CubeSat hyperspectral imaging technology

Goddard Planetary CubeSat symposium

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Overview

We are fabricating a micro-optical chip to augment focal planes, converting standard image sensors into hyperspectral cameras for CubeSats

Nanohmics Background

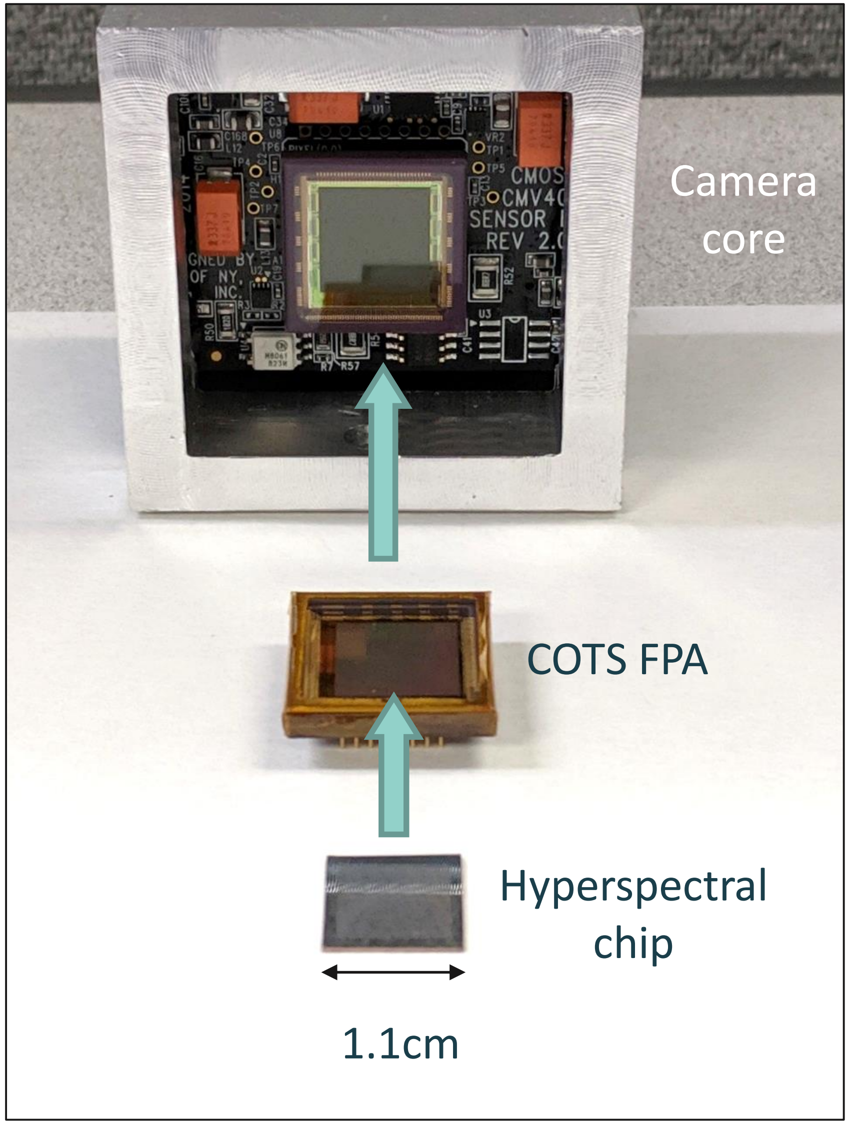
- Based in Austin, TX
- Founded 2002
- Staff of ~40
  - Primarily scientists, engineers, and technicians
- 13,500 sq. ft. of industrial R&D flex space
- Member of the NNCI at University of Texas at Austin
- Core capabilities:
  - Microfabrication
  - Novel materials
  - Electro-optics
  - Instrumentation engineering
  - Sensors & diagnostics

Program Background

- NASA STTR Phase II R&D program with University of Maryland to develop CubeSat hyperspectral imaging sensors
  - Demonstrate in VIS, move into IR in Phase II-E/III
- We are developing a ~1 gram chip that converts a camera into a hyperspectral camera *with full spatial-spectral-temporal registration*
  - Does not require scanning in any dimension (spatial, spectral, or temporal)
  - No spectral filters, radiometrically efficient
  - Trades spatial for spectral information
  - Prototype delivery in September

Hyperspectral chip

- Focal plane augmentation, add ~1 gram of mass by adding a chip very nearly on an FPA
  - Shifts focal plane by ≤1 mm
- A prototype chip is shown on right
  - 100 x 100 spatial elements
  - Target for Gen 1 prototype:
    - 450-950nm bandwidth
    - 5-10nm spectral resolution
  - Frame rate limited by radiometry, underlying image sensor
- Secret sauce:
  - Computational spectroscopy…



"Diagonal" spectroscopy

- Traditional spectroscopy separates bands in essentially linear ways

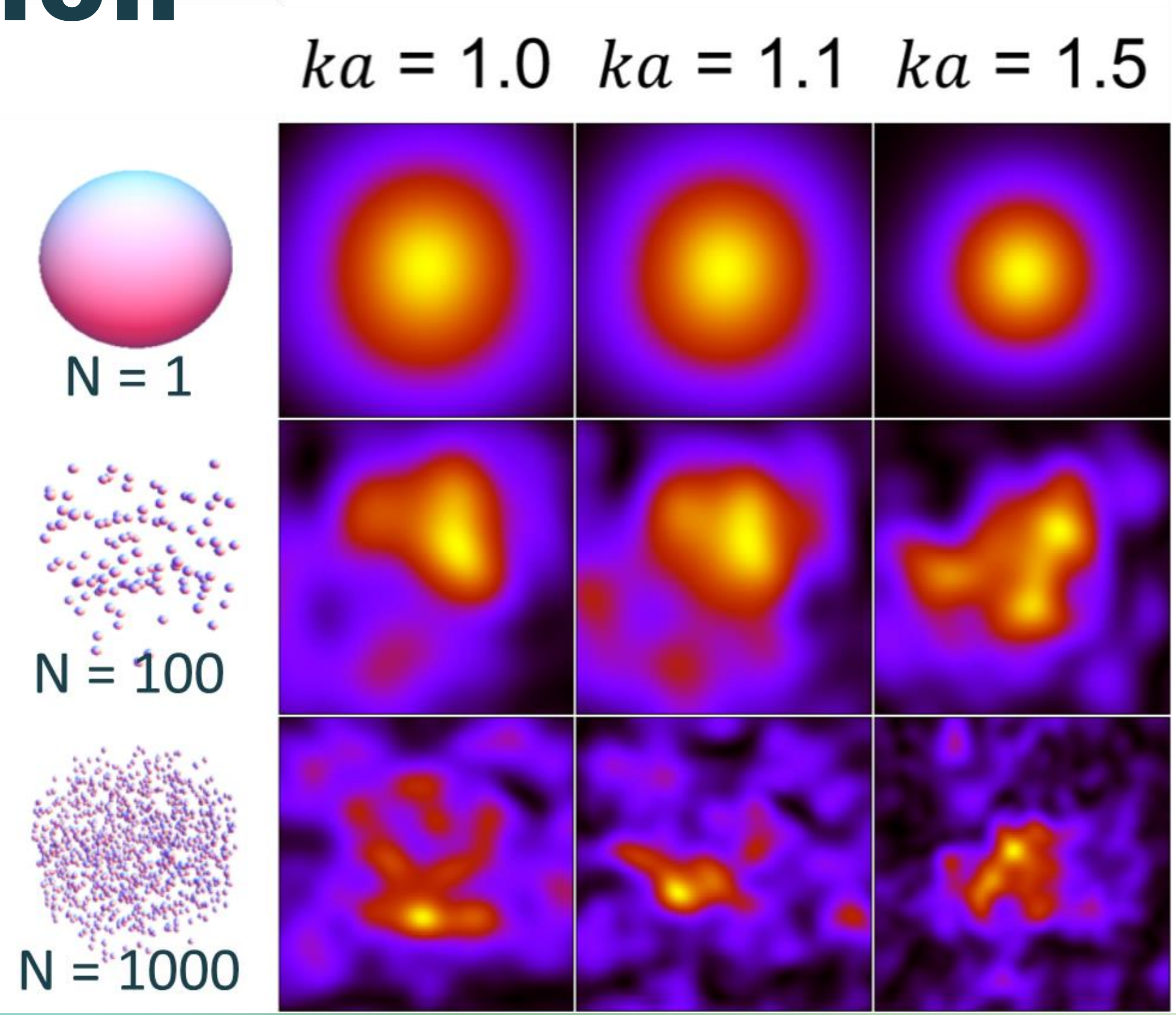
$$S(\lambda) = a_1 I_1 + \ldots + a_N I_N = \begin{pmatrix} a_1 & 0 & 0 & 0 \\ 0 & a_2 & 0 & 0 \\ 0 & 0 & \ldots & 0 \\ 0 & 0 & 0 & a_N \end{pmatrix} \begin{pmatrix} I_1 \\ I_1 \\ \ldots \\ I_N \end{pmatrix} = A\boldsymbol{I}$$

