A method of determining noise in X-ray films

C. Albrecht and J. Proper

In photography, as in electronics, the signal-to-noise ratio is an important quantity; together with the contrast and sharpness of the image, it determines the perceptibility of details. The noise in radiographs is attributable both to the graininess of the film and to statistical fluctuations in the intensity of the X-ray beam. A method for measuring the transmission noise of X-ray films has been developed in which the film sample is scanned by a beam of light that is made narrow because of the relatively great thickness of these films. With this method several film samples can be rapidly investigated one after the other.

Introduction

To make a correct diagnosis a radiologist sometimes has to be able to observe details in a radiograph which are as fine as about 40 microns in diameter. Detail perceptibility may be limited not only by lack of contrast or by blurring but also by noise, caused on one hand by the grainy structure of the film emulsion (film noise) and on the other by the statistical fluctuations in the intensity of the X-ray beam used in making the radiograph (shot noise from the stream of X-ray quanta, briefly referred to as quantum noise).

Instruments known as microdensitometers have long been used for studying fine details in photographs made by visible light or infra-red. The noise is measured by scanning a film specimen with a beam of light and detecting the fluctuations in the quantity of transmitted light by means of a photomultiplier tube or photo-electric cell [1]. The operation of such an instrument is illustrated in fig. 1. An image of the diaphragm $D_1$ illuminated by the lamp $S$ and the condenser lens $C_1$ is formed on the film $F$ by the objective $O_1$, and the objective $O_2$ forms an image of the illuminated patch of film on the measuring diaphragm $D_2$, whose aper-

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ture can be changed by changing the diaphragm. To avoid scattered light, $D_1$ is always made greater than $D_2$. The light transmitted by $D_2$ is focused on to the cathode of the photomultiplier tube $PM$ by the condenser lens $C_2$.

If the film holder $H$ is now made to rotate eccentrically with respect to the optical axis, the light spot will describe a circular path on the film and the photomultiplier tube will give an output signal which is proportional at every instant to the local transmission $T$ of the film, averaged over the area of the light spot. The transmission, averaged over time, through the area of the dimensions it is therefore still possible to use a scanning beam whose cross-section at the film is only a few microns. This can be a great advantage in measuring films of very fine structure, e.g. films for cartography and microphotography.

In radiography maximum absorption of X-ray quanta is required, and for this purpose the film base is coated on both sides with a layer of emulsion, giving such a film a total thickness of 200 to 300 $\mu$m. The scanning beam used here therefore has to have a much smaller angular aperture. The fact that this entails less reduction is not a disadvantage, since the smallest de-

![Diagram](image-url)

**Fig. 2.** New arrangement for measuring noise in X-ray films. $S$ mercury-vapour lamp with a light-emitting area of only 300 $\mu$m cross-section (Philips type CS, 100 W). $C_1$ condenser. $D$ diaphragm. $P_1$ adjustable prism which causes the axis of the parallel light beam to coincide with the optical axis of $L$ and $C_2$. $P_2$ and $P_3$ prisms, mounted in the sleeve $K$ fixed to the rotating shaft of $M$, the motor. $L$ objective lens ("Xenotar" f/2.8; 150 mm). $F$ film. $H$ stationary, adjustable film holder. $B$ image of the diaphragm $D$. The image $B$ can be varied in diameter steps by changing $D$, the minimum diameter is 40 $\mu$m, the maximum diameter 1 mm. $C_2$ condenser. $G$ opal-glass disc, cemented to a rod of transparent plastic coated with Al$_2$O$_3$. $PM$ photomultiplier tube. $M_1$ linear-law meter, and $M_2$ root-mean-square meter. Some dimensional data: $S-C_1$ 50 mm. $C_1-D$ 350 mm. Optical path $D-L$ 800 mm. $L-F$ about 150 mm.

film scanned by the light spot is measured with a linear instrument $M_1$, and the effective value of the transmission fluctuations is measured with an instrument $M_2$ which has a square-law characteristic. This effective value is equal to the standard deviation $\sigma(T)$ of the transmission $T^{[2]}$ and is a measure of the noise intensity. The ratio $T/\sigma(T)$ then gives the signal-to-noise ratio of the transmission and can be used; at a given contrast, as the starting point for determining detail perceptibility.

