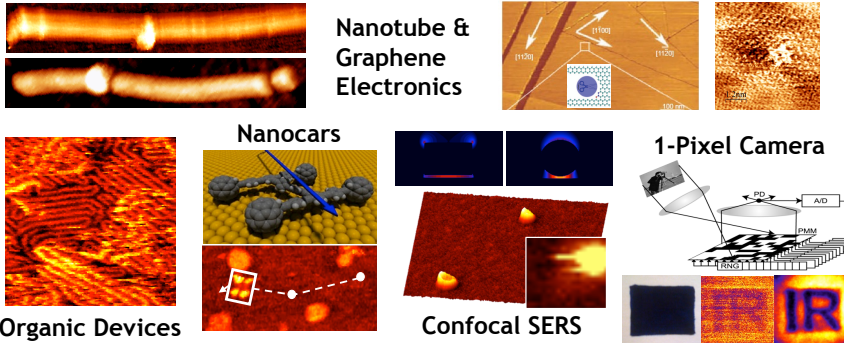


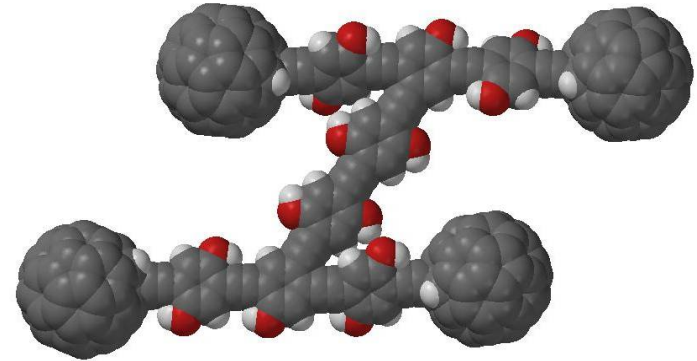
The Kelly Lab: Nanocar Drivers, Single-Pixel Photographers, & Probe Microscopists

- Atomic-scale investigation of doping in semiconductors & conducting polymers.
- Investigating plasmon-based enhancement in near-field spectroscopy
- Imaging based on compressive sensing
- Investigating single molecule machines.
- Characterizing electron transport in carbon nanotubes and graphene

<http://www.ece.rice.edu/~kkelly>
email: kkelly@rice.edu

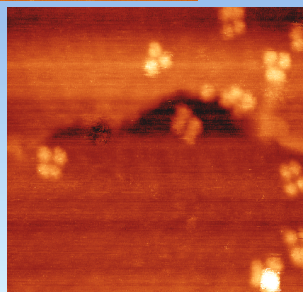
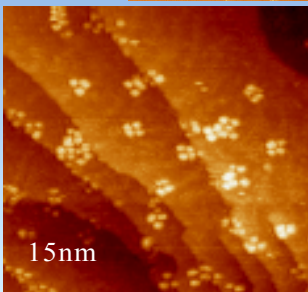
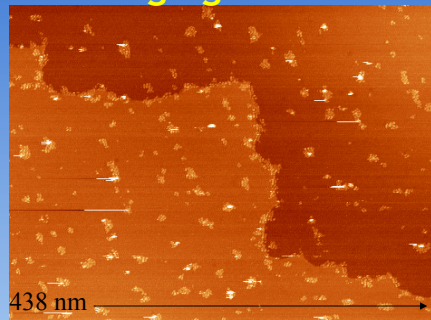


Nanocars



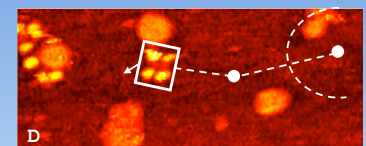
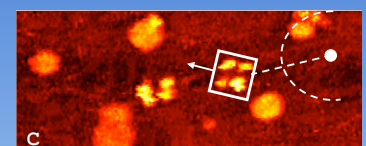
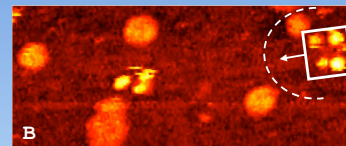
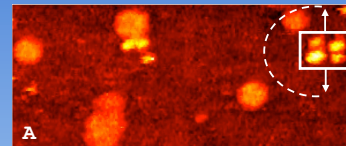
Y. Shirai, T. Sasaki, & J. M. Tour
Department of Chemistry, Rice University, Houston, Texas

STM Imaging of Nanocars

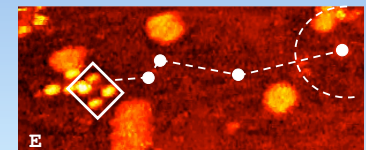


Thermally Driven Nanocars

After heating the substrate, the nanocars begin diffusing on the surface.