"Non-diagonal" spectroscopy

- Non-diagonal spectroscopy separates bands in complicated ways, with multiple spectral lines on each detector (e.g., FTIR)

$$S(\lambda)=\begin{pmatrix} a_{11} & a_{12} & \dots & a_{1N} \\ a_{21} & a_{22} & \dots & a_{2N} \\ \dots & \dots & \dots & \dots \\ a_{M1} & a_{M2} & \dots & a_{MN} \end{pmatrix}\begin{pmatrix} I_1 \\ I_2 \\ \dots \\ I_N \end{pmatrix} = A\boldsymbol{I}$$

Mie scattering for spectral dispersion

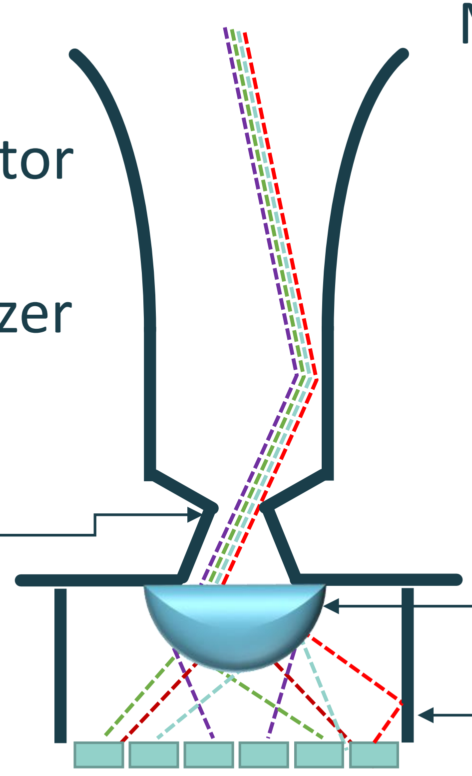


$$k = \frac{2\pi}{\lambda}$$

a = radius of scatterer

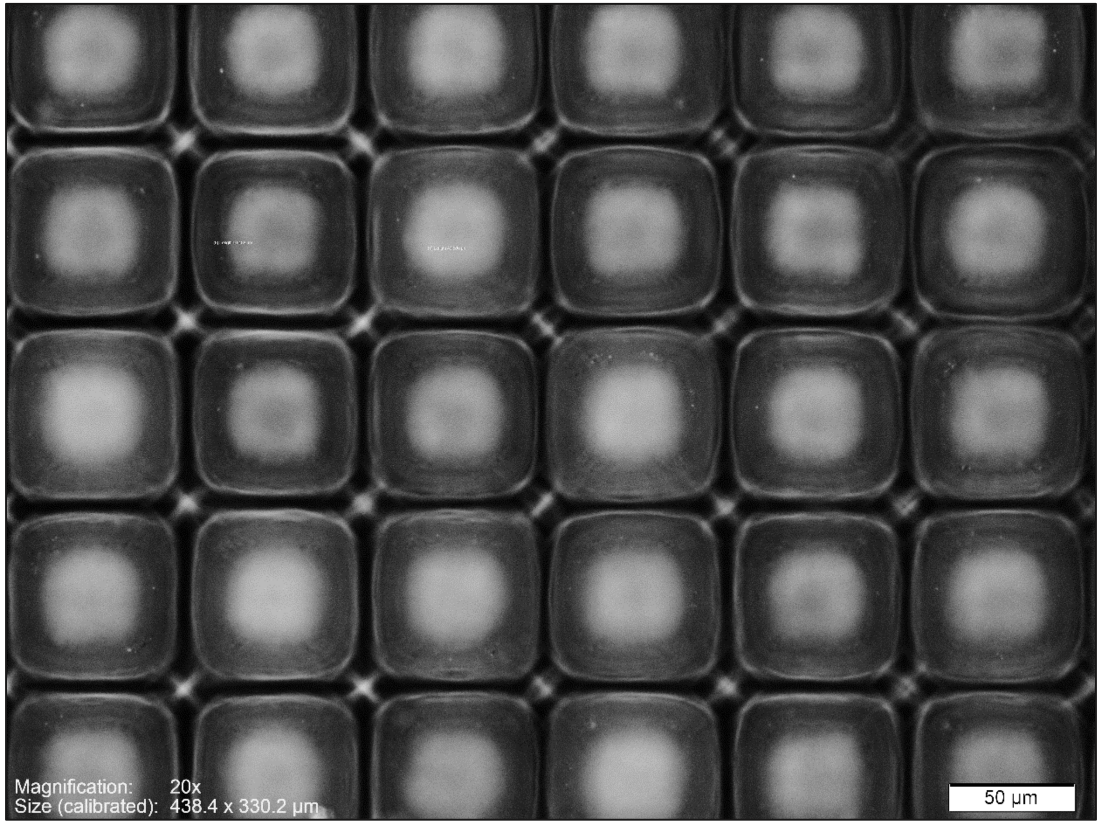
Single element in the hyperspectral array

