

Radiographic Modelling for NDE of Subsea Pipelines

Misty I. Haith^{a,*}, Uwe Ewert^b, Stefan Hohendorf^b, Carsten Bellon^b, Andreas Deresch^b, Peter Huthwaite^a, Michael J.S. Lowe^a, Uwe Zscherpel^b

^aImperial College, Department of Mechanical Engineering, London, United Kingdom

^bBAM Federal Institute for Materials Research and Testing, Berlin, Germany

Abstract

This work presents an investigation of the accuracy of a radiographic simulation model applied to subsea pipeline inspections. Experimental measurements of a sample in a water tank are used to develop a set of calibrated simulation parameters for the modelling software aRTist. Image quality parameters such as signal-to-noise ratio, contrast and basic spatial resolution are compared with the aim of matching simulated values to experimental results. With this method signal-to-noise ratio was successfully matched while differences were still found in contrast-to-noise ratio comparisons. This means that measurements depending on absolute intensity are not accurate enough, however wall thickness measurements in tangential images, which are not based on absolute intensity, were found to produce similar results in simulated and experimental cases. The differences in contrast and intensity are thought to be due to detector backscatter and additional scatter from out-of-setup objects within the exposure bay, due to a lack of source collimation. These would affect the experimental results but were not included in the simulated setup. This was investigated by including different proportions of peripheral water and other objects in the modelled setup and examining the effect on image quality parameters. Results show this additional scatter has a significant impact on the radiograph, particularly on image contrast, and is therefore the likely cause of differences between experimental and simulated images. This implies that it will be very difficult to completely match simulated to experimental results, as including all possible scattering objects in the model would be very complex. An improvement could be made by using real subsea data to estimate this additional scattering, which could then be used to calibrate the model. However there would still be significant uncertainty in the ability of the model to accurately produce realistic intensity and contrast.

Keywords: Digital radiography, Modelling validation, Subsea pipeline inspection, Tangential radiography

1. Introduction

Accurate and reliable detection of subsea pipeline corrosion is required in order to verify the integrity of the pipeline. Often a pipeline can be inspected internally by in-line inspection, however where this cannot be performed external examination must be used. Radiography holds a significant advantage over many other NDT methods in that it does not require surface preparation or insulation removal; in addition it is less sensitive to naturally grown external deposits on the pipe surface than other inspection techniques. Subsea radiography often exploits modern digital detectors, and thus has great potential to benefit from the advantages these offer. Identifying the most suitable imaging setups is crucial, both for cost effectiveness and reliable detection and sizing of defects. Figure 1 shows established radiographic methods for pipeline corrosion imaging, as described in the standards (EN 16407 [1, 2]).

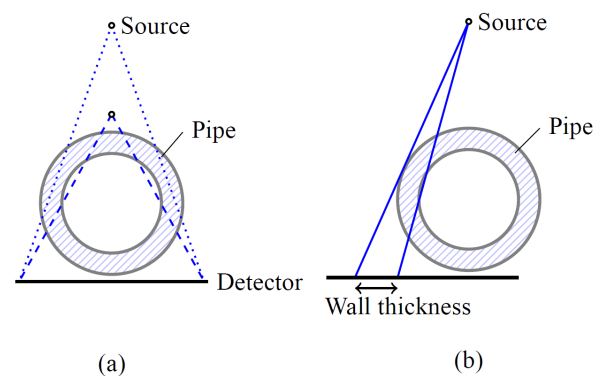


Figure 1: Different methods of radiographic imaging of pipelines for corrosion mapping. (a): Double Wall (EN 16407: part 2 [2]); for Double Wall Single Image the source is placed close to the upper pipe wall, shown as dashed lines, while for Double Wall Double Image, dotted lines, the source is set further back, (b): Tangential (EN 16407: part 1 [1])

The method currently used for practical subsea imaging is Double Wall Single Image (DWSI), shown in Fig 1(a) with dashed lines. In this method the source and detector are placed close to each side of the pipe. As the upper

*Corresponding author: misty.haith09@imperial.ac.uk
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wall is very close to the source any features are magnified across the whole detector, meaning that this method effectively just images the lower pipe wall, close to the detector. Corrosion is visible from the intensity change it causes, as more radiation reaches the detector in areas where the wall is thinner. The DWSI method is used in the current hardware as the relatively short source-to-detector distance reduces the highly attenuating and scattering effects of the water. A variant of double wall imaging is Double Wall Double Image (DWDI), also shown in Fig 1(a) with dotted lines, in which the source is set back from the pipe. In this case the upper wall is not magnified to the same extent, and both upper and lower pipe walls can be clearly imaged in a single exposure. In tangential imaging, Fig 1(b), the source is set back as in DWDI but the detector is offset such that the edge of the pipe is visible in the radiograph. Wall thickness at the tangential position can be measured on the resulting radiograph directly, as the inner and outer wall positions are points of major intensity change and therefore identifiable in a profile across the image.

Standards for radiographic imaging of pipeline corrosion do not currently cover underwater conditions, and as water is highly scattering it can have a significant impact on radiographic image quality: thus it is vital to investigate inspection configurations with water. Subsea radiography is extremely costly, and extensive experimental data for research is difficult to obtain. Simulations are significantly more affordable and accessible than subsea experimental data, and are able to model a wide range of underwater radiographic setups. However, simulation models have not been validated as accurate for underwater imaging, and before conclusions can be drawn from simulation results they must be shown to be comparable to experimental results. In this work we aim to investigate the ability to accurately simulate underwater radiography. To do this we obtain a set of experimental radiographs of a well characterised pipe in water and simulate the same setups in the simulation tool aRTist¹. The experimental data is used to adjust aRTist parameters with the aim of matching simulated radiographs to experimental ones. Some background radiographic theory is explained in the next section, followed by experimental and simulation methods and methods of tuning the simulation to match image quality parameters.

2. Radiographic Theory

Radiographic images are formed through the propagation of high energy radiation (x-rays or gamma rays) through an object to the detector. When photons travel through a material they have a probability of interacting with atoms in the material; they may be absorbed

by the photoelectric effect, scattered through Compton or Rayleigh scattering or undergo pair production [3, 4]. Those photons remaining will reach the detector and have a chance of detection to form the image. The probability of a photon interacting in a material is dependent on the photon's energy but also highly dependent on the density and atomic structure of the material. The attenuation coefficient of a material is directly proportional to the probability of photon interaction; Figure 2 shows the mass attenuation of water, iron and lead for a range of photon energies. Mass attenuation is attenuation normalised by the material density; it allows multiple materials to be compared without the disparity in magnitudes caused by density. It is this disparity that forms the image. Photons will be less attenuated if travelling through a low density, rather than high density, material. Consequently, more radiation will be detected from low density regions of an object.