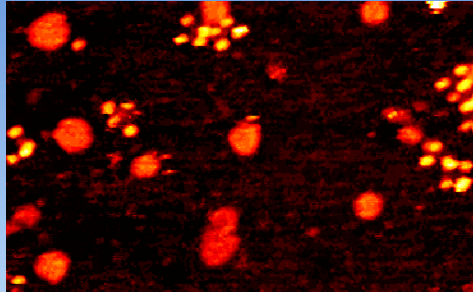


Nanocar molecules at 210°C illustrating translational and pivoting motion
Orientation determined by peak to peak measurements and proportions



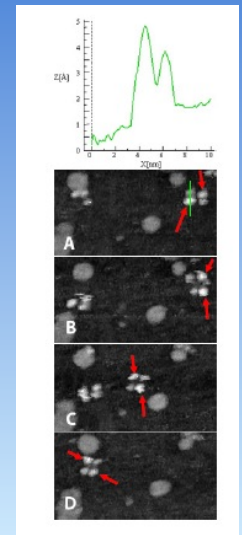
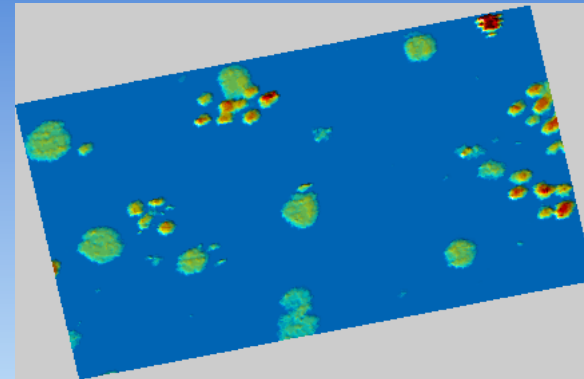
*Y. Shirai, A. J. Osgood, Y. Zhao, K. F. Kelly and J. M. Tour, *Nano Lett.* **5**, 2330 (2006).

Thermally Driven Nanocars

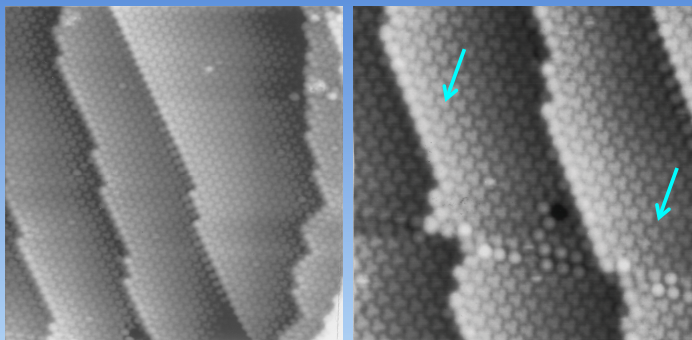


*Y. Shirai, A. J. Osgood, Y. Zhao, K. F. Kelly and J. M. Tour, *Nano Lett.*, **5**, 2330 (2006).

