Tunable Light-guide Image Processing Snapshot Spectrometer (TuLIPSS) for Earth Observation

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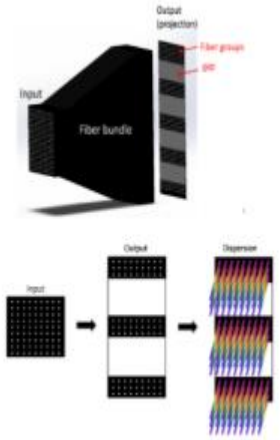
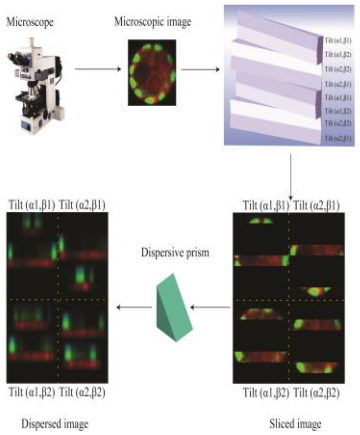
Snapshot Multi / Hyperspectral Systems based on Image Re-organization

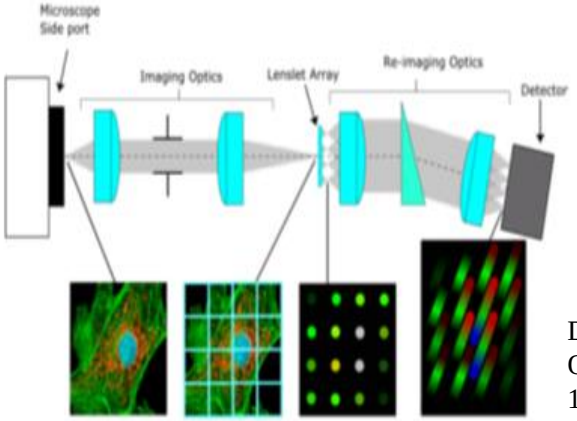


Ye Wang et al, OPTICAL ENGINEERING, Volume: 56 Issue: 8. AUG 2017

- Ye Wang et al, OPTICAL ENGINEERING, Volume: 56 Issue: 8. AUG 2017
- Biomed. Opt. Express 8, 1950-1964 (2017)
- Opt. Express 21, 13758-13772 (2013)
- Biomed. Opt. Express 4, 938-949 (2013)
- Journal of Cell Science, JOCES/2012/108258
- Journal of Biomedical Optics Letters, August 2012 • Vol. 17(8), p.080508-1
- Optical Engineering 51(11), (November 2012)
- Optical Engineering 51(4), 043203 (April 2012)
- JOURNAL OF MICROSCOPY Volume: 246 Issue: 2 Pages: 113-123, MAY 2012
- Biomed. Opt. Express 3, 48-54 (2012)
- Opt. Express 19, 17439-17452 (2011)
- Journal of Biomedical Optics, 16(05), 056005, May 2011
- Opt. Express 18, 14330-14344 (2010)
- Appl. Opt. 49, 1886-1899 (2010)
- Opt. Express 17, 12293-12308 (2009)



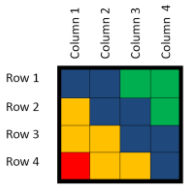
Liang Gao at al 20 July 2009 / Vol. 17, No. 15 / OPTICS EXPRESS



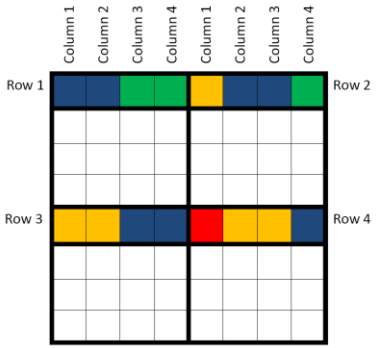
Dwight et al Biomed. Opt. Express 8, 1950-1964 (2017)

- Multi – Dimensional
  - 3D+
- Field distribution
  - Reorganizing the field of view to separate image segments
- Snapshot
  - Instantaneous acquisition
- Simple Reconstruction
  - Calibration + Image Reorganizing

Breaking Down the Image



A



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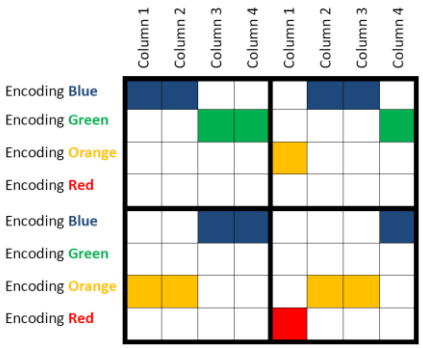

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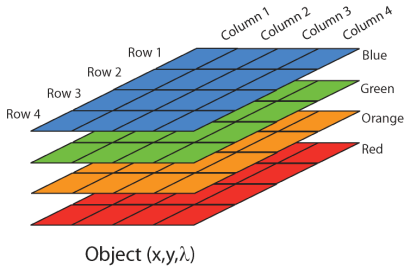

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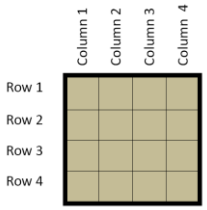

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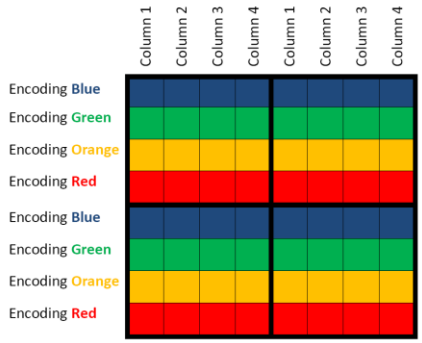


