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Title: Measuring Microfocus Focal Spots Using Digital Radiography

Author(s): David Fry

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Los Alamos
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Measuring microfocus focal spots using digital radiography

David Fry
Los Alamos National Laboratory
(505) 665-2916, dafry@lanl.gov

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.

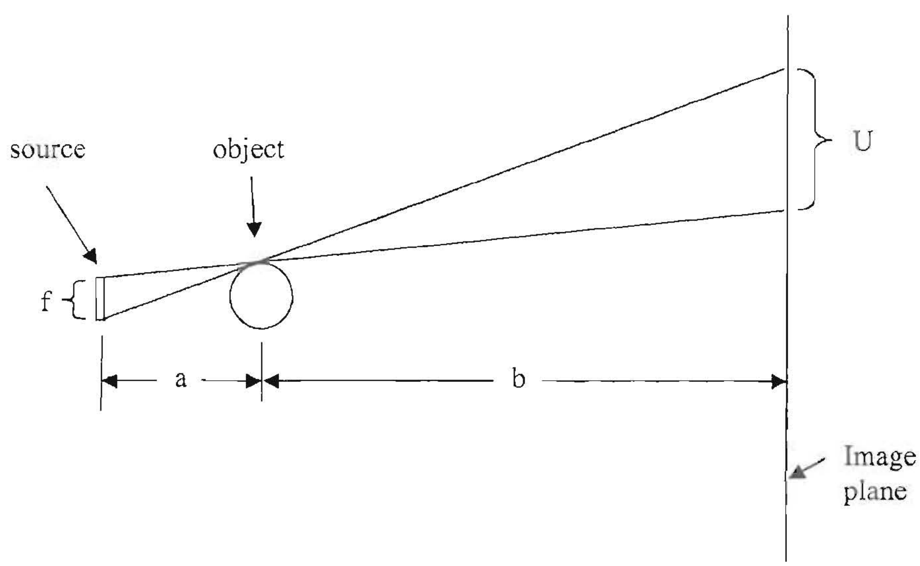

Fig. 1: Unsharpness

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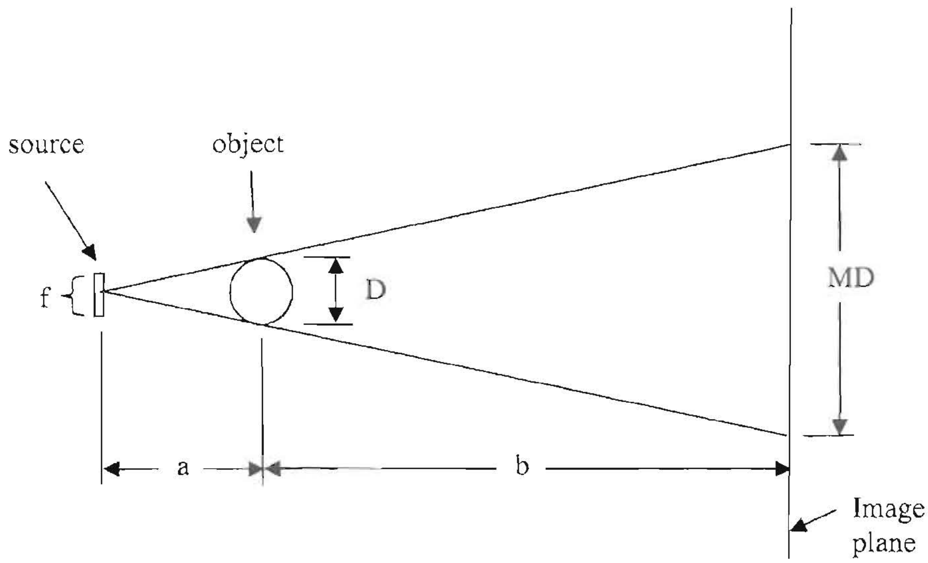

Fig. 2: Magnification

By similar triangles

f/a = U/b and M = (a+b)/a

These equations can be combined to yield the well known expression

$U = f(M - 1)$

Solving for f,

$f = U / (M - 1)$

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 scatter issues (the outside of the object is___ measured).

