LA-UR-14-26423
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Title: Improved SEM Resolution Through the Use of Image Restoration Techniques

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Intended for: Microscopy & Microanalysis 2014 Meeting, 2014-08-03 (Hartford, Connecticut, United States)

Issued: 2014-08-13

Improved SEM Resolution Through the Use of Image Restoration Techniques

Oliver Wells Symposium, August 5, 2014

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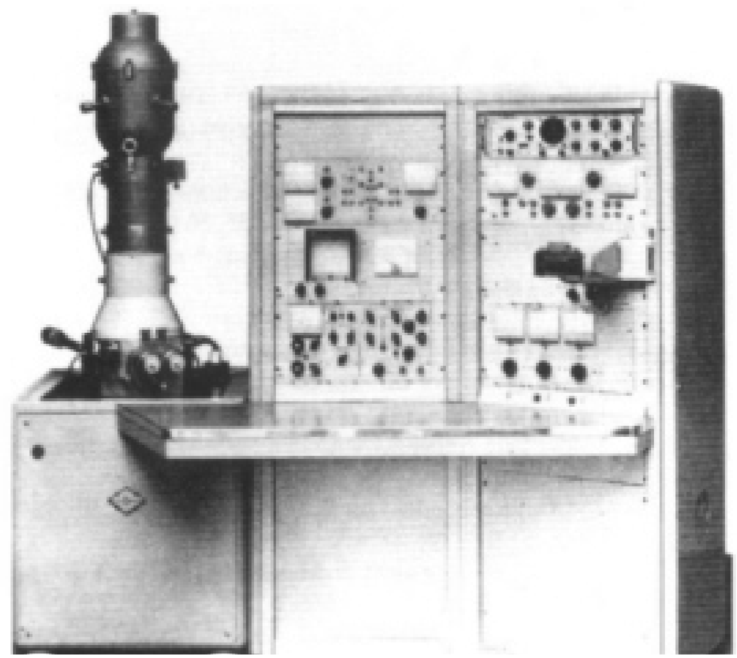
In the Beginning
(well almost)
1950's and 1960's

Bremer, Wells and McMullan

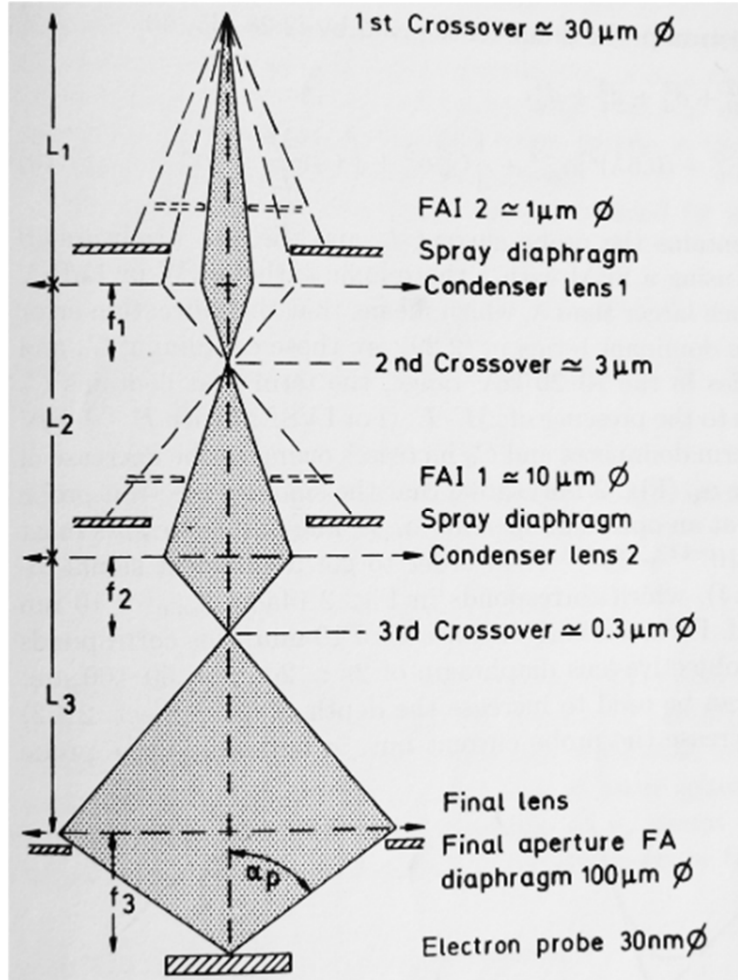
Photo courtesy of David Scharf



The prototype of the first Stereoscan SEM, supplied by the Cambridge Instrument Company to the duPont Company, USA. (Stewart and Snelling 1965). Courtesy of Leica Ltd.

Then Fifty Years of Major Advances

- Vacuum tubes to ULSI
- Digital Scanning
- Faster low noise detectors
- Automation and computer control (knobs are gone)
- Field Emission and Schottky high brightness sources
- Improved lenses
- Advanced computer displays and digital storage of images
- …



From Reimer

However the probe remains a demagnified image of the source (crossover) !

What determines the probe size, d_p?

$$d_p = \sqrt{\left(d_g^2 + d_s^2 + d_c^2 + d_\lambda^2\right)}$$

where

Source Demagnification: $d_g = M d_0 = \sqrt{\left(\frac{4 i_p}{\pi^2 \beta}\right)}\,\alpha^{-1}$

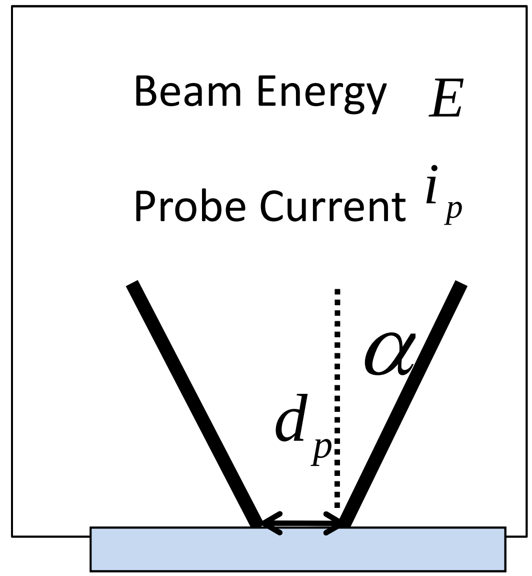
Spherical Aberrations: $d_s = \sqrt{\frac{C_s}{4}}\,\alpha^3$

Chromatic Aberrations: $d_c = C_c\left(\frac{\Delta E}{E}\right)\alpha$

Diffraction Effects: $d_\lambda = .61\lambda\alpha^{-1}$

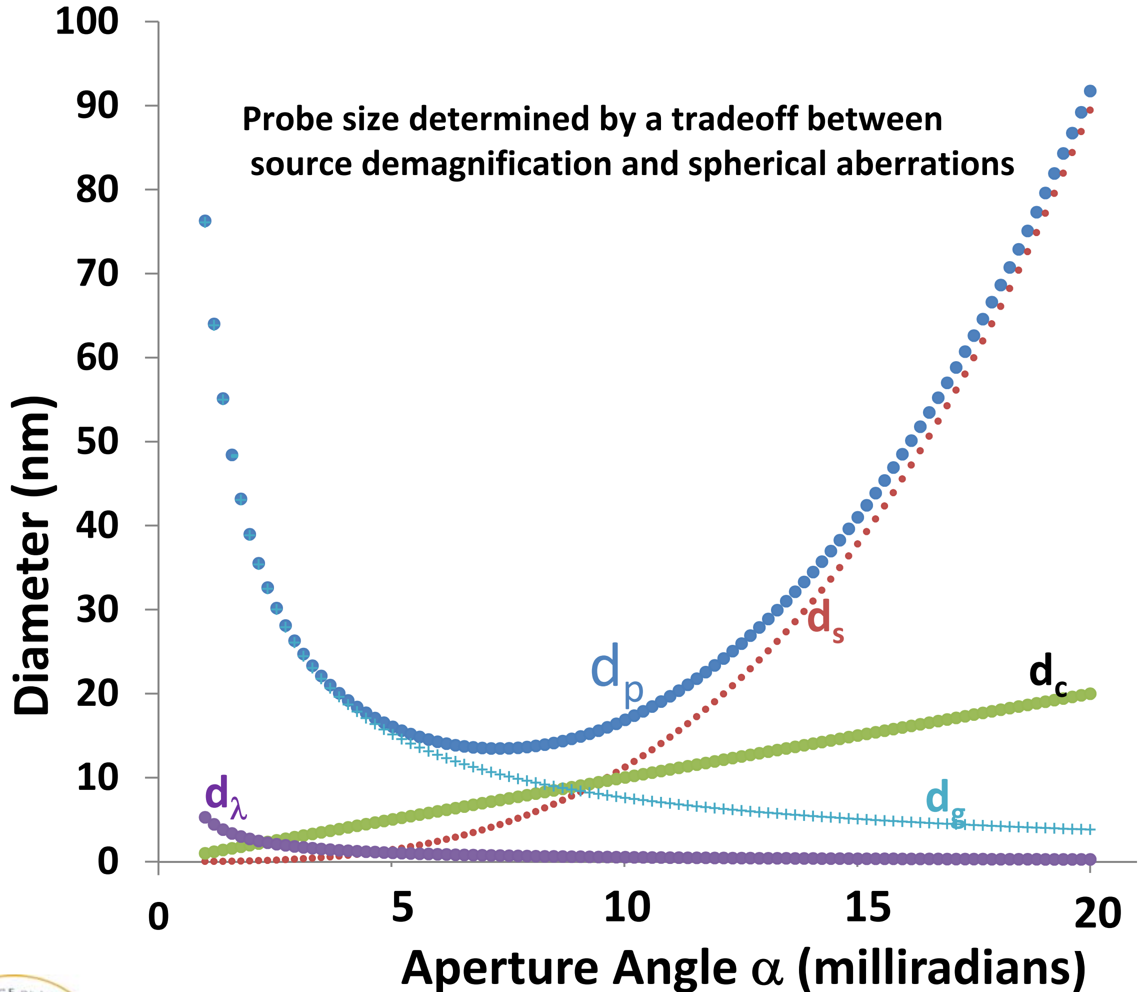
Wavelength: $\lambda = h/mv = 1.226/\sqrt{E}$

Brightness: $\beta = \frac{j_c E}{\pi k T_c}$



λ = 8 pm at 30 KeV
d_λ = .8 nm for α =.006 radians

Probe Diameter tradeoff curves



d_p – Probe Diameter
d_g – Source Demagnification
d_s – Spherical Aberrations
d_c – Chromatic Aberrations
d_λ – Diffraction Effects

Tungsten source, at 20 KeV, ΔE = 1 ev, $\beta = 7 \times 10^4$ Amps/cm^{2}sr and probe current of 10 pA

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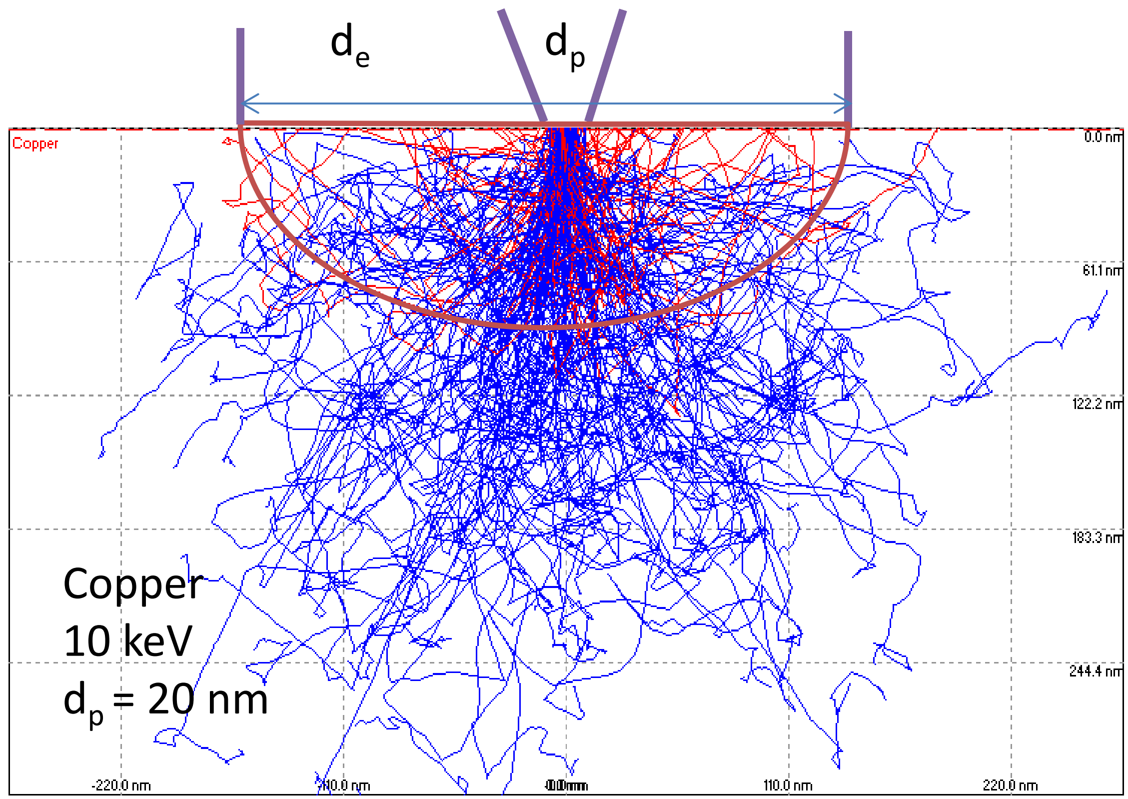
SEM resolution is limited by the probe size, d_p, surface morphology and excitation volume, d_e .

