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PHOTODENSITOMETER MEASUREMENTS OF IMAGES ON RADIOGRAPHS

G. M. Taylor

March 12, 1976

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PHOTODENSITOMETER MEASUREMENTS OF IMAGES ON RADIOGRAPHS

Abstract

An x-ray photodensitometer provided accurate and precise measurements of linear dimensions on radiograph images. These measurements helped me to infer the hidden dimensions of objects radiographed. A goal was to achieve an accuracy of $\pm 25 \mu\text{m}$. The recorded accuracy did not measure up to the precision, which, under favorable conditions, was $\pm 25 \mu\text{m}$. Systematic errors caused the errors in absolute value to be considerably higher in some cases.

To satisfy this, I made auxiliary calibrations.

Many deterrents to successful measurement arose. These included film grain noise, excessive density range and edge penetration, blurring, interfering structures, and scattered radiation. Film grain noise, in particular, limited the resolution of small details (fine structure) in a radiograph. Because of so many deterrents, the applicability of the measurement method used here appears quite limited.

1. Introduction

High cost prevents many companies from making highly precise measurements of linear dimensions on radiograph images. Yet many people would like to precisely and accurately determine the hidden dimensions of objects, dimensions not accessible to ordinary measurement. In particular, nondestructive test people in the weapons, nuclear reactor, and aerospace industries would benefit from such a measurement method.

My work^{*} represents a start in making such measurements. I used an x-ray photodensitometer (XRPD) of special design. The Lawrence Berkeley Laboratory provided this computer-controlled scanning instrument under contract to the Lawrence Livermore Laboratory (LLL). It measures,

^{*} I performed the work in the Nondestructive Testing Section of the Materials Engineering Division,

digitizes, and records light transmission through small areas of a radiograph. It tells us the intensity of light passing through a specific data point on a radiograph image. It also indicates the intensity of light not passing through that data point (known as the light intensity reference value). Finally, the XRPD indicates the x-axis and y-axis positions of that data point.

A computer then takes the four numbers recorded for each data point and accumulates small sets of such points to provide a data set. The computer's program uses the data set information to give me a mathematical picture representing unique points in the radiograph image. Using this information, I can infer the accurate linear dimensions of an object radiographed.

Magnification and distortion occur when an object is radiographed. Corrections have to be made for these two factors to help us calculate an object's actual dimensions. During the inference process, we can determine an empirical correction factor

to reduce the data to absolute measurements.

My goal was to achieve an accuracy of about $\pm 25 \mu\text{m}$. This degree of accuracy would be needed to justify the use of an automated instrument. Accuracy means the degree of agreement between a particular measurement and a standard. It signifies one standard deviation from a known value.

The accuracy attained in this work did not measure up to the precision, which, under favorable conditions, was $\pm 25 \mu\text{m}$. Precision represents how much error we get over a series of repeated measurements. I recorded such repeatability for an estimated standard deviation. Even with an attained precision of $\pm 25 \mu\text{m}$, residual systematic errors were not always eliminated.

I do not know of any universal radiograph measurement method. With this in mind, I had to treat each general category of measurement as a special case. I then discovered many deterrents to successful measurements. Because of this, the applicability of the XRPD measurement method appears quite limited.

2. XRPD Description

SYSTEM FEATURES

The XRPD has a flat plate that serves as a stage to place the

radiograph on. This drive stage, which moves in two mutually perpendicular directions, uses a

vacuum-hold feature to keep the radiograph flat. It takes radiographs up to 356 by 432 mm. Its shaft encoders keep track of motion to a round-off error of $\pm 2.5 \mu\text{m}$. Figure 1 depicts the main elements of the XRPD system.

A 500-W projection bulb serves as the light source. The bulb's light intensity can be varied by changing the applied voltage. A lens system

collimates the light from the source. It then focuses an image of the radiograph onto a round aperture $152 \mu\text{m}$ in diameter. The XRPD provides three magnifications of the image: 1:1, 2:1, and 3:1. A photodiode acts as the light detector. The XRPD uses a variable gain amplifier for the light signal. Power supplies and digitizers comprise the rest of this densitometer's main elements.