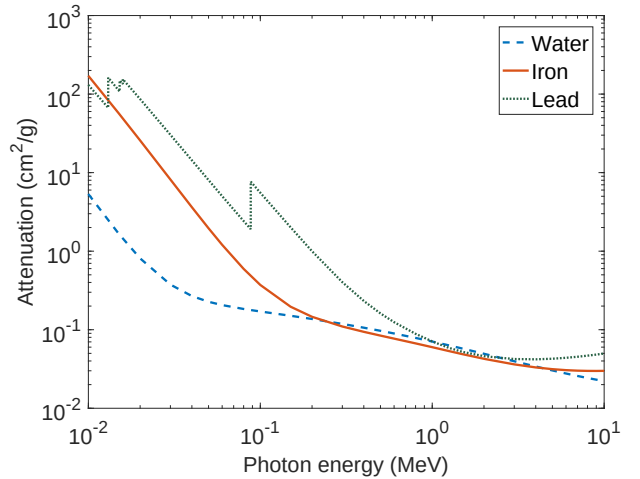


Figure 2: Attenuation, μ/ρ , for photons travelling through water, iron and lead where μ is the total attenuation coefficient and ρ is the material density. Sharp peaks occur when the photon energy is just high enough for the photons to interact with an additional electron shell. The attenuation data was obtained from the XCOM online database [5].

The intensity of direct radiation reaching the detector, I , can be calculated from the material attenuation using the Beer-Lambert Law:

$$I(E) = I_0(E)e^{-\mu(E)x} \quad (1)$$

where E is the energy of the photons, I_0 is the initial radiation intensity, μ is the attenuation of the material and x is the distance travelled through the material.

This equation does not take into account photons which are detected after being scattered; for thin or low density materials, this is often sufficient. However, for thicker or more dense materials, such as the steel pipes and water being examined in this project, scattered photons can have a significant effect on the results through lowering the contrast.

¹analytical RT inspection simulation tool - licensed by BAM (www.artist.bam.de)

There are four interactions that an x-ray photon travelling through a material may have. These are Rayleigh scattering, photoelectric absorption, Compton scattering and pair production. In Rayleigh scattering the photon interacts with an atom causing a change in direction but no loss of energy. Rayleigh scattering is more probable at low energies but is never a very strong effect relative to other interactions.

The important interactions for most of the energy range of interest in industrial radiography are photoelectric absorption and Compton scattering, with pair production becoming significant at higher energies [5]. In photoelectric absorption the photon is completely absorbed through ionising an atom. As well as releasing an electron the atom may emit secondary photons due to electron cascade between energy levels. Compton scattering is where the photon scatters off an electron, changing direction and losing a proportion of energy to the electron.

For high energy photons, over 1.022 MeV, pair production becomes possible. This is where the photon annihilates to create an electron-positron pair. The electron and positron will be dissipated through interactions in the material, with the electron quickly absorbed and the positron combining with a nearby electron to produce two photons with 0.51 MeV energy.

The probability of each interaction depends on the material properties and can be given in terms of cross-sections [6]. Each interaction has an associated attenuation coefficient; combining these gives the total attenuation coefficient as shown in Figures 3 and 4 in which attenuation coefficients are plotted for water and iron respectively.

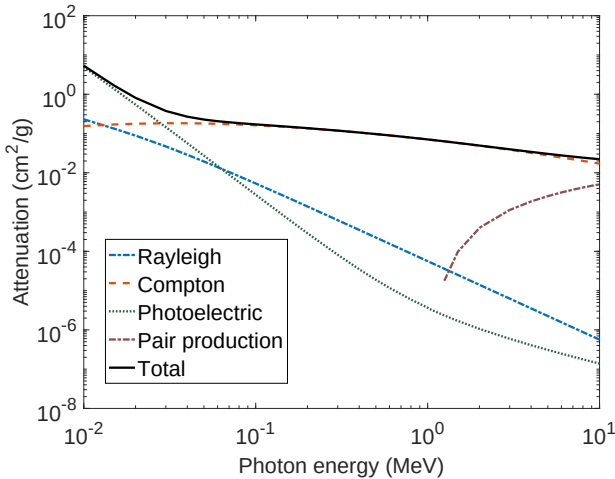


Figure 3: Total attenuation and its components for photons travelling through water. Total attenuation is a combination of atomic scattering and absorption effects whose relative probabilities change with photon energy. Data is from the XCOM online database [5].

Comparing the dominance of interactions in water, Fig 3, and iron, Fig 4, it can be seen why water is considered a highly scattering medium. In water photoelectric absorption is much weaker than in iron. Compton scattering

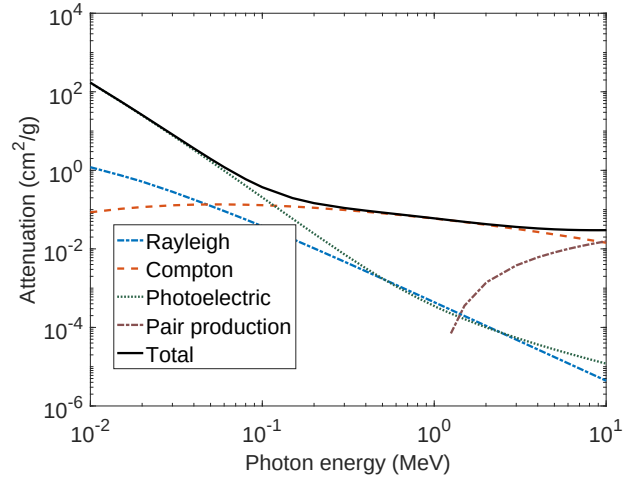


Figure 4: Total attenuation and its components for photons travelling through iron. Data is from the XCOM online database [5].

in water is proportionately higher and becomes the most probable interaction at a lower energy (around 30 keV) compared to iron in which it is most probable from around 100 keV. Compton scattering degrades image quality by changing the direction of photons which will, if detected, reduce contrast in the image.

This demonstrates the potentially large negative impact that water, for example surrounding a subsea pipeline, can have on a radiographic image. Its density is high enough that the number of interactions is non-negligible while its probability of Compton scattering is relatively higher than other materials. Being able to accurately simulate the impact of water would be very useful as it would help determine detection limits and defect characterisation accuracy in real inspections.

3. Methods

3.1. Experimental Method

Experiments were performed in the high-energy X-ray laboratory at BAM, Berlin, Germany. The pipe used for testing and the experimental setup are shown in Figures 5 and 6 respectively. The sample, Fig 5, was a stepped pipe with an outer diameter of 322.6 mm and wall thickness from 8.5 mm to 25 mm. The pipe also has three sets of internal flat bottomed holes with depths of 10%, 20% and 50% wall thickness. The experimental setup, Fig 6, used a pulsed betatron with a maximum energy of 7.5 MeV [7] and a digital detector array. The detector (Perkin Elmer XRD 1621 model [8]) has a sensitive area of 409.6 mm x 409.6 mm with 2048 x 2048 pixels and a pixel size of 200 μm . To provide a higher signal-to-noise ratio the detector was used in pixel binning mode. This is where the image pixel is calculated from the sum of four detector pixels, resulting in an image with 1024 x 1024 pixels of 400 μm .

A source to detector distance of 1650 mm was used, with a pipe centre to detector distance of 504 mm as shown

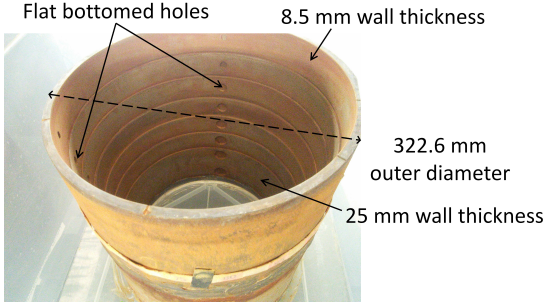


Figure 5: Stepped pipe used as test object.

