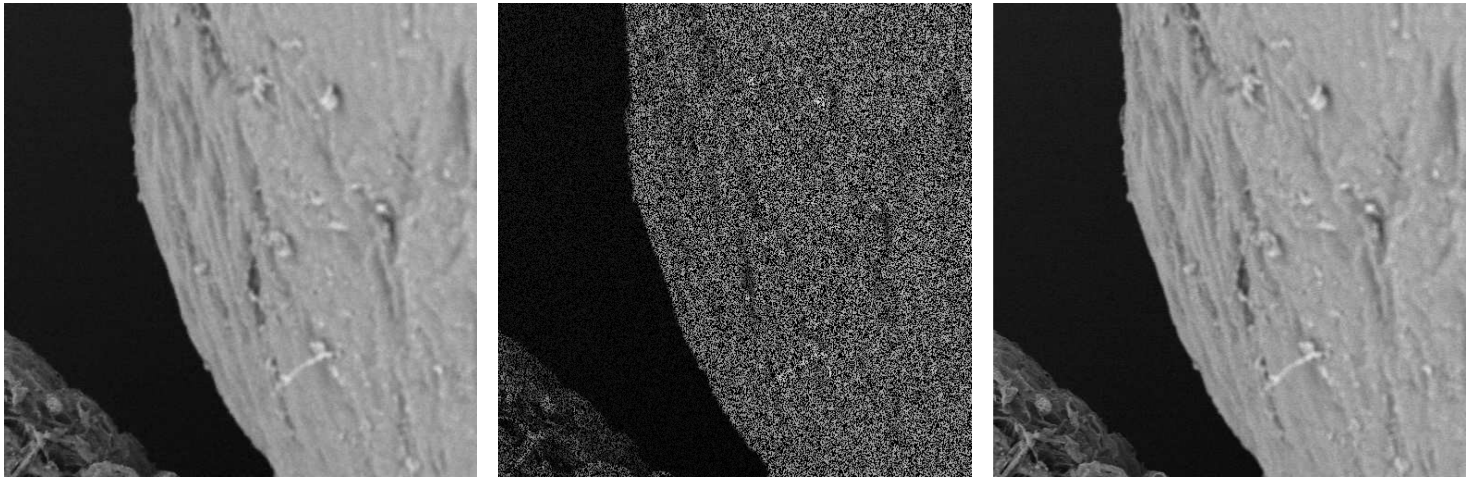
Exceptional service in the national interest

SAND2014-0425C



Compressed Sensing for fast electron microscopy

Hyrum Anderson, Jason Wheeler, Kurt Larson

Sandia National Laboratories

Albuquerque, NM

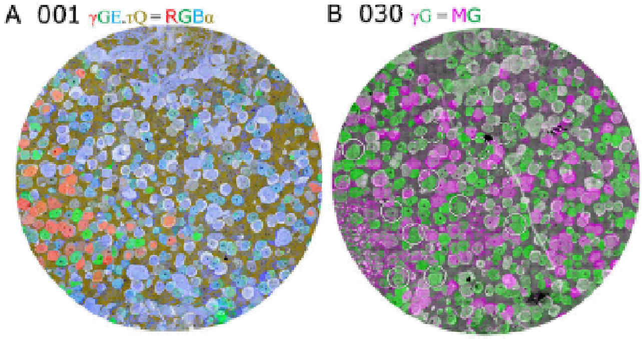
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Outline

- Background and Motivation
- Previous work: sparse sampling an operational SEM
- Analysis of multi-beam measurements
- Summary

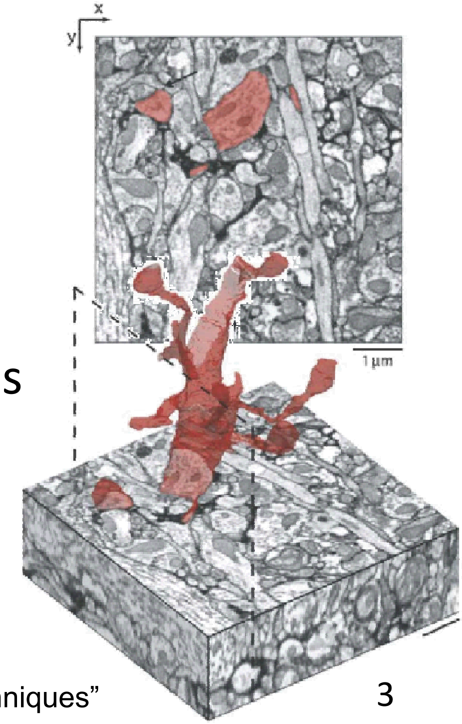
SNR-limited image collection time

- Rabbit retina connectome (Anderson, et al., 2011)
  - Tissue ~ 0.25 mm in diameter
  - ~2 nm resolution
  - 350,000 image tiles (16.5 TB) in 5 months
  - Automated trans. electron microscope



Anderson, et al., 2011, "Exploring the retinal connectome"

- Mouse brain (Briggman and Denk, 2006)
  - Single cortical column from mouse ~0.1 mm^3
  - ~10nm / pixel per 30nm slice
  - Thousands of images (10^8 pixels each) over several months
  - Serial block-face SEM

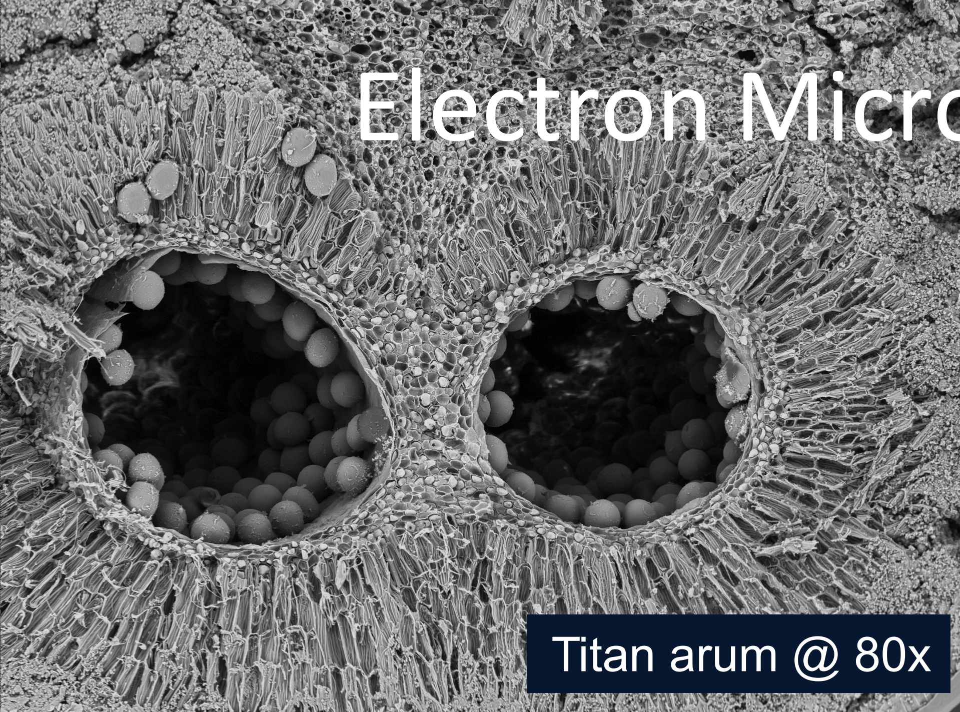


- Many engineering efforts to reduce collection time

(Lichtman et al. @ Harvard)

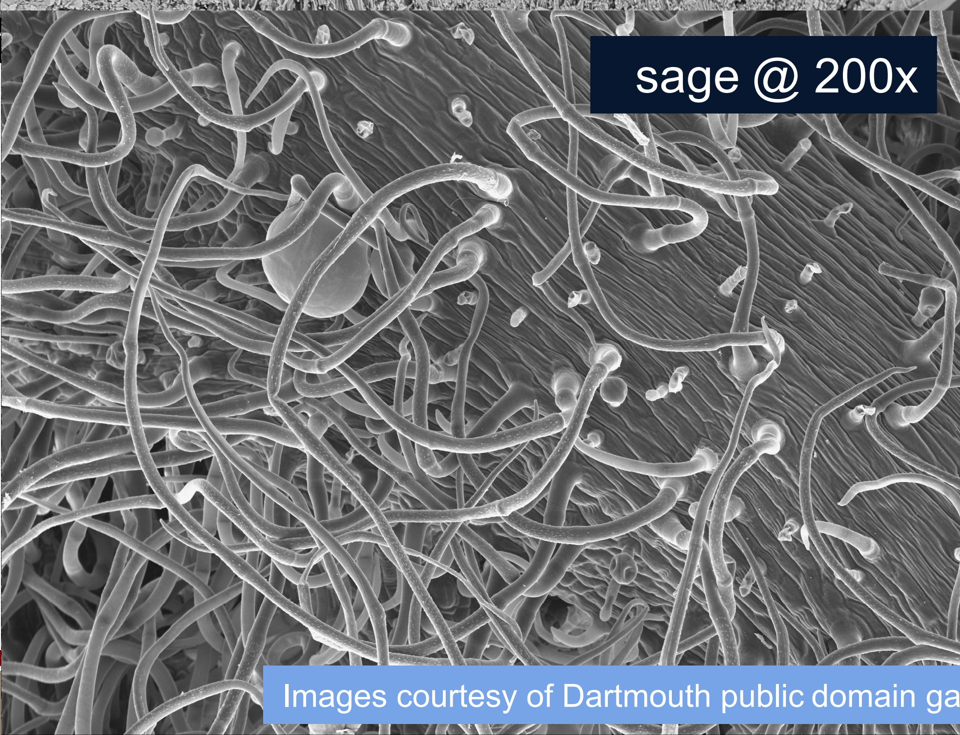
Briggman and Denk, 2006, "Towards neural circuit reconstruction with volume electron microscopy techniques"