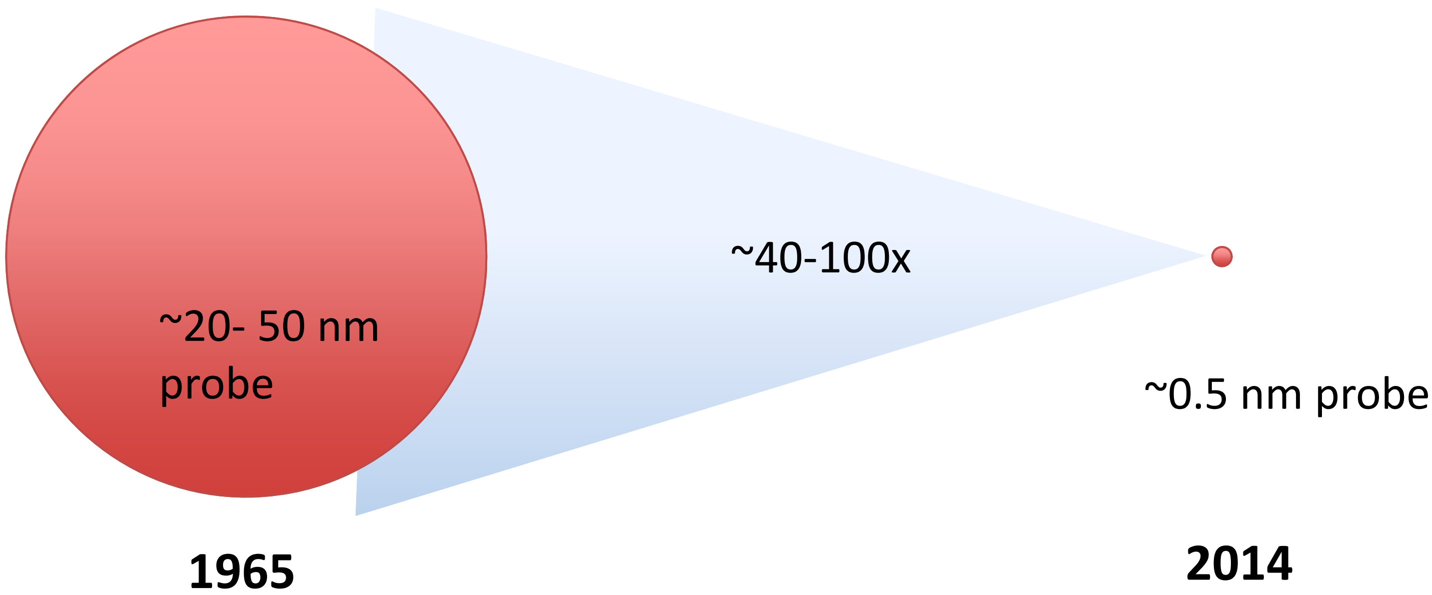
•For backscattered electrons d_e can be >> than d_p unless low kV are used

•For type 1 secondary electrons d_e can be almost equal to d_p

For planar samples d_p is not sample dependent. d_e is !



Current Trends

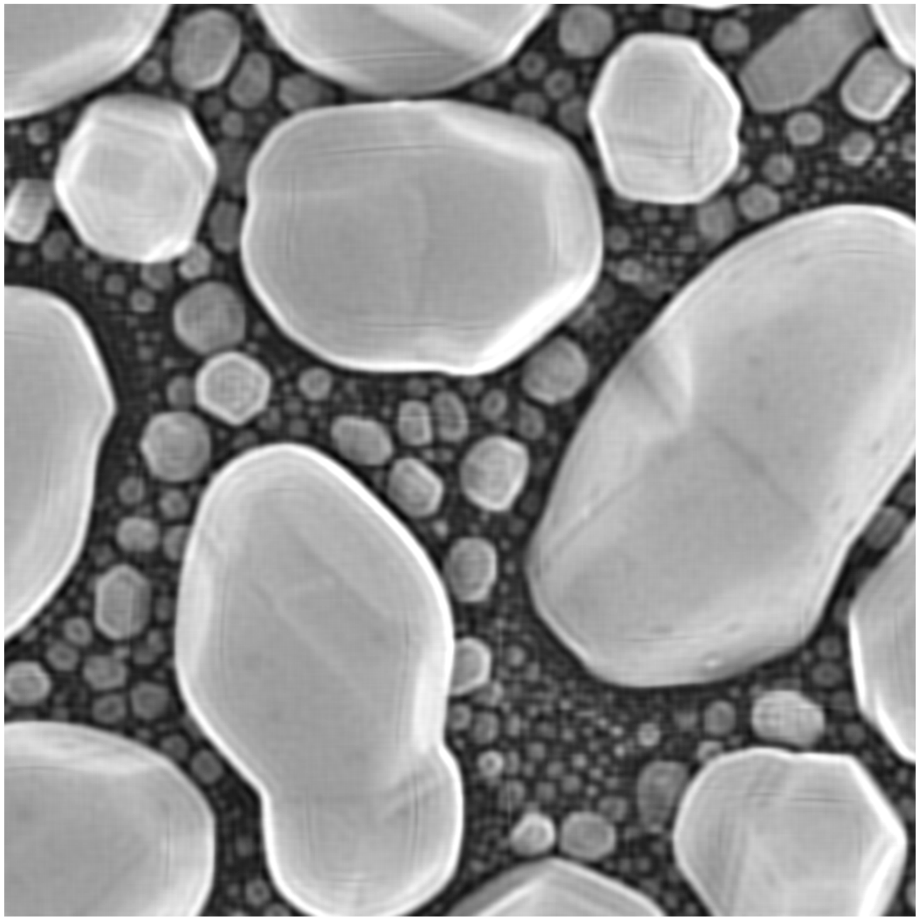


Smaller probes and brighter sources

BUT – at increased complexity and cost.

Our approach

Resolution improvement through Image deconvolution (restoration)



Blurred Image
Restored Image

Achieved through:

- relatively low cost
- high speed computation
- advanced mathematics
- novel algorithms-

Previous Studies

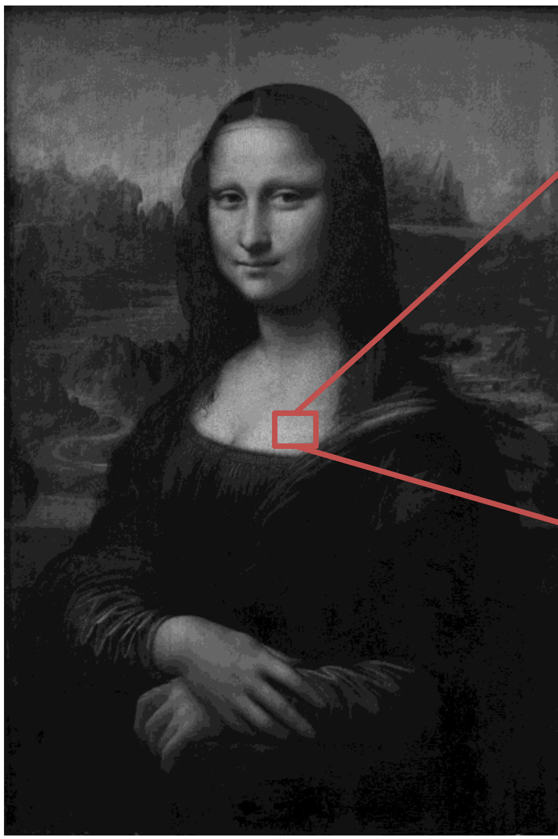
- "Deconvolution of SEM Images" – Yano & Nomura (1993)
  - Used Fourier transform of Image and calculated PSF on very high resolution SEM and STEM images; gained factor of 2 improvement.
    - Recognized potential for LV imaging, signal to noise issues, need for better PSF's

- "Blind Deconvolution of SEM Images"- Vanderlinde & Caron (2007)
  - Used blind deconvolution with Weiner filter; gained 1.2 to 1.4X improvement in 500KX SE images
    - Needed 10 minute acquisition times, noted problem with drift.

- "Increasing Spatial Resolution in the BS Mode of SEM" – Koshev, et. al. (2011)
  - Used 3D excitation volume model, Fourier transforms and Tikhanov regularization, applied to subsurface detail including pn junctions.
    - Recognized need for further algorithm development

A digital image as matrix of numbers

Black and White Mona Lisa



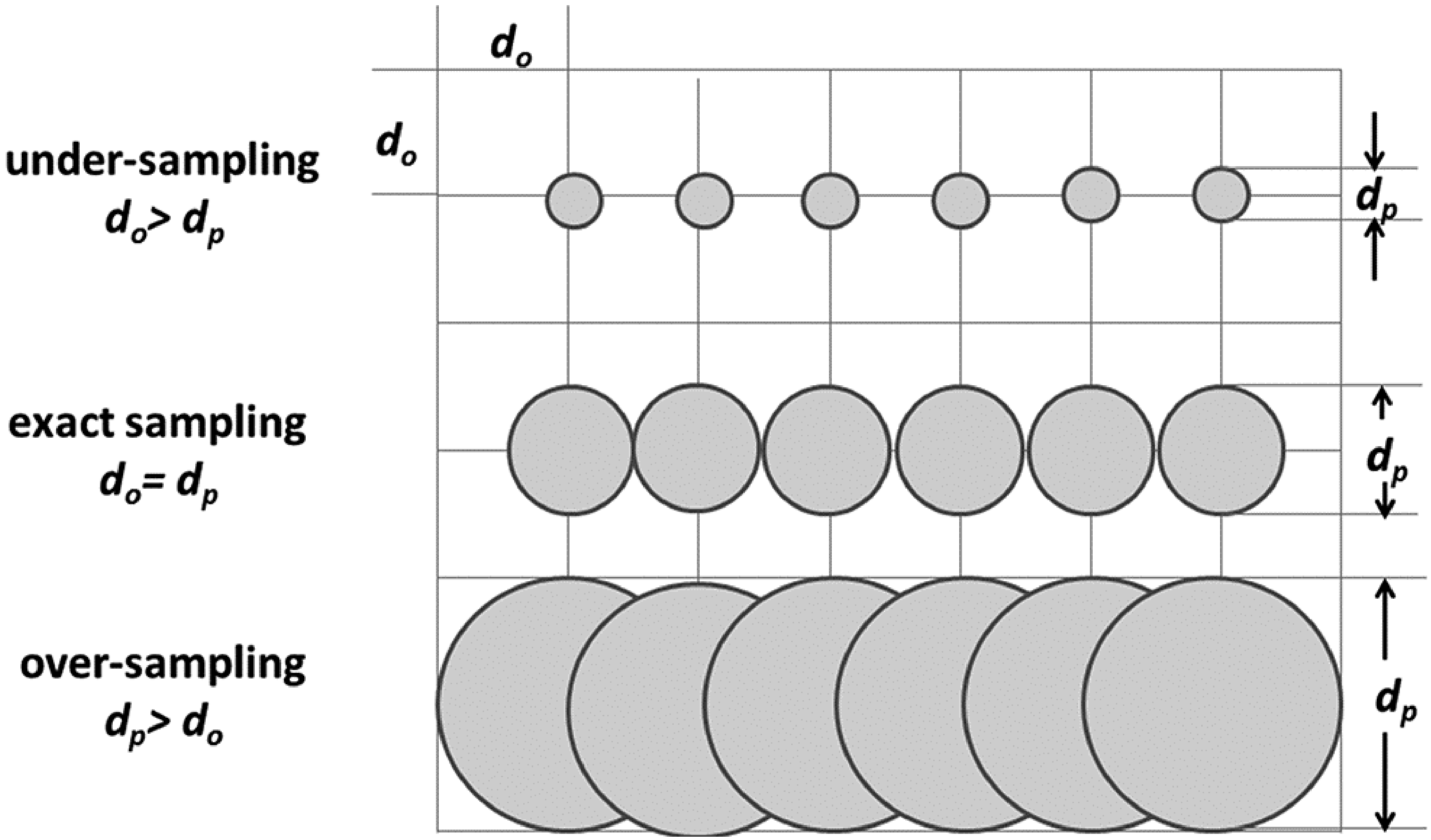
Grayscale map of detail

Data from 11 x 7 pixels

161	177	191	177	155	143	163	192	189	181	180
174	185	197	188	166	151	166	190	184	171	168
181	193	202	197	163	152	162	179	170	148	145
161	182	188	180	151	151	162	173	160	134	135
134	162	164	151	145	159	168	171	162	141	148
140	163	161	152	148	166	161	153	157	151	161
167	175	172	180	167	176	148	127	147	161	170

