Radiographic screen–film noise power spectrum: calibration and intercomparison

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The magnitude of a measurement of the noise power spectrum (NPS) of a radiographic screen–film system is affected by the light-scattering properties of the film studied and the optical characteristics of the microdensitometer used to sample the image. To facilitate absolute NPS intercomparisons among laboratories, NPS in terms of instrument density must be converted to diffuse density. Conversion in terms of a Callier Q factor was found to be inadequate due to nonlinearity of the density response of the microdensitometer. By establishing instrument-to-diffuse density characteristic curves for the microdensitometers at two laboratories and correcting the NPS by the square of the slopes of these curves at the density of the image, good agreement was achieved for independent NPS measurements of a given film sample.

I. Introduction

The determination of the noise power spectrum (NPS) of a radiographic screen–film image is generally accomplished by the microdensitometric measurement of fluctuations of transmission optical density. The squared moduli of Fourier transforms of these density fluctuations are used to calculate the NPS according to the definition[1]

$$W(u,v) = \lim_{X,Y\to\infty} \left\langle \frac{1}{2X}\frac{1}{2Y}\left| \int_{-X}^{+X}\int_{-Y}^{+Y} \Delta D(x,y) \times \exp[-2\pi i(ux+vy)]dxdy \right|^2 \right\rangle, \quad (1)$$

where x and y are the coordinate space axes, u and v are the corresponding frequency space axes, ΔD is the density fluctuation, and $\langle\ \rangle$ denotes an ensemble average.

The actual density quantity whose fluctuations are being measured depends on the optical instrument used and its optical coupling to the emulsion being evaluated. Densitometers that illuminate the sample with a narrow beam of light and collect transmitted light from 2π sr measure diffuse transmission density.[2] Densitometers that both illuminate with and collect very narrow beams measure specular density, which depends on the scattering properties of the emulsion as well as the collecting properties of the instrument optics. The ratio of specular to diffuse density of a sample is called the Callier coefficient Q of the sample.[3] Most microdensitometers both illuminate and collect light over small angles (the sine of the half-angle ranges from 0.05 to 0.25), hence their measurements approximate specular densities. But the illumination and collection angles are finite in practical microdensitometers and vary between instruments. Therefore, the density D_I of a sample measured with a particular instrument will be peculiar to the instrument used. If the density fluctuations in Eq. (1) are expressed in terms of D_I, the resulting NPS will have a magnitude peculiar to the microdensitometer used to perform the measurement. It is desirable to convert the ΔD measured by the microdensitometer to fluctuations of diffuse density D_D so that the magnitude of the NPS is intercomparable between laboratories.

II. Theory

The similar problem of converting measurements of rms granularity, $\sigma(D)$, from instrument to diffuse density was addressed by Schmitt and Altman.[4] Their solution was to measure net (above base but including fog) instrument density and net diffuse density of a particular film type exposed to a given density and to correct granularity measurements by dividing those made in instrument density by the ratio of the instrument-to-diffuse density. This procedure would work

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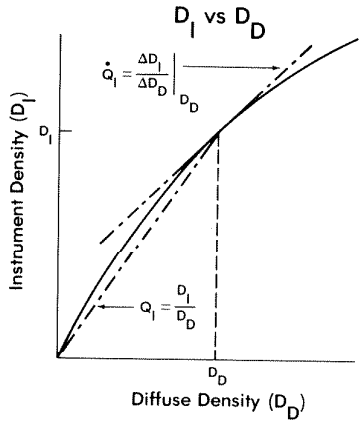

Fig. 1. Hypothetical microdensitometer calibration curve illustrating the difference between Q_I and $\dot{Q}_I$.

in general if the density ratio were constant for all diffuse densities or, equivalently, if the microdensitometer responded linearly for all diffuse densities. The authors state that neither requirement is achieved exactly, although, in practice, the ratio may be sufficiently constant to obtain useful results.

Linear microdensitometers have been designed that measure diffuse transmission density directly.[5,6] The main purpose in designing such microdensitometers is to eliminate problems of partial coherence in the optical system and achieve a system that is linear in the sense that the microdensitometer output is the convolution of the intensity transmittance of the sample with the projected source aperture. However, such a densitometer was not available to the authors or to any of the laboratories with which they have intercompared results, and the need to correct the measured NPS remains.