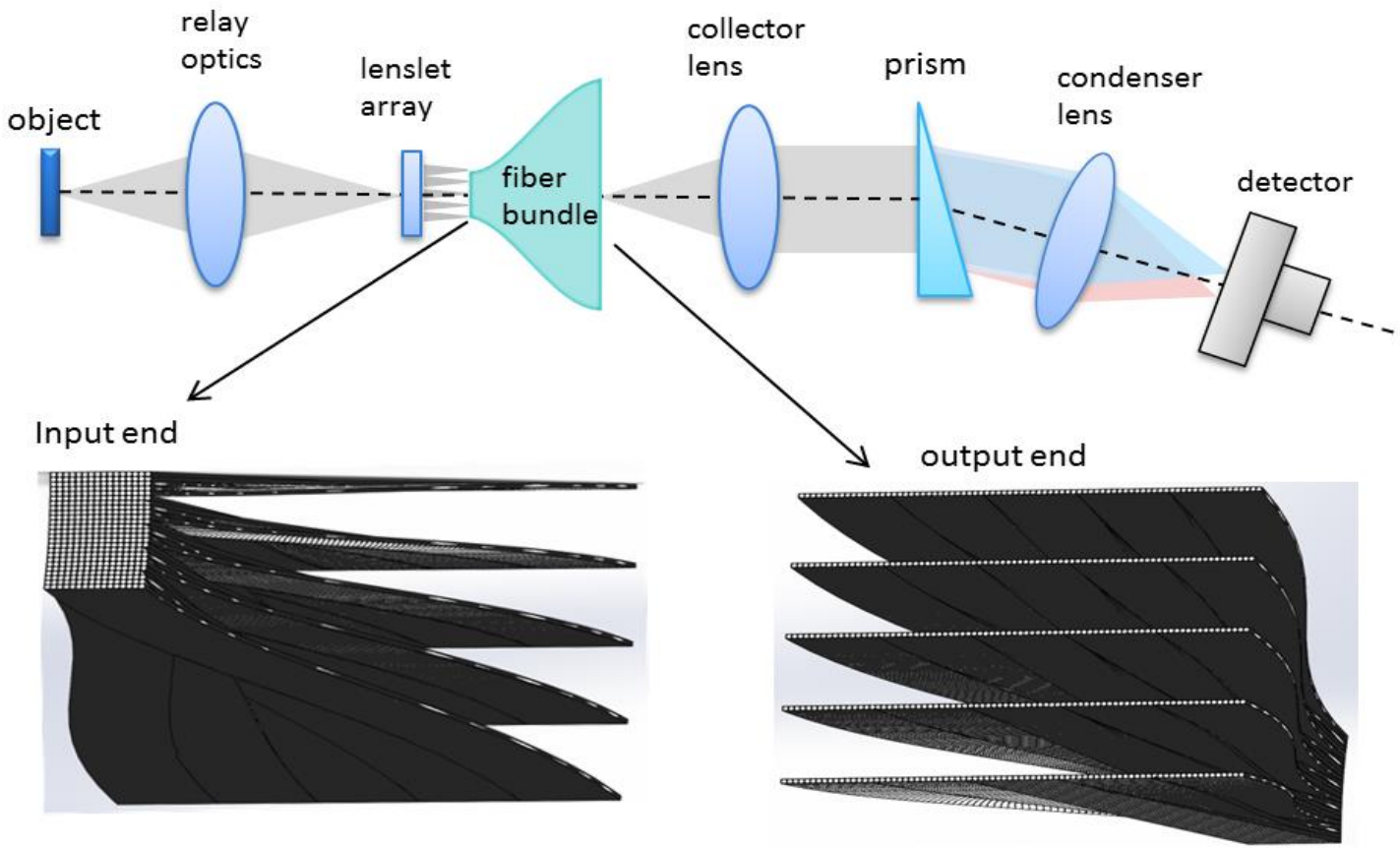
F

System Design

General Design

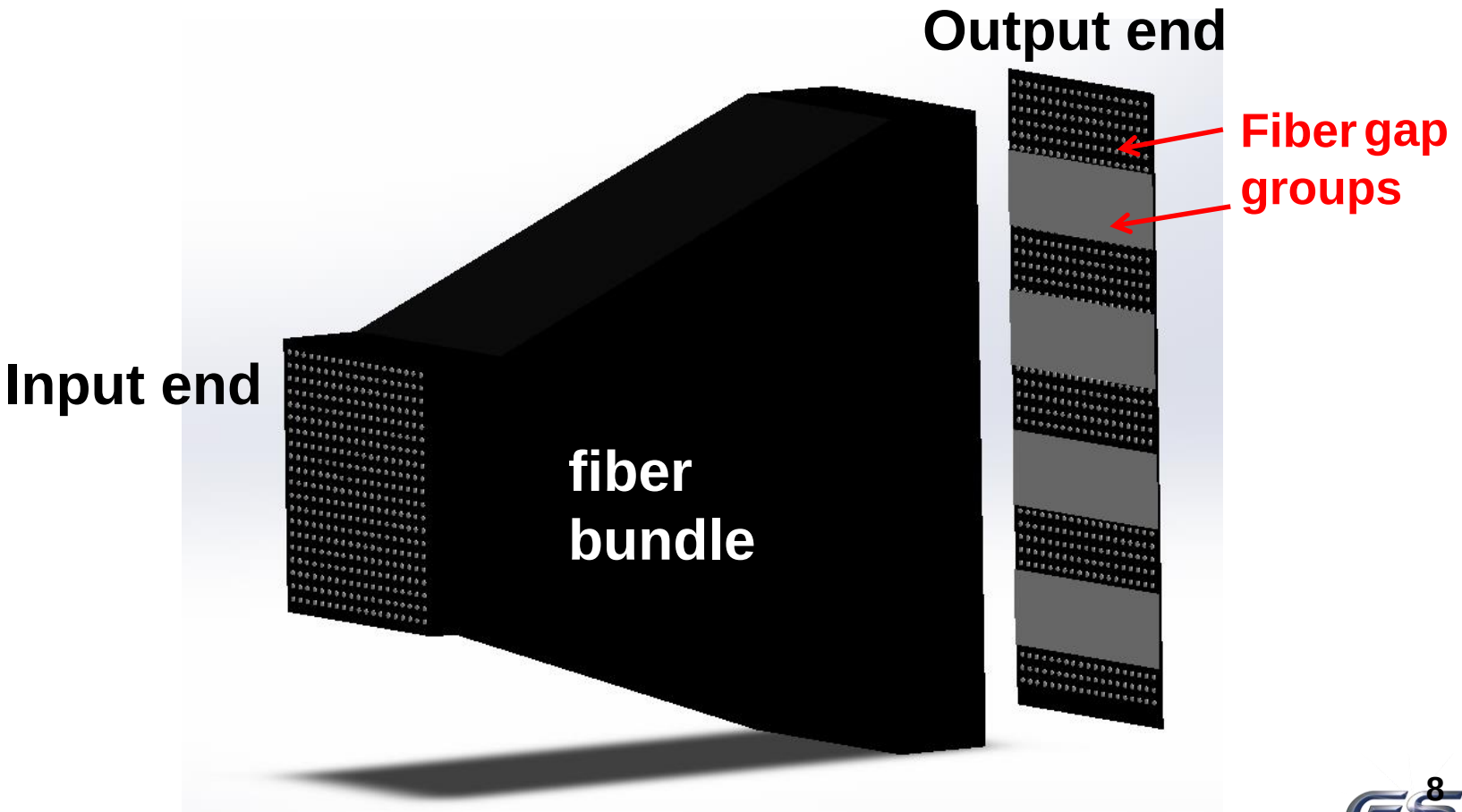
Fiber Parameters vs. System Design

General System Layout



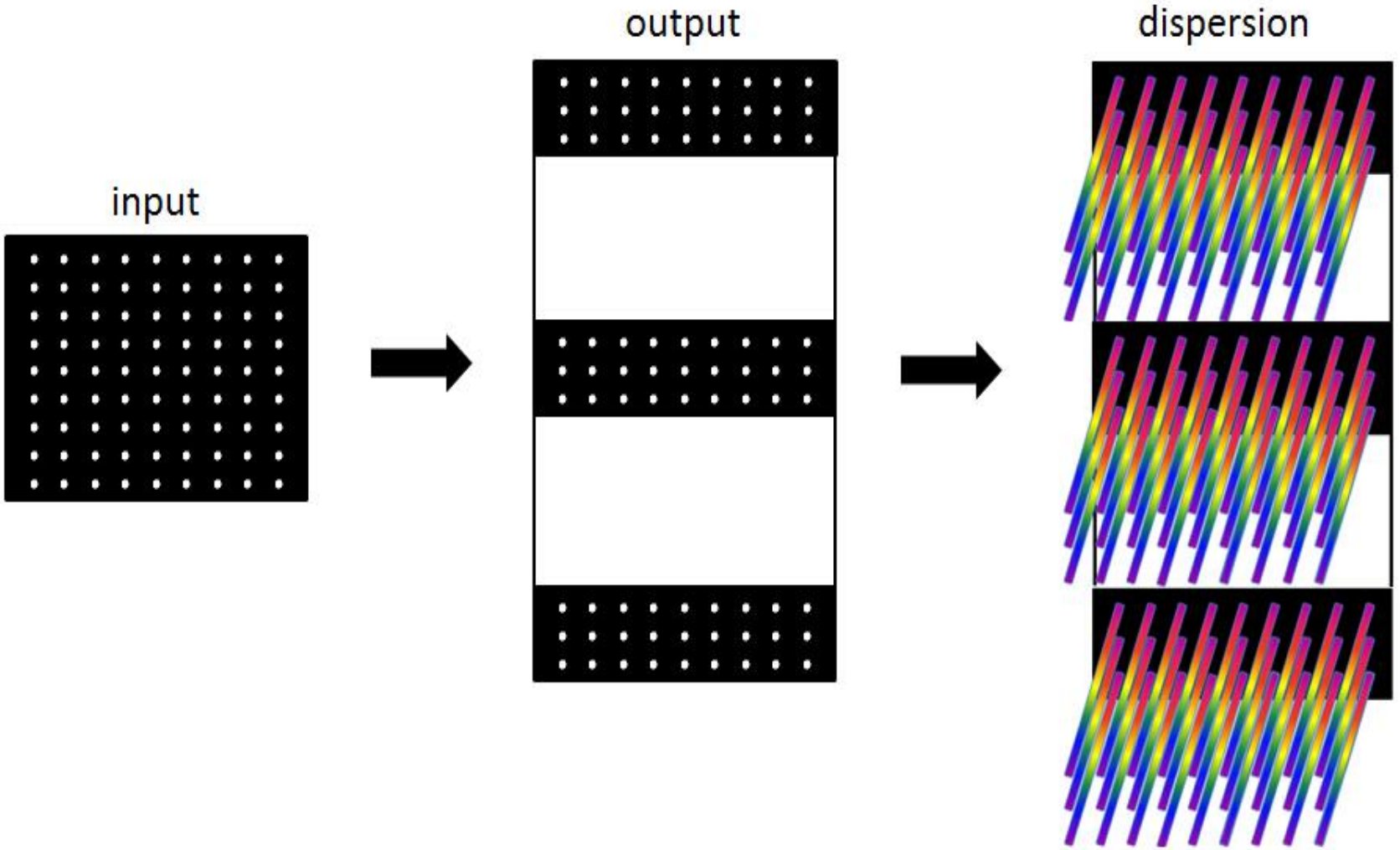
Custom Fiber Bundle System

- **Prototype of a fiber-based snapshot spectrometer**



Ye Wang, Michal E. Pawlowski, Tomasz S. Tkaczyk, "High spatial sampling light-guide snapshot spectrometer", OPTICAL ENGINEERING, Volume: 56 Issue: 8. AUG 2017