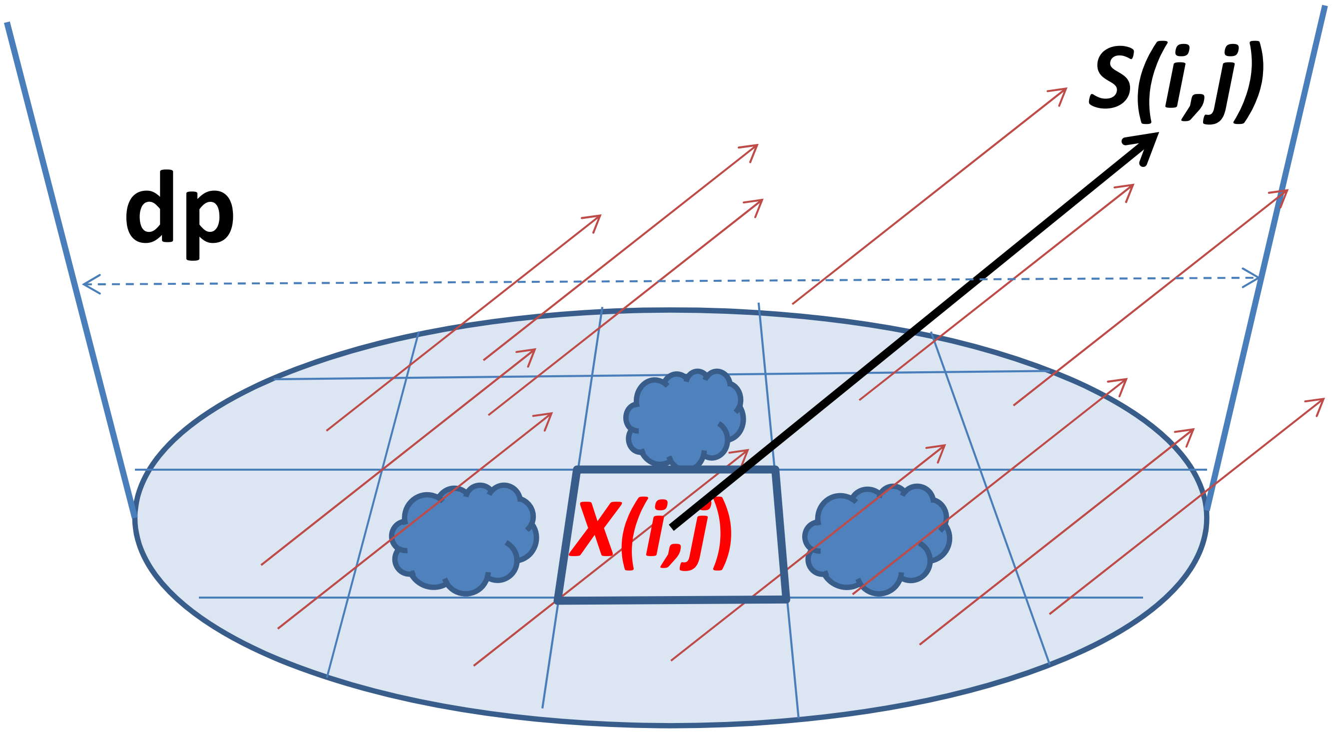
Original image is 3591 by 2403 pixels each with 8 bits of intensity data

Sampling /Terminology



pixel size: d_o probe size: d_p

Probe Size and Object Detail



The measured signal *S* is the sum of the signals from all of the points sampled within the probe spot

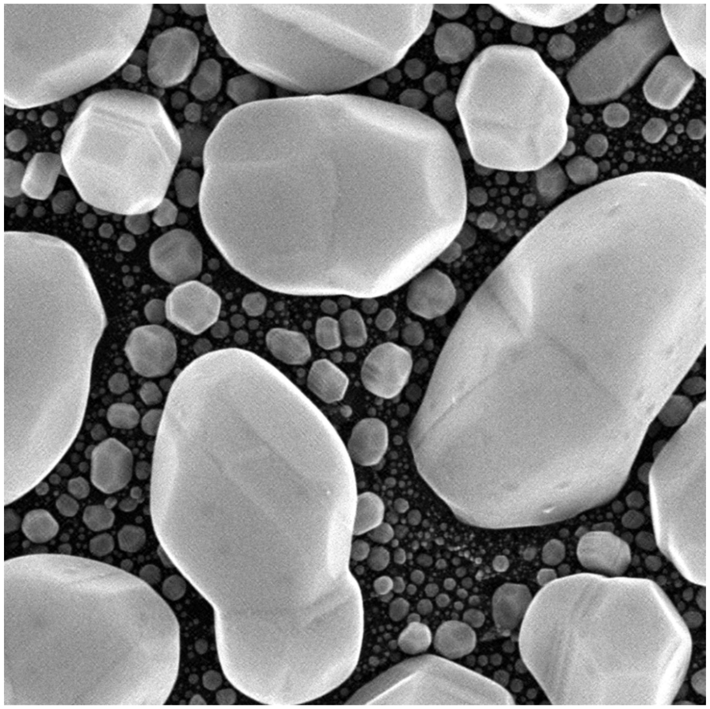
$$S(i,j)=\sum_{k=1}^{m}\sum_{l=1}^{n}PSF(k,l)X((i+\frac{m-1}{2})-k,(j+\frac{n-1}{2})-l)$$

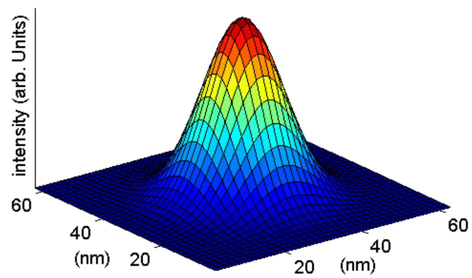
Scanning a 5x5 matrix with a 3x3 PSF

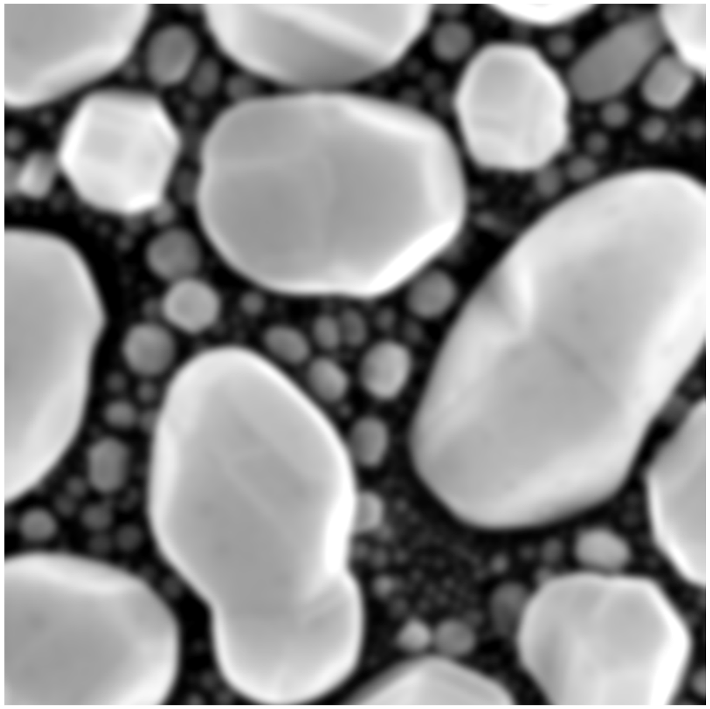
$X_o(1,1)$	$X_o(1,2)$	$X_o(1,3)$	$X_o(1,4)$	$X_o(1,5)$
$X_o(2,1)$	$X_o(2,2)$	$X_o(2,3)$	$X_o(2,4)$	$X_o(2,5)$
$X_o(3,1)$	$X_o(3,2)$	$X_o(3,3)$	$X_o(3,4)$	$X_o(3,5)$
$X_o(4,1)$	$X_o(4,2)$	$X_o(4,3)$	$X_o(4,4)$	$X_o(4,5)$
$X_o(5,1)$	$X_o(5,2)$	$X_o(5,3)$	$X_o(5,4)$	$X_o(5,5)$

9 Equations and 25 Unknowns!

Convolution







Deconvolution

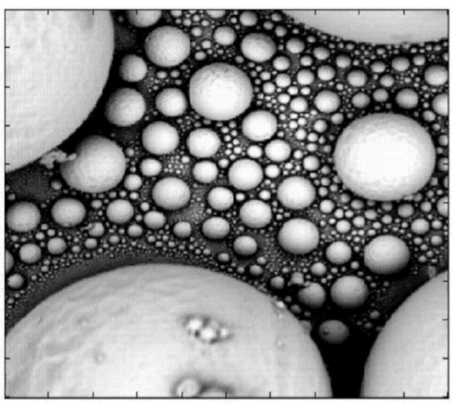
With no noise to the image we get the near perfect reconstruction!

Basic Deconvolution

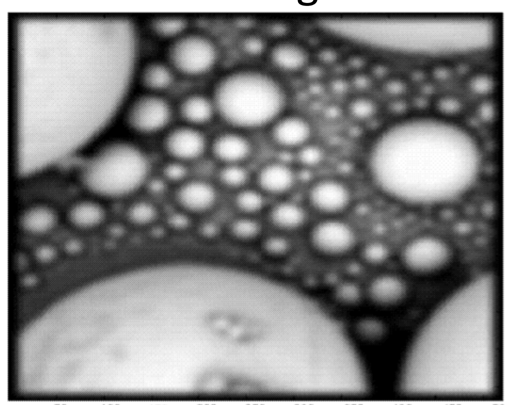
$$\begin{bmatrix} x_{o_{11}} & \cdots & x_{o_{1n}} \\ \vdots & \ddots & \vdots \\ x_{o_{1m}} & \cdots & x_{o_{mn}} \end{bmatrix} \otimes \begin{pmatrix} psf_{11} & \cdots & psf_{1q} \\ \vdots & \ddots & \vdots \\ psf_{1p} & \cdots & psf_{pq} \end{pmatrix} = \begin{bmatrix} x_{i_{11}} & \cdots & x_{i_{1n}} \\ \vdots & \ddots & \vdots \\ x_{i_{1m}} & \cdots & x_{i_{mn}} \end{bmatrix}$$

Object Information X_o	$\otimes$	Point Spread function PSF_i	$=$	Image Map X_i

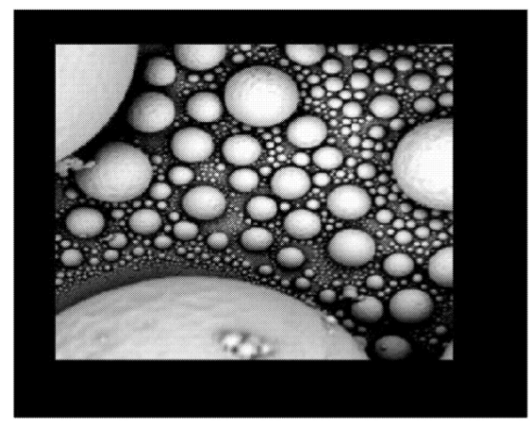
Original image



Blurred image



Restored Image



from US Patent 8,669,524 B2 Lifshin et. al.

In reality …

$$\begin{bmatrix} x_{o_{11}} & \cdots & x_{o_{1n}} \\ \vdots & \ddots & \vdots \\ x_{o_{1m}} & \cdots & x_{o_{mn}} \end{bmatrix} \otimes \begin{pmatrix} psf_{11} & \cdots & psf_{1q} \\ \vdots & \ddots & \vdots \\ psf_{1p} & \cdots & psf_{pq} \end{pmatrix} + \begin{bmatrix} N_{11} & \cdots & N_{1n} \\ \vdots & \ddots & \vdots \\ N_{1m} & \cdots & N_{mn} \end{bmatrix} = \begin{bmatrix} x_{i_{11}} & \cdots & x_{i_{1n}} \\ \vdots & \ddots & \vdots \\ x_{i_{1m}} & \cdots & x_{i_{mn}} \end{bmatrix}$$

Object Information ⊗ Point Spread function + Noise = Image Map

- Basic Convolution Equation becomes

$$X_i = PSF \otimes X_o + N_i$$

- Linearize images and construct circulant matrix *A* from PSF

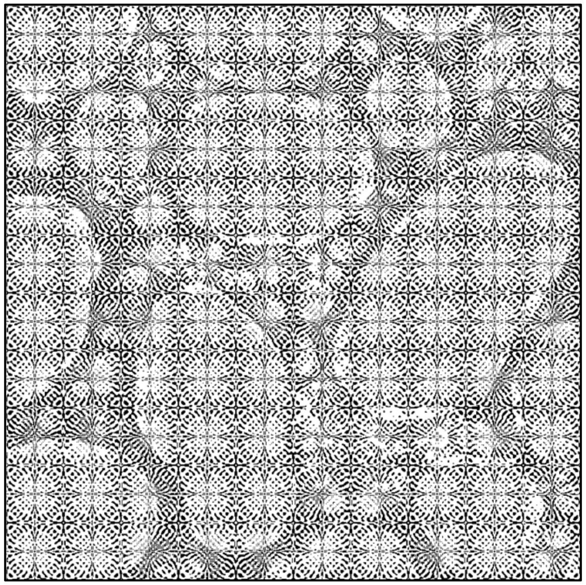
$$I_i = AI_o + N_i$$

$$\Rightarrow I_o = A^{-1}AI_i - A^{-1}N_i$$

Inverse Noise

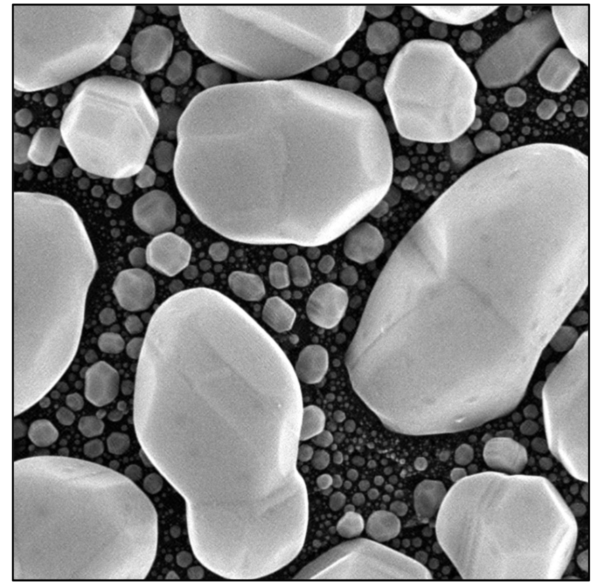
Matrix A needs to be invertible!

