the detector and not just a portion of it. During this process, the actual sensitivity of the equipment was realized. Even the slightest shift of the ob-
ject could result in the image completely missing the detector. For example, Figure 3.28 shows the initial scattering geometry on the detector.

All of the backscatter tests were unsuccessful in producing an image in any capacity because the number of x-rays passing through the pinhole mask was simply too few. The only image from the low power x-ray machine came from a forward scattering configuration, created by increasing the angle between the source to object and object to mask vectors from 90 degrees to 135 degrees. This produced an edge view of the object F, shown in Figure 3.29. This forward scattering configuration allowed for a higher flux at the mask and therefore more x-rays to pass through the pinhole mask. The backscatter configuration was not nearly as effective with the source and the detector perpendicular to one another and the object at a 45 degree angle, as shown in Figure 3.27, which was closer to the arrangement needed to see through a wall.

The term flux has many different definitions depending on the context and field of study. In this case, flux is taken to mean the amount of radiation or light present at a certain distance from the source. This allows for an easier comparison between the different experiments discussed in this report. This is discussed further in Section 3.5.

From these experimental results, shielding was clearly one of the major concerns due to the substantially low backscatter efficiency of the x-rays.
The x-ray machine simply did not produce a sufficient flux to capture a clear image on the detector. Section 3.5 discusses the flux measurement and Chapter 5 contains the flux comparison between experiments.

### 3.4.2 Mask Refining Experiments

During the course of this work, four different lead masks were made. The first mask was a 5 x 5 MURA pattern with each element measuring 10 mm x 10 mm in area. Since the available lead sheets in 1.6 mm thickness were only 7.5 mm x 15 mm, and the desired mask size was about 15 mm x 15 mm, two sheets had to be fit together. The problem which then arose was that there was a seam down the middle of the mask, which would let x-rays through.
Figure 3.26: Differentiate Shielding Capability for Different Thicknesses of lead

Figure 3.27: Experimental Geometry in Backscatter
Figure 3.28: Initial X-Ray Scattering without Shielding in Backscatter

Figure 3.29: Edge View of Object in Forward Scatter
This was seen in the detector response and proved to be a significant intensity with respect to the image.

This first attempt demonstrated that lead can be cut to reasonable tolerances and supported by an outer frame to maintain its position. The experimental runs with this mask confirmed the hypothesis that the transmission signal would be very high, but because of the large area holes, the resolution would be very poor.

The transmission images of this mask indicated that the significant open fraction did indeed let a large amount of x-rays through, and the 1.6 mm lead sufficiently shielded the necessary parts, but the seam down the middle was a problem. This is shown in Figure 3.30. The backscatter image produced by this mask was initially almost entirely black, indicating that nothing was detected. This is shown in Figure 3.31. The detector was suspected as the cause of this issue and a method to compare the signal present in the image was developed.

A MATLAB program was written to analyze the intensity of the detector pixels and uncovered a problem with the detector. About 28 pixels in the detector gave readings of between 20 and 150 counts even when the detector was completely shielded. Since these values were present in each image taken, the only explanation was that some detector pixels were broken and
Figure 3.30: 5 x 5 MURA, 10 mm holes, in transmission

Figure 3.31: 5 x 5 MURA 10 mm holes, backscatter, no intensity scaling
appeared to be always on. This gave a false positive reading, effectively a white pixel regardless of the actual signal. For this reason, the backscattered images were appearing black because the detector images were being displayed as a scaled .TIFF (tagged image file format) file with the highest value representing white and all values in between scaled to shades of grey. Since the intensity of the scattering image was between 1-10 counts, the good signal was showing up almost black, overwhelmed by the broken pixels. Even though the data was present, it was not displayed properly. A MATLAB routine removed these broken pixels by replacing them with an average value of the surrounding 8 pixels and this restored image quality to approximately what it should have been. The MATLAB code to do this is attached in Appendix B as Pixelfix.m. An example of this renormalized detector image is shown below in Figure 3.32. All of the images presented here have been scaled for inclusion in this report and some resolution has been lost in the process.

A very faint outline of the 5 x 5 arrangement of holes can be seen in Figure 3.32, although the flux was not high enough to resolve an outline of the object. The increased flux intensity was positive, but the size of the elements was still a significant problem. The detail of the final image was a function of the size of the smallest hole in the mask. This meant the 10 mm square elements dictate the resolution of the F to centimeters and no better. To solve this problem, a mask with finer elements was required. As a
Figure 3.32: 5 x 5 scatter projection, renormalized
first attempt, this worked well to illustrate the limitations and difficulties in construction and show the areas needing improvement for successive designs.

The second mask attempt was to stay with the 5 x 5 pattern, but shrink the element size to 2 mm square instead of 10 mm square. This was done to increase the resolution in hopes of resolving the letter F object. Also, since the first mask had a seam down the middle, this mask was cut from a single 38 mm square. Since the 5 x 5 pattern of 2 mm square holes occupied an area of 10 mm square, the reduction in total area as compared to the first mask was a factor of 25. About half of the mask area was open space. The improvement in this case was an increase in resolution, which allowed features on the order of 2 mm to be clearly resolved. This is a property of MURA masks, that the size of the smallest hole dictates the smallest feature the mask can resolve [18]. Since this mask was very small in total area, shielding was required around the mask to block unwanted contributions which did not pass through a hole in the mask. In this case, a 6.35 mm thick lead sheet was used as a shield. A 38 mm square hole was milled in the lead shield to accommodate the smaller lead mask plugs and allowed for sufficient shielding around the 5 x 5 mask. As can be seen in Figure 3.33, the seam between the two thicknesses of lead still came through in the final image.

In an effort to compare the strategy used above to minimize edge effects at the transition of the two thicknesses and to compare transmission efficien-
cies, a pinhole plug was made to fit in the same 38 mm hole. It produced a very similar image as shown in Figure 3.34. From these two images, it appeared to be difficult to eliminate the edge effect from the transition between thicknesses without overlapping the two sheets on one side of the mask. In Figure 3.33 it would appear that overlapping the mask and shield would eliminate the seam. While this is true, the 19 x 19 MURA is the full width of the 38 mm hole and would need to be further padded to remove the seam. This would be an option, simply reducing the shielding in the padded portion by making it from 1.6 mm lead instead of 6.35 mm lead and in the process creating another seam. It was decided that the seam could be reduced in the final 19 x 19 MURA design, with tighter tolerances and the thicker 6.35 mm shield with a mask insert design was beneficial. The 6.35 mm shield was also helpful in providing structure for the mask in the geometric setup, allowing for clamps to hold the mask in place.

The comparison of transmission efficiencies was also difficult to quantify. The way the detector worked was by grouping the number of counts for a given pixel into bins and outputting the data to a .TIFF file for analysis. This file format was useful because it gave the absolute counts for each pixel and when the image was displayed, it could be scaled or normalized accordingly. The limitation of the .TIFF file is that it reserved one byte for each entry or in this case each pixel in the detector. What this meant was that each detector pixel could register a maximum of 255 counts. All of the transmission
Figure 3.33: 5 x 5 MURA, 1.6 mm thick, transmission, scaled
Figure 3.34: Pinhole, 1.6 mm thick, transmission, scaled
images shown so far had reached this 255 count maximum at multiple places in the image and there was no way of knowing how many additional counts would have occurred there. In essence, anything over 255 counts was truncated off and there was no way to compare transmission efficiency between images which exceeded this limit.

Since the real purpose of the MURA mask inserts was to test the physical limitations, and many were found, a 19 x 19 MURA was designed to try to minimize these limitations to produce an image. With the image scaling program working, the signal to noise ratio should have been good enough to resolve the letter F. The transmission image of the 19 x 19 MURA is shown in Figure 3.35.

The mask looked reasonable in the transmission images, with only a few concerns. The first was the faint white shadow appearing about 2 cm below the mask in Figure 3.35. This artifact appeared in each transmission image of the 19 x 19 mask and to a lesser extent in all of the images involving the 38 mm square plugs. The cause of the artifact was likely an edge effect caused by the depth dimension of the 6.35 mm lead mask scattering x-rays at angles not originally expected by this arrangement.

The second concern was the rounded corners on the otherwise square elements comprising the 19 x 19 pattern. The effect was similar to the x-rays
bending around the lead near the edges and corners and showing up on the detector behind a solid part of the mask. Ideally, every x-ray encountering the lead mask would have been stopped, but realistically, this was not the case. Some transmission through the solid portion of the mask had to be accepted and the constant transmission was easily subtracted from the entire image, negating its effect. The problem with the rounded corners was that the effect was not uniform and may be slightly modifying the image from the detector. This effect was not severe and the final images could still be reconstructed, but this was another effect that was not anticipated.

3.4.3 Refined X-Ray Experiments

To address the shielding issues, the 19 x 19 element MURA was supported by lead bricks and used in a variety of configurations including transmission, backscattering, and forward scattering. Figure 3.36 shows the experimental setup for the transmission tests and Figure 3.37 shows the same for forward scattering.

Due to a suspected problem with the detector, that the images began appearing saturated when the flux had not changed, image contamination by visible light was investigated. To troubleshoot this, the experiments were performed with the room lights off. Under this condition, the problem was not experienced. Normally, the detector would be sealed properly so that
Figure 3.36: Transmission geometry, 19 x 19 MURA

Figure 3.37: Forward scattering geometry, 19 x 19 MURA
visible light would not contaminate the images, but it was clear that visible light was affecting the image. To address this, a cardboard box, sealed with black electrical tape along each seam, was used to shield the detector. This ensured that no visible light could reach the detector, at the expense of small transmission losses through the cardboard. Once this was done, the problem was no longer experienced. Since the cardboard light shield reduced the visible light that was contaminating the image and did not significantly attenuate the x-rays, this design change contributed to cleaner images overall. This new geometry is shown in Figure 3.38.

![Figure 3.38: Transmission geometry, with light-tight detector box](image)

The other difference between the setup shown in Figure 3.36 and Figure 3.38 was the orientation of the lead bricks supporting the mask. This was
done to discern if spurious artifacts appearing in the detector images were a result of the lead brick supports. This was not the case.