Fig. 1. Schematic of XRPD system.

The XRPD works in conjunction with a PDP 8-E minicomputer.* This computer provides program control for the XRPD. It also records and analyzes data in real time.

MAJOR FUNCTIONS

The XRPD scanning instrument measures, digitizes, and records light transmission through small areas of a radiograph. It tells us the intensity of light passing through a specific data point on a radiograph image. The machine uses a scale of 2047 for these activities. A light pipe monitors the intensity of light from the light source. The XRPD records the light intensity reference value, which is the intensity of light not passing through the data point. It also records the x-axis and y-axis positions of that data point. The instrument has effective aperture diameters of 152, 71, and 51 μm . It records and digitizes translational motion, which is uniform motion in one direction, to $\pm 2.5 \mu\text{m}$.

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research and Development Administration to the exclusion of others that may be suitable.

Figure 2 shows the general nature of the data output for a machine scan across an image edge on a radiograph.*

The computer program controls stage movement and data recording. By manually positioning the stage and pressing a switch on the XRPD, we choose the two end points for a given scan of the radiograph. We then enter the fit routine and number of data points requested into the computer. The fit routine provides an objective,

*This and most of the other figures in this report use unitless abscissas and ordinates. I "normalized" the variables to provide scales of relative values. First, I took the maximum value. Then I divided all the numbers in the set by the maximum and multiplied by 100.

Fig. 2. Typical XRPD image edge scan.

consistent interpretation of the data. It fits data points to a particular mathematical model.

The computer causes the XRPD stage to scan between the two end points. The XRPD records the digitized values for each data point at evenly spaced intervals. The fit routine enables the computer to perform the requested calculations. It prints an estimate of the location of a single point on

the radiograph in coordinates of the x-y plane.

A second similar scan can then be made to locate a second point. The two points are then used to determine the linear dimensions of the image on the radiograph. This information can then be referred back to the object's basic structure. To get the actual distance, we must correct for radiographic magnification.

3. XRPD Response Calculation

Densitometer response depends on film density, which is a measure of how much light does not pass through a film. In this report's case, "film" actually refers to the radiographs measured. The following equation¹ defines film density (D):

$$D = \text{Log}_{10}(1/T), \quad (1)$$

where T = transmittance through film.

Since the XRPD does not measure film density, I used a commercial densitometer to measure what is known as "diffuse" density. This particular designation for film density

Fig. 3. Measured XRPD response.

means that we measure all the light emerging from one side of the film regardless of angle.* Equation (1) shows that a density change of one equals a light intensity change of ten.

I recorded XRPD response²⁻⁴ by inserting areas of uniform-density film. Figure 3 shows the response (R), as represented by the following equation:

$$R = R_0 e^{-3.3D}, \quad (2)$$

where R_0 = response for $D = 0$.

From Eq. (2) and Fig. 3 data, one can derive:

$$dR/R = -3.3D (dD/D), \quad (3)$$

where dR = small change in XRPD response and dD = small change in film density.

This equation relates the relative response of the XRPD to a relative change in film density. It shows that this response increases linearly with film density.

4. Radiography

ASPECTS OF THE RADIOGRAPHS USED

For most cases, a 4-MeV linear accelerator served as the x-ray source for the radiographs made. The process began with fine-grain, single-emulsion x-ray film. Automatic processing was used during the exposure and development phases. Figure 4 shows the general geometry of a typical radiographic exposure.

The film records the two dimensional structure of the radiation field as altered by absorption in the three-dimensional object. In addition to primary radiation carrying image information, appreciable amounts of scattered radiation reach the film and are recorded by it. Because of the divergence of the radiation field, magnification occurs. This makes two points in the radiographed object appear farther apart on the film. The source-to-film distance used is so large that the finite size of the radiation source

*The commercial densitometer has an acceptance angle of 2π . The XRPD has a much smaller angle.

does not introduce any appreciable image blurring.

Film density and x-ray exposure have an essentially linear¹ rather than semilogarithmic relationship. This makes density and exposure proportional. Section 3 discusses the relation between XRPD output and film density.