Noise becomes the primary issue



With very small noise

Deconvoluted images



With no noise

Additionally Need -

- Alignment of multiple of images
- Accurate PSFs for each image
- Consistent brightness and contrast of each image with the degree of blurring
- Minimal drift and contamination
- Planar sample to use a single position independent PSF

Dealing with Noise – "Regularization"

- The basic convolution is given by:

$$I_i = A_i I_o + N'$$

- It can be re-arranged to give:

$$I_i - A_i I_o = N'$$

- Regularization balances a least squares fit and smoothing (noise reduction operation).

Example: Tikhanov Regularization

$$\min_{I_o}[\|I_i - A_i I_o\|^2 + \lambda^2\|D I_o\|^2]$$

where λ and *D* are regularization parameters

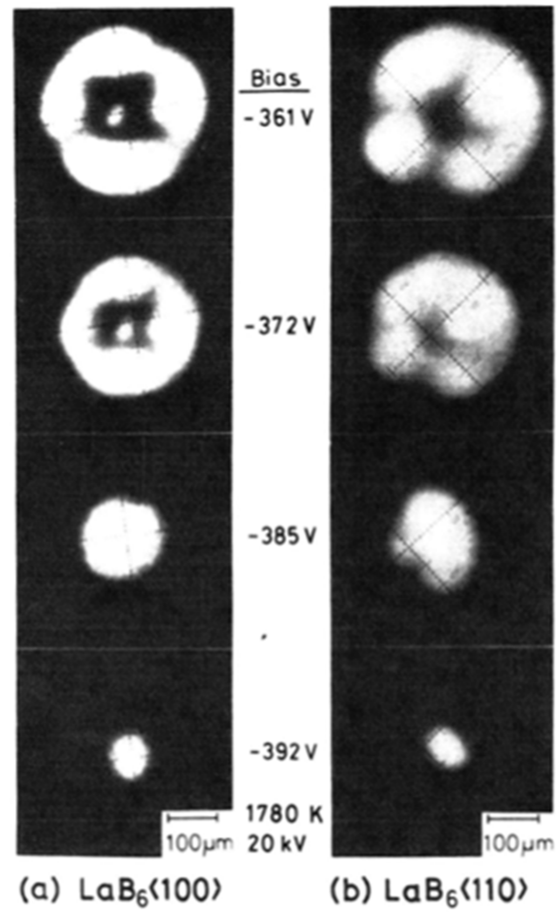
Determining a PSF for an SEM

- No detector in the image plane can directly measure sub-micrometer beams
- Crossover or TEM images may not be accurately predict the shape in the sample plane
- Knife edge scans are limited for small beams
- We use a variant of the method of *Liddle at. al.*
  - Known pixel level resolution reference image X_o
  - Image same structure with selected over-sampling conditions X_i, make N negligible
  - Calculate PSF from:

$$X_i = PSF_i \otimes X_o + N \approx PSF_i \otimes X_o$$

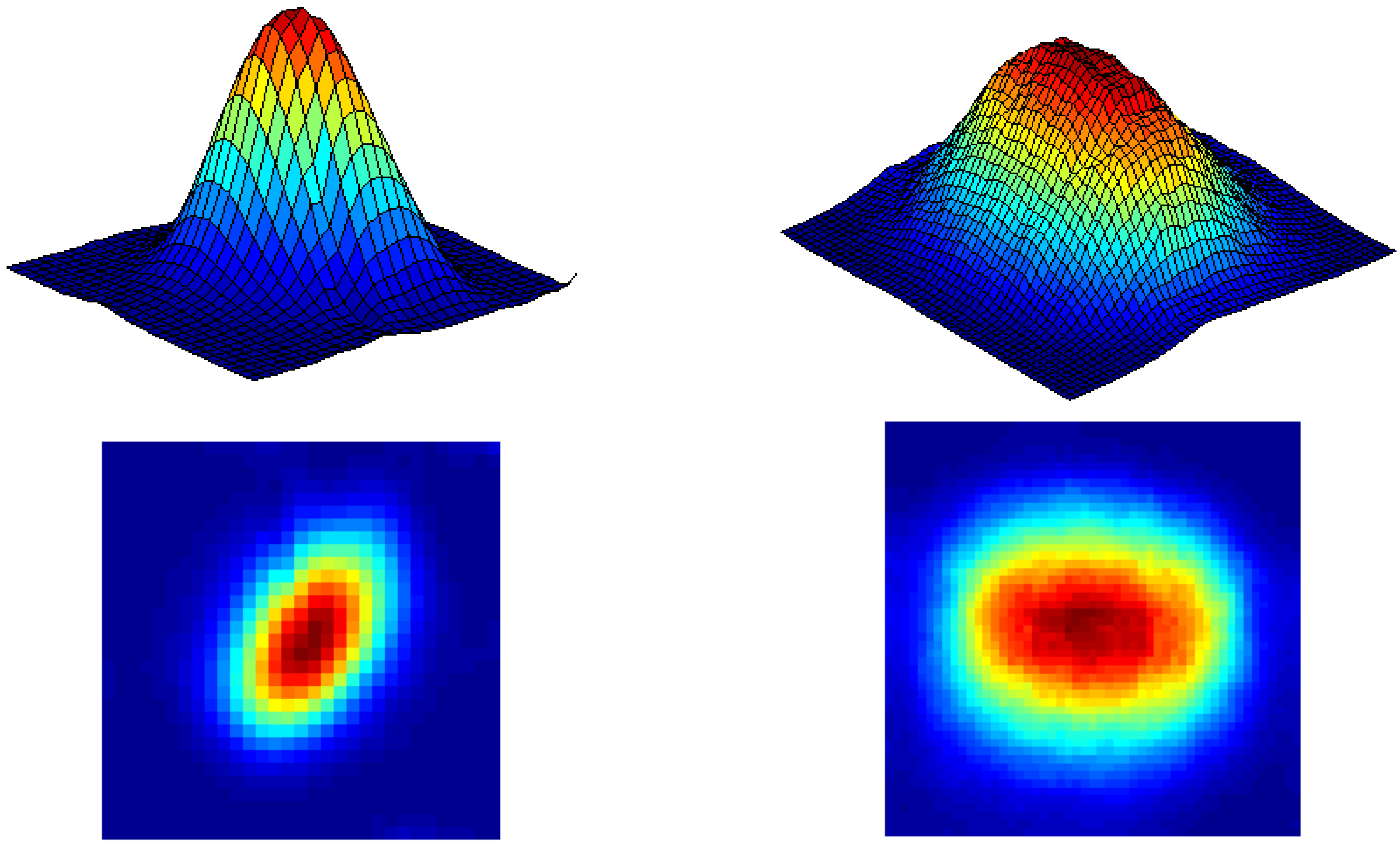
What does the crossover look like?

- Normally characterized as a 2D distribution in the sample plane - the point spread function (PSF)
- Often assumed to be Gaussian
- Difficult or impossible to directly measure at the sample plane



Crossover Images
Shimizu, et. al. (1979)

What do PSF's Really Look Like?



Calculated using blurred images formed by large probes on known structures.

