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Coherent Scatter and Grid-Based Phase Imaging for Materials Discrimination

by

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Abstract.

Traditional X-Ray images provide a meaningful way to differentiate between materials with differing attenuation coefficients. The low contrast provided by this method for materials of low electron density or similar attenuation is a limitation of traditional radiography. Two alternatives have presented themselves as viable candidates for widening the viability of X-Ray imaging, Coherent scatter, and phase contrast imaging provide a means to distinguish between objects of both low absorption and similar attenuation.

An imaging system was created to combine both modalities into a single enclosure. The major limitation of phase imaging, the requirement of high spatial coherence, was mitigated with an alternative approach that utilizes a single coarse mesh. This approach significantly relaxes the spot size requirements. This technique was integrated with coherent scatter to utilize both the direct beam and the diffraction from a sample to provide a more detailed direct image, and phase information, as well as the materials discrimination provided by coherent scatter.
Chapter 1. Introduction.

X-Ray imaging has an important role in everything from security screening to mammography. Unfortunately, conventional X-Ray radiography has limitations in its use. Attenuation contrast in mammography is very limited. Hazardous chemicals can be hidden from direct absorption images, appearing to be water. These limitations have led to the development of various methods to expand the use of this already widely implemented imaging system. Two of these methods, phase contrast imaging and coherent scatter imaging, have shown potential in detecting materials and tissue anomalies that conventional techniques might miss.

Propagation-based phase contrast imaging uses a simple direct beam image to extract some phase information. The detector is placed far from the sample to allow for interference between refracted X-Rays and the un-deflected beam. This technique originally used highly coherent synchrotron radiation sources or tabletop microfocus sources that are low power. Both are unsuitable for widespread use in medical or security screening. This lead to a study of grating-based techniques, which utilized the same differences in refractive index but with gratings to recover the phase information. The disadvantage of this method is it requires a high-quality grating of small period. The alignment requires high stability and precision. To overcome the issues with these methods an alternative technique was used, based on the paper by Bennett et al[1]. This method uses a single conventional grid which was later replaced with a coarse mesh. It allows for easy alignment and far less stringent requirements on the source.

Instead of phase contrast, coherent scatter provides an alternative method to detect various materials based on the intermolecular spacing. Differences in intermolecular spacing lead
to differing angles of coherent scatter. This scatter centered around the angle can be windowed and, given a large enough difference, discriminated. Since this method utilizes X-Rays scattered from the direct beam, it can be used in conjunction with a propagation-based phase imaging system.

A system was developed to utilize coherent scatter simultaneously with a grid-based phase imaging technique. The results and design are discussed in this thesis. Chapter 2 gives an overview of the necessary theoretical background. Chapter 3 explains the experimental setup and what was done to ensure the methods would work together. Chapter 4 shows the results of this system.
Chapter 2. Theoretical Background.
2.0 Traditional X-ray Imaging

Conventional X-Ray imaging stems from the difference in attenuation coefficients. The linear attenuation coefficient, $\mu$, is dependent on the given material and the energy of the incoming X-Rays. A simplified example of a typical X-Ray image is shown in Figure 2-0. $I_0$ is the incident power per area, $I_1$ is the resulting power per area through the material with attenuation coefficient $\mu_1$ and thickness $d$. $I_2$ is the resulting power per area after $\mu_1$ and the same material with thickness $d-x$ and $\mu_2$ with thickness $x$. These intensities are

\[ I_1 = I_0 e^{-\mu_1 d}, \]
\[ I_2 = I_0 e^{-\mu_1 (d-x)} e^{-\mu_2 x} = I_1 e^{-x \Delta \mu}, \]

where $\Delta \mu = \mu_2 - \mu_1$.

Contrast is then defined as

\[ C = \frac{I_1 - I_2}{I_1} = 1 - e^{-x \Delta \mu} \approx x \Delta \mu. \text{ When } x \Delta \mu \ll 1 \]

This method of imaging has a wide array of applications and is the traditional method of X-Ray radiography, however, it is not without its limitations. Many materials of interest have similar linear attenuation coefficients making discrimination via this method extremely difficult.
2.0.1 Index of Refraction.

