# Fiber-based light-guide snapshot imaging spectrometer for Earth Science applications (TuLIPSS)

NASA Instrument Incubator Program
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# TuLIPSS Team

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**Co-Investigators:**

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**NASA Reference Project Support**

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# Summary of Year 2 Activities

## Major Activities

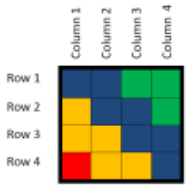
- Implementation of (200x200) low NA TuLIPSS system
- Development of calibration method
- Demonstration and validation of spatial-spectral tuning
- Design of opto-mechanics for the ruggedized system
- Throughput and science application analysis
- In-lab and remote imaging with TuLLIPSS system
- Publication of SNAP-IMS reference imaging (in flight) in Journal of Applied Remote Sensing
- Fiber based spectrometer Optics Express paper (submitted)

## Presentation Outline

- Low NA fiber bundle fabrication
- Calibration Algorithm
- Fiber bundle tuning and cycle testing
- Opto-mechanical design of TuLIPSS system
- Imaging Results with static Tulips Prototype
- Initial Prototype of a Benchtop SWIR TuLIPSS system
- Summary

# FIBER BUNDLE ASSEMBLY

# Breaking Down the Image

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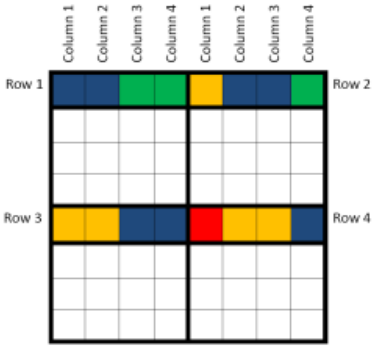


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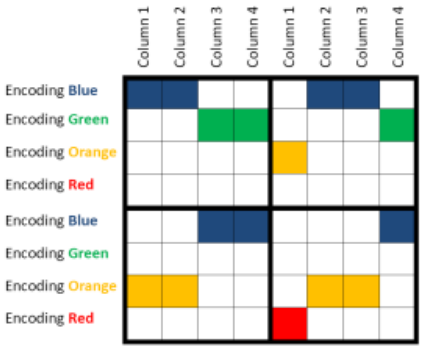


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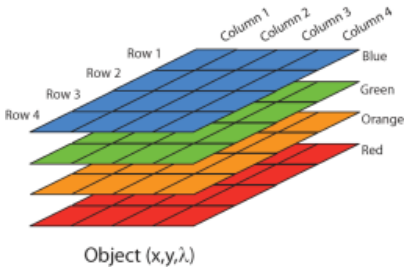


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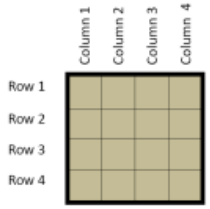


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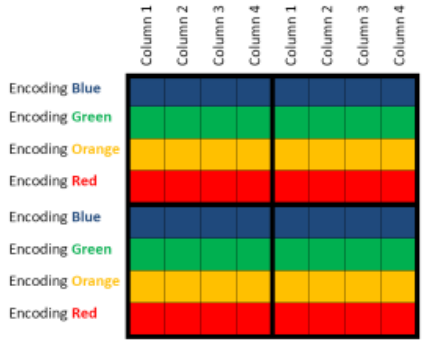
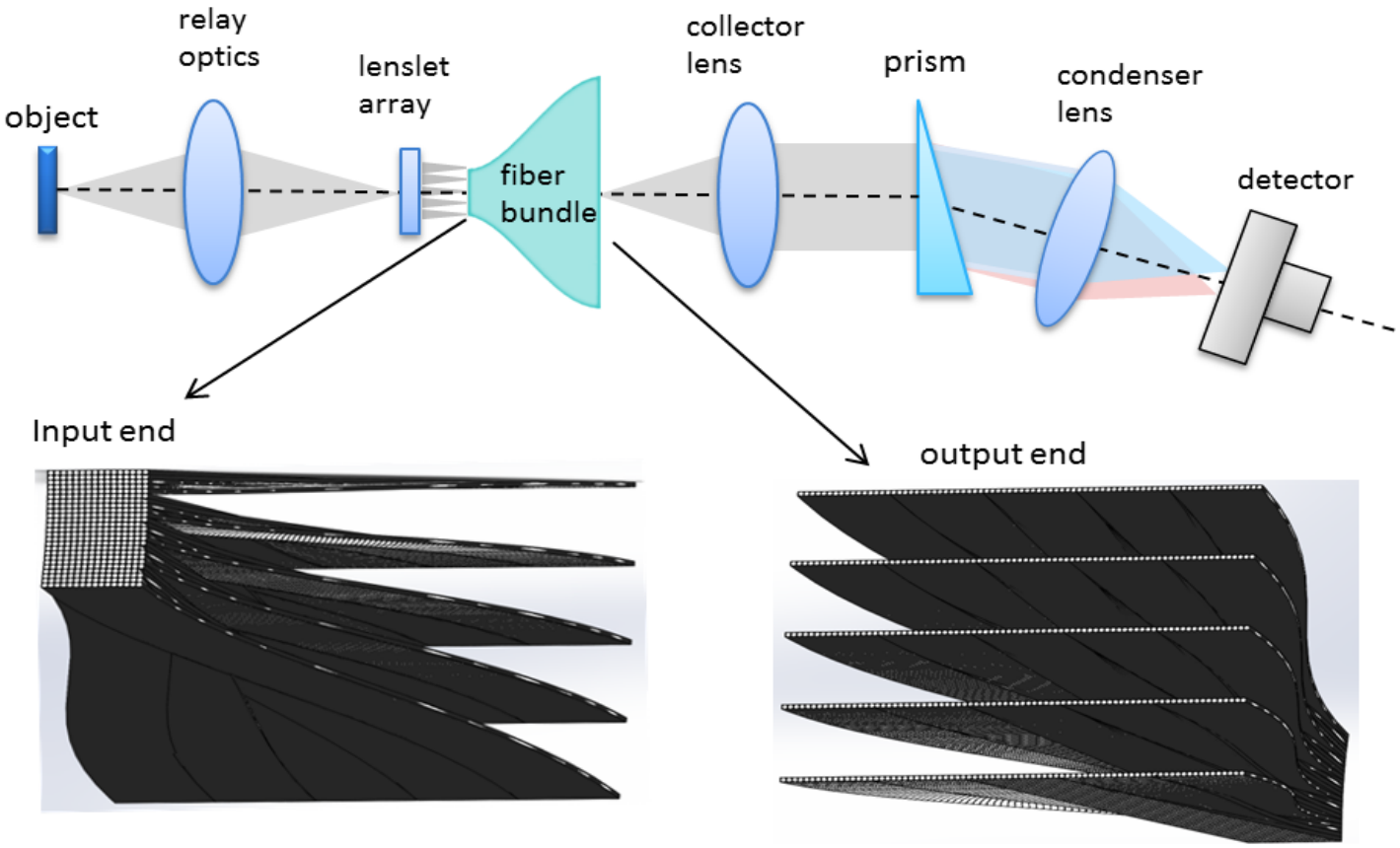


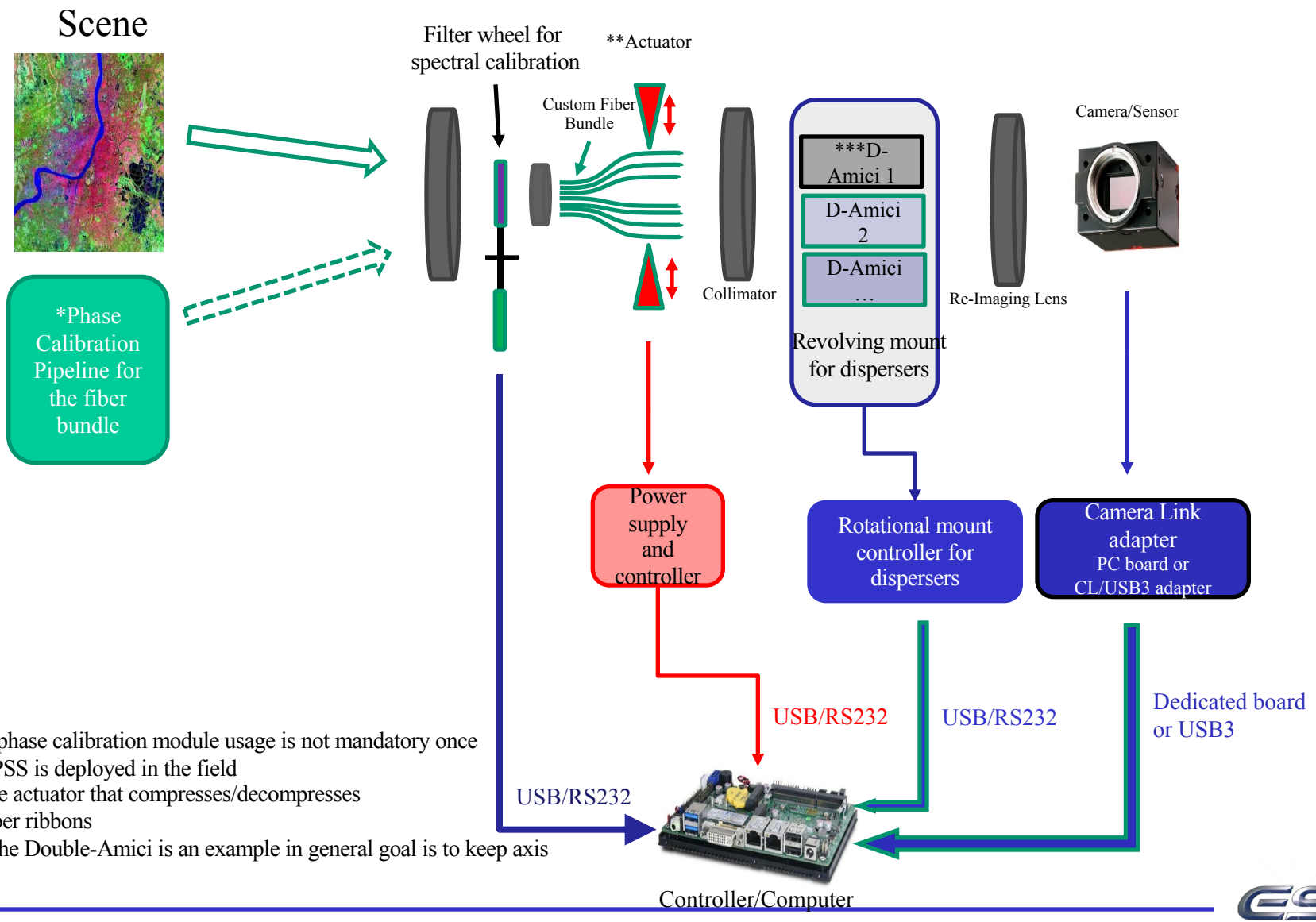

F

# General System Layout



# High Level Layout of the TuLIPSS System

Approach: Spatial Spectral Tuning achieved via actuated fiber bundle and changeable filters/disperser



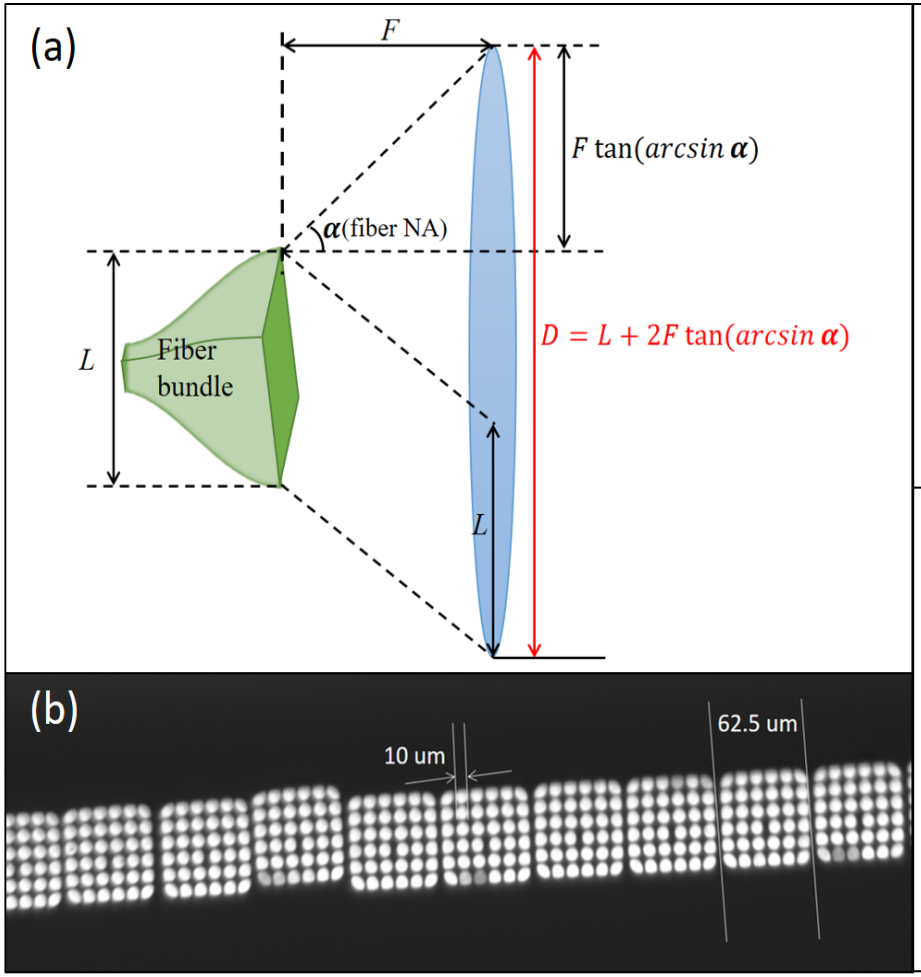

*The phase calibration module usage is not mandatory once TuLIPSS is deployed in the field

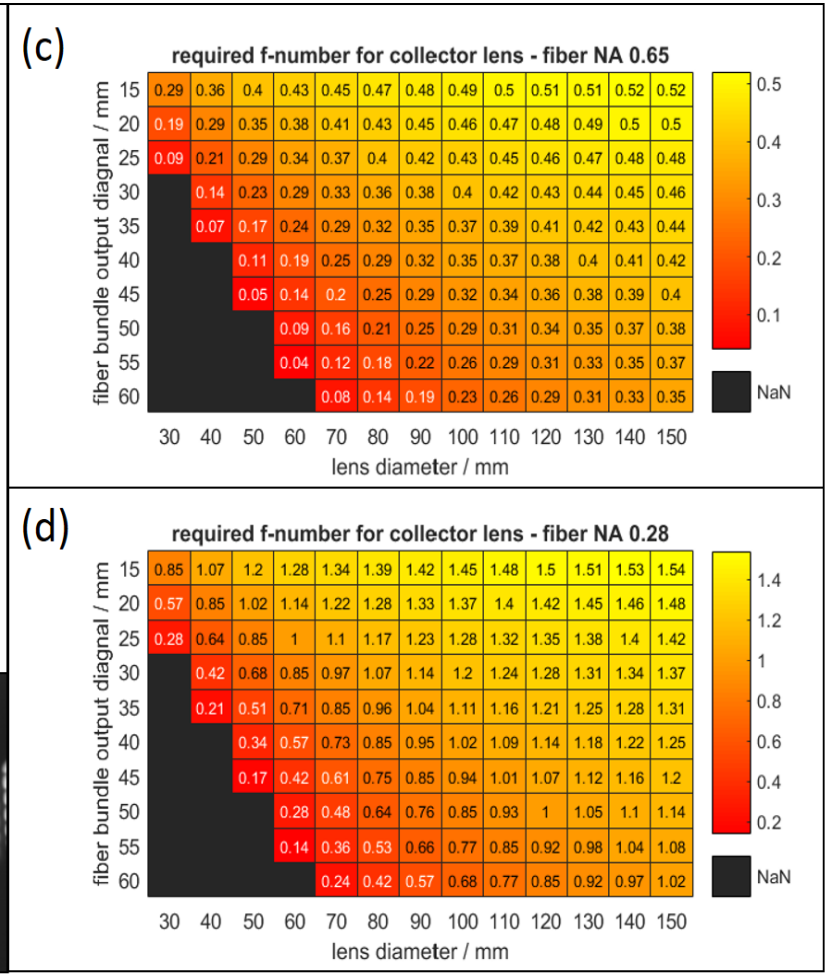
** The actuator that compresses/decompresses the fiber ribbons

*** The Double-Amici is an example in general goal is to keep axis

# FIBER BUNDLE

# Static System – Optical System Operational Space

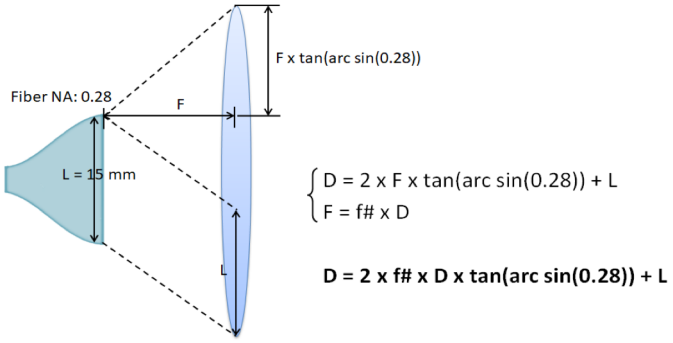


# Solutions to maximize light collection

- Lower NA of the fiber
- Small outer diameter fiber
- Lenslets at fiber tips

TuLIPSS system lens requirements for 0.28 NA




D = 2 x F x tan(arc sin(0.28)) + L
F = f# x D

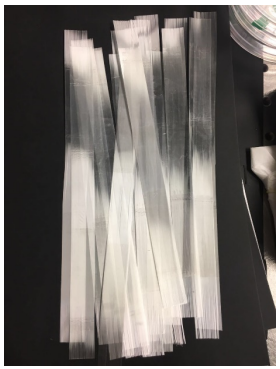
**D = 2 x f# x D x tan(arc sin(0.28)) + L**

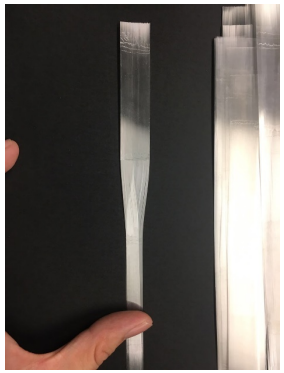
- 0% loss:

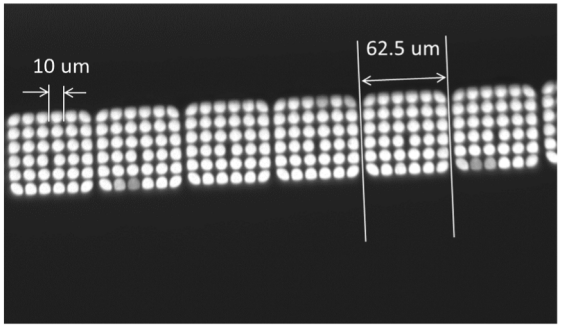
| D | F |
|---|---|
| 30 mm | 26mm |
| 50 mm | 60mm |
| 80 mm | 112mm |
| 100 mm | 145mm |