A very important point about x-ray film density is that, after exposure and development, the film has sources of variation inherent in the medium. Grain noise will be present. Also emulsion thickness may vary, non-uniform development may occur, and adjacency effects* may be present. These factors cause light transmission variations not directly related to the structure of the object radiographed. Their magnitude is sufficiently great so that any attempts at measurements of the type discussed here, which rely on absolute values of the light transmission, will almost surely fail.

NOISE PROBLEMS

Film Grain Noise

Film grain noise poses a major problem in this type of work. In contrast, electronic noise represents a minor irritation with the XRPD.

*Adjacency effects cause changes in film density that distort the image.

Fig. 4. Typical radiographic geometry.

Film grain noise^{5,6} can be attributed to statistical variations in the number of silver grains per unit volume in the rather small volumes involved in densitometer measurements. If we scan an area supposedly uniformly exposed, the output values vary appreciably because of this noise source. The variations appear to be reproducible

when the scans are repeated. The process producing the noise is assumed to be such that a relatively small amount of data can be used to characterize the noise caused by film grain.

The procedure used to obtain data with which to characterize grain noise will be described with no attempt to justify the method completely. The XRPD scanned areas of uniformly exposed film with enough spacing to prevent correlation. As an example, various step images were used from a radiographed step wedge. A commercial densitometer measured the approximate density. An autocorrelation program checked the scan data for hidden structure after subtracting any linear trends. A second program then did a least-mean-squares (LMS) fit of a straight line and subtracted out this linear trend. The program then computed an estimate of the standard deviation for the corrected data set. This program also computed an autocorrelation for adjacent points. This turned out to be very high in negative value (i.e., nearly -1) on some of the high-density film. I haven't any idea why or whether or not any significance should be attached to these values. Some adjacency effect may be involved during the chemical processing of the film.

Grain noise was reduced to relative value by division by the

average followed by multiplication by 100. Table 1 shows some results of the procedure used to obtain data that characterize grain noise. Table 2 shows more extensive results for various film densities. These two tables provide results for films made with a 4-MeV source. Similar data for 2 and 13 MeV were essentially the same. The data indicate a rapid increase of grain noise as effective light beam size decreases.

Section 3 revealed that relative response of the XRPD to density changes was a linearly increasing function of density. Film grain noise also increases with film density. If this increase is as rapid as relative response, we would not expect to get better results at higher film densities. Table 3 demonstrates that noise increases more rapidly with density than does XRPD relative response.

The data show a fairly constant value for the ratio of film grain noise to density, over a film density

Table 1. Root-mean-square grain noise for three effective aperture sizes.

Line-spread function width, one standard deviation (μm)	Grain noise (%)
25	5.0
41	2.5
152	1.6

Note: Film density is about 1.

Table 2. Grain noise for selected film densities over a 0.66 to 2.30 range.

Film density	Grain noise (%)		
	152- μ m LSF ^a	41- μ m LSF	25- μ m LSF
0.66	1.1	3.0	3.0
0.81	1.2		
0.87		2.4	3.6
1.00	1.0		5.0
1.15		2.5	5.8
1.32	1.5	2.5	3.8
1.55		3.3	5.9
1.74	1.6	2.3	5.5
2.01		4.0	8.0
2.30	2.4		

^aLSFW = line-spread function width

Table 3. Ratio of film noise to density.

Film density	Film noise (%)	Film noise/density
0.66	1.0	1.5
0.87	1.6	1.8
1.15	1.6	1.4
1.35	2.2	1.6
1.57	2.9	1.8
1.74	3.4	2.0
2.01	6.1	3.0
2.30	18.2	7.9
2.60	25.6	9.5

range of 0.66 to 1.74, followed by a rapid increase in ratio.

The data support the conclusion that the XRPD should perform best with the 1:1 magnification and in the

general density range of 0.7 to 1.7. Rather extensive attempts to measure films of various structures at a variety of film densities bear out this conclusion.

The response to essentially one-dimensional structures, such as edges, could be substantially improved (as far as grain signal-to-noise ratio goes) by changing from the XRPD's round aperture to a narrow, rectangular slit with the narrow dimension in the direction of travel. This modification is not straightforward.