So the equation becomes

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

In practice ½ U is measured from the 50% to the 90% signal points on the transition profile from "black" to "white," or unattenuated to attenuated portion of the image (Fig. 4)

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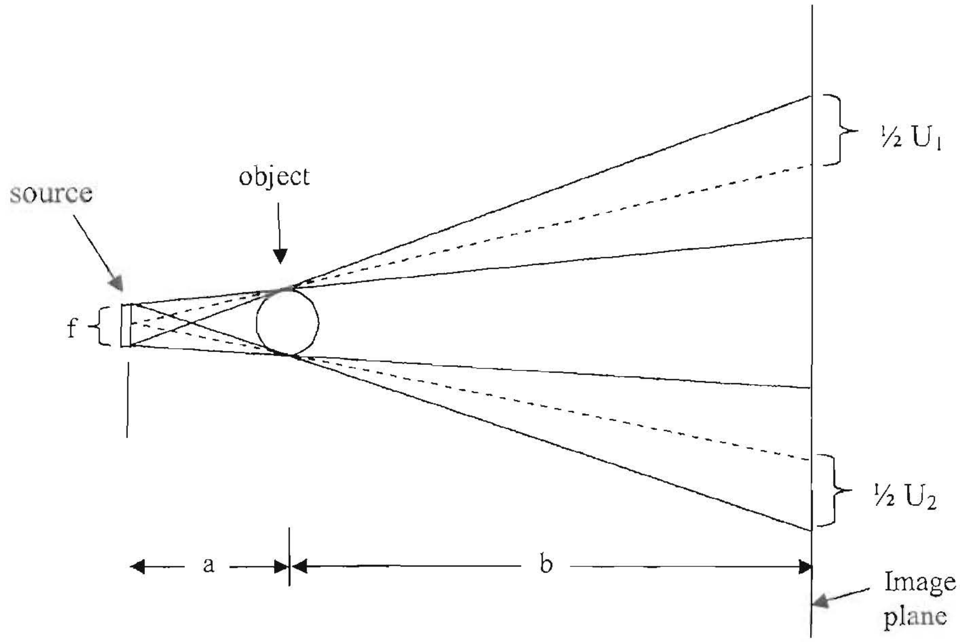

Fig. 3: One-half unsharpness from both outside sides of the object

A highly absorbing material (Tungsten, Tungsten Alloy, or Platinum) is used for the object. Either crossed wires or a sphere are used as the object to eliminate alignment issues.

