Noise evaluation of a digital neutron imaging device

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ABSTRACT

To assess the applicability of neutron radiography technology, it is important to compare the performance characteristics of different neutron detection systems and their implementations. Although widely used in X-ray imaging, performance evaluation measures, such as the noise power spectrum (NPS) and the detective quantum efficiency (DQE), have not been readily applied to neutron radiography. This paper introduces the concepts of NPS and DQE and presents an adopted procedure for the calculation of NPS and DQE, using an in-house developed digital neutron radiography device as an example. This low-cost radiography apparatus has remarkable features such as using an off-the-shelf digital camera modified by open-source code and a front surface aluminized mirror made of Li-doped glass. The results show that a high spatial resolution does not necessarily translate to better detectability of faint details and noise evaluation has to be taken into account. In order to improve the poor DQE of the evaluated system, it is suggested to reduce the fast neutron content and increase the light collection efficiency. Such improvements would bring the output signal-to-noise ratio (SNR) much closer to the input quantum noise, which would consequently increase DQE.

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1. Introduction

The earliest neutron radiography work dates back to 1948 [1]. Extensive work was performed during the following decades to develop this technique [2] that continues to provide solutions to this day for hard-to-solve problems that encompass a wide variety of topics, such as imaging water flow in fuel cells [3], detecting drugs and explosives [4], and revealing illicitly smuggled special nuclear materials [5,6], to name a few. Such increased number of applications was made possible by the rapid advancement of detector technologies [7], especially the digital radiography instruments [8]. This transition has fostered the advancement of methodologies that allow characterization of image quality and provide metrics used to compare existing and emerging neutron detector technologies.

However, the performance evaluation criteria and methods for neutron radiography have fallen far behind what has been practiced in X-ray imaging, where the modulation transfer function (MTF) [9], noise power spectrum (NPS), and detective quantum efficiency (DQE) [10] have become widely accepted metrics. In short, MTF describes the detector or system’s spatial resolution in terms of contrast, which is defined as the ratio of output modulation to an input sinusoidal modulation with varying spatial frequency. NPS measures noise amplitude observed in images obtained in a uniform field of radiation. It is argued that contrast alone (i.e., MTF only) is insufficient in describing image quality [11], since MTF ignores noise components. An example of such poor detectability is a high-contrast edge profile image embedded with high noise levels. Therefore, DQE, which quantifies the effects of noise level and contrast performance, better describes the ability to discern small details. A detailed discussion given in this paper shows that DQE, which involves the calculation of both MTF and NPS, reflects how a detector/imaging device produces an output SNR that is degraded from an input SNR in the spatial frequency domain.

In neutron radiography, MTF has won acceptance as the figure-of-merit for spatial resolution [12,13]. However, the debate over MTF and DQE present in X-ray imaging is far from being observed in neutron radiography. A rare discussion of DQE in digital neutron radiography detector can be found in Barmakov’s work [14], but the discussion of DQE’s frequency dependency and its measurement are not included. In X-ray radiology, an imaging system with 20% DQE will require double the amount of incoming photons to produce the same SNR as an imaging system with 40% DQE. Naturally, it is preferred to design an imaging system with a high DQE to reduce patient dose exposure. Even though a patient’s health is not a concern with regard to neutron radiography, it is still desirable to reduce the exposure time, and hence, the ambient radiation and the activation in both the sample and the working environment. More importantly, it is necessary to compare the performance characteristics of different neutron detectors or system implementations to support various applications of neutron radiography technology. The concepts of NPS and DQE are discussed in this paper, with emphasis given to neutron radiography, and the calculation protocol has been partially revised and applied to an in-house developed digital neutron radiography system.

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2. Theory and concepts

2.1. Noise and SNR

An image with good contrast marred by a high noise level points the discussion to the original concept of SNR ratio. The Poisson distribution governing both X-ray photons and neutrons renders a simple relationship between SNR and incident quanta at the input stage, which is given by

\[ \text{SNR}_{\text{input}} = \frac{N}{\sigma_N} = \frac{N}{\sqrt{N}} = \sqrt{N} \]  

(1)

where \( N \) is the number of incident neutrons and \( \sigma \), the standard deviation, is equal to the square root of \( N \). While this parameter (known as photon noise or quantum noise) shows that the performance of an imaging system (radiation source included) can be improved by improving the radiation source strength or exposure time, it has little to do with the detector’s performance.

Thus, the output SNR has to be accounted for, given by

\[ \text{SNR}_{\text{output}} = \frac{\bar{P}}{\sigma_{\bar{P}}} \]  

(2)

where \( \bar{P} \) is the mean pixel value and \( \sigma_{\bar{P}} \) is the standard deviation of the pixel value.

