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Measuring microfocal spots using digital radiography

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INTRODUCTION

Measurement of microfocus spot size can be important for several reasons:

- Quality assurance during manufacture of microfocus tubes
- Tracking performance and stability of microfocus tubes
- Determining magnification (especially important for digital radiography where the native spatial resolution of the digital system is not adequate for the application)
- Knowledge of unsharpness from the focal spot alone

The European Standard EN 12543-5 is based on a simple geometrical method of calculating focal spot size from unsharpness of high magnification film radiographs (see fig. 1-4). The following equations are used for the focal spot size measurement:

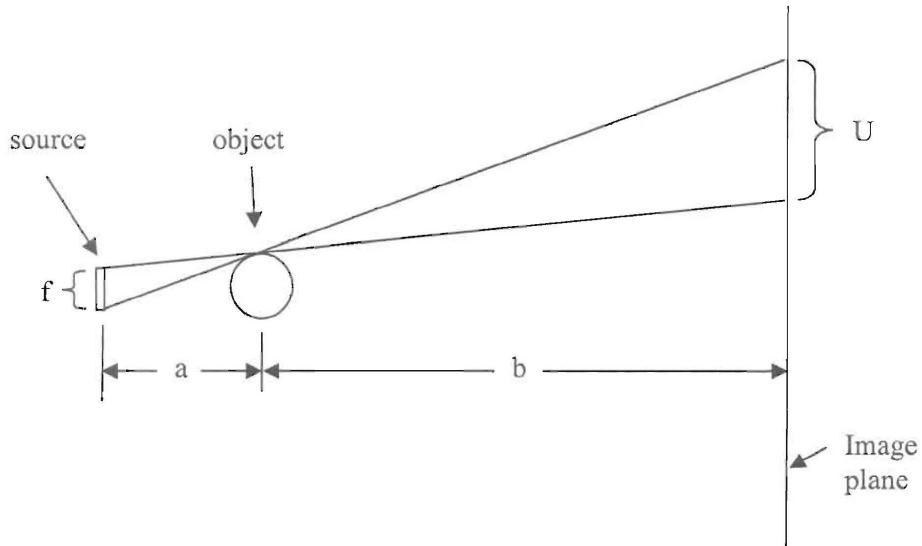


Fig. 1: Unsharpness U caused by the focal spot size

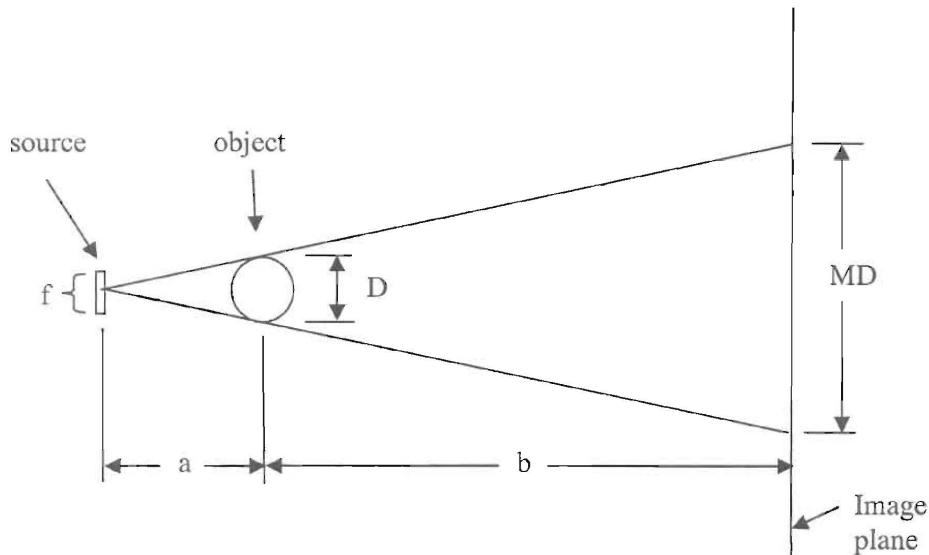


Fig. 2: Magnification of object projection

By similar triangles the following equations are presupposed:

$$f/a = U/b \text{ and } M = (a+b)/a \quad (1)$$

These equations can be combined to yield the well known expression:

$$U = f(M - 1) \quad (2)$$

Solving for f ,

$$f = U / (M - 1). \quad (3)$$

Therefore, the focal spot size, f , can be calculated by measuring the radiographic unsharpness and magnification of a known object. This is the basis for these tests.