Thermally Driven Nanocars in 3D



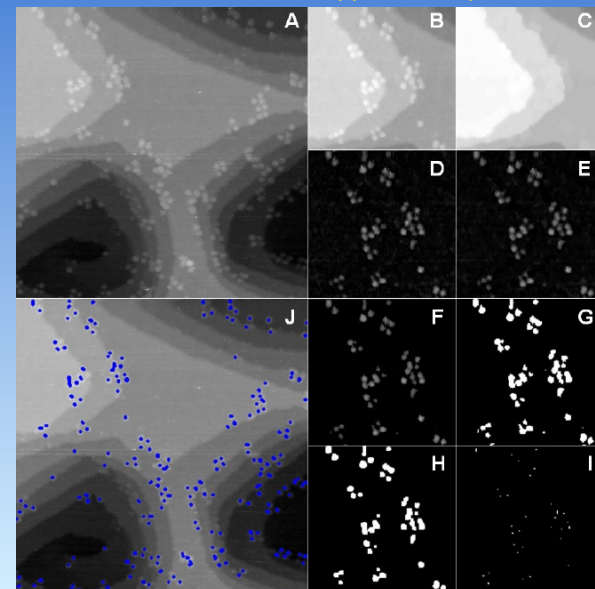
Intra-molecular structure of C₆₀



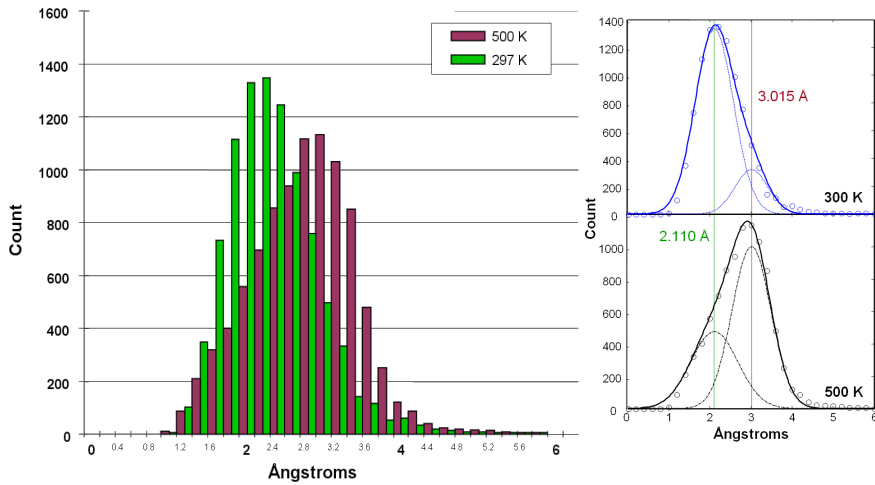
STM Images of the C₆₀ array on the Cu(111)1x1 surface at room temperature. Individual C₆₀ molecules inside the terraces are anchored, stop their rotation and show their intra-molecular structure. Some at phase boundary or step edges are still rotating. (with H. Shinohara group)

(T. Hashizume et al, *Phys. Rev. Letts* 71, 2956 (1993))

Automated Fullerene Wheel Measurement



Automated Fullerene Wheel Measurement



And now for something completely different...

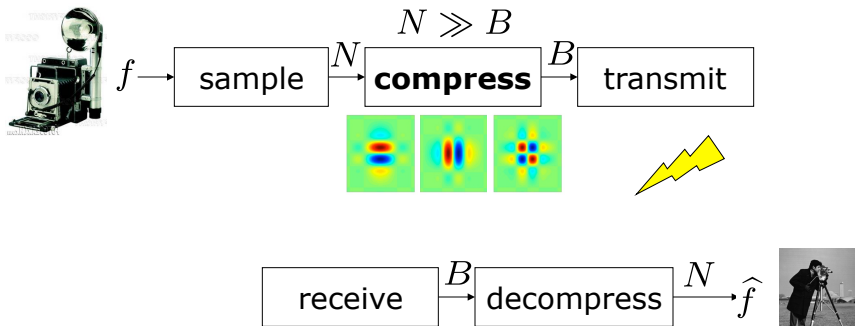
Implementing Compressive Imaging & Sparsity

A 1-Pixel Camera & Beyond



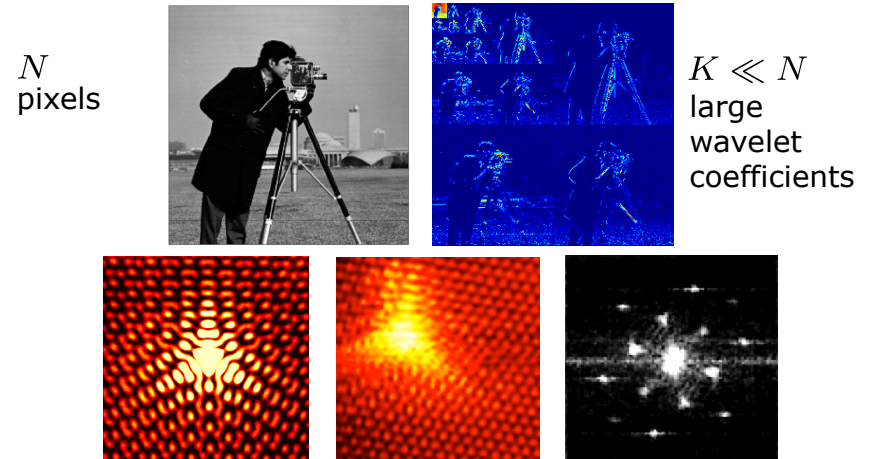
Conventional Imaging

- The typical sensing/compression setup
 - compress = transform, sort coefficients, encode
 - most computation at *sensor* (asymmetrical)
 - lots of work to throw away >80% of the coefficients