Electron Microscopy Images

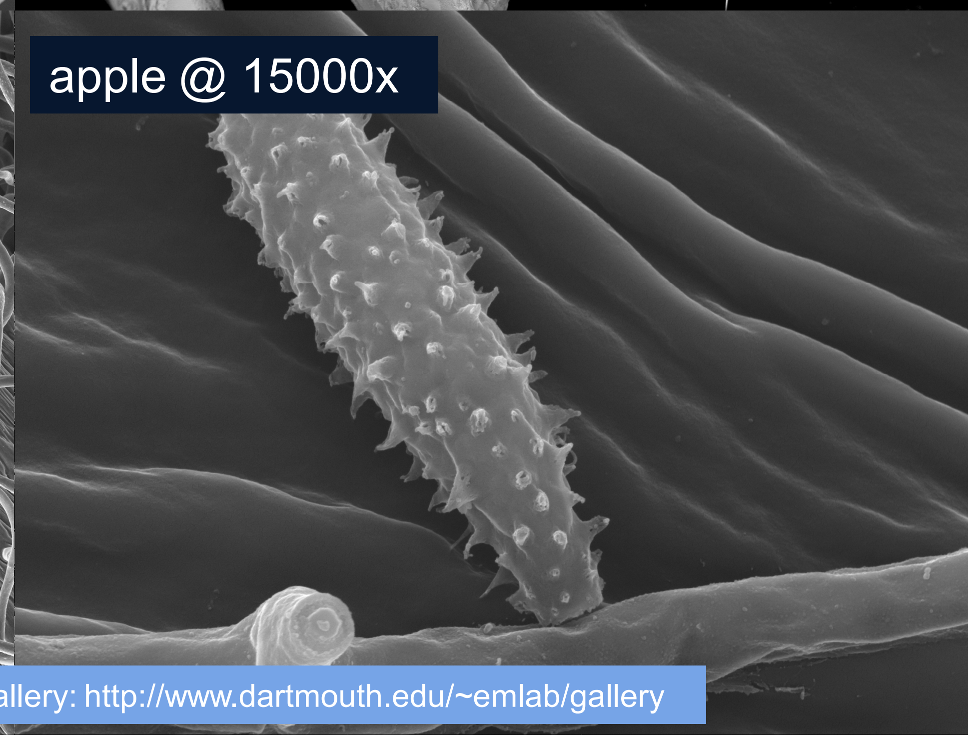


Titan arum @ 80x

Hawaiian volcanic sand @ 30x



sage @ 200x

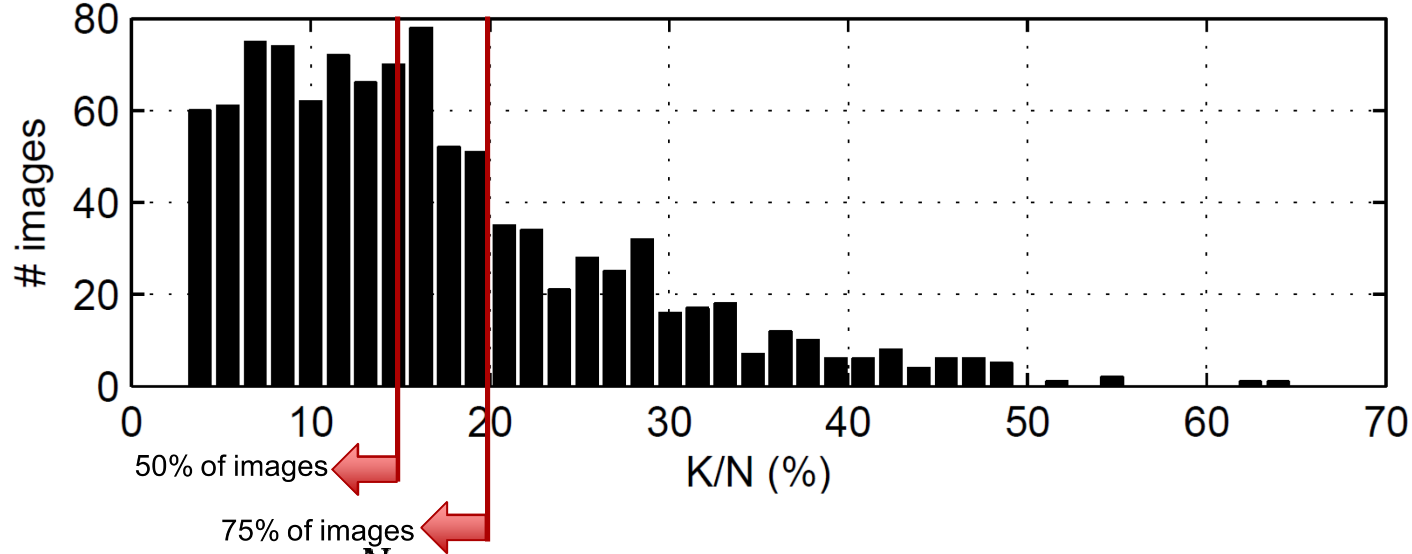


apple @ 15000x

Images courtesy of Dartmouth public domain gallery: http://www.dartmouth.edu/~emlab/gallery

SEM Image Compressibility

- Compression basis: block-DCT (similar to JPEG)
- K = # of coefficients required to capture at least 99.75% of image energy
- N = # of image pixels



- $M \geq O(K \log \frac{N}{K})$ # of measurements for recovery by CS

Images courtesy of Dartmouth public domain gallery: http://www.dartmouth.edu/~emlab/gallery

Previous Work

- Visit a random subset of pixel locations ($\mathbf{\Phi}$ a subset of $\mathbf{I}$)
- Measurement model: $\mathbf{y} = \mathbf{\Phi x} + \mathbf{n}$ $\quad E\left(\mathbf{nn}^T\right) = \sigma^2 \mathbf{I}$
- From $M < N$ measurements, reconstruct via

$$\begin{aligned} \min_{\mathbf{x}} \quad & \|\mathbf{\Psi}^T \mathbf{x}\|_1 + \|\nabla \mathbf{x}\|_1 \\ \text{s.t.} \quad & \|\mathbf{y} - \mathbf{\Phi x}\| \leq \sigma^2 \end{aligned}$$

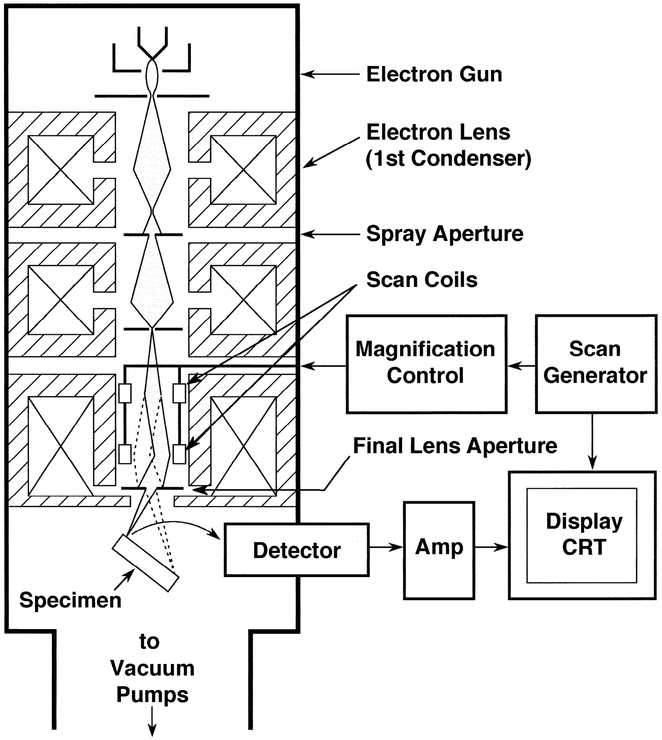
- Compression basis $\mathbf{\Psi}$ chosen to be block-DCT
  - Good compressibility of SEM images
  - Low mutual coherence
- Total variation regularizer $\|\nabla \mathbf{x}\|_1$ to denoise and promote smoothness between block boundaries