The index of refraction, \( n \), of a material is

\[
\frac{\epsilon}{\epsilon_0} = 1 - \delta - i\beta. \tag{2-4}
\]

The imaginary part of the index, \( \beta \), is the absorption term, proportional to the cross section for absorption. The real part of the index, \( \delta \), is proportional to the cross section for forward coherent scatter.

2.1 Coherent Scatter

Every volume element of a sample emits coherent scatter. Bragg's law relates the angle of diffraction to the wavelength \( \lambda \), and interplanar spacing \( d \),

\[
2d \sin \theta = n\lambda. \tag{2-5}
\]

Where \( n \) is a positive integer. For amorphous materials, the wider range of intermolecular spacing results in broader diffraction peaks. A schematic of a typical coherent scatter measurement is given in Figure 2-1. X-Rays are sent through an aperture, usually a pinhole or a rectangular slit. When they hit the target, diffraction occurs and a cone of coherent scatter
propagates with angle $2\theta$. Coherent scatter angles range from $0^\circ$ to $180^\circ$ depending on the energy of the X-rays.

Figure 2-1 Schematic of coherent scatter.

The ability to distinguish small differences in coherent scatter angle is dependent on both the size of the aperture and the distance of propagation to the detector.

2.1.1 Coherent Scatter Imaging.

Using the variation of intermolecular spacing for various chemical compounds we can use the coherent scattering angle to selectively search for specific compounds of interest. For example, using the Mo Ka photon energy of 17.5 KeV, ethanol and water are easily separated. The sample size is limited by the size of the aperture, and a tradeoff between superior discrimination and larger samples must be considered. This tradeoff can be negated slightly by taking scanned images, a process that will be outlined in section 3.5.
2.2 Phase Contrast Imaging

Conventional X-Ray imaging relies on absorption or scatter to create the variations in intensity needed to form an image. The variations in absorption stem from the imaginary part of the index of refraction ($\beta$), and can be very insignificant for soft tissue. The real part of the index of refraction ($\delta$), is responsible for phase differences, which can offer contrast many orders of magnitude greater than the differences in absorption. Assuming propagation along the z axis, the total phase can be approximated as the integral along a straight path through the sample, and can be represented as,

$$
\phi(x, y) = -k \int \delta(x, y, z) dz,
$$

(2-6)

where $k = 2\pi/\lambda$ is the wave number and $\lambda$ is the wavelength. For an X-ray energy of 10 to 100 KeV, $\delta$ ranges from $10^{-6}$ to $10^{-8}$. This provides one with a 1000-fold enhancement over $\beta$, which ranges from $10^{-9}$ to $10^{-11}$. Given that absorption contrast stems from the integral over $\beta$, this 1000-fold enhancement leads to the development of phase contrast imaging. Phase retrieval techniques in the X-ray regime are far more difficult than their visible light counterparts. Small angles of refraction and the extreme difficulty involved in creating optics led to greater challenge in exploiting this source of contrast. Despite this difficulty, a few techniques have been successfully implemented.
2.3 Grid-based imaging.

In a relatively recent approach to phase-based imaging, a grid-based technique was proposed by Bennett et al [1]. This method employed a single grid and minimal alignment. This method was a response to help overcome some limitations of grating based techniques. Grating-based methods required high quality gratings, careful alignment, and multiple images. Instead of the 1D grid, the conventional grating was replaced with a 2D wire mesh. This provides an even more accessible mask and still produces meaningful phase contrast [4].

When an X Ray passes through an object a small-angle refraction occurs due to differences in the

\[ \text{Figure 2-2 A grid-based imaging setup. [4]} \]
refractive index, resulting in deformation of the propagated wave. This deformation distorts the image of the grid. Due to this deflection, the X-Rays strike the detector at a position with displacement $\Delta X$, from where it would have struck with no objection in place. This deflection is

$$\Delta X = d_{eff} \theta(x, y),$$

(2-7)

where $d_{eff}$ is the effective distance propagated by a deflected X-Ray [2]. $\theta(x, y)$ is the vector angle of deflection and is approximately

$$\theta(x, y) = \frac{1}{k} \nabla_{\perp} \phi(x, y)$$

(2-8)

where $\nabla_{\perp}$ denotes the gradient in the phase transverse to the $z$ axis, and the phase $\phi(x, y)$ is given by equation 2-6. The mesh introduces a high intensity contrast to help determine the produced deflection. This is done by taking two images, the first with the object and the second without. The image with the object will cause the mesh edges to shift, and by comparison to the image without an object, the deflection can be inferred.