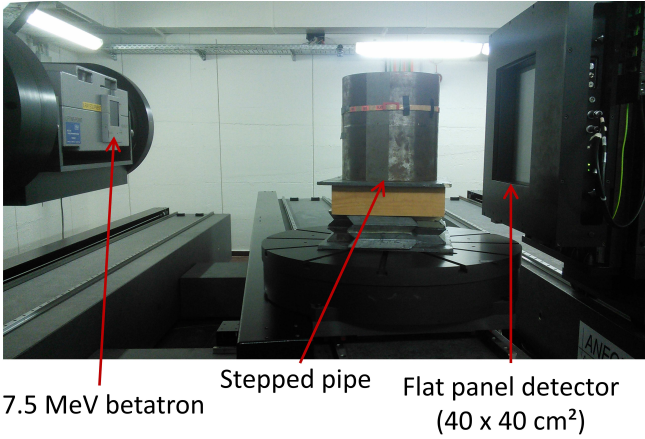


Figure 6: Setup for high energy radiography of the pipe.

in Figure 7. Due to equipment constraints it was not possible to move the source or detector closer to the pipe, as required for the double wall single image method. Instead images were taken with the double wall double image and tangential methods. All images were taken with the same exposure time of 2 s per frame and the same calibration, using a 100 frame gain image and a 20 frame offset image. Copper filters (1 mm thickness) were used at the source and/or detector in some images to improve image quality.

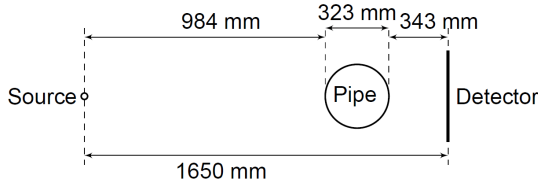


Figure 7: Setup dimensions used for experimental image acquisition.

In order to add water to the setup the pipe was placed in the centre of a rectangular plastic water tank. This allowed for setups with two different water thicknesses to be imaged by rotating the water tank, as illustrated in Figure 8. Silicone was used to create a seal around the base of the pipe allowing for images to be taken with water around the pipe but air inside, in addition to those with water both inside and outside the pipe.

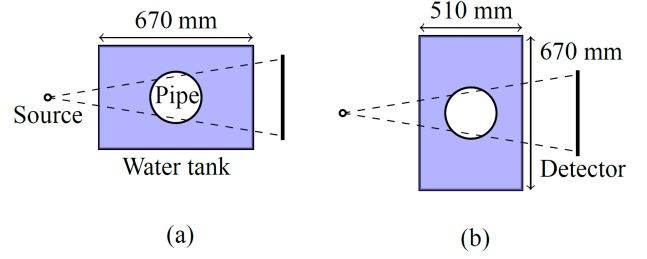


Figure 8: The stepped pipe was placed in a rectangular water tank, (a) & (b) show two setups with different water thicknesses made possible by rotating the water tank.

3.2. Simulation Method

The same setups as used experimentally were simulated in aRTist, a simulation tool developed by BAM. A visualisation of the simulation setup is shown in Figure 9.

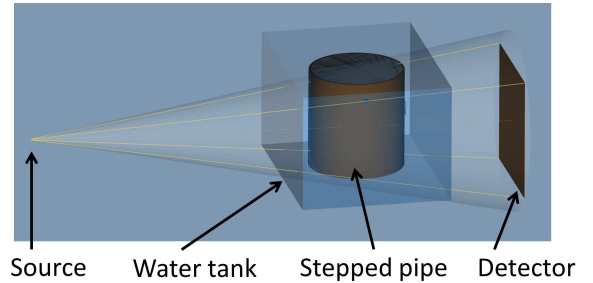


Figure 9: Radiographic setup modelled in aRTist. Dimensions and distances used were as in experimental setups.

Further details on aRTist can be found in [9] and [10]. The detector was modelled using a new Detector Calculator module [11] which uses data from an experimental reference image to characterise the detector, while the betatron source was modelled with the spectrum calculator incorporated into aRTist [12]. The source spectrum is plotted in Figure 10. Although the maximum energy of the betatron is 7.5 MeV the majority of the photons produced are at much lower energies. This makes simulation of photon scattering very important as Compton scattering is the dominant photon interaction for most of the betatron energy range.

Scattering in aRTist is simulated using a Monte-Carlo technique, a commonly used method of simulating scatter [13, 14, 15, 16]. Monte Carlo methods are often used where it is difficult to deterministically solve a problem. This is the case for photon scattering, as it is not possible to calculate the exact path of a photon, only the probability of each possible path. In the Monte-Carlo algorithm random sampling is used to decide on a photon's interactions based on the relative probabilities of each interaction. While any given photon will follow a random path, summing the results of many photons will give a realistic distribution based on these underlying probabilities. If run for long enough Monte Carlo methods will accurately simulate both direct and scattered radiation, producing

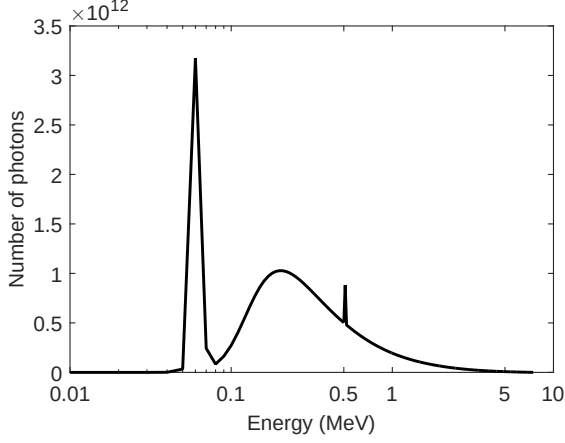


Figure 10: Spectrum of the 7.5 MeV betatron as modelled in aRTist.

the complete radiograph. However the computing time required would be correspondingly high; therefore many models have applied a method of combining a straight-line analytical model using the Beer-Lambert Law, Equation 1, with a Monte Carlo method used to add scattering effects [14, 17, 18]. This is the technique applied in aRTist.

3.3. Image Quality Parameters & Simulation Tuning

The simulation was adjusted with the aim of matching the main image quality parameters to those measured experimentally. These include Signal-to-Noise ratio (SNR), Contrast-to-Noise ratio (CNR) and basic spatial resolution ($SR_b^{detector}$).

Signal-to-noise ratio is defined as the ratio of the mean value of the gray value to the standard deviation of the gray level in a given region of the image [1]. In practice a rectangular region of interest is taken in an area of the image free from significant intensity changes. For each horizontal line of pixels i , with n pixels per line, the mean gray level ($\overline{GV_i}$) and sample standard deviation (σ_i) are given by [19]:

$$\overline{GV_i} = \frac{1}{n} \sum_{j=1}^n GV_{ij} \quad (2)$$

$$\sigma_i = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (GV_{ij} - \overline{GV_i})^2} \quad (3)$$

where GV_{ij} is the gray level at line i and column j in the region of interest. These are calculated for each horizontal line of pixels, where there are N lines. Signal-to-noise ratio is then given by:

$$SNR = \frac{\text{Median}[\overline{GV_i}]_{i=1}^N}{\text{Median}[\sigma_i]_{i=1}^N} \quad (4)$$

This is the unnormalised SNR, however as the same equipment and calibration was used for all images the unnormalised value is a suitable measure to evaluate. SNR

was measured in experimental images and could be varied in simulated images by changing the number of frames per image in the simulation. The number of frames for an image refers to the number of separate exposures, or frames, which are averaged to produce the final image. For example an image taken with 2s exposure time per frame and 10 frames will take 10 separate shots with 2s exposure time each, and average them to produce the final image.