- Concentrator improves radiative throughput, homogenizes input light
- Aperture provides spatial filter, sets up a reproducible light source (*ala* entry slit to monochromator)
- Dispersive media separates light
- Isolators prevent crosstalk
- Detector array detects a wavelength and polarization-dependent speckle pattern

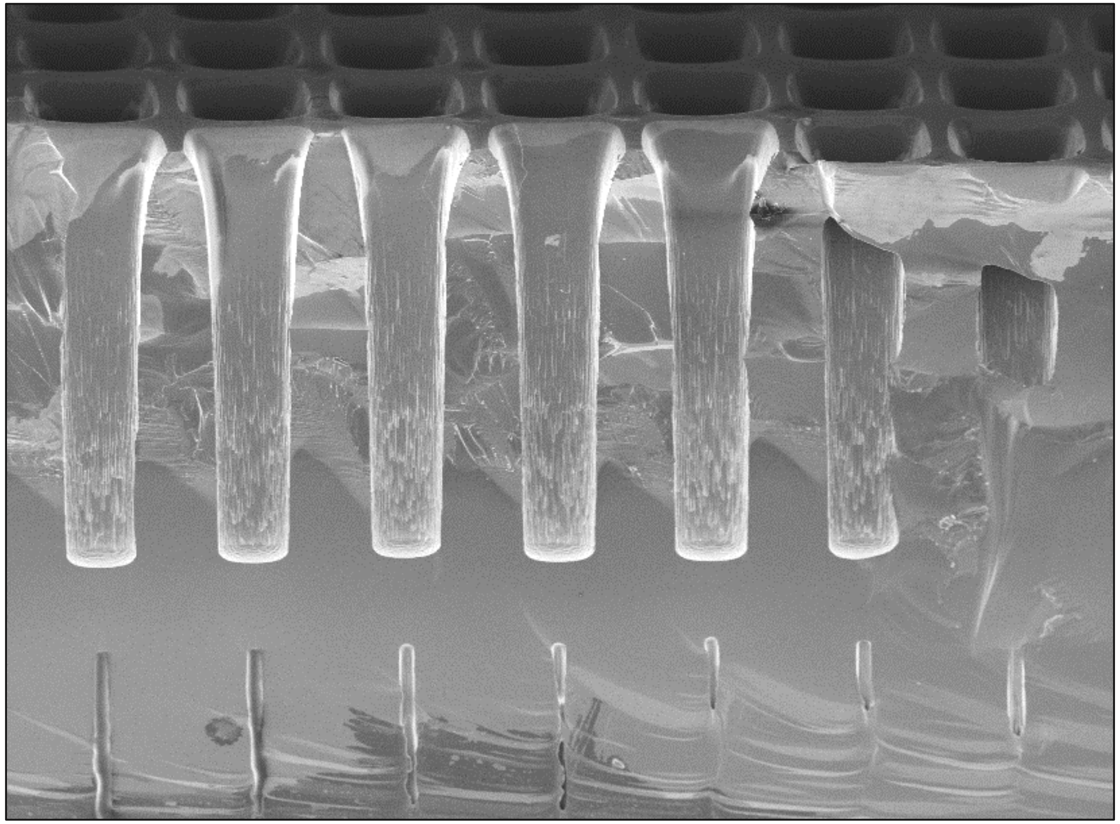


Wavelength-dependent speckle pattern reveals spectral content