The nature of the error in an NPS corrected by a ratio of densities is illustrated in Fig. 1, which shows a hypothetical microdensitometer characteristic curve. A correction factor Q_I analogous to that described above is defined in terms of gross instrument density, D_I, and gross diffuse density D_D, as

$$Q_I = D_I/D_D. \tag{2}$$

Q_I is the slope of a linear operating characteristic defined over the range of 0–D_D gross diffuse density. However, the slope of the microdensitometer characteristic may differ from that given by Q_I when measuring small fluctuations of density about D_D. Since it is these fluctuations that must be used in Eq. (1), the calibration of the microdensitometer must be in terms of the slope of the characteristic at the density of the film being analyzed. This slope is defined as

$$\dot{Q}_I = \left.\frac{\Delta D_I}{\Delta D_D}\right|_{D_D}, \tag{3}$$

where the dot identifies an instantaneous or point value of Q_I.

A relation linking Q_I and $\dot{Q}_I$ can be derived if one assumes that Q_I does vary with D_D and expresses the differential of D_I as

$$\Delta D_I = Q_I \Delta D_D + D_D \Delta Q_I. \tag{4}$$

Then

$$\frac{\Delta D_I}{\Delta D_D} = \dot{Q}_I = Q_I + D_D \frac{\Delta Q_I}{\Delta D_D}, \tag{5}$$

or

$$\dot{Q}_I = Q_I \left(1 + \frac{D_D}{Q_I}\frac{\Delta Q_I}{\Delta D_D}\right). \tag{6}$$

If Q_I is independent of D_D, then $\dot{Q}_I = Q_I$. However, in general, using Q_I instead of $\dot{Q}_I$ to correct the NPS introduces a relative error of $\sim 2(D_D/Q_I)(\Delta Q_I/\Delta D_D)$ into the resulting NPS since the correction is applied to the squared density fluctuations. The magnitude of this error will be estimated for a particular case in Sec. IV.

III. Methods

Film samples for the measurement of NPS were prepared at the Kurt Rossmann Laboratories for Radiologic Image Research (K. Doi, director), U. Chicago, as part of a general screen–film imaging-characteristic intercomparison project.[7,8] Kodak XRP films[9] were exposed with DuPont Hi-Plus and Detail screens[9] to a gross diffuse density of 0.98 and 0.97, respectively. For the intercomparisons described here, NPS measurements were performed on the same set of film samples at the Bureau of Radiological Health, Division of Electronic Products, Medical Physics Branch (BRH) and at the Los Alamos National Laboratory.

At BRH the film samples were scanned on a Perkin-Elmer PDS microdensitometer[9] equipped with 4×, 0.11 N.A. objectives and a slit size of $15 \times 588\ \mu m^2$ at the film plane. The method of NPS determination has been described in detail.[8,10,11] Factors of relevance to the present discussion are the effective slit length, which was extended to 5.88 mm by acquiring ten contiguous scans, and the standard error of the spectral estimates,

which was ±5%. A section of the 2-D NPS was estimated from linear, 1-D microdensitometric scans using standard methods.[12–14] The calibration of the microdensitometer was accomplished by performing a Tchebycheff polynominal fit of the measurements of D_I obtained from a scan of a sensitometric image (described below) vs the diffuse densities on the image; typically a fifth or sixth-order fit was used. The slope $\dot{Q}_I$ of the curve fit at the average gross diffuse density of the NPS image was used to convert the NPS to express fluctuations of diffuse density by dividing the original NPS by $(\dot{Q}_I)^2$ at each spatial frequency.