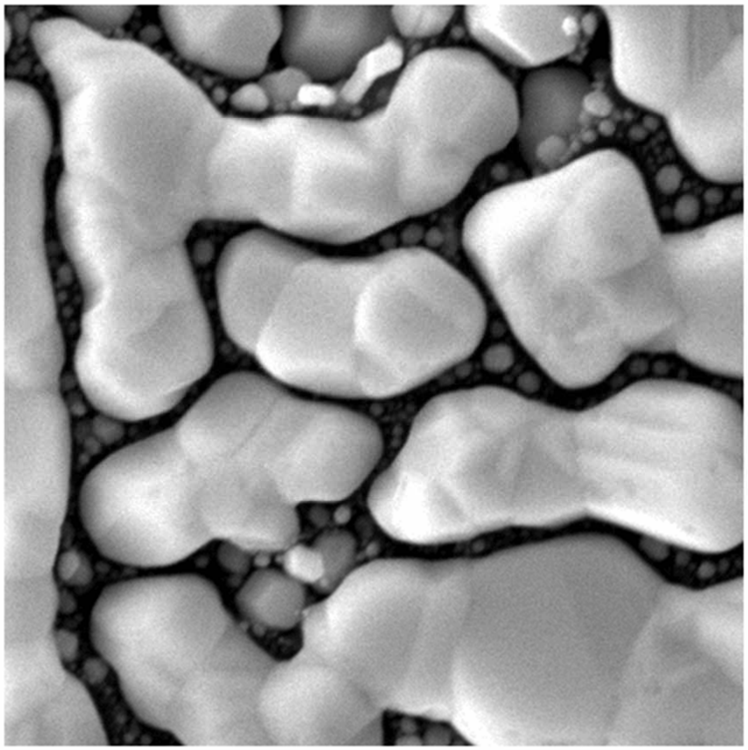
PSF variation with probe current

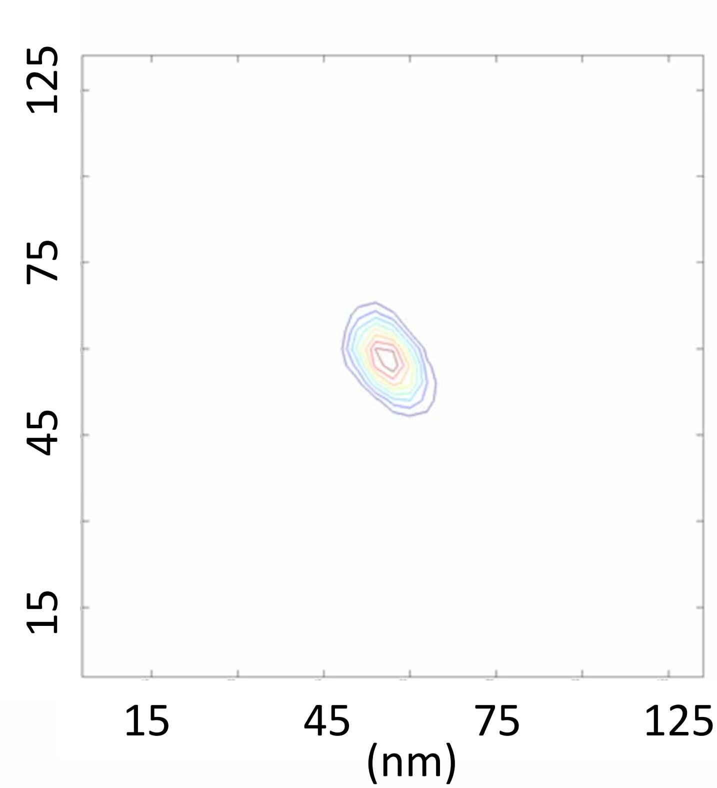
Beam Index - 4

Pixel Size - 6.0 nm

Spot size - 7.28 nm

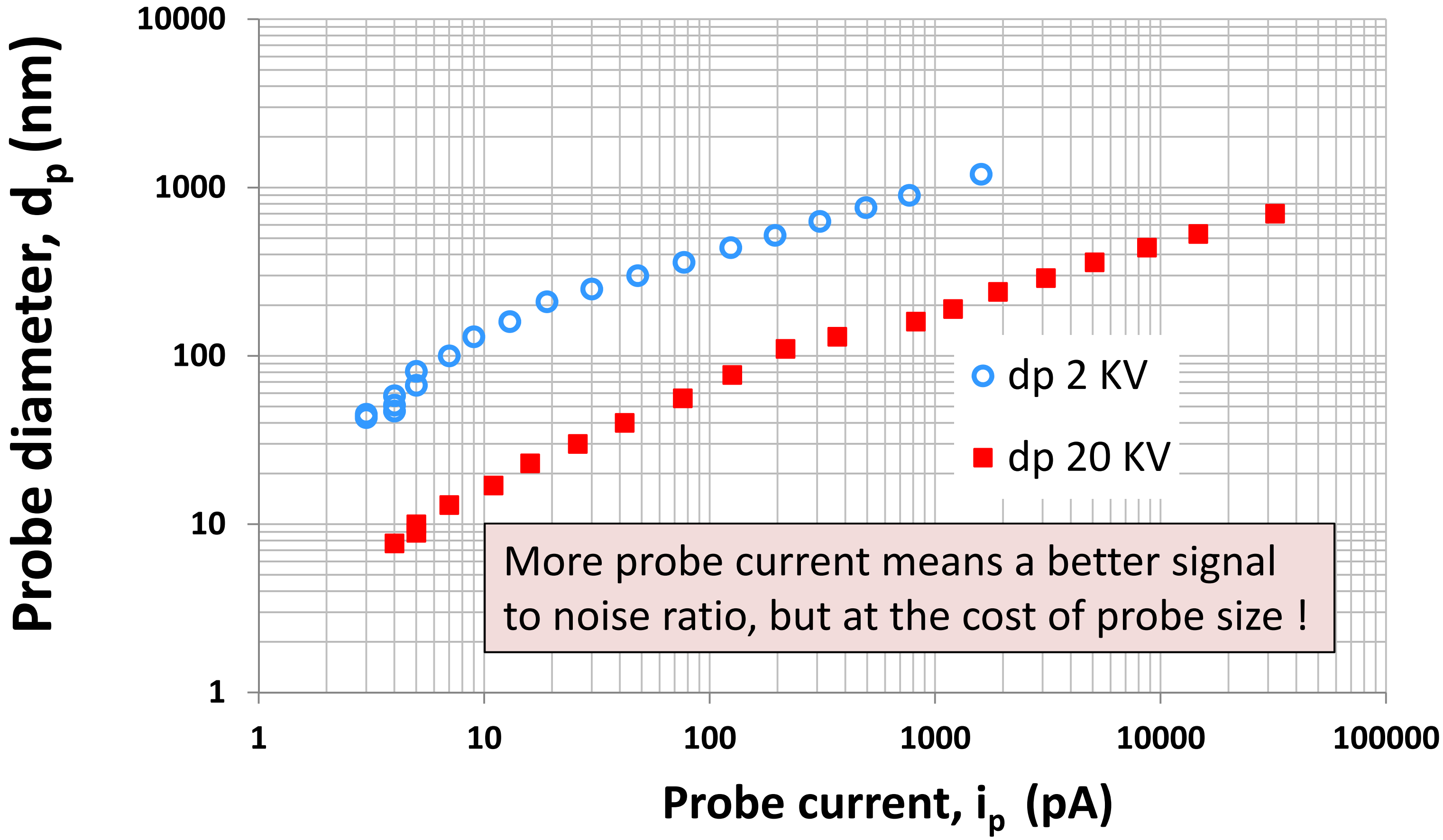
Probe Current - 4.10 pA



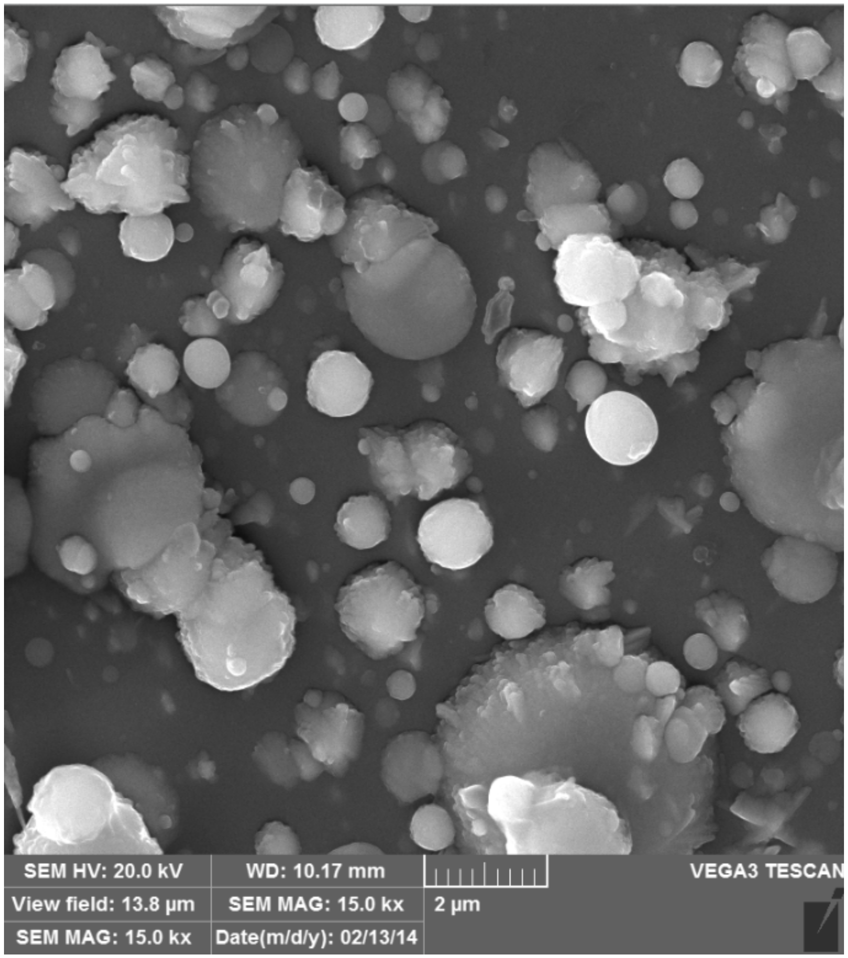


Probe diameter, d_p, vs. probe current, i_p

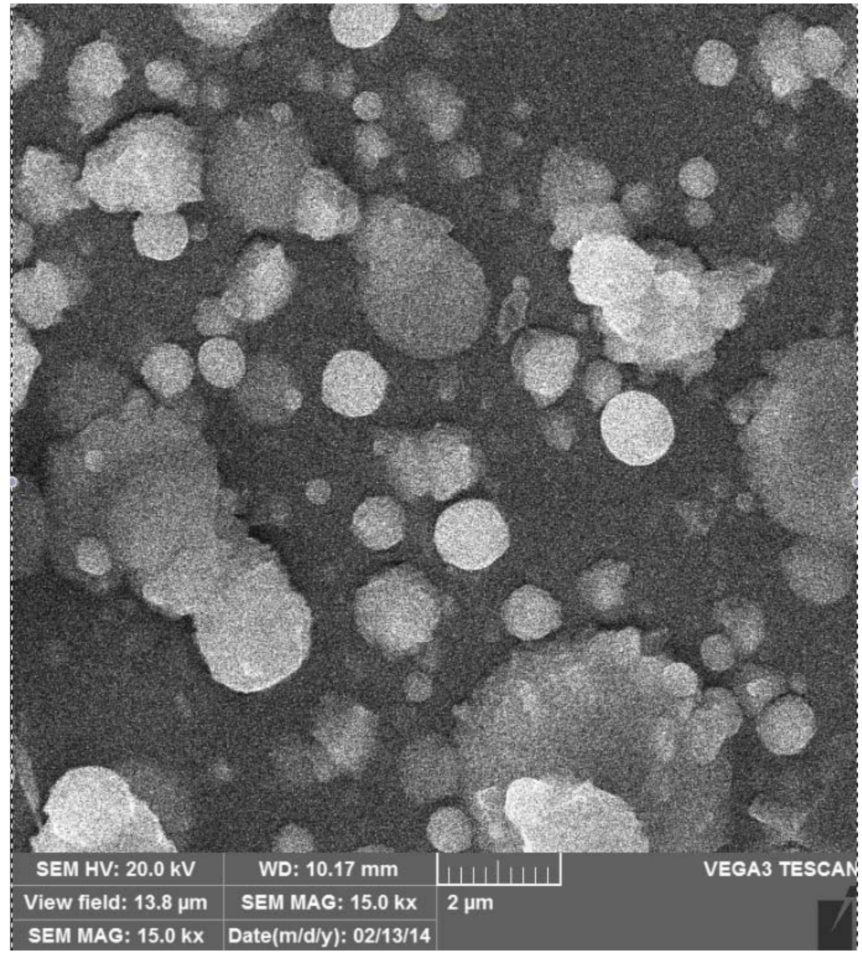
(Tungsten Source)



Noise – Current & Dwell Time Per Pixel is Critical



1000 µs per pixel
(~250 seconds for 500x500 pixel)



3µs per pixel
(~0.83 seconds for 500x500 pixel)

SUNY College of Nanoscale Science and Engineering

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Brightness and Contrast

- When a given pixel resolution object is blurred by progressively larger PSFs contrast is reduced.
- Contrast often represented by the Michelson equation:

$$C = \Delta I / I = (I_2 - I_1)/(I_2 + I_1)$$

- This expression refers only to two adjacent points 1 and 2. We propose a new concept, total image contrast defined by:

$$C = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\frac{\left|I_{i,j} - I_{ave}\right|}{I_{ave}} \qquad \text{where} \qquad I_{ave} = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n} I_{i,j}$$

- Images adjusted to maintain the average intensity and decrease contrast consist with degree of blurring

Our work: Algorithm

1. Determine PSF for one or more beam sizes
   - PDET program
2. Obtain one or more images of selected areas
3. Align images if more than one
4. Adjust contrast and brightness
   - image adjust function
5. Apply regularization equation
   - TIRP (total image restoration program) – multiple images
   - Total variation (TV) single image restoration/padding required

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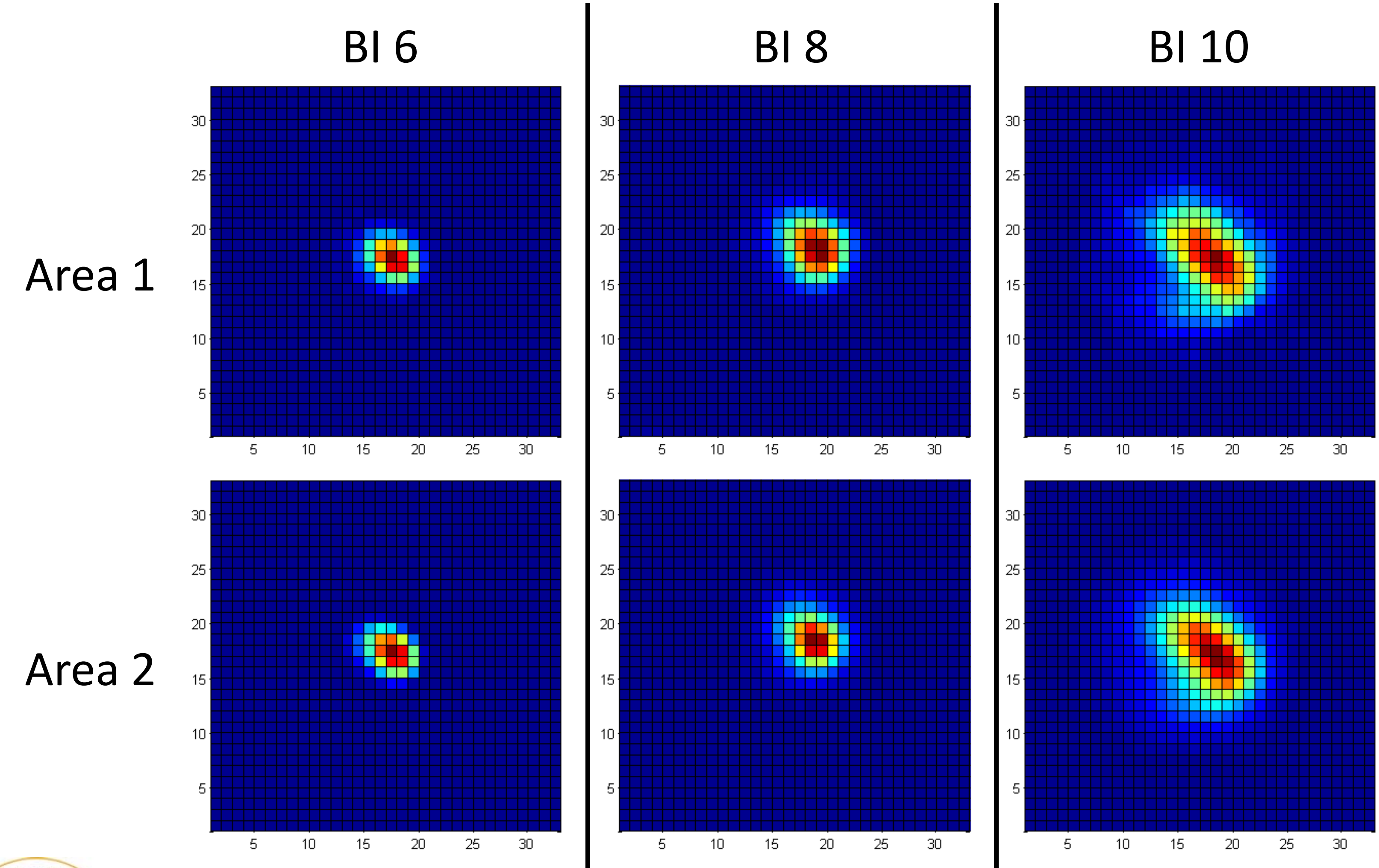
For validation compare restored image with a reference image – difference with histogram or direct comparison with blurred images