Scan coil dynamics

- Electron probe positioned via electromagnetic coils

$$\mathbf{F} = q\left[\mathbf{E} + (\mathbf{v} \times \mathbf{B})\right]$$

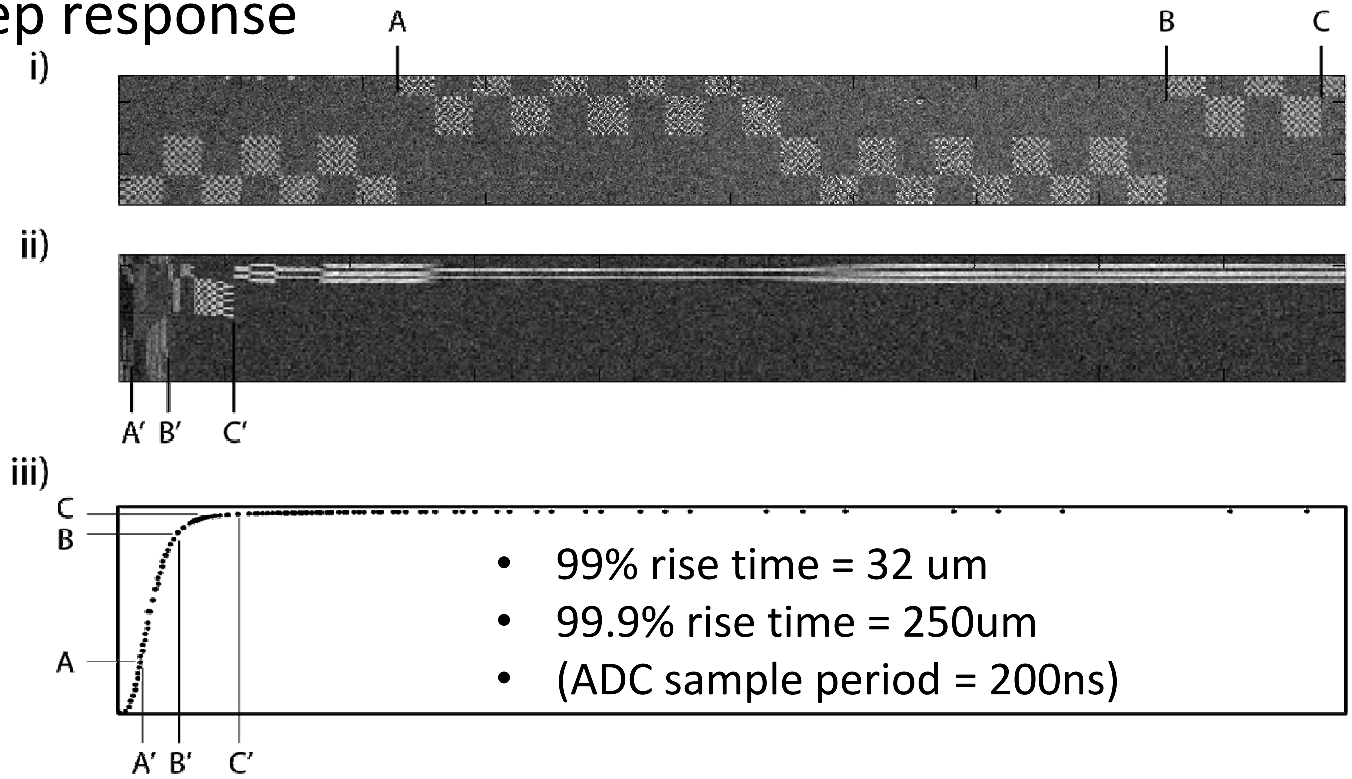
- Slow compared to sample period
- Commanded position ≠ actual position
  - Transient delay
  - Steady state lage



Source: J. Goldstein, et. al, *Scanning Electron Microscopy and X-Ray Microanalysis* (Springer, New York, 2003).

Scan coil dynamics

- Measure step response



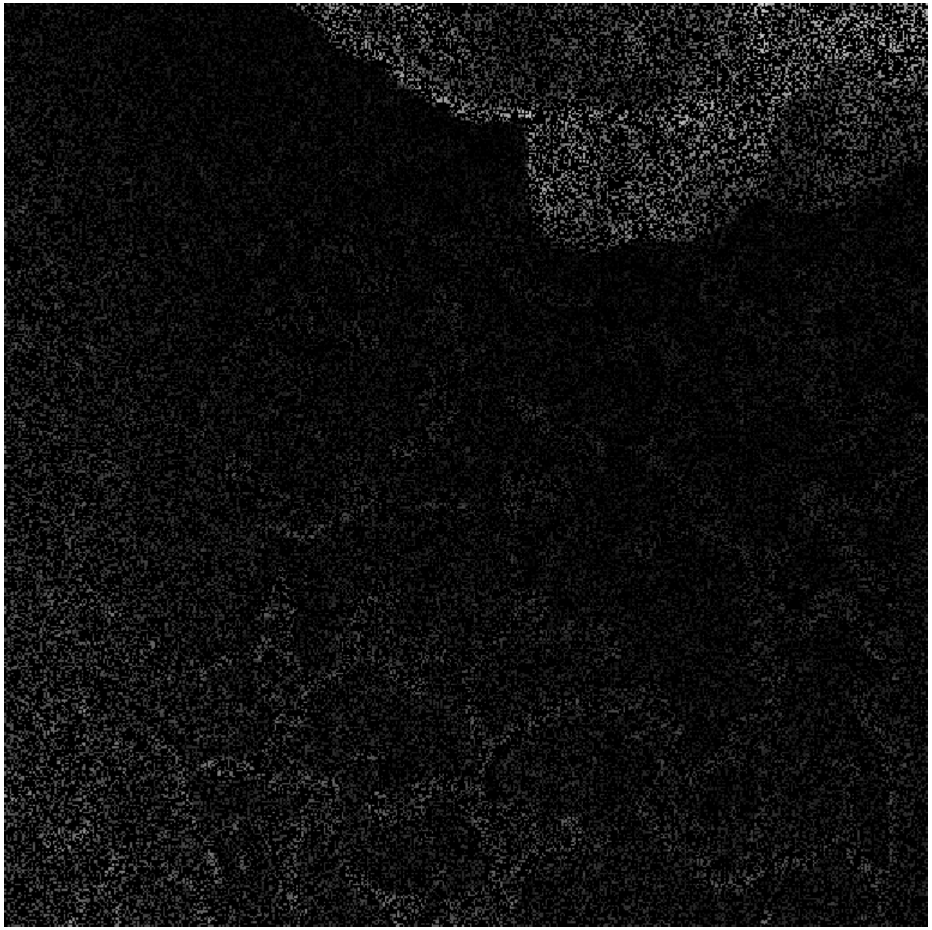
- Linear dynamical model to predict “actual” location

$$\frac{d^5x(t)}{dt^5} = a_0(\hat{x}(t) - x(t)) - a_1\frac{dx(t)}{dt} - a_2\frac{d^2x(t)}{dt^2} - a_3\frac{d^3x(t)}{dt^3} - a_4\frac{d^4x(t)}{dt^4}$$

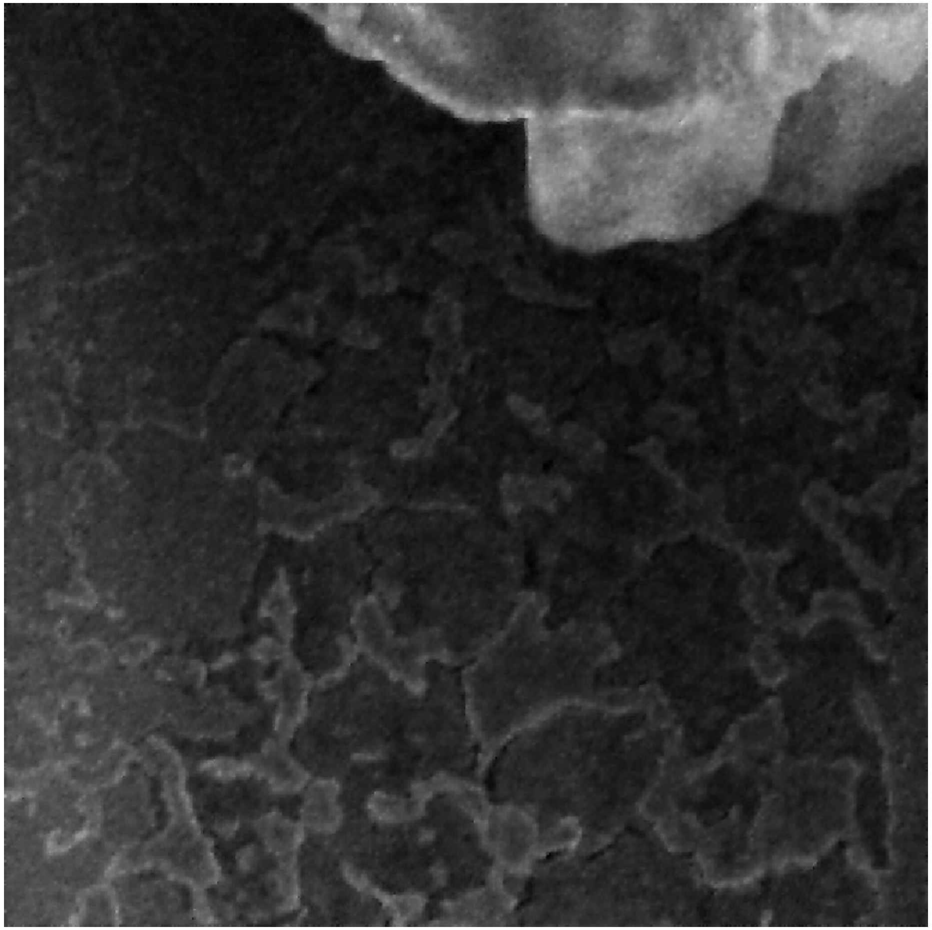
Simulated: Gibeon meteorite surface

(noiseless simulated recover)