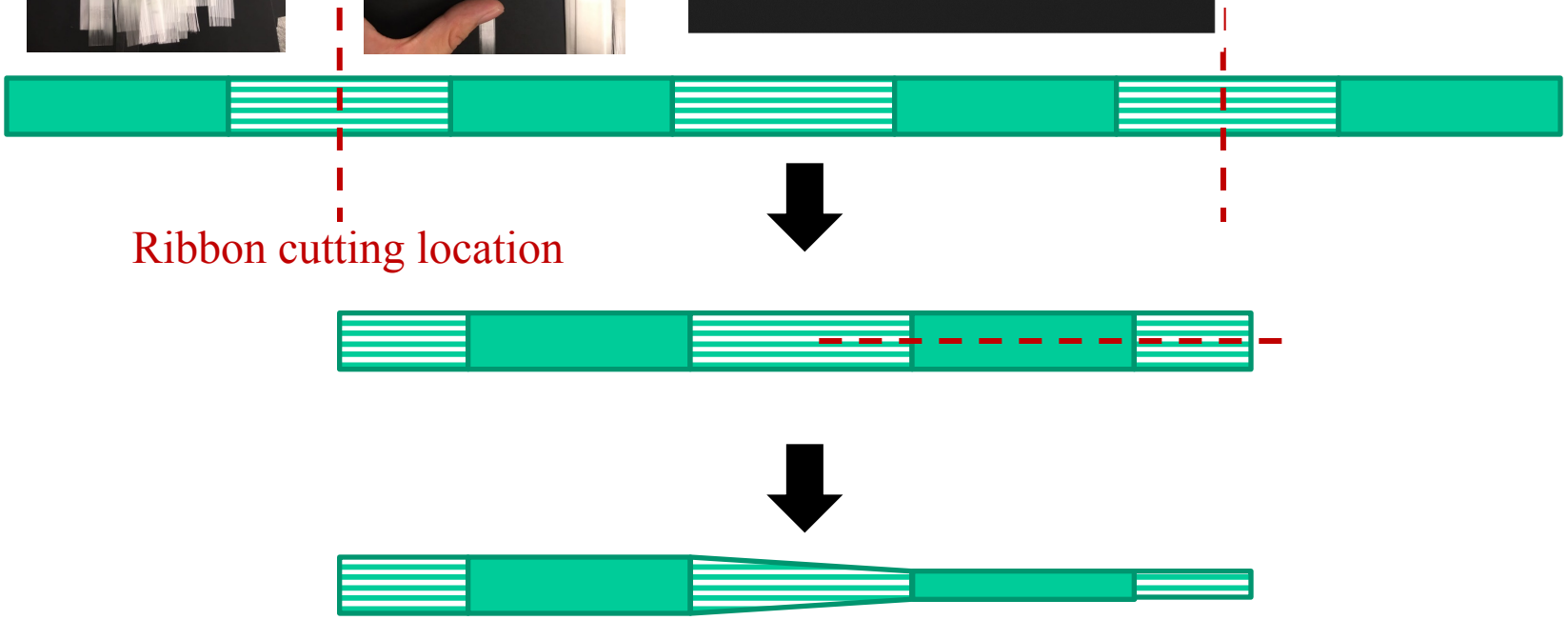
200 x 200 x 30
L = 15 mm

# Cutting and assembling procedure

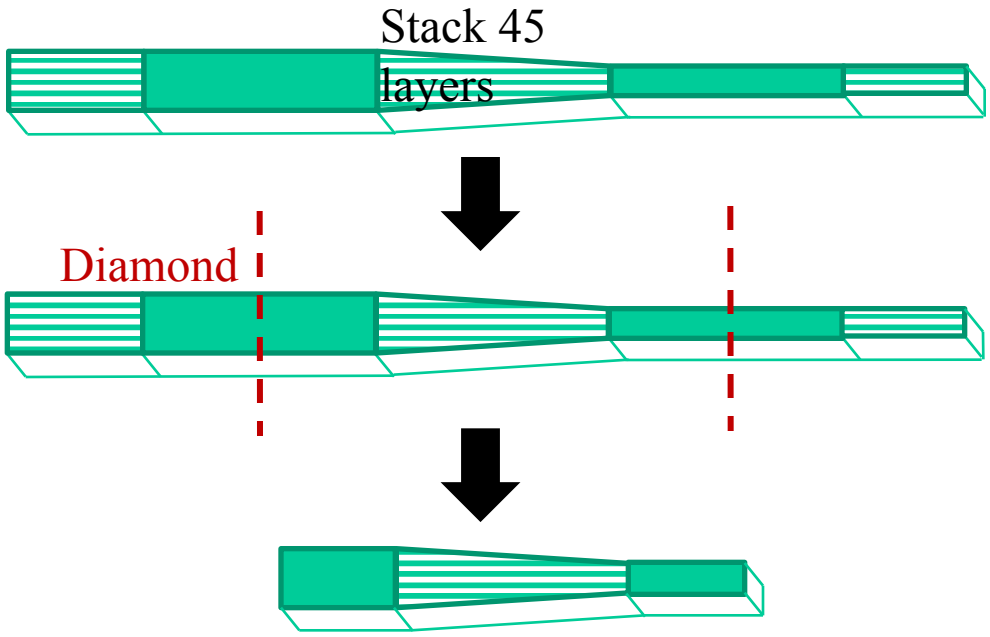




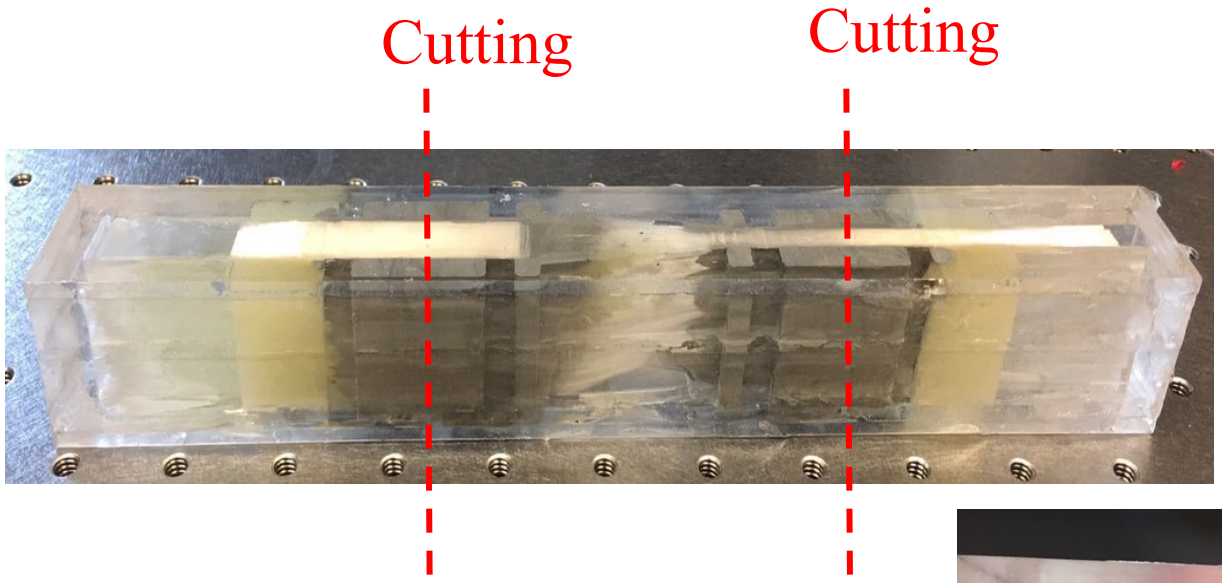


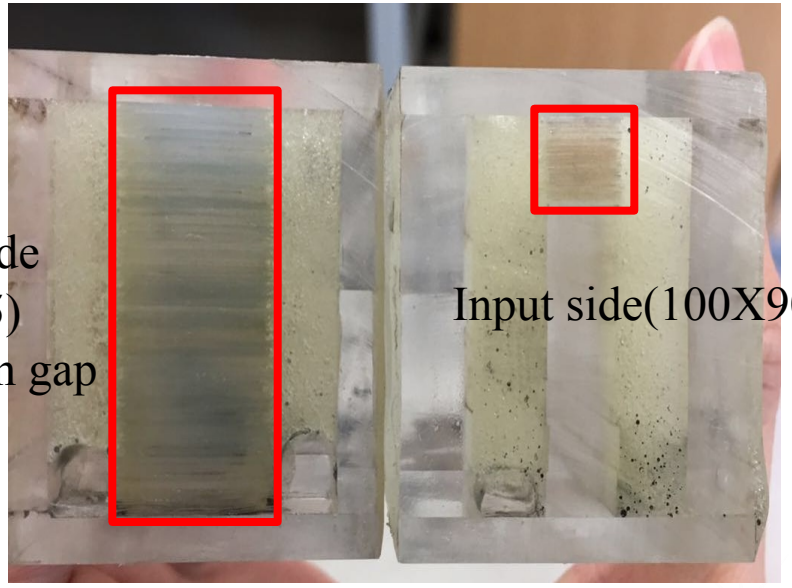
# Cutting and assembling procedure



# Assembled fiber bundle before cutting




Output side
(200X45)
with ~400um gap



RICE

Cutting

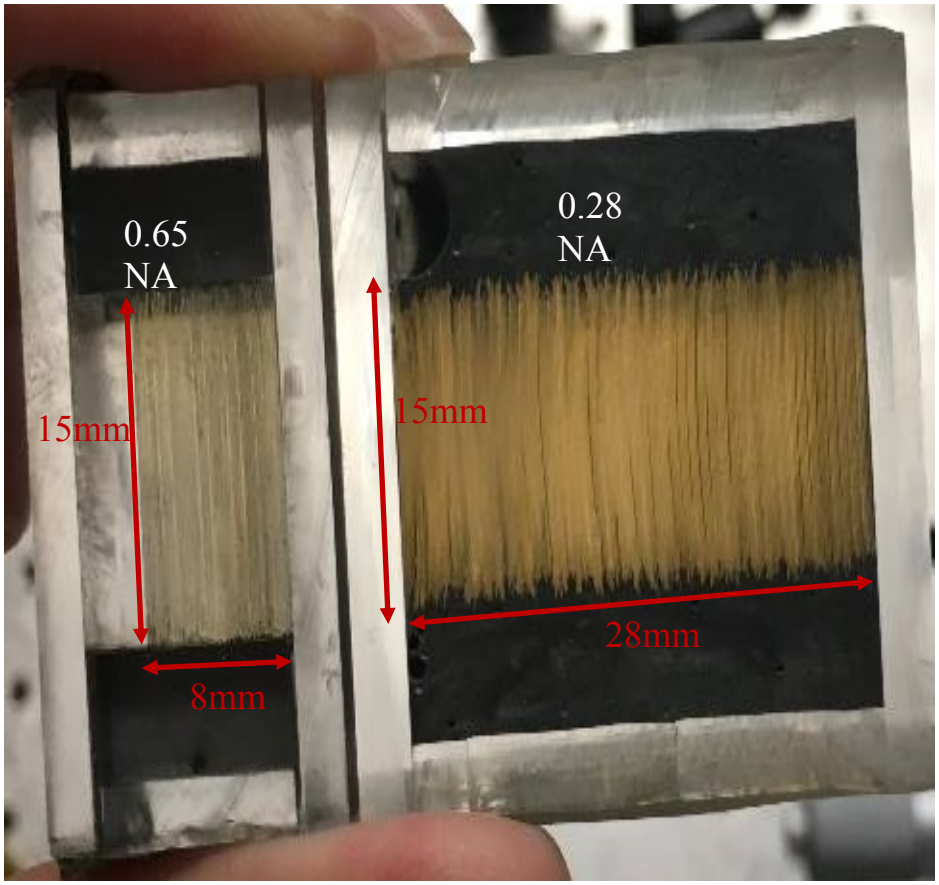
Fiber bundle

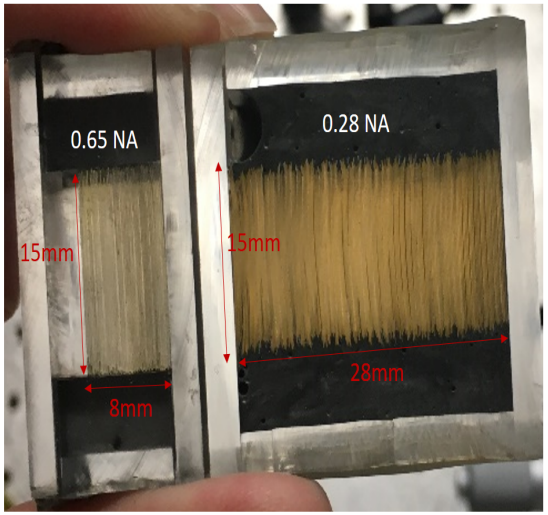
Polishing

Fiber bundle

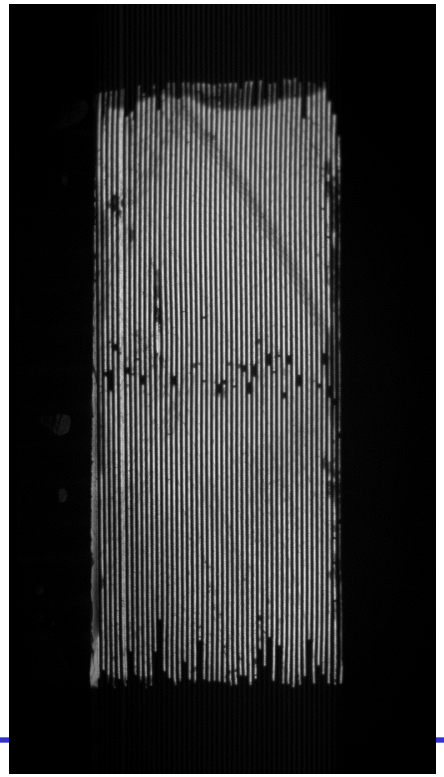
# Throughput Uniformity Comparison: 0.28 NA vs 0.65 NA