- COMPARE program

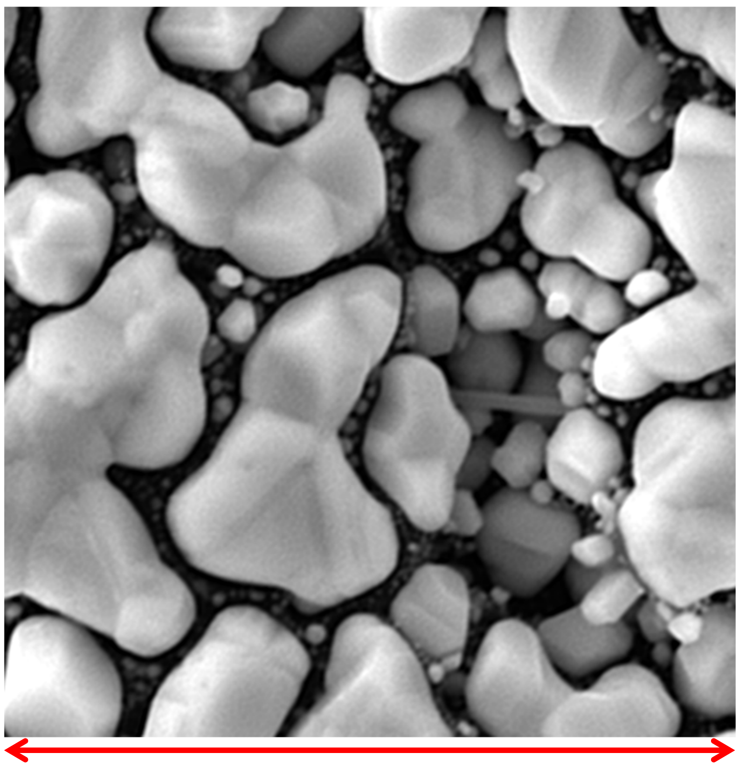
Is the PSF consistent across different areas on a sample?

Comparison of PSFs from Area 1 to Area 2



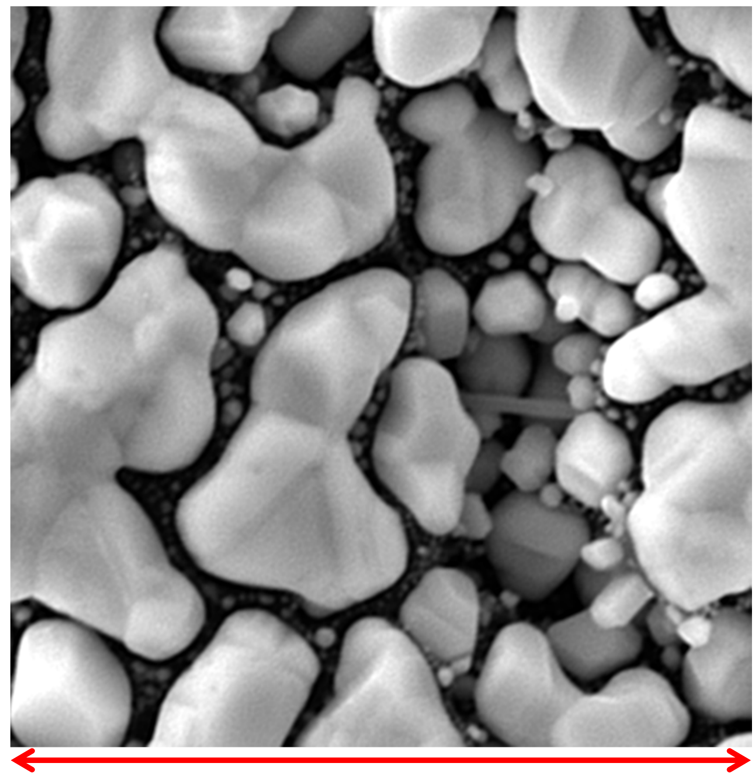
TIRP Reconstructions with PSFs from Different Areas

Area 2 Psf 1



4 µm

Area 2 Psf 2



4 µm

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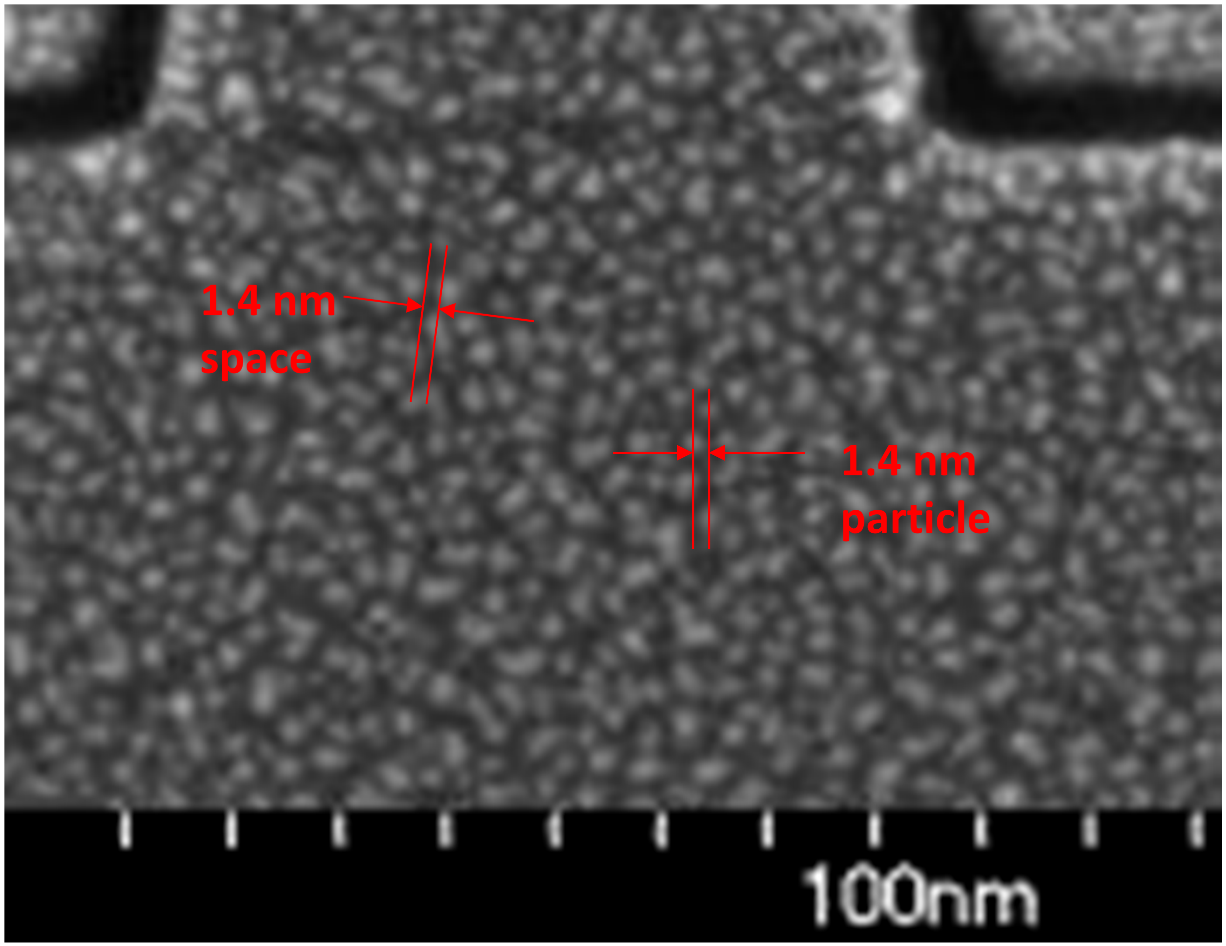
Many Faces of Resolution

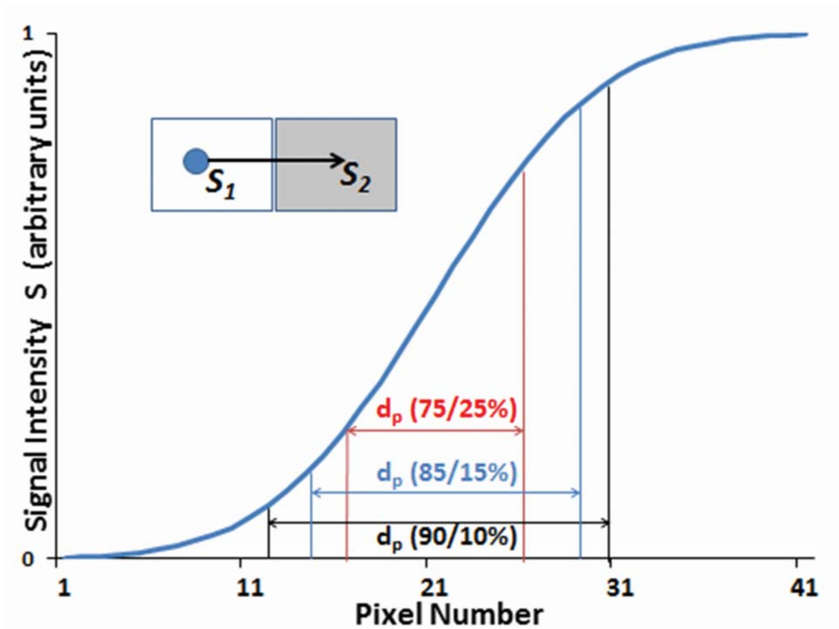
- We think we know, but difficult to explain!
- Smallest object you can see or distinguishing one feature from another, e.g. two particles or a sequence of evenly space lines.
- Discussion starts with digital photography where we are pixel limited or with optical microscopy with diffraction limits.

Resolution 1
particle size and spacing

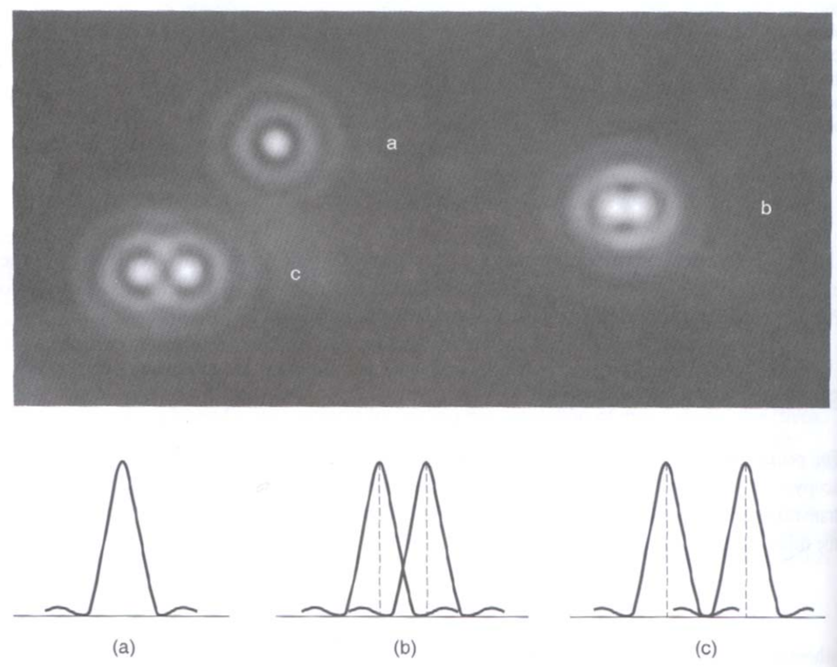


Tracy (2003)