Optical concentration

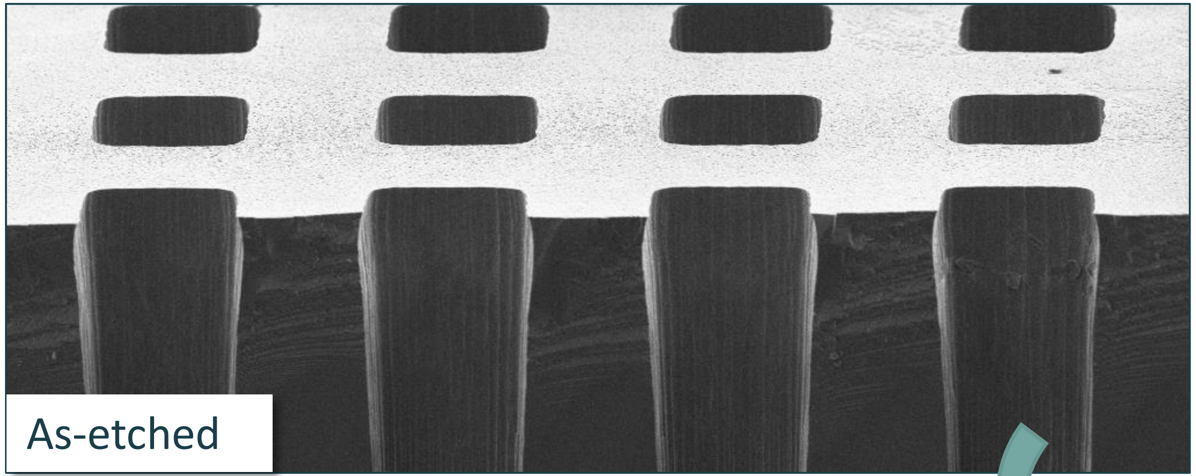


Optical micrograph – view from top

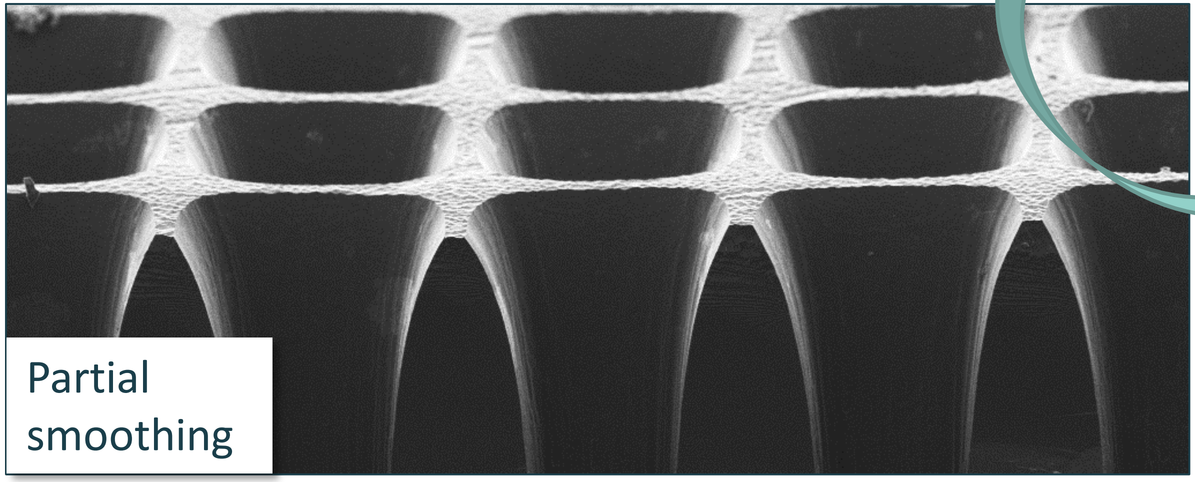


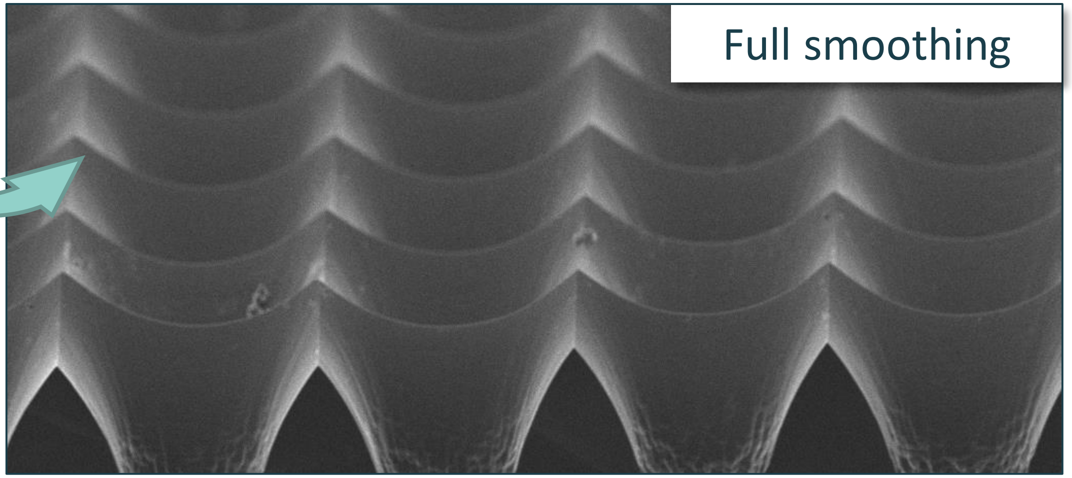
Cleaved sample, cross-section
(note, different sample)

Tailoring concentrator entrance

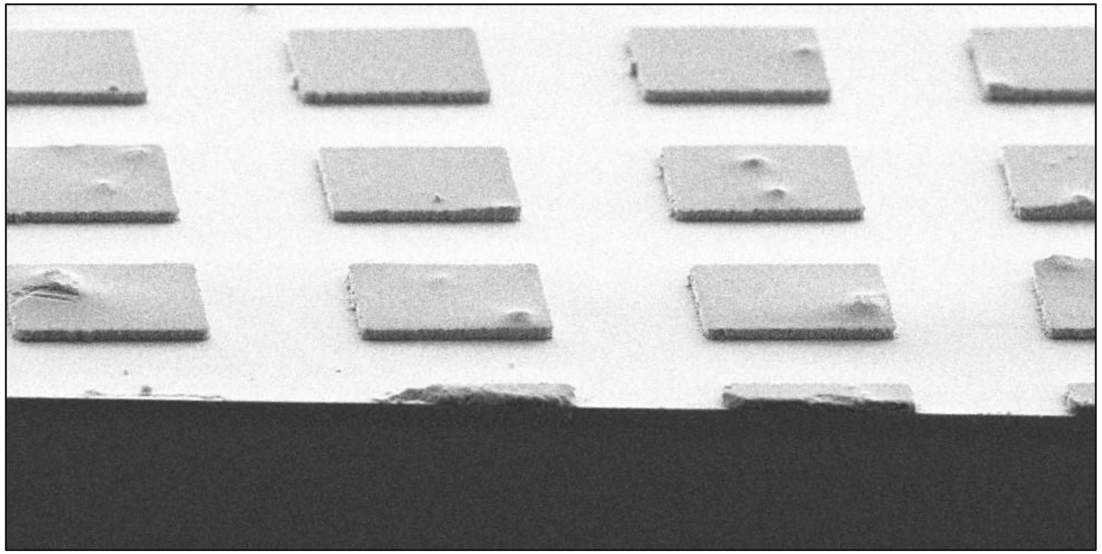


- Perform a post-etch sidewall cleanup to maximize fill factor, reduce roughness
- Tunable chemical & plasma etch processes