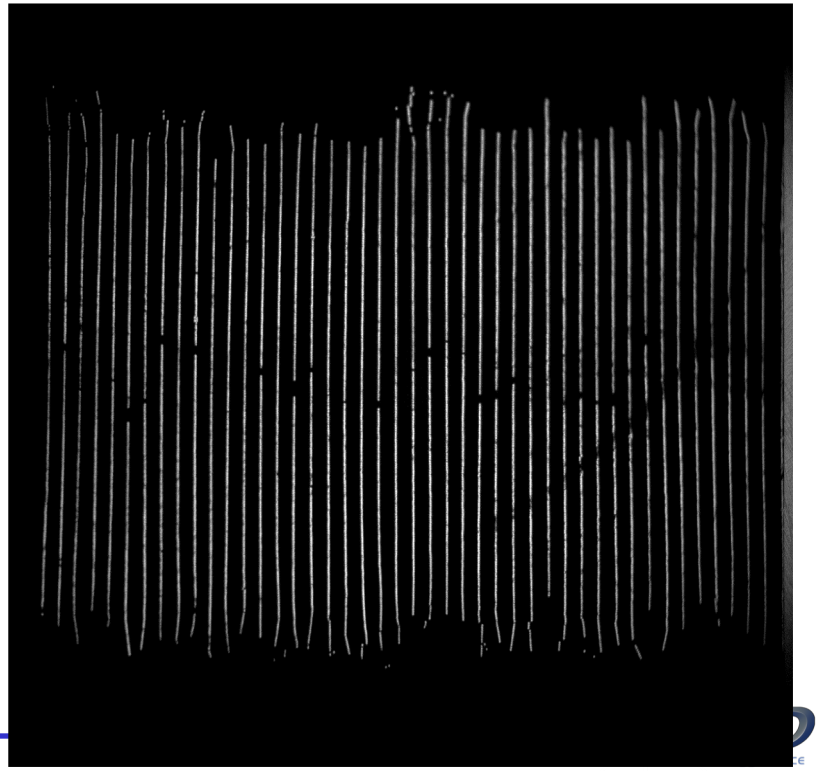
# 0.65 NA and 0.28 NA fiber bundle



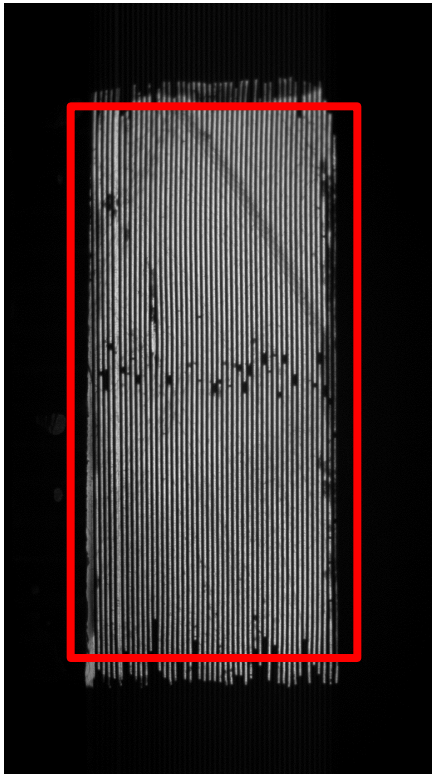


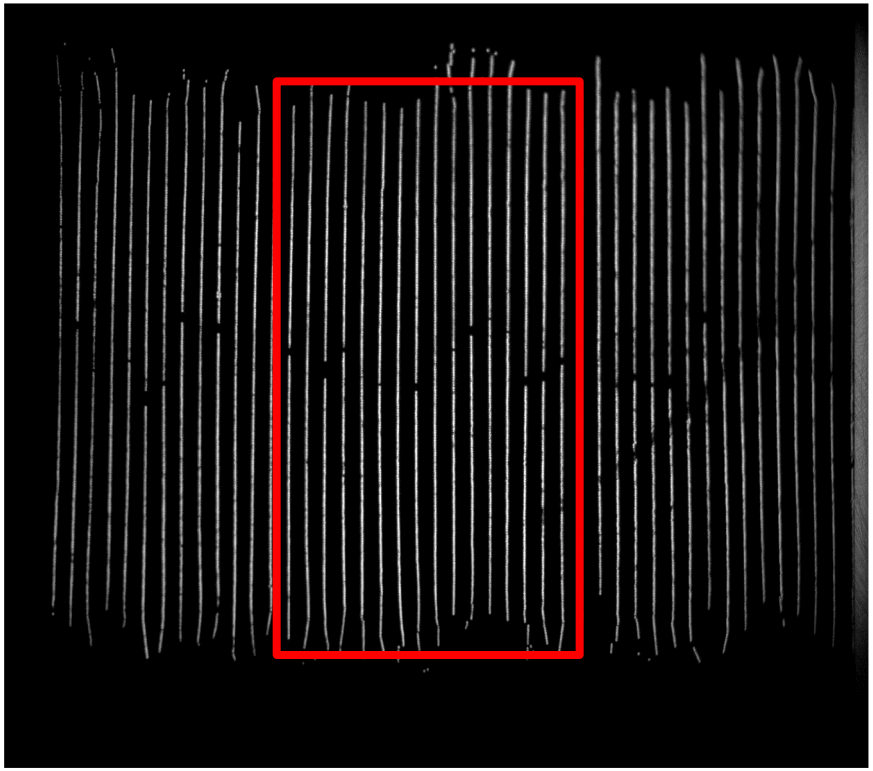

# Raw images



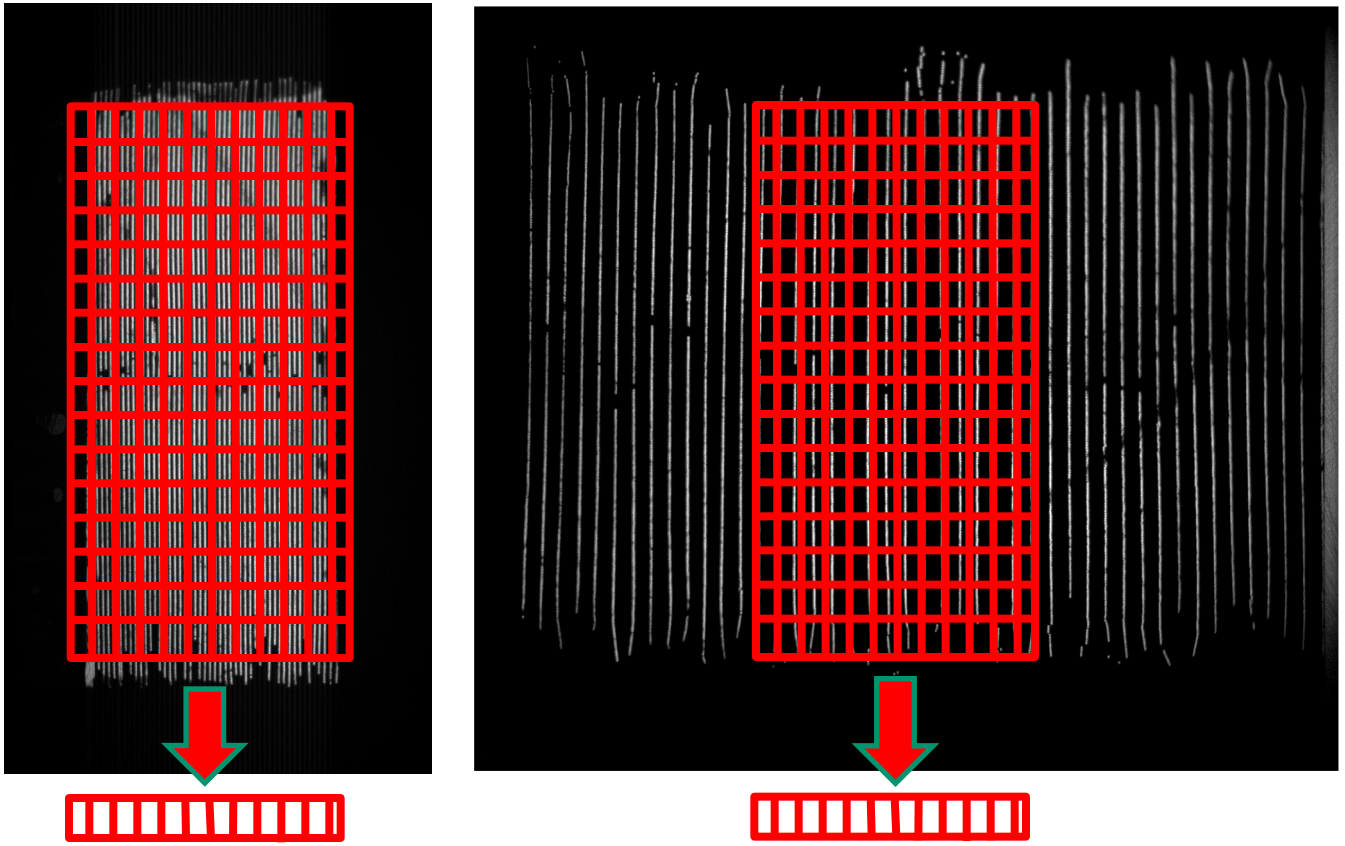


# Same field compared



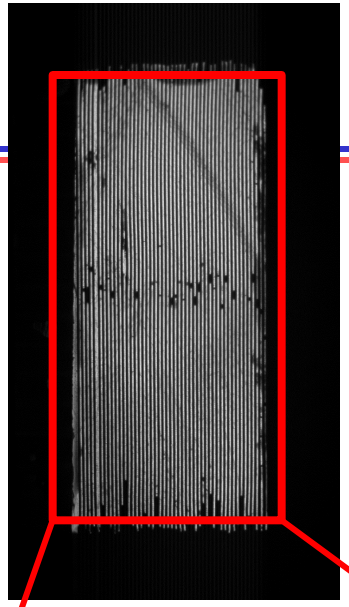


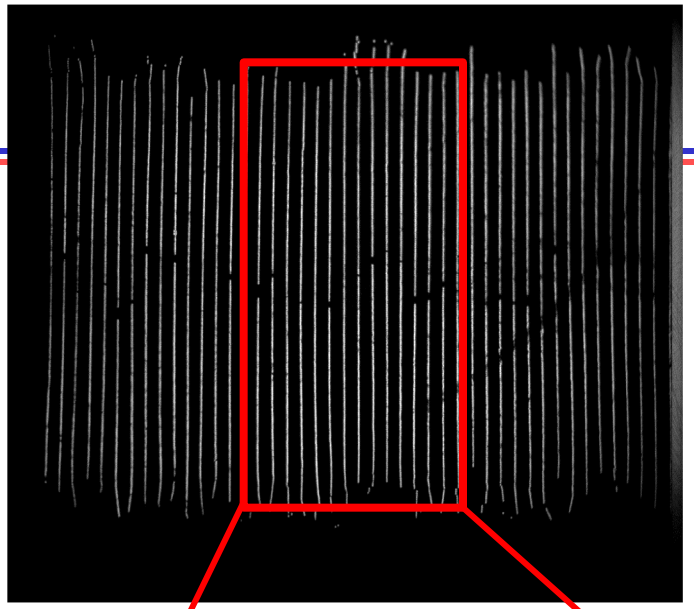
# Same field compared



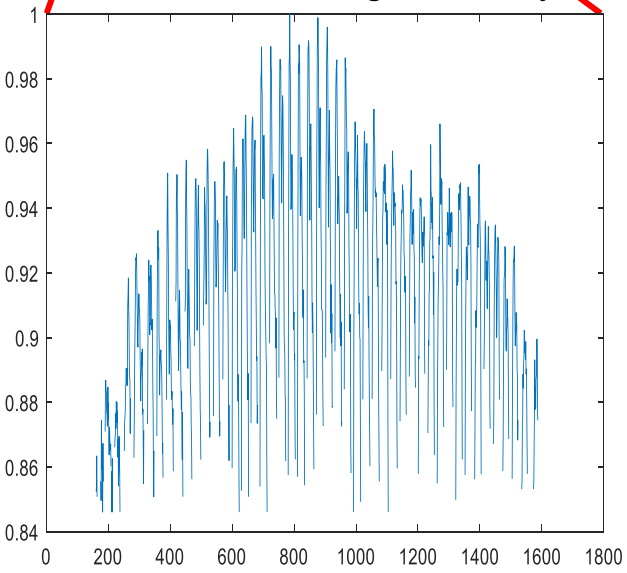
Column-wise average

Column-wise average

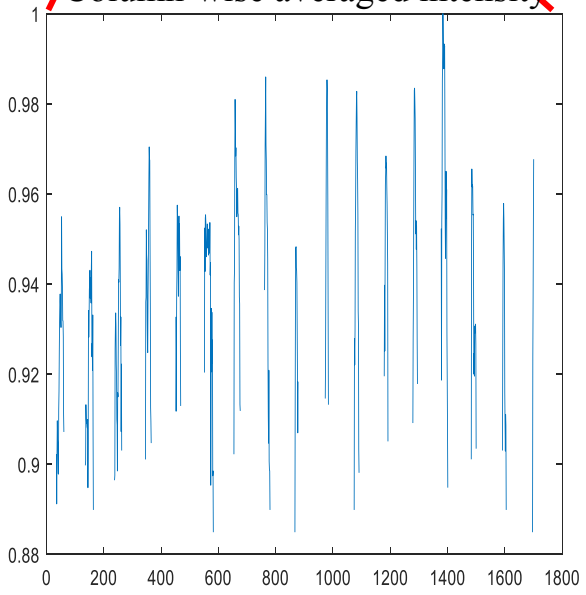




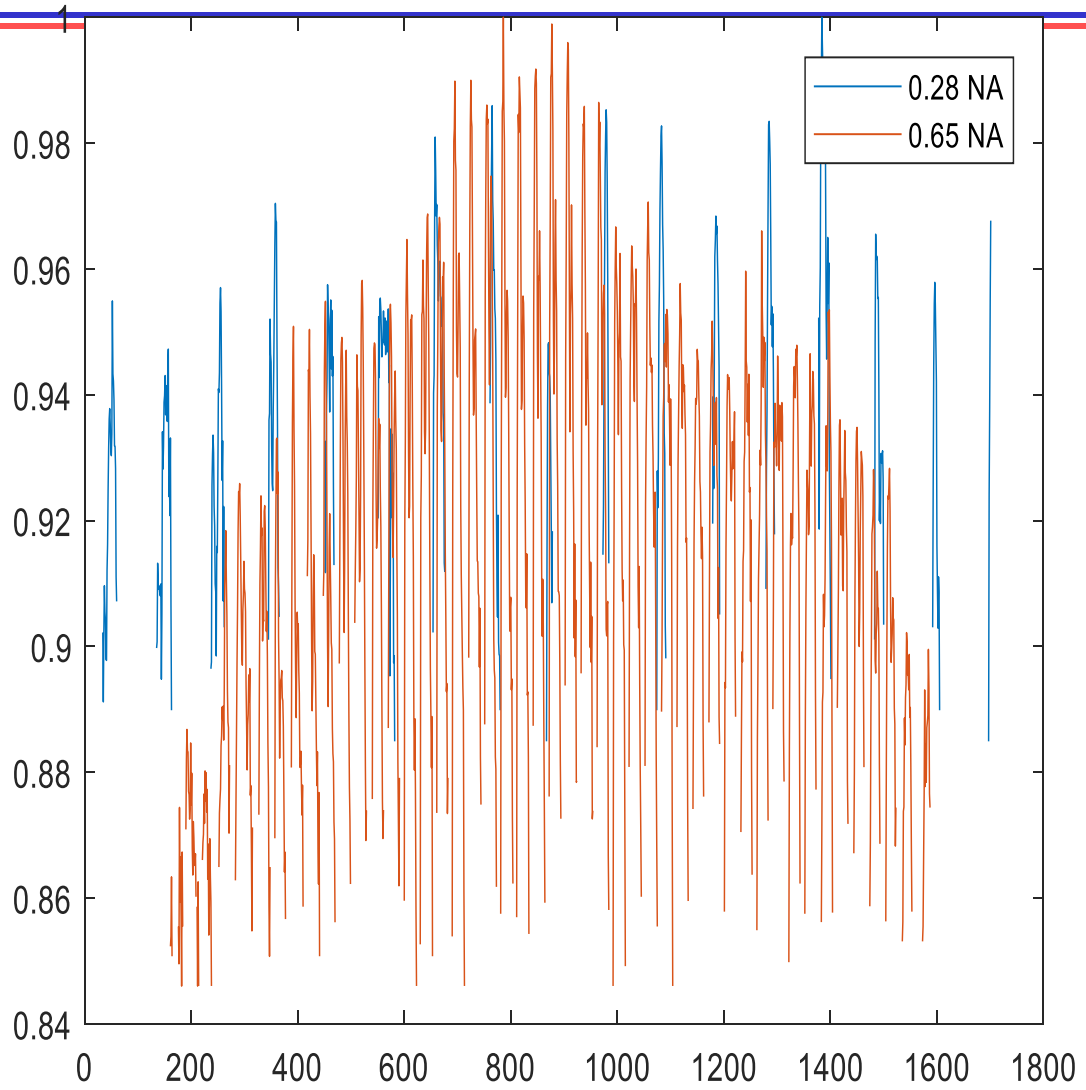
Column-wise averaged intensity




Column-wise averaged intensity



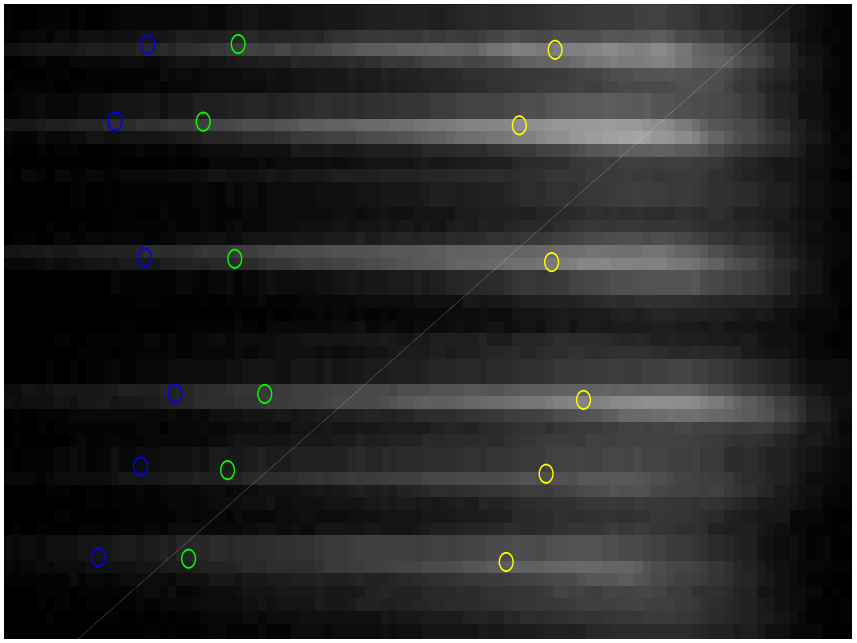
# Low NA show more uniform values across FOV



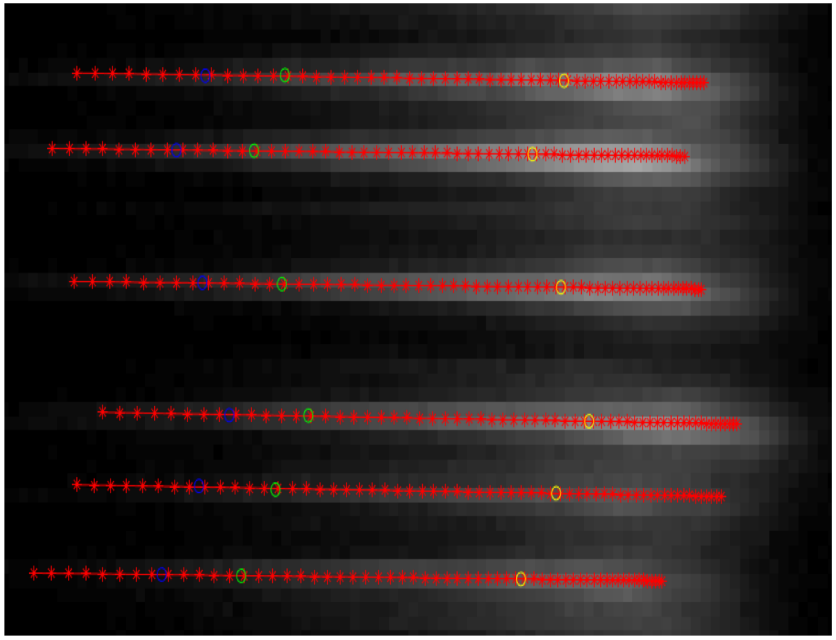
# CALIBRATION ALGORITHM

# Spectral calibration procedure

Step 1: Locate 3 single wavelengths using 1-nm filters: 488nm, 514nm, 633nm



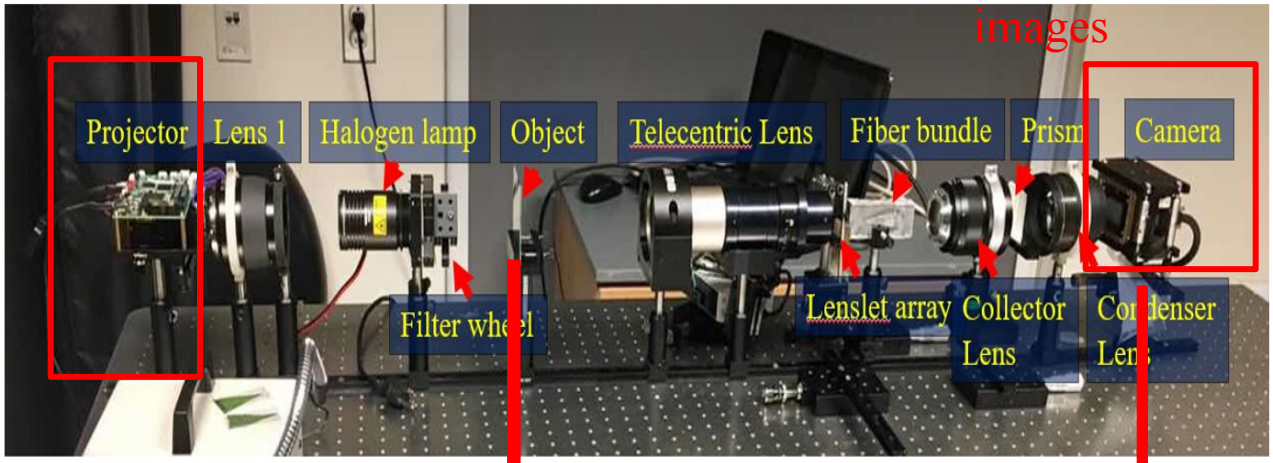
Step 2: second-order polynomial interpolation for 450nm – 750nm

