X-Ray Source Considerations in Operation of Digital Detector Arrays

Terrence Jensen and Scott Wendt

_Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011_

**Abstract.** Digital Detector Arrays (DDA) are increasingly replacing film in radiography applications. Standards exist for characterizing the performance of these detectors, and for using them in specific inspections. We have observed that the selection of the x-ray source to use with these detectors can also have a significant influence on the performance. We look at differences between standard, and micro-focus x-ray tubes, and end-window vs. side-window micro-focus tubes. We find that for best results, one must calibrate the DDA for the source settings used during an inspection. This is particularly true for variable-focus sources.

**Keywords:** Digital Radiography, Digital Detector Array, X-ray Imaging

**PACS:** 87.59.bf, 07.85.Fv

**INTRODUCTION**

Over the past decade, Digital Detector Arrays (DDA) have benefited from advances in technology and have gained general acceptance as a replacement for film in many radiographic applications. A number of standards have been developed to quantify the performance of these detectors and to establish procedures for their use in radiography.

A radiographic inspection requires the specification of both source and detector. General issues of image unsharpness due to source size, and detector sensitivity relative to source voltage and power are well understood. In this study we examine the interplay between the choice of source and the detector calibration procedure in determining the performance of DDAs.

**EQUIPMENT**

**Digital Detector Arrays**

The most common types of DDAs are amorphous silicon or CMOS flat panels coupled to an x-ray conversion screen of CsI or GdSO₄. The high-density screen converts the impinging x-rays to visible light that is then converted to electrical signals by an array of photodiodes, and subsequently digitized to form an image. To produce useful images, it is necessary to equalize the response of the individual photodiodes. This is generally done by recording the response of the detector to a uniform incident flux of x-rays, as well as the response when no x-rays are present. These calibration images are used to calculate a calibration slope and offset for each pixel element of the detector.

In our studies we have used a General Electric model DXR500L detector with a CsI screen, 100 µm pixels, and 14-bit digitization, and a Varian PaxScan 2520 detector with GdSO₄ screen, 127 µm pixels, and 12-bit digitization. Each manufacturer has provided software for calibrating their detector, along with a recommended procedure for setting the x-ray source strength during calibration.
X-ray Sources

A wide variety of x-ray sources, ranging from radioactive isotopes of various energies and strengths to large linear accelerators, are available for NDT applications. In our study we will consider only the more common types of Bremsstrahlung-production x-ray tubes. A number of different metal targets can be used, the most common for NDT being tungsten. X-ray tubes can be further classified according to the orientation of the target with respect to the incident electron beam, as indicated in Figure 1. High-power x-ray tubes are generally of the side-window type. In this case, x-rays produced just below the surface of the target are extracted roughly perpendicular to the electron beam. The angle of the target surface relative to the electron beam is set to help define the focal spot size, and typically ranges from 10 to 45 degrees. This also limits the maximum angle of the cone beam in one direction. The end-window x-ray tube has limited power capabilities, as the target must be fairly thin to allow penetration of the electron beam. In this case, x-rays are extracted along the direction of the electron beam, and a large cone beam angle is possible. This type of tube is often used for microfocus sources, as it allows a sample to be placed very close to the source for high magnification.

In our studies we have compared two different side-window tubes and an end-window tube. The Comet MXR-320/23 tube has a 3 mm thick Beryllium side window, a 20-degree target angle, and 1.9 mm focal spot. The Phoenix xs225 is a microfocus tube with variable focus in the range 2-200 microns. The x-ray beam is extracted at an angle of 60 degrees relative to the electron beam through a 0.5 mm thick Beryllium side window. The Kevex PXS10 is a low-power micro-focus tube with a 0.25 mm thick Beryllium end window, and variable focus in the range 5-20 microns.

RESULTS

For our studies we have imaged fairly simple objects, the principal one being a step wedge composed of a stacked series of 3mm aluminum plates. In Fig. 2 we present a radiographic image of this step wedge acquired using the Comet MXR-320/23 tube and the GE DXR500L DDA. There is a subtle gradient in intensity from left to right along each step. This is quantified in the plot of the greyscale values along Step 2 (6 mm Aluminum) of the sample. The orientation of the detector with respect to the x-ray tube corresponds to Fig. 1a; that is, the higher greyscale values are observed for x-rays emitted at angles (to the right) closer to the surface of the tube target. We also observed that the slope increases if the detector is positioned closer to the tube, such that it subtends a larger solid angle of the x-ray beam.
The variation in greyscale value across the image is ~10%. To give an idea of how this might affect the detectability of features in a sample, we have imaged a 10 mil penatrometer placed on a ¼ inch plate of aluminum, shown in Fig. 3. The profile across the image quantifies the effect. It can be seen that small features will still be easily detected on top of the gradually changing background trend. However, measurements of density or thickness variations in a sample will be critically affected by this gradient.