The contrast, C , of an object in a radiograph is given by [20]:

$$C = I - I_{obj} = \Delta I \quad (5)$$

where I_{obj} is the intensity measured on the object indication and I the intensity nearby. The contrast-to-noise ratio can then be calculated from:

$$CNR = \frac{|\Delta I|}{\sigma} \quad (6)$$

where σ is the standard deviation measured in an area near the intensity measurements. CNR is more difficult than SNR to vary independently in the simulation, so measurements from simulated and experimental images were compared and analysed. Another measure is the relative contrast (Cr). Cr is independent of the noise and is instead based on the relative change in gray level, given by:

$$Cr = \frac{|\Delta I|}{I} \quad (7)$$

Relative contrast is particularly useful when comparing images with different noise or gray levels in the area of measurement.

Basic spatial resolution is measured with a duplex wire IQI placed on the detector in the experimental radiographs. Basic spatial resolution is determined from the smallest number of the duplex wire pair which is separable by a profile function with less than 20% modulation depth in a linearized profile [21]. $SR_b^{detector}$ measured from experimental images is an input parameter to the detector calculator module in aRTist, ensuring a match of simulation to experiment in this case.

In addition to matching the main image quality parameters, the profile across the edge of the pipe in tangential images was also taken and compared in simulated and experimental cases. Taking a line profile across the radiograph, the edge profile is a portion of this in which the edge of the pipe is visible, as visualised in Figure 11(a). Figure 11(b) shows the gray value (intensity) versus pixel plot for this portion of the radiograph, where the pixel refers to the detector pixel number and is equivalent to a distance along the radiograph. The main parameter affecting the shape of the profile is unsharpness. Images with low unsharpness have clearer, better defined edges, while those with high unsharpness have smoother edges and lower contrast. Unsharpness has been shown to be a superposition of a short range effect and a long range effect [22]. The short range unsharpness can be seen by measuring the slope of

an edge profile, while the long range component manifests as the extended rounded spurs to either side of the edge. In aRTist the long range unsharpness can be varied directly, while the ‘unsharpness ratio’ parameter sets the relative proportions of long and short range unsharpness. Results of simulations with example values of low, medium and high unsharpness, both long and short range, are plotted to illustrate the effects of these parameters, along with the experimental profile. The unsharpness parameters were varied to get a similarly shaped profile to experimental results.

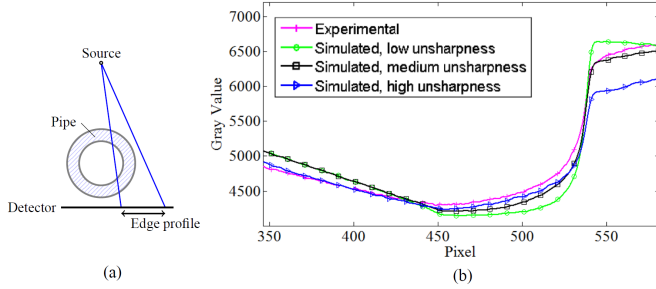


Figure 11: (a) Diagram illustrating the edge profile, a portion of the line profile across the radiograph in which the edge of the pipe is visible, (b) The edge profiles of experimental and simulated images are plotted. The minimum intensity seen at pixel 451 identifies the inner pipe wall position, while the outer pipe wall is at the point at pixel 542 where the rate of increase in intensity suddenly stops or slows significantly.

4. Results

An example of an experimental tangential radiograph with points of interest highlighted is shown in Figure 12.

Edge profiles across simulated and experimental images were taken and compared. These profiles include the edge of the pipe and a distance to either side. Figure 13 shows simulated and experimental profiles for (a) the setup with no water either inside or outside the pipe, and (b) the setup with water outside the pipe but not inside.

Examining these profiles it can be seen that there is an offset in intensity in some areas. The differences in simulated and experimental intensity values means that the contrast-based measurements of double wall imaging in simulated images will not match the same measurement in experimental images. However, tangential imaging does not depend on the particular intensity values but on the positions of the inner and outer pipe wall given by the minimum intensity (inner wall) and the point where the sharply increasing intensity stops or slows significantly (outer wall). From the profiles in Fig 13 it can be seen that these pipe wall positions are fairly accurately reproduced in the simulated results, meaning tangential measurements may be equivalent to experimental results.

To test this, wall thickness measurements were taken of the thickest, 25 mm, pipe wall in a set of images. Results are shown in Figure 14 for one simulated and exper-

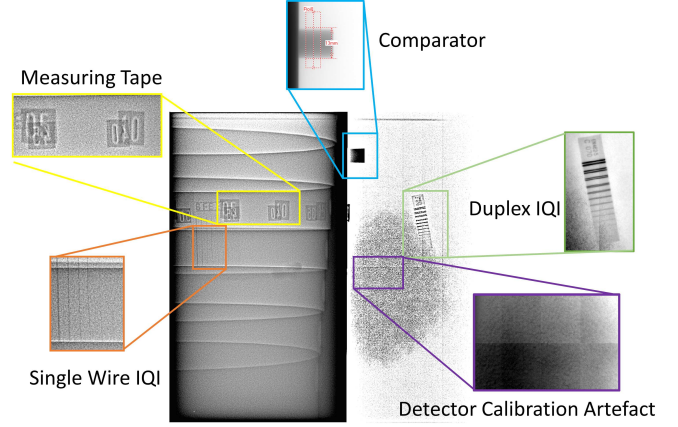


Figure 12: An example of an experimental tangential radiograph. It has been high pass filtered for better visualisation and points of interest are highlighted. A 13 mm comparator was fixed to the edge of the pipe to calibrate dimensions in the image. A measuring tape with lead numbers was wrapped around the pipe. A single wire IQI was placed on the outer pipe wall, on the side nearest the detector while a duplex wire IQI was placed on the detector in the free beam area of the image. Although a detector calibration was applied there are still some step-like artefacts visible in the free beam area of some of the images.

imental image in each of the five setups used: those with water both inside and outside the pipe and with either the longer, 670 mm, or shorter, 510 mm, water tank thickness, those with water just outside the pipe and with the 670 mm or 510 mm thickness and finally those with no water. All measurements are within ± 0.8 mm of the actual value, and although the simulated results tend to be lower than experimental ones this difference is fairly small. Analysis of more images is needed but an initial conclusion is that the simulation produces results comparable to experimental ones for tangential measurements.

Contrast-to-noise and signal-to-noise ratios were also measured and compared in experimental and simulated images. CNR was measured across several pipe wall thickness steps in each radiograph and results averaged to get a single value to compare for each image. While there is a trend in CNR with wall thickness within each image there is also an overall trend between images. Comparing just a single step measurement has more inaccuracy as it is only a single measurement for each image. Since we are interested in the differences between images rather than actual CNR values then averaging reduces the noise and shows the trend between images more clearly. Using the same measurement points in each image ensures comparability of the resulting CNR. Figure 15 shows the CNR for images in all five setup types. Images are numbered with 1 – 5 referring to the setup type, while a – d refers to the copper filter used, as labelled in the figure.