Sparsity

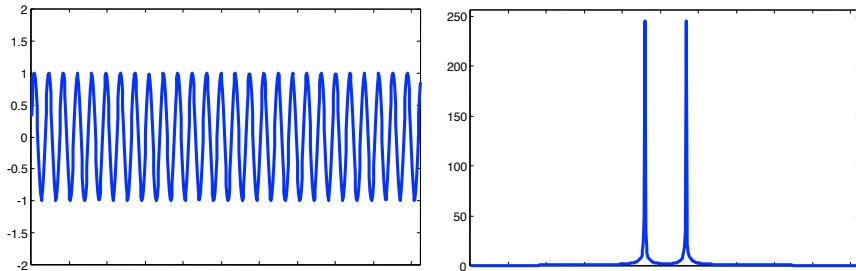
- Many images can be *sparsely represented* in some representation/basis (Fourier, wavelets, ...)



Kelly et al., Science vol.273, pg.1371 (1996).

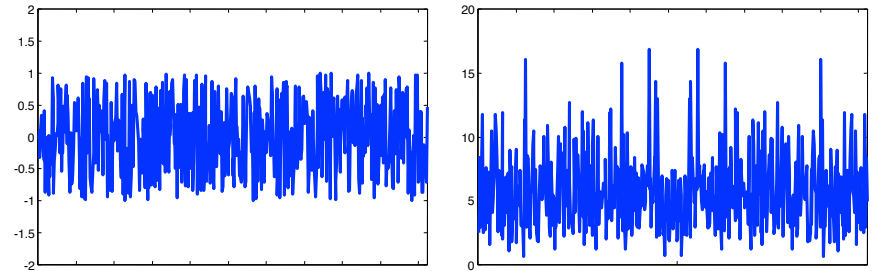
From Samples to *Measurements*

- Shannon/Nyquist sampling theorem
 - must sample at 2x signal bandwidth
- *Compressive sensing* (CS) principle [Donoho, Candes, Tao, Romberg]
 - *integrates sensing, compression, processing*
 - enables sub-Nyquist “measuring”
 - based on new *uncertainty principles* that extend Heisenberg’s



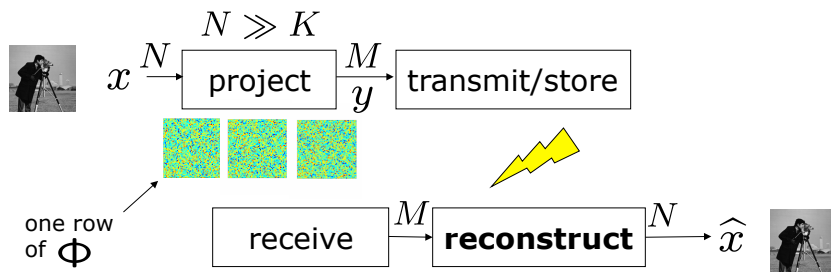
From Samples to *Measurements*

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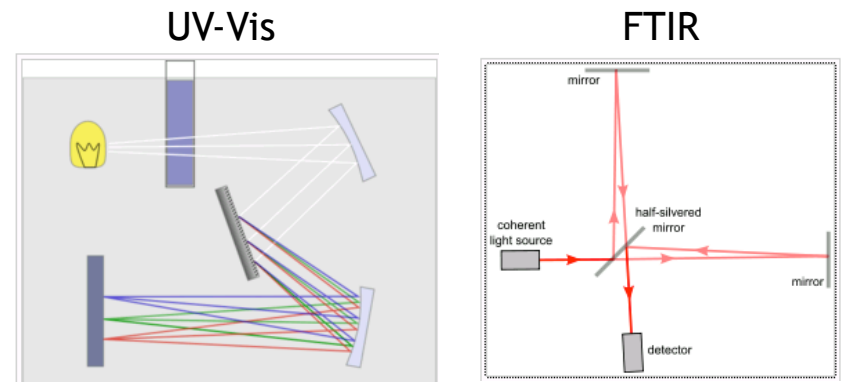
Compressive Imaging