3.5 Low Flux X-ray Measurement

The specifications for the low flux x-ray machine were taken from the Golden Engineering XR200 manual [37]. Measurements were taken at a distance of 30 cm from source:

- X-ray dose per pulse: 2.6 - 4.0 mRad (0.026 - 0.040 mSv)
- max photon energy: 150 KVP
- max number of pulses per exposure: 99
- pulse width: 60 ns

The fluence at 30 cm is calculated in Equation 3.1 [39], assuming a mean photon energy of 50 KeV and a weighting factor of $w_r = 1$. 

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\[ \text{Dose} = \text{Fluence} \times \left( \frac{\text{Mass energy absorption coefficient}}{\text{Tissue density}} \right) \times \text{Energy} \]

\[ \text{Fluence} = \left( \frac{\text{Mass energy absorption coefficient}}{\text{Tissue density}} \right) @50keV \times \text{Energy} \]

\[ \text{Fluence} = \frac{4.0 \times 10^{-5} \text{Sv/pulse} \times 99 \text{ pulses} \times w_r \times 1 \frac{J/kg}{Sv}}{(3.99 \times 10^{-3} m^2/kg \times 50 keV \times 1.6 \times 10^{-16} J/keV)} \]

\[ \text{Fluence} = 1.2 \times 10^{14} \text{photons/m}^2(\text{per image}) \]

(3.1)

Since the x-ray specifications were provided for dose at 30 cm, this was converted to energy in Joules at the given distance to the object F, and then to fluence in photons per square meter for comparison with the other experiments. The comparison is provided in Chapter 5.

### 3.6 Discussion

After the initial x-ray experiments, a number of conclusions were drawn. The first was that the x-ray machine and detector work well in transmission, as designed. The second was that the transmission experiments agreed well with the simulations, while limitations arose with the actual apparatus. The simulation appeared to produce an image far more easily than the lab experiment did in reality. Quite typical of a simulated environment, however, this may have had something to do with the way MCNPX evaluated
the point detector tallies and determined the particle paths. In addition to the idealized simulated environment where edge effects are non-existent, MCNPX had a method of calculating point detector tallies that was not originally anticipated. Basically, when a particle interacts in MCNPX, the program calculates the probability of the scattered vector reaching each element in the detector array, however unlikely. This has the effect of forcing a detector hit and associating a likelihood of that event. If a single x-ray is simulated, the illuminated object can still be seen even though the likelihood is extremely small. This works well for producing images, but was initially deceptive.

What can be seen from the comparison with experimental results was that the lead pinhole masks allowed a lot more x-rays through the solid portion of the mask than in the MCNPX simulation. This is possibly due to MCNPX ignoring the small fraction of x-rays that pass though the lead mask. In order to visualize the object, the shielding needed to improve along with an increase in the flux reaching the detector.

For the refined x-ray experiments, shielding was still a concern and the new masks, refined geometry, and light-tight detector box did a great deal to improve this problem area. There were still spurious artifacts appearing in the detector images that were probably due to edge effects in the lead shield and this problem needed to be addressed.
In addition, the detector image intensity had not been scaling properly because of broken pixels in the detector that always gave a signal, even when they should not have. The MATLAB routine written to remove these broken pixels worked very well initially, however, as the experiments progressed, additional pixels appeared broken in the images. This meant the MATLAB routine had to be modified to include the new broken pixels and also indicated that the detector itself may be degrading.

Finally, on the mask fabrication process, lead working techniques had been refined to the point that, given enough time, a 79 x 79 MURA mask could be made by hand. The current 19 x 19 mask was of sufficient size and quality to demonstrate the image reconstruction process. From the experimental runs performed, it was clear that noise was an issue with this detector and the reconstruction algorithm had to decode the object in spite of the contaminated data. In all the pinhole and x-ray backscatter experiments performed in the lab at UOIT, a discernible image was never seen. In order to understand the other limitations of the experiment, the source flux needed to be increased substantially. This would allow the finer points of the process to be refined.

In order to test the reconstruction code on a realistic geometry, a replica experiment was created in the visible light range with a digital camera detec-
tor. This increased the fluence levels by about five orders of magnitude and allowed the reconstruction code to be refined and the process to be optimized to apply back to the x-ray configuration. The fluence comparison is given in Chapter 5.
Chapter 4

Light Experiments

The x-ray scattering experiment was limited in the flux it could generate, primarily by the specifications of the x-ray machine. In order to test the reconstruction code, a higher flux was needed to obtain a higher signal to noise ratio which would give less importance to the random noise and focus more on the desired signal. To this end, a similar experiment using light was designed to create a higher flux and allow for fine tuning of the reconstruction algorithm.
4.1 Light Setup

4.1.1 Initial Experimental Design

A Sawyer’s model 550ER slide projector, using a type DAK 500 watt bulb was initially used as an intense light source, projected at the object. The slide projector used is shown in Figure 4.1. In this case, the object was a white letter F on a black background, shown in Figure 4.2. The colour white gave the best light reflection and the black background gave the highest contrast.

Although the intended object was made of aluminum, a white letter was used in the light experiment. This was an attempt to better represent the
the effect of light interacting with the object, without the added benefit of a shiny metal surface. The x-rays behave the same way no matter which colour the object is; the linear attenuation coefficient is the determining factor. In order to avoid any advantage to the light reflection, in comparison to the x-ray experiment, solid white was chosen as the best choice of object colour to simulate x-ray behaviour with light. The key to this apparatus was in the detector, which was designed in a similar fashion to a pinhole camera. The detector was composed of three boxes that could slide into each other, as depicted by Figure 4.3 and Figure 4.4.

Starting from the front, the first box housed the pinhole which allowed the light reflected by the object to enter the cavity, shown in Figure 4.5 and
Figure 4.3: Light detector in operational position

Figure 4.4: Light detector in compact form
Figure 4.5: Pinhole box, outside

Figure 4.6: Pinhole box, inside
The second box contained a ground glass screen, shown in Figure 4.7 and Figure 4.8. Any white surface could have displayed this same projection, but in this case, a ground glass screen enables the projection to be photographed from the back side. This was the vital component which made this system work.

The image was captured on the opaque side of the ground glass, by a 5.0 mega-pixel Canon Powershot SD450 digital camera. The outer box had a cut-out to fit the lens of a digital camera. The light entering the pinhole was projected onto this screen and produced an image of the object, which could be seen by the human eye or captured by a camera.

Figure 4.7: Ground glass box, outside
The cut-out was centered such that the field of view of the camera was centered with the ground glass projection screen. A ledge on the outside of this box served as a resting place for the digital camera. With this arrangement the projection could be captured digitally as a photograph. The third box is shown in Figure 4.9 and Figure 4.10.

The camera was then connected to the computer, which took the image and reconstructed it using the MATLAB algorithm attached in Appendix B. The system was designed in three sections so each could move independently to capture the field of view of the pinhole and focus the image onto the ground glass. The optimal focal length for this box was found to be 28 cm. This was determined by looking through the digital camera at the black

Figure 4.8: Ground glass box, inside
Figure 4.9: Camera box, outside

Figure 4.10: Camera box, inside

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letter F shown in Figure 4.12 and ensuring that the entire white page was visible. The 28 cm distance was marked on the top of the first and second sliding box sections so they could be easily lined up. Sample images of the light box during construction are shown in Figure 4.11 and Figure 4.12. The important dimensions for imaging are shown in Figure 4.13.

Figure 4.11: Ground glass box, during construction

4.1.2 Methods of Construction

The wall material was chosen to be 6.35 mm hardboard which had reasonable strength, workability, and was opaque. The three sections were assembled with glue along the seams and for added strength metal L shaped brackets were glued along the edges. A large diameter hole was drilled in the front
Figure 4.12: Ground glass box, determining ground glass to camera distance

Figure 4.13: Camera box dimensions
box and a piece of cardboard glued over the hole so the pinhole could be easily made in the cardboard. This allowed more pinholes to be easily added or the cardboard insert replaced. Stoppers were glued to the bottom of the two interior sections for two reasons: (i) so the smaller boxes could not fall inside the larger box and get stuck or damaged, and (ii) so the system could balance on a level surface.

4.1.3 Experimental Setup

The light experiment setup is shown in Figures 4.14 to 4.16.

![Experimental setup](image)

Figure 4.14: Experimental setup

Images were taken through a single pinhole centered in the box and again
Figure 4.15: Experimental setup, side view

Figure 4.16: Experimental setup, lights off
with a second pinhole 2 mm to the right of the first. The images produced through the single and double pinholes are shown in Figure 4.17 and Figure 4.18, respectively.

Figure 4.17: F through single pinhole (very faint in black and white)

Comparing Figures 4.17 and 4.18, the single pinhole generates a faint image and the double pinhole a brighter image, but a duplicated object. This was where the image reconstruction would align both objects in the centre and strengthen the desired signal.
4.2 Refined Light Experiment

In order to validate and expand upon the results seen by the x-ray experiment, a similar experimental setup was developed in the visible light region. These initial trials indicated the success of a pinhole and double pinhole and progressed into the application of a 19 x 19 MURA mask.

4.2.1 Light Experiment Geometry

First, a 19 x 19 mask was made from aluminum foil. The aluminum was much easier to work with than the lead in making the holes and sufficiently opaque to block the incoming light rays. The surface dimensions of the mask were kept the same with 2 mm x 2 mm holes, 38 mm x 38 mm total size; the

![Figure 4.18: F through double pinhole](image-url)
only difference being the thickness. This mask is shown in Figure 4.19.