As the layer of emulsion on ordinary photographic films has a thickness of the order of 10 $\mu$m, the light beam used for scanning such films can have a large angular aperture. In this way greatly reduced images can be obtained (a reduction factor of 200 is no exception). With a measuring diaphragm of reasonable tails of interest in an X-ray film are generally larger than in the other photographic films mentioned.

Another difference between the method of measurement we have developed and the conventional microdensitometer is that the light beam rotates and the film holder is kept stationary. This facilitates quick changing of the film specimens and also makes it possible to investigate different zones on one specimen in rapid succession.

**The measuring arrangement for X-ray films**

The arrangement we have designed is shown schematically in fig. 2. The light source $S$ is a Philips type CS 100 W mercury-vapour lamp. This lamp was specially designed for measurement and projection purposes, and has a light-emitting area with a diameter of
only 0.3 mm. The condenser \( C_1 \) forms the light from the mercury lamp into a practically parallel beam, which is directed on to the interchangeable round diaphragm \( D \). The aperture of this diaphragm can be varied in steps from 0.2 mm to 6 mm. The transmitted light beam is reflected by the adjustable prism \( P_1 \) in such a way that the beam axis coincides with the optical axis of the lens system \( L-C_0 \). From the prisms \( P_2 \) and \( P_3 \) the beam then goes to a lens \( L \), an \( f/2.8 \) "Xenotar" objective with a focal length of 150 mm, which produces a 6 times reduced image of the diaphragm on the film \( F \). The prisms \( P_2 \) and \( P_3 \) are mounted in a sleeve \( K \) connected to the shaft of the motor \( M \). When the shaft rotates, the light spot describes a circular path on the film \( F \). The light beam rotates at a speed of 25 revolutions per second, the diameter of the circular path is 35 mm. By changing \( D \) the diameter of the light spot on the film can be varied from 40 \( \mu \)m to 1 mm. The specimens of the film under investigation can simply be inserted in the stationary film holder \( H \), without the motor having to be stopped, which is necessary in the microdensitometer in fig. 1. Moreover the film holder can be adjusted in three directions, lengthwise for good focusing, and horizontally or vertically for examining different parts of the film.

The light passing through the film is directed by the condenser lens \( C_2 \) on to an opal glass disc. This is connected to the window of the photomultiplier tube \( PM \) by a plastic rod coated with \( Al_{2}O_{3} \), so that the light is diffusely distributed over the photocathode of the photomultiplier tube. This ensures that changes in the diameter and point of incidence of the beam have no effect on the output signal, which would otherwise be affected by local differences in the sensitivity of the photocathode. As in the microdensitometer of fig. 1, \( T \) and \( \sigma(T) \) are measured by means of meters \( M_1 \) and \( M_2 \). It has been found that an axial displacement of the film holder by 1 mm in either direction has hardly any effect on the results, indicating that the depth of focus is sufficient to measure relatively thick X-ray films accurately.

Comparison of the measured transmission noise with the quantum noise

The noise measured by the method described is a combination of film noise and quantum noise. The share of the quantum noise can be determined separately in the following way. A measurement is made of the exposure \([3]\) needed to produce a predetermined blackening of the film. This exposure and the quantum energy give the number of quanta incident on unit area of the film; this number is called the fluence, \( \Phi \). The fluence and the absorption coefficient of the film, \( \alpha \), which is determined from the mass-absorption coefficient of the silver bromide in the film emulsion and the mass of \( AgBr \) per m\(^2\), give the number of quanta absorbed per unit area, \( \alpha \Phi \). Since the quantum noise follows a Poisson distribution, the standard deviation or noise related to a surface area of diameter \( d \) is:

\[
\sigma(\alpha \Phi) = \frac{1}{2}d \sqrt{\alpha \Phi}, \quad \ldots \quad (1)
\]

and the signal-to-noise ratio is:

\[
\frac{1}{2}d \sqrt{\alpha \Phi} = \frac{1}{2}d \sqrt{\pi d \Phi}. \quad \ldots \quad (2)
\]

Both quantities are in this case equal.

In order to compare the measured signal-to-noise ratio of the transmission with that which is caused by the quantum noise, it is desirable to express the transmission fluctuations in terms of equivalent fluence fluctuations.