- Measure linear projections onto *random* basis where data is *not sparse/compressible*



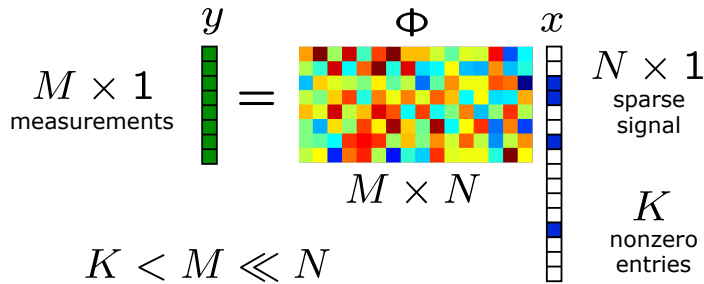
- Reconstruct via *nonlinear processing* (optimization) (using sparsity-inducing basis)

Visible vs. Infrared Spectroscopy



CS Signal Recovery

- Reconstruction/decoding: given $y = \Phi x$
(ill-posed inverse problem) find x



CS Signal Recovery

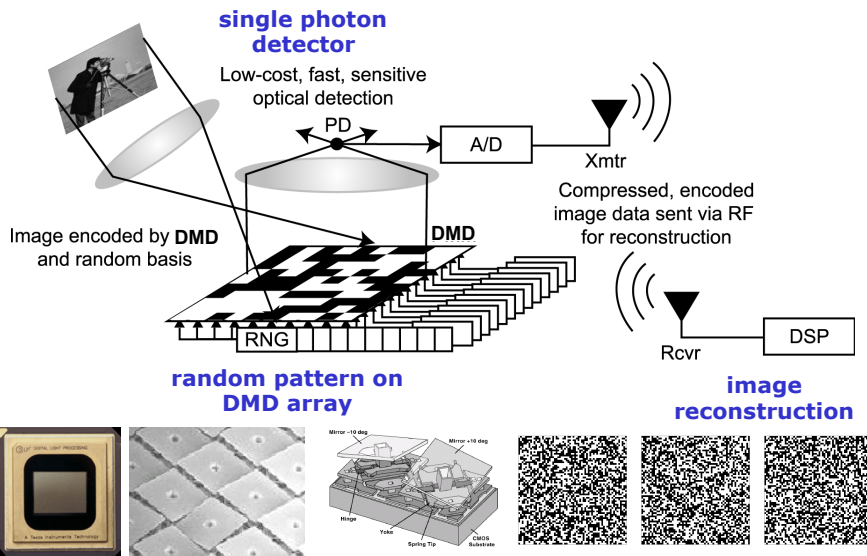
- Reconstruction/decoding: given $y = \Phi x$
(ill-posed inverse problem) find x

- L_2 fast, wrong $\hat{x} = \arg \min_{y=\Phi x} \|x\|_2$
- L_0 correct, slow $\hat{x} = \arg \min_{y=\Phi x} \|x\|_0$
- L_1 **correct, mild oversampling** $\hat{x} = \arg \min_{y=\Phi x} \|x\|_1$
 [Candes, Tao, Romberg; Donoho] *linear program*

$M = O(K \log(N/K)) \ll N$

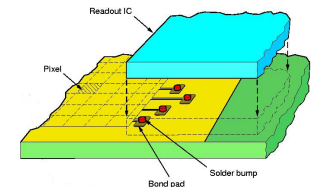
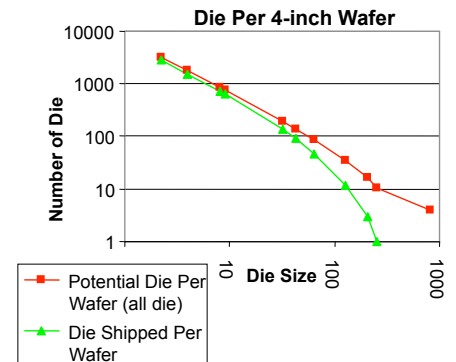
<http://www.acm.caltech.edu/l1magic/>