Electronic Noise

Electronic noise, not a major problem with the XRPD, is inherent in

the XRPD amplifier. This causes random variations in the output signal in the absence of external causes. The amplifier has three gain settings: 1, 5, and 25. A one-sigma value for the electronic noise is about 4 scale divisions on the 25 scale and proportionately less on the 5 and 1 scales. Thus, on the 5 scale, electronic noise is of the same order as the digitizing error. The reason for its lack of importance on the 25 scale is the presence of film grain noise, which tends to far overshadow it.

5. Mathematical Basis for Interpreting Data

Useful mathematical methods for this work include LMS fits of first and second degree polynomials and the Gaussian function. Not useful have been Fourier transform methods, particularly the modulation-transfer function. Details of the methods used will not be discussed because of the general availability of adequate discussions in the literature.⁷⁻¹⁴

Before getting to the line-spread function technique used in this work, I would like to discuss Fourier transform methods and the modulation-transfer function. Section 6 explains why Fourier methods have not proven useful. These methods assume an image can be represented as the sum

of a discrete series of wavelengths in a way analogous to the Fourier series representation of an alternating electric signal. For many of the radiographs examined with the XRPD, a one-dimensional series would suffice.

The modulation-transfer function would then relate input and output in the reciprocal wavelength domain. This would be directly analogous to a filter function in ac theory. We often normalize the values to one for an infinite wavelength. Shorter wavelengths have values less than one. This transfer function has been used to represent the various components in an optical system. It enables us

to combine the effects of sequential operations on the waveform under measurement.

A similar technique, used in Section 6 for explanatory purposes, is the line-spread function. This function represents the output response expected from an XRPD when a thin line of light passes through the spot imaged into the aperture of the light intensity detector. It can be regarded as a weighting function which, when convolved* with the input obtained in scanning a film, gives the expected response.

The line-spread function is in the space or wavelength domain. A circular aperture has a line spread function analogous to a low pass filter. This function reduces the instrument response to short wavelengths. Regions that might represent sharp corners appear rounded in the scanned output and have an indefinite location. In some cases, the goniometer scan laterally shifts a region that might appear to be an edge.

* Convolution, as used here, describes the action of an observing instrument when it takes a weighted mean of some physical quantity over a narrow range of some variable. This sliding, weighted average accounts for the XRPD detector not getting as much light from a line near the edge of an object's circular aperture as from a line near the center.

Since the line-spread function comes so close to being Gaussian for the XRPD, such a distribution model will be assumed. A line-spread function can also be associated with the x-ray film and its processing. A Gaussian function appears reasonable for this latter association too. Assuming a Gaussian function for both the XRPD and the film/film processing association, we can calculate the overall line-spread function by combining the standard deviations as follows:

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}. \quad (4)$$

An experimental procedure for obtaining the XRPD line spread function calls for scanning across an opaque edge. This produces a data set that, when plotted, results in an s-shaped curve (see Fig. 2). Next, determine the differences between adjacent data points (known as "first differences"). Then fit a Gaussian function to the first differences by using an LMS routine. Figure 5 uses actual data to show how the Gaussian curve fits over the marks for the first differences of the edge scan data points. Table 4 provides the calculated line-spread function widths (at one standard deviation) for the three XRPD image magnifications.

Fig. 5. Data sets for image edge scan and first differences of edge scan. The lower curve (Gaussian function) fits the differences between adjacent data points of a machine scan of an opaque edge (upper curve). The $51\text{-}\mu\text{m}$ spacing represents the distance between adjacent data points in either set.

Table 4. Standard deviations of line-spread functions.

Magnification	Line-spread function width, one standard deviation
	(μm)
1:1	152
2:1	41
3:1	25

6. Discussion of Image Edge Determination

This work centered on finding the position of an image edge on a radiograph. A simple object to radiograph would be a step wedge. Figure 6 presents an idealized XRPD scan of a single step on a step wedge image.