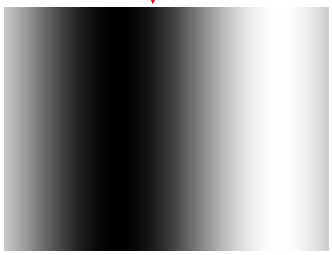


# Spatial calibration: setup

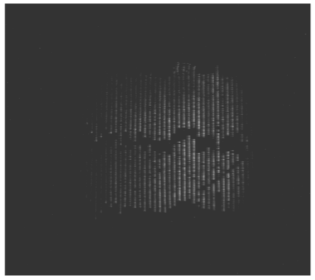
Projector: Project sinusoidal patterns

Camera: takes raw images



Sinusoidal patterns

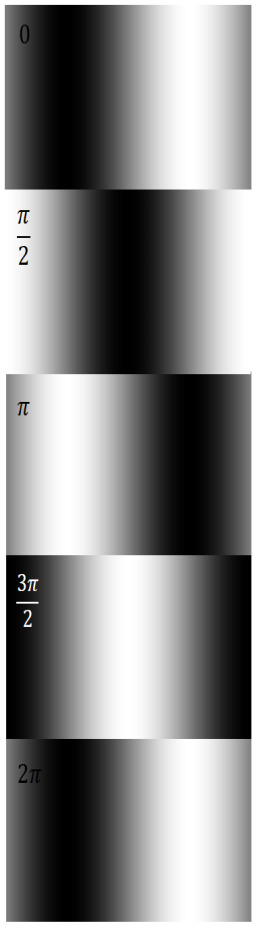


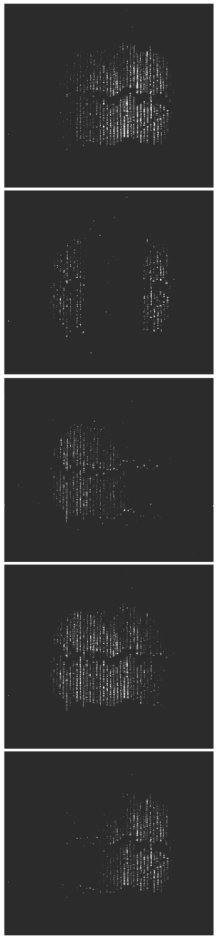
Raw images

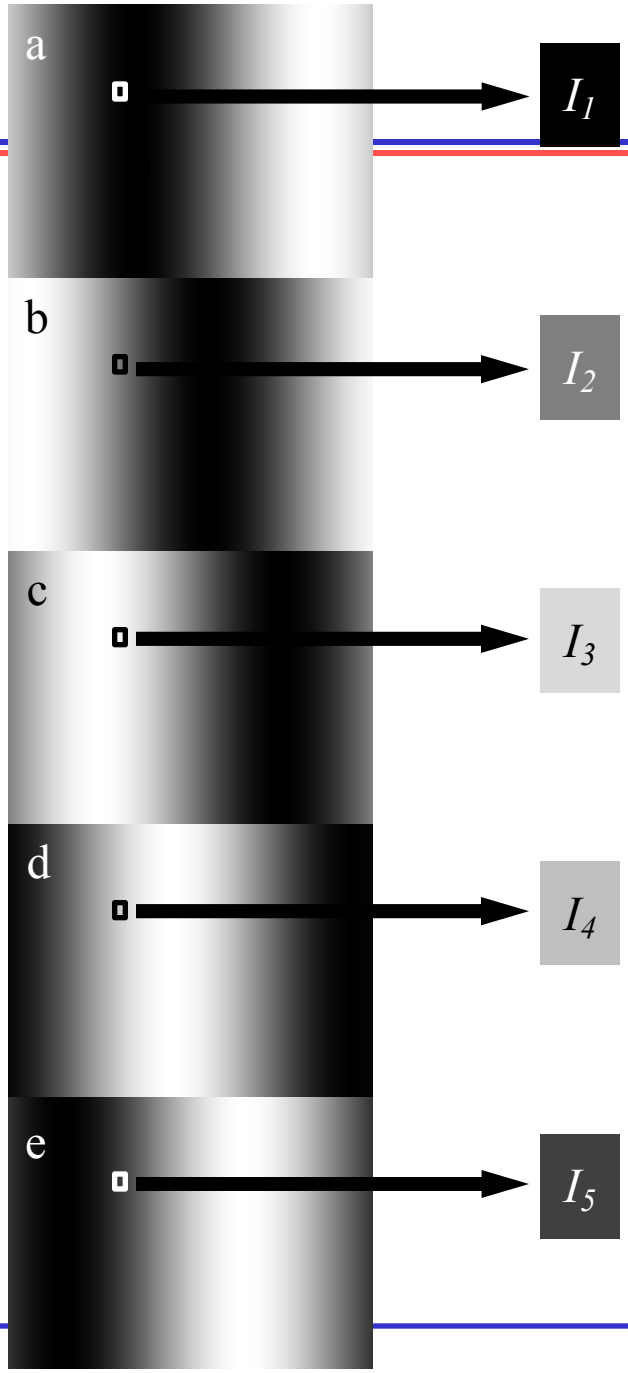
# Spatial calibration: principle

sinusoidal patterns

raw images



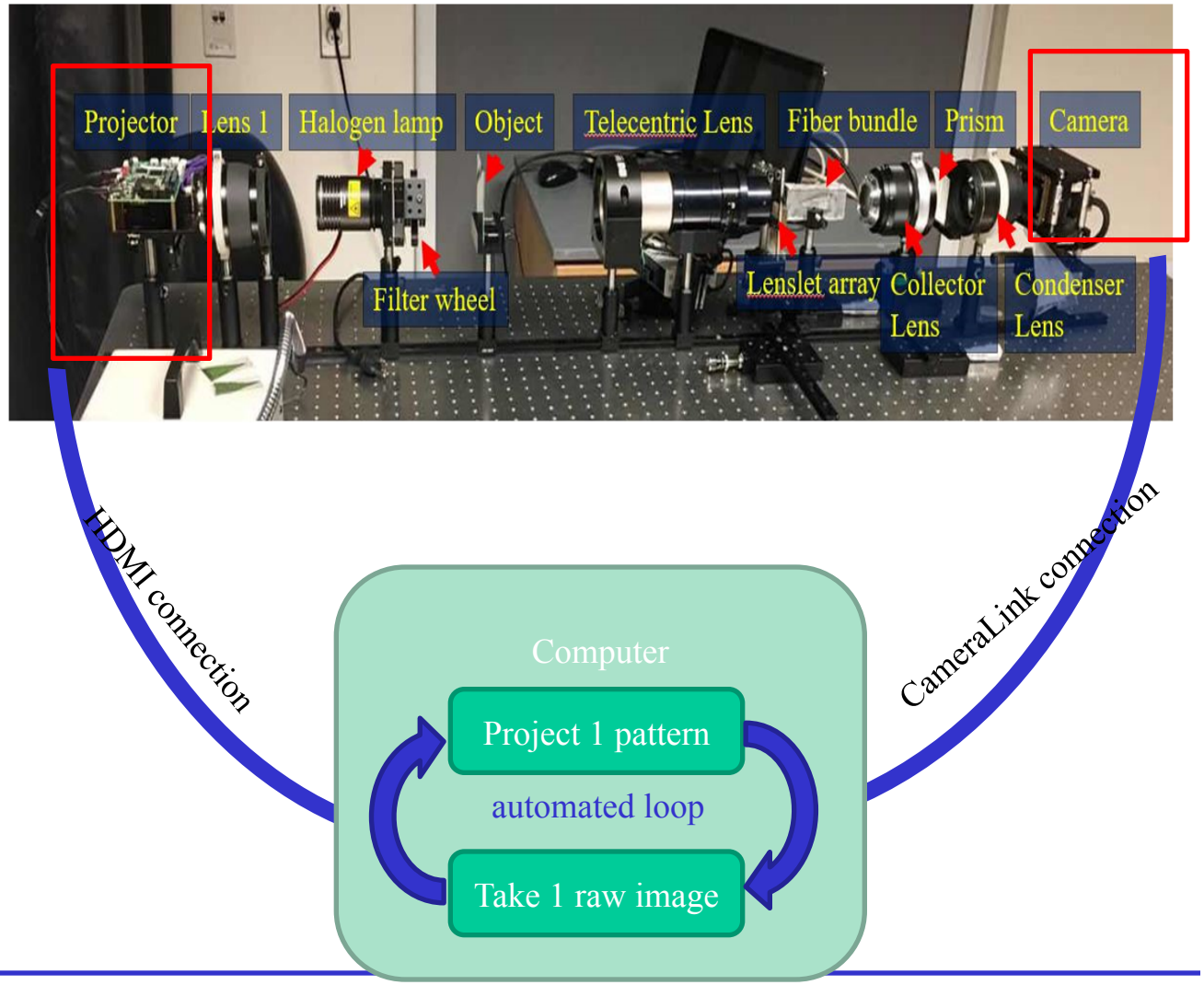






$$\tan x = \frac{2(I_4 - I_2)}{I_1 - 2I_3 + I_5}$$

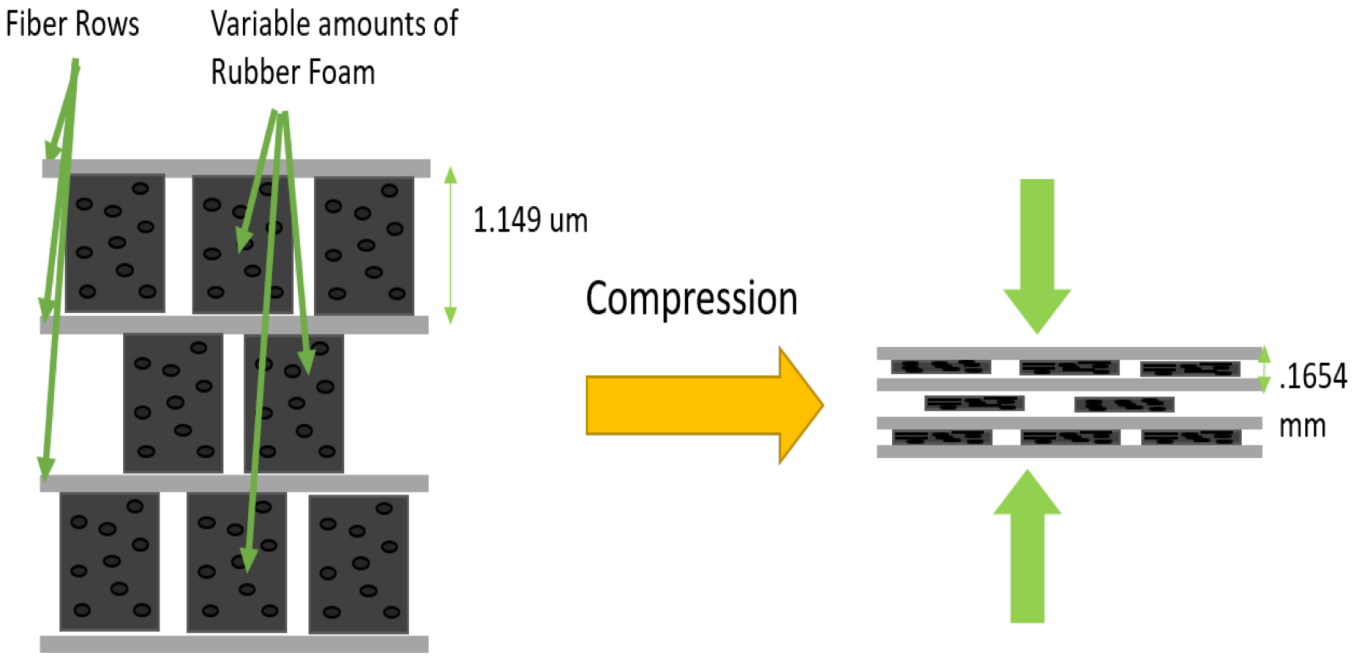
Spatial coordinate

# Spatial calibration: control and automation

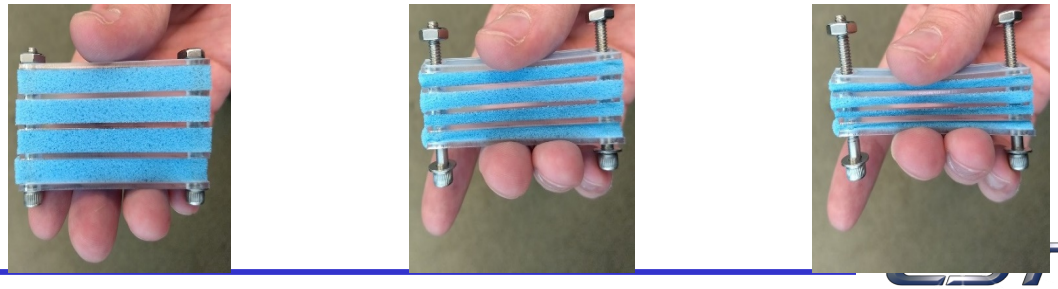


# FIBER BUNDLE TUNING AND CYCLE TESTING

# Foam sheet tuning




## Foam test



# Materials Used for Tunable Fiber Bundle

Two classes of compressible materials that can be introduced between fiber ribbons were tested in the lab

1. Rubbers - PDMS (prepared in the lab)
   - limited compressibility
   - bulging at extremities – obstruction of fibers' output
2. Polyurethanes (foams)
   - Cost-effective, off the shelf material - PORON™ produced by Rogers Corporation
   - Excellent compression results after thousands of compression cycles

# Characteristics of Roger's Co. PORON™ material

## PORON foam official specifications

| FLAMMABILITY AND OUTGASSING | | | |
|---|---|---|---|
| Flammability | UL 94HBF (File E20305) (Pass ≥)<br>MVSS 302 (Pass ≥)<br>CSA Comp HBF (File 188149) (Pass ≥) | -<br>-<br>- | |
| Fogging | SAE J-1756 3 hrs @ 100°C (212°F) | Pass | |
| Outgassing, Total Mass Loss (TML) % | ASTM E 595-93 24 hrs @ 125°C (257°F) @ <7kPa (1.02 psi) | 1.0 | 1.3 |
| Outgassing, Collected Volatile Condensable Materials (CVCM) % | | 0.1 | 0.2 |
| Outgassing, Water Vapor Regain (WVR) % | | 0.3 | 0.6 |

Required specifications

ref: https://www.sspinc.com/silicones_that_work/Outgassing-EMI-Silicones-and-ASTM-E595-07-_83-blog.htm

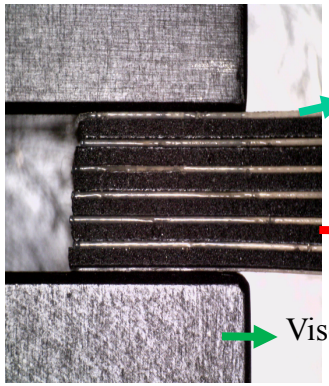
### ATSM E595-07 and SSP-502-65

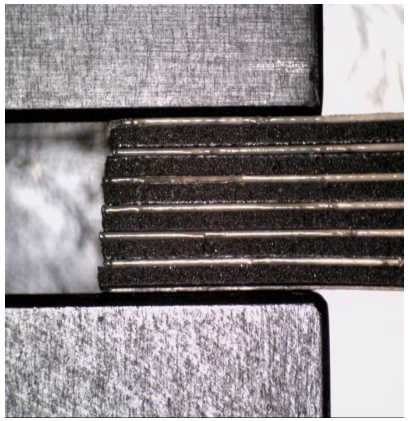
ASTM E595-07 defines testing procedures for evaluating changes in material mass caused by outgassing in high-vacuum environments. In addition to total mass loss (TML), this specification from ASTM International measures collected volatile condensable materials (CVCM). An additional test, for water vapor recovered (WVR), can be performed after TML and CVCM measurements are obtained. Note that NASA's goal for acceptable TML is less than 1%. For CVCM, the space agency's target is less than 0.1%.

# Validation experiments for compressible material

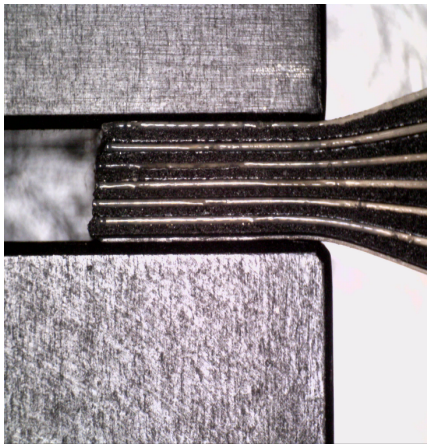
Preliminary testing – experiment 1

- PORON™ foam and transparent plastic layers were laser cut and placed in a translation stage used as vise

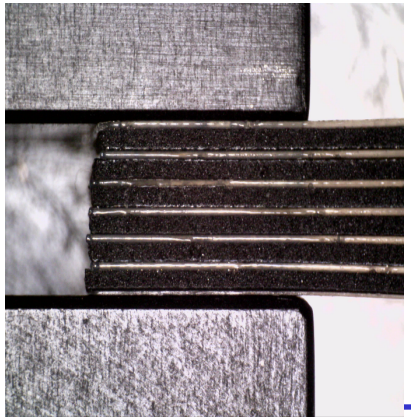


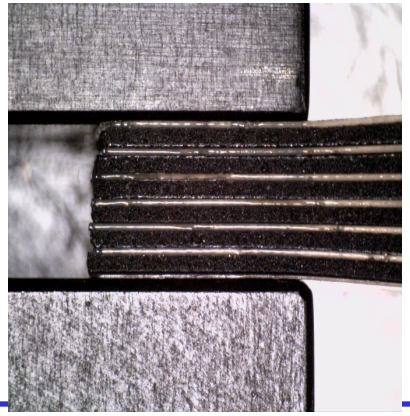
decompression



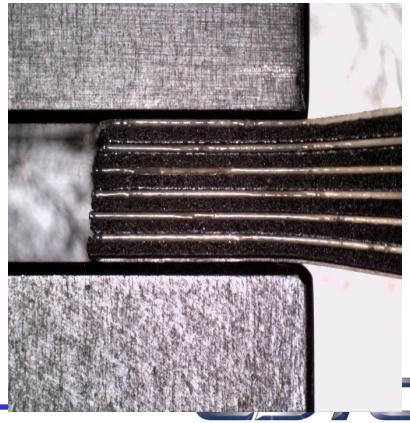
compression



compression



compression



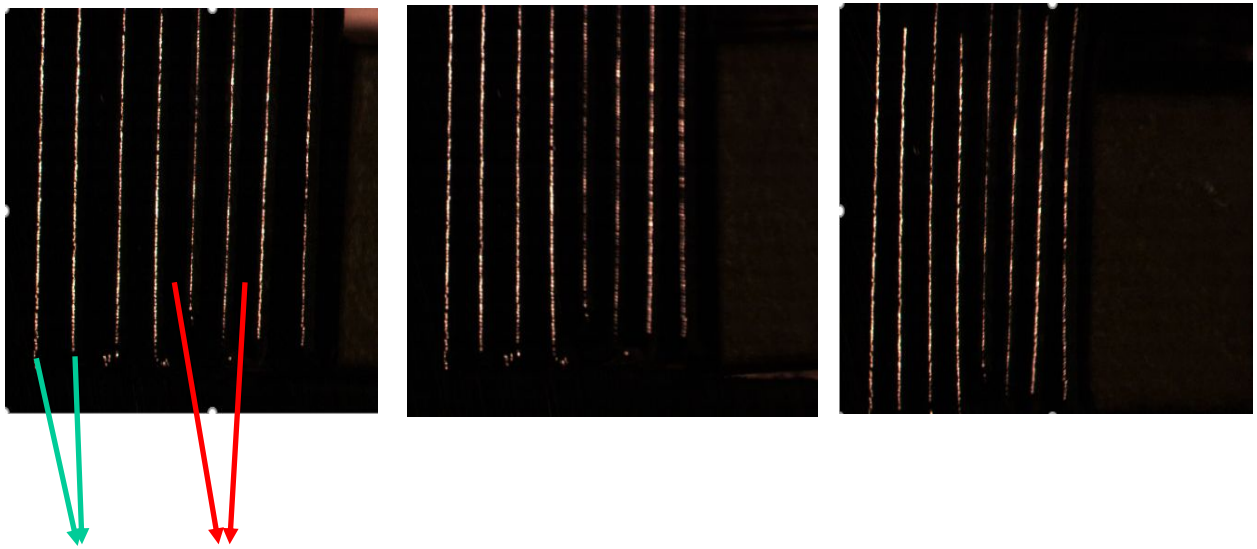
Earth Science Technology Office

# Validation experiments for compressible material

Preliminary testing – Experiment 2

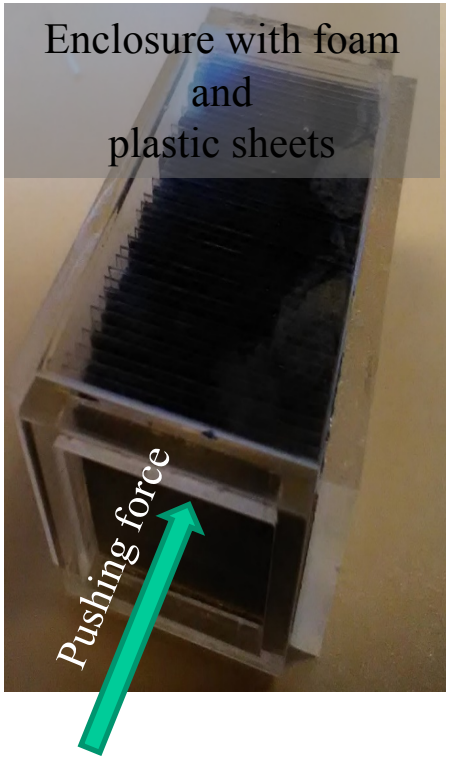
Simple compression test featuring PORON foam and illuminated fiber bundles

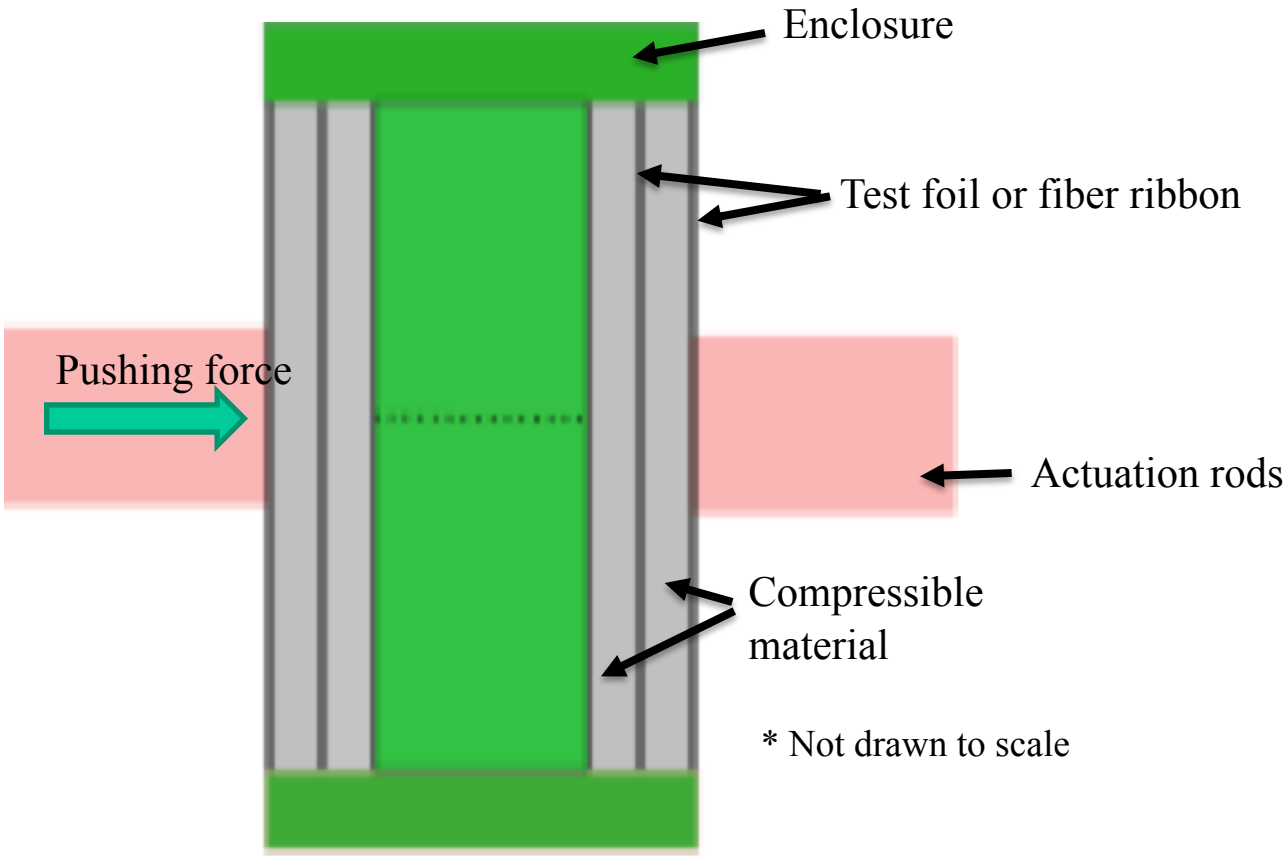
Video frame snapshots for different compressions of PORON foam



# Tunable Fiber Bundle Design

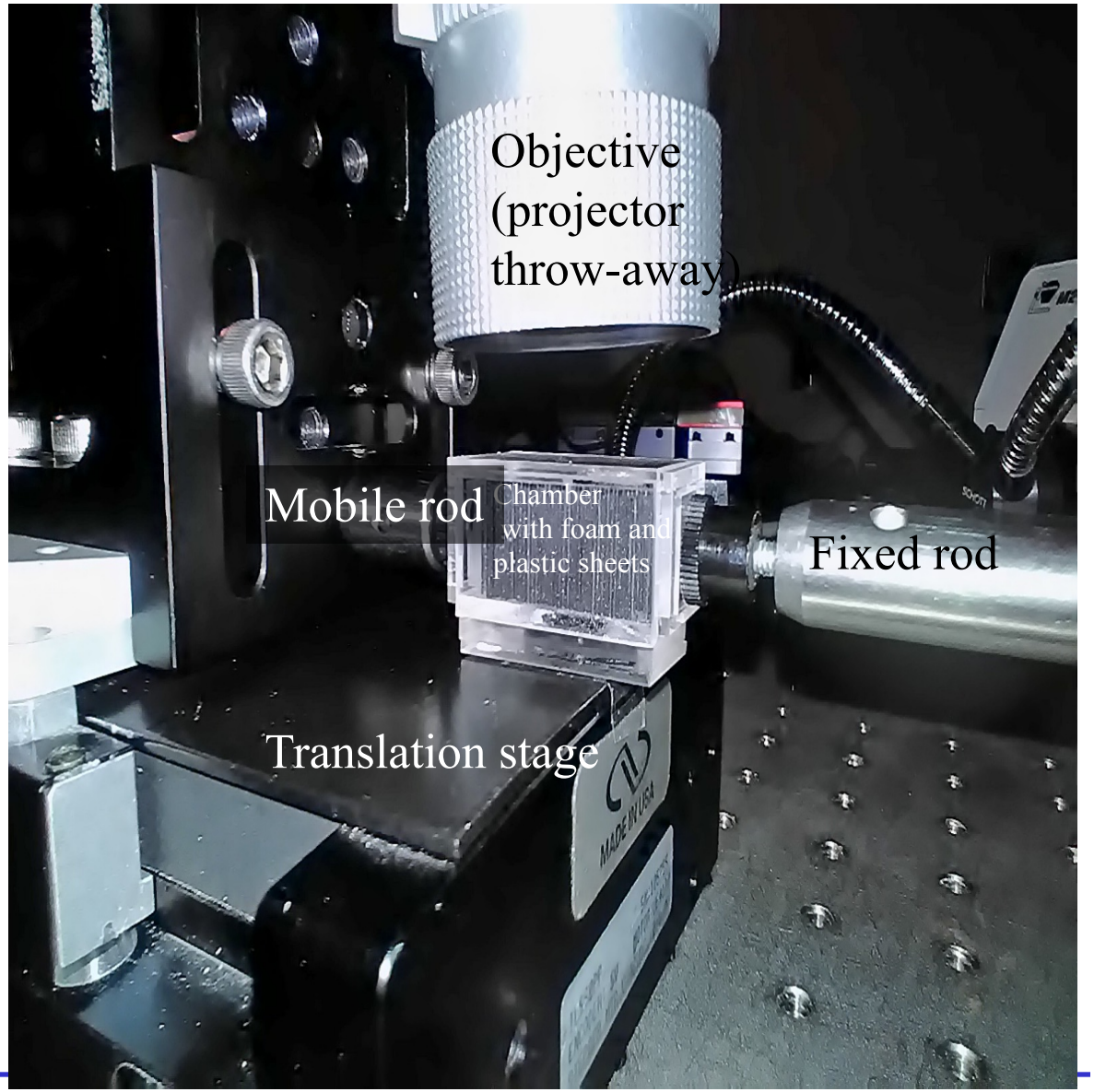
Basic principle of tunable fiber bundle/
Concept used for validation of material that could be used in the tunable fiber bundle