The European standard actually uses one-half of the unsharpness (which are then added together) from both sides of the object to avoid additional unsharpness contributions due to edge transmission unsharpness of the round test object (the outside of the object is measured).

So the equation becomes

$$f = (\frac{1}{2} U_1 + \frac{1}{2} U_2) / (M - 1) \quad (4)$$

In practice $\frac{1}{2} U$ is measured from the 50% to the 90% signal points on the transition profile from "black" to "white," (positive image) or attenuated to unattenuated portion of the image (Fig. 4). The 50% to 90% points are chosen as a best fit to an assumed Gaussian radiation distribution from the focal spot and to avoid edge transmission effects. $\frac{1}{2} U_1 + \frac{1}{2} U_2$ corresponds about to the full width at half height of a Gaussian focal spot.

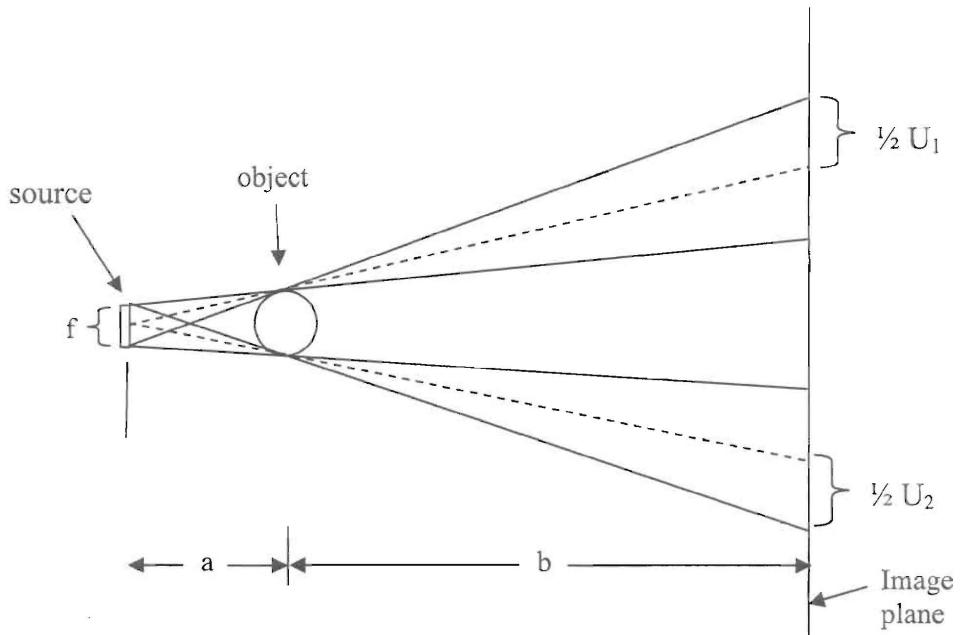


Fig. 3: Measurement of U from one-half unsharpness from both outside sides of the object

A highly absorbing material (Tungsten, Tungsten Alloy, or Platinum) is used for the object. Either wires or a sphere are used as the object to eliminate alignment issues. One possibility is to use the wires in the ASTM E2002 unsharpness gage and take two orthogonal images. The signal levels in the image need to be linear with radiation exposure and so may need conversion if a nonlinear detector is used to acquire the image.