Rice 1-Pixel Camera

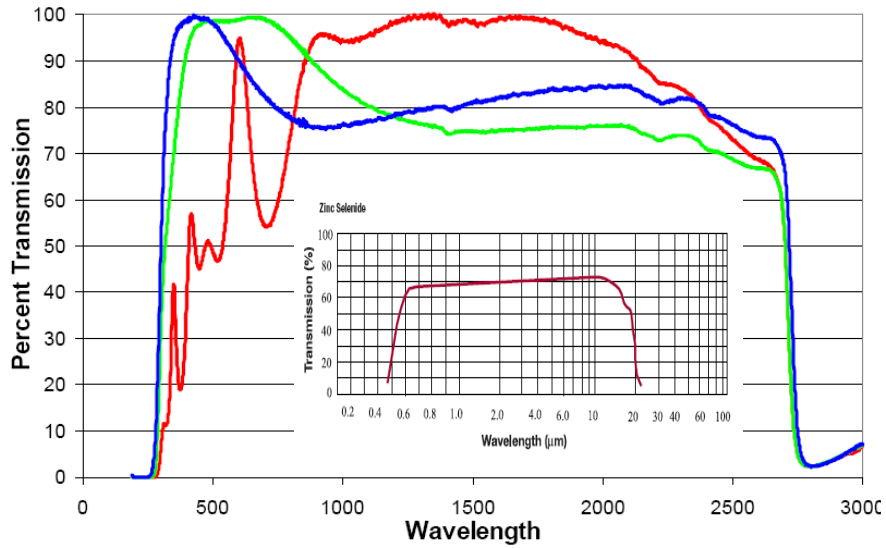


Limitations of Infrared Focal Plane Arrays

- Goodrich sensor array (640 x 512)**
 - Die Size of 205 mm²
 - 16 potential die per 4-inch wafer
 - 3 die shipped per wafer
- Single element sensor (1 x 1)**
 - Die Size of 9 mm²
 - 753 potential die per 4-inch wafer
 - 622 die shipped per wafer

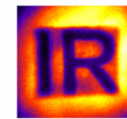
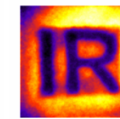
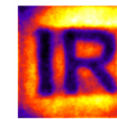
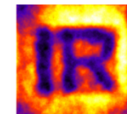
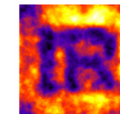
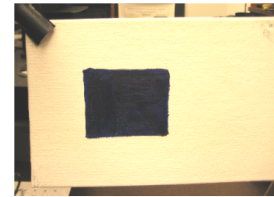
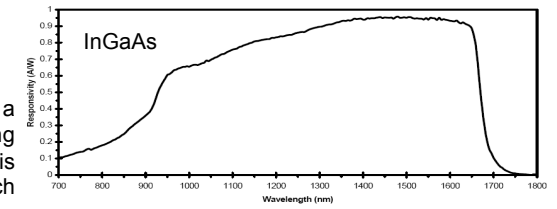


Spectral Range of the DMD



CS Imaging in the Infrared

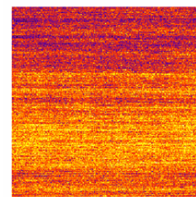
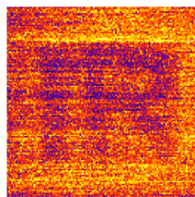
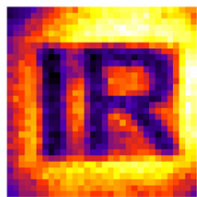
A canvas board with a handwritten letter "IR" using charcoal pencil. On top of that is a layer of blue oil paint which completely covers the lettering.



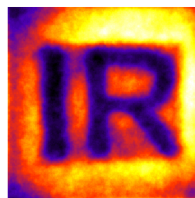
CS reconstruction of 256×256 pixel image based on 1%, 2%, 5%, 10%, 100% measurements respectively. ($M \geq O(K \log(N/K))$)

CS Imaging in the Infrared

Raster : pixel scanning under different sampled resolutions



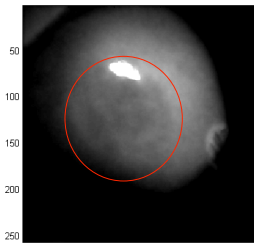
CS : Light combination from half of all the pixels