In an ideal detector, in which there are no other sources of noise and a one-to-one correspondence exists between an absorbed neutron and a registered pixel value, the output SNR is equal to the input SNR. However, in reality, there are signal loss and noise gain during the signal conversion stages inside the imaging detectors. This causes the output SNR to be smaller than the input SNR.

2.2. Noise equivalent quanta and DQE

When assuming that quantum noise is the dominating factor in the system noise, it is useful to determine how the other minor sources of noise decrease the ideal SNR. Intuitively, one can relate the measured output SNR to an imaginary incident neutron quantity that would be known if the imaging system served as an ideal neutron counter. This quantity is called the noise equivalent quanta (NEQ) [10] and is written as

\[ \text{NEQ} = (\text{SNR}_{\text{output}})^2 \]  

(3)

NEQ informs about the effective number of neutrons used by the detector or system (radiation source excluded) to produce the measured SNR. With this definition and (1), DQE [10], can be expressed as

\[ \text{DQE} = \frac{(\text{SNR}_{\text{output}})^2}{(\text{SNR}_{\text{input}})^2} = \frac{\text{NEQ}}{N} \]  

(4)

In this form, DQE becomes a metric that relates the imaging system’s ability to receive incident quantum and produce an output of a desired quality. The best output SNR obtainable in an ideal system is equal to the input SNR. Such condition would suggest a one-to-one correspondence and an absence of measurement errors and other extraneous factors. Naturally, DQE will always fall in the range 0–1.

2.3. Noise power spectrum (NPS)

The second challenge presented by (1) and (2) is their weakness in addressing the spatial correlation of noise. It is known that the image formation chain normally consists of multiple signal transform processes. Some of the intermediate signals inside the detector may be spatially (or partially) correlated even though neutrons are spatially independent of each other. Thus, it is necessary to use second-order statistical measures that not only describe the power or intensity of the noise, but also describe the spatial correlations within it.

NPS, also recognized as the Wiener spectrum, is routinely applied in X-ray radiology, and should be used in neutron radiology to characterize the noise. For a stationary random process, NPS is the Fourier transform of the auto-covariance function. The computational equation is given as [15]

\[ \text{NPS}(u,v) = \lim_{M,N \to \infty} \frac{\Delta x \Delta y}{M \cdot N \cdot \bar{S}} \sum_{m=1}^{M} \sum_{n=1}^{N} [l(x_m,y_n) - \bar{S}]^2 \]  

(5)

According to (5), a gray scale radiographic output consists of \( M \) regions of interests (ROI), where each ROI is a matrix of \( N_x \) by \( N_y \) elements, or pixels. Each pixel position within a ROI is identified by Cartesian coordinates \((x,y)\) and its gray scale intensity is denoted as \( I(x,y) \). In addition, for each ROI, a two-dimensional polynomial \( S \) is fitted to determine the mean of the region. The two-dimensional Fourier transform is applied to each ROI corrected for the mean trend, \( r(x,y) = I(x,y) - \bar{S}(x,y) \), and then squared. The resulting sum of squared Fourier transform amplitudes must be divided by \( M \) to achieve a representative result for an average ROI. Furthermore, the results of the average ROI must be multiplied by the pixel size (where \( \Delta x \) and \( \Delta y \) are pixel width and height in the \( i \) and \( j \) directions, respectively) and then normalized by the number of pixels in the ROI \( N_x \) and \( N_y \) that correspond to number of pixels in the \( i \) and \( j \) directions.

A complete derivation of a one-dimensional case can be found in the book written by Blackman [16], and the extension to a two-dimensional case is obvious. Eq. (5) implies that NPS can be understood as the variance of image intensity described in a spatial frequency domain. Not surprisingly, the internal mechanism of the detector/imaging device has a tendency to blur both the input signal and noise alike, which usually translates to a decrease in power of these noise sources with increasing spatial frequency [17].

2.4. The DQE in frequency domain

Many authors [18] express NEQ as function of spatial frequency. In particular, Dobbins [19] gives NEQ as the ratio of MTF to NPS at a given frequency \( f \), shown in

\[ \text{NEQ}(f) = \left( \frac{\text{SNR}_{\text{output}}^2}{\text{SNR}_{\text{input}}^2} \right) = \frac{\text{MTF}^2(f)}{\text{NPS}(f) / \bar{S}^2} \]  

(6)

here \( \text{NPS}(f) \) is normalized by the square of the mean pixel value of the image, \( \bar{S} \). Since all the terms are ready to be measured, (6) is inserted into (4) to determine DQE as a function of frequency

\[ \text{DQE}(f) = \frac{\bar{S}^2 \cdot \text{MTF}^2(f)}{\text{NPS}(f) \cdot N} \]  

(7)

Eq. (7) is used to calculate DQE of a low-cost neutron radiography system developed originally at the National Institute of Standards and Technology (NIST) by the author and further modified at The Ohio State University for this study.