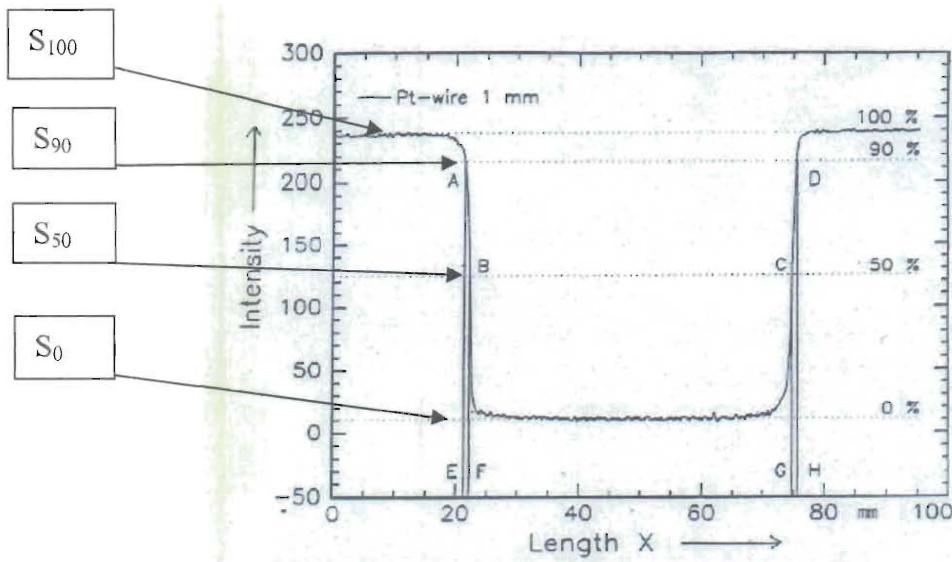


Fig. 4: Measurement of $\frac{1}{2} U$ on each side of the transition profile (note: greater Intensity means less attenuation, i.e., the outside of the object is where $\frac{1}{2} U$ is measured). $\frac{1}{2} U_1$ is between points A and B or Length EF, $\frac{1}{2} U_2$ is between points C and D or Length GH. (Figure from EN 12543-5)

ACCURACY

Accuracy depends mainly on how well Fig. 4 lengths EF and GH can be measured.

EN 12543-5 requires scanning film radiographs at a 10 μm pixel size. ASTM Committee E07 on Nondestructive Testing is pursuing a standard that includes both scanned film and direct digital (Radioscopic, Digital Detector Array (DDA), and Computed Radiography (CR)) methods. An ASTM Collaboration Area has been created for gathering data for this standard. Participation is open to all interested individuals and companies. Contact the authors for further information.

In any case the image is digital, made up of pixels. Table 1 shows the parameters involved in making the focal spot determination.

TABLE 1

$n(u1)$	number of pixels across 1st edge 50-90% profile (E-F in Fig. 4)
$n(u2)$	number of pixels across 2nd edge 50-90% profile (G-H in Fig. 4)
$n(D)$	number of pixels across sphere diameter 50-50% profile (F-G in Fig. 4)
D_a	actual diameter of sphere or wire
P	dimension of one pixel
$\sigma(u1)$	uncertainty in number of pixels of $\frac{1}{2} u1$
$\sigma(u2)$	uncertainty in number of pixels of $\frac{1}{2} u2$
$\sigma(D)$	uncertainty in number of pixels of D
σD_a	uncertainty/tolerance in diameter of sphere or wire

substituting the digital values from Table 1 into $f = (\frac{1}{2} U_1 + \frac{1}{2} U_2) / (M - 1)$:

$$f = \{[n(u1)P] + [n(u2)P]\} / \{[[n(D)P]/[D_a]] - 1\} \quad (5)$$

With uncertainties:

$$f = \{[n(u1)P \pm \sigma(u1)P] + [n(u2)P \pm \sigma(u2)P]\} / \{[[n(D)P \pm \sigma(D)P]/[D_a \pm \sigma(D_a)]] - 1\} \quad (6)$$

The sources of uncertainty are noise on the signal levels of 0% (S_0), 50% (S_{50}), 90% (S_{90}), and 100% (S_{100}) transmission, calibration effectiveness (or non-flatness of the 0% and 100% signal levels), and the tolerance of the actual diameter of the object. Noise on S_0 and S_{100} affects the selection of S_{50} and S_{90} . Noise on S_{50} and S_{90} in turn affects the ability to determine their pixel position. The best case is that $\sigma(ui)$ and $\sigma(D)$ are ± 1 pixel. Typically, $\sigma(D_a)$ is $\ll 1\%$ and so can be ignored (a 1 mm tungsten sphere can be purchased inexpensively with a diameter tolerance of 0.000635 mm or 0.06%). It will also be assumed that the effect of S_0 can be ignored (i.e., $S_0 \ll S_{100}$).