At Los Alamos the film samples were also scanned with a Perkin-Elmer PDS microdensitometer using either 6×, 0.17 N.A. or 3×, 0.10 N.A. objectives. However, the 2-D NPS was obtained directly by 2-D sampling of the image and application of a 2-D FFT. The high-frequency portion of the NPS was measured by sampling with a 25×25-μm^2 aperture in 12-μm steps in both directions. A total film area of 1.84×1.84 cm^2 was segmented into 256×256-pixel^2 regions. Each region was windowed with a square Hanning window and 2-D Fourier transformed. The average NPS from these thirty-six regions was corrected for the aperture size and normalized using the known effect of the windowing function and the $\dot{Q}_I$ measured for the microdensitometer. Finally, the average radial frequency dependence was obtained from the 2-D NPS. The low frequencies were measured by sampling with a 100×100-μm^2 aperture in 40-μm steps. A total film area of 7.17×7.17 cm^2 was segmented into forty-nine regions, each 256×256 pixels^2 in size. The analysis then followed that used for the high frequencies. The low- and high-frequency NPS were in good agreement between 2 and 6 cycles/mm and, arbitrarily, the low-frequency data were used up to 4.4 cycles/mm and the high-frequency data above that. The standard deviation in the spectral densities is ~5% at 0.39 cycles/mm and improves as the frequency increases since the number of contributing 2-D frequency bins increases. The calibration of the microdensitometer at Los Alamos was carried out using the sensitometric image described below.

Values of Q_I and $\dot{Q}_I$ vs D_D were determined from microdensitometric scans of sensitometric images generated by inverse square, x-ray sensitometry using radiographic intensifying screens with Kodak XRP film. The sensitometric image consisted of twenty-one steps at increments of 0.1 on a logarithmic (base 10) x-ray exposure scale. Diffuse densities were measured on a Macbeth model TD404 densitometer[9] calibrated with a National Bureau of Standards photographic step tablet, standard reference material 1008. The step wedge was scanned with all apertures used for the NPS measurements and appropriate corrections applied to each NPS.

IV. Results

Figure 2 shows plots of Q_I and $\dot{Q}_I$ vs D_D for measurements made at BRH. The data for Q_I are typical of those for the Callier Q factor expressed in terms of gross densities.[3] The slope $\Delta Q_I/\Delta D_D$ of the linear portion of the plot between $D_D = 0.5$ and 2.5 is −0.10. At $D_D = 1.0$, the typical density of the noise images we have examined, $Q_I = 1.57$. Hence, in Eq. (6), the term $(D_D/Q_I)(\Delta Q_I/\Delta D_D) = -0.064$. Correcting the NPS by Q_I^2 instead of $\dot{Q}_I^2$ would underestimate the NPS by ~13%. The value of $\dot{Q}_I$ used to correct the NPS was 1.47.

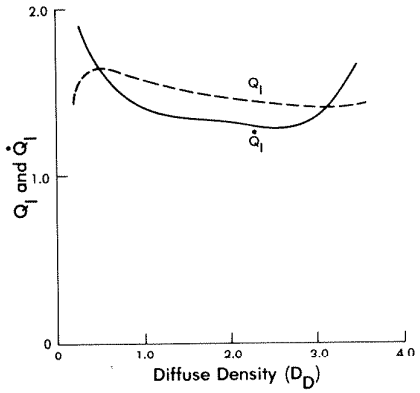

Fig. 2. Q_I and $\dot{Q}_I$ vs diffuse density measured at BRH on Kodak XRP film; sampling aperture = 15×588 μm^2, N.A. = 0.11.

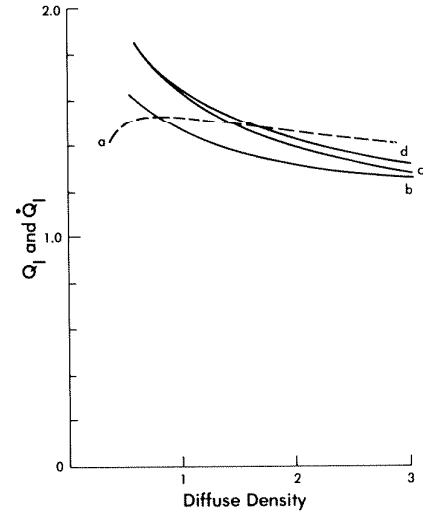

Fig. 3. Q_I and $\dot{Q}_I$ vs diffuse density measured at Los Alamos on Kodak XRP film: (a) Q_I, 100-μm square aperture, 0.17 N.A.; (b) $\dot{Q}_I$, 100-μm square aperture, 0.17 N.A.; (c) $\dot{Q}_I$, 25-μm square aperture, 0.17 N.A.; (d) $\dot{Q}_I$, 25-μm square aperture, 0.10 N.A.