M/N = 30%

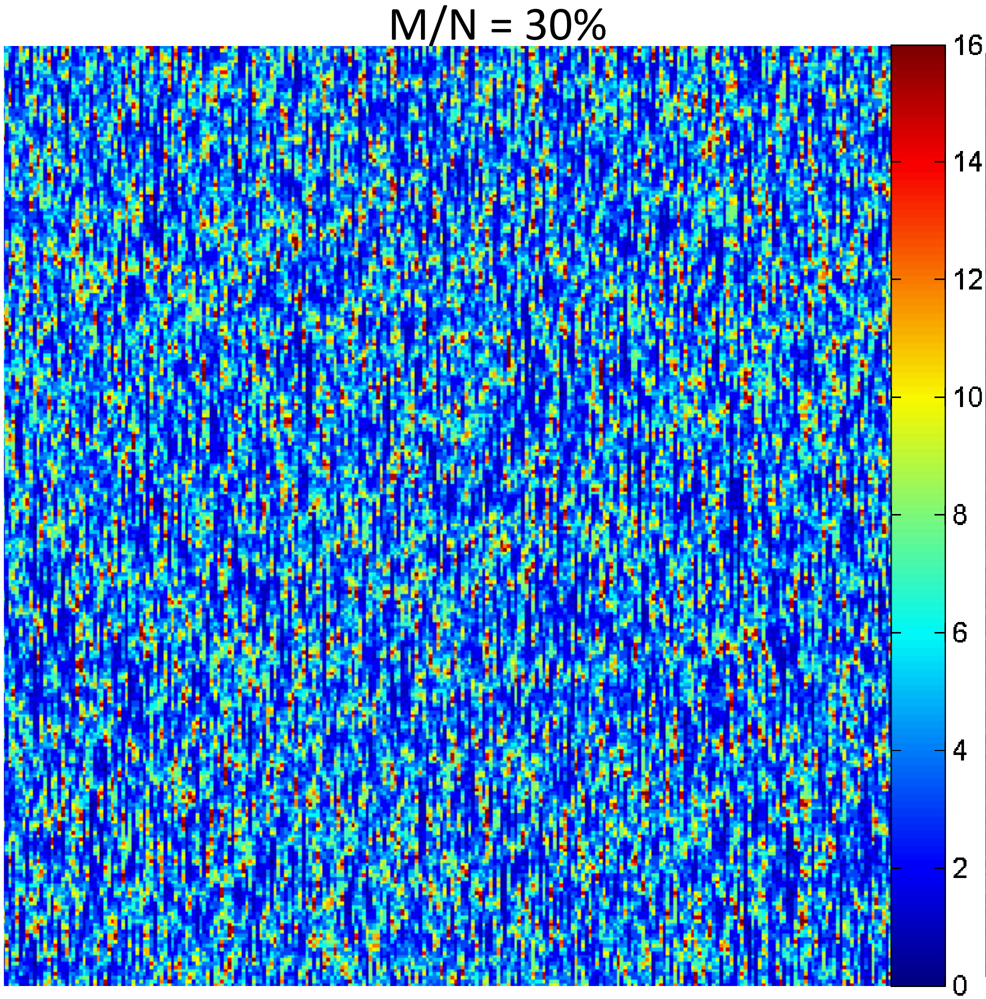


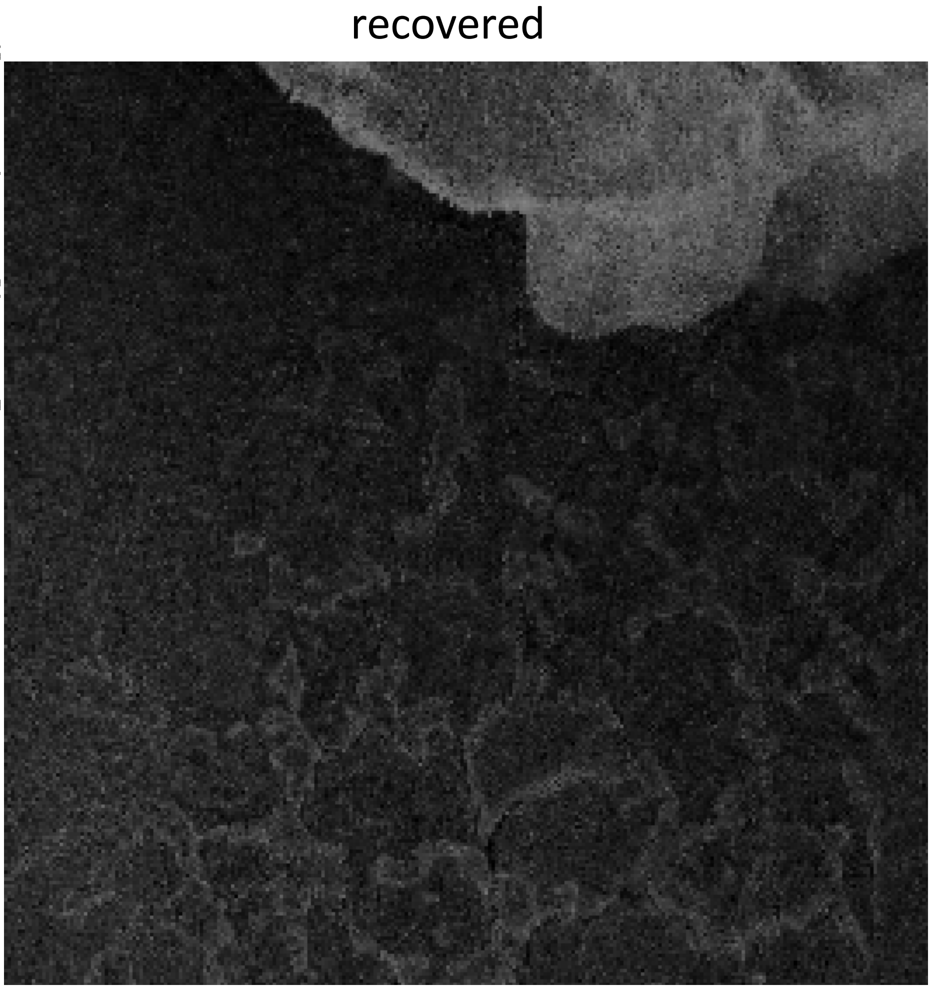
recovered



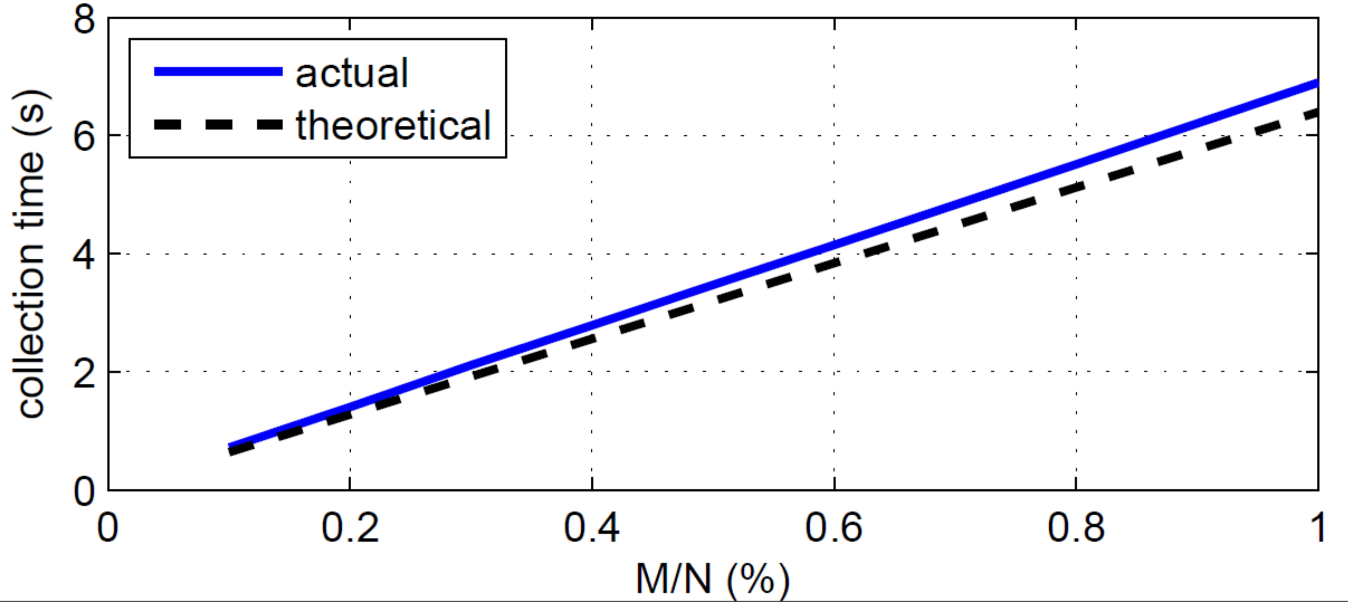
Actual: Gibeon meteorite surface

(actual measurement location + recovery)