If a requirement that S_{100} be at least 75% of full scale (FS, i.e., saturation), then some control of uncertainty can be gained. If $S_{100}=0.75FS$, S_{90} then becomes 0.675FS and S_{50} is 0.375FS and their difference $S_{90} - S_{50}$ is 0.3FS. Assuming the profile between the 50% and 90% signal levels is linear, each pixel changes $0.3FS/n(ui)$. In order to control $\sigma(ui)$ to ± 1 pixel, $\sigma(S)$ must be less than $0.3FS/n(ui)$. This means that Signal-to-Noise Ratio (SNR) must be controlled. In general, for signal level "j", SNR_j is $S_j/\sigma(S_j)$.

Therefore, $\sigma(S_{100}) = 0.75FS/SNR_{100}$

Assuming that SNR is a function of the square root of dose,

$$SNR_{90} = (90/100)^{1/2} * SNR_{100} = 0.95 SNR_{100} \text{ and } SNR_{50} = (50/100)^{1/2} * SNR_{100} = 0.71 SNR_{100}$$

So, for ensuring that any point is determined to ± 1 pixel

$$\sigma(S_j) = S_j/\text{SNR}_j < 0.3\text{FS}/n(ui) \text{ and } n(ui) < 0.3\text{FS} * \text{SNR}_j/S_j$$

For the 50% point,

$$n(ui) < 0.3\text{FS} * \text{SNR}_{50}/S_{50} = (0.3\text{FS})(0.71 \text{ SNR}_{100}/0.375\text{FS}) = 0.57 \text{ SNR}_{100}$$

For the 90% point,

$$n(ui) < 0.3\text{FS} * \text{SNR}_{90}/S_{90} = (0.3\text{FS})(0.95 \text{ SNR}_{100}/0.675\text{FS}) = 0.42 \text{ SNR}_{100}$$

Therefore the limiting case is the 90% point and the optimal number of pixels in a 50% to 90% profile is $n(ui)_{\text{opt}} = 0.42 \text{ SNR}_{100}$, otherwise a smooth profile is not obtained (see Fig. 5).

If a sphere is used as the object only one line profile can be taken through the diameter. However, when using wires multiple profile lines perpendicular to the wire can be averaged to increase the SNR by the square root of the number of profile lines averaged.

This says that, for the case where S_{50} and S_{90} can be determined within ± 1 pixel, the higher the SNR, the more pixels are able to represent the $\frac{1}{2} U$ profiles and the better the accuracy of the measurement of the focal spot size. Of course, more pixels can be across the profile than $n(ui)_{\text{opt}}$ but the accuracy will never exceed ± 1 pixel; that is, a continuously increasing/decreasing profile is not obtained.