To do this we must take the roundabout route of using the characteristic curve of the film. This gives the relationship between the density \( D \), i.e. the blackening of the film, and the logarithm of the fluence \( \Phi \) (see fig. 3). The density is defined as the negative logarithm of the transmission \( T \):

\[
D = -\log_{10} T. \quad \ldots \quad (3)
\]

![Fig. 3. Typical characteristic curve of an X-ray film, showing the density \( D \) plotted against the logarithm of the fluence \( \Phi \). The gradation \( \gamma \) of the film is the tangent of the slope of the curve \( \beta \). Unlike the characteristic curve obtained on irradiation with visible light, the curve shown in this figure has no linear region. The gradation increases with increasing density.](image)

\[\text{[3]}\] For continuously varying transmission the standard deviation \( \sigma(T) \) is equal to \( \frac{\sqrt{2}}{\pi} \int \frac{(T-\bar{T})^2}{dx} dx \), where \( 2r \) is the diameter of the scanning track. This expression is equivalent to the rms value of \( T \) measured over the circular path.

\[\text{[3]}\] This quantity used to be called the exposure dose; see, for example, J. Hesselink and K. Reinsma, Philips tech. Rev. 23, 36, 1961/62.
The gradation of the film, i.e., the steepness of its characteristic curve, is given by \( dD/d \log_{10} \Phi = \tan \beta \) and is denoted by the symbol \( \gamma \). From (3) it can be shown that

\[
\gamma = \frac{dD}{d \log_{10} \Phi} = \frac{dT}{d \phi} \cdot \frac{\phi}{T}. \quad (4)
\]

In all parts of the film, therefore, a relative increase \( \Delta T/T \) of the transmission is associated with a relative decrease \( \Delta \phi/\phi \) in the fluence, which is given by:

\[
\frac{\Delta \phi}{\phi} = \frac{1}{\gamma} \frac{\Delta T}{T}. \quad \ldots \quad (5)
\]

Here \( T \) and \( \phi \) represent the average values of the transmission and fluence that relate to the background. We may therefore write:

\[
\left\{ \frac{\sigma_{eq}(\phi)}{\phi} \right\}_d = \frac{1}{\gamma} \left( \frac{\sigma(T)}{T} \right)_d, \quad \ldots \quad (6)
\]

where the subscript \( d \) indicates that the measurements were made for surface area of diameter \( d \). The quantity \( \sigma_{eq}(\phi) \) is the “equivalent” standard deviation of the fluence that the measured standard deviation of the transmission would cause if all the noise were due to the X-ray beam. We can now compare quantum noise and film noise in quantitative terms.

If a particular detail with the relative contrast \( \Delta T/T \) is to be perceptible against a background of transmission \( T \), then \( \Delta T/T \) must be at least three times the value of \( \sigma T/T \). Together with equation (6) this gives:

\[
\left\{ \frac{\sigma(\phi)}{\phi} \right\}_d \geq 3 \frac{\gamma T}{\Delta T}. \quad \ldots \quad (7)
\]

We have thus found an expression for the minimum value of the equivalent signal-to-noise ratio of the fluence at which a detail with a particular transmission contrast is still perceptible.

In order to be able to calculate the signal-to-noise ratio with the aid of (7) we still have to determine the value of \( \gamma \) at the given density. To measure \( \tan \beta \) from the density increment accompanying a slight increase in \( \log_{10} \phi \) would not be accurate enough. For this reason, and also to avoid errors due to the Callier effect, we have devised a method of measurement in which the noise meter itself is used for determining \( \gamma \). An underlying principle of this method is that the accuracy of a measurement is increased by frequent repetition of the observation.

For the determination of \( \gamma \) we start by making a test pattern. A lead wheel with about thirty spokes and an inside diameter a little greater than the diameter of the track scanned by the noise meter is placed on a strip of film. After the piece of film has been exposed to X-rays and developed, a high-contrast image of the spoked wheel is obtained. When the strip is scanned with the noise meter the light spot illuminates in turn the exposed parts of the film and the unexposed parts where the spokes were, giving a measurement of the root-mean-square (rms) variation of the transmission. A static measurement at and between the “spokes” gives the peak-to-peak value. From this the calibration constant of the noise meter is found, and with this constant we can thus translate a root-mean-square value into a contrast.

To measure the noise and determine the \( \gamma \) of a film the spoked wheel is now placed on a test strip of the film and a short exposure is made. The wheel is then removed and the test strip is exposed again until the parts of the film outside the spokes of the wheel reach the required density on developing. The initial exposure time is chosen so as to give a relatively small contrast between the spokes and the rest of the film (5 to 10% difference in transmission). When the image of the wheel is scanned with the noise meter in the way described above, the rms value of the transmission variations and the knowledge of the calibration constant give an accurate indication of the difference in contrast caused by a known small change in exposure. From this the value of \( \gamma \) can be calculated. The noise measurement is made on another part of the test strip.