The image processing required to retrieve $\Delta X$ is made simple with the use of periodic meshes and Fourier transform-based processing.
For a one dimensional periodic mesh, the transmissivity can be expressed as [2]

\[ G(X) = \sum_{n=-\infty}^{\infty} c_n \exp(i\mathbf{g}_{n,m} \cdot \mathbf{X}), \]  

(2-9)

where \( \mathbf{X} = (x, y) \), \( c_n \) is a complex constant, \( \mathbf{g}_{n,m} = 2\pi(\mathbf{\hat{g}}_1 \frac{n}{p_1} + \mathbf{\hat{g}}_2 \frac{m}{p_2}) \), and \( \mathbf{\hat{g}}_1 \) and \( \mathbf{\hat{g}}_2 \) are unit vectors perpendicular to the mesh lines, \( p_1 \) and \( p_2 \) are the periods, and \( n \) and \( m \) are integers.
Without the presence of an object, the mesh image produces delta-function-like spikes when Fourier transformed. With an object, the rays are deflected, producing a distorted image. This displacement $\Delta x$ is given by

$$\Delta x = \frac{d_{so}}{d_{sc}} d_{GC} \theta.$$  

The intensity immediately after the mesh is the product of the object transmissivity, $I_0(x)$, and the mesh transmissivity, $G(x)$. The intensity measured at the detector, is a deformation of the intensity immediately after the mesh by $\Delta X$. This leads to the differential phase contrast image to be expressed as

$$\Psi_{m,n} = \frac{d_{so}}{d_{sc}} d_{GC} g_{m,n} \cdot \theta(x),$$  

which is proportional to the directional derivative of the phase in the direction of the grids, $g_{n,m}$. Scattering of incident rays introduces an additional scattering amplitude to each harmonic (Bennett et al [1]). An inverse Fourier transform of a single harmonic yields

$$I_{m,n} = I_0(x) S_{m,n}(x) \exp \left[ i \Psi_{m,n}(x) \right],$$  

where $S_{m,n}(x)$ is the scattering amplitude with $S_{0,0}(x) = 1$. A flow diagram of the image processing is shown in Figure 2-3.
The Fourier spectra of the raw images were obtained with a 2D Fast Fourier transform (FFT) and a series of mesh harmonics were produced, as shown in Figure 2-3. The center peak (zeroth harmonic) contains information only about the intensity $I_0(x)$ and absorption. Higher order peaks contain absorption, scattering and phase information. The individual harmonics were isolated using a 2D Blackman windowing function, shifted to the center of the Fourier domain then transformed with an inverse 2D FFT. Previous discussion treated the mesh harmonics as delta functions, however, the mesh produces Fourier harmonics with some spatial bandwidth. This was corrected with by normalizing the images with objects by the bare mesh images. This produces normalized harmonic images, $\tilde{I}_{m,n}(x)$, expressed as,

$$I_{m,n}(x) \approx \tilde{I}_{m,n}(x) = \frac{I_{m,n,meas}(x)}{I_{m,n,BG}(x)} \quad (2-12)$$

where $I_{m,n,meas}(x)$ is the $(m,n)^{th}$ harmonic of the image with both the object and mesh in place. $I_{m,n,BG}(x)$ is the same harmonic from the mesh-only image. Use of these normalized harmonics in Equation 2-11 yields,

$$\tilde{I}_{0,0}(x) \approx I_0(x) \quad (2-13)$$

and

$$I_{diff_{m,n}}(x) = \frac{\tilde{I}_{m,n}(x)}{\tilde{I}_{0,0}(x)} = S_{m,n}(x) \exp \left[ i \Psi_{m,n}(x) \right]. \quad (2-14)$$

From this, the scattering amplitude and differential phase contrast (DPC) images can be constructed as

$$S_{m,n}(x) = |I_{diff_{m,n}}(x)|, \quad (2-15)$$

and
\[
\Psi_{m,n}(x) = \text{arg}\left[ I_{diff,m,n}(x) \right].
\] (2-16)

The DPC image \( \Psi_{m,n} \) shows the phase contrast most strongly along the direction of the derivative. In order to ensure this processing can perform there are some specific criteria that need to be satisfied first.