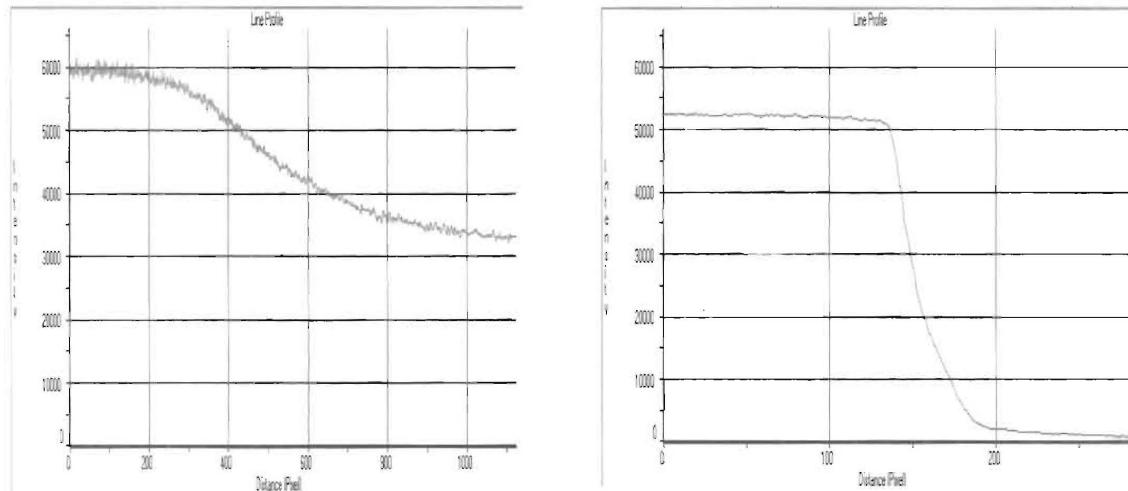


Fig. 5: Left profile shows oversampled case where the profile cannot be measured within ± 1 pixel. Right profile shows case where accuracy is ± 1 pixel.

The final control of accuracy is magnification. Magnification should be adjusted to maximize the number of pixels representing the $\frac{1}{2} U$ profiles (while within the SNR constraint if ± 1 pixel is desired).

$$\frac{1}{2} U = n(ui) * P \quad (7)$$

Then from $U = f(M - 1)$

$$M = 1 + [2n(ui) P] / f \quad (8)$$

However, the magnification must be realistic for the geometric conditions of the x-ray system. Generally magnifications cannot be greater than 100, and even then the 1 mm object will be magnified to 100 mm (~ 4 inches).

If a simple square root of the sum of the squares of the uncertainties of the individual parts is applied as an estimate of the total uncertainty, then:

$$\sigma(f)/f = \sqrt{[\sigma(u1)/n(u1)]^2 + [\sigma(u2)/n(u2)]^2 + [\sigma(D)/n(D)]^2 + [\sigma(Da)/Da]^2} \quad (9)$$

if all the unsharpness half profile measurements $\sigma(u)/n(u)$ have accuracy σ/n of ± 1 pixel and the diameter measurements $\sigma(D)/n(D)$ and $\sigma(Da)/Da$ are $\ll 1\%$ then

$$\sigma(f)/f = \sqrt{2}/n(u) \quad (10)$$

In general, find $n(ui)_{opt} < 0.42 \text{ SNR}_{100}$,
then determine $M_{opt} = 1 + 2n(u)P/f$.

M must be realistic for the conditions; if not, pick a $n(u)$ for a given accuracy and recalculate M or determine the maximum system M and calculate $n(u) = f(M-1)/2P$ and the associated accuracy. If the desired accuracy cannot be obtained a smaller pixel size will be required.

If $n(ui)_{opt}$ is put into the $\sigma(f)/f$ formula,

$$[\sigma(f)/f]_{max} = \sqrt{2}/0.42 \text{ SNR}_{100} = 3.3/\text{SNR}_{100}$$

This is the maximum accuracy for a given SNR. Now putting $n(ui)_{opt}$ in the magnification formula,

$$M_{opt} = 1 + 2 * 0.42 \text{ SNR}_{100} * P/f = 1 + 0.84 * \text{SNR}_{100} * P/f, \quad (11)$$

It is seen that the ratio P/f has a large effect on the magnification needed. When P/f is < 1 and $\text{SNR} \sim 100$ then M is < 100 which is usually easily achievable. When P/f is ~ 1 and SNR is ~ 100 then M is ~ 100 which is the usual maximum M . However when P/f becomes > 1 and $\text{SNR} \sim 100$ then $M > 100$. In this case when $P/f > 1$, lesser than optimal M must be used with a resultant less than maximum $n(u)$ and finally less than maximum accuracy predicted by SNR_{100} .

When $M_{opt} < 100$, a larger M can be used, but the accuracy will be limited by $3.3/\text{SNR}_{100}$.