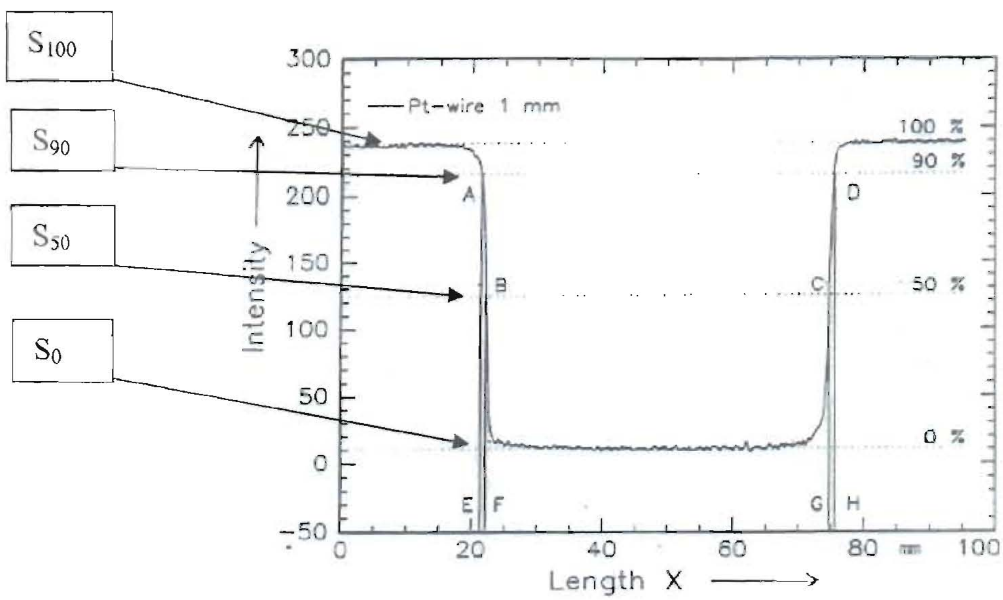

Fig. 4: Measurement of ½ U on each side of the transition profile (note: greater Intensity means less attenuation, i.e., the outside of the object is where ½ U is measured). ½ U_1 is between points A and B or Length EF, ½ U_2 is between points C and D or Length GH.

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Accuracy

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

Both scanned film and direct digital (Radioscopic, Digital Detector Array (DDA), and/or (CR)) methods are desired.

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)
Da	actual diameter of sphere
P	dimension of one pixel
σ(u1)	uncertainty in number of pixels of ½ u1
σ(u2)	uncertainty in number of pixels of ½ u2
σ(D)	uncertainty in number of pixels of D
σDa	uncertainty/tolerance in diameter of sphere

Repeating the formula to compute the focal spot size from the measurement data:

$f = (½\ u1 + ½\ u2)/(M - 1)$

where $M = D_{measured}/D_{actual}$

then substituting the digital values from Table 1:

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

With uncertainties:

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

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 σ(ui) and σ(D) are ± 1 pixel. Typically, σ(Da) is << 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.

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 σ(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,

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

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

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

$\sigma(S_j) = S_j/SNR_j < 0.3FS/n(ui)$

$n(ui) < 0.3FS * SNR_j/S_j$

For the 50% point,
$n(ui) < 0.3FS * SNR_{50}/S_{50} = (0.3FS)(0.71\ SNR_{100}/0.375FS) = 0.57\ SNR_{100}$

For the 90% point,
$n(ui) < 0.3FS * SNR_{90}/S_{90} = (0.3FS)(0.95\ SNR_{100}/0.675FS) = 0.42\ SNR_{100}$

Therefore the limiting case is the 90% point and the optimal number of pixels in a 50% to 90% profile is $n(ui)_{opt} = 0.42\ SNR_{100}$

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 ½ 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 $n(ui)_{opt}$ but the accuracy will never exceed ±1 pixel.