If a radiograph gave an accurate record of the primary radiation field, as modified by absorption in the object, the problem of determining an image edge would be simple. Unfortunately, a number of things that lead to a lateral smearing of the image prompt much more indirect measurements.

Scattered radiation, both general and highly localized, serves to decrease the sharpness of the density gradient at the image edge. Density gradient refers to the rate of change of film density. Adjacency effects caused by film processing, produce a similar result. When the XRPD scans an image, it causes a further loss of short wavelength detail. References 15-21 contain more elaborate discussions of some of these factors.

Because of the above negative factors, the XRPD scan will show a lateral smearing of the image. The result resembles the curve in Fig. 2. Note that the smearing is such that, in the resultant data set, the edge

position is no longer uniquely defined in any direct way.

Short wavelength boosting in the Fourier domain and a related technique known as deconvolution²²⁻²⁴ comprise two sometimes useful image-enhancement methods. Boosting increases the amplitude of the short wavelength. Deconvolution is the inverse process of convolution. The need to sample at least at the Nyquist rate interferes with Fourier methods. This rate requirement cannot be met when taking XRPD data samples. As the XRPD aperture gets smaller, the grain noise goes up rapidly. The data thus gets too

Fig. 6. Idealized image edge scan.

noisy to be useful. Grain noise also strongly influences deconvolution. An examination of the XRPD response function indicates that a signal-to-noise ratio of at least 1000:1 would be required to avoid instability trouble.

The best signal-to-noise ratio for grain noise is about 100:1 (as derived from Table 3). Neither the Fourier methods nor the various deconvolution methods suggested in the literature for image enhancement have proven useful in this work.

7. Image Measurements

MEASUREMENT REQUIREMENTS

Certain conditions must be met before dimensional measurements can be made with sufficient precision to justify the method used here. Table 5 gives estimated numerical values for some parameters. Other conditions will be described below.

The data set from a single scan for structure location must be extremely stable in film position for repeat radiographs and measurements. The data-set fit routine must reproduce the location accurately to achieve precision. The end points of the data set are chosen manually. Thus, either the operator must determine these points judiciously or the fit routine for determining the edge position must be programmed to choose a suitable subset of the data set for use. This subset must give a solution that is not highly dependent on the end points chosen for the data set. In the first case, the burden

on the operator is appreciable; the latter requirement is difficult to meet.

Most of the time, the operator must use his judgment in selecting suitable end points for the machine scan and subset for the data-set fit routine. A high degree of automation, provided for in the machine design and computer programming, may be realizable only where many essentially identical films are made day after day.

Table 5. Parameter requirements for dimensional measurements.

Rate of change of signal (%/μm)	1/25
Total signal change (%)	10
Noise (%)	1
Film density	0.8 - 1.7
Line-spread function width (μm)	152

EXAMPLES OF MEASUREMENTS

The following five cases exemplify successful and partially successful image measurements. They represent a moderate amount of the total measurements made. I used the 1:1 magnification in these examples. Data points were spaced so closely that adjacent points were highly correlated. Most of the radiographs were made at energies greater than one MeV.

Outer Edge of High-Atomic-Number Spherical Shell

Figure 7 shows a data set obtained from an XRPD scan of the radiograph image of the outer edge of a high-atomic-number shell. A 13-MeV linear accelerator acted as the radiographic source. A study of a number of such data sets revealed a linear region near the location of the image of the outer shell edge. This study inspired the following procedure, which automates the selection of the data set:

1. Take successive first differences and find the maximum.
2. Take 0.7 times the maximum slope.
3. Select a data set that uses the result in step two as the criterion for the bounds.
4. Fit the data with an LMS first degree polynomial.

5. Find the minimum value of light transmission.
6. Substitute this value into the equation for the first degree polynomial.
7. Calculate position value.
8. Use this value to represent the edge position.

This procedure, used repeatedly, gave a precision less than 25 μm for data sets that have a substantial linear region. Unfortunately, the procedure introduced a systematic error (about 250 μm) that made the accuracy at least ten times worse than the precision. The procedure made use of the part of the data set where the rate-of-change of the light transmission (with respect to distance along the film) was a maximum. The computer was programmed to do all the necessary calculations and to print out the edge position. As part

Fig. 7. Data set for image scan of outer edge of spherical shell. The 102- μm spacing represents the distance between adjacent data points in the set.

of this program, the computer had an automatic routine for selecting a subset.