# Validation experiment for compressible material

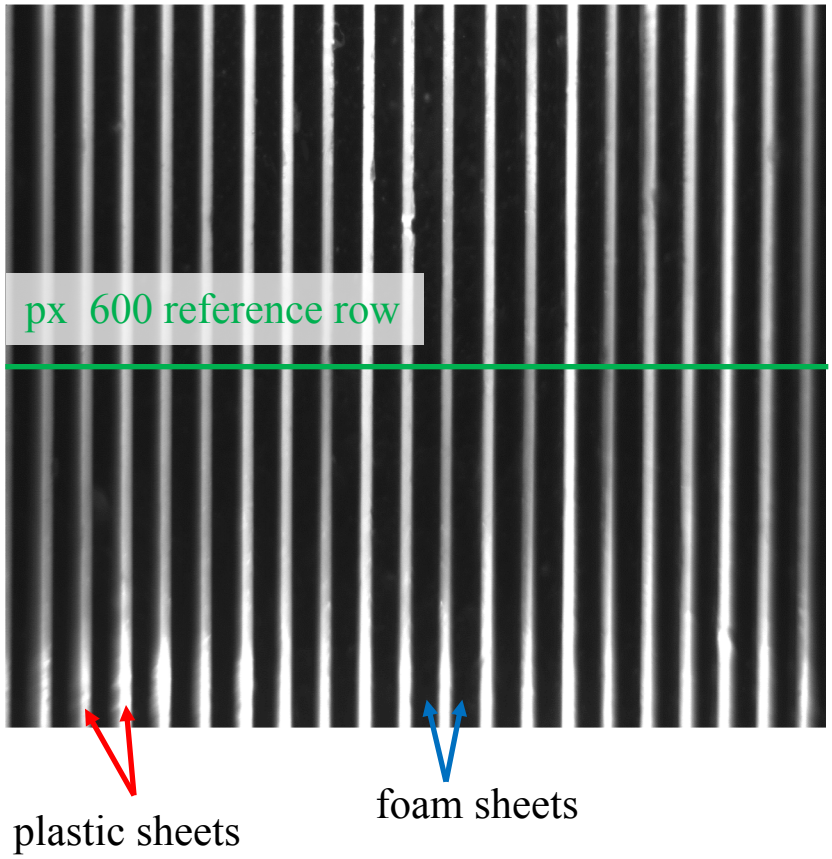
Close snapshot of the automated foam compressor

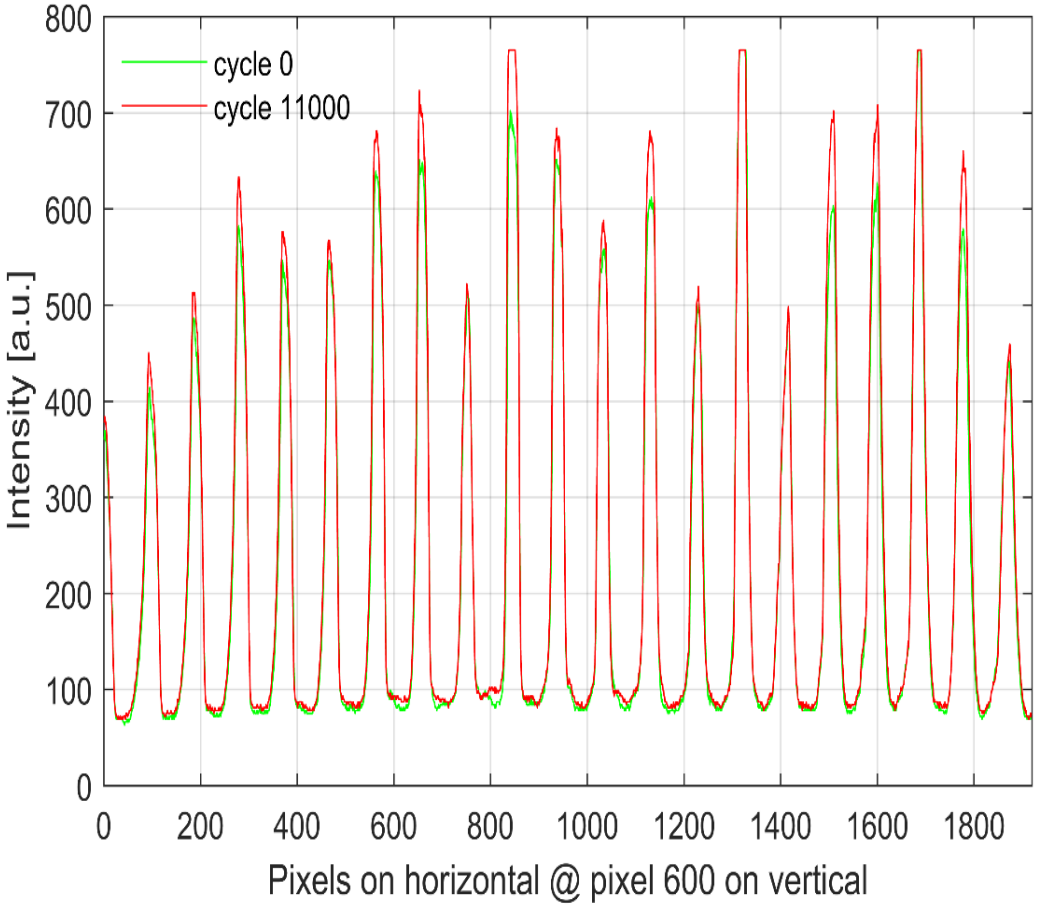


Real-time video of the compression sequence during validation experiment
More than 20,000 compression cycles were performed to test PORON's compression reliability

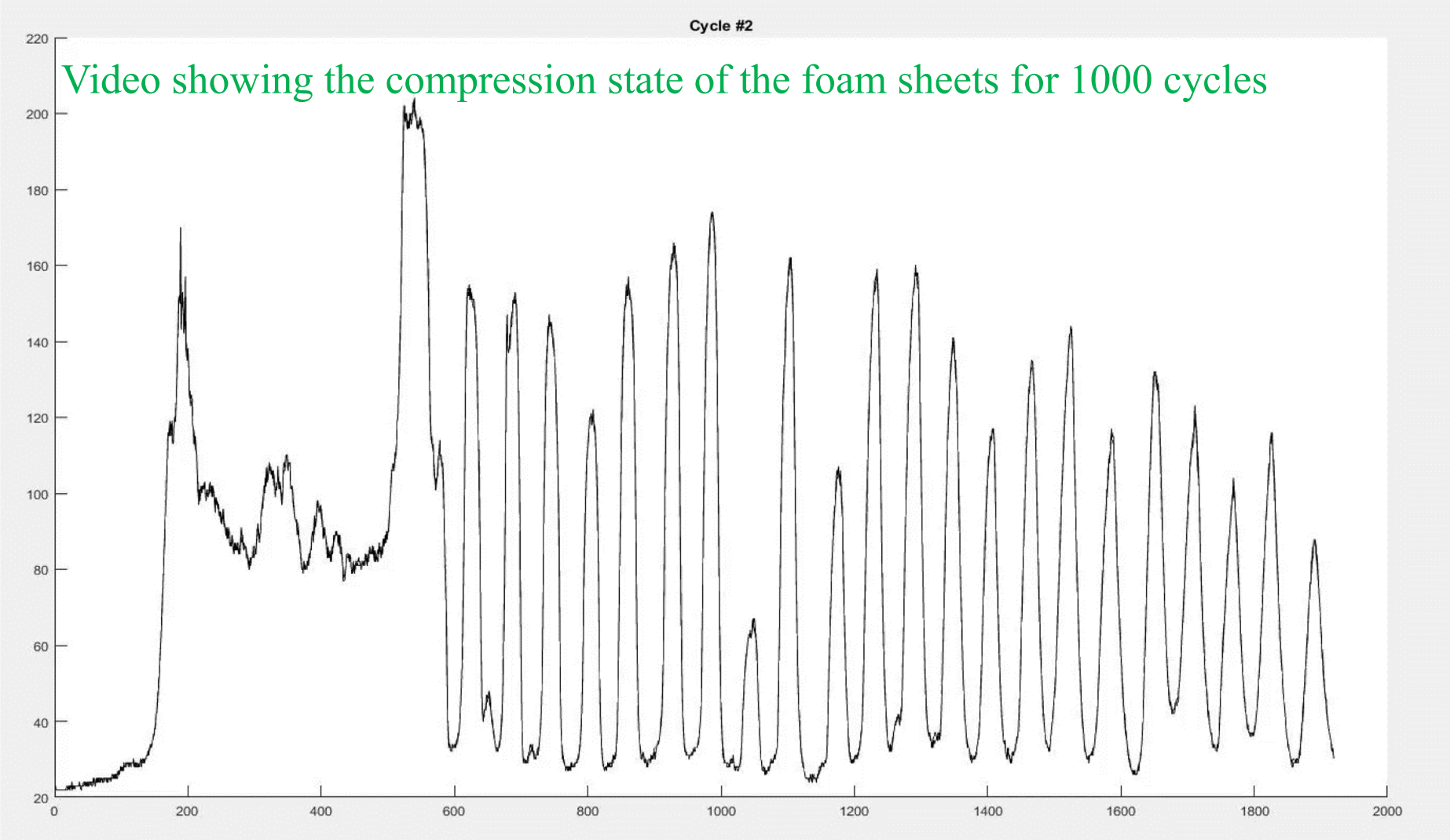
- Experiment 1 – match between individual foam sheets' baseline configuration thicknesses after more than 10000 compression cycles

Foam/plastic sheets image as recorded for



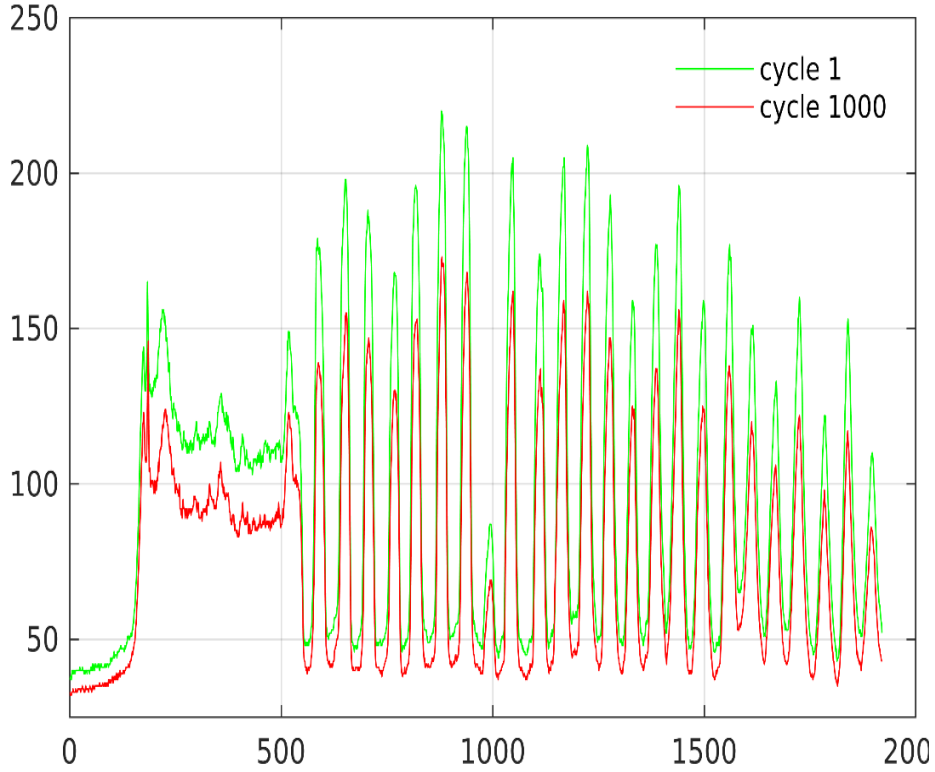



- Experiment 2 - match between individual foam sheets displacements after more than 20,000 compression cycles – compression state

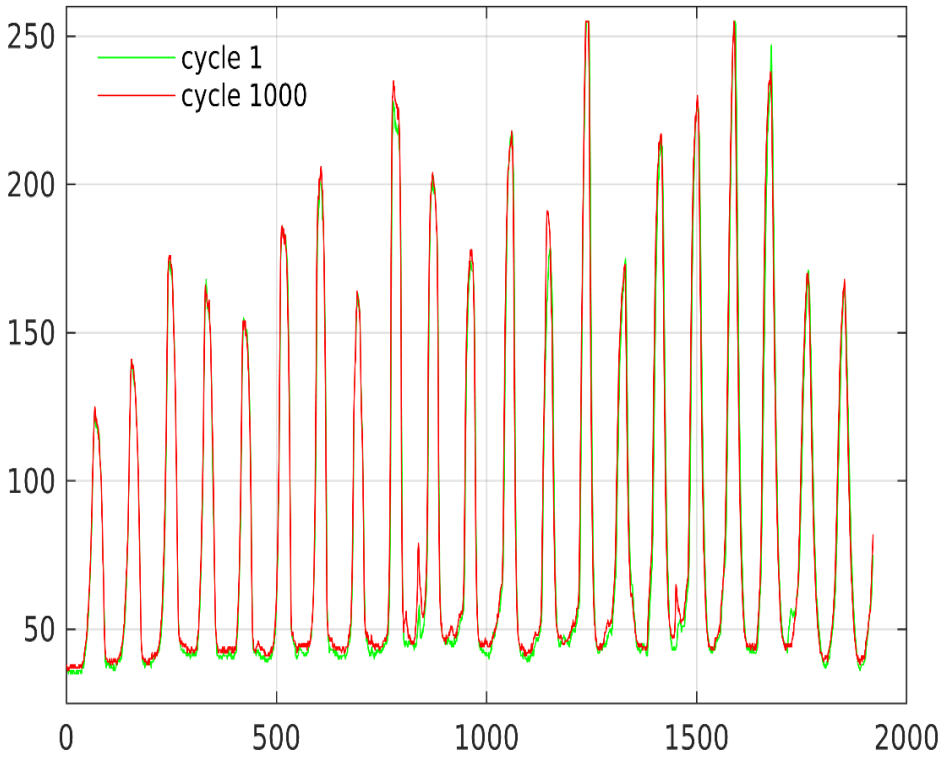


- Experiment 3 – Compression/Decompression plots show traces after more than 22,000 compression cycles
  - 1.8 seconds compression followed by 1.8 second decompression
  - Match between individual foam sheets displacements in their decompressed baseline configuration*

Compression plots at pixel 600 on vertical



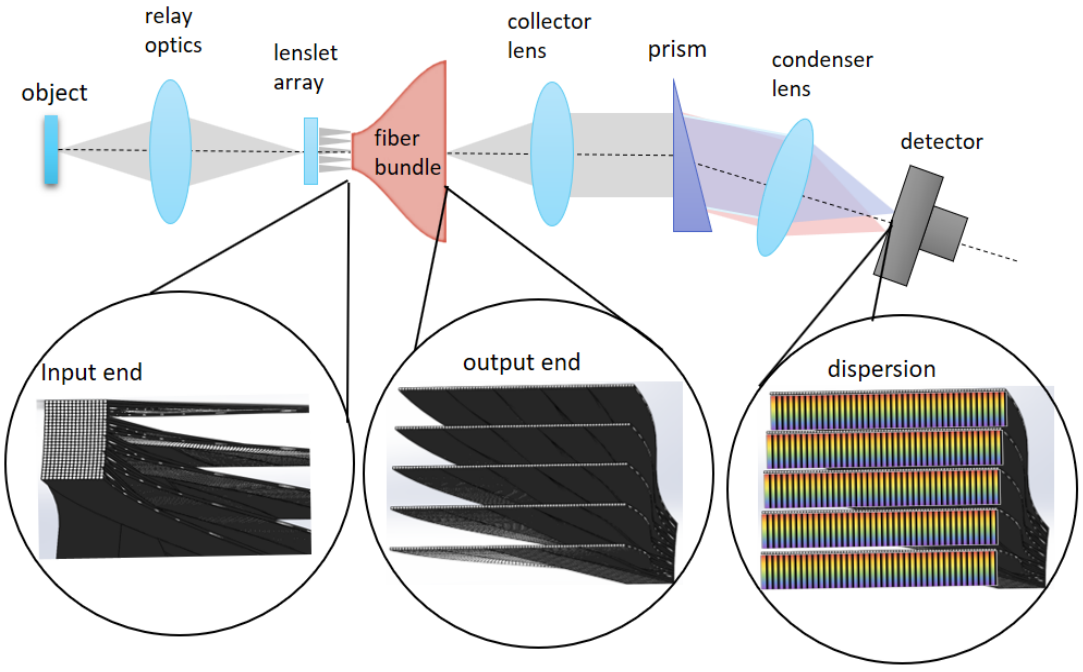

Decompression plots at pixel 600 on vertical

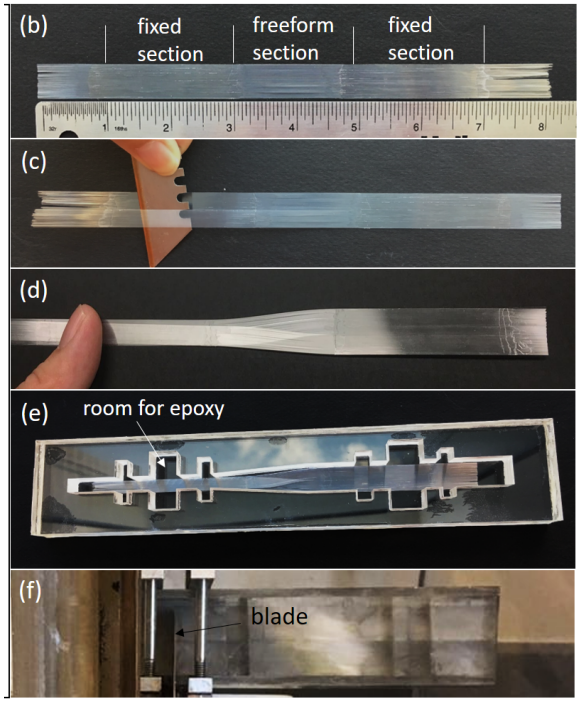



- Decompressed baseline configuration is defined as slightly compressed state of the foam. Also, a slight re-centering of the foam sheets inside the acrylic case was performed due to some mechanical friction during the compression from 11000th to 21000th compression cycles

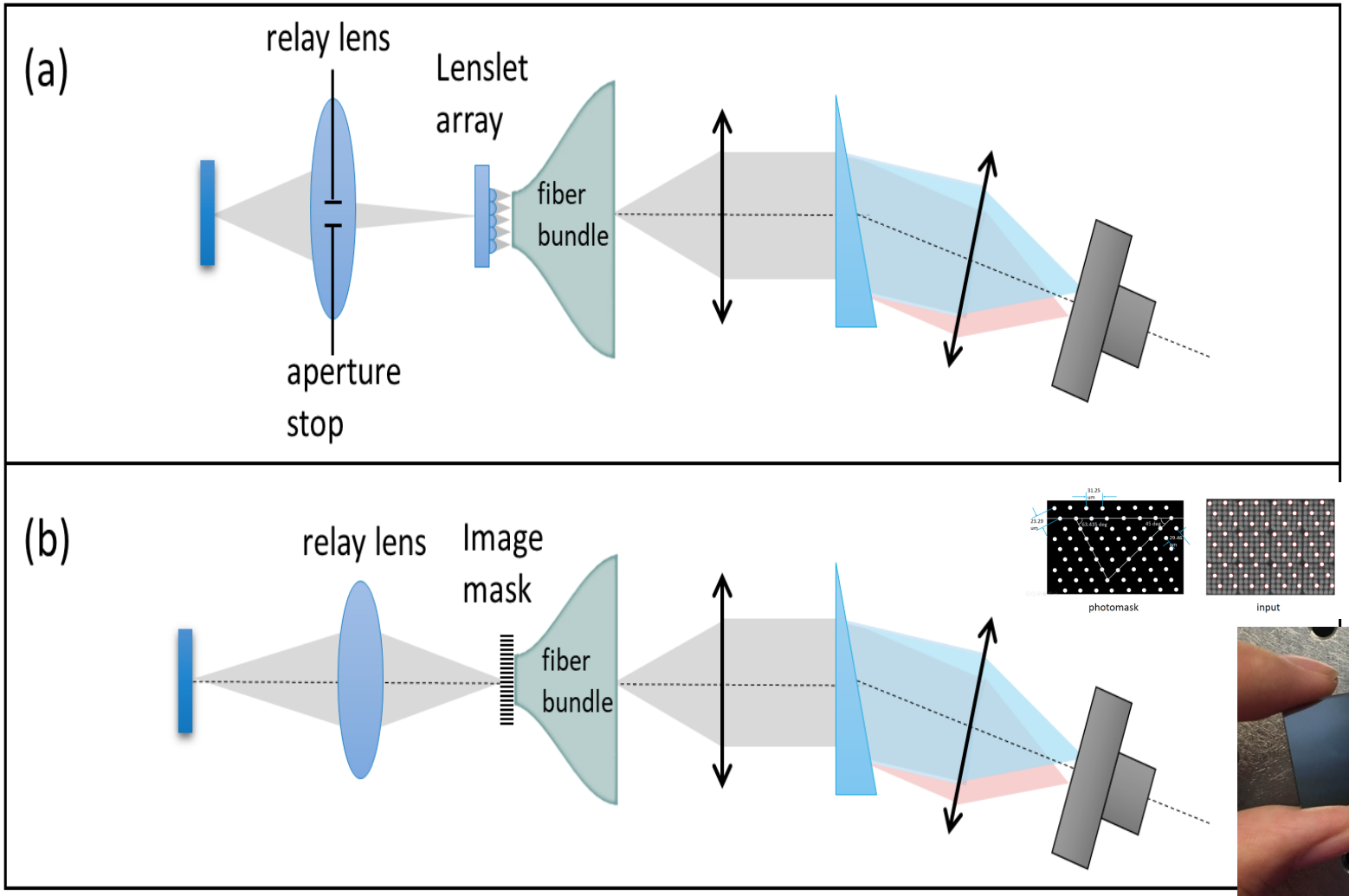
# IMAGING RESULTS WITH STATIC TULIPSS PROTOTYPE

# Principle and fabrication



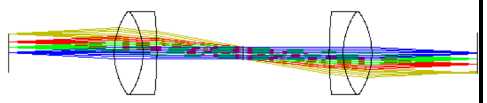



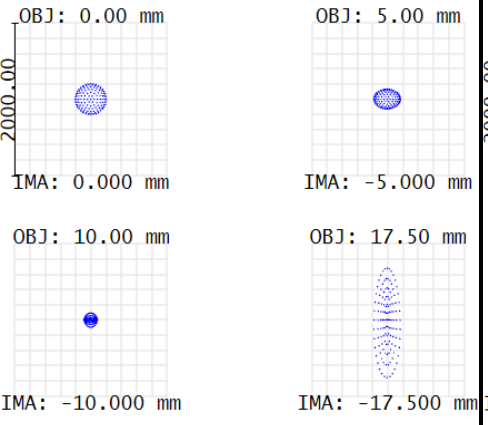
# Lenslet vs Mask Options



# Zemax simulations

(a)