General principle



Ye Wang, Michal E. Pawlowski, Tomasz S. Tkaczyk, “High spatial sampling light-guide snapshot spectrometer”, OPTICAL ENGINEERING, Volume: 56 Issue: 8. AUG 2017

Snapshot advantages

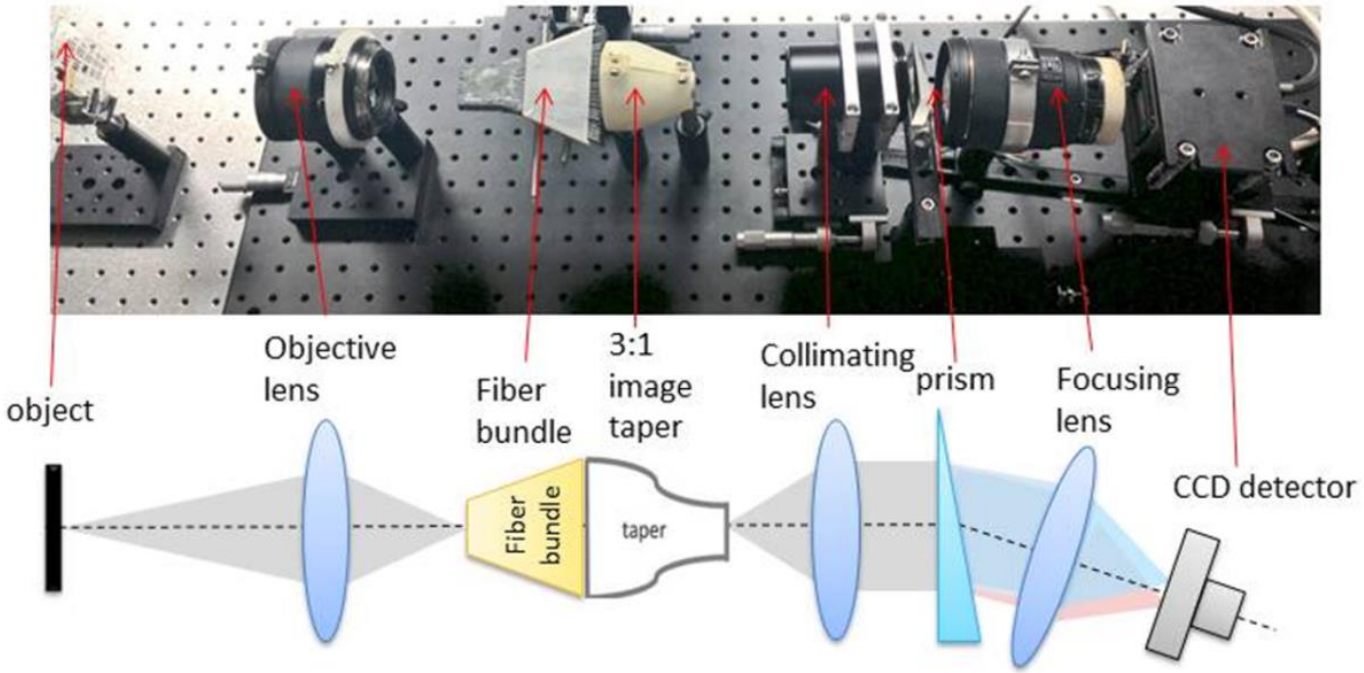
- Monitoring of fast processes
  - Range: FPA speed to end-user-specified timeframes
- Less susceptible to vibrations/movements
- 3D capability for snapshots taken at different inclinations/zenith
  - Tomography, topography
- Improvement of signal quality
  - Via scene overlap (UAV/satellite speed-dependent)
- Glint compensation
  - Via tilting capability
- Orbital scanning for imaging scenes adjacent to “along-track” direction
- Reverse gimbaling for prolonged exposure/integration time/number of images to improve signal quality and resolution for area of interest
- Gimbal scanning for extending resolution imaging/super sampling
- Predicting scene change for setting tuning parameters e.g. land to water
- Lightning detection

Tunability advantages

- Optimization of spectral resolution within a given spectral range to ascertain greater spectral detail of spectral lines
  - Change spectral range
  - Multiple high spectral resolution subsets of range
    - Different datasets for same target for analysis
  - Change spectral sampling within subset
    - Compensate for signal conditions – improvement of dynamic range
  - Change spatial sampling (trade-off)
- Increased signal collection for reduced spatial sampling in low irradiance conditions
- Filter image conjugates of scenes with both dim and bright objects via ND filters and DMDs (Digital Mirror Device)
- Target of opportunity adaptability
  - Quick adjustment for fast fly-bys
- Optimization of DATA transfer – only critical data can be collected

Major Focus of Year 1

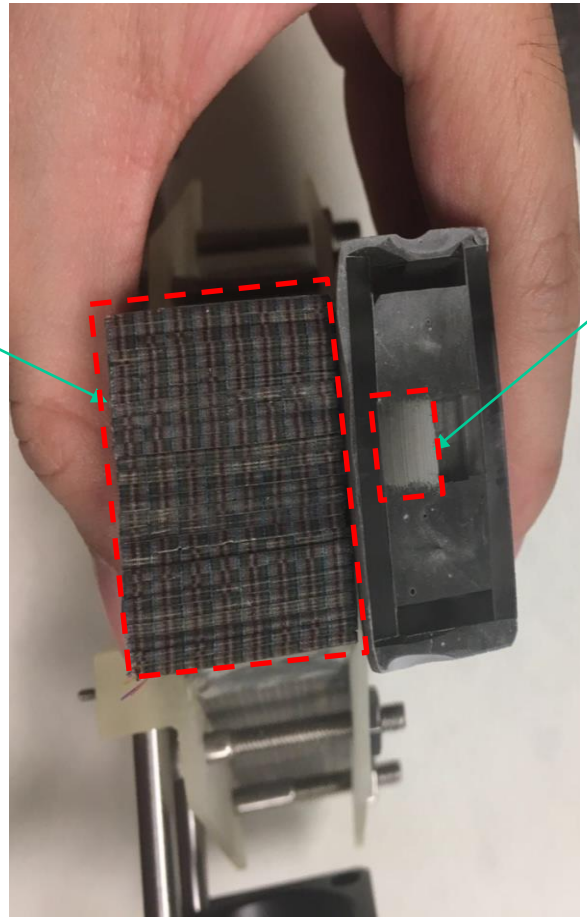
- Decrease fiber module dimensions to allow compact tunable spectrometer. The fiber module parameters drive system's design.