The series of harmonics produced by the Fourier transformation of the images are at multiples of the magnified grid frequency.

\[
g = \frac{2\pi d_{SG}}{p d_{SC}}
\] (2-17)

To acquire images from the harmonic spectra, it is important that the Fourier harmonics \( \frac{2\pi}{p} \) are separated by more than the spatial bandwidth of the object, \( \frac{2\pi}{MS} \), where \( S \) is the x-ray source spot size and \( M \) is the magnification factor \( M = \frac{d_{GC}}{d_{SC}} \).

The source size results in blurring of the image. This blurring acts to destroy any information above a certain spatial frequency. This creates a low pass cutoff proportional to \( 1/S \), which leads to the criterion, [1].

\[
C_1 = \frac{S d_{GC}}{p d_{SC}} \ll 1.
\] (2-18)

This criterion ensures adequately separated harmonics that are not destroyed by the source blur.
The next issue is to ensure adequate intensity at the harmonics of interest. Ideally the object should be placed close to the source to ensure maximum exposure, leading to the second criterion,

$$C_2 = \frac{S d_{OC} d_{SG}}{P d_{SO} d_{SC}} > 1.$$  \hspace{1cm} (2-19)

In our work, it was found that this criterion can be relaxed slightly with more aggressive processing.

2.3.1 Grid-based imaging motivation.

A potential demonstration of the usefulness of this technique for materials analysis was performed by Danielle Hayden in another enclosure [2]. A Microfocus brand x-ray source with a W anode and a 100 μm focal spot was operated at 25 KVP and 0.4 mA. A 100 μm x 100 μm mesh was used and placed 21.5 cm from the source. The samples were placed 17 cm from the source and the camera was placed 17 cm from the sample.

Figure 2-5 Images of vials filled with ethanol. Left to right: Raw Image, processed attenuation image from the zeroth harmonic, the scatter amplitude from the (1,0) harmonic, and last the phase from that harmonic. [2]
Line plots of the intensity were taken from the center of the top of the ethanol filled vials and are shown in Figure 4-5. To discriminate different materials from water in a meaningful way the ratio of the absorption edge height to the scatter edge height was computed, these values were then normalized to the same ratio of the water sample. This ratio is independent of thickness and could be used to detect a chemical, regardless of container size. The results of this ratio with normalization to water are shown in Figure 4-6.
Materials with a significant deviation from unity could potentially be differentiated from water. These results provided motivation to attempt to incorporate this technique into an already working coherent scatter enclosure.
Chapter 3
3.1 X-Ray source

Figure 3-1 Schematic of the experimental setup.

The source used in these experiments was a molybdenum anode fixed tube source from Oxford Instruments. The maximum voltage is 50 kV and the maximum current is 1 mA. The Kα peak for molybdenum is at 17.5 keV, and the Kβ peak is at 19.6 keV. Kβ is suppressed using a zirconium filter. A schematic of the internal workings of a fixed anode tube is shown below on the left of Figure 3.1, and a picture of the specific x-ray source used is on the right. The current will cause electrons to escape the heated filament. The potential difference between the filament and anode causes the freed electrons to accelerate toward the anode. Upon impact, X Rays are produced with bremsstrahlung and characteristic radiation, where the
wavelength emitted is determined by the elemental composition of the metal target on the anode. The maximum energies of the bremsstrahlung X Rays are determined by the maximum voltage applied to the tube. The X Rays then leave the vacuum-sealed chamber through a window.

3.2 Image Plates.

Image plates are reusable sheets made from a phosphorescent material. When these plates are exposed to X Rays, they excite electrons into a metastable trap state. The plates are then exposed to their image reader. This reader shines red light onto the plate, with enough energy to excite the electrons out of their metastable state. These electrons then fall back down to their ground state and emit blue light. A photomultiplier tube detects the blue light, and an image is then created. The intensity of blue light is a direct representation of the intensity of its X-Ray exposure.

The two plates used in this experiment are Fuji Imaging Plates Type BAS-III, with dimensions 20 cm × 25 cm. The image is displayed using the Image Gauge software, which gives output in terms of Photo-Stimulated Luminescence (PSL) units.