From Fig 15 it can be seen that the simulated CNR values are higher than the experimental ones. This is the same problem as seen in the profile comparisons. However, although the CNR values differ, the same overall trend of

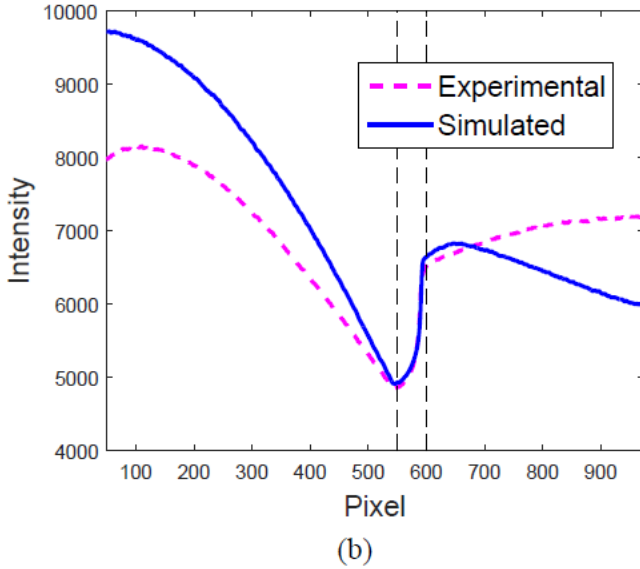
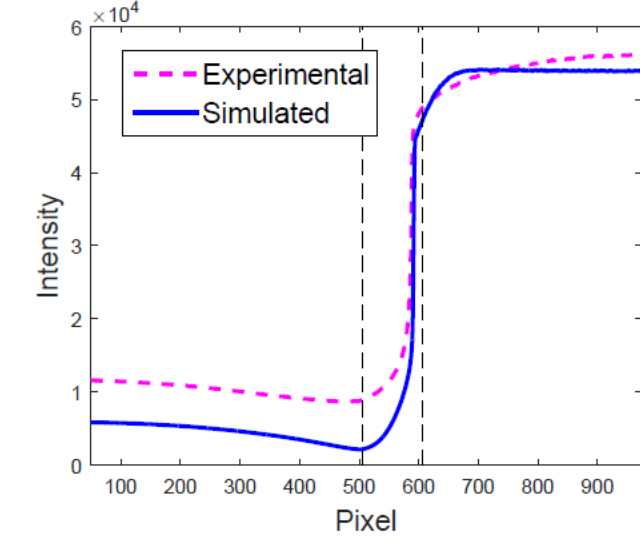


Figure 13: Profiles across the radiograph for experimental and simulated images in the cases of (a) No water, (b) With water outside the pipe but not inside. For each image the dashed black line indicates the positions of the inner and outer pipe walls. For (a) the profiles are for a wall thickness of 22.5 mm, while for (b) the wall thickness is 11 mm.

increasing CNR with decreasing water thickness seen experimentally is reproduced in the simulation results. This demonstrates that the model takes into account the effects of water and correctly responds to changes in water thickness.

SNR was also measured, near to the CNR measurement points, and similarly averaged. Results are shown in Figure 16. In the case of SNR both the absolute values and overall increasing trend of experimental measurements are reproduced in the simulated results. This is an encouraging result as the frame number used in the simulations,

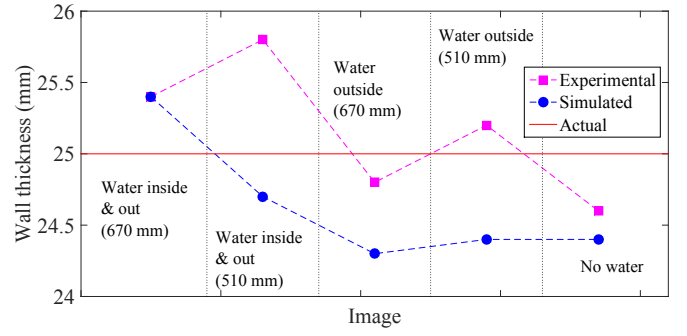


Figure 14: Wall thickness measurements of the 25 mm pipe wall in tangential experimental and simulated images for the five different setups used. Measurement error is taken as plus or minus two pixels for each measurement, which is equivalent to ± 0.5 mm.

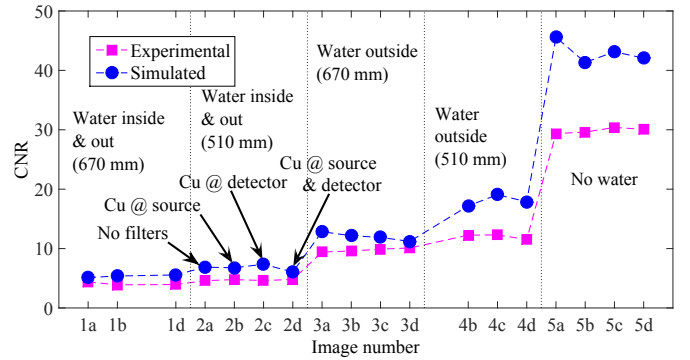


Figure 15: Contrast-to-noise ratio for a series of simulated and experimental images in the five different setup types. The images were all taken with 100 frames. Copper filters were used in some images, labelled a – d where a = no filter, b = 1 mm copper at the source, c = 1 mm copper at detector and d = 2 mm copper in total with 1 mm at both source and detector.

which directly affects SNR, was tuned using experimental images from only one setup type. All simulated images were then taken with the same frame number, with the agreement in trend again demonstrating that the effects of water are being taken into account correctly by the model.

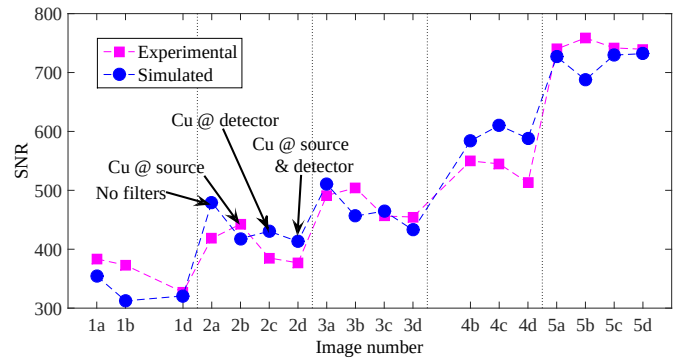


Figure 16: Signal to noise ratio for the same set of images as in Fig 15.

5. Investigation of Peripheral Scattering

The simulated setup, while including all objects in the direct source-detector path, does not account for scattering from out-of-setup objects that would have occurred experimentally. Peripheral scattering refers to the case in which a photon is emitted off to the side of the object being imaged, in this case the stepped pipe, and then undergoes one or more scattering interactions with other objects in the exposure bay. With each scattering event the photon's direction may be changed, which could result in the photon reaching the detector after one or more peripheral interactions. No source collimation was used either in the experimental or simulation methods, meaning photons will have been emitted over a wide angular range. The next section describes simulation setups used to investigate how significant this additional scattering is, followed by results.