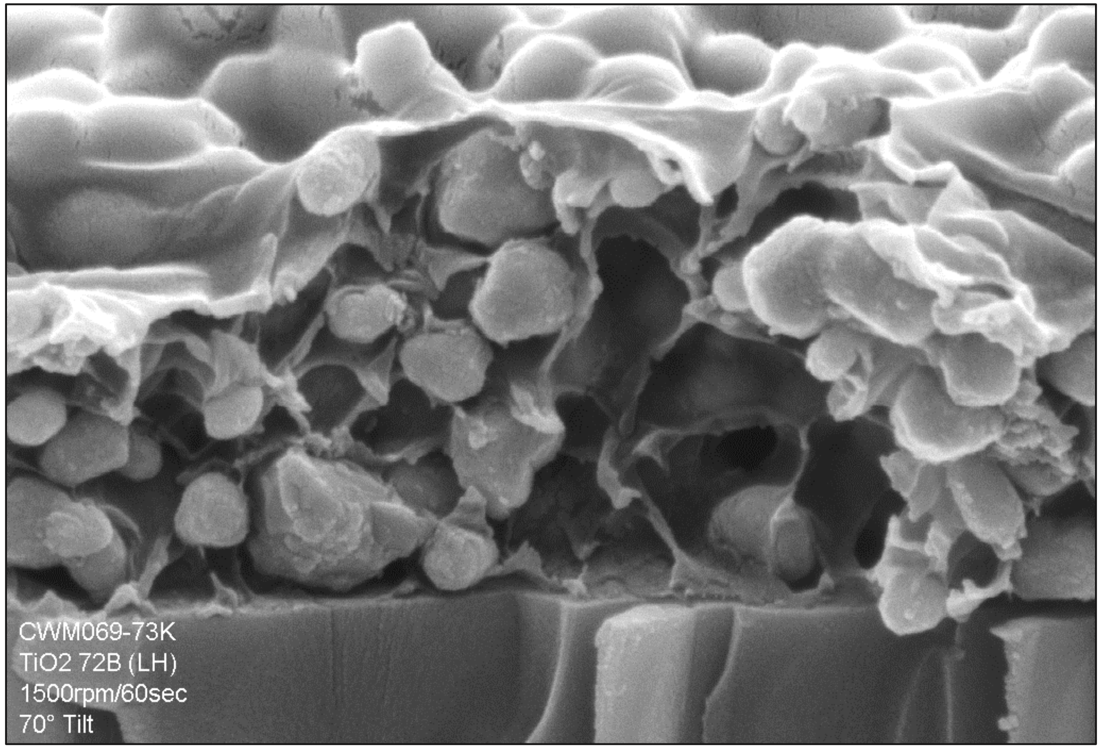




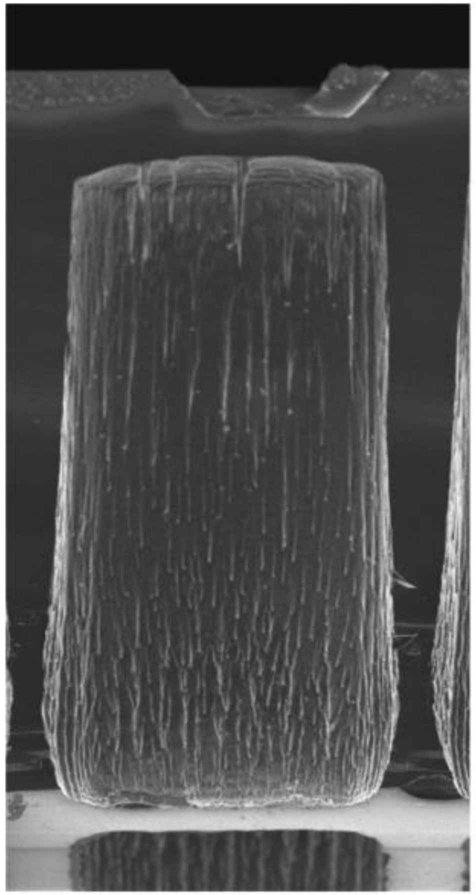
Speckling media

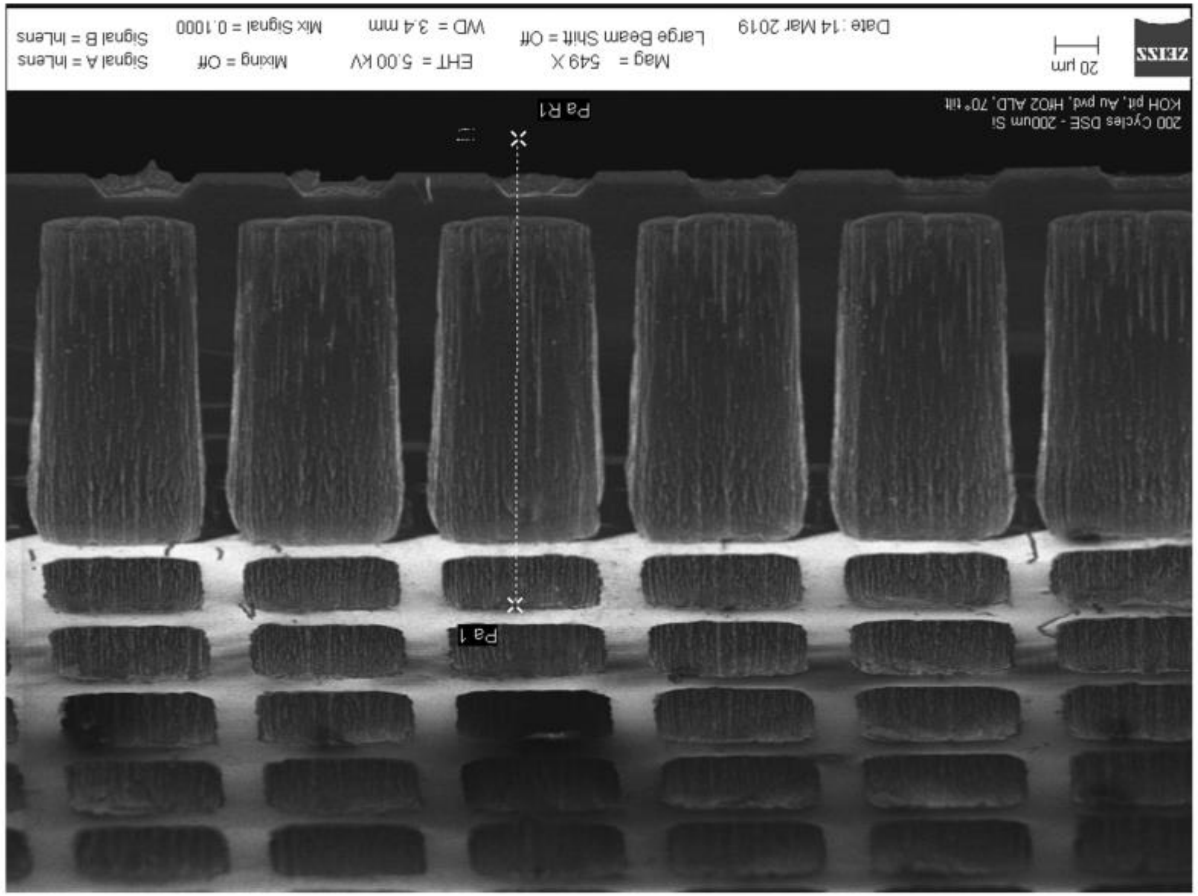


Integrate scattering media with photolithographic processes



Scene element isolation

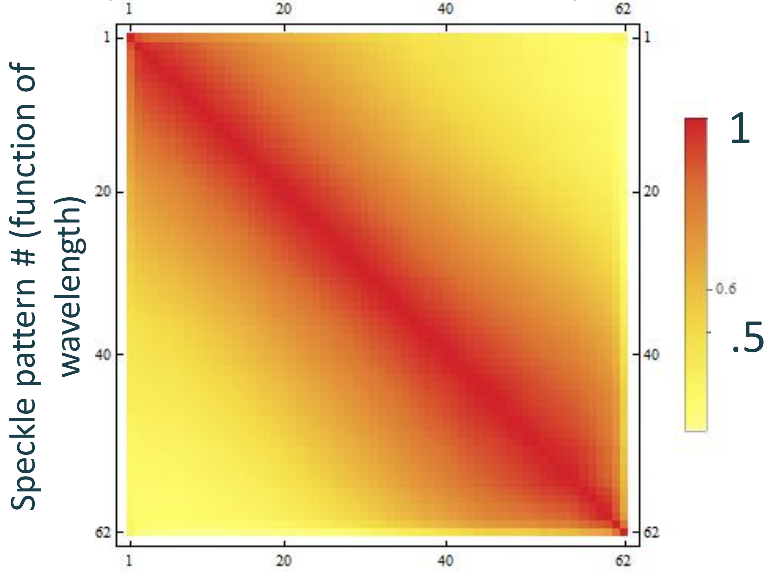




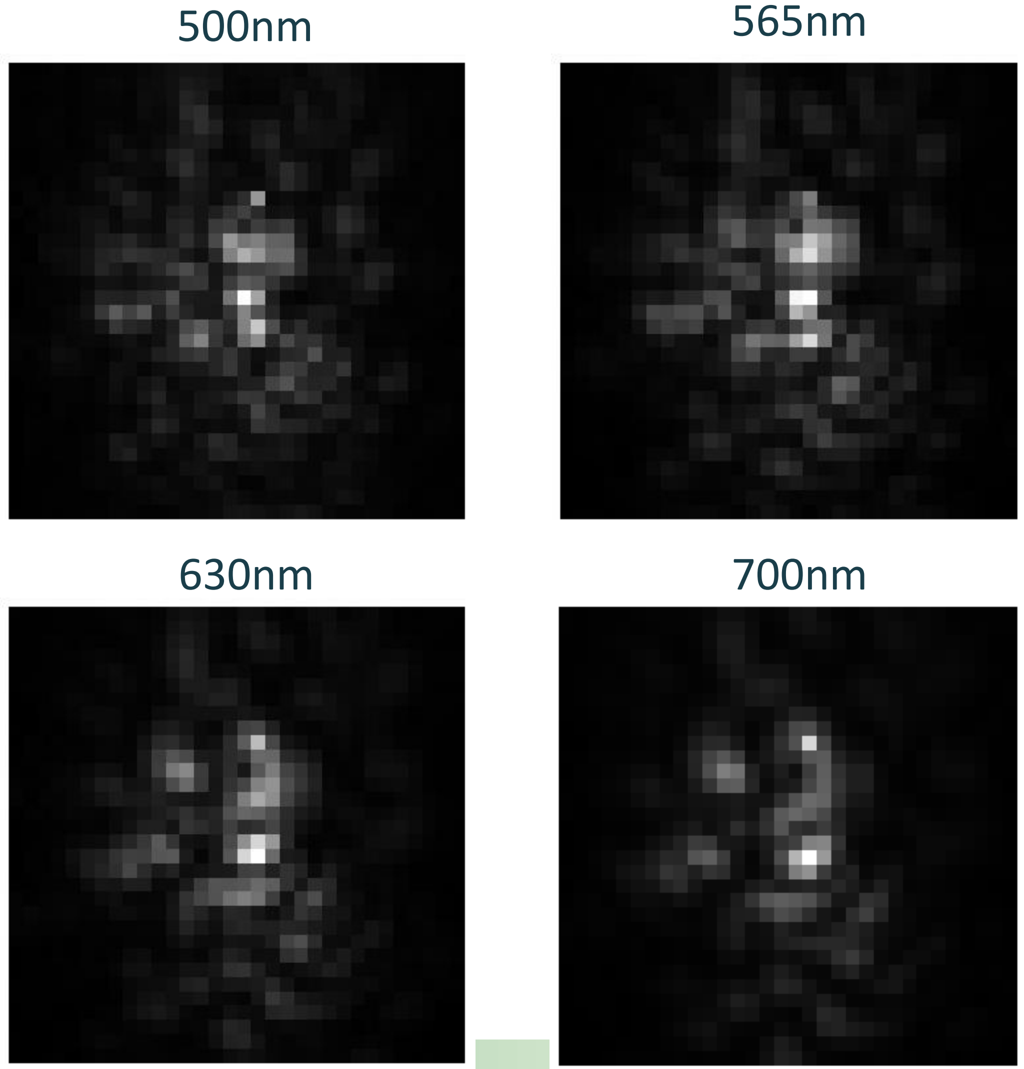
Wavelength-dependent speckle

- Each speckle pattern evolves differently

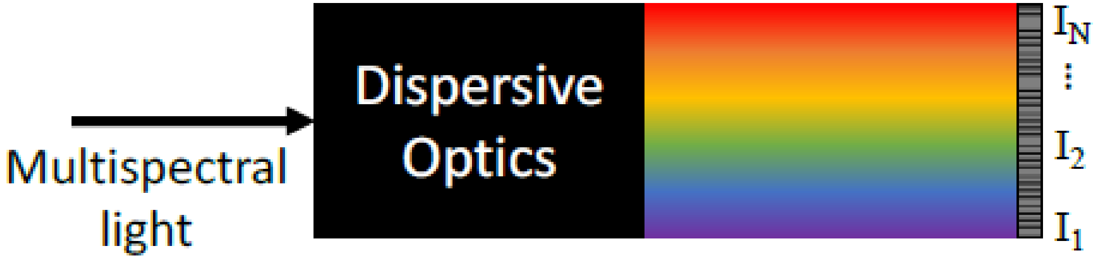
Spectrally-lagged speckle pattern correlation analysis



Speckle pattern # (function of wavelength)



Computational reconstruction