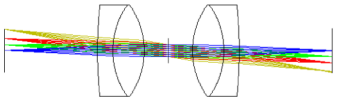


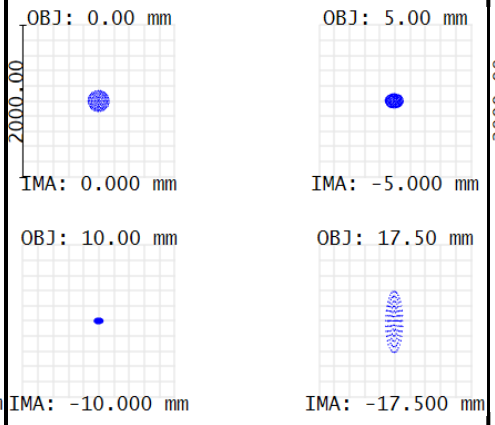

Units are µm.

| Field | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| RMS radius | 168.408 | 130.605 | 68.712 | 381.110 |
| GEO radius | 203.754 | 174.070 | 96.995 | 756.808 |

Scale bar : 2000 Reference : Chief Ray

(b)



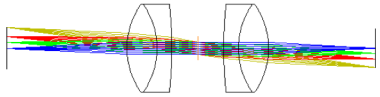


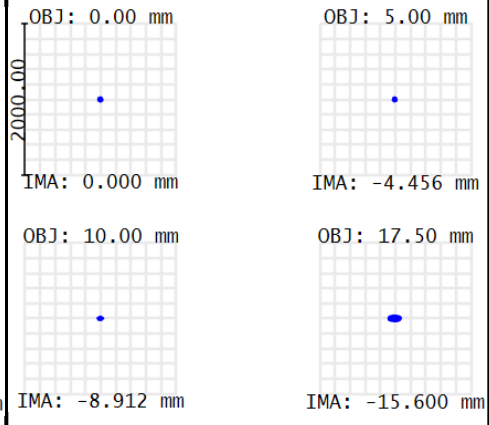

Units are µm.

| Field | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| RMS radius | 104.339 | 81.149 | 36.239 | 222.688 |
| GEO radius | 135.453 | 115.733 | 56.290 | 415.223 |

Scale bar : 2000 Reference : Chief Ray

(c)



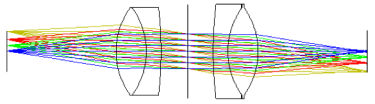


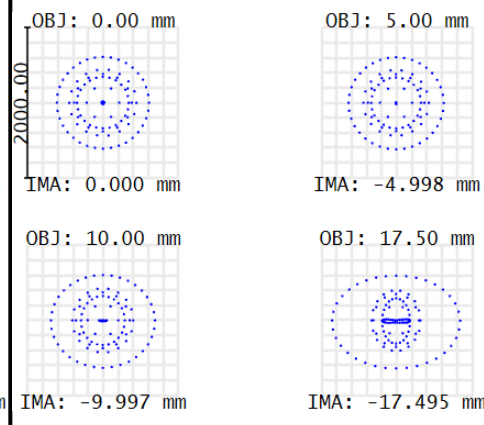

Units are µm. Legend items refer to wavelengths

| Field | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| RMS radius | 17.756 | 16.623 | 17.036 | 35.891 |
| GEO radius | 25.640 | 24.409 | 33.321 | 80.490 |

Scale bar : 2000 Reference : Chief Ray

(d)






Units are µm.

| Field | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| RMS radius | 415.875 | 417.623 | 424.139 | 450.486 |
| GEO radius | 612.851 | 633.355 | 691.863 | 851.024 |

Scale bar : 2000 Reference : Chief Ray

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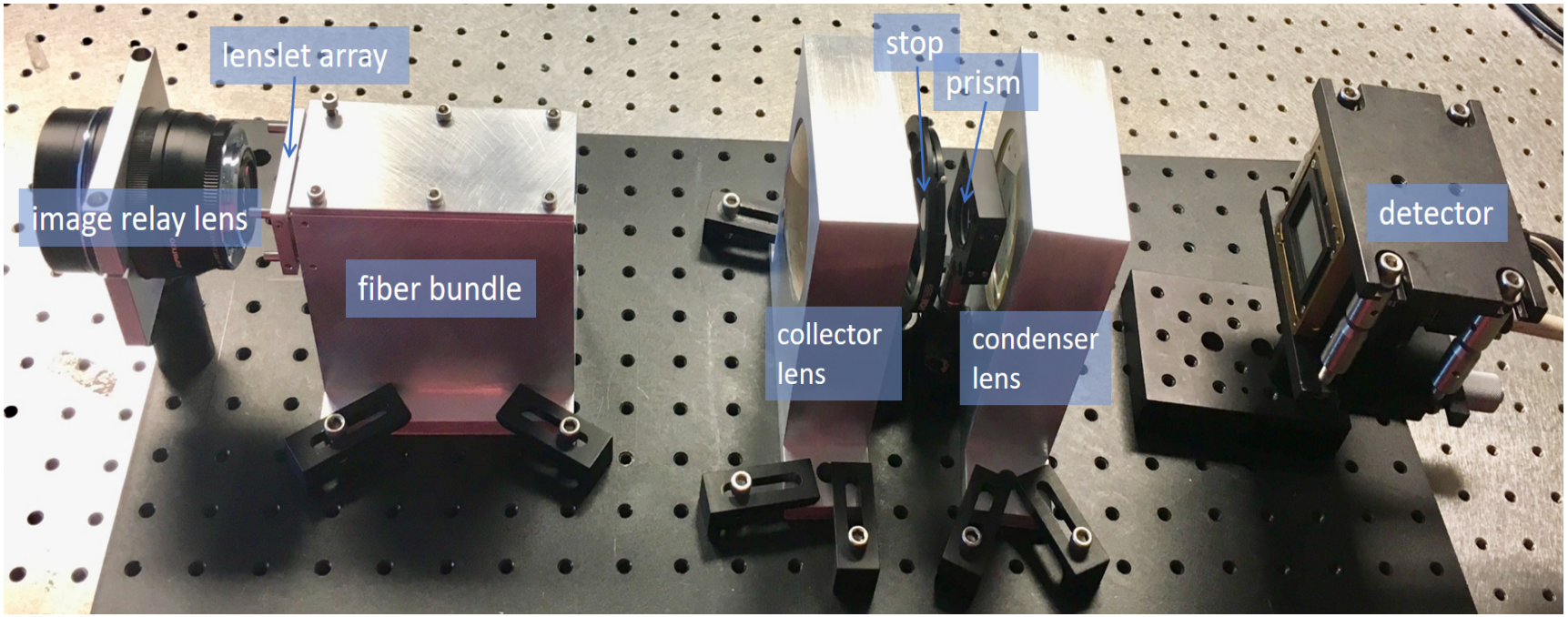
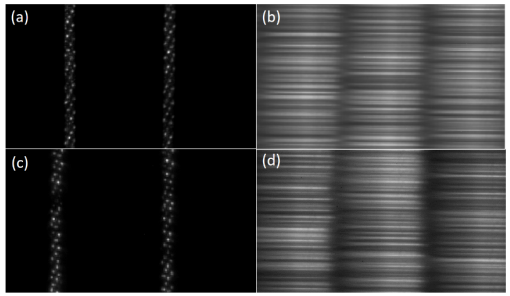
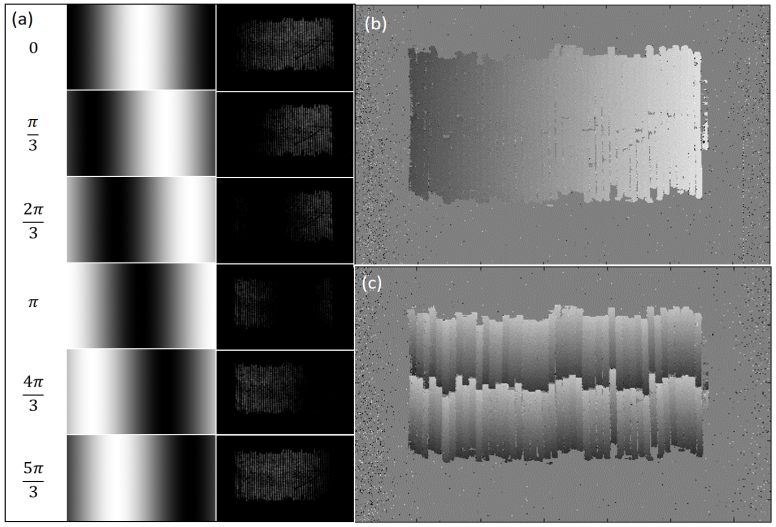
# Benchtop Prototype

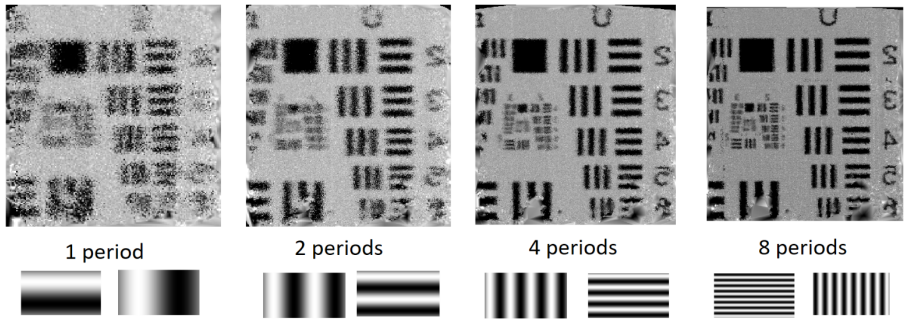
- Approx. 30,000+ (188x170) spatial points
- 60+ spectral values, VIS range
- Volume 60x15x15 cm3
- Max. readout rate 3.6 frames/sec, integration time 75-400ms



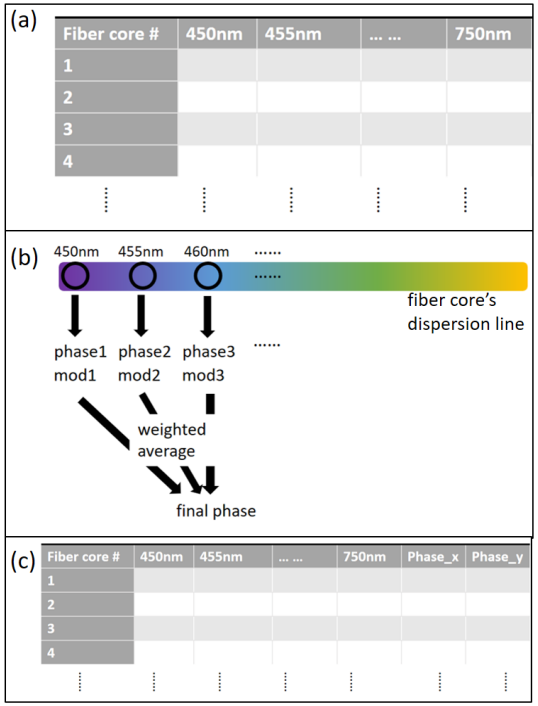
# Calibration

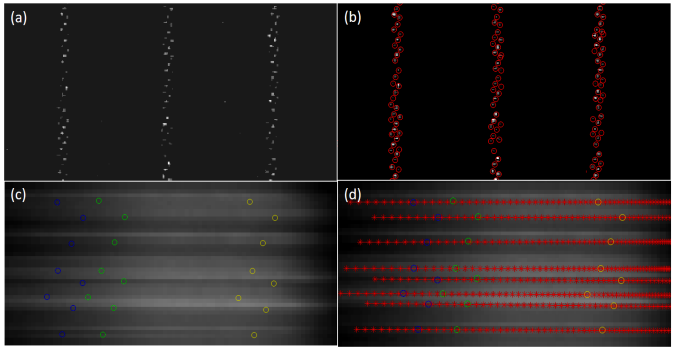


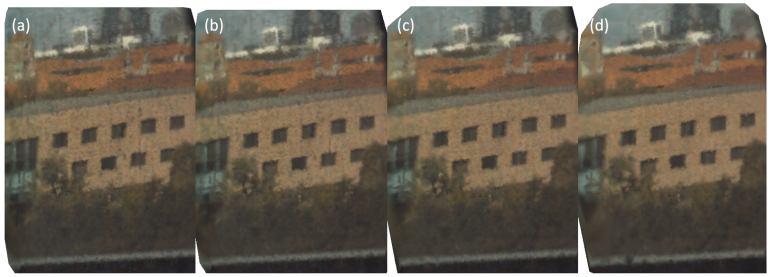



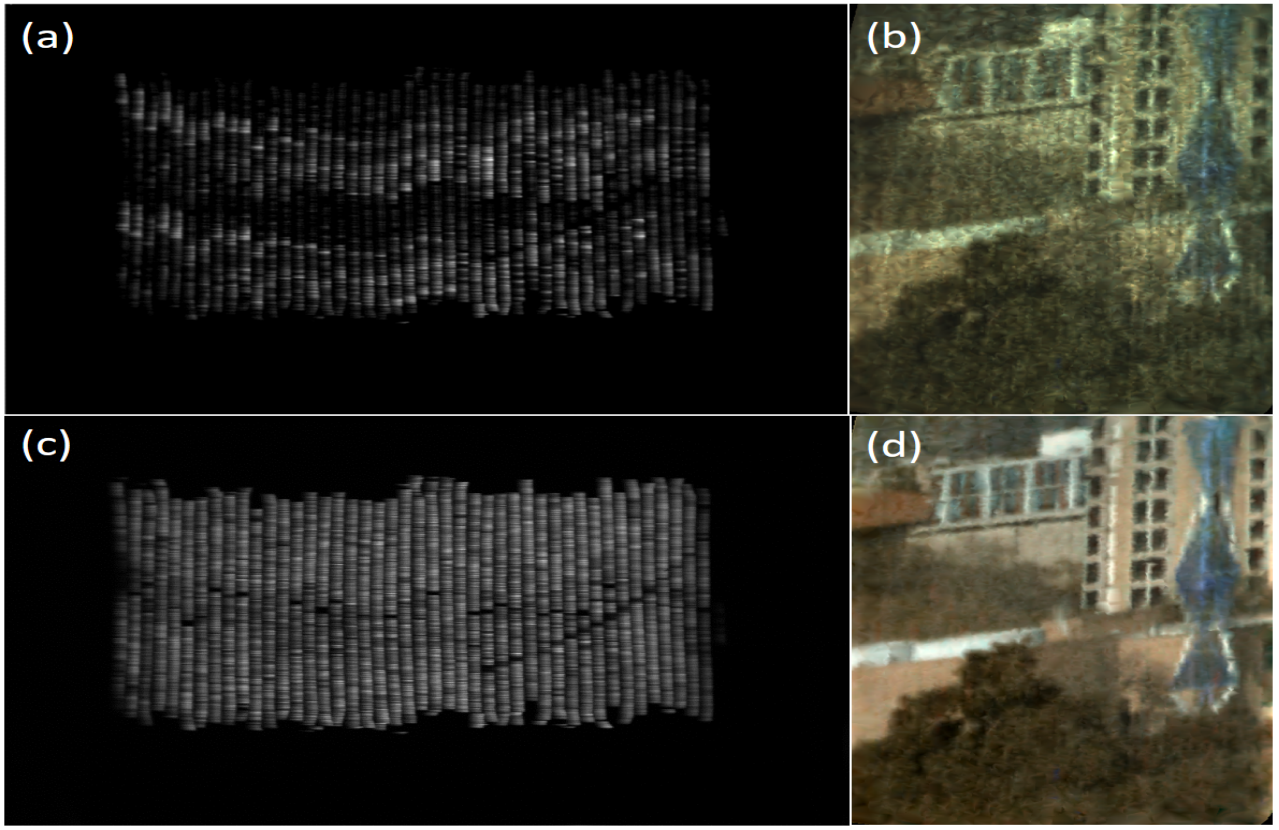
# Calibration



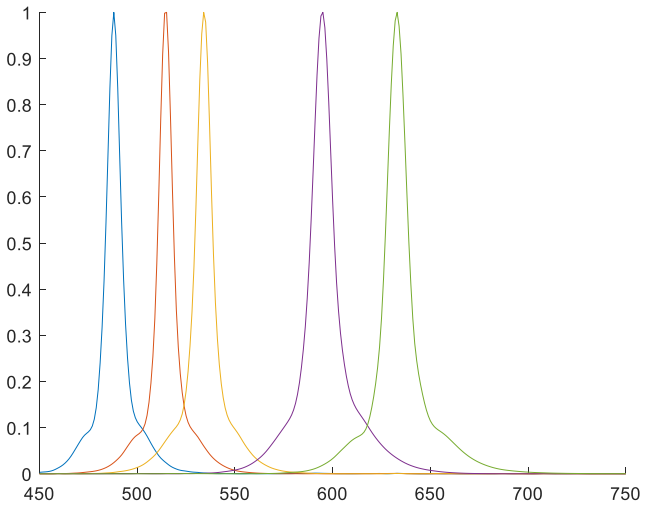



# Flat Field Correction



# Spectral resolution

| Wavelength/nm | 488 | 514 | 532 | 589 | 633 |
|---|---|---|---|---|---|
| Average FWHM ± STD across FOV /nm | 9.04 ± 2.68 | 8.81 ± 2.81 | 9.49 ± 2.73 | 12.83 ± 4.13 | 13.09 ± 4.44 |

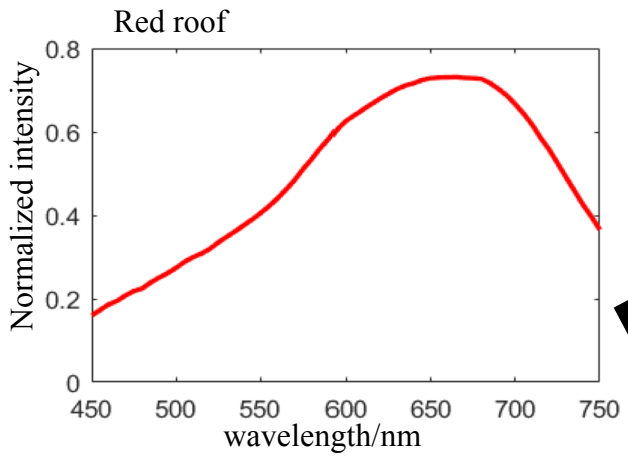


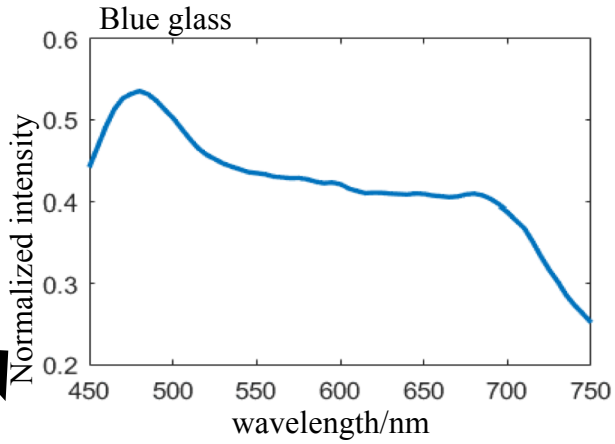
# Crosstalk

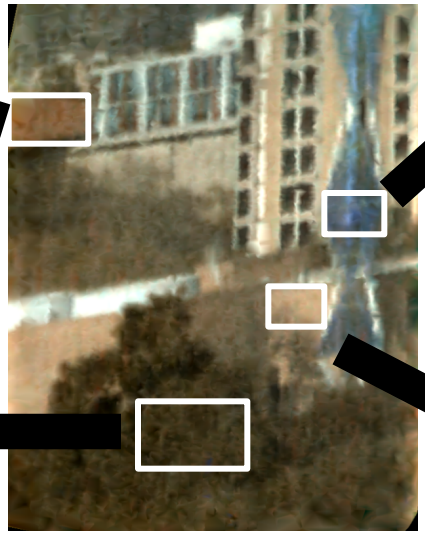
| Pitch (10um pinhole) | Custom (6 cores/block) | 31.5um (4 cores/block) | 37um (3 cores/block) |
|---|---|---|---|
| Crosstalk | 49.7% | 27.5% | 18.2% |
| Std | 17.9% | 11.6% | 2.6% |