When a magnification other than M_{opt} is used then

$$n(u) = (M - 1)/2(P/f). \quad (12)$$

To avoid geometric distortions, the source object distance a should be selected in dependence on the object diameter D :

$$a \geq 5 \cdot D \quad (13)$$

EXAMPLES

Table 2: 10 micron pixel (such as high resolution film scanner)

P (μm)	f (μm)	SNR_{100}	$n(ui)_{opt}$ (pixels)	M for $n(u)_{max}$	$\frac{1}{2} u$ (mm)	$n(u)$ (pixels)	D (mm)	$n(D)$ (pixels)	Total accuracy
10	100	100	42	9.4	0.42	42	9.4	940	3.3%
10	100	400	168	34.6	1.68	168	34.6	3460	0.8%
10	100	100	42	100	4.95	495	100	10000	3.3%*
10	50	100	42	17.8	0.42	42	17.8	1780	3.3%
10	10	100	42	85	0.42	42	85	8500	3.3%
10	5	100	42	169	$M > 100$, retry with $M=100$ below				
10	5	100	42	100	0.25	25	100	10000	5.6%
10	5	100	42	50	0.12	12	50	5000	11.7%

* limited by SNR

Table 2 shows that when using a 10 micron film scanner, for larger focal spots ($\geq 50 \mu\text{m}$), the magnification required for 3% accuracy is $< 20X$ which is usually doable in microfocus systems. If SNR can be improved, accuracy can be improved but the magnification required is greater. For very small spots, the magnification required for 3% accuracy probably cannot be obtained but a lesser accuracy measurement can be gotten, with accuracy depending on the magnification that can be achieved. It is also seen that $n(D)$ is very large compared to $n(u)$ and so ignoring its uncertainty is justified.

Table 3: 50 micron pixel (such as high resolution CR system)									
P (μm)	f (μm)	SNR ₁₀₀	$n(ui)_{\text{opt}}$ (pixels)	M for $n(u)_{\text{max}}$	$\frac{1}{2} u$ (mm)	$n(u)$ (pixels)	D (mm)	$n(D)$ (pixels)	Total accuracy
50	100	100	42	43	2.1	42	43	860	3.3%
50	100	100	42	100	4.95	99	100	2000	3.3%*
50	100	400	168	169	M > 100, retry with M=100 below				
50	100	400	168	100	4.95	99	100	2000	1.4%
50	100	100	42	43	2.10	42	43	860	3.3%
50	100	100	42	50	1.23	25	50	1000	5.6%
50	50	100	42	85	2.10	42	85	1700	3.3%
50	10	100	42	421	M > 100, retry with M=100 below				
50	10	100	42	100	0.50	10	100	2000	14%
50	10	100	42	50	0.25	5	50	1000	28%

* limited by SNR

Table 3 shows that when using a 50 micron CR system, magnifications for $\geq 50 \mu\text{m}$ spots are greater than when using a 10 micron system, as expected. For 10 micron spots accuracy is quite a bit less for the magnifications that can be achieved. An increase in SNR can help accuracy for larger focal spots.

Table 4: 127 micron pixel (such as DDA)									
P (μm)	f (μm)	SNR ₁₀₀	$n(ui)_{\text{opt}}$ (pixels)	M for $n(u)_{\text{max}}$	$\frac{1}{2} u$ (mm)	$n(u)$ (pixels)	D (mm)	$n(D)$ (pixels)	Total accuracy
127	100	100	42	107.7	5.34	42	107.7	848	3.3%
127	50	100	42	214	M > 100, retry with M=100 below				
127	50	100	42	100	2.48	19	100	787	7.4%
127	10	100	42	1068	M > 100, retry with M=100 below				
127	10	100	42	100	0.50	4	100	787	35%

Table 4 shows that when f is greater than P magnifications around 100 can be used to obtain 3.3% accuracy but when f is smaller than P accuracy is sacrificed. The greater SNR of DDAs lends no gain in accuracy.

DATA

Data is being taken to compare to the calculations. One example is shown (fig. 6).