CS Imaging in the Infrared



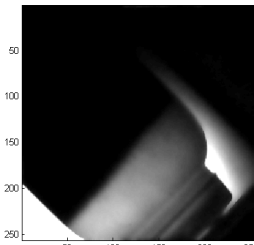
Can not see the bruise using visible camera



bruises can be seen in the SWIR



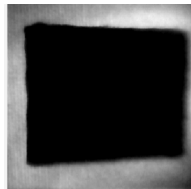
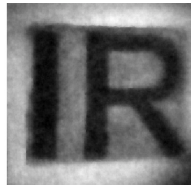
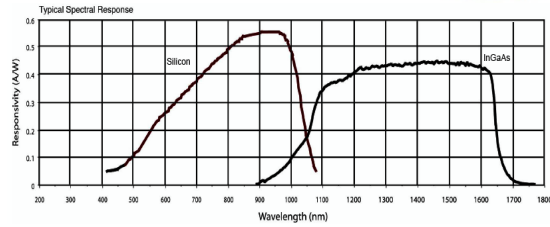
powder bottle above is opaque to the visible camera



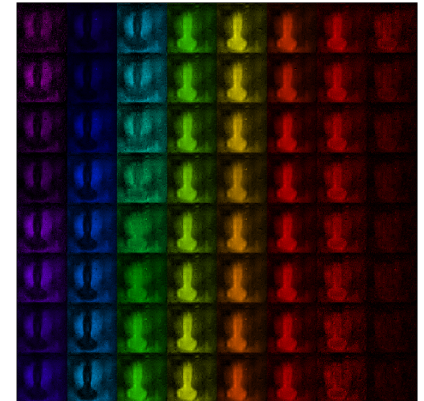
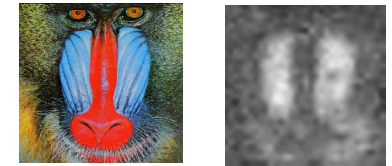
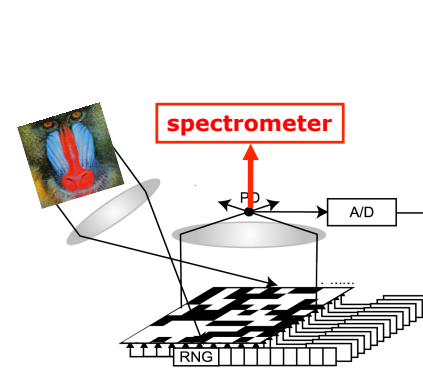
SWIR can see through the plastic

Dual Visible/Infrared Imaging

Detector: commercial dual-band sandwich photodetector with a Si substrate mounted above an InGaAs substrate

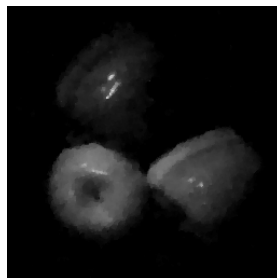
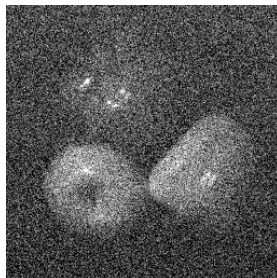
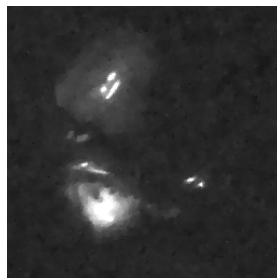
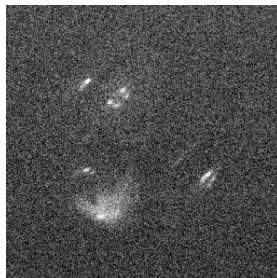