A slide projector was used as the light source and the aluminum foil attached to the existing pinhole camera box. This meant the ground glass was still needed as a projecting surface inside the camera box. The difference this time was the use of a Canon Rebel XSi digital SLR camera as the detector. Due to the flexibility in controls of the DSLR, the camera was mounted at a fixed distance behind the ground glass and covered with a black cloth to block other sources of light. The camera was then focused on the back of the ground glass sheet. Since the camera could be controlled from a laptop, via USB, there was no need to disturb the camera setup between images. This setup is shown in Figures 4.20 to 4.24.
Figure 4.20: Light experiment object

Figure 4.21: Light experiment ground glass
Figure 4.22: Light experiment camera

Figure 4.23: Light experiment covering
4.3 Light Masks

The first few images had issues of clarity and suffered from a phenomenon related to the physical geometry, called vignetting, which was not encountered in the simulated MATLAB images. An example of the picture quality is shown in Figure 4.25, before reconstruction.

The causes were related to artifacts from the ground glass sheet. The main contributor to this was determined to be vignetting, an unintended and undesired effect often seen in photography. Vignetting is a reduction of image brightness at the edges of the image as compared to the centre of the image [31]. This effect was observed here due to the ground glass sheet and could not be corrected mathematically. Since the reconstruction process

Figure 4.24: Light experiment setup
relied on defined edges to produce a clear image, the etched glass and vignetting effect needed to be removed from the process. This meant using the DSLR as a pinhole camera. In order to do this, the mask holes needed to be much smaller. This changed the geometry and required some modifications. The lens was removed from the camera and the size of the detector array measured. The distance from the array to the new mask was calculated and the new holes of the 19 x 19 mask were made to be as small as pinholes.

The new 19 x 19 mask was created by scaling down an image of the mask in Adobe Photoshop to fit on a 10 mm x 10 mm sheet. This paper was placed over a sheet of aluminum foil and pinholes punched through the centre of the open sections of the matrix into the foil. Achieving mask dimensions small enough to allow the image to invert within the camera meant the ground

![Figure 4.25: Light experiment sample detector image](image_url)
glass could be removed from the process and the DSLR photo array could capture the entire image. With the aluminum covering the opening in the camera, there was no need for the black cloth, as seen in Figure 4.26 to Figure 4.28.

Figure 4.26: 19 x 19 MURA of pinholes in aluminum foil

The results were better in this configuration, however, the pinhole mask was not very precise since the holes were made freehand, so another technique for making small masks was needed. This method was photo etching, with a technique similar to that used by electronics hobbyists to etch a prototype printed circuit board.

A 1:1 scaled 19 x 19 mask image, 10 mm square, from MATLAB was
Figure 4.27: Camera with 19 x 19 MURA of pinholes

Figure 4.28: New light experimental setup, no cloth
printed on a sheet of glossy photo paper using a laser printer. This caused
the laser toner to be loosely attached to the photo paper. Then, toner side
down, the paper was placed on a piece of clean 0.005 inch thick sheet brass.
Next, a hot clothes iron was pressed on the sandwich, heating the toner and
causing it to also adhere to the brass. After the sandwich cooled, it was
placed in warm water and the paper and glossy surface were gently brushed
off, leaving the toner attached to the brass sheet. A piece of clear packing
tape was stuck to the back side of the brass sheet to serve as support and to
prevent the etchant from attacking the back of the brass. Finally, the brass
sheet was placed in a bath of warm ferric chloride solution and the brass was
etched away except where the laser toner was covering the brass. This photo
etched mask is shown in Figures 4.29 and 4.30. The experimental setup is
shown in Figures 4.31 to 4.33.

A 50 W flood light was used in place of the projector in the new arrange-
ment, adding flexibility in beam orientation. For enhanced contrast, objects
were made of white letters mounted on black stands. A black back drop
was added to removed unwanted lighting effects from the field of view. In
addition to the 10 cm x 6 cm white letter F shown in Figure 4.34, some 2 cm
x 2 cm (approximately) letters were created for depth of field experiments.
They are shown in Figure 4.35.
Figure 4.29: Photo etched 19 x 19 MURA in brass, back view
Figure 4.30: Photo etched 19 x 19 MURA in brass, front view

Figure 4.31: New light experiment with objects B and F
Figure 4.32: Light experiment side view

Figure 4.33: Light experiment front view
Figure 4.34: White letter F target

Figure 4.35: Multiple letter targets
4.4 Results

With the new etched mask and geometry setup, the result of a reconstructed letter G is shown in the foreground of Figure 4.36 while a large letter F at more than twice the distance is difficult to see in the background. This is because the image plane is set at the distance to the letter G. This was the first successfully reconstructed image, produced with light and the brass etched mask. This was also the first confirmation that the reconstruction code worked.

The clearest images were of the large letter F at a distance of 90 cm with an optimal exposure (time with shutter open, as determined by the camera) of 0.5 s. This was simply based on available light reaching the camera array,
but was used for comparison here. The same geometrical setup was used with the F moving closer to the camera and the relative light levels remaining the same. Two examples of the letter F at different distances are shown reconstructed in Figure 4.37 and Figure 4.38.

![Image of F reconstructed at 90 cm](image)

**Figure 4.37: Sample F, reconstructed at 90 cm**

In the image shown in Figure 4.38, the full compilation (i.e. the sum of individual Fs through each pinhole) of Fs is not contained within the detector array because the object was too close. The data which had fallen off the edge and was lost lead to a partially reconstructed image. Due to scaling, the centre appeared the brightest, as did the top and bottom artifacts. These were artifacts that could have been removed by mask/anti-mask summation [18]. The difficulty in implementing this artifact cancellation process was
that the registration of the centre element must be extremely precise so the
two images align, otherwise the result would be unrecognizable.

The image in Figure 4.39 was taken at 60 cm, larger in size and with more
missing data, from being too close. The small 2 cm high F at a distance of
37 cm was fully illuminated and reconstructed as shown below in Figure 4.40.

In order to confirm whether an image which could not be resolved by a
single pinhole could be resolved by a 19 x 19 mask, because the same faint
object was overlaid with others without having defined edges, the following
experiment was performed. The 19 x 19 mask was covered with black elec-
trical tape so that only a single 2 mm x 1 mm pinhole mask remained. The

![Figure 4.38: Same letter F, reconstructed at 75 cm](image)

Figure 4.38: Same letter F, reconstructed at 75 cm
Figure 4.39: Sample F, reconstructed at 60 cm

Figure 4.40: Small sample F, reconstructed at 37 cm
images were taken at the optimal distance of 90 cm with the large F, varying
the exposure time. The results are shown in Table 4.1.

Table 4.1: Light experiment, varied exposure time

<table>
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<th>Mask number</th>
<th>Image number</th>
<th>Distance (cm)</th>
<th>Exposure time (s)</th>
<th>Notes</th>
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<td>1 x 1</td>
<td>5543</td>
<td>90</td>
<td>1/2</td>
<td>Very clearly visible (as is)</td>
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<td>1 x 1</td>
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<td>1/10</td>
<td>Faintly visible (as is)</td>
</tr>
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<td>90</td>
<td>1/20</td>
<td>Visible (only after scaling in Photoshop)</td>
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<td>90</td>
<td>1/50</td>
<td>Visible (with Photoshop)</td>
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<tr>
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<td>5547</td>
<td>90</td>
<td>1/100</td>
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<td>1/200</td>
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<td>19 x 19</td>
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<td>90</td>
<td>1/2</td>
<td>Reconstruction clearly visible (as is)</td>
</tr>
<tr>
<td>19 x 19</td>
<td>5551</td>
<td>90</td>
<td>1/10</td>
<td>Reconstruction clearly visible (as is)</td>
</tr>
<tr>
<td>19 x 19</td>
<td>5552</td>
<td>90</td>
<td>1/20</td>
<td>Reconstruction clearly visible (as is)</td>
</tr>
<tr>
<td>19 x 19</td>
<td>5553</td>
<td>90</td>
<td>1/50</td>
<td>Reconstruction clearly visible (as is)</td>
</tr>
<tr>
<td>19 x 19</td>
<td>5554</td>
<td>90</td>
<td>1/100</td>
<td>Reconstruction barely visible (as is)</td>
</tr>
<tr>
<td>19 x 19</td>
<td>5555</td>
<td>90</td>
<td>1/200</td>
<td>Not visible unless scaled first</td>
</tr>
<tr>
<td>19 x 19</td>
<td>5556</td>
<td>90</td>
<td>1/400</td>
<td>Not visible unless scaled first</td>
</tr>
</tbody>
</table>

After this test, it was observed that the 19 x 19 mask did provide some
additional benefit over a single pinhole. The first pinhole image, Figure
4.41, could not been seen unless auto-scaled on light level and contrast in
Adobe Photoshop, producing Figure 4.42. With the equivalent exposure
time through a 19 x 19 mask, Figure 4.43 shows a noticeable improvement.
By reducing the exposure time incrementally and comparing when the image
can no longer be seen, a relative measure of the 19 x 19 MURA improvement
is produced.
Image 5545 was the pinhole image before and after scaling in Adobe Photoshop and image 5552 is the same 1/20 s exposure time through a 19 x 19 mask, shown in Figure 4.41, Figure 4.42 and Figure 4.43, respectively. It may look as though Figure 4.42 is clearer than Figure 4.43, and this is the result of scaling in Adobe Photoshop, which Figure 4.43 did not have. Figure 4.43 is clearer than Figure 4.41, before the benefit of scaling, which was not available with the x-ray detector images. The equal comparison is at 1/20 s exposure on the DSLR, where Figure 4.43 is much more detailed than Figure 4.41, which is essentially black.

Figure 4.41: Pinhole image 5545 before scaling

The main difference shown here was in the scaling. New cameras, such as the DSLR used here, support 14bit .TIFF files which provided so much
Figure 4.42: Pinhole image 5545 after scaling

Figure 4.43: 19 x 19, image 5552, reconstructed
light information at low levels that Adobe Photoshop was used to normalize the signal by adjusting light and contrast levels to recover the object, where no other visible differentiation was possible. The x-ray detector used 8 bit .TIFF files which did not have the same precision to resolve such low signal levels.