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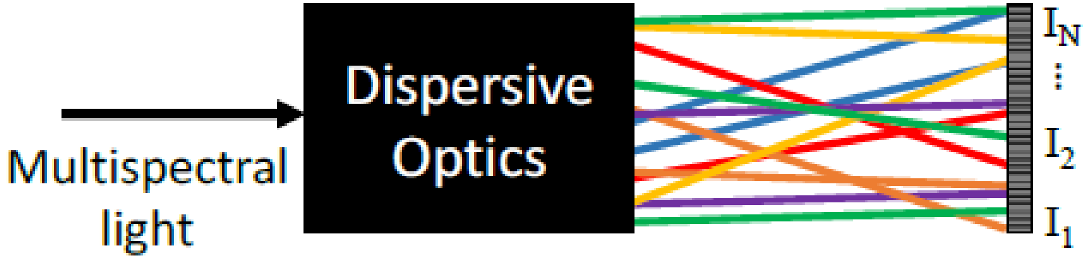

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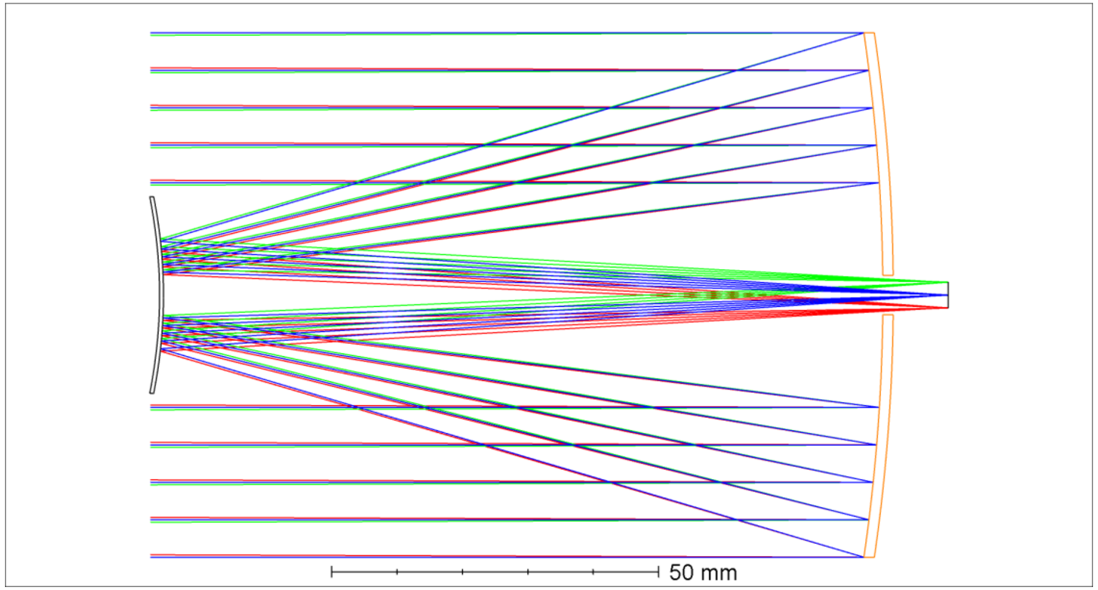
- Spectrum is determined by coefficients, x:
  - $Min(\|\boldsymbol{T}x - S\| + \alpha\|Dx\| + \beta\|x\|)$
  - $\boldsymbol{T}$ the calibrated transfer matrix
  - S the measured speckle pattern vector
  - D the difference operator
  - α, β are reconstruction stabilization parameters and are chosen to be as small as possible
- Calculate after downlink, not on-board (excepting potential preview images)