Proposal Prototype

Light guide Fiber bundle: input area

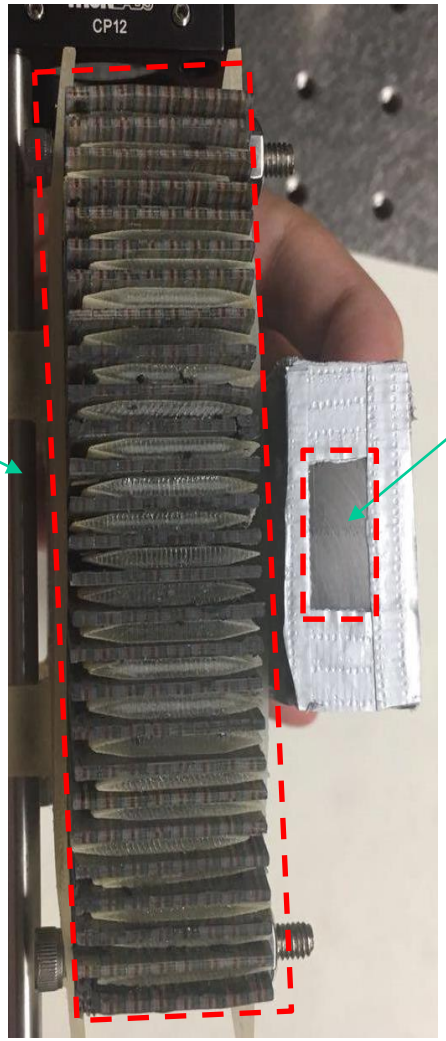
Proposal
Prototype



New
TuLIPSS

Light guide Fiber bundle: output area

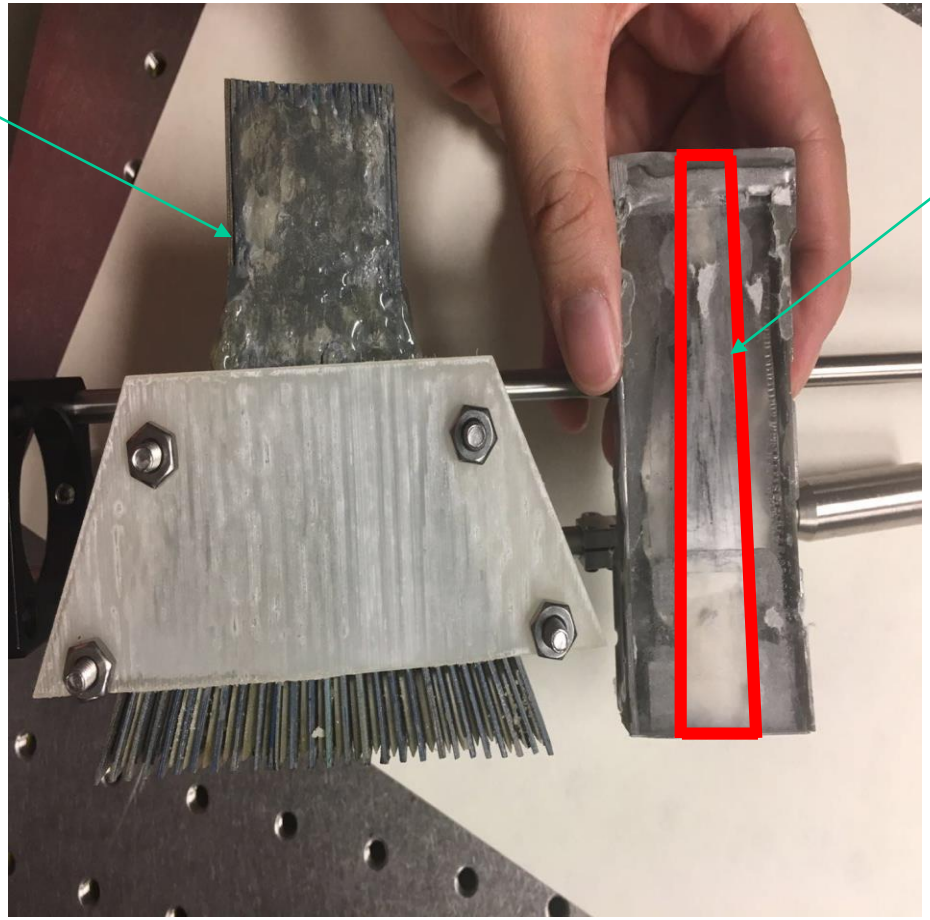
Proposal
Prototype



New
TuLIPSS

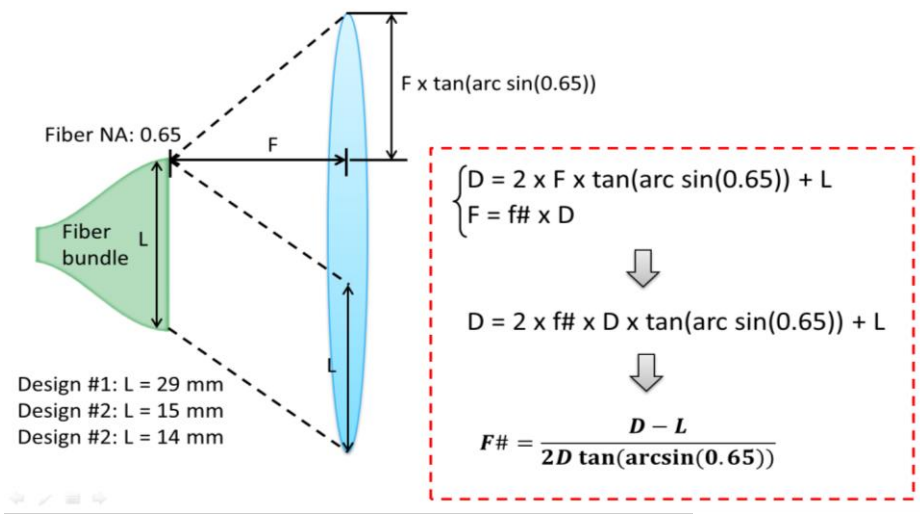
Light guide Fiber bundle

Proposal
Prototype



New
TuLIPSS

Fiber NA vs. System Design



Calculations Performed for 200x200x30 configuration

design #1
L = 29 mm

D	F#
50 mm	0.25
80 mm	0.37
100 mm	0.42
150 mm	0.47

design #2
L = 15 mm

D	F#
50 mm	0.41
80 mm	0.48
100 mm	0.50
150 mm	0.53

design #3
L = 14 mm

D	F#
50 mm	0.42
80 mm	0.48
100 mm	0.50
150 mm	0.53

Light Loss for NA=0.64

Loss = 25%

D	F#
50 mm	0.50
80 mm	0.57
100 mm	0.59
150 mm	0.62

Loss = 50%

D	F#
50 mm	0.65
80 mm	0.72
100 mm	0.74
150 mm	0.77

Loss = 75%

D	F#
50 mm	0.99
80 mm	1.06
100 mm	1.08
150 mm	1.11

Loss = 80%

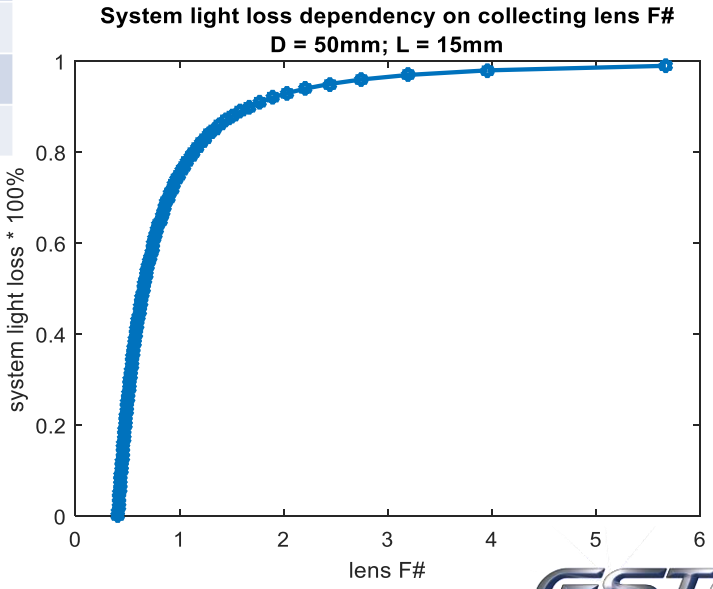
D	F#
50 mm	1.13
80 mm	1.20
100 mm	1.22
150 mm	1.25

Loss = 85%

D	F#
50 mm	1.33
80 mm	1.40
100 mm	1.42
150 mm	1.45

Loss = 90%

D	F#
50 mm	1.67
80 mm	1.74
100 mm	1.76
150 mm	1.79



Light Loss vs. Fiber NA and F#

NA = 0.65

D	F#
50 mm	0.41
80 mm	0.47
100 mm	0.50
150 mm	0.52

NA = 0.55

D	F#
50 mm	0.53
80 mm	0.62
100 mm	0.65
150 mm	0.68

NA = 0.45

D	F#
50 mm	0.69
80 mm	0.81
100 mm	0.84
150 mm	0.89

NA = 0.35

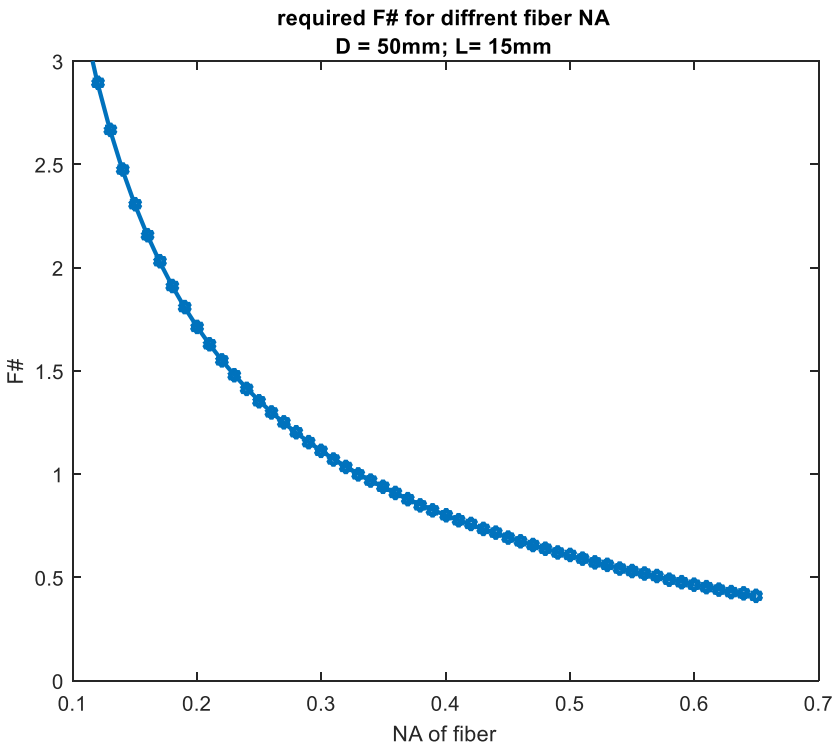
D	F#
50 mm	0.94
80 mm	1.09
100 mm	1.14
150 mm	1.20