4.5 Light Flux Measurement

Normal lighting in the room was measured to be 950 lux. The room lights were soft white fluorescent bulbs. With the room lights off, Table 4.2 was compiled from the measured light produced from the soft white floodlight used in the light experiments (General Electric, R20, 05431, 50 W floodlight). A 50 W tungsten filament incandescent bulb has a 2% overall luminous efficiency [36].

Equation 4.1 was used to calculate the radiometric column in Table 4.2.

\[
\text{Photometric (lm/m}^2\text{)} = \text{Radiometric (W/m}^2\text{)} \times 685 \times \text{efficiency}
\]

\[
\text{Photometric (lm/m}^2\text{)} = \text{Radiometric (W/m}^2\text{)} \times 13.7(\text{lm/W})
\]

\[
\text{Radiometric (W/m}^2\text{)} = \frac{\text{Photometric (lm/m}^2\text{)}}{13.7(\text{lm/W})}
\]

(4.1)
### Table 4.2: Floodlight flux levels (room lights off)

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Photometric (lux = lm/m²)</th>
<th>Radiometric (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>128</td>
<td>9.34</td>
</tr>
<tr>
<td>80</td>
<td>133</td>
<td>9.71</td>
</tr>
<tr>
<td>70</td>
<td>178</td>
<td>12.99</td>
</tr>
<tr>
<td>60</td>
<td>215</td>
<td>15.69</td>
</tr>
<tr>
<td>50</td>
<td>274</td>
<td>20.00</td>
</tr>
<tr>
<td>40</td>
<td>340</td>
<td>24.82</td>
</tr>
<tr>
<td>30</td>
<td>448</td>
<td>32.70</td>
</tr>
<tr>
<td>20</td>
<td>590</td>
<td>43.07</td>
</tr>
</tbody>
</table>

One of the clearest images of the letter F was at 90 cm, corresponding to 9.34 W / m² from Table 4.2. The fluence can be calculated at 90 cm based on the 0.5 s exposure time, as shown in Equation 4.2.

\[
\text{Fluence} = \text{Radiometric} \times \frac{\text{Exposure time}}{h\nu}
\]

\[
\text{Fluence} = \frac{9.34(W/m^2) \times 1J/s}{W} \times 0.5s \times \frac{6.626 \times 10^{-34} J s}{\text{photon}} \times 3.0 \times 10^8 m/s \times 575 \times 10^{-9} m
\]

\[
\text{Fluence} = 1.4 \times 10^{19} \text{photons/m}^2 \text{(per image)}
\]

(4.2)

By comparing the fluence at the object using light and low flux x-rays, the light fluence is more than five orders of magnitude higher. As seen in this comparison, the additional light fluence made the testing and refinement of the reconstruction code much easier.
4.6 Discussion

The additional flux in the light experiment was instrumental in understanding the reconstruction code and how the process worked. Since the three experiments were all slightly different, a consistent metric was needed to compare flux levels across the board. The method chosen was to compare fluence at the target. The comparison is discussed in Chapter 5.

With the reconstruction algorithm confirmed to work, it was applied to the low flux x-ray images. Since the object was still not visible, the conclusion was that the flux was still too low and a more powerful x-ray machine was required. The best option to obtain the necessary results was to conduct experiments at Defence Research and Development Canada (DRDC) labs in Ottawa where an existing high powered x-ray machine could be used.

With higher flux levels, the light experiments showed the first successfully reconstructed images. This was a monumental step towards a working x-ray system. It confirmed that the process worked from start to finish and all that was required to image with x-rays was a higher flux.
Chapter 5

High Flux X-Ray Experiments

Since the light experiments showed clearly reconstructed images, the computer code worked and the limitation was in the amount of x-ray flux reaching the detector. To maximize the flux, the same experiment was conducted at Defence Research and Development Canada (DRDC) in Ottawa with a high power LPX300 x-ray machine and a Logos film type imager. With the code recalibrated for the different parameters, a successful reconstruction showed that the process worked with high energy radiation as well as visible light.

5.1 DRDC Setup

The laboratory setup at DRDC is shown in Figures 5.1 to 5.4. Trials were performed between 50 and 300 kV x-ray tube potential and between 3 and
9 mA tube current. Exposure times were between 20 s and 600 s, depending on the run. See Table 5.1 and Table 5.2 for details. The experimental setup had the source project directly at the object with the x-rays reflecting off the object toward the detector at approximately a 30 degree angle. The actual angle was less important than the alignment with the mask and detector, so the angle changed as the experimental alignment was refined.

### Table 5.1: DRDC experiments, Day 1

<table>
<thead>
<tr>
<th>Trial</th>
<th>Voltage (kV)</th>
<th>Amperage (mA)</th>
<th>Exposure (s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>5.0</td>
<td>20</td>
<td>Pinhole, image not clear, mask too close</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>5.0</td>
<td>20</td>
<td>Pinhole, same, underexposed</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>5.0</td>
<td>30</td>
<td>Pinhole, same, underexposed</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>9.0</td>
<td>60</td>
<td>Pinhole, same, underexposed</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>9.0</td>
<td>60</td>
<td>Pinhole, geo. change, underexposed</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>9.0</td>
<td>60</td>
<td>Pinhole, adjustments, underexposed</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>9.0</td>
<td>120</td>
<td>Pinhole, lead added, underexposed</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>9.0</td>
<td>60</td>
<td>Pinhole, same, faint F seen</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>9.0</td>
<td>60</td>
<td>Pinhole, same, clearer</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>9.0</td>
<td>120</td>
<td>Pinhole, refined dist., no image</td>
</tr>
<tr>
<td>11</td>
<td>100</td>
<td>9.0</td>
<td>60</td>
<td>Pinhole, same, still misaligned</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>9.0</td>
<td>90</td>
<td>Pinhole, same, faint image</td>
</tr>
<tr>
<td>13</td>
<td>100</td>
<td>9.0</td>
<td>90</td>
<td>Pinhole, same, faint image</td>
</tr>
<tr>
<td>14</td>
<td>100</td>
<td>9.0</td>
<td>90</td>
<td>Pinhole, same, clear image</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
<td>9.0</td>
<td>300</td>
<td>Pinhole, same, clear image</td>
</tr>
</tbody>
</table>

The objects imaged were the same aluminum letter F as the initial x-ray experiments and a new aluminum flange. The distances from source to object (SO) and object to mask (OM) were varied, from between 50 cm and
<table>
<thead>
<tr>
<th>Trial</th>
<th>Voltage (kV)</th>
<th>Amperage (mA)</th>
<th>Exposure (s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>100</td>
<td>9.0</td>
<td>300</td>
<td>Pinhole, shielded, clear, 2cm</td>
</tr>
<tr>
<td>17</td>
<td>300</td>
<td>3.0</td>
<td>180</td>
<td>Pinhole, shielded, clear</td>
</tr>
<tr>
<td>18</td>
<td>100</td>
<td>9.0</td>
<td>600</td>
<td>Pinhole, shielded, very clear</td>
</tr>
<tr>
<td>19</td>
<td>100</td>
<td>9.0</td>
<td>600</td>
<td>19x19, shielded, no image</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>9.0</td>
<td>150</td>
<td>19x19, shielded, no image</td>
</tr>
<tr>
<td>21</td>
<td>100</td>
<td>9.0</td>
<td>300</td>
<td>19x19, adjustments, no image</td>
</tr>
<tr>
<td>22</td>
<td>100</td>
<td>9.0</td>
<td>150</td>
<td>19x19, adjustments, no image</td>
</tr>
<tr>
<td>23</td>
<td>100</td>
<td>9.0</td>
<td>150</td>
<td>19x19, adjustments, no image</td>
</tr>
<tr>
<td>24</td>
<td>100</td>
<td>9.0</td>
<td>150</td>
<td>pinhole, not clear</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
<td>9.0</td>
<td>600</td>
<td>pinhole, not clear</td>
</tr>
<tr>
<td>26</td>
<td>100</td>
<td>9.0</td>
<td>600</td>
<td>pinhole, not clear</td>
</tr>
<tr>
<td>27</td>
<td>100</td>
<td>9.0</td>
<td>600</td>
<td>pinhole, clear F</td>
</tr>
<tr>
<td>28</td>
<td>100</td>
<td>9.0</td>
<td>300</td>
<td>19x19, good signal</td>
</tr>
<tr>
<td>29</td>
<td>100</td>
<td>9.0</td>
<td>300</td>
<td>19x19, adjustments, good signal</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
<td>9.0</td>
<td>150</td>
<td>19x19, Flange, good signal</td>
</tr>
<tr>
<td>31</td>
<td>50</td>
<td>10</td>
<td>150</td>
<td>19x19, Flange, underexposed</td>
</tr>
<tr>
<td>32</td>
<td>200</td>
<td>4.5</td>
<td>150</td>
<td>19x19, Flange, underexposed</td>
</tr>
<tr>
<td>33</td>
<td>200</td>
<td>4.5</td>
<td>30</td>
<td>19x19, Flange, underexposed</td>
</tr>
<tr>
<td>34</td>
<td>200</td>
<td>4.5</td>
<td>45</td>
<td>19x19, Flange, underexposed</td>
</tr>
<tr>
<td>35</td>
<td>200</td>
<td>4.5</td>
<td>75</td>
<td>19x19, F and Flange, faint</td>
</tr>
</tbody>
</table>
Figure 5.1: DRDC experimental setup

Figure 5.2: DRDC experimental setup, letter F
Figure 5.3: DRDC experimental setup, flange

Figure 5.4: DRDC experimental setup, from behind
100 cm, in an attempt to capture the clearest image while maintaining a similar geometry to the light setup. Again, more important than the actual distances was the alignment. The mask to detector (MD) distance was made as close as possible to the OM distance so the image would appear the same size as the object. This also was flexible and simply resulted in a scaled version of the object in the reconstruction. The use of a flashlight was helpful in aligning the object, mask, and detector. If the light was projected along the path of the source x-rays, the object would reflect some light toward the detector. When the light appeared on the detector, through the mask, the alignment was within range. Fine adjustments were sometimes needed, even after the flashlight was used.