For this example, measurements can be made very rapidly at the 25- μm precision. A comparable accuracy can be attained only by deriving a correction factor to reduce the systematic error of 250 μm .

Inner Edge of High-Atomic-Number Spherical Shell

In this example, I noted suitable radiographic contrast and obtained relatively "sharp" radiographic images. A calculation assuming a

value for the material absorption coefficient based on radiographic data and an exponential absorption model gives a data set shown in Fig. 8 (the circles). This calculation does not account for scattered radiation and some of the other second-order effects that may lead to a different curvature. If we convolve this curve with a discrete set derived from a Gaussian line-spread function, we obtain the second data set of Fig. 8 (the triangles). The standard deviation of the Gaussian used is 0.2 mm, which is an estimate based on XRPD measurements of a number of radiographs.

The most important result reveals that the radiographic process and the XRPD scan combine to cause a lateral shift in the data set's maximum. We know this shift occurs because dimensions inferred from radiographs of this type have been larger than the real object's dimensions after correcting for magnification. Figure 9 compares convolved values with XRPD measurements. Both data sets were normalized to the same maximum by multiplication by a constant. Although the details of the agreement between the data sets are not too impressive, the general shape of each data set obtained is consistent with the assumption that the position of the scan data set's maximum will not be correct for the "edge" position.

Fig. 8. Data sets for image edge scan of inner diameter of spherical shell. This case compares convolved values with calculated values. The 102- μm spacing represents the distance between adjacent data points in either set.

An LMS fit of a second degree polynomial with the edge position taken to be the maximum is reproducible to about $\pm 25 \mu\text{m}$. The minimum lateral shift of the apparent maximum in this particular case is about $178 \mu\text{m}$. Since the shift occurs at each end of a diameter, if we measured the diameter in absolute value, the result would be at least $356 \mu\text{m}$ too large. This is easily seen to be considerably larger than the $25 \mu\text{m}$ accuracy goal.

Thin Plate Radiographed Edge On

Figure 10 shows a data set obtained by scanning a radiograph of

Fig. 9. Data sets for image edge scan of inner diameter of spherical shell. This case compares convolved values with XRPD measurements. The $102\text{-}\mu\text{m}$ spacing represents the distance between adjacent data points in either set.

Fig. 10. Data set for image edge scan of thin plate radiographed edge on. The $28\text{-}\mu\text{m}$ spacing represents the distance between adjacent data points in the set.

a thin plate edge on. The point spacing is very close since the radiographic contrast was great. The data set is symmetrical. Two mathematical routines appear to be suitable: a Gaussian function for the entire set and a second degree polynomial for the upper portion only. Both routines were tried. They appear to be equally good, yielding a precision of $25 \mu\text{m}$ and an accuracy about the same. For this data set, convolution with the line spread function would tend to widen the data

set but would not lead to a systematic error by a lateral shift.

The Gaussian function is relatively insensitive to the end points chosen for the set since it will properly fit the "skirts" of the curve. The Gaussian program weights the data points by amplitude so the skirt values count less anyway. If we use the second degree polynomial, the data set must be terminated on each side far enough from the skirts for a simple parabola to be a good model. Including data from the skirt on one side and not the other leads to an appreciable error. For this reason, the polynomial is more subject to operator error and harder to automate.

The maximum of the second degree polynomial was automated. It works well (with the limitation of possible operator error).

Outer Diameter of Steel Cylindrical Shell Radiographed at 13 MeV

Figure 11 depicts a data set from an XRPD scan of the image of the outer diameter of a steel cylinder. Because of the high radiation energy and steel's moderate density and atomic number, the cylinder is penetrated appreciably. There may be more effect from scatter than in previous examples. The data set appears to have no unique feature that would allow me to develop an accurate pro-

cedure for locating a particular abscissa. Note particularly how the abscissa scale of Fig. 11 differs from the other examples.