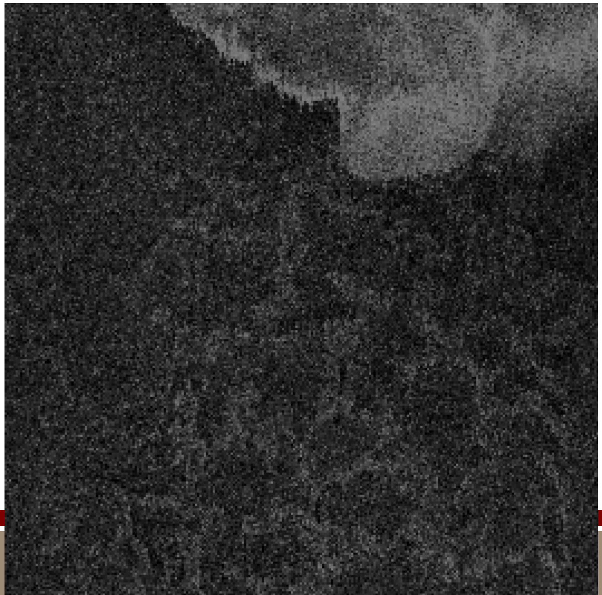




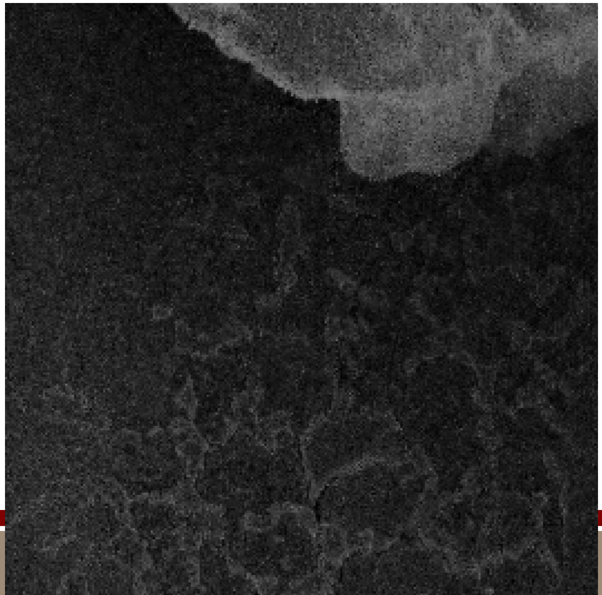
Undersampling timing results



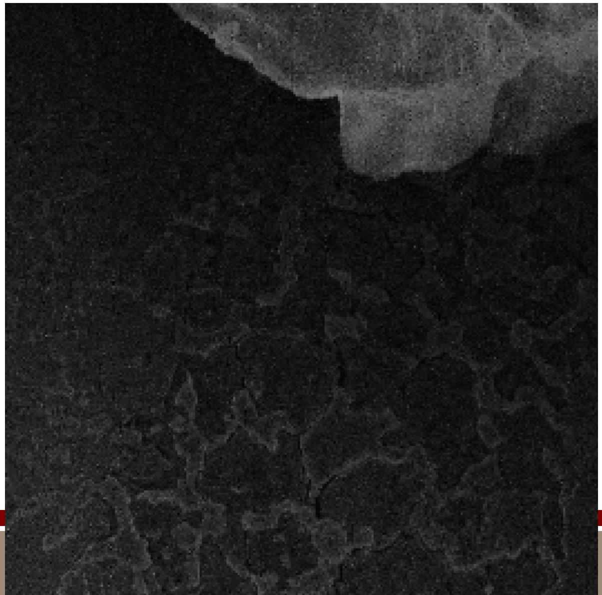
M/N = 10%



M/N = 30%



M/N = 50%



Sparse sampling summary

- Preliminary demonstration of sparse sampling & reconstruction in an operational SEM
- Acceptable image quality at 2-3x speedup
- Speedups **in series** with other engineering advances

Shortcomings:

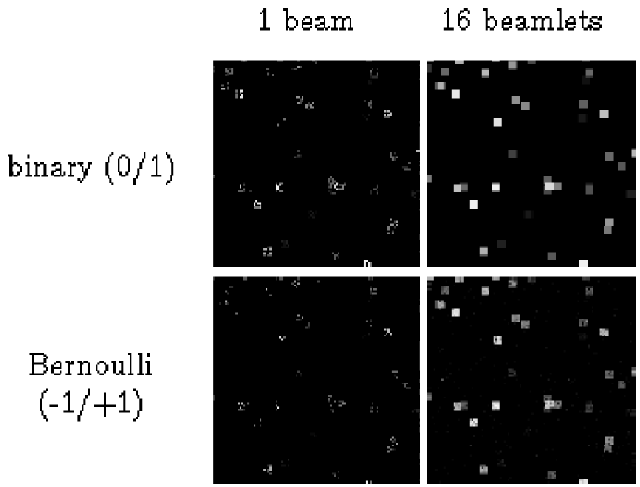
- Requires ~10x more time to reconstruct data than to collect
- Only viable for "smooth" images (compressible by block-DCT)

Outline

- Background and Motivation
- Previous work: sparse sampling an operational SEM
- Analysis of multi-beam measurements
- Summary

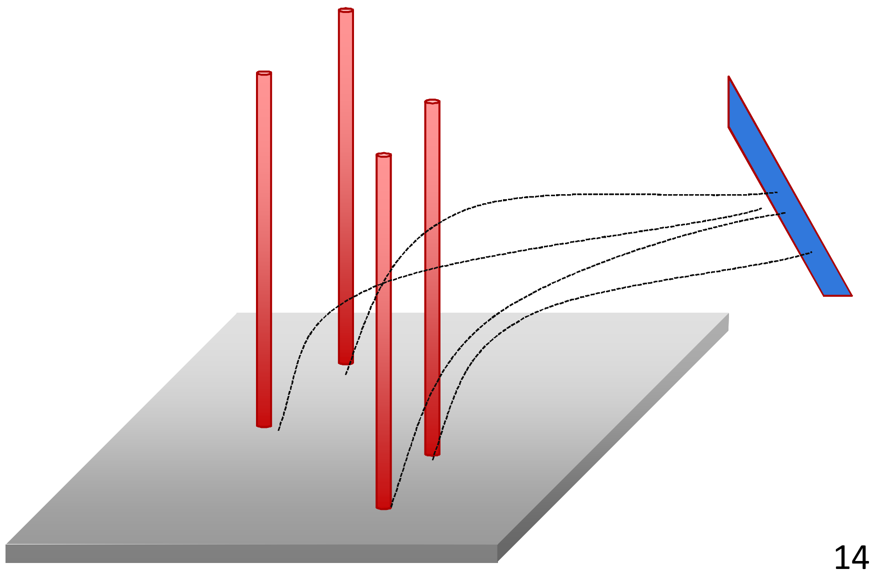
Multiple beams, single detector

Multiplexed measurements enable reconstructing broader class of images



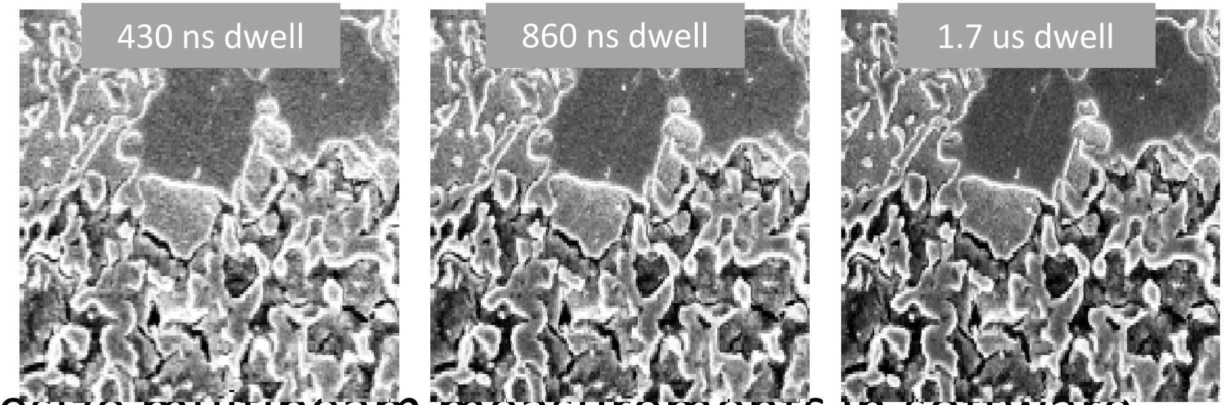
Hypothetical multibeam tool:

- Multi-beam source projects sparse, programmable pattern on the sample
- Single detector with linear response and sufficient dynamic range