5.1. Simulation method

It is too complex to model the entire experimental area, but an idea of how big an impact this type of scattering has was obtained by increasing the height and length of the modelled water tank as shown in Figure 17. Images with a range of water tank sizes were simulated, with the tank depth kept constant such that the straight line path from the source to any detector pixel was the same for all images. All images were simulated with an air-filled pipe and a fixed source opening angle.

A more realistic setup including simulated surroundings was also modelled, as shown in Figure 18. In this case objects similar to those in the experimental surroundings were placed in the model. Two scattering regimes were tested by setting the model surroundings first as low scattering iron and then as higher scattering water. No water tank was used and the pipe was air-filled, making these images comparable to the experimental setup with no water present.

Simulation parameters were kept as previously set, however exposure time was varied between images. This was in order to keep the maximum gray level constant as images receiving higher scattering have higher gray levels making direct comparisons difficult.

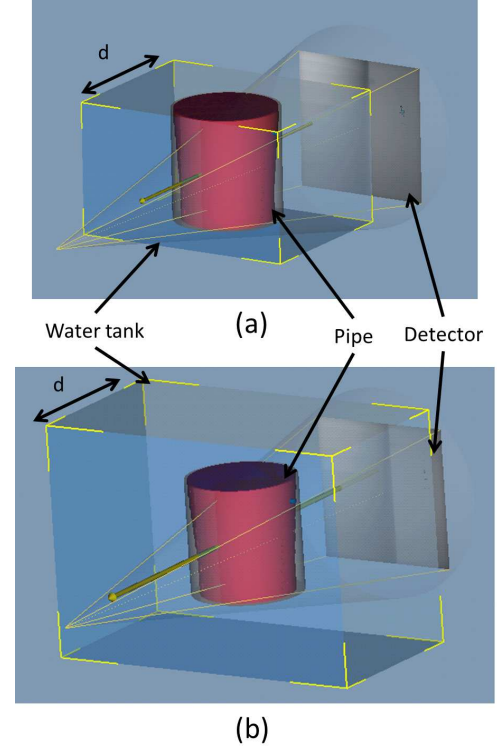


Figure 17: Radiographic setup modelled in aRTist, (a) Original setup matching experimental dimensions, (b) With water tank height and length increased. Tank depth, d , is kept constant meaning the thickness of water in the source-detector line is as in the experimental setup. The impact of scattering from the additional peripheral water can be examined by comparing images with different sized water tanks.

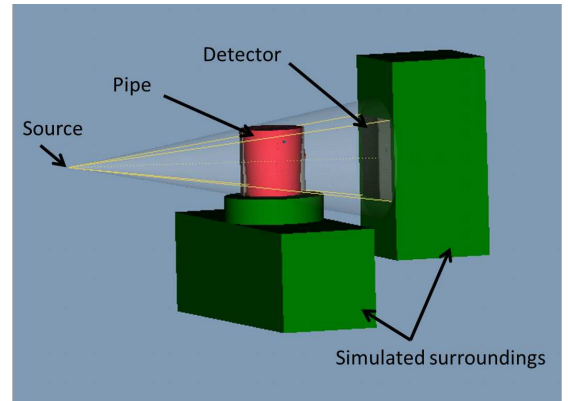


Figure 18: Radiographic setup modelled in aRTist including some nearby, peripheral objects similar to actual surroundings in the experimental setup. The material of the additional objects was set to be either iron or water, as examples of a weakly and a strongly scattering material.

5.2. Results

Profiles across an experimental tangential radiograph and simulated results for water tanks varying in size are shown in Figure 19. The water tank size was varied from the original 670 mm length and 400 mm height up to a maximum of 1150 mm length and 880 mm height, corre-

sponding to an additional 480 mm in each dimension. The increased size of the water tank is seen to have a significant impact on the profile with the contrast and definition of the pipe wall very much reduced for the larger water tanks. This is due to the additional scattering reaching the detector in these cases, as the source to detector direct path remains unchanged.

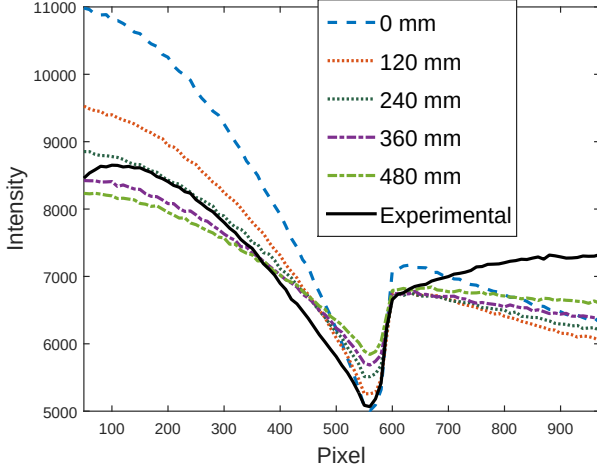


Figure 19: Profiles across the radiograph for experimental and simulated tangential images with increased water tank lateral dimensions. Numerical values in the legend indicate the increase in water tank size, with 0 mm as the original 670×400 mm tank and 120 mm as an increase to a 790×520 mm tank, etc. The experimental water tank size is 670×400 mm, as before.

Contrast-to-noise ratio was also measured for each image. The method of CNR measurement is as previously described, with measurements taken across seven wall thickness steps in an image. The measurements were then averaged, giving a mean CNR value for each image. Mean CNR as well as CNR measured across three of the steps is shown in Figure 20 for a series of images with different water tank sizes. Simulated images are labelled from 0 to 12 and have a difference of 40 mm in water tank height and length between them, ranging from the original 670×400 mm tank, labelled 0, up to the 1150×880 mm tank, labelled 12.

From Fig 20 it can be seen that increasing the water tank size causes a sharp decrease in contrast for the first few 40 mm increases (images 0 to 4). These differences begin to tail off, becoming insignificant around image 8, corresponding to a water tank size of 990×720 mm. This is consistent with expected behaviour of out-of beam scattering objects as additional water close to the beam will have a larger effect than that further away.

The mean signal-to-noise ratio for the same set of images is shown in Figure 21. The simulation was not directly calibrated with the experimental image in this case, and exposure times were varied to get better matching gray levels, hence SNR has no clear trends and shows the simulated results to be much higher than experimental.

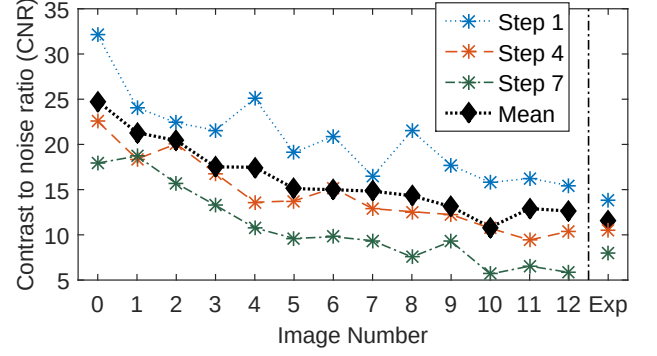


Figure 20: Contrast-to-noise ratio for images with different sized water tanks. Simulated images are numbered from 0 to 12 in order of increasing water tank size, with increases in 40 mm steps. Mean CNR is the mean of seven measurements for each image, three of which are also shown as Steps 1, 4 and 7. Step 1 is a measurement taken near the thinner, top area of the pipe, step 4 is near the centre and step 7 is near the thickest, lower portion of the pipe.