NA = 0.25

D	F#
50 mm	1.36
80 mm	1.57
100 mm	1.65
150 mm	1.74

NA = 0.15

D	F#
50 mm	1.36
80 mm	1.57
100 mm	1.65
150 mm	1.74

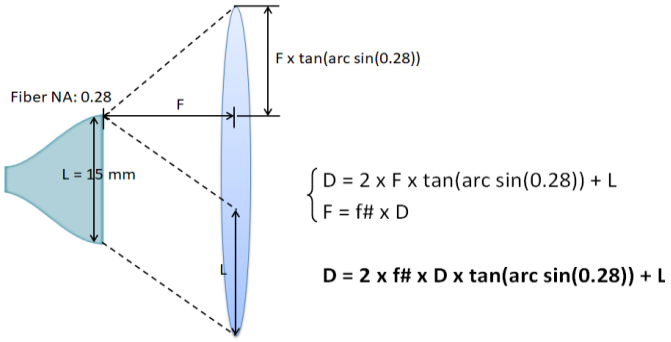


ESTO
Earth Science Technology Office

Solutions to maximize light collection

- Lower NA of the fiber
- Lenslets at fiber tips
- Custom Optimized Fresnel Lens

TuLIPSS system lens requirements for 0.28 NA



$$\begin{cases} D = 2 \times F \times \tan(\arcsin(0.28)) + L \\ F = f\# \times D \end{cases}$$

$D = 2 \times f\# \times D \times \tan(\arcsin(0.28)) + L$

- 0% loss:

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

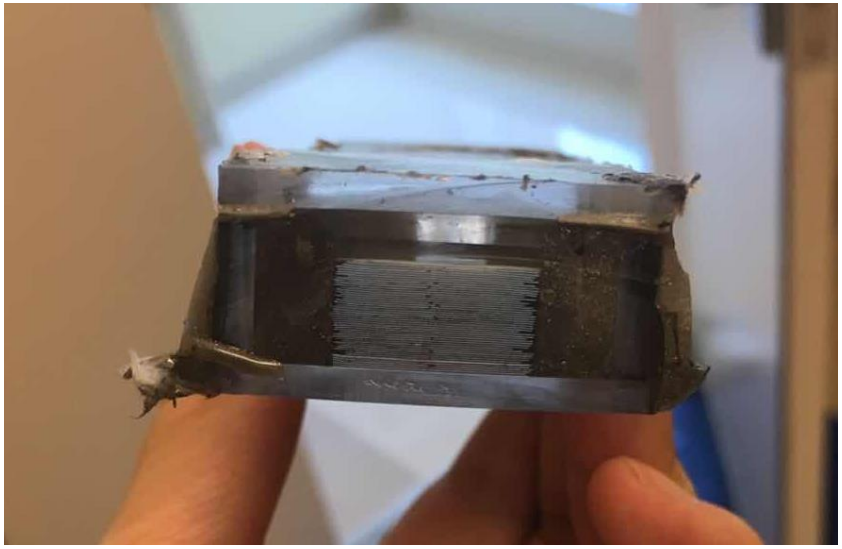
200 x 200 x 30
L = 15 mm

Fresnel Lens

100 x 100 x 30 fiber bundle

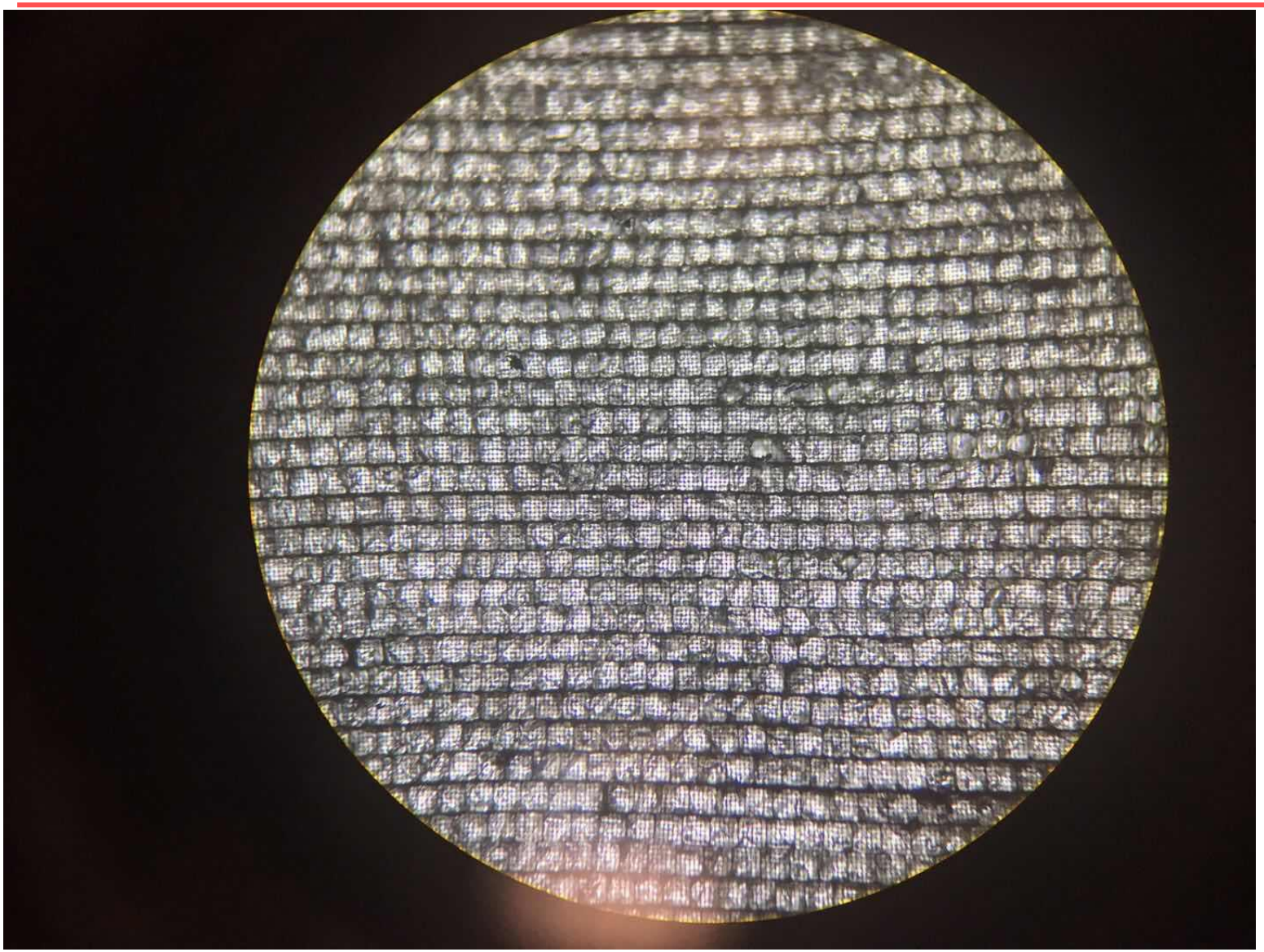
Assembly and Polishing

Input

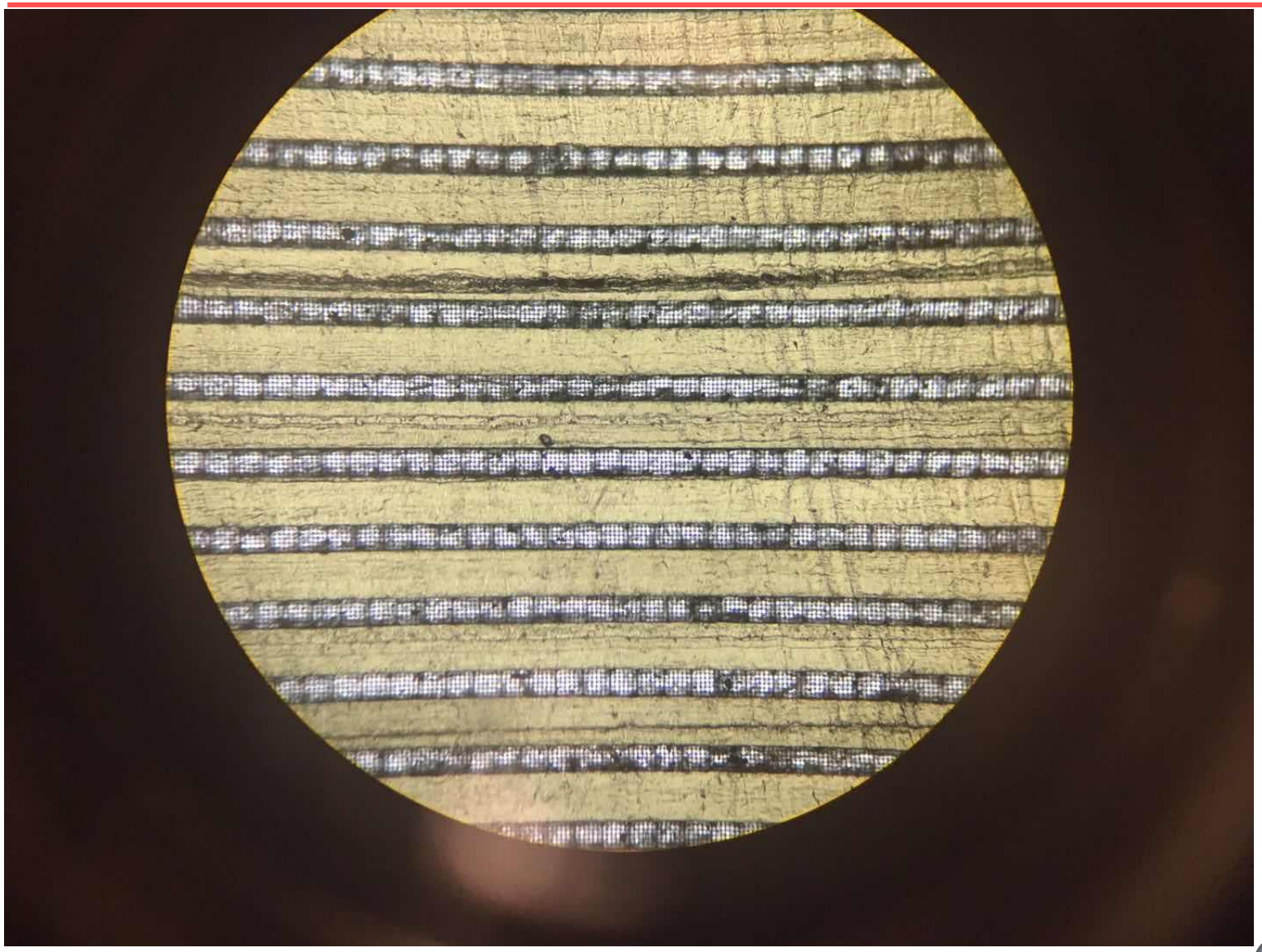


Output

LIP Intput – Before Polishing



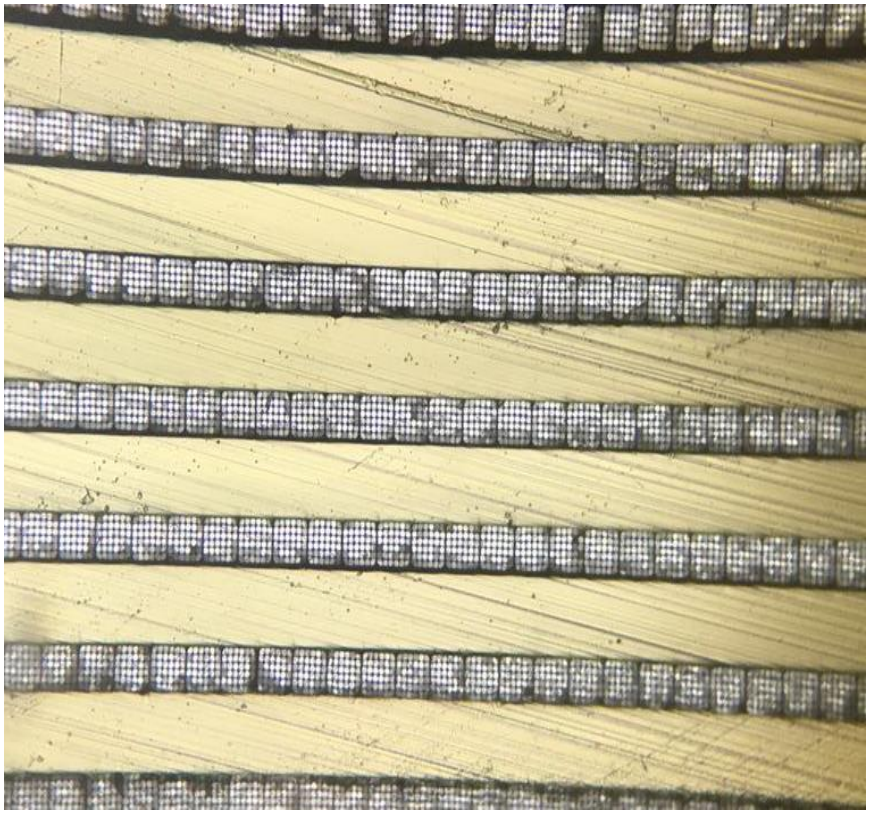
LIP Output – Before Polishing



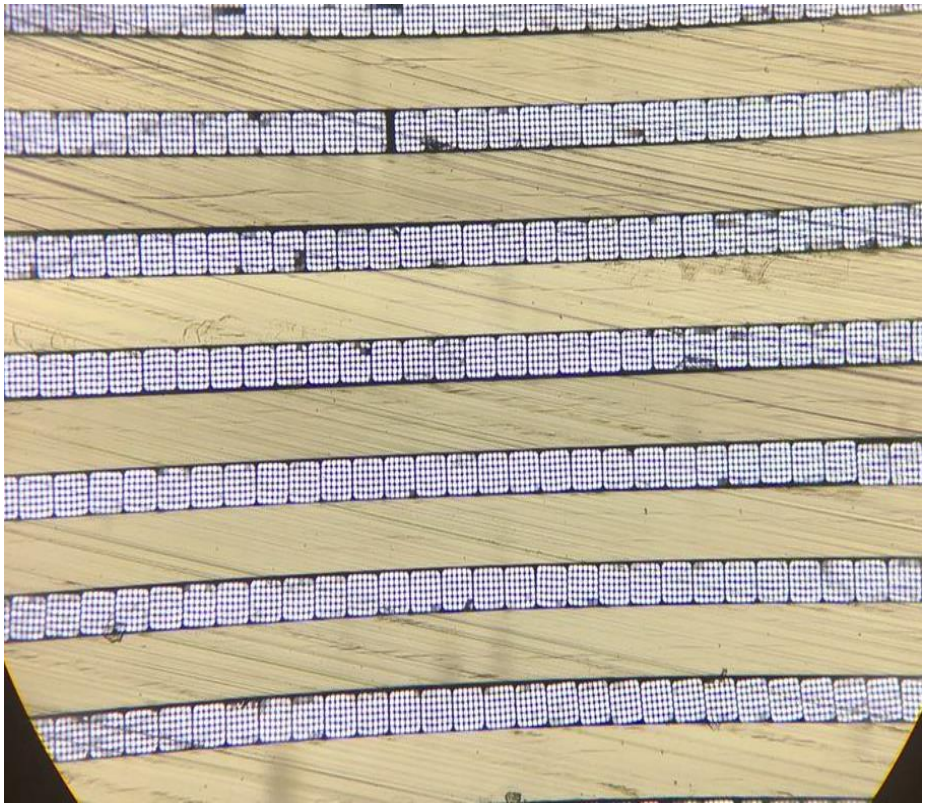
Earth Science Technology Office

Water polish

before

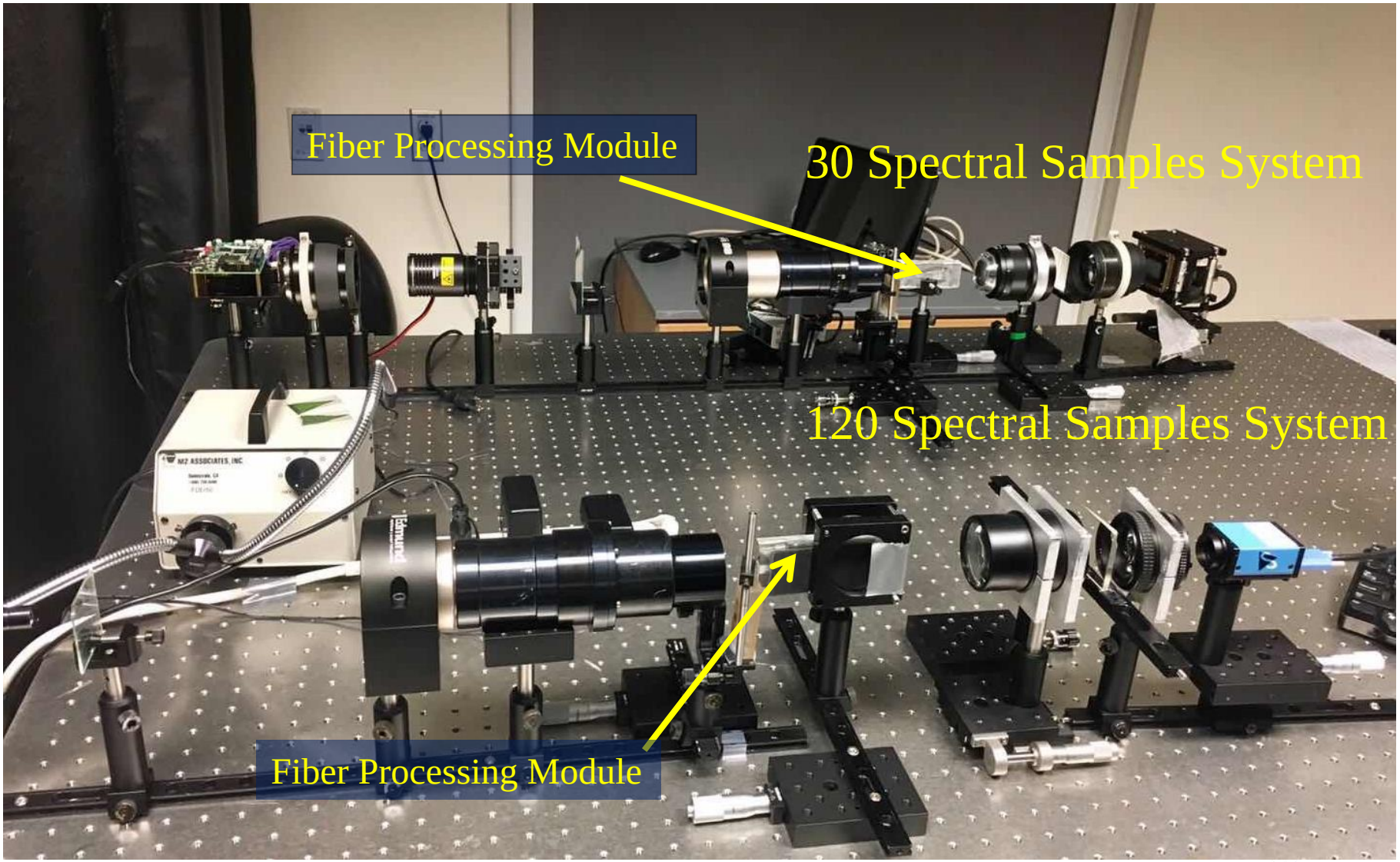


after



Polishing process significantly improves fiber face quality