Experimental setup

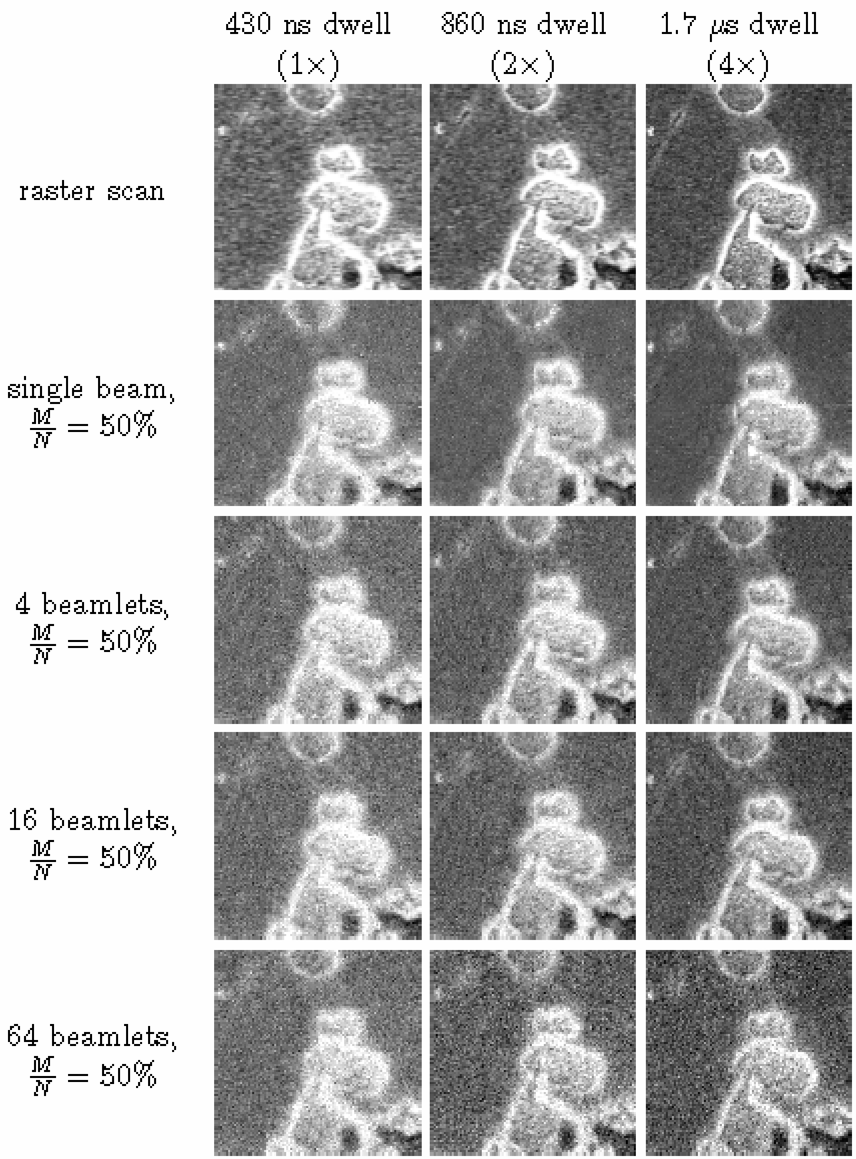
- Commercially available SEM column from Zeiss GmbH
  - Schottky thermal field emission source
  - Nominal beam energy of 10 kEV, 10 um aperture, ~200 pA beam
  - Secondary electron detector
- Collect 1000 800x800-pixel images of single area of interest
  - Register image stack after collection to compensate for drift

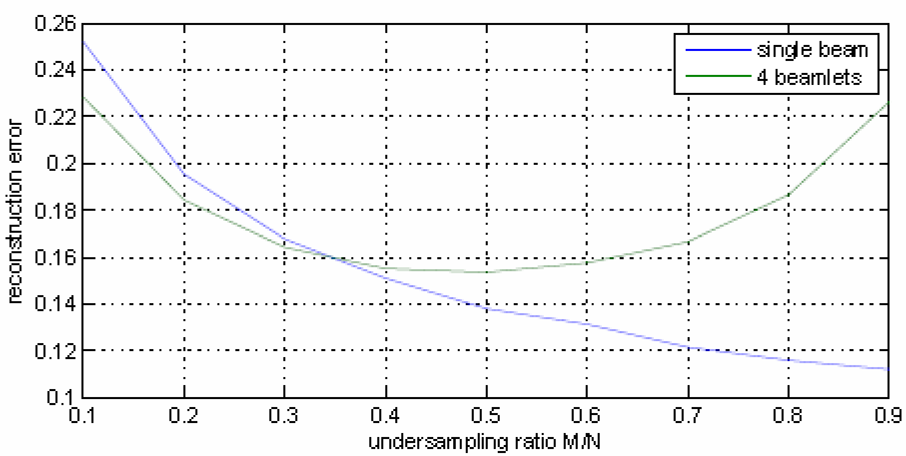


- Synthesize multibeam measurements in software
  - Simple sum of responses from selected pixels, adds intensity + noise
  - Assumes (incorrectly) no detector noise

Results

- Using a few beamlets
  - Provides moderate quality improvement over sparse imaging for "large" M/N (50%)





Summary

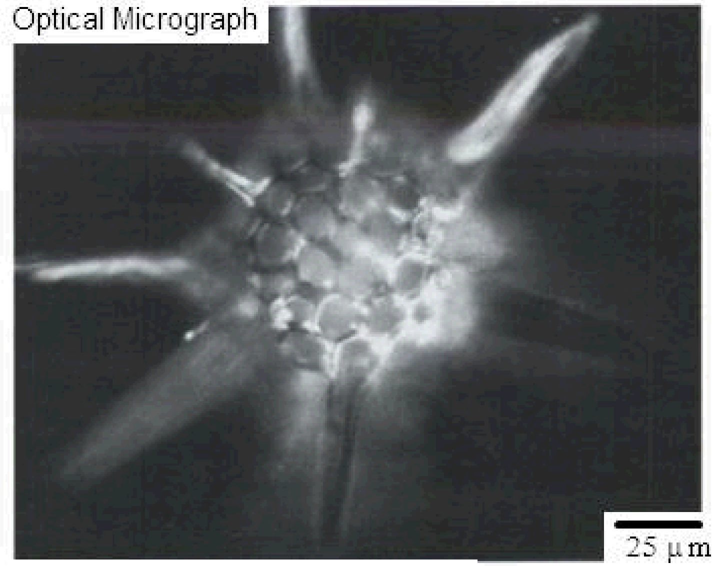
- **Single-beam sparse sampling**:
  - acceptable image quality at 2-3x speedup
  - speedups **in series** with other engineering advances
  - **demonstrated in operational tool**
  - Doesn’t generalize to non-smooth images

- **Multibeam compressed sampling:**
  - Possibly provides modest quality improvement over sparse sampling for speedsup of ~2x or less
  - Generalizes to non-smooth images
  - Synthetic multibeam measurements lack appropriate noise conditions, optimistic in some settings (linear detector), pessimistic in others (detector noise)

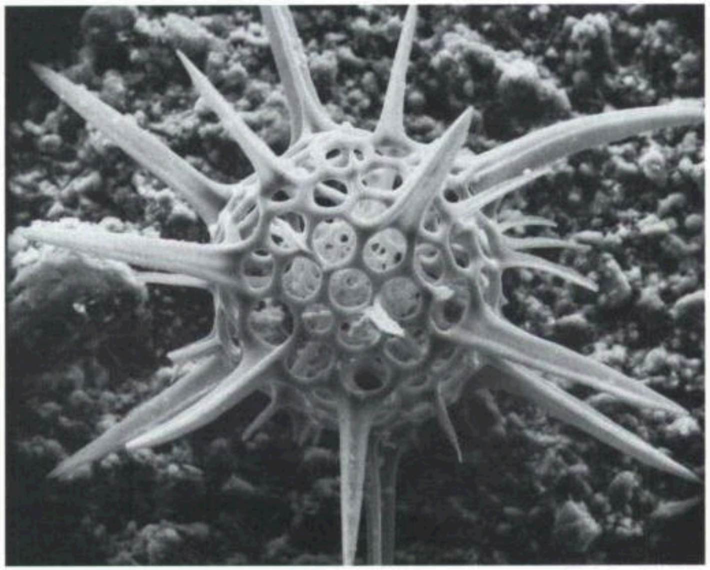
[backup slides]

Why SEM?

Optical Microscope Image | **SEM Image**



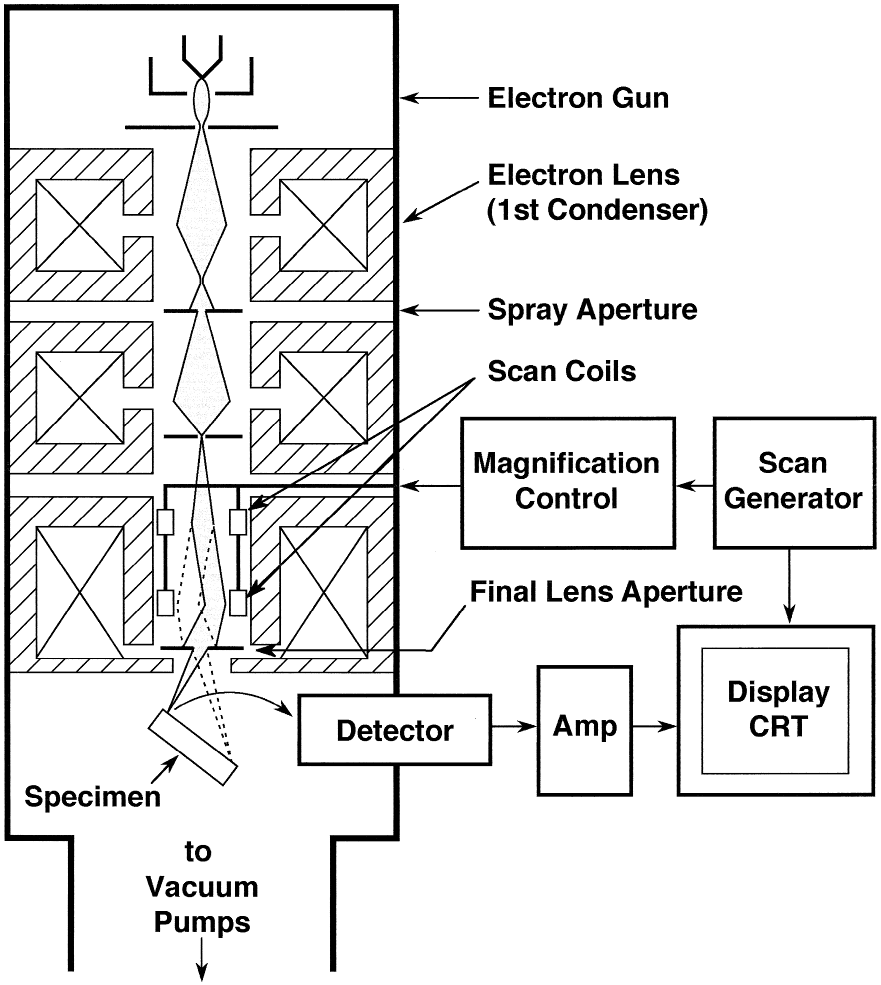
Radiolarian (marine organism)