The images of Figs. 2 and 3 were acquired on a system calibrated according to the manufacturer’s recommendations. That is, a series of images with no x-ray exposure were acquired to determine an “offset” value for each pixel, and another series of images were acquired with no object in the beam and exposure to achieve about 2/3 of the maximum greyscale value to produce a “gain” value for each pixel. This calibration was done at 100 kVp, whereas the images of Figs 2 and 3 were acquired at 80, and 150 kVp, respectively.

We have repeated the above images using a different calibration procedure. We placed a 1.5 mm aluminum plate at the output of the x-ray tube, and adjusted the current to achieve approximately 2/3 saturation value (still at 100 kVp), which we refer to as a “Filtered Calibration”. (Note that this plate was removed when acquiring the step-wedge images.) We compare this calibration result with those of the “Normal Calibration” in Fig. 4 for the aluminum step wedge. Here we plot relative intensity along each step of the sample, with the average being normalized to 1.0, and the line for each step being offset from the previous by 0.1 units. The profiles for Steps 1-4 have a fairly uniform slope, with the slope for the Filtered Calibration being less than that for the Normal Calibration. Step 0 corresponds to a region where there is no sample, and shows a different slope. In this case, the Normal calibration curve is fairly flat, while the Filtered Calibration curve has a negative slope.
These behaviors can be understood to result from variations in the x-ray energy spectrum incident on the detector. To investigate this, we have set up a High-Purity Germanium detector in place of the DDA. This detector measures the energy of each x-ray with a precision of 0.5 keV. A very small collimator (~0.5 mm diameter, 10 mm long) was placed in front of the detector to allow only a small angular range of x-rays to reach the detector. We then positioned this detector to point at the source at varying angles with respect to the nominal beam direction.

Example spectra are plotted in Fig. 5 for the Comet MXR 320/23 tube. Spectra at 80 kVp and 150 kVp, with no sample present and with a 6mm aluminum plate in the beam, are shown. The zero-degree direction is chosen along the nominal beam centerline, with negative angles defined as the direction toward the target. In these plots the relative amplitude of the different curves is not meaningful. Due to the fact that the focal spot of the tube is large relative to the detector collimation, slight shifts in alignment can lead to significant changes in observed intensity. The shapes of the spectra show a clear trend. The closer the direction of the emitted x-ray is to the target surface, the higher the average energy of the x-ray beam. This shift is more pronounced for the no-sample spectra, and is not symmetric about the zero-degree direction. X-rays produced in the target are attenuated as they escape the target. Those x-rays traveling closer to a direction parallel to the target surface must travel through more material to exit the target, so are attenuated more. Low-energy x-rays are attenuated much more than high energy x-rays, so this leads to a directional dependence of the energy spectrum from a side-window x-ray tube. Furthermore, absorption of x-rays by the phosphor screen at the input to the DDA (CsI in this case) is energy dependent. Thus, if the detector is calibrated using a particular energy distribution, and utilized under different conditions, it can be expected that the detector response may not be uniform.

In the above examples, the Normal Calibration has only air in the beam path, which emphasizes the low-energy portion of the spectrum. Even a small amount of aluminum attenuates much of the low-energy portion of the spectrum. By using a filter during calibration, we are calibrating the detector with a spectrum that is closer to that observed during measurement with a sample. Thus, in Fig. 4 we see a flat response across the detector when no sample is present (Step 0) using the Normal Calibration, but, using the Filtered Calibration, there is a decreasing trend from left to right. Steps 1-4 show an increasing trend across the detector, with the Filtered Calibration results having a smaller slope because the spectrum used for calibration is closer to that used for imaging.
Higher power micro-focus x-ray tubes, such as the phoenix xs225, also tend to use a side-window design. An image of the step wedge, acquired at 150 kVp using this tube and the GE DXR500L DDA is shown in Fig. 6. This too shows a trend across the image, however, as the profile indicates, it is nonlinear, with a much steeper slope as the x-ray beam approaches a parallel with the target surface. The arrangement of the target and electron beam is as indicated in the inset to Fig. 6. This is different than for the Comet MXR 320/23, but is not expected to have a significant effect on the shape of the spectrum.