In this case, after a large number of trials of possible fit routines, the desired accuracy cannot be attained even for relative measurements.

Steel Step Wedge

Figure 12 presents the pertinent dimensions of a steel step wedge. The LLL shop milled the plates along the edges, then pinned and bolted them together. The location of each edge was then measured to a tolerance of $\pm 2.5 \mu\text{m}$ along the center line.

Fig. 11. Data set for image edge scan of outer diameter of steel cylinder radiographed at 13 MeV. The 249- μm spacing represents the distance between adjacent data points in the set.

p. 12. Layout of steel step wedge radiographed at 4 MeV.

The wedge was radiographed at 4 MeV on a single emulsion fine grain film at a target-to-film distance of 7.32 m. Automatic processing was used to develop and fix the film.

One line-spread function can be associated with the radiographic exposure and processing and another with XRPD scanning. If both are Gaussian in form, the result of the radiography and XRPD scan can be represented by a Gaussian function and a standard deviation.

A procedure for finding an edge in simple geometry, such as with this example, is to scan an edge, take first differences, and fit a Gaussian function to the set. The abscissa equivalent to the midpoint of the Gaussian function denotes the edge location. If we correctly assume that the change in data from a step function to the data set given by the XRPD can be represented by a single

Gaussian function, the data should fit such a step function and the procedure described should give the proper position.

The XRPD data contains a considerable amount of noise, primarily from film grain. I put the data in this example through a prefilter* before fitting the Gaussian function. This operation, which is a convolution, shortens the convergence time for the Gaussian fit. Figure 13 has a sample curve taken directly from the computer output. In the fit routine, the data points are weighted proportionally to the amplitude of the ordinate so the values on the "skirts" of the curve do not have much influence on the fit. Data from all the edges fit the model very closely.

* A long-wavelength passing filter.

Fig. 13. Data set for image edge scan of steel step wedge. This sample Gaussian curve fits the first differences of the set. The 51- μ m spacing represents the distance between adjacent data points in the set.

Dimensions from the radiograph must be corrected for magnification to make a valid comparison with physical dimensions. The value taken

Table 6. Comparison of wedge measurements with XRPD step widths.

Wedge plate width (mm)	XRPD step width (mm)	Error (mm)
304	305	0.2
178	178	0
127	127	0
76.2	76.3	0.08
25.5	25.5	0

for the distance from a step edge to the film is the distance from the film to the center of the step height. A second small correction is made because of XRPD stage positional error at the larger distances. When both corrections have been applied, measurement comparisons are obtained for the average of three trials (Table 6). For the 304- and 76.2-mm plates, the errors are somewhat larger than the accuracy goal of 0.025 mm, but the accuracy is good enough to be useful. Table 7 gives estimates of precision for each plate width. The precision is on the order of or a little better than the 0.025 mm goal.

The excellent fit of the data to the Gaussian function and the relatively accurate determination of edge positions using the Gaussian justify this model as satisfactory for very simple cases of edge geometry.

Table 7. Estimates of precision for each plate width. There were three independent sets of measurements.

Plate width (mm)	Precision (mm)
304	0.011
178	0.011
127	0.015
76.2	0.028
25.5	0.023

8. Conclusions

The XRPD can be used to obtain data for dimensional measurements on radiographs with a precision of $\pm 25 \mu\text{m}$ for an estimated standard deviation. Accurate relative measurements are possible in favorable cases. In some situations, such relative measurements may suffice when we can use extra measurement data from methods other than those used here. We may also be able to determine an empirical correction factor that can reduce the data to absolute measurements.

Deterrents to successful measurement include film grain noise, insufficient contrast, excessive density range, blurring from any cause, excessive edge penetration for cylinders or spherical shells,

patterns from scattered radiation, and images of interfering structures. Since the list is long and one or more deficiencies occur in most routine radiographs, the XRPD method clearly does not have a wide field of applicability. However, a number of real problems have been solved. Also, by using the method with radiographs made by improved techniques, further dimensional measurement problems may be solved.

The XRPD can be improved for radiograph measurements by adding an optional aperture. The upper limit of density is about 2 with the current light source. Maximum light intensity can be increased to make measurements on films of higher density.