Q_I and $\dot{Q}_I$ data measured at Los Alamos are plotted vs diffuse density in Fig. 3. These data were acquired for both sampling apertures—25×25 and 100×100 μm^2—and both numerical apertures—0.10 and 0.17—used when measuring the NPS. Q_I has a density dependence similar to that shown in Fig. 2. Changing the sampling aperture (Fig. 3, curves b and c) was observed to have a greater effect on $\dot{Q}_I$ than changing the numerical aperture (curves c and d). Apparently, in-

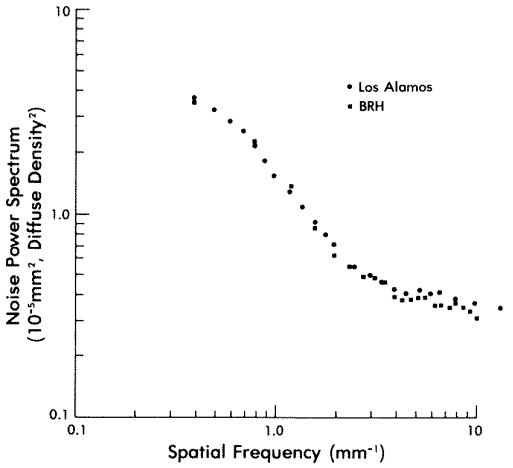

Fig. 4. Comparison of NPS of Hi-Plus/XRP film sample measured by BRH (■) and by Los Alamos (●). BRH measurements used 5.88-mm slit length; Los Alamos low-frequency measurements used a square Hanning window with a FWHM of 5.1 mm.

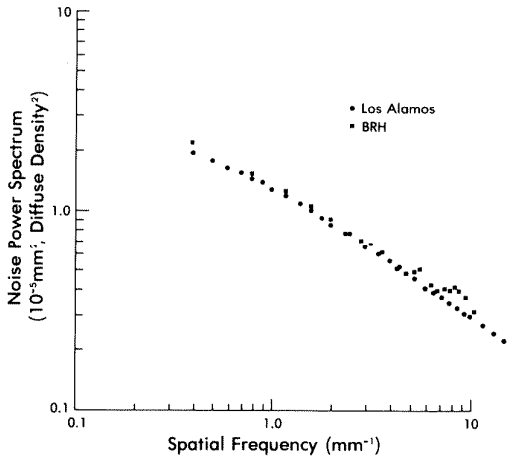

Fig. 5. Comparison of NPS of Detail/XRP film sample measured by BRH (■) and by Los Alamos (●). Measurement conditions are as for Fig. 4.

creasing the illuminated areas of the film and the optics by a factor of 16 by increasing the sampling aperture has more effect on reducing the specularity of the transmission than does increasing the acceptance area by a factor of ~2.9 by increasing the N.A. Although only one plot of Q_I vs D_D is shown in Fig. 3, Q_I exceeded $\dot{Q}_I$ at D_D = 1.0 for all sampling and numerical apertures. This excess was ~4% for the 100 × 100-μm^2 sampling aperture and ~7% for the 25 × 25-μm^2 aperture. Values of $\dot{Q}_I$ used to correct the NPS were 1.46 for the large sampling aperture and 1.62 for the small one.

Figures 2 and 3 demonstrate that both Q_I and $\dot{Q}_I$ are density dependent and, therefore, so is the error in the NPS corrected by Q_I instead of $\dot{Q}_I$. At a particular low density—D_D = 0.5 in Fig. 2 and 0.8 in Fig. 3—Q_I equals $\dot{Q}_I$ and no error is introduced. However, at lower densities the curves deviate rapidly. At higher densities the curves are approximately parallel and slowly varying over a range of ~1.5 density units. At D_D = 2.0, Q_I exceeds $\dot{Q}_I$ by 12% in Fig. 2 and 11% in Fig. 3. NPS at this density corrected by Q_I^2 would be underestimated by more than 20%.

A comparison between the two laboratories of NPS expressed in diffuse density is shown in Fig. 4 for measurements on the Hi-Plus/XRP system and in Fig. 5 for the Detail/XRP system. The agreement is very good. In the 0.4–5-cycles/mm frequency range the spectra agree to within 10%; at frequencies up to 10 cycles/mm the agreement is to within 20%. It is expected that, at the higher frequencies, frequency-dependent effects of the microdensitometers may begin to influence the spectra. Nevertheless, in a frequency range of importance to the analysis of radiographic screen–film imaging, the NPS was measured with very good precision by two laboratories using independent methods of data acquisition and analysis.