Some results obtained with the new method

Fig. 4 shows the results of measurements on two types of X-ray film, one for industrial use (Gevaert type D4) and one for medical use (Gevaert type D10). The equivalent signal-to-noise ratio of the fluence \( \{\phi/\sigma_{eq}(\phi)\}_d \) is plotted as a function of the diameter of the scanning spot, both on a logarithmic scale for a density \( D = 1.75 \) (solid curves). The measurements were done with X-rays with rms quantum energies of 32 keV and 105 keV. The radiation was so closely filtered that for our purposes it may be regarded as monochromatic. The dashed curves give the value of the signal-to-noise ratio expressed as the number of absorbed X-ray quanta, calculated from (2). This quantity is equal to the value of \( \{\phi/\sigma_{eq}(\phi)\}_d \) that would be found if the transmission fluctuations were caused solely by the statistical fluctuations in the distribution of the incident radiation and by the absorption processes in the film.

As can be seen in fig. 4, the equivalent signal-to-noise ratio of the transmission is virtually equal to that of the quantum noise for both films. Moreover the difference lies within the margin of error in the calculation of the quantum noise. One may therefore conclude that the limiting factor for both films is the quantum noise, since no higher value of the signal-to-noise ratio can be measured on the film than that determined by the quantum noise. From what we have said it follows that the resolution of our noise meter is more than sufficient to determine the noise in the very fine-grained D4 film. The instrument is therefore certainly suitable for measuring the usually rather faster and coarser films for medical applications.
Fig. 4. Signal-to-noise ratio as a function of the diameter \( d \) of the scanning spot for Gevaert films D4 and D10 at two quantum-energy values. The film density \( D \) was in all cases 1.75. Solid lines: signal-to-noise ratio \( \frac{\langle \Phi \rangle}{\sigma_{\Phi}(\Phi)} \) of the fluence obtained from transmission measurements. Dashed curves: signal-to-noise ratio calculated from \( d \), the fluence \( \Phi \) and the absorption coefficient \( \mu \). Apart from slight differences probably due to inaccuracy in the data used for calculating the quantum noise, the measured signal-to-noise ratio is identical with the calculated values in all cases. This implies that in this case the resolution is determined by the quantum noise.

The horizontal chain-dotted lines give the value of the signal-to-noise ratio required for details with a relative transmission contrast of 2% and 10% to be perceived. For example, the circle indicates that for a D4 film with X-radiation of 32 keV and a contrast of 2%, details with a diameter of 250 \( \mu \)m are still perceptible.

It might appear that, as long as the film noise is lower than the quantum noise, the film could be made coarser to increase its speed. In this case, however, the number of quanta required for a particular density will be less, so that the signal-to-noise ratio will be lower. This can be seen clearly for the Gevaert D10 film, which is 30 times faster than the D4 film and has emulsion layers twice as thick, thus requiring 15 times as many quanta to produce the same density. The signal-to-noise ratio would thus have to be a factor of \( \sqrt{15} \) smaller, and this is confirmed by the measurements.

Another thing shown by fig. 4 is that the signal-to-noise ratio is proportional to the diameter of the scanning spot: this also follows from equation (2).

For radiation with a quantum energy of 105 keV the signal-to-noise ratio is smaller than for radiation of 32 keV, because fewer quanta of 105 keV are needed to produce a given density.

One further and final conclusion can be drawn from fig. 4. The smallest transmission contrast \( \frac{\Delta T}{T} \) that is still perceptible to the eye is about 2%. It follows then from (7) that for \( \gamma = 2.5 \), the value of \( \langle \Phi \rangle/\sigma_{\Phi}(\Phi) \) must be at least 375 if details with a diameter of about 250 \( \mu \)m on the D4 film and about 800 \( \mu \)m on the D10 film are to be perceived at an energy of 32 keV. For a contrast of 10%, the D4 film gives a minimum detail size of about 50 \( \mu \)m and the D10 film one of about 150 \( \mu \)m at this quantum energy (lower horizontal chain-dotted line).