Resolution 2
profiles and valleys



Edge Profile

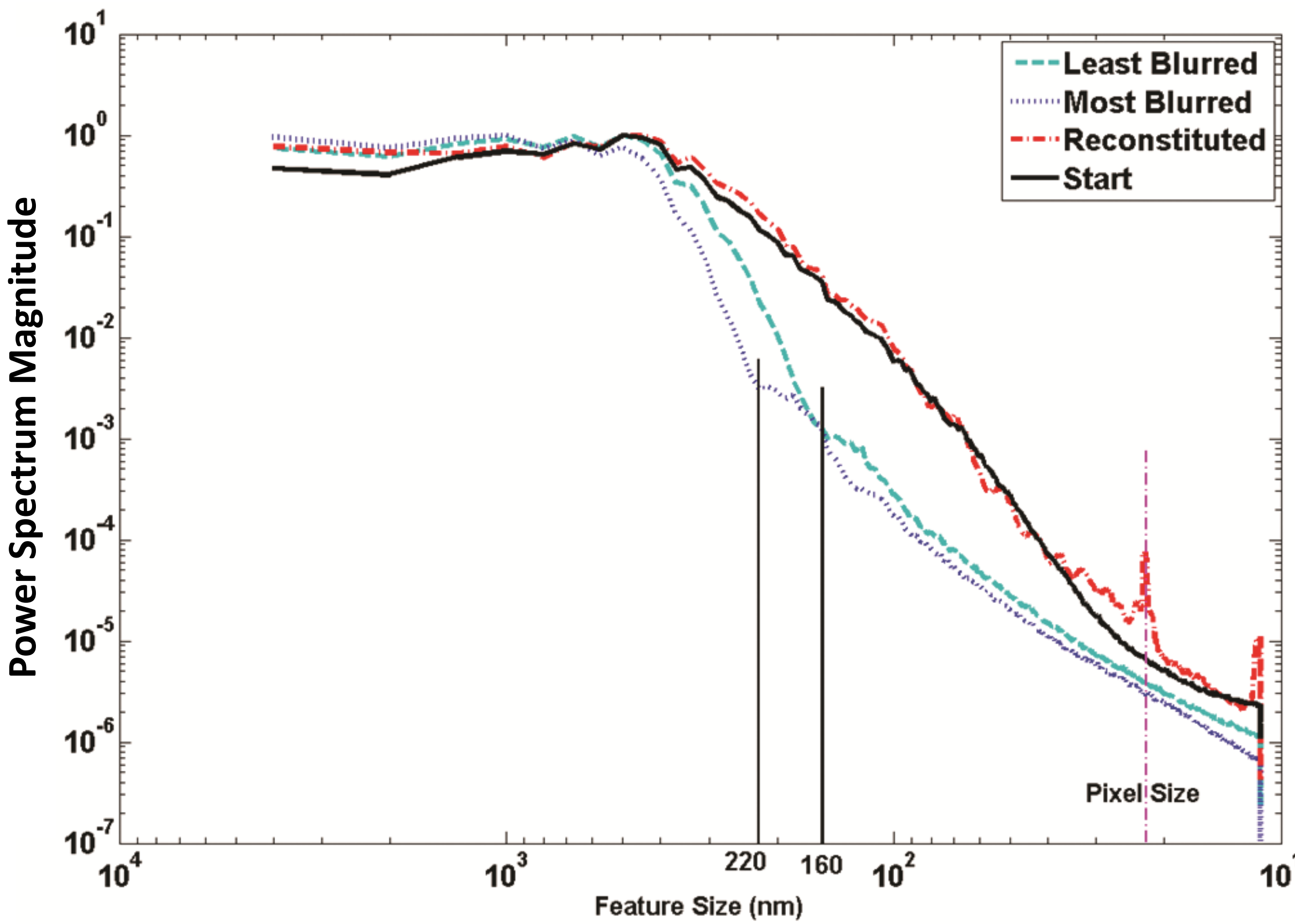


$d = 0.61\lambda/NA$

Diffraction limited

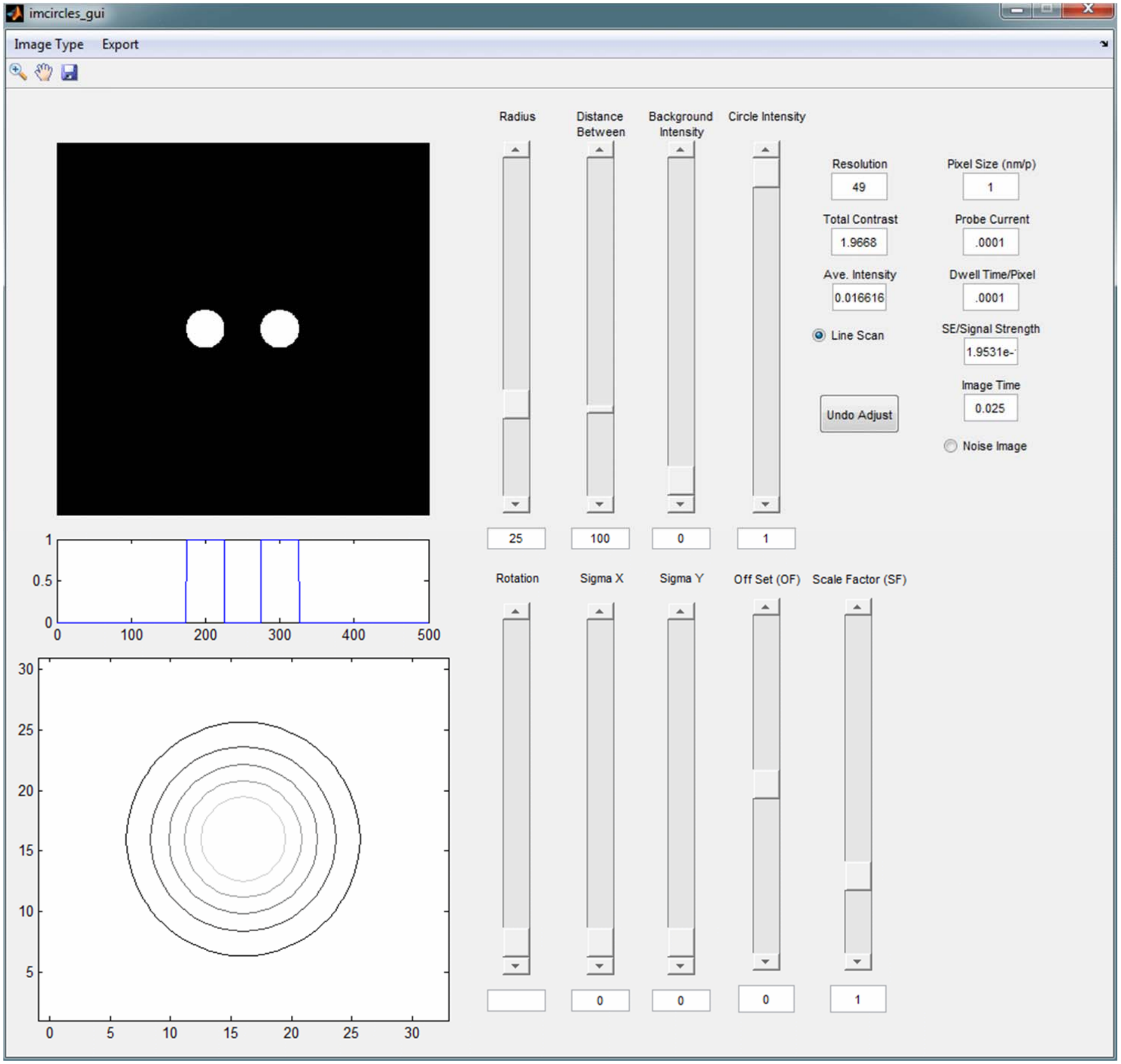
Murphy 2001

Resolution 3: *spatial frequency*



Based on “SMART” - Joy, D. C. (2002)

Resolution Study Tool



No blurring

→ B = 0, C = 1

→ 1 pixel resolution

Gaussian, σ = 8, Blurring

→ B = 0, C = 1

→ 4 pixel resolution

Adjust to B = .5, C =1

→ 6 pixel resolution

Resolution depends on brightness and contrast.

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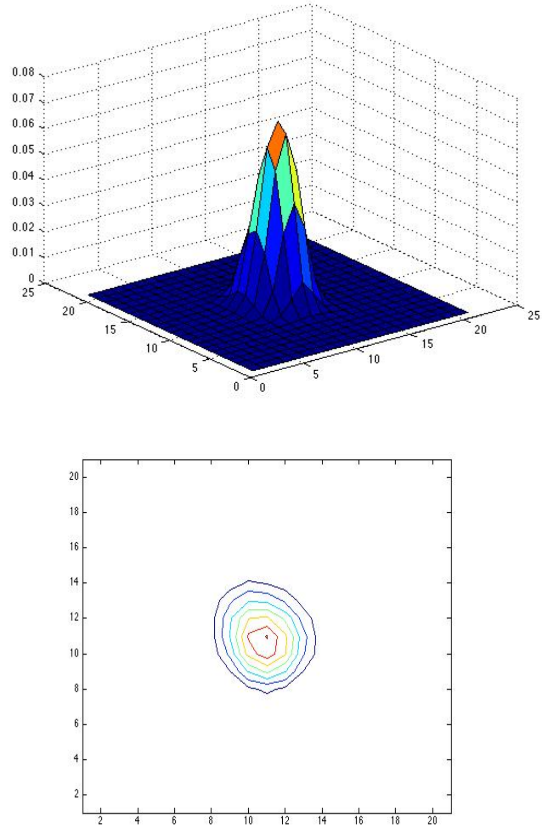
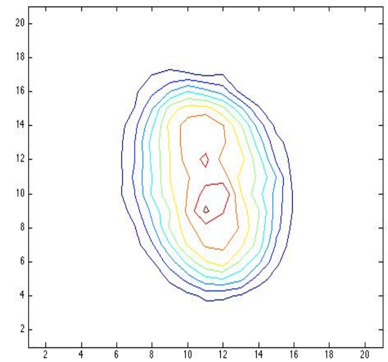
Results/Opportunities

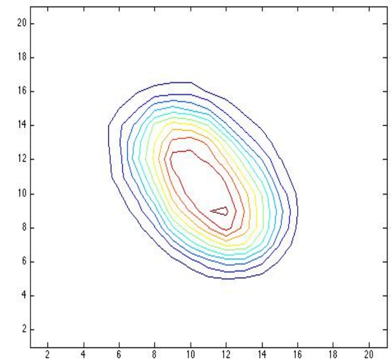
1. A New Way to Reduce Astigmatism Based on Observation of the PSF