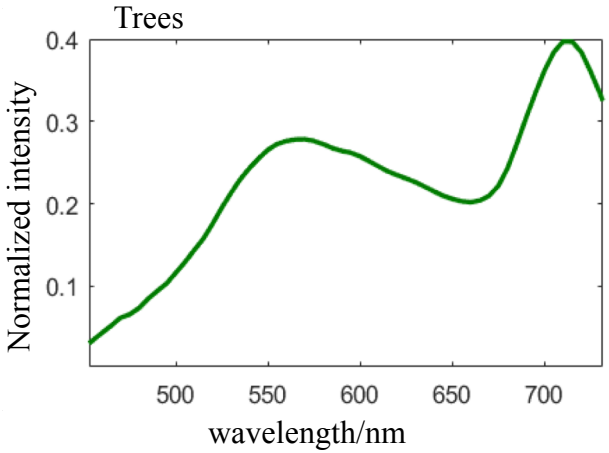
| Pinhole diameter (31.5um pitch) | 10um | 7.5um | 5um |
|---|---|---|---|
| Crosstalk | 27.5% | 25.2% | 22.7% |
| Std | 11.6% | 17.2% | 13.4% |

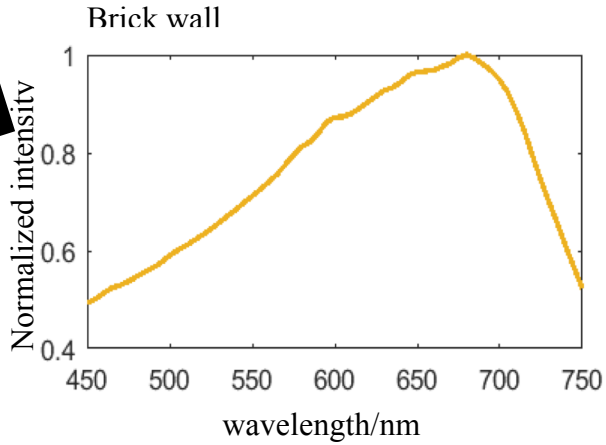
Lenslet array: 22.0% ± 13.9%


Red roof
Normalized intensity
wavelength/nm

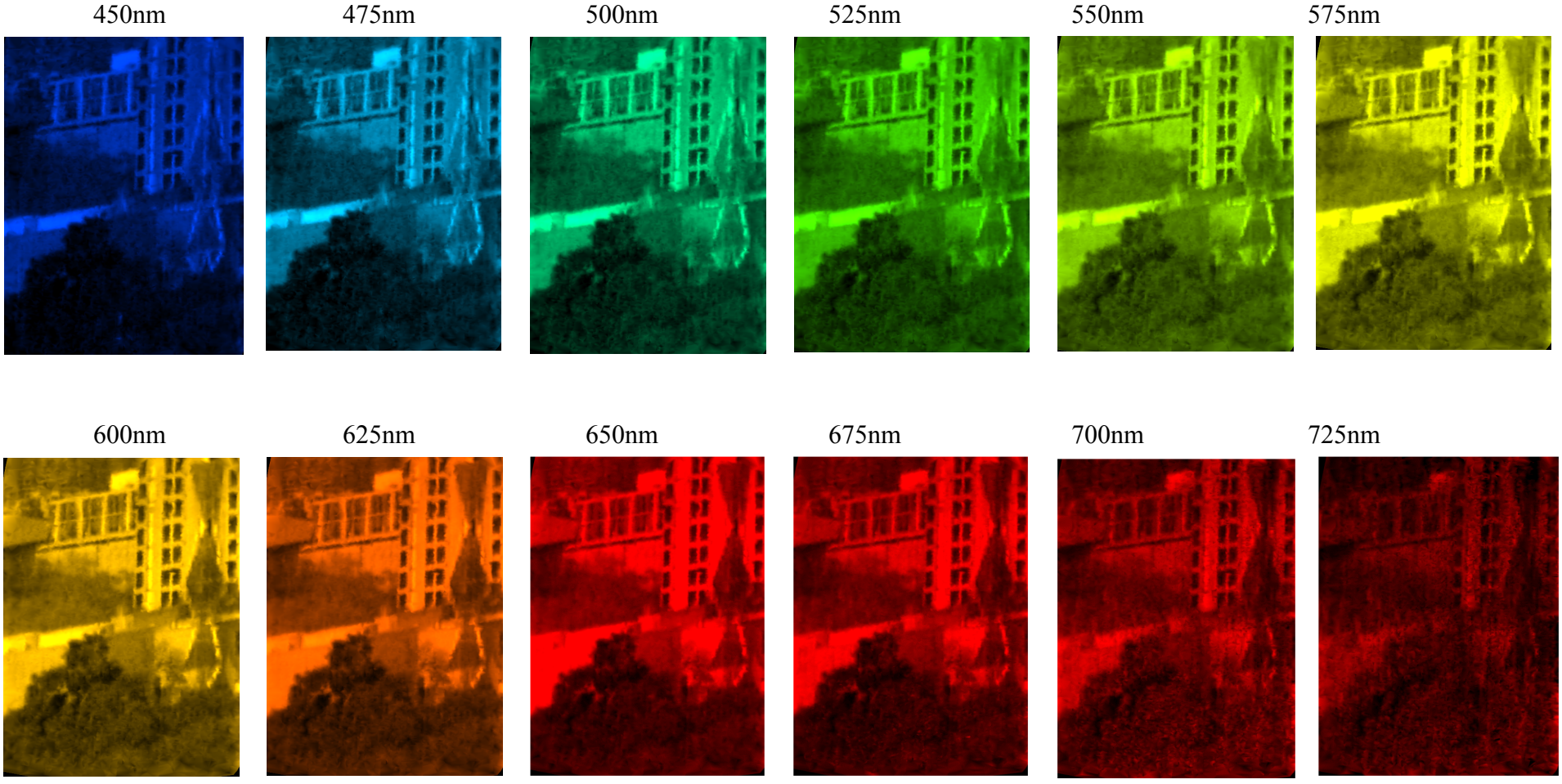

Blue glass
Normalized intensity
wavelength/nm




Trees
Normalized intensity
wavelength/nm


Brick wall
Normalized intensity
wavelength/nm

RICE

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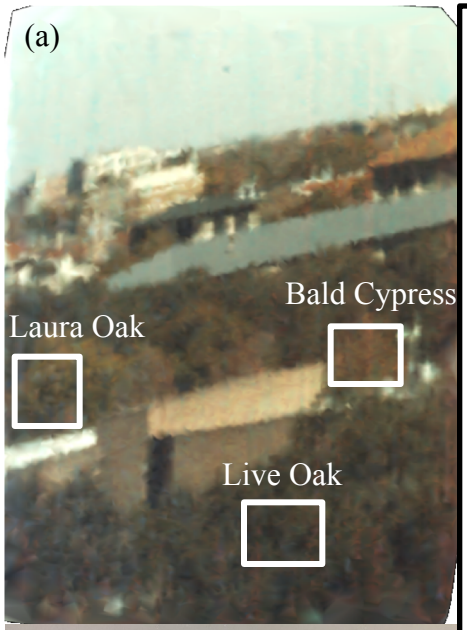
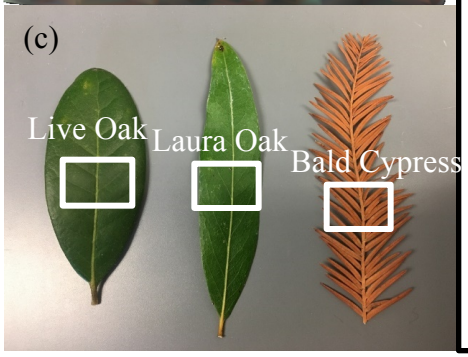
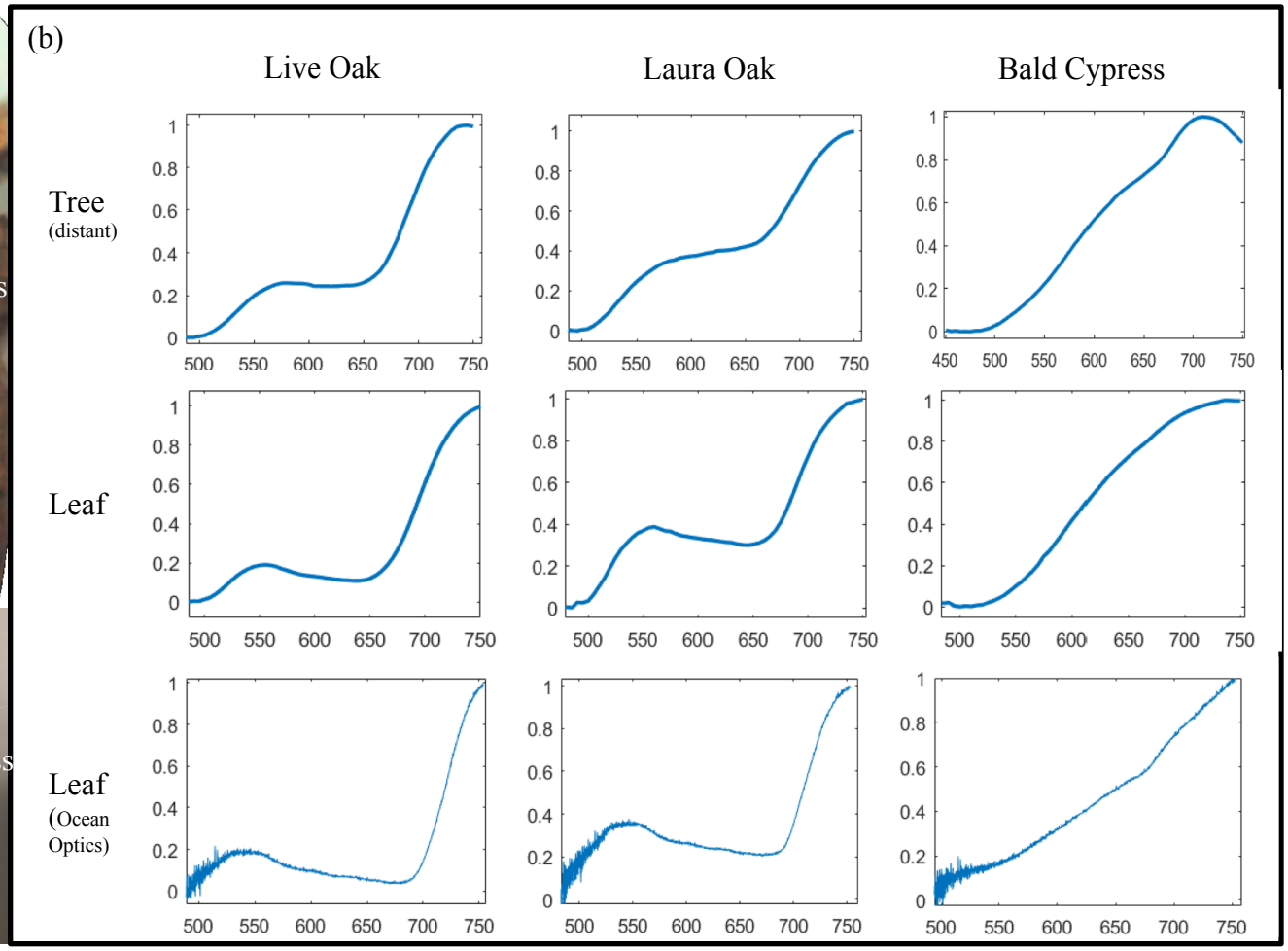
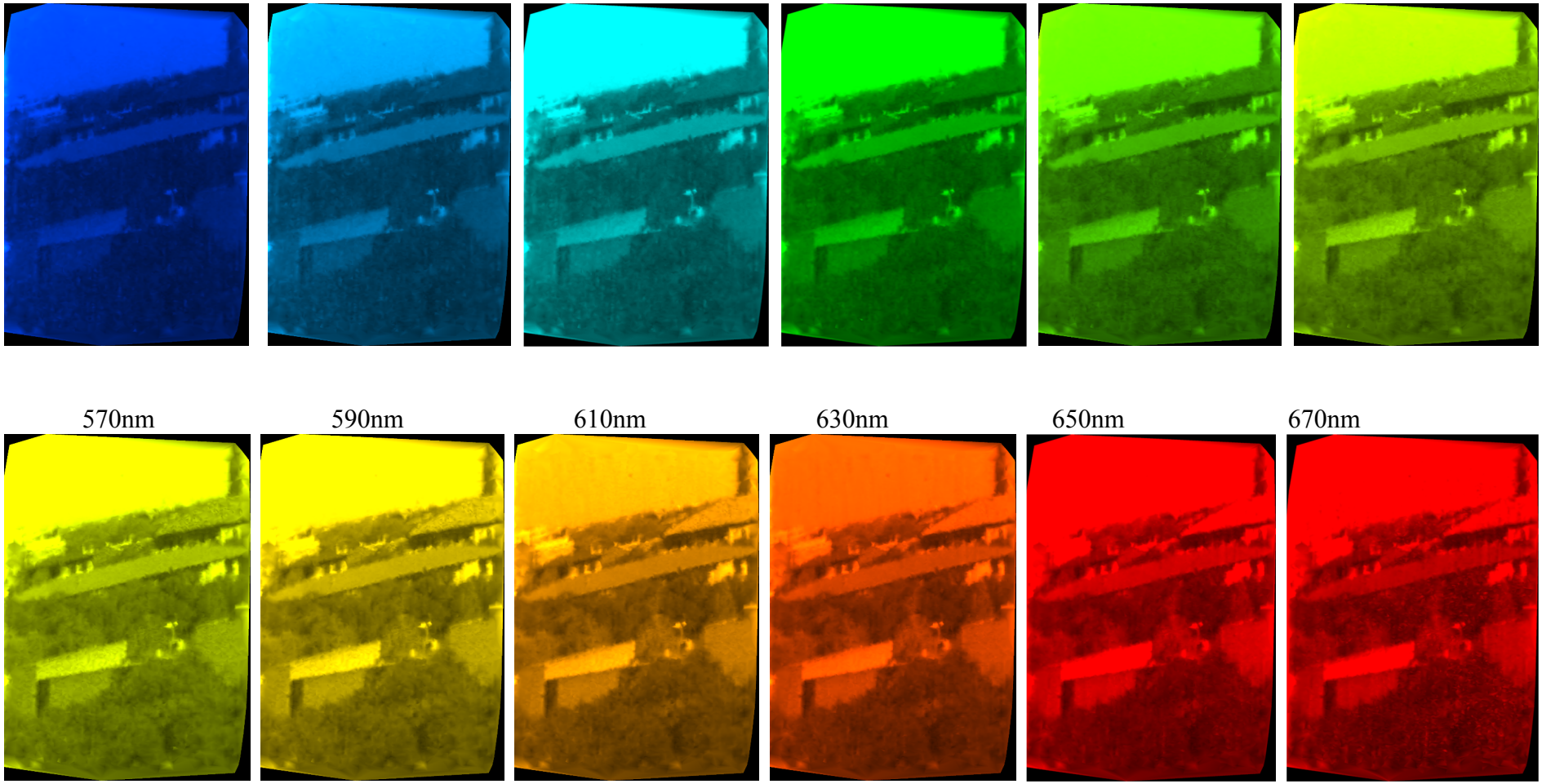

(a)
Laura Oak
Bald Cypress
Live Oak


(c)
Live Oak
Laura Oak
Bald Cypress


(b)
Live Oak
Laura Oak
Bald Cypress
Tree
(distant)
Leaf
Leaf
(Ocean
Optics)

RICE

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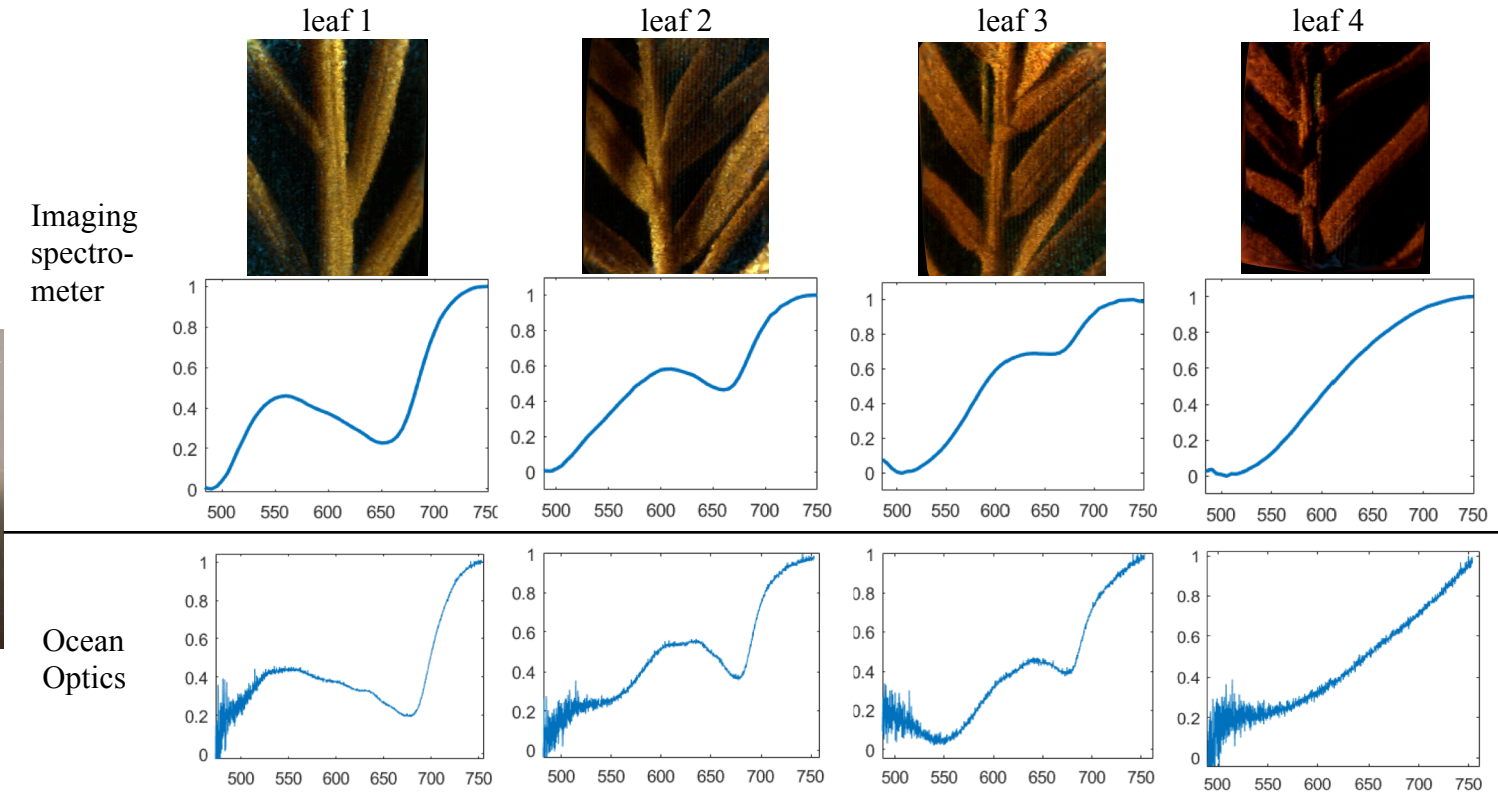
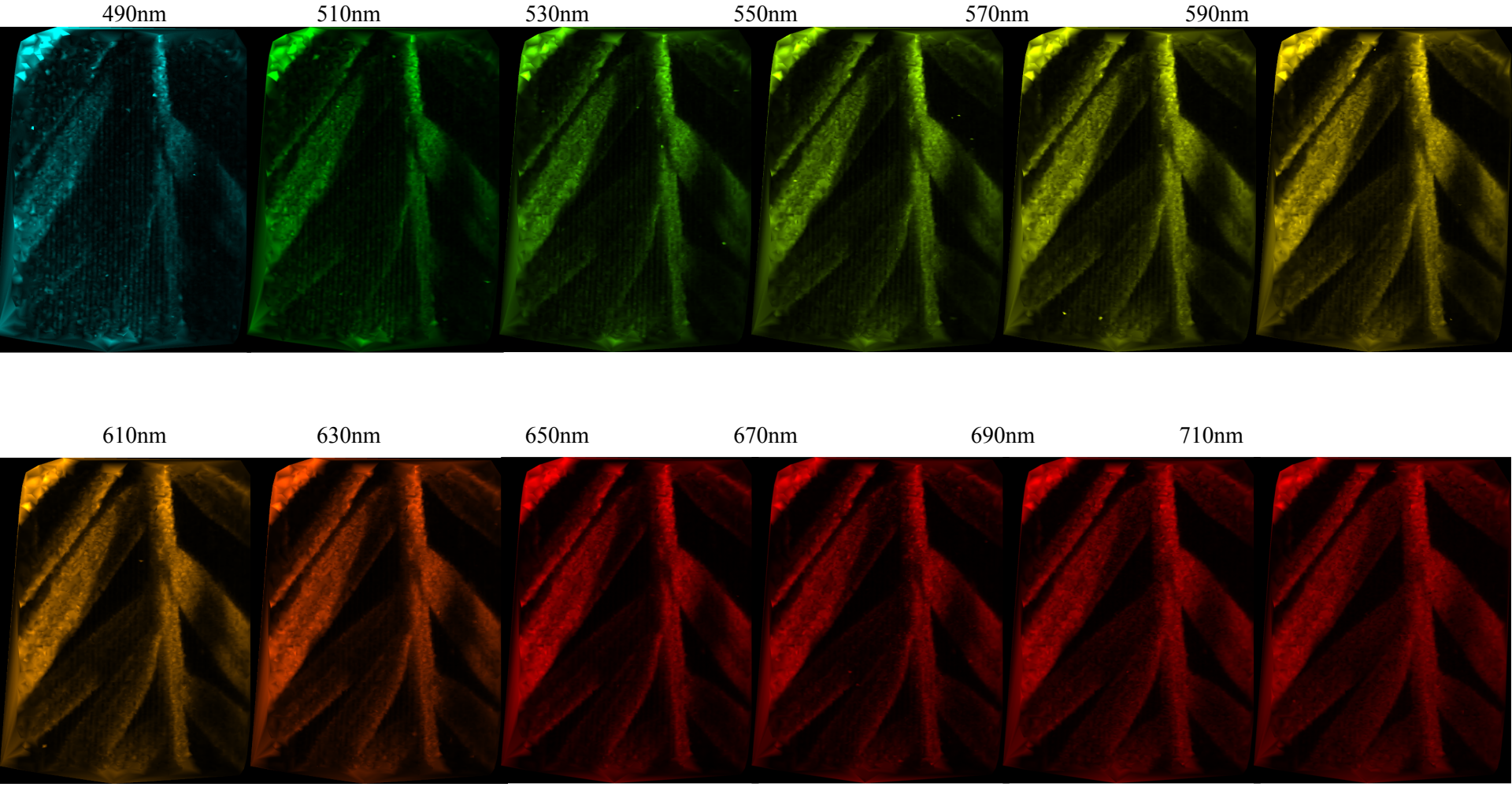
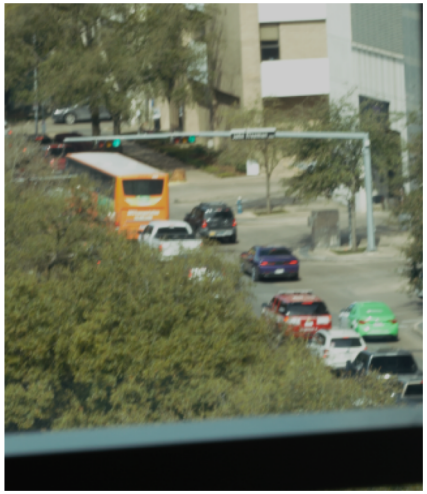
1
2
3
4