This method of measurement has also been used for X-ray films that are used with a fluorescent layer pressed against each side during the exposure, a technique used to increase the sensitivity of the emulsion layers \( [6] \) and reduce the X-ray dose. Our method can also be used for determining noise in radiographs obtained with the aid of an X-ray image intensifier.

Summary. The noise in a radiograph is due not only to the quantum noise of the X-ray beam but also to the grainy structure of the film emulsion. This film noise can be a limit to the quality of the radiograph and thus reduce its usefulness for diagnosis. A simple method has been developed for measuring the signal-to-noise ratio of X-ray films. It uses a rotating beam of light of small angular aperture which scans a stationary film specimen along a circular path. The small angular aperture gives a sufficient depth of focus for the measurement of relatively thick X-ray films (thickness about 0.3 mm). The use of a stationary film holder makes it possible to change film specimens quickly and to measure different parts of films in rapid succession. One interesting result of measurements by this method is that the signal-to-noise ratio of type D4 and D10 Gevaert films has been found to be limited by quantum noise. The method can also be used for measuring the noise characteristic of radiographs taken with the aid of an X-ray image intensifier.


Recent scientific publications

These publications are contributed by staff of laboratories and plants which form part of or co-operate with enterprises of the Philips group of companies, particularly by staff of the following research laboratories:

- Philips Research Laboratories, Eindhoven, Netherlands
- Mullard Research Laboratories, Redhill (Surrey), England
- Laboratoires d'Electronique et de Physique Appliquée, Limeil-Brévannes (Val-de-Marne), France
- Philips Forschungslaboratorium Aachen GmbH, WeiBhausstraße, 51 Aachen, Germany
- Philips Forschungslaboratorium Hamburg GmbH, Vogt-Kölln-Straße 30, 2000 Hamburg 54, Germany
- MBLE Laboratoire de Recherches, 2 avenue Van Becelaere, 1170 Brussels (Boitsfort), Belgium.

Reprints of most of these publications will be available in the near future. Requests for reprints should be addressed to the respective laboratories (see the code letter) or to Philips Research Laboratories, Eindhoven, Netherlands.


C. J. Bouwkamp: Determination of the characteristic of a non-linear resistor by harmonic excitation. Ingenieur 82, ET 1-2, 1970 (No. 5).


K. Mouthaan: Niet-lineariteit van de lawine-looptijdsoscillator. Ingenieur 82, ET 4-7, 1970 (No. 5).


R. Plumier (Centre d’Etudes Nucléaires de Saclay, France) & F. K. Lotgering: Antiferromagnetic interactions between Fe8+ ions at a large distance in Fe12Cu12Rh8S4. Solid State Comm. 8, 477-480, 1970 (No. 6).


H. Schweppe: Excitation of two adjacent resonances with a chosen frequency separation in a ceramic piezoelectric resonator. IEEE Trans. SU-17, 12-17, 1970 (No. 1).


F. F. Westendorp: On the coercivity of SmCo₅. Solid State Comm. 8, 139-141, 1970 (No. 3).


Contents of Mullard Technical Communications 11, No. 108, 1970:

A. J. Guest: Channel multiplier plates for image intensification (pp. 170-176).

J. Wickens: 15 W class A audio amplifier (pp. 177-178).


M. H. Jervis & F. D. Morten: Mercury cadmium telluride infrared detectors, at 5 µm and normal ambient temperature (pp. 182-184).

Contents of Valvo Berichte 16, No. 1, 1970:

F. Weitzsch: Farbabweichungen als Folge von Exemplarstreuungen im Farbart-Teil von Farbfernseh-Empfängern (pp. 1-12).

One of our most loyal readers has recently celebrated the 40th anniversary of his joining Philips on 1st December 1930. Anniversaries do not usually receive any attention in our pages, but we feel that this one is rather special, since the reader we have in mind, one of the founders of our Review, is the President of the group of companies that bears his name. The photograph above shows our President (on the left) and Dr. Rinia, the former director of Philips Research Laboratories, looking at an experimental Stirling motor for heavy traction work. We join the authors in presenting to Ir. F. J. Philips this issue, whose articles are all on subjects that have attracted his special interest.
Hydraulically driven precision lathe with hydrostatic bearings for the main spindle and for the carriages, designed in the Philips Research Laboratories. The two numeric displays above the lathe show the coordinates of the cutting tool in ten-thousandths of a millimetre. Machine tools are the subject of the article on the adjoining page.