225 kV Micro focus tube operated at 55 kV 100 μA , no filter
Perkin Elmer DDA 2048 x 2048 Pixel (0.2 mm)²

SDD: 1147.5 mm, SOD: ~10-15 mm, Distance of sample as near as possible in front of the tube window.
Magnification is about 80

DDA Offset correction –average over 100 exposures at 1 sec
DDA Gain correction –average over 100 exposures at 1 sec

Duplex wire exposures: average over 60 exposures at 1 sec

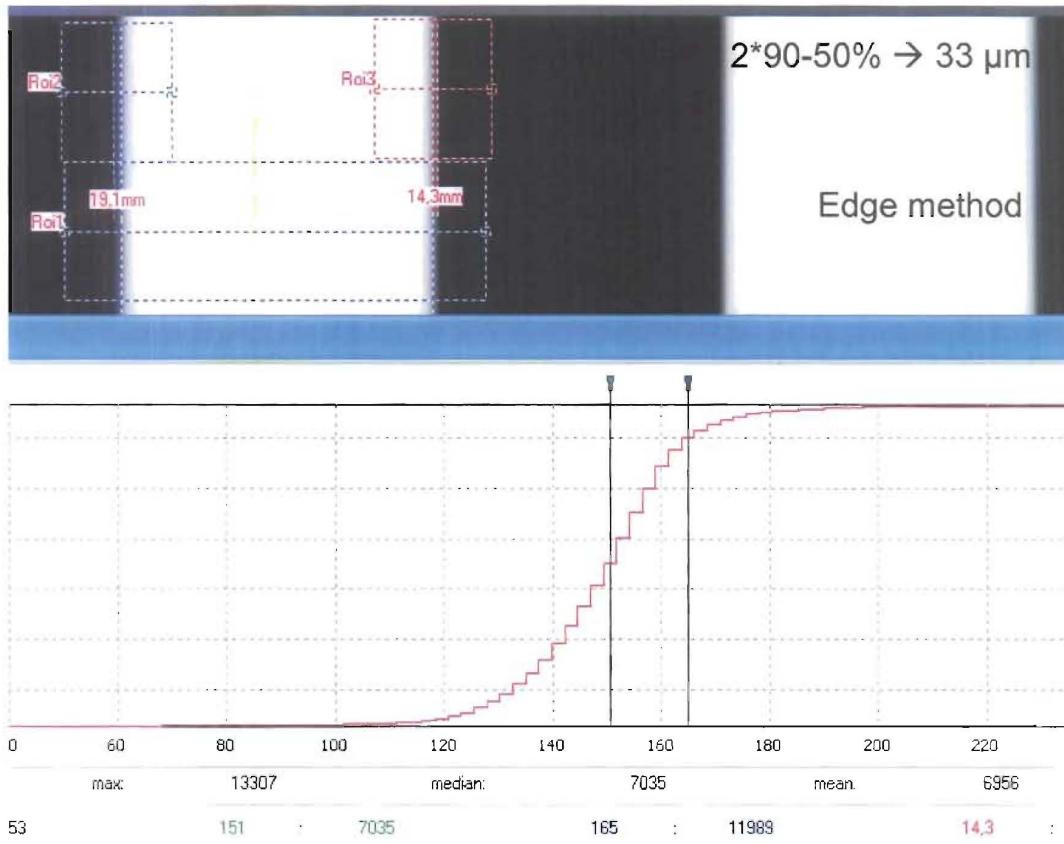


Fig. 6: Example of profile measurement and analysis by ISee! Software

CONCLUSION

When determining microfocus focal spot dimensions using unsharpness measurements both signal-to-noise (SNR) and magnification can be important. There is a maximum accuracy that is a function of SNR and therefore an optimal magnification. Greater than optimal magnification can be used but it will not increase accuracy.

Implications of these limitations in practice are:

- When $P/f < 100/\text{SNR}_{100}$, the maximum accuracy predicted by SNR can be achieved because M_{opt} can be achieved.
 - The smaller pixel size of scanned film is limited by the low SNR of film. Typically $M > M_{\text{opt}}$ and so $n(ui) > n(ui)_{\text{opt}}$ and therefore accuracy is limited by SNR
- When $P/f > 100/\text{SNR}_{100}$, the maximum accuracy predicted by SNR cannot be achieved because an unattainable M would be required.
 - The higher SNR of CR and DDA is limited by pixel size. Typically $M < M_{\text{opt}}$ and so $n(ui) < n(ui)_{\text{opt}}$ and therefore accuracy is limited by $n(ui)$

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