The process used at DRDC to generate the images was to first align the geometry, position the film, and leave the lead-lined room. From outside the room, the x-ray machine was set for voltage, current, and exposure time. Once the run had completed, the film was retrieved and scanned in a cylindrical scanner to produce a digital image file. The file was then loaded into the reconstruction code. Scaling differences were encountered in the reconstruction code because the resolution in the digital scanner was a parameter chosen by the user. It took some time to determine this and correct for the scaling, before the first reconstructed images were seen. Since the film was scanned and formatted into a digital file, the resolution changed from the pixel to area ratio on the film itself.
In the reconstruction routine, the image was scaled based on the experimental distances, to recover the original object. Since the exact calculated dimensions of a single pixel in the image did not account for the scaling from film to digital file, the object was not reconstructed. Once this was recognized and the scaling factors corrected for the Logos imager, the reconstruction process worked and the images were revealed.

5.2 Masks

For the experiments at DRDC, the same 19 x 19 MURA mask was inserted into the same lead frame as previous x-ray experiments. With respect to the masks, the other aspects of the setup remained the same. The mask is shown in Figure 5.5.

Figure 5.5: DRDC 19 x 19 lead mask, 1.6 mm thickness
5.3 Results

The initial runs with the letter F yielded a detector response shown in Figure 5.6 and the reconstruction in Figure 5.7. The results show that the x-ray machine could generate enough flux to produce an image. For comparison, the aluminum letter F inserted in the stand is shown in Figure 5.8. The raw data files are much larger in area than the reconstructed product, due to scaling in MATLAB. For reproduction here, the images are scaled to different degrees.

Figure 5.6: DRDC Trial 21, detector, aluminum F

In this case, the wood stand holding the aluminum F was also visible. To show the results of a different object, an aluminum flange was also used. This object had considerably more depth than the flat F and this third dimension was evident in the shading cast in the detector response shown in Figure 5.9 and reconstructed in Figure 5.10. Again, for comparison, the aluminum flange is shown in Figure 5.11.
Figure 5.7: DRDC Trial 21, reconstructed letter F

Figure 5.8: Aluminum letter F with stand

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Figure 5.9: DRDC Trial 30, detector, flange

Figure 5.10: DRDC Trial 30, reconstructed flange
5.4 High Flux X-ray Measurement

DRDC x-ray machine was a LPX300 with a tube output of 900 W. Tube potential and current could be varied, without exceeding the 900 W maximum output.

The specifications for measured radiation output from a LPX300 supplier were:

Exposure = 30 Roentgen / min @ 50 cm

Source is 300 kV, 3.0 mA filtered with 0.5” aluminum [38].

The fluence at 50 cm is calculated by Equations 5.1, 5.2 and 5.3 [39], assuming a mean photon energy of 100 KeV.

Figure 5.11: Aluminum flange
\[
\frac{\mu_m}{\rho_m} = \left( \frac{\text{linear attenuation}/\text{density}}{\text{tissue}} \right)
\]
\[
\frac{\mu_a}{\rho_a} = \left( \frac{\text{linear attenuation}/\text{density}}{\text{air}} \right)
\]
\[
\frac{\mu_m}{\rho_m} = \frac{1.69 \times 10^{-2} m^2/kg}{1.541 \times 10^{-2} m^2/kg}
\]
\[
\frac{\mu_m}{\rho_m} = 1.097
\]  

(5.1)

Dose to tissue = \[ \frac{87.7}{100} \times \text{Exposure} \times \frac{\mu_m/\rho_m}{\mu_a/\rho_a} \times \frac{1 \text{Gy}}{100 \text{Rads}} \]

Dose to tissue = \[ \frac{87.7}{100} \times 30 \text{Roentgen/min} \times 2.5 \text{min} \times 1.097 \times \frac{1 \text{Gy}}{100 \text{Roentgen}} \]

Dose to tissue = 0.722 Gy

(5.2)

Dose = \text{Fluence} \times \left( \frac{\text{Mass energy absorption coefficient}}{\text{Tissue density}} \right) \times \text{Energy}

Fluence = \left( \frac{\text{Mass energy absorption coefficient}}{\text{Tissue density}} \right) \times 100 \text{keV} \times \text{Energy}

Fluence = 0.722 Gy \times 1 \frac{J/kg}{Gy} / (2.511 \times 10^{-3} m^2/kg \times 100 \text{keV} \times 1.6 \times 10^{-16} J/\text{keV})

Fluence = 1.8 \times 10^{16} \text{photons/m}^2(\text{per image})

(5.3)
5.5 Flux Comparison

Since the three experiments were all slightly different, a consistent metric was needed to compare flux levels across the board. The method chosen was to compare fluence in photons per square meter at the target.

The low flux experiment generated a fluence of $1.2 \times 10^{14}$ photons/m$^2$ per image. The light experiment produced a fluence of $1.4 \times 10^{19}$ photons/m$^2$ per image, more than five orders of magnitude greater than the low flux experiment. The high flux experiment generated a fluence of $1.8 \times 10^{16}$ photons/m$^2$ per image. This was almost two orders of magnitude greater than the low flux experiment.

Both the light experiment and high power x-ray experiment produced discernible images and this would agree with their higher fluence. The low power x-ray experiment suffered from a much lower fluence and a difference of two orders of magnitude would explain this also.

5.6 Discussion

The experimental parameters changed significantly from the low power x-ray setup at UOIT to the lab at DRDC. The computer code required substantial modification to reconstruct the DRDC images. The distances changed, and that was expected. The surprise was in how different the detector was
at DRDC. Due to the scanning of the film into a digital file, the pixels per area was a parameter that could be varied and this complicated the scaling calculations required in the reconstruction code. Once this was discovered, the code was modified and the reconstruction worked.

The alignment of the object, mask and detector was not a straightforward process. Rulers and measuring tapes were used to find a coarse alignment, to the point that a flashlight or laser level could be used to make the final corrections. A simple visual estimation was not sufficient. Aligning the experiment correctly made the most significant difference in the quality of the reconstructed images. Almost identical shots with a slight alignment difference looked completely different in the final images. The highest quality images came after a few iterations of alignment, result, and realignment.

The results of the experiments at DRDC clearly show the process worked in its entirety and the limitations of the low x-ray flux in the previous experiments were compensated for by a much stronger x-ray machine and a more sensitive imager. The unfortunate finding was the high dose level at which the DRDC x-ray machine was operating at to obtain the clear images; almost full capacity. This level was much higher than a practical dose field for a portable system. The result was a process that worked in the lab, had many variables and applications, with one condition that the flux field was very high. In the case of a portable one sided imaging system, this technique
does not work practically enough for field deployment, due to the high doses required.
Chapter 6

Conclusions and Future Work

6.1 Conclusions

The quality of mask fabrication and geometric alignment were sufficient to produce a system that captured the signal. As documented in numerous research papers, the reconstruction code worked successfully to decode the convoluted signal. This was seen in both the visible light and high powered x-ray experiments. The low powered x-ray experiment never produced a clearly reconstructed image. There was simply not enough flux and detector sensitivity. The flux improvement from the high powered machine at DRDC enabled clear images to be produced from x-rays, demonstrating that the process worked in its entirety.

Due to the flux level required, image acquisition took longer than ex-
pected; it simply took longer to fire enough x-rays to illuminate the object. Similarly, the resolution of the images and the quality desired meant the image reconstruction took longer than expected, as more pixels were present in the same area. Both of these factors made real time deployment impractical. In addition to the above time constraints, clear x-ray images were only seen under significant irradiation at DRDC. This dose field was too high to stand behind the machine in the same room. The operators were shielded behind a lead door. The fields existing in the beam path of the x-ray machine were even higher and would cause detrimental health effects to an exposed human. This made the possibility of imaging through a wall imprudent because an unsuspecting human would be seriously harmed before they could be identified in the image.

In general agreement with the original hypothesis, the system was demonstrated to work, while the high flux levels and time involved in image production presented serious limitations to the real-time system feasibility. There are aspects of this research which could be applied to other environments, however, the purpose of this experiment, real-time one-sided imaging, could not be satisfactorily achieved within the bounds of reasonable radiation exposure.
6.2 Future Work

In these experiments, the distances from the source to object and from the object to detector were around 1 m. Since flux intensity decreases proportionally with the square of the distance, considerably more x-rays are required as the object moves farther away. Conversely, this same system would require much less flux if the distances were decreased by an order of magnitude. This, however, is not the geometry studied or the useful working distance of a portable imaging system. It is possible to translate the results presented here to a slightly different application, although continued research toward the present hypothesis would not lead to significantly different conclusions.

In order to apply the findings of this research to a different problem, the benefits should be highlighted. The transmission imaging worked very well. The reconstruction code worked and can still be optimized with computational techniques. Masks can be fabricated, in a reasonable time frame, with lead, to suit a variety of imaging scenarios. Other mask materials can be explored and would provide even better results.

Real time imaging in transmission may be possible from a mobile platform. The available flux in transmission is much higher than backscatter and the imaging system is designed specifically for transmission applications, so a robot mounted coordinated motion system in transmission could be suc-
cessful. It would not have the ability to see through walls, as in a one-sided imaging system, but there are many industrial applications where this consideration is not paramount. Imaging in a hostile chemical environment for example is a situation where it is preferable to send a robot instead of a human. A coordinated motion robot system could enter an access controlled area and image the surroundings while humans watch from a safe distance. There are also areas of an operating nuclear power plant which are not accessible to humans, but where real time imaging would be beneficial for troubleshooting and diagnostics.