Longer polishing time and change of polishing material allows achieving necessary <10 nm roughness

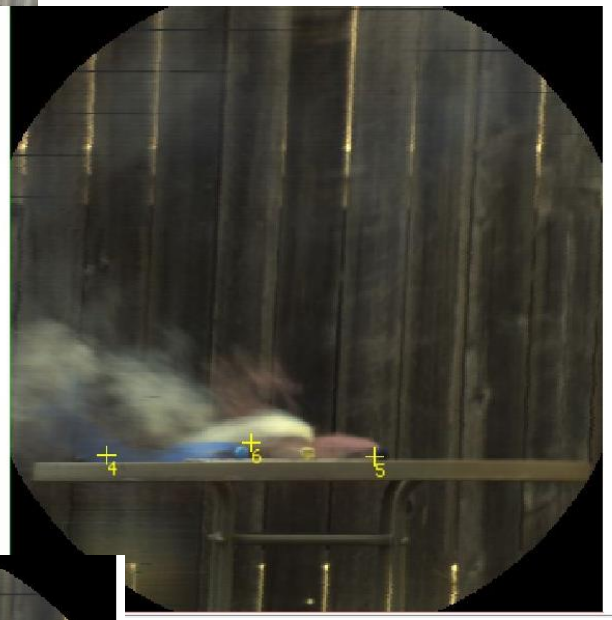
Benchtop Prototypes

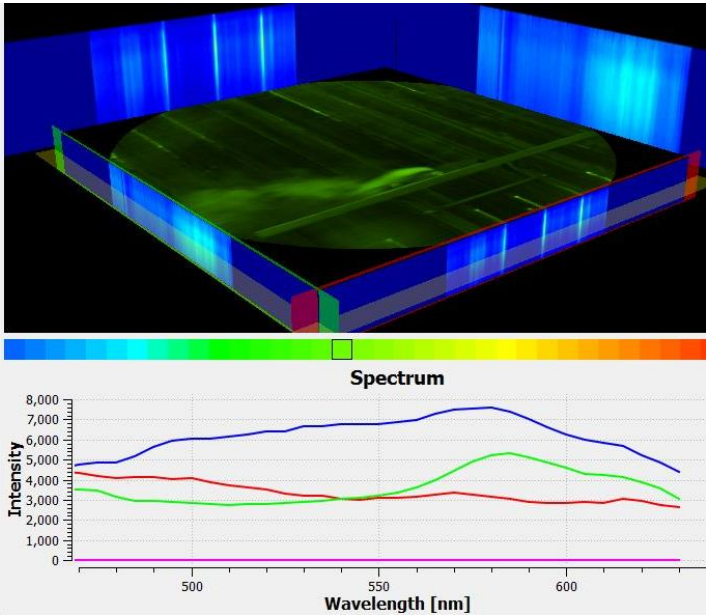


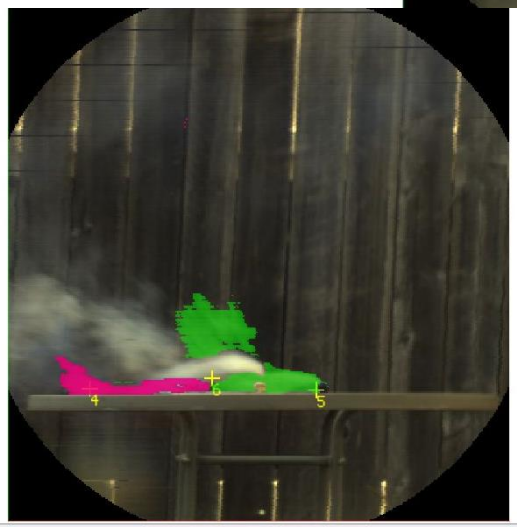
System Level results

SNAP-IMS Reference Results

Gas Detection

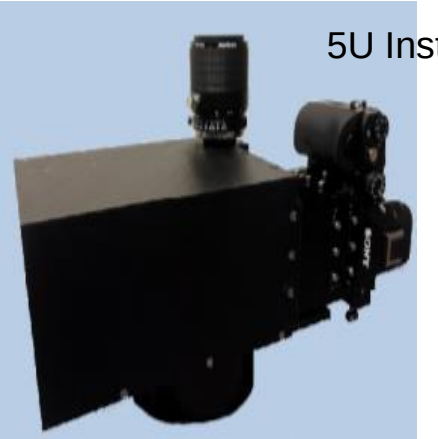






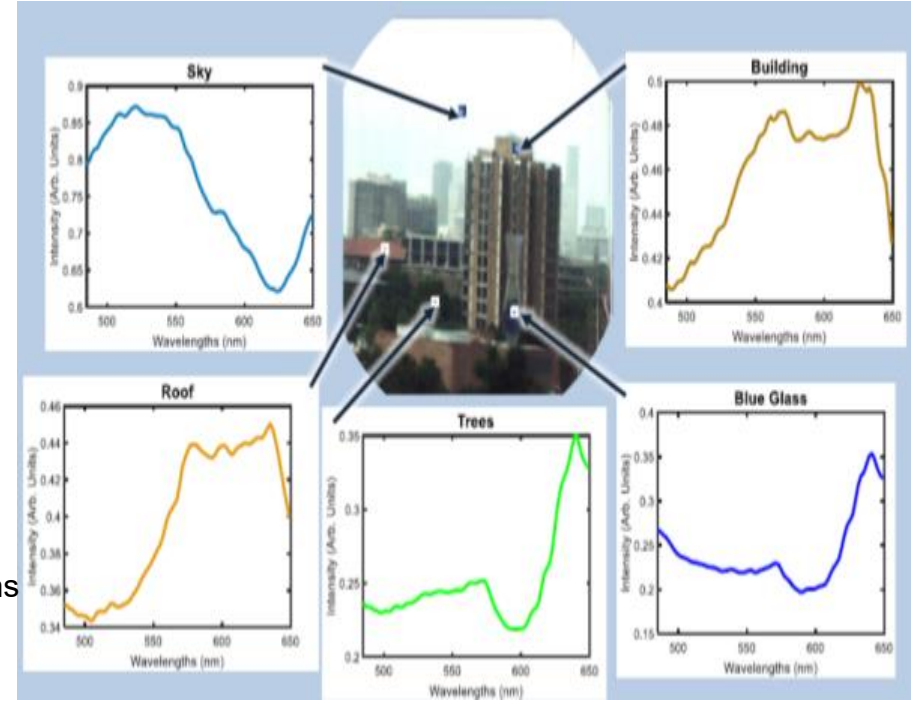
RT.Kester, N.Bedard, TS. Tkaczyk, Image mapping spectrometry – a novel hyperspectral platform for rapid snapshot imaging, Proc. of SPIE Vol. 8048, April 2011