3.2.1 Digital Detectors.

Digital detectors give real time read out, as well as improved image quality. These detectors use thick high density materials for a direct conversion from X Rays to electric charges. Alternatively, indirect detection is possible via a phosphor, sometimes deposited directly on the detector. In either case the charge is created from photoelectric absorption and is shifted out, and
converted to voltage. This voltage is then converted to a number via an analog-to-digital converter. These detectors can have high sensitivity and can be used to reduce noise of an image or take better images with less exposure time. Unfortunately, digital detectors suffer from high production costs and relatively small active area. A 1200×1600 pixel Remote RadEye HR CCD camera manufactured by Teledyne with a pixel size of 22 μm was used.

Both Image plates and digital detectors will be used in this paper.

3.3 Materials

The need to have materials selectivity plays an important role in both alignment of the shielding, and processing of the image. Some tests done in this paper are dual phantom exposures. What this means is we exposed two different materials that we have interest in discriminating from one another, then, use phase or coherent scatter to tell the difference.

For this paper, there are two groups that are chosen for discrimination. The first group is a trio of water, peroxide, and ethanol. These materials were chosen to simulate interest in determining water from similar flammable liquids for security screening. The second group is a larger selection of easily flammable solids or other hazardous liquids, such as sawdust or acetone. These groups were chosen to be a proof of concept for a larger list of more dangerous chemicals.

3.4 Experimental setup

The basic experimental setup is shown in figure 3-1. The first set of shielding is used to create a slit for the coherent scattering image. This image is then captured by the image plate aligned at the desired angle. The direct beam passes though the wire mesh needed for the phase
imaging then into a CCD camera. This system is designed for simultaneous phase and coherent scatter measurements.

3.5 Alignment

The alignment of the optical system has two important elements to take into consideration, the phase imaging criteria outlined by Section 2.3 and the desired angle of coherent scatter.

The phase imaging set up is not optimal for phase imaging, however, its extended nature allows for a wider array of angular discrimination for coherent scatter.

After the initial distances were all chosen the next element to align was the image plate to the desired angle. This angle was variable, depending on the materials of interest. The first step was to align the source to the slit. The slit was made up of large sheets of lead and was placed along a long rail. This rail served as a rough alignment. Further down the rail the high and low angle shields were placed on micrometers for easy adjustment. Behind them the image plate was placed on a platform. This platform was attached to actuators for remote movement while the enclosure was active. While a ratio of distances could be used to find the actual angle, the peaks were much easier to isolate using a progression of images taken after slightly closing the high and low angle shields down on the desired angle. The images were all done with a pinhole placed at the slit. This pinhole produces narrow diffraction rings, which gave a stronger indication of the desired angle than the broader rings produced by a larger aperture.
After the desired angle was isolated the system was aligned and ready for exposures. The pinhole was then removed, allowing for larger samples.

A third element to consider is the grid for phase imaging. While it is helpful to have the grid aligned so that the wires are parallel to the pixels, a precise alignment is unnecessary. A rotated or tilted grid will lead to rotated harmonics in Fourier space, however if one can effectively window these harmonics, the rotation has only a small effect. Awkwardly rotated grids would lead to some lost resolution, and careful alignment was employed to keep the mesh square to the pixels.
3.6 Experimental Procedure

After alignment of the digital camera and the image plate, a single exposure yields two images. The image plate for coherent scatter begins to collect exposure the moment X-rays are turned on. The digital camera for phase imaging must be activated via software.

A simple exposure was possible by turning on the X-rays to expose the image plate. While the plate was being exposed several images could be taken with the CCD camera. The direct beam provided the information necessary for the phase processing, while the coherent scatter was collected.

Due to the need for a 5mm slit to restrict the coherent scatter angle, images produced are limited in size, as well as forcing a limited sample size. For our small tubes of various chemicals this did not prove to be an issue. However, for larger samples a scanning system was implemented for coherent scatter, and digital panoramic stitching was implemented for the CCD camera.

Scanning for coherent scatter required the phantom and image plate to be moved using actuators connected to the Newport Universal Motion Controller/Driver, Model ESP300. These scans also required that the phantom and image plate be moved at velocities in the ratio

\[
\frac{v_{\text{plate}}}{v_{\text{phantom}}} = M, \quad (3-1)
\]

where \(v_{\text{plate}}\) is the velocity of the plate, \(v_{\text{phantom}}\) is the velocity of the phantom, and \(M\) is the magnification.