CubeSat telescopes

- Sensor puts few constraints on telescope
  - *f*/4 or slower is best, though concentrators can be tailored for faster optics
  - Faster/wider FOV optics, prefer image-space telecentric
- 1U telescope options:
  - 80mm Cassegrain (right) for long-range
  - Central obscuration blocks ballistic rays
- Because of our large spatial elements (~90µm), relaxed imaging constraints
  - Deployable optics may be an option

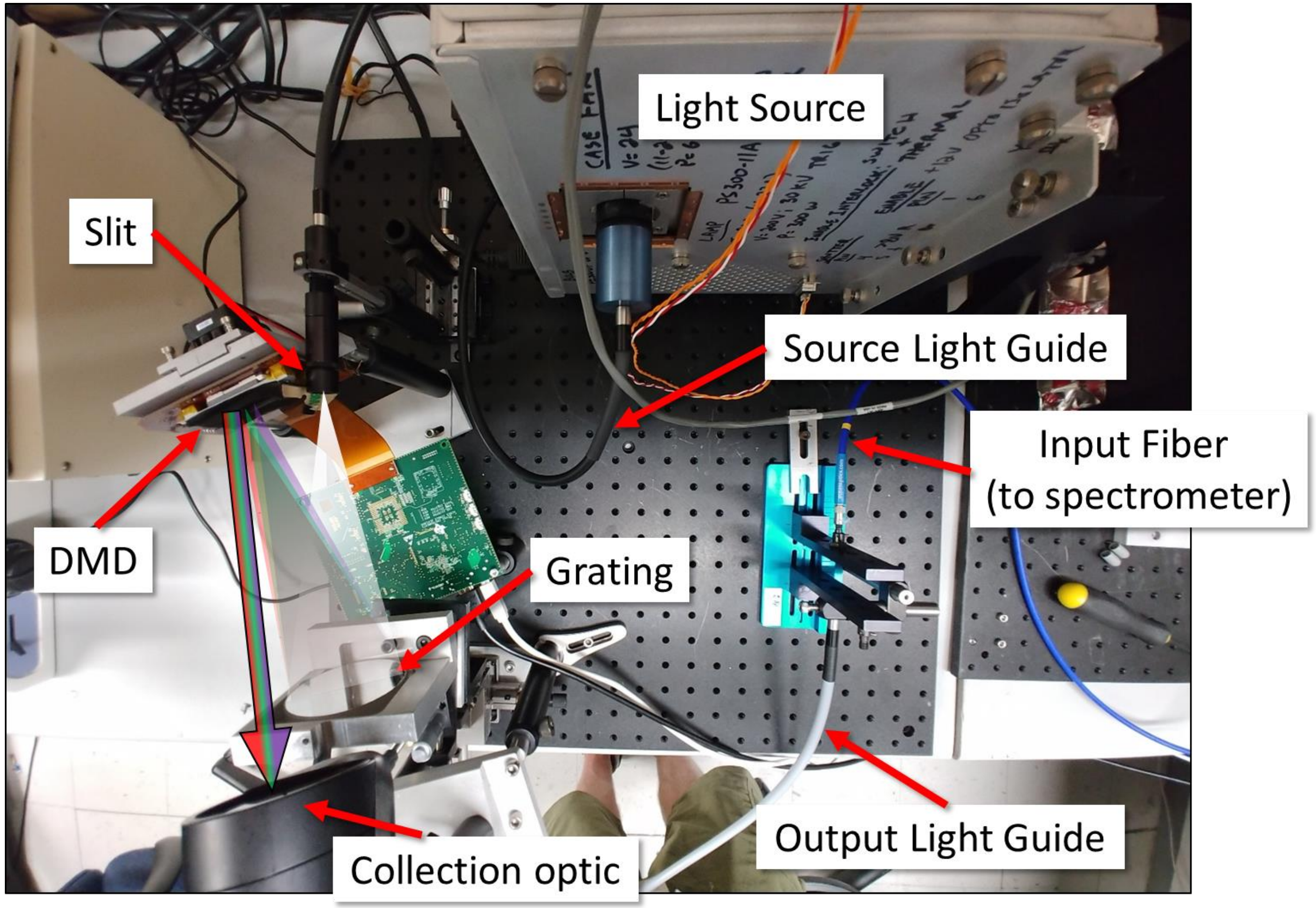


Niche for technology

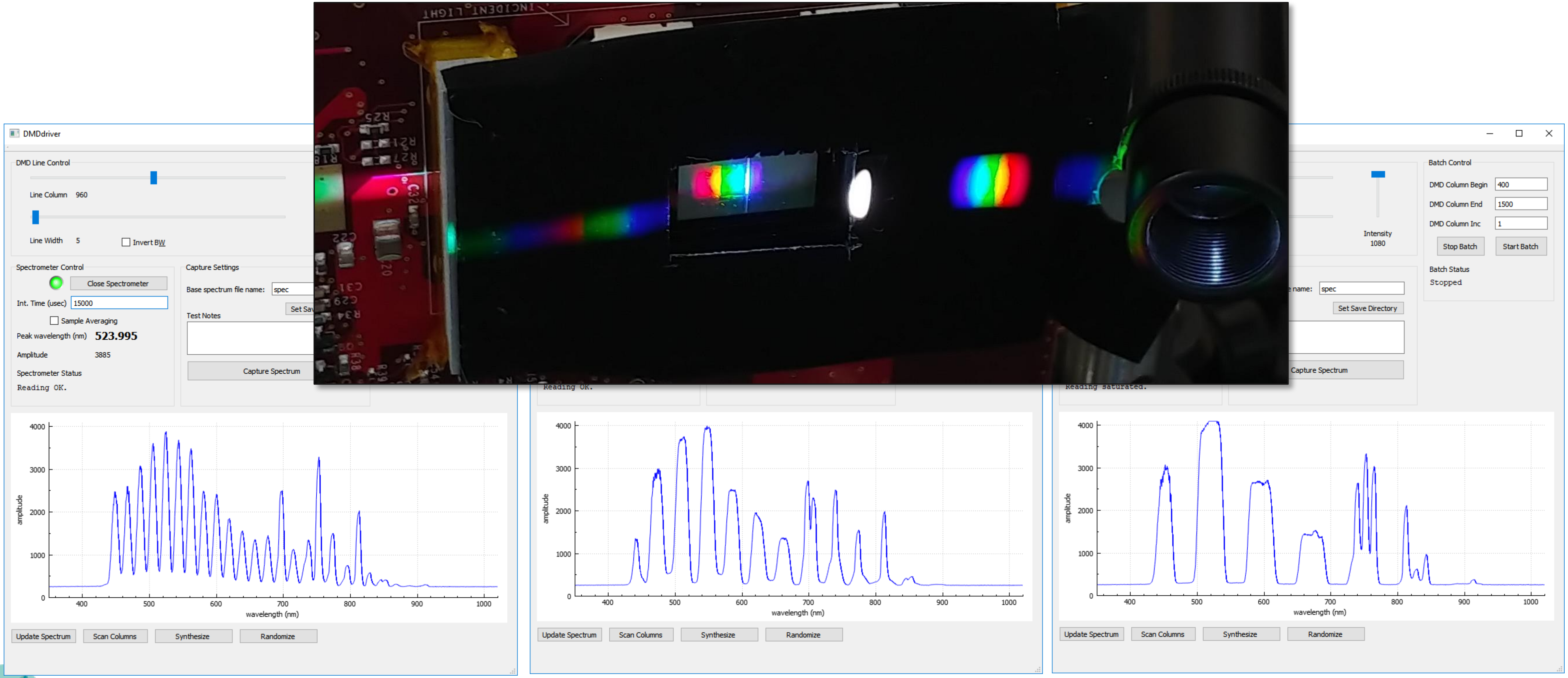
- Applications where pushbroom is inappropriate
  - Pushbroom provides better spectral, spatial resolution
- Great for transient, full-frame operation
  - CubeSats without pointing control
  - Auxiliary instrument that doesn't constrain platform motion
  - Semi-disposable CubeSats
    - Comet approach, high probability of damage
    - Surface approach & impactors
- Applications with modest spectral, spatial tradeoffs
  - Color filter wheels take up space and mass, have moving parts prone to failure