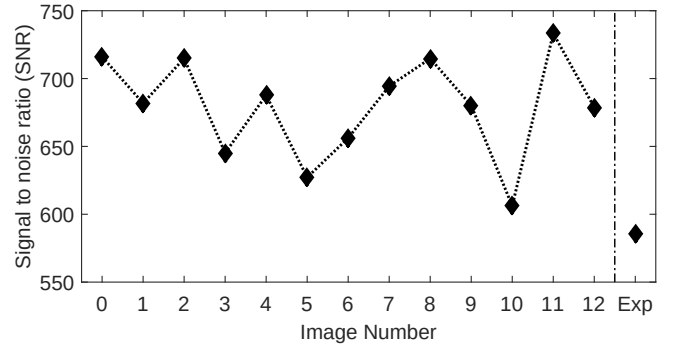


Figure 21: Mean signal-to-noise ratio for images with different sized water tanks. Images are labelled and ordered as in Fig 20. In this case only the mean value is plotted, calculated as the average of measurements near each of the seven steps.

To ensure differences in noise were not responsible for the observed change in CNR the relative contrast (Cr) was also measured, shown in Figure 22. With some minor differences the relative contrast produces the same trend as CNR.

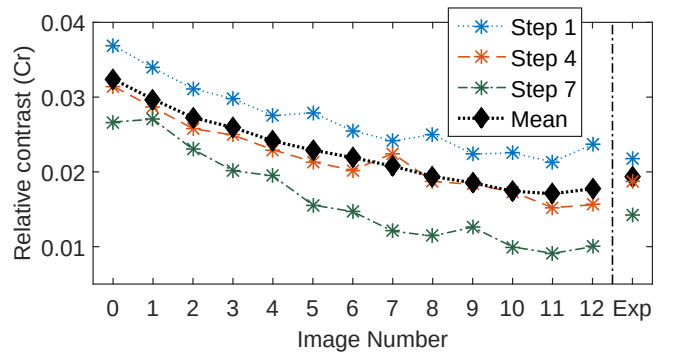


Figure 22: Relative contrast for images with different sized water tanks. Images are labelled and ordered as in Fig 20.

The same comparisons were also performed for the images without water inside or around the pipe, but with simulated surroundings as in Fig 18. In this case four images were compared: one experimental, the original simulated image without surroundings, a simulated image with iron (Fe) surroundings and a simulated image with water surroundings. Profiles of these four images are shown in Figure 23. Again, the change caused by additional peripheral scattering is significant. The case of iron surroundings results in a slight decrease in contrast from the original. Iron is relatively weak scattering so this is as expected. For the stronger scattering water the change is much greater, with the inner pipe wall barely identifiable in the profile.

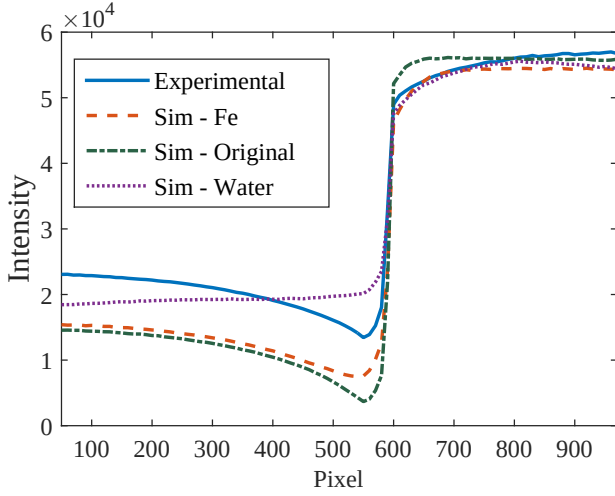


Figure 23: Profiles across the radiograph for experimental and simulated images with no water in the beam path. Three simulated images are shown, one with no peripheral objects, one with iron surroundings and one with water surroundings both simulated using the setup shown in Fig 18.

Contrast-to-noise ratio for the four images is shown in Figure 24. CNR with additional scattering is much lower compared to the original simulated image, with experimental CNR higher than the simulated water case but lower than simulated iron, indicating an actual rate of additional scattering between the two. To check that results are not due to differences in noise the relative contrast is shown in Figure 25. Relative contrast can be seen to produce the same trend, confirming this result.

To examine how different energies within the betatron spectrum contribute to peripheral scattering simulations were also run with monoenergetic sources. Two energies were chosen; 300 keV and 2 MeV. 300 keV was used because it is near the peak in photons produced by the betatron in the 100 keV to 1 MeV range as shown in Fig 10. 2 MeV was used as an example of a high energy (over 1 MeV) in the betatron spectrum. The setup in Fig 18 was used as the test setup. Four simulations were run; two with each monoenergetic source, of which one included water surroundings while the other had no additional scattering objects. For each image the scatter-to-primary ratio, SP ,

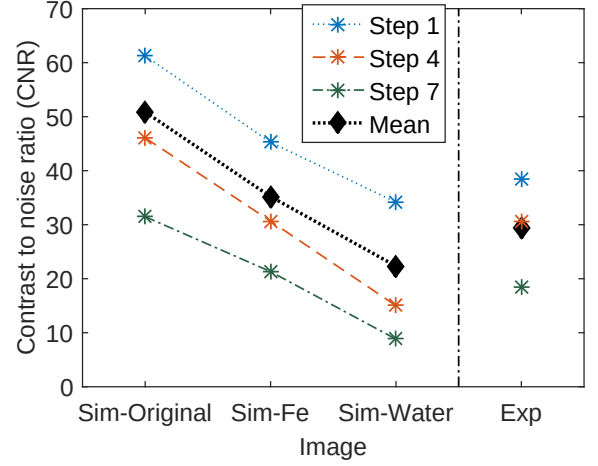


Figure 24: Contrast-to-noise ratio for images with different peripheral objects. Sim-Original has no additional objects, while Sim-Fe and Sim-Water have simulated surroundings made of iron and water respectively.

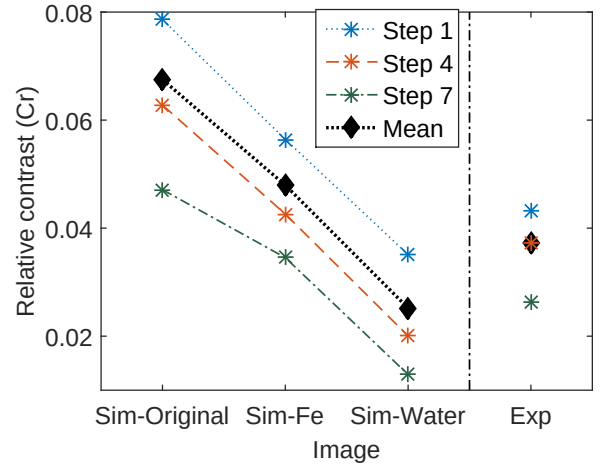


Figure 25: Relative contrast for images with different peripheral objects, as in Fig 24.

was calculated at every pixel. SP is given by:

$$SP = \frac{I_S}{I_P} \quad (8)$$

where I_S is the intensity of scattered radiation and I_P the intensity of primary radiation. In order to compare the difference in scattering between the two source energies a relative scatter-to-primary ratio for each source was calculated. The relative scatter-to-primary ratio, S_{Rel} , demonstrates the change in scatter ratio caused by the water surroundings and is calculated from:

$$S_{Rel} = \frac{SP_{water}}{SP_{none}} \quad (9)$$

where SP_{water} is the scatter-to-primary ratio in the image with water surroundings and SP_{none} is the scatter-to-primary ratio in the image without additional surroundings. The relative scatter ratio for each image pixel is

calculated, however for ease of comparison a cross section down the image, in the free beam area, was taken.