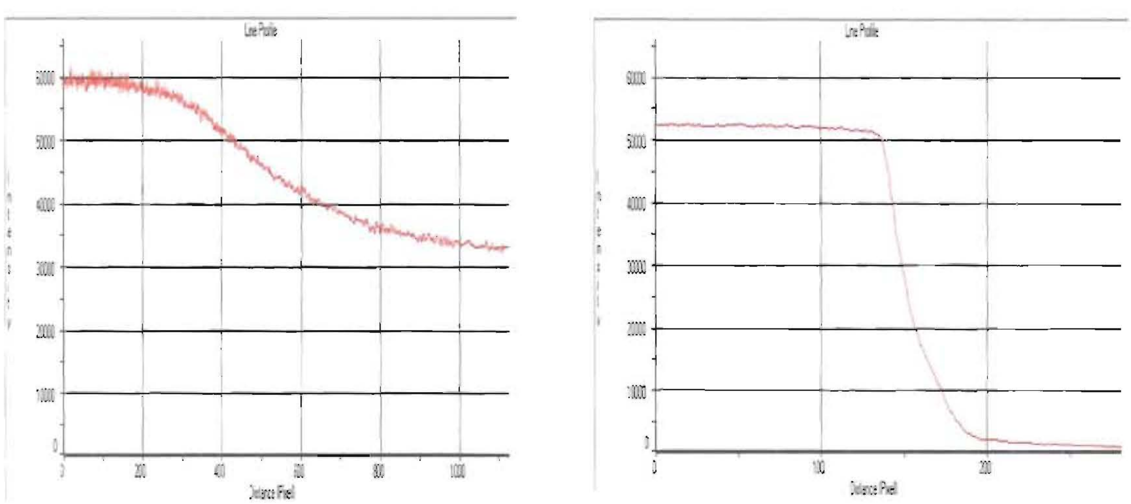

Fig. 5: Left profile shows oversampled case where the profile cannot be measured within ± 1 pixel. Right profile shows case where accuracy is ± 1 pixel.

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The final control of accuracy is magnification. Magnification should be adjusted to maximize the number of pixels representing the ½ U profiles (while within the SNR constraint if ±1 pixel is desired).

$½ U = n(ui) * P$

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

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

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) and must fit on the image detector.

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:

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

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 << 1% then

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

So, for example if n(u) is 10 then σ(total) will be 0.14 or 14%.

In general, find $n(ui)_{opt} < 0.42\ SNR_{100}$,
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 maximum n(u) is put into the $\sigma(f)/f$ formula,

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

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

$$M_{opt} = 1 + 2 * 0.42\ SNR_{100} * P/f = 1 + 0.84 * SNR_{100} * P/f,$$

It is seen that the ratio P/f has a large effect on the magnification needed. When P/f is < 1 and SNR ~100 then M is < 100 which a 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 SNR ~100 then M > 100. In this case when P/f > 1, lesser than optimal

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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 $3.3/SNR_{100}$.

When a magnification other than Mopt is used then

n(u) = (M -1)/2(P/f).

<u>Examples</u>

10 micron pixel (such as high resolution film scanner)									
P (μm)	f (μm)	SNR_{100}	$n(ui)_{opt}$ (pixels)	M for $n(u)_{max}$	½ 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 (≥50 μm), 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.

50 micron pixel (such as high resolution CR system)									
P (μm)	f (μm)	SNR_{100}	$n(ui)_{opt}$ (pixels)	M for $n(u)_{max}$	½ 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 ≥50 μm 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.

127 micron pixel (such as DDA)									
P (μm)	f (μm)	SNR_{100}	$n(ui)_{opt}$ (pixels)	M for $n(u)_{max}$	½ 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. The following tables show parameters for images that will be acquired. *Unsharpness profiles and focal spot dimensions will be inserted.*

Radiographic System:
Hamamatsu L8121-01 microfocus source in Hytec Cabinet
Per the L8121-01 manual: Large Spot = 50 μm, Medium Spot = 20 μm, Small Spot = 7 μm

The maximum magnification in the cabinet is 80 (60 inch SID / 0.75 inch SOD).

Scanned Film (Kodak M100/Microtek 1000)

Large Spot	**Medium Spot**	**Small Spot**
P = 15 μm	P = 15 μm	P = 15 μm
SNR = 50	SNR = 50	SNR = 50
$n(ui)_{opt}$ = 21	$n(ui)_{opt}$ = 21	$n(ui)_{opt}$ = 21
max accuracy = 6.7%	max accuracy = 6.7%	max accuracy = 6.7%
M_{opt} = 13.6	M_{opt} = 32.5	M_{opt} = 91

M can be larger but accuracy will not improve unless SNR is > 50.