Questions?

Calibration – Spectral Engine

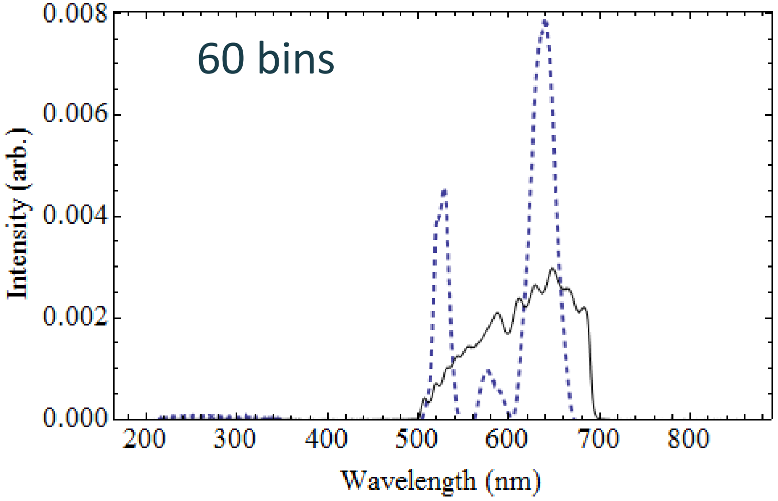


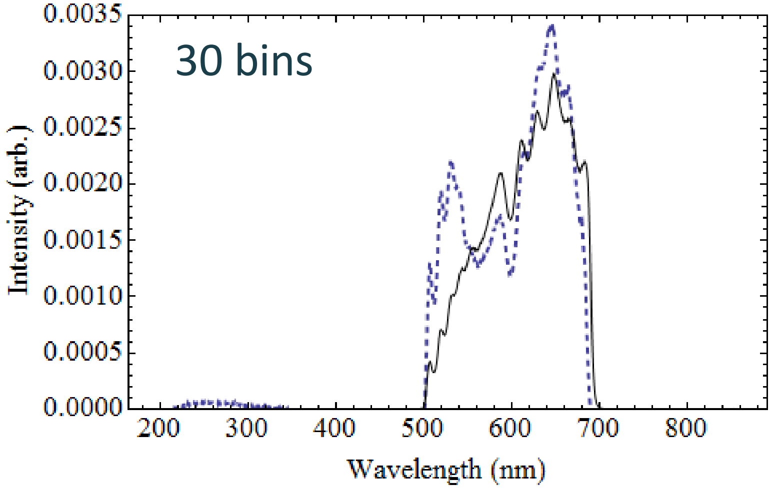
Custom spectra

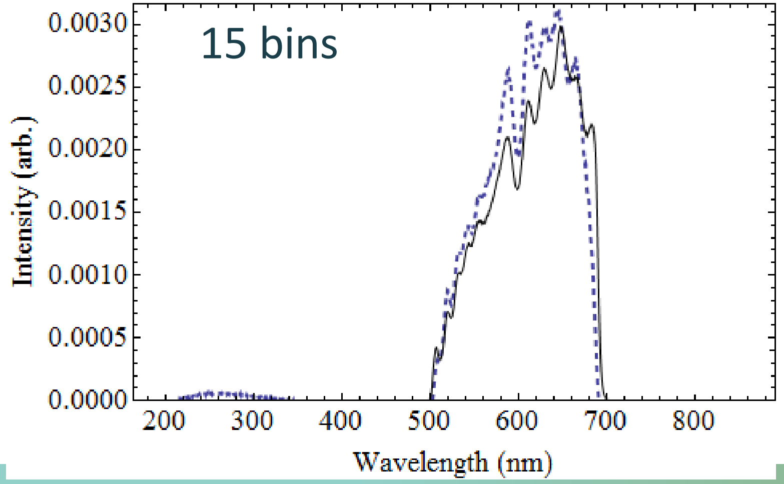


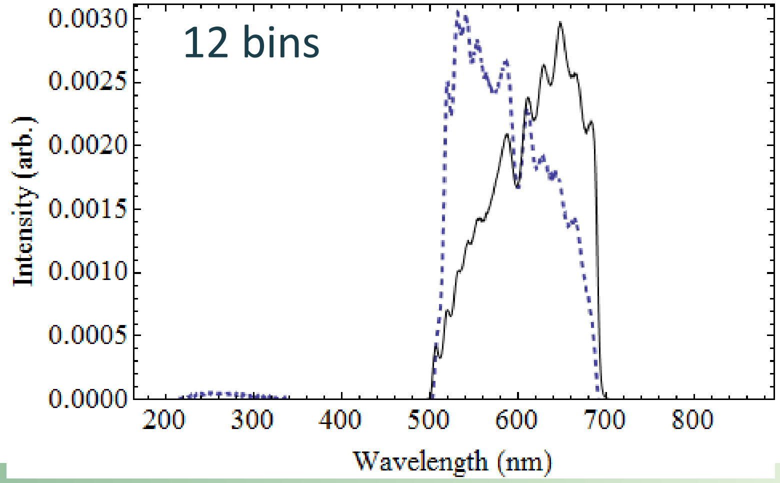
Reconstruction stability

Under constrained









Over constrained