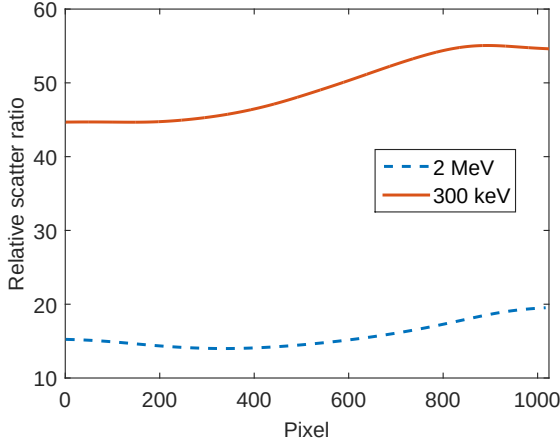


Figure 26: Relative scatter ratios for the cases of monoenergetic 300 keV and 2 MeV sources. The plotted section is a cross section down the image in the free beam area. Pixel 1 is at the top of the image while pixel 1024 is the lowest pixel. The increasing trend from pixel 1 to pixel 1024 is due to the additional scattering objects being placed under the pipe, giving higher scattering in the lower portion to the detector. The difference between the 300 keV and 2 MeV cases demonstrates that the lower energy is impacted by peripheral scattering to a much greater extent.

The relative scatter ratio, S_{Rel} , for each source is plotted in Figure 26. This shows that the relative scatter ratio is much greater for the 300 keV source than the 2 MeV source. The implication is that peripheral scattering has a much more significant effect on low to medium energy photons. This is consistent with the attenuation coefficients plotted in Fig 2, showing total attenuation to decrease with energy until much higher, tens of MeV, energies.

6. Discussion of Errors and Uncertainties

Results from the original simulation-experiment comparison (Section 4) show differences between the two, particularly in image contrast. However, the simulation did not account for the additional scatter from other objects in the exposure bay which would have happened experimentally. This scatter was initially assumed to be negligible, however when investigated in aRTist (Section 5) it was found to have significant effects on the image, reducing the contrast to values closer to those measured in the experimental data. The high impact from peripheral scattering can be explained by looking at the source spectrum of the betatron, Fig 10, and the attenuation coefficients of water and iron shown in Figs 3 and 4. The source spectrum shows that, although the maximum energy is 7.5 MeV, most photons are at much lower energies. Those below about 100 keV are likely to be absorbed relatively quickly, particularly if passing through the pipe as, from Fig 4, photoelectric absorption is the most probable interaction for photons below 100 keV in iron. This leaves

most photons in the 0.1 MeV to 1 MeV range. At these energies Compton scattering is the most probable interaction, and the photons also have high enough energies that they are likely to be able to undergo multiple scattering events before reaching negligibly low energies. This makes it more likely that photons that have been scattered away from the detector will, after one or more additional scattering events, still reach the detector with significant energy remaining. The high impact of peripheral scattering on an image with a 300 keV monoenergetic source is demonstrated in Fig 26, in which the relative scatter ratio is plotted along with that from a 2 MeV source. These effects, combined with the simulated results in Section 5, demonstrate that the probable cause of the difference between experimental and simulated data is peripheral scattering. To confirm this, additional experiments in a more highly controlled environment could be performed, with lead shielding around the setup and fewer potential scattering objects in the exposure bay. While there would still be scattering from the lead, it has a much higher probability of photoelectric absorption compared to other materials such as iron or water. In lead, photoelectric absorption is a larger effect than Compton scattering up to about 500 keV, compared to 30 keV in water and 100 keV in iron. So a much greater proportion of the betatron spectrum would be absorbed rather than scattered if lead shielding were used. However, lead generates x-ray fluorescence at about 80 keV meaning some detectors may need additional copper shielding between the detector and lead.

The high proportion of peripheral scattering found in this study could have significant impacts for accurate simulation of radiographic inspections. Modelling is often used to check the feasibility of inspection setups and to calculate the expected quality of results. However generally only materials between the source and detector are included in the model, meaning scattering may be underestimated and results not representative of the actual inspection. For the example of a subsea pipeline inspection, accurate modelling would need to include the equipment surrounding and manipulating the source and detector as well as the water for some distance around the setup. In this case the actual inspection setup may be simpler to model than a laboratory setup, as in the actual inspection there is a large thickness of water all around which will greatly reduce scattering from objects at more than a short distance from the beam. In the laboratory case the water is likely to be in a relatively small container, allowing scatter to potentially reach all around the exposure bay.

The effects of additional scattering also make it harder to fully validate simulation models. It is very difficult to include an accurate representation of all possible scattering objects from an experimental setup in a modelling setup. Therefore when comparing simulated and experimental data there are likely to be differences even if the simulation is accurate for the modelled setup. This makes it harder to identify any other potential differences between experiment and simulation.

Instead of attempting to model many potential scattering objects it may be possible to achieve a better matching model by calibrating it with real data. In this case real data means data from the type of inspection being modelled rather than experimental laboratory data. For the case of subsea pipelines, if real data of a subsea inspection can be obtained it could be used to estimate the proportion of peripheral scattering, which could then be added into the model. This would greatly simplify the model as it would not need to include the equipment surrounding the setup. However there would still be significant uncertainties, for example due to the sea floor. This could cause uneven scattering across the detector which would change if the setup were rotated. Any type of local scatter like this could cause inaccurate calibration of the model, either including the local scatter in all images or in none, depending on which experimental data was used for calibration.

7. Summary

The aim of this work is to investigate the accuracy of a radiographic simulation model for subsea pipeline imaging. A set of experimental data was obtained and used to adjust simulation parameters, aiming to match simulated results to experimental ones. The model was found to produce matching signal-to-noise ratios and the correct trend in contrast-to-noise. However differences were found in the profile across the radiograph and the CNR values. A possible cause of the discrepancies is scattering from objects in the experimental exposure bay which were not included in the simulation setup. Compton scattering is the dominant effect for the range of energies most common in the betatron spectrum, meaning the contribution of uncollimated scatter may be particularly strong for the setups examined in this work. Additional simulations were performed to test this possibility. Scatter from peripheral, out-of-setup objects was found to have a significant effect on the resulting image, in particular reducing the contrast. These results show that additional scattering from objects not included in the model is probably the cause of differences between experimental and simulated data. The implication is that for accurate modelling of an inspection scenario an area around the setup should be included in the model to account for additional scattering. An alternative would be to calibrate the model using a set of experimental data from the actual inspection being modelled. However there will still be unavoidable uncertainties, particularly in interpretations based on intensity.

8. ACKNOWLEDGEMENTS

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