V. Discussion

The need for an improvement in the method of expressing NPS in terms of diffuse density became apparent after replacing the photomultiplier tube (PMT) in the BRH microdensitometer. When expressed in terms of D_I, NPS measured after replacing the PMT agreed, within the estimated statistical uncertainty, with the NPS measured previously on the same film sample. However, the average D_I over the scanned area of a particular film sample was 1.54 with the old PMT and 1.44 with the new one. Since D_D of the sample had not changed, this 6.7% shift in Q_I would produce a shift of ~13% in an NPS converted by division by Q_I^2.

During the course of expanding the screen–film imaging-characteristics intercomparison study, the concept of using the differential measurement of Q_I to convert NPS to fluctuation of diffuse density evolved. Subsequently, measurements of the microdensitometric characteristic curve were made routinely, and the conversion of NPS was performed using $\dot{Q}_I^2$ as described above.

Measurements of $\dot{Q}_I$ made before and after changing the PMT are shown in Fig. 6. At D_D = 1.0, $\dot{Q}_I$ was 1.40 before the change and 1.42 after—a 1.4% difference. The difference in the correction applied to the NPS would be <3%. After both NPS were converted to diffuse density, the rms deviation between corresponding frequency elements over the range of 0.39–10.16 cycles/mm was 4.5%.

Naturally it is prudent to reexamine the characteristics of an instrument after replacing one of its major components. Being able to generate and analyze the characteristic curves with reasonable facility can provide such information as well as provide additional insights about the behavior of the instrument. For ex-

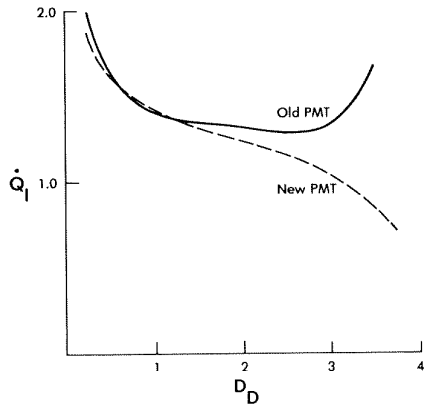

Fig. 6. $\dot{Q}_I$ vs diffuse density for characteristic curves measured before and after changing PMT.

ample, by acquiring D_I vs D_D data at intervals over a 25-h period, we established the warm-up characteristics of the BRH microdensitometer. We found that the instrument must remain on for at least 5 h before the D_I and $\dot{Q}_I$ readings attain a plateau value for $D_D = 3.8$. At $D_D = 1.0$, the readings were stable after 3 h.

Finally, it is apparent from Fig. 6 that $\dot{Q}_I$ is not constant. Therefore, the D_I to D_D conversion is nonlinear, and ideally it should be performed prior to the Fourier transformation given in Eq. (1). While this conversion would be straightforward for digitally processed data, it may be difficult to implement in analog NPS systems. However, for D_D in the 1.00 ± 0.02 range that is typically achieved, $\dot{Q}_I$ has a range of ~0.015 and a typical magnitude of 1.50 (for XRP film). Therefore, we consider it sufficiently accurate to apply the correction to the NPS instead of to the density measurements. This manner of correction should also be readily adaptable to analog systems.

VI. Conclusion

Since film densities and their fluctuations measured with a microdensitometer will vary between instruments, it is desirable to convert an NPS expressed in terms of instrument density to one expressed in terms of diffuse density for which standard measurement methods exist. This can be done by establishing an instrument density-to-diffuse density calibration curve of the microdensitometer and correcting NPS by the square of the slope $\dot{Q}_I$ of that curve at the diffuse density of the examined image. $\dot{Q}_I$ has been found to be ~1.5; hence, the correction is by a factor of ~2. NPS measured independently and by different methods at two laboratories were found to be in good agreement when corrected to fluctuations of diffuse density by this method. We feel that establishment of the NPS magnitude with this technique will facilitate the intercomparison of NPS between laboratories and contribute to a consensus methodology for NPS measurement.

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