- Typical SEMs can resolve ~1 nm features (10^3x smaller diff. limit than optical)
- Large depth of focus
- Flexible viewing conditions, e.g., 10x to 500,000x mag

Image source: J. Goldstein, et al., *Scanning Electron Microscopy and X-Ray Microanalysis* (Springer, New York, 2003).

SEM Electron Column

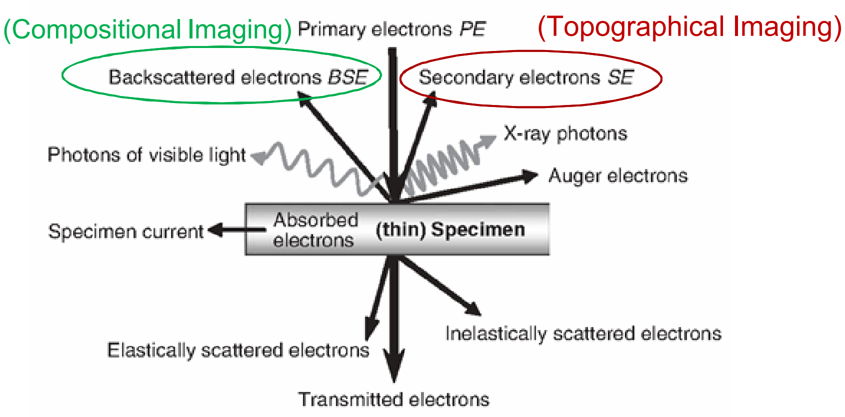


- Electron gun generates electrons
- Electromagnetic condenser lenses and apertures focus electrons into a beam w/ small spot size (~1 nm)
- Scan coils raster beam across sample area to be images
- Detector collects electrons at each point of raster pattern and plots on computer display (typically a single SE/BSE, but there may be other, specialized detectors).

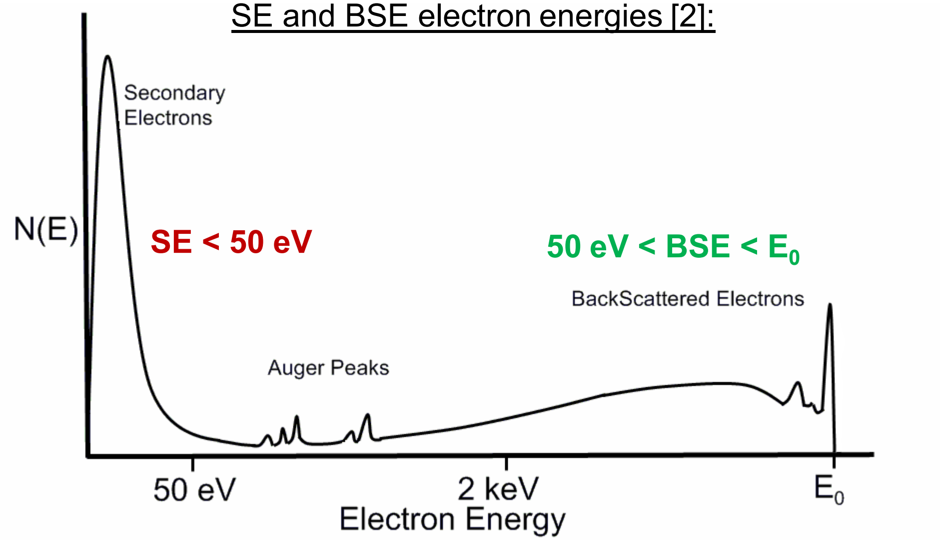
Source: J. Goldstein, et. al, *Scanning Electron Microscopy and X-Ray Microanalysis* (Springer, New York, 2003).

Interaction of Electrons with Solids

Probe/sample interactions [1]:



SE and BSE electron energies [2]:



- Electron interaction with a solid results in a number of processes
- SEM uses scattered electrons for sample imaging
- Backscattered electrons (BSEs):
  - elastic collisions with atoms nuclei
  - high energy => heavily influenced by atomic number of material (He Z=2, Au Z=79)
- Secondary electrons (SEs):
  - weakly bound electrons excited from the sample
  - low energy => heavily influenced by surface topography

[1] D..J. Stokes, *Principles and Practice of Variable Pressure/Environments Scanning Electron Microscopy* (John Wiley & Sons, Ltd., UK, 2008).

[2] From J. Mabon, *SEM and FIB in Materials Research*, UIUC

Collection of Scattered Electrons

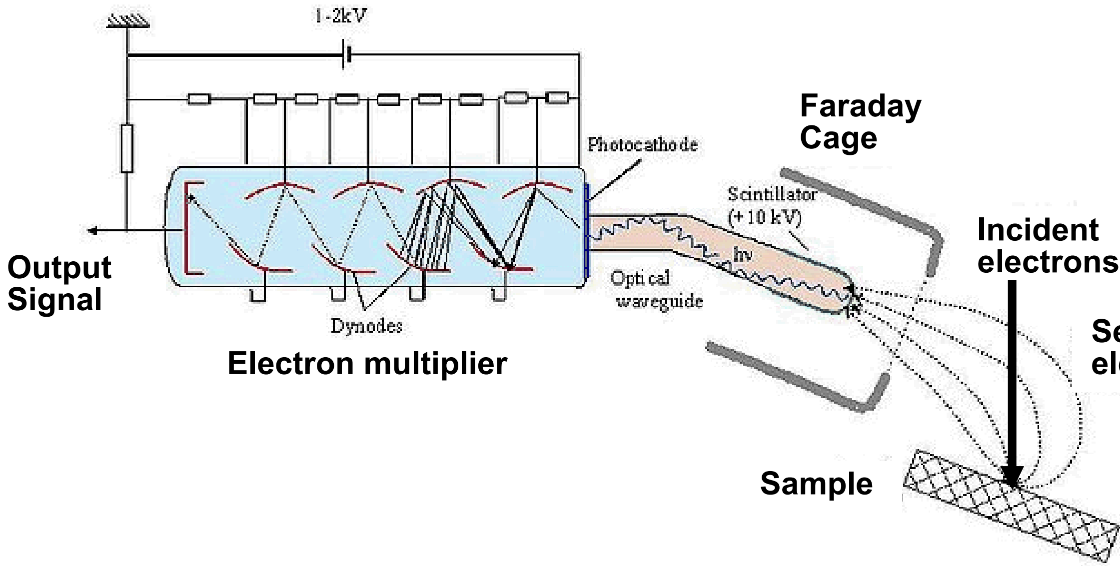
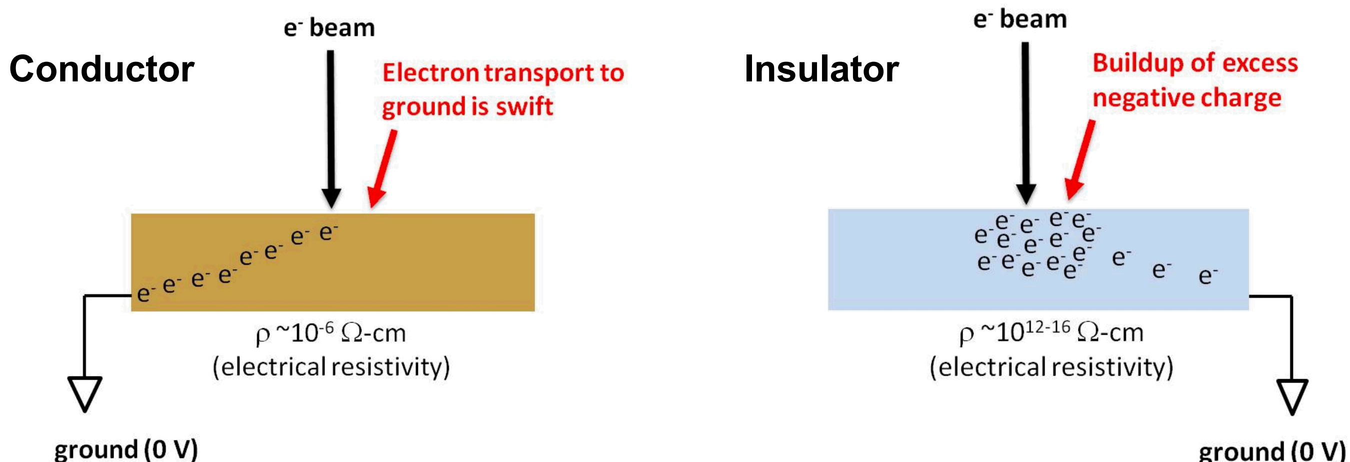