CS Hyperspectral Imager

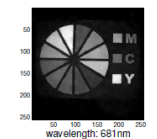
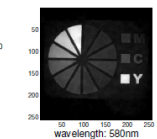
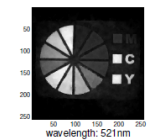
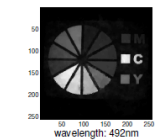
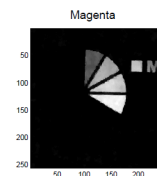
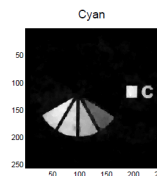
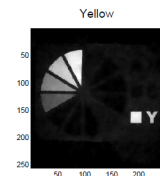
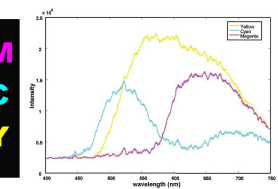
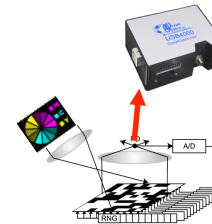


hyperspectral data cube
450-850nm
1M space x wavelength voxels
200k random msmts

Raster Scan vs. CS Hyperspectral

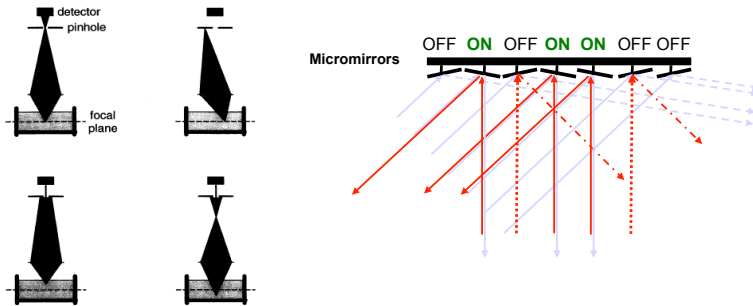


Spatially Compressive Hyperspectral Imager utilizing CS Endmember Unmixing



CS Confocal Microscopy

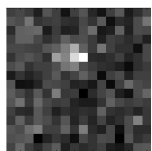
An imaging technique used to increase contrast and/or to reconstruct 3-D images by using a pinhole to eliminate out-of-focus light



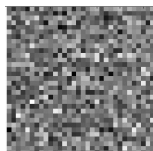
Compressive Sensing vs. Traditional Raster Scan

- 50% of the illumination used in the CS measurement compared to less than 1% used in a raster measurement
- Additionally, CS will make far fewer measurements but will still obtain the same size final image

CS Fluorescence Microscopy



16 x 16 raster
(Gain: 2e6)



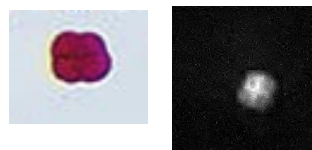
32 x 32 raster



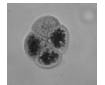
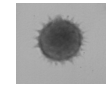
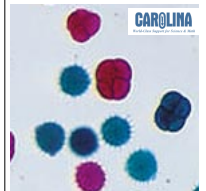
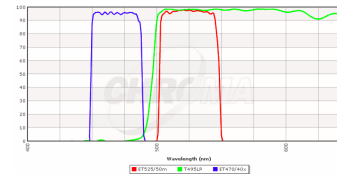
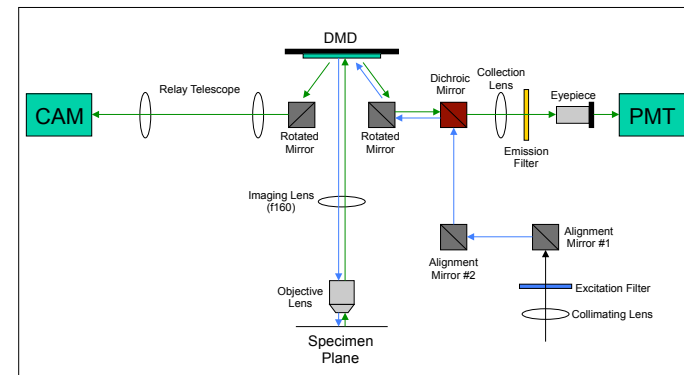
128 x 128 CS
1600 measurements
(Gain: 6e5)

• Using the raster scan, the signal quickly drops below our detection limit.

• Compressive sensing we can obtain a high resolution even with decreased detector gain and without the threat of photobleaching.



DMD-based CS Microscope Layout



Acknowledgements



Dr. Andrew Osgood
Dr. Jun Zhang
Dr. Jungho Kang
Albert Chang
Corey Slavonic

Dr. Rajiv Giridharagoal
Prof. Lili Wang
Chaitra Rai
Chad Byers

Dr. Dharmpal Takhar
Ting Sun
Lina Xu
Matt Turner

“My mind is a raging torrent, flooded with rivulets of thought cascading into a waterfall of creative alternatives.”