Imaging without a wall or with less limiting obstructions may also be possible. If portable shields or a three robot system, where the third robot carries a shield, could be used to reduce the collateral x-ray dose, the source strength could be increased without affecting neighbouring rooms as significantly. This would be a more complicated coordinated motion system, and would not be able to image every conceivable situation, however, it may provide value in certain imaging scenarios. An example of this situation would be in scanning abandoned buildings for structural stability or hazardous substances. There is an inherent risk when sending humans into such an environment, however the information relayed back from the robots could confirm the hazards without the need for humans to enter the building. These are just a few example of the potential applications of this technology.
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Appendix A

Mathematics

A.1 Fourier Transforms

Any continuous periodic function can be approximated by a Fourier series. Given a function $f(t)$ on an interval $(-L, L)$, the Fourier series would be as follows:

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left( a_n \cos \frac{n\pi x}{L} + b_n \sin \frac{n\pi x}{L} \right)$$  \hspace{1cm} (A.1)

where the coefficients $a_n$ and $b_n$ are:

$$a_n = \int_{-L}^{L} f(x) \cos \frac{n\pi x}{L} \, dx$$  \hspace{1cm} (A.2)

$$b_n = \int_{-L}^{L} f(x) \sin \frac{n\pi x}{L} \, dx$$  \hspace{1cm} (A.3)
Substituting $k$ for $\frac{n\pi}{L}$ and applying identities such that:

\[
\sin(\theta) = \frac{(e^{i\theta} - e^{-i\theta})}{2i} \quad (A.4)
\]

\[
\cos(\theta) = \frac{(e^{i\theta} + e^{-i\theta})}{2} \quad (A.5)
\]

$f(x)$ then becomes:

\[
f(x) = \sum_{n=1}^{\infty} (c_n e^{ikx}) \quad (A.6)
\]

\[
c_n = \frac{1}{2L} \int_{-L}^{L} f(x)e^{-ikx}dx \quad (A.7)
\]

where $c_n$ is a complex number.

In order to approximate a continuous function, let $L \to \infty$. In this particular function, as the interval increases, the terms change. Note also that $\Delta k = \frac{\pi}{L}$ and as $L \to \infty$, $\Delta k = dk$:

\[
\lim_{L \to \infty} \left( \frac{1}{2\pi} \sum_{n=1}^{\infty} \left( \int_{-L}^{L} f(x)e^{-ikx}dx \right) e^{ikx} \frac{\pi}{L} \right) = \frac{1}{2\pi} \int \int f(x)e^{-ikx}dx e^{ikx} dk \quad (A.8)
\]

The Fourier Transform $F(k)$ for the function $f(x)$ is given by:

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\[ F(k) = \int_{-\infty}^{\infty} f(x)e^{-ikx}dx \]  
(A.9)

and the function \( f(x) \) is given by the inverse Fourier Transform, where \( F(k) \) is a complex number:

\[ f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(k)e^{ikx}dk \]  
(A.10)

This is implemented in the reconstruction code by the Fast Fourier Transform (FFT) routine included in Matlab.

### A.2 Convolution and Correlation

Both convolution and correlation operations are shift invariant and linear, i.e. they perform the same operation on every point and each new point is a linear combination of all neighboring points. They are typically expressed as \( * \) for convolution and \( \star \) for correlation:

\[ (f * g)(x) = \int f(u)g(x-u)du \]  
(A.11)

\[ (f \star g)(x) = \int f(u)g(x+u)du \]  
(A.12)

In discrete cases of \( f(x) \) and \( g(x) \) the integration can be replaced by a simpler summation. These calculations are simple but time consuming due
to the number of iterations. Applying Fourier Transforms allow for much faster computation. To take the Fourier Transform ($F$) of the convolution of $f(x)$ and $g(x)$:

$$F((f * g)(x)) = \int \int f(u)g(x-u)du \cdot e^{-ikx}dx$$  \hspace{1cm} (A.13)

If $z = x - u$, where the Jacobian of this substitution is 1:

$$F((f * g)(x)) = \int \int f(u)g(z)e^{-ik(z+u)}dudz$$
$$= \int \int f(u)e^{-iku}du \cdot g(z)e^{-ikz}dz$$
$$= \int f(u)e^{-iku}du \int g(z)e^{-ikz}dz$$
$$= F(k)G(k)$$

This means the Fourier Transform of the convolution of $f(x)$ and $g(x)$ is the same as multiplying their individual Fourier Transforms. This also means since multiplication is an associative and commutative operation, so is convolution:

$$(f * g)(x) = F^{-1}F((f * g)(x)) = F^{-1}(F(k)G(k))$$  \hspace{1cm} (A.14)

Applying Fourier Transforms to the correlation operation will also significantly decrease computation time.
\[ \mathcal{F}\left( (f \ast g)(x) \right) = \int \int f(u)g(x + u)du \cdot e^{-ikx}dx \quad (A.15) \]

If \( z = x + u \), where the Jacobian of this substitution is also 1:

\[
\mathcal{F}\left( (f \ast g)(x) \right) = \int \int f(u)g(z)e^{-ik(z-u)}dudz \\
= \int \int f(u)e^{iku}du \cdot g(z)e^{-ikz}dz \\
= \int f(u)e^{iku}du \int g(z)e^{-ikz}dz \\
= F(k)'G(k)
\]

Where \( F(k)' \) is the complex conjugate of \( F(k) \), demonstrating that correlation is associative but not commutative, because the order of operation determines the conjugate:

\[
(f \ast g)(x) = \mathcal{F}^{-1}\mathcal{F}\left( (f \ast g)(x) \right) = \mathcal{F}^{-1}\left( F(k)'G(k) \right) \quad (A.16)
\]

### A.3 Decoding

Since each hole in the MURA mask casts an image on the detector, where \( r_i \) is the position of a pinhole, the detector projection (R) is related to the object (O) and the mask (A) in the following way:
\[ R(r_i) \propto (O \ast A)(r_i) \quad (A.17) \]

Applying Fourier Transforms to this relation leads to:

\[ \mathcal{F}(R) \propto \mathcal{F}(O' \ast A') = \mathcal{F}(O')\mathcal{F}(A') \quad (A.18) \]

Solving for \( O' \) yields:

\[ \mathcal{F}^{-1}\left( \frac{\mathcal{F}(R)}{\mathcal{F}(A')} \right) \propto \mathcal{F}^{-1}\mathcal{F}(O') = O' \quad (A.19) \]

The disadvantage of this method is that \( \mathcal{F}(A') \neq 0 \) and the noise factor is not constant as \( \mathcal{F}(A') \to 0 \). Realistically, the Fourier Transform of the relation is:

\[ \mathcal{F}(R) \propto \mathcal{F}(O' \ast A') + \mathcal{F}(N) \quad (A.20) \]

\[ \hat{O} \propto \mathcal{F}^{-1}\left( \frac{\mathcal{F}(R)}{\mathcal{F}(A')} \right) - \mathcal{F}^{-1}\left( \frac{\mathcal{F}(N)}{\mathcal{F}(A')} \right) \quad (A.21) \]

A more advantageous decoding method involves the use of a decoding array \( (G) \), the perfect pair of the mask \( (A) \). Applying the associative and commutative laws of convolution and correlation to this relation yields:
\[ \hat{O} = R \star G \]
\[ = (O' \star A' + N) \star G \quad (A.22) \]
\[ = O' \star (A' \star G) + N \star G \]
\[ = O' \star \delta + N \star G \]
\[ = O' + N \star G \]

The noise term in this form is much easier to deal with. It is assumed to be a constant and can be factored out as a constant from a sum:

\[ N \star G = \int N(x)G(x + y)dx \]
\[ = N \int G(x + y)dx \quad (A.23) \]
\[ = N \int G(\mu)d\mu \]

Ignoring the noise term, and applying the unique property of the delta function to the perfectly matched pair of $A$ and $G$:
\[ \hat{O}(r_j) = (R \ast G)(r_r) \]
\[ \quad = \iint R(r_j)G(r_i + r_j)d^2r_i \]
\[ \quad = \iint O'(r_o^i) \iint A'(r_i - r_o^i)G(r_i + r_j)d^2r_i d^2r_o^i \quad (A.24) \]
\[ \quad = \iint O'(r_o^i)\delta(r_o^i + r_j)d^2r_o^i \]
\[ \quad = O'(-r_j) \]
\[ \quad = Reflection(O') \]

The correlation routine shifts G by the coefficient \( r_j \), multiplies the shifted G array point by point with R and sums the result. The sum is equal to the brightness of the image at point \( r_j \).

The above mathematics is written in Matlab code in the attached Appendix B.
Appendix B

Computer Code

% Reconstruction code

Pixel_fix.m

clear
clc
close all

% load image
I=imread('C:\Bill\Masters_Thesis\Winter2010\RAW images\xray_pics...\2010_02_06\Image V.tif');
%figure('Name','A'),imshow(I);
% known broken pixel rows

r = [304;
    328;
    328;
    328;
    72;
    303;
    66;
    260;
    288;
    85;
    505;
    544;
    225;
    130;
    81;
    232;
    269;
    28;
    318;
    131;
    194;
    530;
    372;]
% known broken pixel cols
c = [20;
    27;
    28;
    86;
    179;
    215;
    235;
    261;
    268;
    284;
    321;
    329;
    330;
    333;
    333;
    387;
    480;
    488;
    510;
    518;
    540;]
% before
for j=1:length(r)
    B(j,:) = I(r(j),c(j));
end

% after
for j=1:length(r)
    I(r(j),c(j)) = (I(r(j)-1,c(j)-1) + I(r(j)-1,c(j)) + I(r(j)-1,c(j)+1) +
                   I(r(j),c(j)-1) + I(r(j),c(j)+1) +
                   I(r(j)+1,c(j)-1) + I(r(j)+1,c(j)) + I(r(j)+1,c(j)+1))/8;
    A(j,:) = I(r(j),c(j));
end

% search for potential new broken pixels
[r,c,v]= find(I>40)

imwrite(I,'C:\Bill\Masters_Thesis\Winter2010\RAW images\xray_pics...
\2010_02_06\Image A_scaled.tif');  % I image with broken pixels...
figure('Name','A'),imshow(I);
%[X,Y] = size(I);
%figure, surf(1:X,1:Y,I)

Decode.m

%decoded.m
%decode.m requires the mask dimension (p), decode matrix (G1) and
% detector image (R) as inputs
% the result is the decoded image of the object (O)
function [O]=decode(p,G1,R)