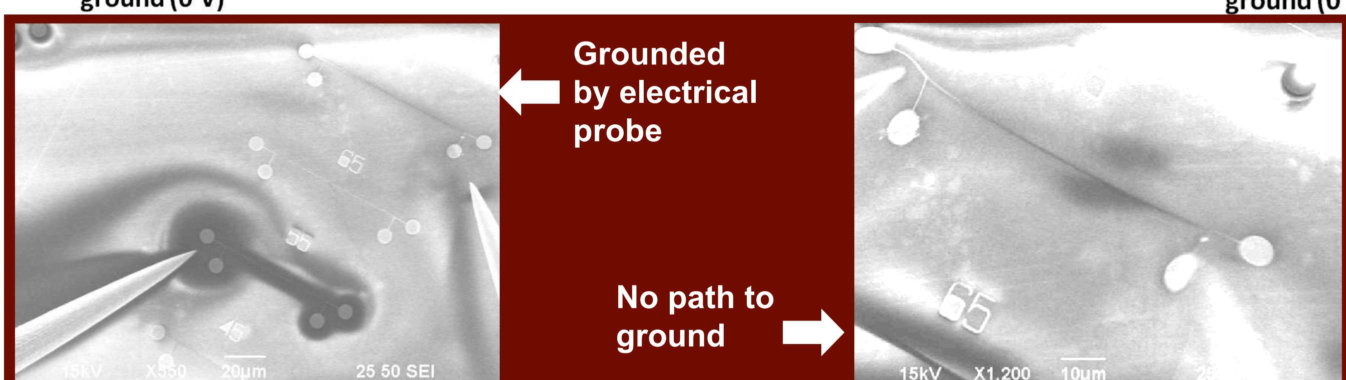
Image courtesy of fr.wikipedia.org

- Everhart-Thornley (E-T) detectors are the most widely used detectors in SEM. Can measure both backscattered electrons (BSE) and secondary electrons (SE).
- Bias voltage on Faraday cage & scintillator selects between BSE and SE. This is small compared to the primary beam (~few hundred V).
- Electron that passes Faraday cage strikes a scintillator, which converts the signal to light that is directed down an optical waveguide
- The light signal is converted back to electrons (at photocathode), which is amplified by an electron multiplier (gain ~10^5-10^6) and collected by software

Challenge #2: sample charging

- Charging: electron buildup in sample with no path-to-ground
- Causes image distortion: Surface potential large enough to deflect electrons incident to or reflected from the sample



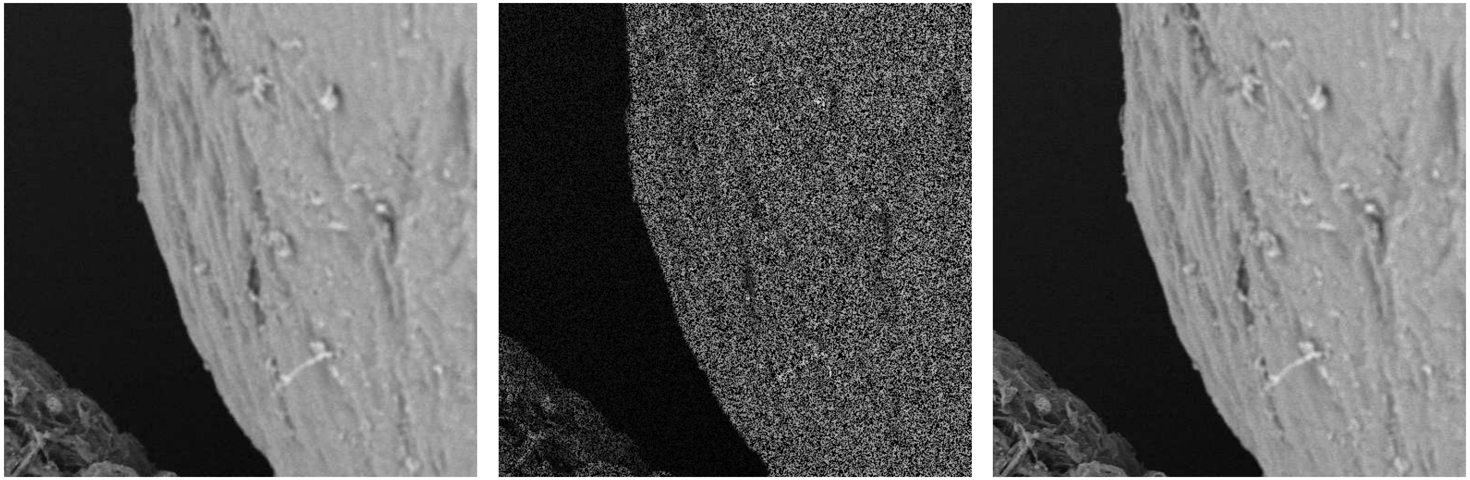


Images courtesy of the Technical University of Graz (Graz, Austria)

source: http://lamp.tu-graz.ac.at/~hadley/sem/charging/charging.php

Sparse reconstruct example

- Interpolation + denoising using block-DCT with TV regularizer



original   50% samples   reconstruction (36 dB PSNR)

- What about simpler/more efficient bilinear interpolation?

(more efficient, but brittle to noise)

Implementation

- Solve efficiently via split Bregman method (Goldstein & Osher, 2009)

(unconstrained) $$\min_{\mathbf{x}} \|\mathbf{\Psi}^T\mathbf{x}\|_1 + \|\nabla\mathbf{x}\|_1 + \frac{\mu}{2}\|\mathbf{y} - \mathbf{\Phi}\mathbf{x}\|_2^2$$

<u>solve for image and auxiliary variables:</u>

$$\min_{\mathbf{x},\mathbf{u},\mathbf{v},\mathbf{w}} \|\mathbf{w}\|_1 + \|(\mathbf{u},\mathbf{v})\|_2 + \frac{\mu}{2}\|\mathbf{\Phi}\mathbf{x} - \mathbf{y}\|_2^2 + \frac{\lambda}{2}\|\mathbf{u} - \nabla_u\mathbf{x} - \mathbf{b}_u^k\|_2^2 + \frac{\lambda}{2}\|\mathbf{v} - \nabla_v\mathbf{x} - \mathbf{b}_v^k\|_2^2 + \frac{\gamma}{2}\|\mathbf{w} - \mathbf{\Psi}^T\mathbf{x} - \mathbf{b}_w^k\|_2^2$$

<u>update Bregman parameters</u>

$$\mathbf{b}_u^{k+1} = \mathbf{b}_u^k + \left(\nabla_u\mathbf{x}^{k+1} - \mathbf{u}^{k+1}\right)$$

$$\mathbf{b}_v^{k+1} = \mathbf{b}_v^k + \left(\nabla_v\mathbf{x}^{k+1} - \mathbf{v}^{k+1}\right)$$

$$\mathbf{b}_w^{k+1} = \mathbf{b}_w^k + \left(\mathbf{\Psi}^T\mathbf{x}^{k+1} - \mathbf{w}^{k+1}\right)$$

Implementation

$$\min_{\mathbf{x},\mathbf{u},\mathbf{v},\mathbf{w}} \|\mathbf{w}\|_1 + \|(\mathbf{u},\mathbf{v})\|_2 + \frac{\mu}{2}\|\mathbf{\Phi x} - \mathbf{y}\|_2^2$$
$$+ \frac{\lambda}{2}\|\mathbf{u} - \nabla_u \mathbf{x} - \mathbf{b}_u^k\|_2^2 + \frac{\lambda}{2}\|\mathbf{v} - \nabla_v \mathbf{x} - \mathbf{b}_v^k\|_2^2 + \frac{\gamma}{2}\|\mathbf{w} - \mathbf{\Psi}^T\mathbf{x} - \mathbf{b}_w^k\|_2^2$$

- Alternating minimizations
  - Efficient solution for $\mathbf{w}, \mathbf{u}, \mathbf{v}$ via elementwise shrinkage
  - Efficient (inexact) solution to $\mathbf{x}$ via Fourier (circulant approx)

diagonal (non-constant)

circulant

$$(\mu\mathbf{\Phi}^T\mathbf{\Phi} - \lambda\Delta + \gamma\mathbf{I})\mathbf{x} =$$
$$\mu\mathbf{\Phi}^T\mathbf{y} + \lambda\nabla_u^T\left(\mathbf{u}^k - \mathbf{b}_u\right) + \lambda\nabla_v^T\left(\mathbf{v}^k - \mathbf{b}_v\right) + \gamma\mathbf{\Psi}\left(\mathbf{w}^k - \mathbf{b}_w\right)$$

Phase transition curves