3. The in-house made digital neutron radiography system and its MTF

The low-cost digital neutron radiography system, for which the performance is evaluated as an example, was first developed at NIST 20 MW research reactor to “see” the focal spot of a neutron lens in real-time [20]. The remarkable components of this
imaging device include a commercial off-the-shelf webcam and an aluminized front surface mirror deposited on a $^6$Li-doped glass. The $^6$LiF(ZnS) scintillation screen used in this work emits green light when exposed to neutrons. The dimensions of the screen are about $8.89 \text{ cm} \times 8.89 \text{ cm}$. The mirror not only reflects the visible light but also absorbs remaining neutrons to eliminate the sources of prompt gamma rays and scattered neutrons that are harmful to a CCD camera.

However, the low neutron flux level present in the 0.5 MW Ohio State University Research Reactor (OSURR) is insufficient to allow using a webcam for real-time imaging. As shown in Fig. 1, an off-the-shelf Canon digital camera was used in a light-tight aluminum box with the same scintillation screen and $^6$Li doped front surface mirror. Canon PowerShot 8 MP digital camera was modified using an open-source code to permit infinitely long exposure, replacing a conventional deployed high-cost and cooled CCD camera. A remote trigger was attached to the camera to allow for long-distance control over the camera’s focus and image capturing mode. As an example of the imaging system's performance, a beam purity indicator (BPI) that is in-house fabricated per the instruction of ASTM standard [21] was imaged for 64 s. The BPI is a polytetrafluoroethylene (PTFE) block containing two boron nitride disks, two Pb disks and two cadmium wires. An image from neutron radiography and a photo of BPI are shown in Fig. 2.

The incident neutrons are provided by OSURR, capable of 500 kW of thermal power, through a neutron collimator in Beam Port 2 [22]. The thermal equivalent neutron flux is $(4.75 \pm 0.11) \times 10^6 \text{ cm}^{-2} \text{s}^{-1}$ at 250 kW when imaging the BPI, and the cadmium ratio is $266 \pm 13$. It is worth noting that this cadmium ratio indicates a relatively higher fast neutron content from the

![Fig. 1.](image1)  
(a) A schematic representation of the imaging system. (b) Open view of the light-tight box with Canon digital camera (1), $^6$Li doped mirror (2), and $^6$LiF(ZnS) scintillation screen (3). (c) Photo of the setup during the imaging experiment: (1) lift column with shutter raised to allow for the neutron beam to pass, (2) light-tight box with a digital camera inside, (3) beam stop.

![Fig. 2.](image2)  
(a) A photo of a beam purity indicator, which is a polytetrafluoroethylene (PTFE) block containing two boron nitride disks, two Pb disks and two cadmium wires. (b) A radiographic image of a beam purity indicator captured using the experimental imaging setup; the exposure time is 64 s. Cadmium rulers with ticks every one centimeter were placed on the front surface of the box as a position reference.
neutron source than those of cooled with cold source at national laboratories. Therefore, the scattering of fast neutrons may account for the spatially correlated noise found in the evaluation. The spatial resolution is determined from MTF measurements of a thin edge-polished cadmium target according to the angulated edge method [23]. The geometry of the imaging system is set up in a way that each pixel in camera represents 54.3 μm of real object dimension. To preserve the generic shape, a MATLAB smoothing filter is applied during the calculation. Fig. 3 shows MTF after application of the digital filter. The spatial frequencies at 50%, 10%, and 3% of MTF are at about 0.24, 0.39, and 1.07 cycles/mm or lp/mm, respectively. The 10% MTF spatial frequency suggests the system’s spatial resolution of about 1.28 mm.