%periodic correlation of projection (R) and decoding array (G) using FFT
FR=fft2(R);
%conjugate
FCR=conj(FR);
FG=fft2(G1);
%correlation
FO=FCR.*FG;
O=ifft2(FO);
%The object needs to be centred and then reflected
O=circshift(O, floor(p/2), floor(p/2));
O=rot90(rot90(O));
Makemask.m

% makemask.m make mura A1 and G1 arrays
%
% makemask(p,figs) creates:
% a MURA mask A1 of dimension pxp, where p is prime,
% A is the basic MURA mask,
% A1 is the MURA mask after it has been shifted
% to make it symmetric about the centre
% assume 0's are lead, 1's are holes, since we are accumulating light
% not dark (imshow displays 0 as black, 1 as white which is correct)
% the accompanying decoding array G1
% G is the basic decoding array
% G1 is the decoding array after it has been shifted
% to make it symmetric about the centre
% G1 values have been shifted from (0,1) to (-1,1) for "balanced decoding"

% 10dec2009 - added figs parameter in call
% if figs=1, figures of the masks are output, if figs=0 they are not output

function [A1, G1] =makemask(p,figs)
iptsetpref('ImshowAxesVisible','on')  %nice to see axes on imshow output

%isprime returns 0 if p is not prime, 1 if p is prime, where p is MURA dim.
if isprime(p)==0
    error('p must be prime')
end

%"ci and cj are equivalent vectors since the dimensions are square.
% ismember returns 0 if i is not a member of modp (x^2) and 1 if it is. The
% algorithm that generates ci and cj have i and j indexed from [0,p1]. For
% i=0 A(i,j)=0 and j=0 A(i,j)=1 (i =/0), if we let i=[0,p-1] and j=[0,p-1]
% the matrix cj'*ci (' is transpose) would be the appropriate size so we
% don't have to initialize A. since the dimensions are the vector ci is
% equivalent to cj, so cj'=ci'.
% The vector ci is a binary vector but we want the 0's in the vector to be
% -1's, so piecewise multiplication by 2 and subtracting 1 creates the
% appropriate vector."

%MURA MASK
ci=ismember([0:p-1],mod([1:p].^2,p))*2-1;
A= ( (ci'*ci) +1) /2;
A(:,1)= ones(p,1);
A(1,:)=zeros(1,p);
Decoding array

"MURAs have approximately 50% open fraction, so a mismatched decoding matrix is appropriate. All the 0's become -1."

% Code added for DRDC experiments as mask is different

A = (A-1)*-1;
A(:,1) = ones(p,1);
A(1,:) = zeros(1,p);

G = A*2 -1;
"i+j modulo p =0 only happens for i,j=1 and i,j=p because p is prime."
G(1,1) = 1;
% note that the only difference between A and G is that A(1,1) is 0 and % G(1,1) is 1. After both are centred, (1,1) becomes the % center of the array

%circshift shifts the value of A(1,1) (floor(p/2, floor(p/2)) spaces to % the right and down. floor function rounds any real number down to the % nearest integer."
% We do this to make the MURA symmetric about the centre.
A1 = circshift(A, floor(p/2) floor(p/2));
G1 = circshift(G, floor(p/2) floor(p/2));

% maybe we put it on the box camera rotated
%A1 = rot90(A1);
%G1 = rot90(G1);
% maybe we put it on box camera inside out
%A1 = fliplr(A1);
%G1 = fliplr(G1);

% imshow displays the minimum value as black, the maximum value as white,
% and values in between seem to come out white
% call mat2gray to get the gray shades
if figs == 1
    figure('Name','MURA Mask A'), imshow(mat2gray(A),'Init','fit');
    figure('Name','Decode Mask G'), imshow(mat2gray(G),'Init','fit');
    figure('Name','MURA Mask A1'), imshow(mat2gray(A1),'Init','fit');
    figure('Name','Decode Mask G1'), imshow(mat2gray(G1),'Init','fit');
end

% for DRDC experiments, mask is different
Xray_final.m

camera3_xray4.m  image from the xray source at DRDC Ottawa Aug 2010

clear
clc
close all

using decode from scaling4.m

requires makemask.m and decode.m

for 19x19 pinhole MURA in lead in front of LPX300 X-ray source

the x-ray machine produces a .TIF file which can be read directly

Scanned_001.tif is a 9944x4726 landscape grayscale tiff of an "F"
in row col notation it is a 4726x9944 array

these file names and variables need to match,

Im_name = 'Scanned_011.tif';

modify this path to find the saved image

I=imread(strcat('C:\Bill\Masters_Thesis\Recon Code\Data\',Im_name));
figure('Name',Im_name),imshow(I);

resize image to a more managable size, unless the resolution is needed
Ip = imresize(I, [4726/20 9944/20], 'nearest');  % scale to pixels
figure('Name', Im_name), imshow(Ip);
imwrite(Ip, 'Scaled Scanned_011.tif');

% convert to grayscale, unless already grayscale
%%GRAY = rgb2gray(I);
GRAY = I;
% code to crop to 1:1 aspect ratio
% %GRAY = imcrop(I, [5300, 0, 2399, 4000]);
% use if data requires padding with background levels
% %GRAY = padarray(GRAY, [0, 800], 52000);
% invert colours
GRAY = 65536 - GRAY;
% code to clear out specific artifact to left of signal
% Scanned_003.tif
%
% {
for i = 1000:3500
    for j = 5548:6750
        GRAY(i, j) = 13000;
        %GRAY(i, j) = GRAY(i, 8765);
    end
end
%
}
% for image Scanned_010.tif
%
for i = 1000:3800
    for j = 5548:6500
        GRAY(i,j) = 13000;
    end
end
%
% save it as a tif
%imwrite(GRAY,strcat('GRAY',Im_name));  % F Optical Gray
figure('Name',Im_name),imshow(GRAY);

% cast GRAY from uint8 to double
GRAY=cast(GRAY,'double');
% reduce image to a more manageable 800x800 landscape
%G64=imresize(GRAY,[800 800], 'bicubic');
% go for more pixels in arrays
%G64=imresize(GRAY,[800 1200], 'bicubic');
%figure('Name','G64 from camera'),imshow(mat2gray(G64),'Init','fit');

% decode taken from scaling4.m

% most of the variable names follow Accorsi’s nomenclature
% T is the target array, where we will create some simple shapes
% A is the MURA mask array
% R is the detector image array (projection of T through A onto R)
% G is the decoder array (derived from A)
% O is the decoded object array; similar to T

% define the MURA mask array A1 and decode array G1
p=19; %dimension of the square mask array, p is prime
pm=2; %pitch of a mask hole (etch them square) in mm
dm=p*pm; %width of the mask in mm
[A1,G1]=makemask(p,0); %generate standard MURA A1 and G1
% (both are centred)
figure('Name', 'A1'), imshow(mat2gray(A1),'Init','fit');

%mosaic the centred G1, to make G1M 2px2p
G1M=[G1,G1;G1,G1]; %2x2 mosaic
G1M=circshift(G1M,[floor(p/2) floor(p/2)]); % then centre the mosaic

% define the plane spacing, depends on the image
if Im_name == 'Scanned_001.tif'
a=60*10; % distance from T to A in mm
b=28*10; % distance from A to R in mm (generally a~ =~b)
elseif Im_name == 'Scanned_002.tif'

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a=50*10; % distance from T to A in mm
b=28*10; % distance from A to R in mm (generally a~=b)
elseif Im_name == 'Scanned_003.tif'
a=60*10; % distance from T to A in mm
b=11*10; % distance from A to R in mm (generally a~=b)
elseif Im_name == 'Scanned_004.tif'
a=60*10; % distance from T to A in mm
b=11*10; % distance from A to R in mm (generally a~=b)
elseif Im_name == 'Scanned_005.tif'
a=60*10; % distance from T to A in mm
b=28*10; % distance from A to R in mm (generally a~=b)
elseif Im_name == 'Scanned_006.tif'
a=66*10; % distance from T to A in mm
b=42*10; % distance from A to R in mm (generally a~=b)
elseif Im_name == 'Scanned_007.tif'
a=62*10; % distance from T to A in mm
b=42*10; % distance from A to R in mm (generally a~=b)
elseif Im_name == 'Scanned_008.tif'
a=66*10; % distance from T to A in mm
b=28*10; % distance from A to R in mm (generally a~=b)
elseif Im_name == 'Scanned_009.tif'
a=63*10; % distance from T to A in mm
b=24*10; % distance from A to R in mm (generally a~=b)
elseif Im_name == 'Scanned_010.tif'
    a=63*10; % distance from T to A in mm
    b=11*10; % distance from A to R in mm (generally a~b)
elseif Im_name == 'Scanned_011.tif'
    a=60*10; % distance from T to A in mm
    b=21*10; % distance from A to R in mm (generally a~b)
elseif Im_name == 'Scanned_012.tif'
    a=60*10; % distance from T to A in mm
    b=21*10; % distance from A to R in mm (generally a~b)
elseif Im_name == 'Scanned_013.tif'
    a=60*10; % distance from T to A in mm
    b=21*10; % distance from A to R in mm (generally a~b)
elseif Im_name == 'Scanned_014.tif'
    a=60*10; % distance from T to A in mm
    b=21*10; % distance from A to R in mm (generally a~b)
elseif Im_name == 'Scanned_015.tif'
    a=60*10; % distance from T to A in mm
    b=21*10; % distance from A to R in mm (generally a~b)
elseif Im_name == 'Scanned_016.tif'
    a=60*10; % distance from T to A in mm
    b=21*10; % distance from A to R in mm (generally a~b)
else
    disp('dimensions not defined, using default');
a=63*10;  % distance from T to A in mm
b=24*10;  % distance from A to R in mm (generally a~b)
end

z=a+b;   % sum of a and b, used in some calculations in mm

% magnification terms
mp=b/a;   % "magnification of the pinhole"
m=b/a + 1; % "magnification coefficient"