In focus

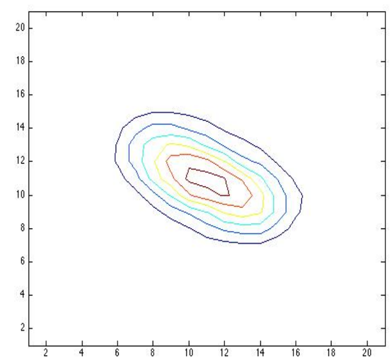




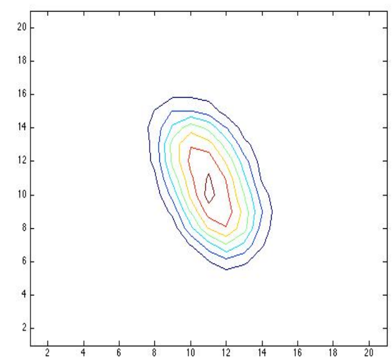
X = 1.5 Y = 2.0



X = 0.0 Y = 2.4



X = 0.0 Y = 2.4



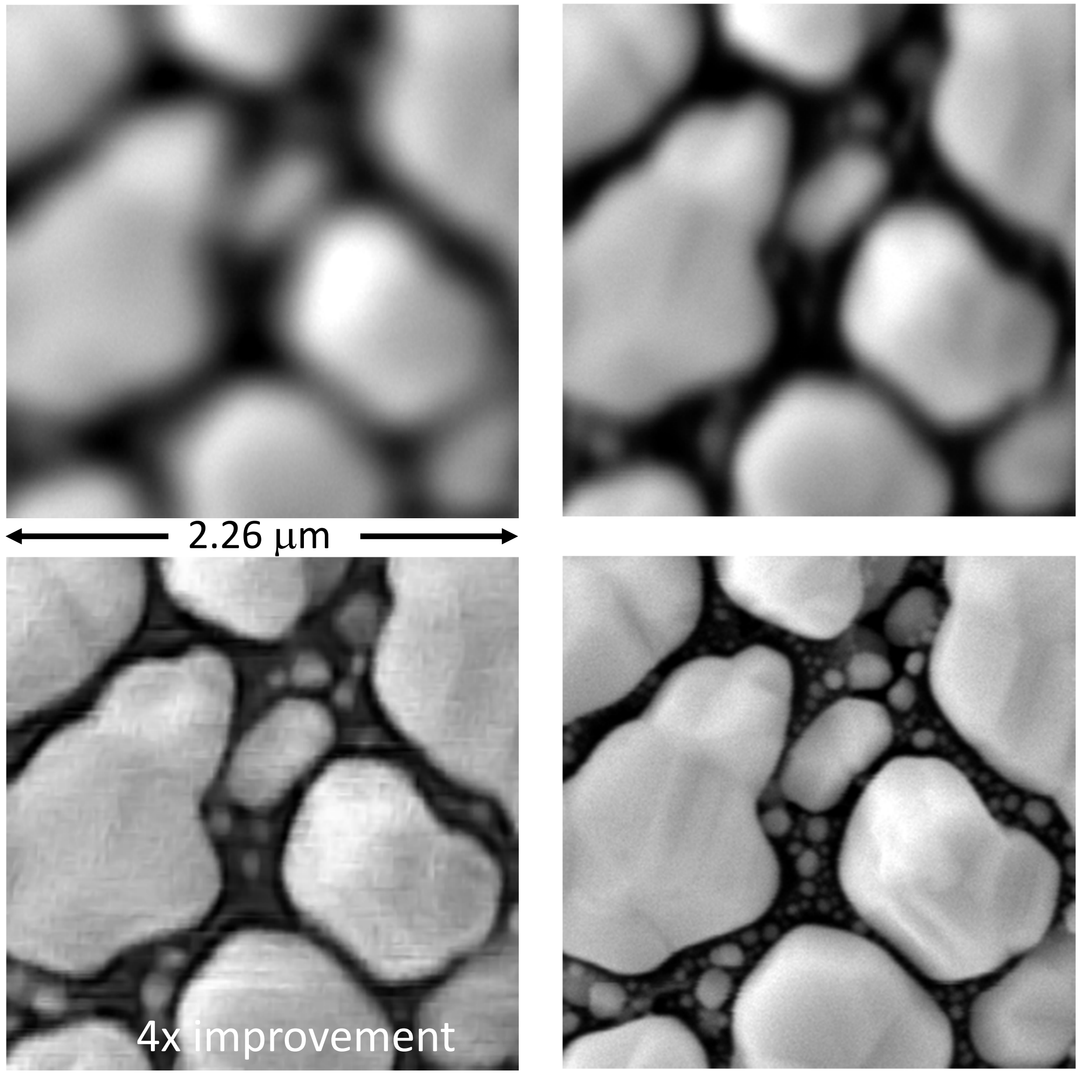
X = 0.8 Y = 2.4

2. Increase Image resolution

True Image Reconstruction Program

Most blurred

Least blurred
Spot size: 50 nm
Beam current: 373 pA



Restored Image

Reference Image
Spot size 7 nm
Beam Current: 5.9 pA

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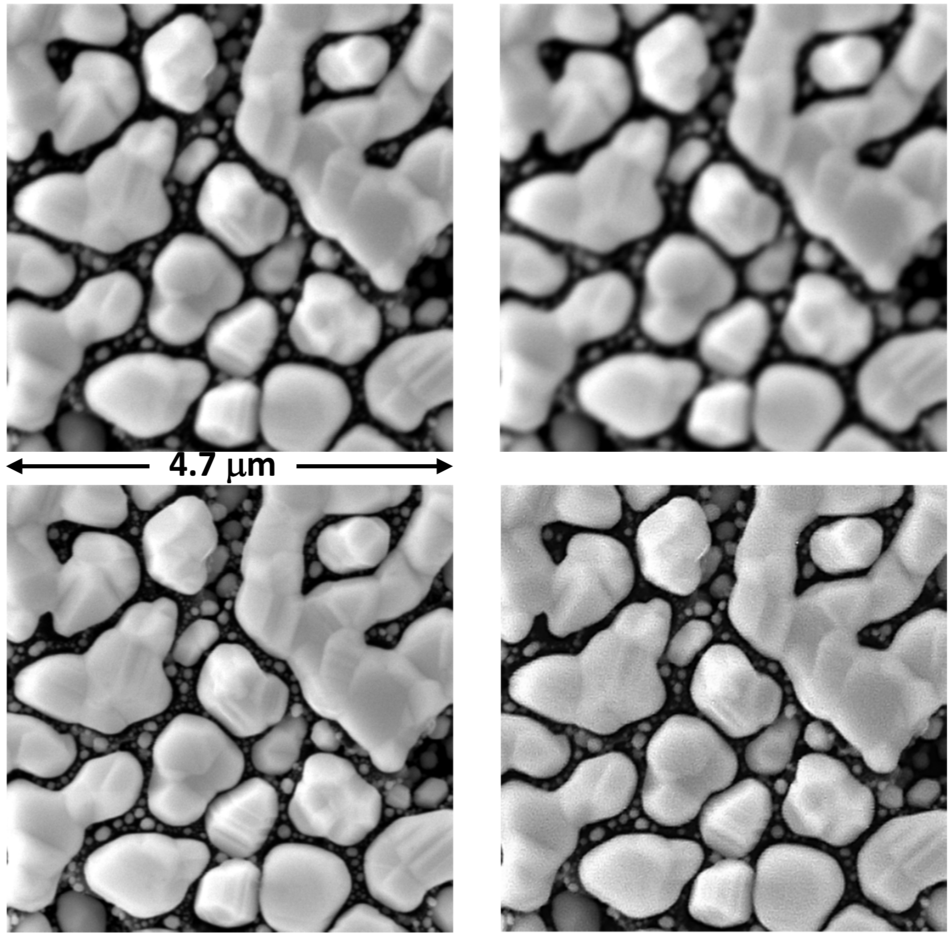
3. Same resolution faster acquisition time

1 min 5 seconds
probe 28.6 nm

1 min 5 seconds
Probe > 28.6 nm



10 min 50 seconds
probe 7.3 nm

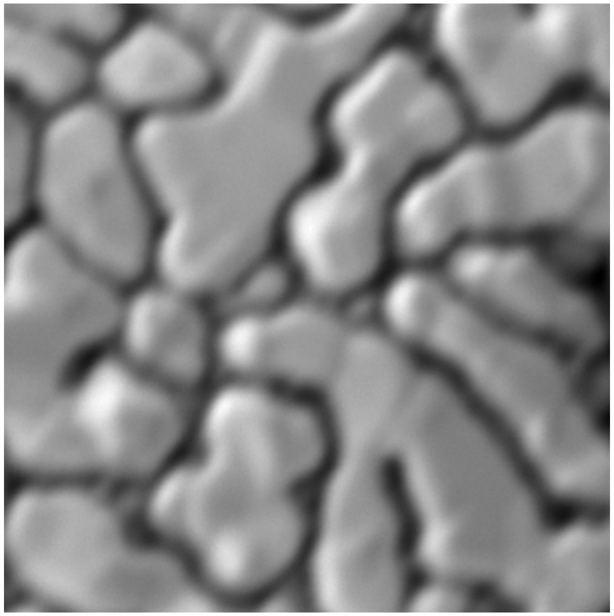
Reconstructed

Large beam with high current still gives the resolution of a small beam

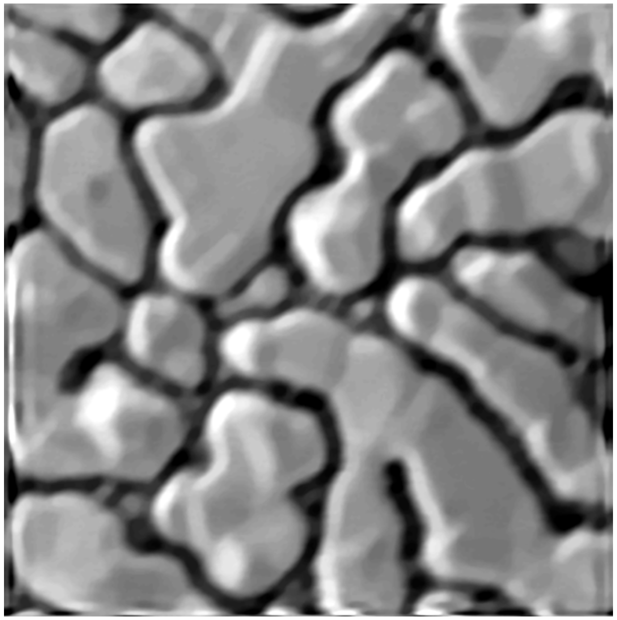
~5x gain in speed!

4. Improve low voltage performance for thermionic emitters using large beams with high current for better statistics.

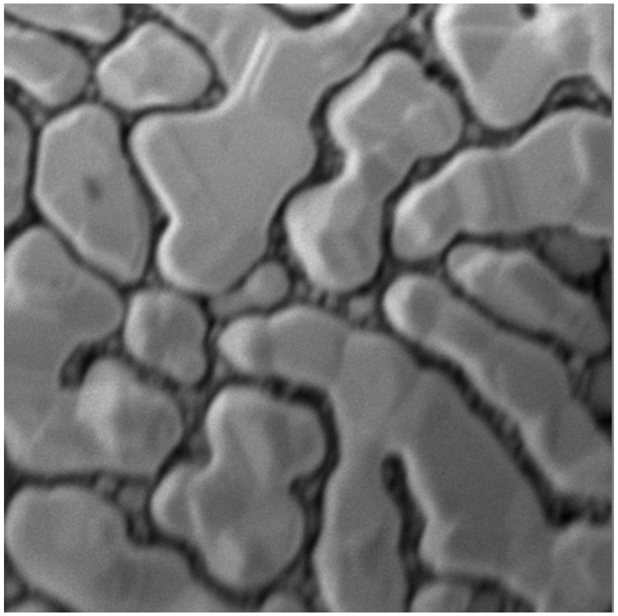
2 KV Images with LaB6 Source – FOV 5x5 μm



BI 10 Image
Spot size 27.4 nm - 5.8 pA



Restored Image
Total Variation –one image



Reference Image
Spot size 13.2 nm – 1.1 pA

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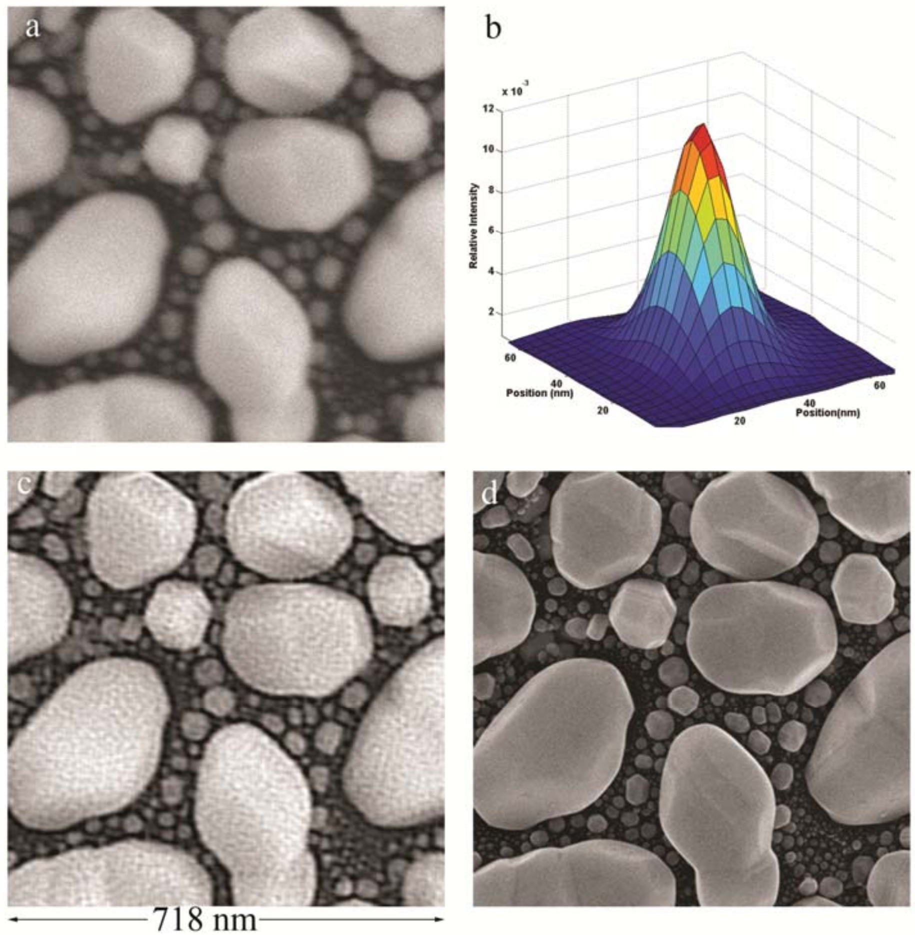
5. Increase Image Resolution - *Even better than expected based on minimum probe size*

LaB$_6$ image

PSF of LaB$_6$ source

Restored image

Schottky source image



From Lifshin et. al., Microscopy and Microanalysis 20, 78, 2014

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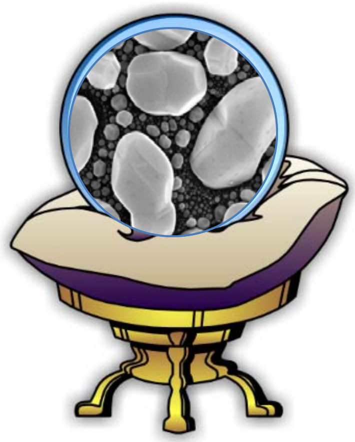
Future Opportunities and Technical Challenges

- Noise reduction.
  - Artifact prevention: a mottled appearance in the restored image and Gibb's type ringing.
- Optimize model, computational algorithm and parameters
- Experimental parameters to minimize noise
- 3D PSFs and inclusion of surface topography
- Increase computational capability
  - Expanded multi-core processing
  - GPU processing
  - Cloud computing
- Standards development for PSF determination
- Improvements in SEM design
  - Source and operation
  - Mechanical and electronic stability
  - Scan linearity
  - Improved detection chain (linear and 16 bit plus)
- Apply to other signals:
  - x-ray, backscattered and low loss electrons, STEM, ESEM, …

Conclusion

- Successfully demonstrated 3X or better improvement in resolution or speed for a variety of practical experimental conditions!
- Identified and systematically developing approaches to overcoming technical limitations.
- The door is now open for both major research and product development opportunities through instrumental and computational advances.



Acknowledgements

- Jeffery Moskin – Nanojehm
- Jack Mershon – TESCAN USA
- Aron Cepler – CNSE
- Clem Karl – Boston University
- Timothy Groves – CNSE
- John Henry Scott - NIST

Thanks Oliver:
for your friendship, wisdom, humor & uniqueness

Fin