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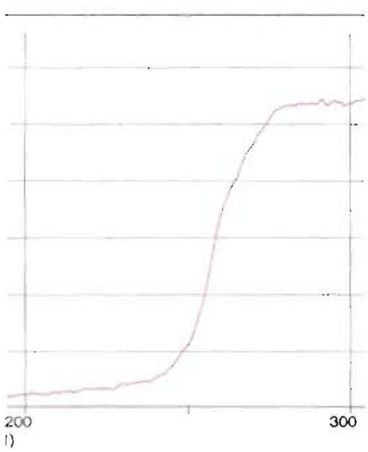
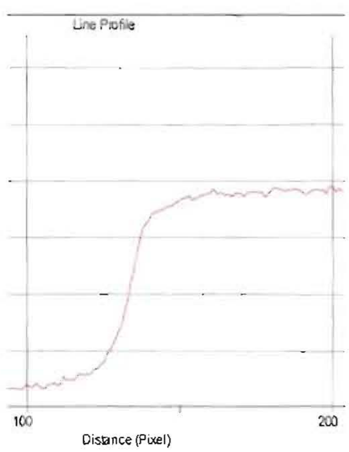
Computed Radiography (GE CR50P)

Large Spot	**Medium Spot**	**Small Spot**
P = 50 μm	P = 50 μm	P = 50 μm
SNR = 100	SNR = 100	SNR = 100
$n(ui)_{opt}$ = 42	$n(ui)_{opt}$ = 42	$n(ui)_{opt}$ = 42
max accuracy = 3.3%	max accuracy = 3.3%	max accuracy = 3.3%
M_{opt} = 85	M_{opt} = 211	M_{opt} = 601
	M = 100	M = 100
	n(u) = 20	n(u) = 7
	accuracy = 7%	accuracy = 20%

Digital Detector Array (Varian 2520)

Large Spot	Medium Spot	Small Spot
P = 127 μm	P = 127 μm	P = 127 μm
SNR = 500	SNR = 500	SNR = 500
$n(ui)_{opt}$ = 210	$n(ui)_{opt}$ = 210	$n(ui)_{opt}$ = 210
max accuracy = 0.7%	max accuracy = 0.7%	max accuracy = 0.7%
M_{opt} = 1068	M_{opt} = 2668	M_{opt} = 7621
M = 80	M = 80	M = 80
n(u) = 15	n(u) = 6	n(u) = 2
accuracy = 9.3%	accuracy = 23%	accuracy = 70%
SNR_{100} = 168 $n(ui)_{opt}$ = 70	SNR_{100} = 197 $n(ui)_{opt}$ = 82	
n(D) = 635 M = 80.6	n(D) = 635 M = 80.6	
actual n(u left) = 10	actual n(u left) = 8	
actual n(u right) = 16 *	actual n(u right) = 9 *	
actual n(u top) = 11	actual n(u top) = 11	
actual n(u bottom) = 25	actual n(u bottom) = 15	
f = 42 x 58 μm	f = 27 x 42 μm	





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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 $P/f < 100/SNR_{100}$, 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 $M > M_{opt}$ and so $n(ui) > n(ui)_{opt}$ and therefore accuracy is limited by SNR

- When $P/f > 100/SNR_{100}$, 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 $M < M_{opt}$ and so $n(ui) < n(ui)_{opt}$ and therefore accuracy is limited by n(ui)

Appendix: Proposed Procedure

1. determine the maximum magnification (M_{max}) for the radiographic system by calculation or experiment
2. determine SNR_{100} for the imaging conditions
3. from SNR_{100} calculate $n(ui)_{opt}$ and M_{opt}
4. determine if $M_{opt} \leq M_{max}$
   a. If yes, use an $M \geq M_{opt}$ and accuracy is $3.3/SNR_{100}$
   b. If no, use M_{max}. The accuracy will be reduced to

$$\sigma(f)/f = \sqrt{1/n(u1)]^2 + [1/n(u2)]^2}$$

5. take image of object at M determined in step 4
6. determine actual magnification M = n(D) P
7. determine n(u1) and n(u2) from image for both vertical and horizontal profiles
8. width of f = P [n(u1)+n(u2)]/[M – 1] for horizontal profiles
9. height of f = P [n(u1)+n(u2)]/[M – 1] for vertical profiles