4. Measurement of NPS

NPS of the neutron detector/imager is determined using a flat-field image obtained under the same conditions that are used to determine the system’s MTF curve. The computation method is based on the performance evaluation of an X-ray radiology device [24–26] and partially follows the international standard IEC 62220-1 [27]. In the standard, an X-ray tube serves as the radiation source, whereas in this evaluation, a nuclear reactor provides neutrons. The following steps summarize the procedure:

1. A portion of the uniformly illuminated image area used for the NPS analysis is divided into square areas (ROIs) with dimensions of 64 × 64 pixels. The ROIs are sequentially generated by moving previous ROI 32 pixels in the horizontal direction to the right until a boundary is reached and then by moving 32 pixels down in the vertical direction. A series of overlapping ROIs is produced in this way.
2. Due to the non-uniformities of the neutron detector, trend removal is performed to subtract low frequency content by fitting a two-dimensional, second-order polynomial to each ROI. According to (5), the resulting function \( S(x_i,y_j) \) is subtracted from the original pixel value, \( I(x_i,y_j) \).
3. A two-dimensional Fourier transform is applied to each ROI.
4. The procedure is repeated for each ROI and the results are averaged.
5. To obtain one-dimensional cuts through the two-dimensional NPS along the axis of the spatial frequency plane, 33 rows or columns of the two-dimensional spectrum around each axis are used. However, the average is taking using only sixteen rows or columns on both sides of the corresponding axis (a total of 32), omitting the axis itself.

Since NPS is interpreted as the variance of a particular frequency component, its unit is \( (1/mm^{-1}) \times (1/mm^{-1}) = mm^2 \) for two-dimensional images.

The code developed to calculate NPS in this work was tested by a noise pattern provided by Padgett [24]. The noise pattern contains a Poisson noise distribution with a mean value of 1000. With the pixel size of 0.2 mm, the normalized NPS of this white noise is a near constant value, \( 3.0 \times 10^{-5} mm^2 \). The above procedure correctly predicted NPS, as shown in Fig. 4. While the power spectrum of white noise is preserved as an approximate constant as shown in Fig. 4, NPS is expected to decrease with an increasing frequency in a real scenario depending on the degree of partial correlation of noise [28].

5. Discussion of NPS and DQE

NPS of the developed neutron imaging device is computed using a flat-field image obtained by the digital camera. Fig. 5 shows the results, from which it can be observed that NPS contrary to the results of Fig. 4 does not remain constant. Constant-shaped NPS such as the one shown in Fig. 4 is representative of Poisson-governed neutrons entering the imaging system. The deviation from this theoretical state suggests an inherent system/process error that leads to a distortion of signals. More specifically, this result indicates a correlation of noise, which may be explained by the scattering effect of the fast neutrons in the detector and the light spread out within the scintillation screen and the pixel array. The effect of neutron scattering tends to behave like a smoothing filter and thus cause disruptions in signal at higher spatial frequencies. For instance, an image of sharp edge will experience blurring and smoothing due to a neutron scattering. In addition, the decrease in NPS visible in Fig. 5 suggests that the additional noise introduced into the final output outweighs the Poisson distribution of the quanta noise, which would have otherwise remained constant.

After NPS and MTF are determined, (7) is used to calculate DQE, which is shown in Fig. 6. It can be seen that DQE also
decreases as the spatial frequency increases. Furthermore, based on the results of Fig. 6 in comparison with Figs. 3 and 5, it appears that the shape of the system's DQE is more reminiscent to that of the MTF curve. This can be partially explained by the rapid decrease in the system's MTF at higher spatial frequencies and a curve approaching a near zero value. The square of MTF in (7) appears to outweigh the influence of the shape of the NPS curve as evidenced in Fig. 6.

From Fig. 6, the highest DQE value is about $3.1 \times 10^{-4}$. In comparison, DQE of X-ray radiology devices commonly ranges from 0.1 to 0.4. This is not surprising since the intensity of incident quantum in neutron radiography is normally several orders of magnitude lower than that of a photon quantum used in X-ray radiology. In addition to this prominent factor, the lower DQE may be also due to: (1) the relatively low neutron detection efficiency; (2) the higher content of fast neutrons, whose scattering not only contributes noise, but also the spatially correlated noise; and the loss of signal collection in the optical chain as a result of poor light collection in a light-tight box [29].

6. Conclusion

DQE describes the noise transfer characteristics of a detector in terms of how the input SNR, or the pure quantum noise, is degraded after passing through a neutron detector or imaging system. Since a radiography system's detectability of small details is better quantified by DQE instead of MTF, NPS and DQE were applied to evaluate the performance of a high-resolution digital camera neutron detector. A Poisson noise test pattern was used to verify the correctness of NPS calculation. The results indicate that although the radiography system exhibits a high performance in terms of spatial resolution, it does not necessarily have a great detectability of small details. The DQE is dominated by MTF in this example. The reduction of SNR at increased spatial frequencies suggests the need to decrease the fast neutron content and to increase the light collection efficiency. Both implementations are necessary to bring output SNR closer to the input SNR.

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