The absolute velocities depended on the physical limits of the actuators used coupled with the magnification. Given a maximum plate velocity, a larger magnification for the same actuators would yield a slower phantom velocity. Often the velocity of the phantom depended on
a desired exposure as well. This would yield a time, and using $v = \frac{d}{T}$ would give a desired velocity, where $d$ is the thickness of the sample, and $T$ is the desired time.

For the digital camera with a small physical exposure window, scanning a continuous image is not an option, as this would result in blurring of the image. A different approach was taken for this method. The sample and grid were moved specific distances, then a new exposure was taken. A sample with continuous gridlines was tested to test stitching.

Figure 3-4 A panoramically stitched resolution phantom. The resolution phantom was imaged in 5 rectangular sections and stitched horizontally.
Figure 3-4 shows the result of a panoramically stitched resolution phantom. It was produced from five images crudely stitched together in MATLAB. This stitching was done by manually matching the overlapping pixels and extending the matrix.

![Graph showing a horizontal profile across the stitched phantom.](image)

A profile though the image is shown in Figure 3-5. The profile shows some light spiking at the stitch points, approximately every 170 to 200 pixels. This is due to pixels not linking up properly. A more sophisticated method of stitching might produce superior results.

Chapter 4. Results of combined modalities
4.1 Coherent Scatter Discrimination

The coherent scatter images produced by this setup provided a wide range of discrimination between chemicals as well as providing high contrast images of graphite and fat for the mammography simulation. The ability to differentiate materials depended on how different the

Figure 4-1 Coherent scatter rings A: empty tube, B: water, C: peroxide, D: ethanol, E: flour, F: citric acid, G: sugar, H: Methanol fuel, I: acetone
characteristic angle was. The first step was to collect the cones of coherent scatter for each desired substance, shown in Figure 4.1.

Once the cones were acquired the images were radially integrated using the software FIT2D. These plots provided us with an easy, quantitative, means to check characteristic angles. These integrations were background subtracted to help ensure equal intensities. Background was defined as a single number chosen from the original integrations in the area shadowed by the beam stop. Additionally, the raw tube was subtracted from every plot. This background and tube data subtraction process is shown in Figure 4-2. The results of these modifications for the remaining samples were compared to water and shown in Figure 4-3. The x axis gives angle, while the y provides intensity.

**Figure 4-2** top to bottom: unprocessed radial integrations for an empty tube and water filled tube, background subtracted integrations, tube and background subtracted water.
Figure 4-3 Resulting radial Integrations, compared to water for discrimination potential.
Once the characteristic angles were determined, it was easy to see what materials could be discriminated. For example, a radial integration of peroxide yielded a characteristic angle very similar to water, as shown in figure 4-3A. After the system was aligned to that angle, two vials were placed for exposure, one with peroxide and one with water. Comparing this to an image taken with two vials of water, we had a difficult time attempting to isolate the existence of peroxide in the exposure. This lead to the conclusion that the peroxide rings were too much alike water to allow for good discrimination based on coherent scatter alone. Giving a contrast, defined as,

\[ C = \frac{I_S - I_B}{I_B} \]  

Of 1.19 ± .2. Where \( I_S \) is the intensity of the signal, in this case ethanol, and \( I_B \) is the signal of the background, water.

One of the more successful chemicals was ethanol. With a window placed at 10 degrees it could easily be separated from water. Two vials were placed in front of the slit. Water was chosen as the background. An initial image was taken, with one vial filled with ethanol and the other filled with water. The angular shielding was aligned to the 10° peak of ethanol with a

Figure 4-4 Left: Image from two vials of water (one above, one below). Right: two vials, top filled with ethanol, bottom with water.
high angle shield around 13° and a low angle shield of 7°. Then a second image was taken with two water filled vials. The vial with ethanol is clearly visible, as seen in figure 4-2. The ethanol gives a signal-to-background ratio of 2.18 ± .23 consistent with Figure 4-3 B.