References

1. C. E. K. Mees, *The Theory of the Photographic Process* (The MacMillan Co., New York, 1954).
2. D. Galburt, R. A. Jones, and J. W. Bossung, "Critical Design Factors Affecting the Performance of a Microdensitometer," *Phot. Sci. Eng.* 13, 205 (1969).
3. A. S. Meiss, "Optimizing Film Density Sensing," *Electrical-Optical Systems Design* 3, 28 (1971).
4. S. Johansson and K. Biedermann, "On the Compensation for the Transfer Function of the Microdensitometer in Measurements of MTF of Photographic Emulsions," *Phot. Sci. Eng.* 18, 151 (1974).
5. H. A. Klassens, "Measurement and Calculations of Unsharpness Combinations in X-Ray Photography," *Philips Research Reports* 1, 241 (1946).
6. V. P. Abramov and V. I. Gorbunov, "Noise Due to Graininess of X-Ray Film and Effect of that Noise on Optimized Dimension of Scanner Aperture," *Soviet Jour. NDT* 8, 90 (1972).
7. R. J. Jones and J. F. Coughlin, "Elimination of Microdensitometer Degradation from Scans of Photographic Images," *App. Opt.* 5, 1411 (1966).
8. R. A. Jones, "An Automated Technique for Deriving MTF from Edge Traces," *Phot. Sci. Eng.* 11, 102 (1967).
9. R. A. Jones and E. C. Yeadon, "Determination of the Spread Function from Noisy Edge Scans," *Phot. Sci. Eng.* 13, 200 (1969).
10. C. B. Johnson, "MTFs: A Simplified Approach," *Electro-Optical Systems Design* 4, 22 (1972).
11. R. A. Jones and J. T. Kelly, "Reliability of Image Evaluation Techniques," *App. Opt.* 8, 941 (1969).
12. G. C. Higgins, "Methods for Analyzing the Photographic System, Including the Effects of Nonlinearity and Spatial Frequency Response," *Phot. Sci. Eng.* 15, 106 (1971).
13. C. B. Johnson, "A Method for Characterizing Electro-Optical Device Modulation Transfer Functions," *Phot. Sci. Eng.* 14, 413 (1970).
14. S. Johansson and K. Biedermann, "On the Compensation for the Transfer Function of the Microdensitometer in Measurements of the MTF of Photographic Emulsions," *Phot. Sci. Eng.* 18, 151 (1974).

15. H. Hoerlin, "The Photographic Action of X Rays in the 1.3 to 0.01 A Range," *J. Opt. Soc. Amer.* 39, 891 (1949).
16. J. W. Coltman, "The Specification of Imaging Properties by Response to a Sine Wave Input," *J. Opt. Soc. Amer.* 44, 468 (1954).
17. K. Rossmann, G. Lubberts, and H. M. Cleare, "Measurement of the Line Spread-Function of Radiographic Systems Containing Fluorescent Screens," *J. Opt. Soc. Amer.* 54, 187 (1964).
18. R. Halmshaw, "Photographic Aspects of the Definition Attainable in Radiographs," *J. Photo. Sci.* 12, 110 (1964).
19. C. H. Dyer and E. L. Criscuolo, "Measurement of Spatial Frequency Response of Certain Film Screen Combinations to 10 MeV X Rays," *Materials Evaluation* 34, 201 (1966).
20. E. L. Criscuolo, "Slit Detection by Radiography," *Materials Evaluation* 34, 201 (1966).
21. I. Panaitescu, "Some Thoughts on Radiographic Definition," *Brit. J. Non-Destruct. Test.* 17, 1 (1975).
22. D. G. Falconer, "Image Enhancement and Film Grain Noise," *Optica Acta* 17, 693 (1970).
23. C. W. Helstrom, "Image Restoration by the Method of Least Squares," *J. Opt. Soc. Amer.* 57, 297 (1967).
24. D. H. Janney, B. R. Hunt, and R. K. Zeigler, "Concepts of Radiographic Image Enhancement," *Materials Evaluation* 30, 195 (1972).