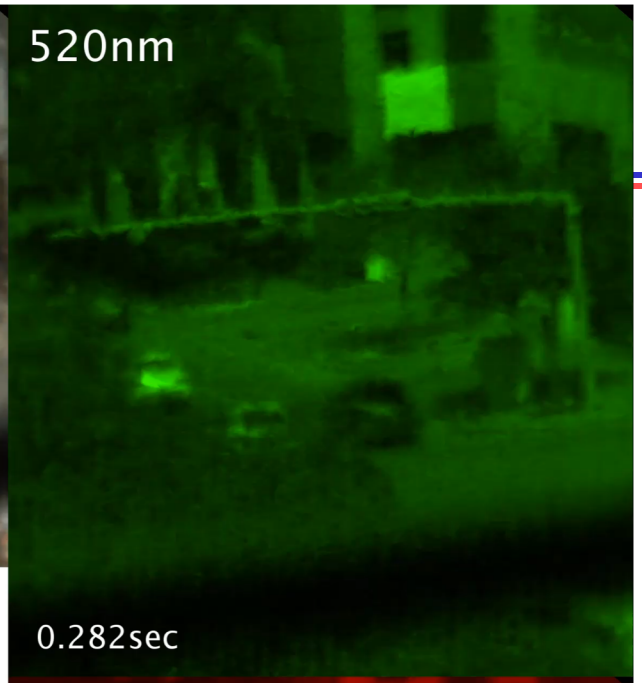

leaf 1
leaf 2
leaf 3
leaf 4
Imaging spectro-meter
Ocean Optics
0
0.2
0.4
0.6
0.8
1
500
550
600
650
700
750

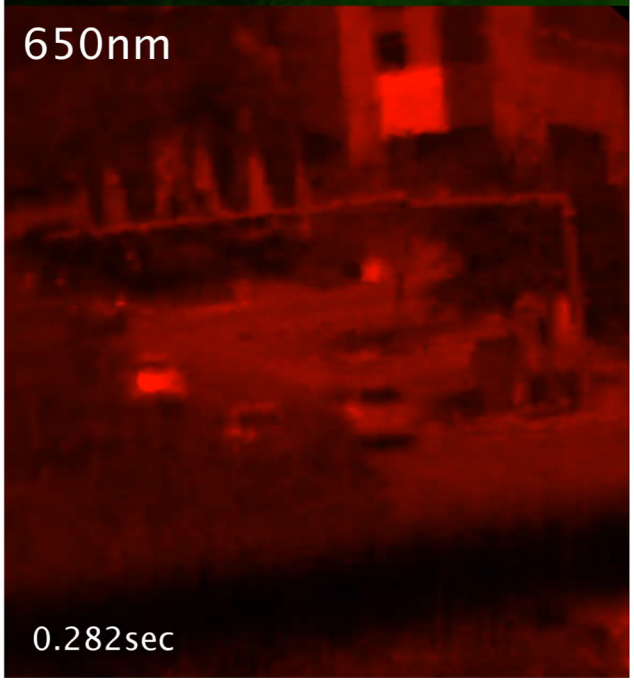

490nm
510nm
530nm
550nm
570nm
590nm
610nm
630nm
650nm
670nm
690nm
710nm

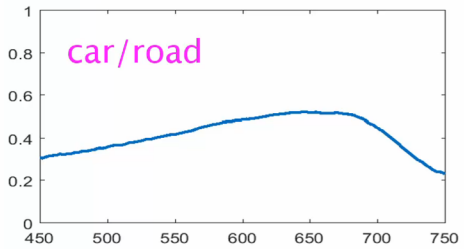
# Traffic video imaging

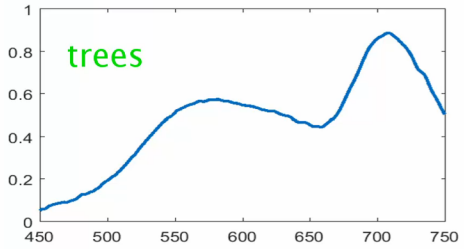
Field of view (RGB image, DSLR camera)

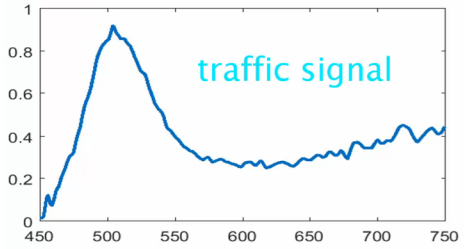





# Urban traffic hyperspectral video

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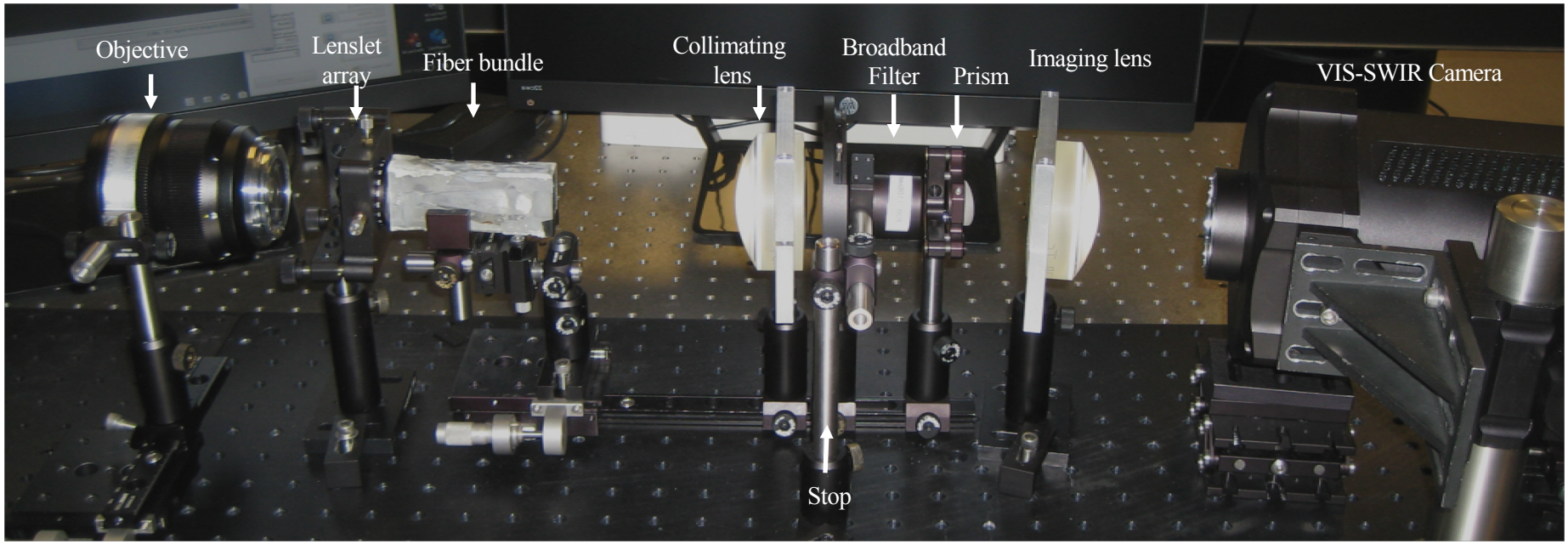
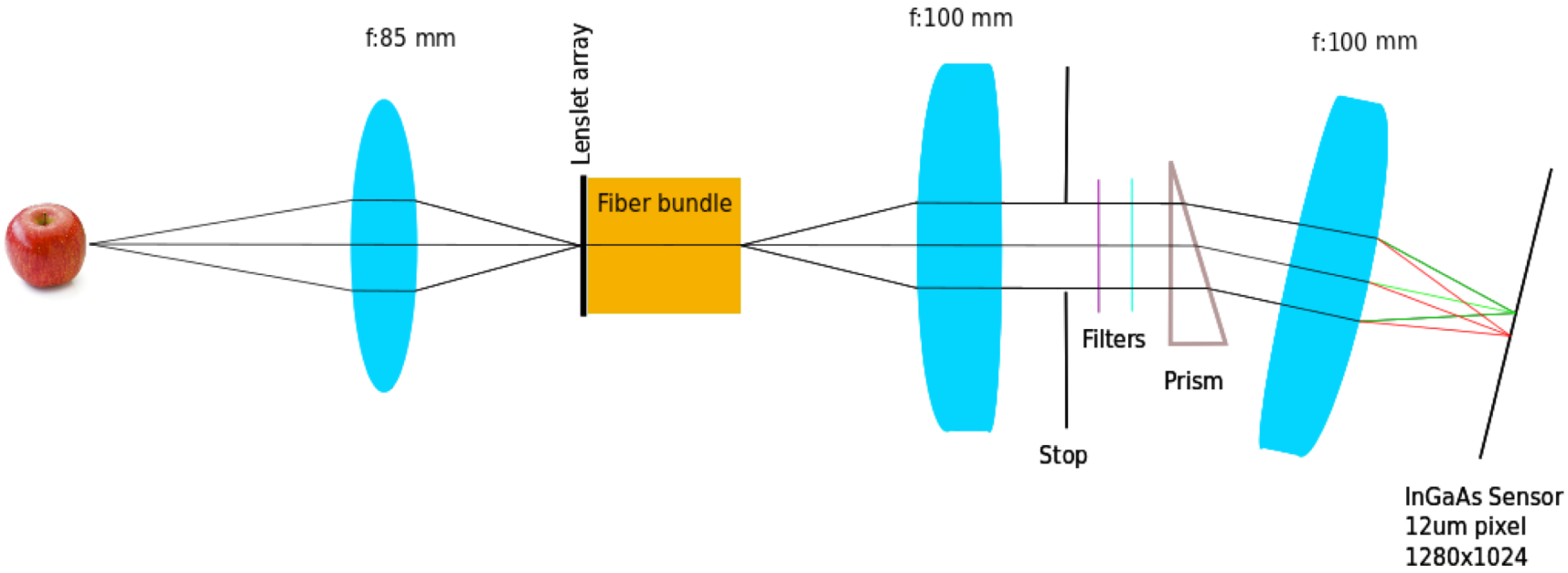
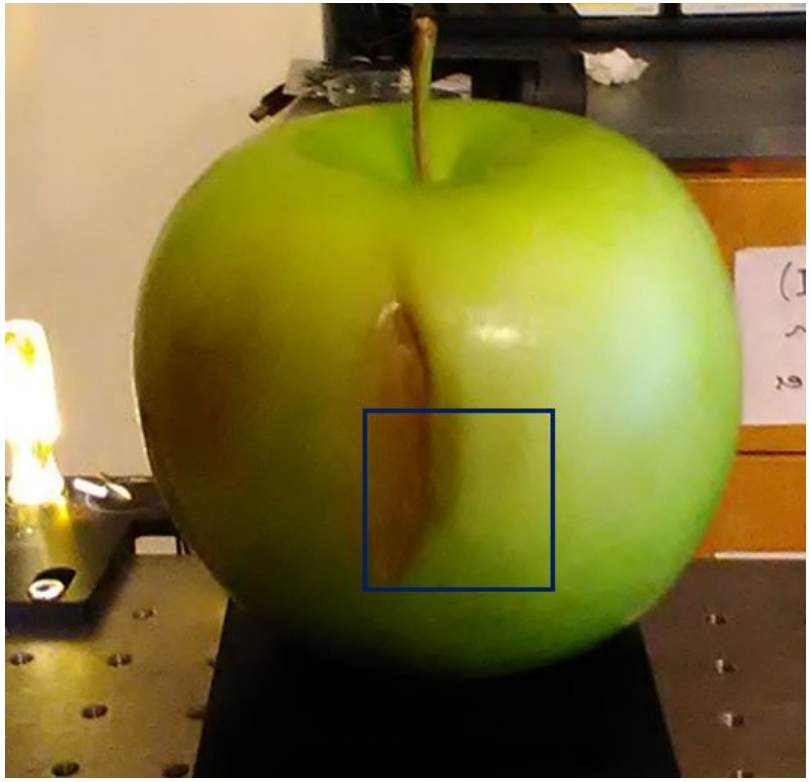
# SWIR – INITIAL PROTOTYPE

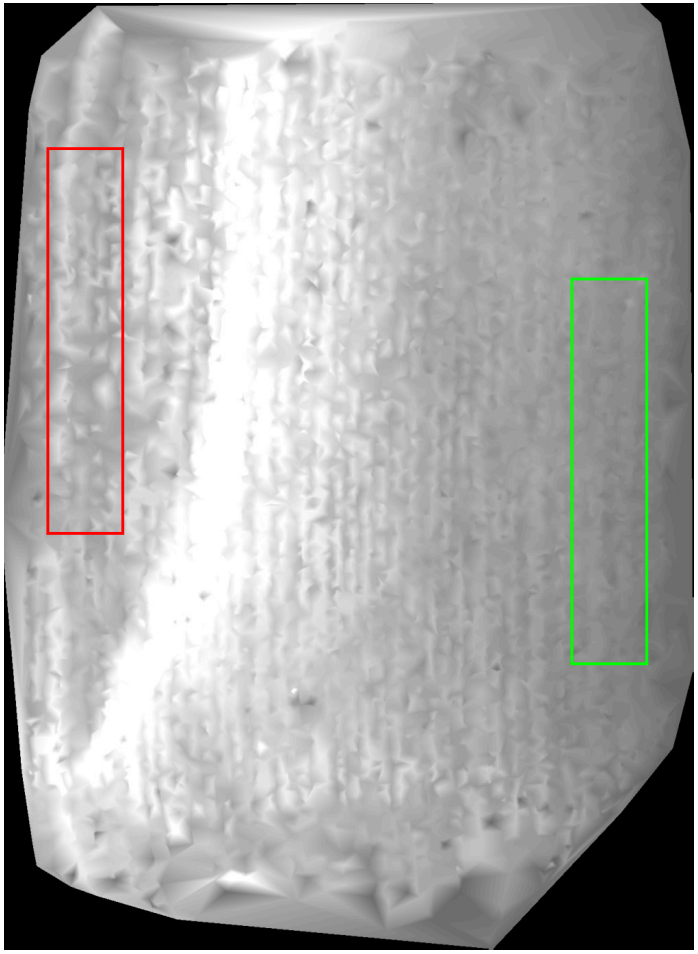
# SWIR TuLIPSS Preliminary Setup

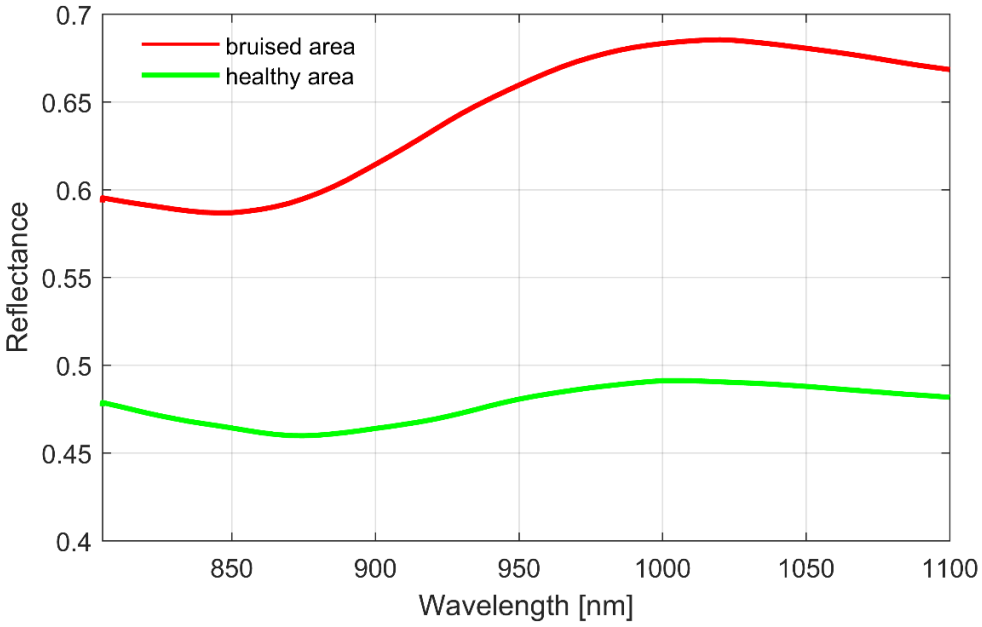


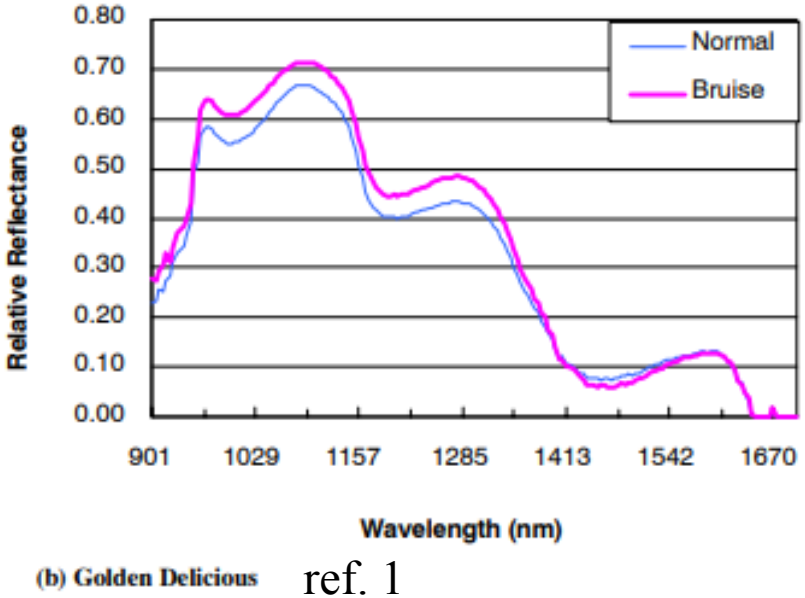
# Optical schematics










(b) Golden Delicious

ref. 1

ref. 1- Detection of Bruises on Apples Using NIR Hyperspectral Imaging – R. Lu

# TuLIPSS - Current Activities/ Improvements / Summary

- Decreasing bundle dimensions – smaller individual fiber diameter (10 microns and below)
- Optimizing throughput – fiber NA and optimized optical system
- Increasing spatial sampling (targeted 400x400)
- Elastic tuning (1-2 second mode switching) of fiber distance
- Dispersion and bandwidth tuning (selection of sub-bands and spectral sampling)
- ROI dynamic range tuning
- Incorporating SWIR range

- Field distribution techniques can effectively enable fast non scanning imaging
- Field distribution techniques require limited data reconstruction
- Tuning of spectral – spatial content will allow optimization of data transfer and SNR

**Details of design and imaging results are presented in:**

Ye Wang, Michal E. Pawlowski, Shuna Cheng, Jason G. Dwight, Razvan I. Stoian, Jiawei Lu, David Alexander, and Tomasz S. Tkaczyk, "Light-guide snapshot imaging spectrometer for remote sensing applications," Opt. Express 27, 15701-15725 (2019)