Table sugar was also chosen as a test material. The 8° peak provided to be of interest, as it was unknown if the scatter from water would completely eclipse the peak. To test this the angular shielding was aligned to the 8° peak of sugar with a high angle shield around 10° and a low angle shield of 6°. Then a second image was taken with two water filled vials. The speckled nature of the sugar image made it clear that something was present other than the water, however the intensity of this was barely above background. A finer grain of sugar would not produce these speckles and may be lost in the scatter band visible in Figure 4-5 B. The contrast of the sample was

![Figure 4-5 Left: two vials, top filled with sugar, bottom with water. Right: two vials of water.](image-url)
attempted using the averages taken over a rectangle 100 pixels by 200 pixels. This gave a contrast of $0.715 \pm 0.61$. This number is consistent with the images and shows that the texture of the image won’t allow for straight contrast. However the standard deviation for sugar is almost three times that of water, which itself might be a signal.

4.2 Phase Retrieval

The direct beam from these experiments passed onto our digital detector and was processed by the method outlined in section 2-3. The first step was to ensure that at our given geometry Bennet’s criteria are satisfied. The original configuration was optimized for coherent scatter and resulted in a large $d_{SO}$. This yielded us a $C_2$, the criteria which ensured adequate intensity at the harmonics of interest, of $0.54$, far from a desired value greater than one. After the source was moved closer to the object, the final values of $C_1$ and $C_2$ ended up as $0.29$ and $1.46$ respectfully. A two-dimensional woven stainless steel wire mesh 100 μm pitch, normally used for liquid

![Figure 4-6 The Fourier transformation of an image with a grid. The object is a cluster of glass beads, approximately 2mm in diameter. The Fourier transform was obtained with a 2D Fast Fourier transform (FFT). This leads to a series of mesh harmonics. These harmonics will later be windowed and processed.](image)
filtration, was placed 53 cm from the source. The object was placed 25 cm from the source. The camera, a 1200×1600 pixel Remote RadEye HR CCD camera manufactured by Teledyne with a pixel size of 22 μm, was placed at 20 cm from the grid.

This geometry proved to be adequate to acquire some enhancement from our phase processing but was not ideal in the long run. A lead slit in the setup created an extremely strong edge. This served to wash out the meaningful but less intense edge effects of the glass beads, as shown in figure 4-7. This effect could be somewhat counteracted by cropping, with the result shown in Figure 4-8. Without the panoramic stitching the sample size was limited. Additionally, overall intensity in the Fourier transform was low. These drawbacks left limited results, and a need to modify the

![Figure 4-7. The DPC image of a cluster of glass beads. The large speckled areas above and below are lead shielding.](image)

![Figure 4-8. Left: The absolute image extracted from the zeroth harmonic. Right: DPC image of a cluster of glass beads.](image)
enclosure, or improve processing in some way.

4.3 Combined results

While the original goal to set up a dual modality enclosure capable of preforming both techniques simultaneously, further optimization would be required. Results of the two modalities when done properly show that it is still an effort worth making. The phase contrast edge height ratios provide a 50% -150% increase over water, except for ethanol and citric acid [2]. Coherent scatter allows us to see ethanol clearly as well as gives us the opportunity to window out unique peaks to search for specific chemicals. Coherent scatter also has the potential to show weaker peaks, as shown in figure 4-5.

Chapter 6. Conclusion

An optical system capable of simultaneous phase contrast imaging as well as coherent scattering imaging was developed. The goal was to use single exposures to take two images.

The grid-based phase contrast imaging technique yielded phase, scatter and absorption information of a direct beam exposure, work done showed that in the current system while un-optimal for this type of imaging, phase could be seen in a cluster of glass beads, as shown in figure 4-8 B. Additionally, this imaging technique showed good discrimination between a variety
of powder materials as well as peroxide, water, and ethanol. Because the absorption DPC and scattering can all be acquired from a single shot, the technique is promising for future use.

The coherent scatter images provided meaningful materials discrimination. The system produced discrimination for ethanol compared to water. It was also demonstrated that a large array of samples show significant angular discrimination as compared to the large scatter produced by water. This provides an opportunity for high contrast scans when two samples are imaged next to the other.

Future work in this system should include experimenting with pushing the source closer to the slit. This displacement would greatly increase the mesh-based phase techniques ability to enhance direct beam exposures at the cost of some geometric blur. An optional balance could be found. Additionally, shifting of the grid with multiple images has the potential to improve contrast significantly.
Chapter 7 references.