The observed nonlinearity is believed to be due to pitting of the target by the electron beam. The power concentration from the focused electron beam can melt the tungsten target and create a small pit. X-rays produced in the pit must travel through additional target material on their way to the detector. This can create severe trends in images, as seen in Figure 6. When this happens, it is necessary to rotate the target to a fresh surface region.

We have measured the spectra in the zero-degree direction for a pitted target and a fresh target at 80 and 150 kVp, as plotted in Fig. 7. Very strong differences in the shape of the spectra are observed. Unfortunately, we did not have time to put the DDA back to image the step wedge after the fresh target was installed, but expect that the nonlinearity would go away.
FIGURE 6. Image of an aluminum step wedge (left) using Phoenix xs225 tube at 150 kVp and GE DXR500L DDA, and profile (right) across Step 2 of the image. The inset shows the relative orientations of electron beam, target, and x-ray beam.

FIGURE 7. Comparison of spectra from a micro-focus x-ray tube using a clean target surface and a target that has been pitted.
Another phenomenon related to target pitting is the sputtering of molten target material onto the exit window of the x-ray tube. This will leave thin deposits of material that can attenuate the x-ray beam locally. This is very close to the focal spot, so for larger focal spots, image unsharpness will blur out any effects. However, in a micro-focus tube with a very small focal spot, these deposits can be magnified, to show up in the image. With DDAs, to first order, the calibration of the detector should compensate for the deposits on the window. But if the detector is calibrated using a relatively large focal spot, and then an image is acquired using a small focal spot, these deposits will be observed. An example is shown in the left image of Fig. 8, where the DDA was calibrated using a 30 \( \mu m \) spot size, and then an image was acquired using a 2 \( \mu m \) spot size. Dark spots from target deposits show up quite clearly in the image. If, on the other hand, we calibrate the detector using a 5 \( \mu m \) spot size, and then acquire an image using a 2 \( \mu m \) spot size, these blemishes largely disappear, as seen in the right image of Fig. 8. For such small spot size, the signal strength at the detector cannot reach the 2/3 maximum recommended by the DDA manufacturer for calibration. But, the calibration done at lower intensity does cover the range of values that will be observed for micro-focus imaging, and thus produces better results than the standard recommended calibration procedure.

![Figure 8](image-url) **FIGURE 8.** Background images (no sample) from a micro-focus x-ray tube under different calibration conditions- (Left) large-spot calibration, small-spot imaging, (Right) small-spot calibration, small-spot imaging.

Finally, we examined the response for an end-window micro-focus tube (Kevex PXS10). Figure 9 shows an image of the step wedge acquired at 100 kVp using a 9 \( \mu m \) spot size. In this case, the DDA is a Varian Paxscan 2520 with GdSO\(_4\) screen (this older detector displays greater noise fluctuations than modern DDAs do). The detector was calibrated at the same settings used for imaging. The monotonic trend (~5% gradient across the detector), similar to that seen for the side-window tubes is a surprise. Because the electron beam is nominally perpendicular to the target, we would expect any trend to be symmetric about the center of the detector. However, it is possible that the electron beam is slightly off-axis, and that the target thickness may not be uniform. We measured spectra over the angular range subtended by the DDA, and found only a slight shift to higher energies for the region that shows higher greyscale. This is consistent with the trend observed for the two side-window tubes, though smaller in magnitude. It would be instructive to measure the output of additional end-window tubes to determine whether there is a pattern.
CONCLUSIONS

We have demonstrated that significant trends in DDA images can occur when standard calibration procedures are followed. These trends correlate with differences in the shape of the x-ray spectrum at different angles with respect to the nominal beam axis. Although fine details in an image are not compromised by this trend, quantitative measurements of density or thickness become problematic. The effect is most pronounced at low energies.

Best results from DDA imaging are obtained by calibrating the detector under conditions similar to those used for imaging. Thus, a filter of the same material and thickness as the sample should be used for calibration at the same kVp to be used for imaging. These effects can also be reduced by positioning the detector farther from the source to reduce the solid angle. For micro-focus tubes, the focal spot for calibration should be similar to that used for imaging, even though the greyscale value may not reach the recommended maximum for calibration.

In future work we plan to extend these measurements to higher energies and additional materials. We would also like to obtain data from additional end-window x-ray tubes to check the single measurement that we made.

ACKNOWLEDGMENTS

This research was funded through the Pratt & Whitney Center of Excellence at Iowa State University.

REFERENCES