% detector plane dimensions
% assume the projected image is exactly centered in the detector array
dh=200;  % height of detector in mm (camera view area)
dw=421;  % width of detector in mm (ratio is 3:2, 4272 pix x 2848 pix)
       % (Accorsi uses dd, instead of dh,dw assuming that
       %  the detector is square)
dhn=4726; % number of pixels in dh
dwn=9944; % number of pixels in dw
pd=dh/dhn; % size of pixel in mm (assume they are square)
hd=z/a*dm; % projection of mask on detector in mm

% can we use a 2px2p G matrix; is 2*hd <= dh and dw?
if (2*hd > dh) || (2*hd > dw)

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disp('Note: the detector is not big enough for a 2px2p G decode');
disp(2*hd);
disp(dh);
disp(dw);
end

% how many pixels across does each mask hole illuminate?
% Accorsi pg 69-72 "Detector Sampling", & pg 120-123 "Sampling"
% and pg 191-195 "3D Imaging"
alpha=m*pm/pd; % need to handle alpha ~= 1, and not integer
hmn=round(p*alpha); % projection of mask in pixels

% Make an object, which we call a target T.
% given the mask size dm (in mm), and the distances a and b (in mm), we
% Calculate the field of view of the object plane.
% The projection of the mask on the detector (hd in mm, hmn in pixels)
% defines the area we can decode, so we project hd back to the
% target plane to calculate the field of view: fov=hd*a/b in mm.
% In more basic parameters:
fov=(1+a/b)*p*pm; % in mm
% For p=19, pm=2mm, a=500mm, b=280mm; fov=106mm.
% Note: an "F" of 10cmx6cm will fit in this fov
% 1mmx1mm grid is too coarse for the final Om array
t=100; % number of mm across

% Creating the detector image
% Accorsi pg 31-35
% note: Accorsi calls the object O; but we use T for the object and O for
% the reconstructed object.

% 1) project the object T onto the detector R
% scaling is -b/a (note it is inverted)
% call it Tp (for T prime, or T projected) Accorsi calls it O'
%htn= round(t*b/a/pd); %number pixels across Tp
%Tp=imresize(Tm, [htn htn],'nearest'); % scale Tm to pixels
%figure('Name', 'Tp in pixels'),imshow(mat2gray(Tp),'Init','fit');

% 2) project the mask A1 onto the detector R
% scaling is z/a (i.e. 1+b/a) (note it is not inverted)
% call it A1p (for A1 prime or A1 projected)
A1p=imresize(A1, [hmn hmn],'nearest'); % scale to pixels
figure('Name', 'A1p in pixels'),imshow(mat2gray(A1p),'Init','fit');

% 2b) project the decode G1M onto the detector R
% scaling is z/a (i.e. 1+b/a) (note it is not inverted)
% call it G1Mp
G1Mp=imresize(G1M, [2*hmn 2*hmn],'nearest'); % scale to pixels
% G1p = imresize(G1, [hmn hmn], 'nearest'); % scale to pixels
figure('Name', 'G1Mp in pixels'), imshow(mat2gray(G1Mp), 'Init', 'fit');
%figure('Name', 'G1p in pixels'), imshow(mat2gray(G1p), 'Init', 'fit');

% 3) the image formed on R is the convolution (sum of) Tp with Ap
%    a) "the projection is the sum of magnified mask patterns, each shifted
%        according to the location [of ro] of the point source casting the
%        shadow and weighted according to its irradiance" Accorsi pg 33
%    This is how mosaigc.m did the summation.
%    But by the commutative property of convolution, we could also do:
%    b) "the projection is the sum of equal pinhole images of the object,
%        shifted and weighted according to the various positions in the
%        mask" Accorsi pg 34
%    This second method will be simpler to code since the object T can be
%    a fairly complicated image of shapes and intensities, but the mask A
%    remains a simple array of 1's and 0's

% hmn is the number of pixels across projected mask, 263
% pick Rp(2*hmn 2*hmn) out of the middle of the G43 array
% Rp = G43(floor((300-2*hmn)/2):floor((300-2*hmn)/2)+2*hmn-1,...
% floor((400-2*hmn)/2):floor((400-2*hmn)/2)+2*hmn-1);

% centre of projected image (from pinhole image)
if Im_name == 'Scanned_001.tif'
    Img_cen = [2500, 6300]; % 1_1.jpg Scanned_001 centre
elseif Im_name == 'Scanned_003.tif'
    Img_cen = [2200, 7000]; % 3_1.jpg Scanned_003 centre
    Img_cen = [2200, 7300]; % 3_2,3,4,5.jpg Scanned_003 centre, padded
    Img_cen = [2300, 7300]; % 3_6.jpg Scanned_003 centre, padded
    Img_cen = [2120, 7280]; % 3_7.jpg Scanned_003 centre, padded
elseif Im_name == 'Scanned_009.tif'
    Img_cen = [2500, 6450]; % 9_1.jpg Scanned_009 centre
    Img_cen = [2473, 6521]; % 9_2.jpg Scanned_009 centre
    Img_cen = [2450, 6400]; % 9_3.jpg Scanned_009 centre
    Img_cen = [2400, 6400]; % 9_4.jpg Scanned_009 centre
    Img_cen = [2500, 6450]; % 9_5.jpg Scanned_009 centre
    Img_cen = [2700, 6450]; % 9_6.jpg Scanned_009 centre
    Img_cen = [2000, 6450]; % 9_7.jpg Scanned_009 centre
    Img_cen = [2500, 6450]; % 9_8.jpg Scanned_009 centre
    Img_cen = [1794, 6550]; % 9_9.jpg Scanned_009 centre
elseif Im_name == 'Scanned_010.tif'
    Img_cen = [2200, 7000]; % 10_1.jpg Scanned_010 centre
    Img_cen = [2300, 7100]; % 10_2.jpg Scanned_010 centre
    Img_cen = [2200, 7200]; % 10_3.jpg Scanned_010 centre
    Img_cen = [2150, 7200]; % 10_4.jpg Scanned_010 centre
    Img_cen = [2150, 7200]; % 10_4.jpg Scanned_010 centre
Img_cen = [2250, 7200]; % 10_5.jpg Scanned_010 centre

elseif Im_name == 'Scanned_011.tif'
    %Img_cen = [1974, 6280]; % 11_1,2,3.jpg Scanned_011 centre
    %Img_cen = [1854, 6220]; % 11_4.jpg Scanned_011 centre
    %Img_cen = [2000, 6330]; % 11_5.jpg Scanned_011 centre
    %Img_cen = [1974, 6280]; % 11_6.jpg Scanned_011 centre
    Img_cen = [1950, 6350]; % 11_7.jpg Scanned_011 centre

elseif Im_name == 'Scanned_015.tif'
    %Img_cen = [1950, 6350]; % 15_1.jpg Scanned_011 centre
    %Img_cen = [1890, 6330]; % 15_2.jpg Scanned_011 centre
    Img_cen = [1920, 6380]; % 15_3.jpg Scanned_011 centre

elseif Im_name == 'Scanned_016.tif'
    %Img_cen = [1920, 6380]; % 16_1.jpg Scanned_011 centre
    Img_cen = [1920, 6330]; % 16_2.jpg Scanned_011 centre

else
    Img_cen = [2500, 6450]; % .jpg Scanned centre
end

%Rp = GRAY(floor(Img_cen(1)-(hmn/2)):floor(Img_cen(1)-(hmn/2))+hmn-1,...
% floor(Img_cen(2)-(hmn/2)):floor(Img_cen(2)-(hmn/2))+hmn-1);
Rp = GRAY(floor(Img_cen(1)-(2*hmn/2)):floor(Img_cen(1)-(2*hmn/2))+2*hmn-1,...
floor(Img_cen(2)-(2*hmn/2)):floor(Img_cen(2)-(2*hmn/2))+2*hmn-1);
%Rp=GRAY(floor((800-hmn)/2):floor((800-hmn)/2)+hmn-1,...
floor((800-hmn)/2):floor((800-hmn)/2)+hmn-1);  
what if we are off registration by 10 pixels in up/dwn or r/l  
they are a little different, but not better  
Rp=G64(floor((400-2*hmn)/2)+10:floor((400-2*hmn)/2)+2*hmn-1+10,...  
floor((600-2*hmn)/2+10):floor((600-2*hmn)/2)+2*hmn-1+10);  
figure('Name','Rp pxp from DRDC X-ray,'),...  
imshow(mat2gray(Rp),'Init','fit');  
imwrite(mat2gray(Rp),'DRDC X-ray Rp.tif');  
figure('Name','Rp'),meshc(Rp)  
%decode  
%{  
O=decode(hmn,G1p,Rp);  
figure('Name','O from DRDC X-ray, using G1p pxp'),...  
imshow(mat2gray(O),'Init','fit');  
imwrite(mat2gray(O),'cameraO.tif');  
figure('Name','O'),meshc(O)  
}%  
OM=decode(2*hmn,G1Mp,Rp);  
figure('Name','OM from DRDC X-ray, using G1Mp 2px2p'),...  
imshow(mat2gray(OM),'Init','fit');  
imwrite(mat2gray(OM),'DRDC X-ray OM.tif');  
%keep the middle pxp (hmnxhmn)and throw out aliases
fhmnd2 = floor(hmn/2);

O = O(fhmnd2:fhmnd2+hmn-1,fhmnd2:fhmnd2+hmn-1);

% invert image due to pinholes
O = rot90(rot90(O));

% scale O back from detector plane in pixels to Tm plane in mm
%(wanted to call it Om, but that conflicts with OM; so call it Ot)
%Ot = imresize(O, [t4 t4], 'nearest'); % back to units of 0.25mm
%Ot = imresize(O, [t4 t4], 'bilinear'); % bilinear looks best
%Ot = imresize(O, [t4 t4], 'bicubic');
figure('Name','O from DRDC X-ray using G1p pxp'),...
    imshow(mat2gray(O), 'Init', 'fit');
%imwrite(mat2gray(O), 'cameraO.tif');
save 'DRDC X-ray'