Mirror Based – compact image slicing/mapping system – cont.



5U Instrument

J.Dwight et. al, poster presentation at Hyspiri Workshop, Caltech, October 2017



J.Dwight et. al, poster presentation at Hyspiri Workshop, Caltech, October 2017

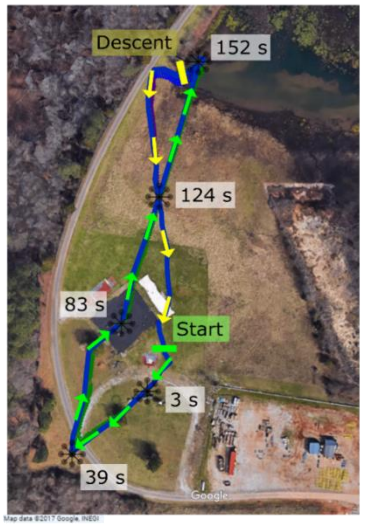
- A cost effective platform for environmental sensing applications that include monitoring water quality, land use, air pollution, vegetation and agriculture.
- Small size, power, and weight of payloads allows for a wider range of applications, incorporation of additional instrumentation or the augmentation of flight parameters such as altitude, distance and duration.
- System demonstrates high light-throughput.
- Hyperspectral datacubes can be acquired at 1/500 sec to 1/100 sec, eliminating motion artifacts
- Applications include monitoring plant pigmentation, vegetation state, leak detection at petrochemical plants, and urban sustainability, lightning etc.

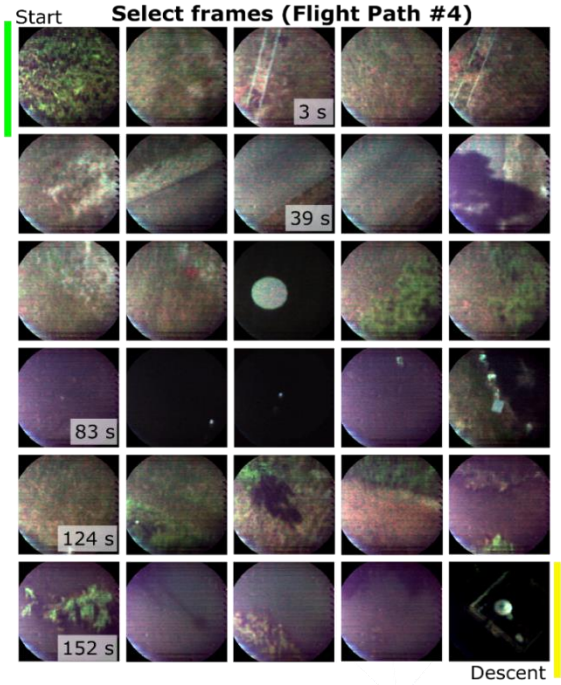
Supported by NASA Cooperative Agreement Notice (CAN) No. NNM16567212C for Dual-Use Technology Development at MSFC

Mirror Based – compact image slicing/mapping system – cont.

Photos taken of the flight. Shown is the SNAP-IMS with its UAV mounting bracket (left), the SNAP-IMS/UAV integration (center), and the drone midflight with the SNAP-IMS (right).

Proc. SPIE, April 2018, Orlando, FL
Defense and Commercial Sensing 2018



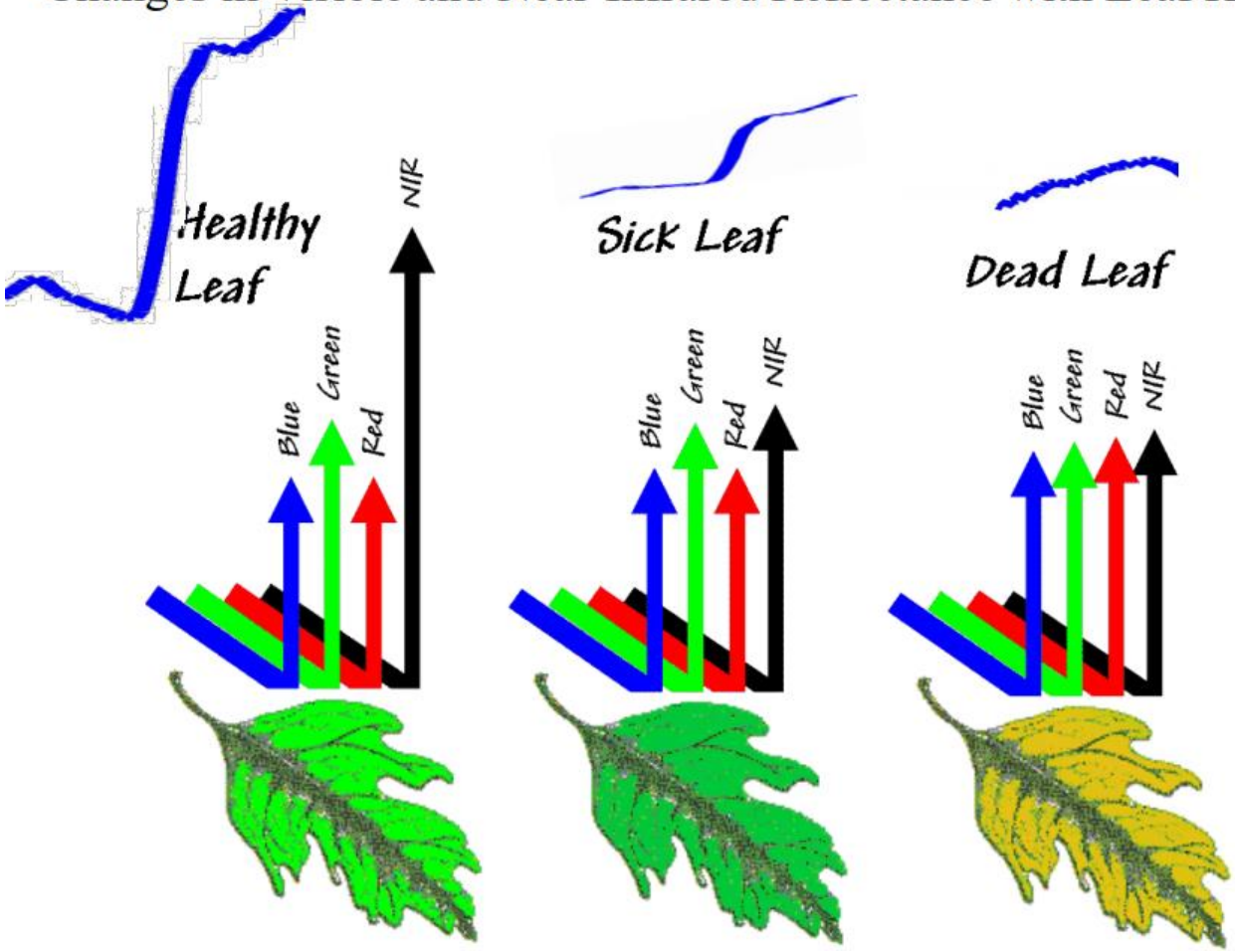


The flight path of #4 with select frames and their corresponding times

Test flights performed in collaboration with NASA MSFC

Supported by NASA Cooperative Agreement Notice (CAN) No. NNM16567212C for Dual-Use Technology Development at MSFC

Changes in Visible and Near-Infrared Reflectance with Leaf Health



SNAP-IMS imaging (chlorophyll content)

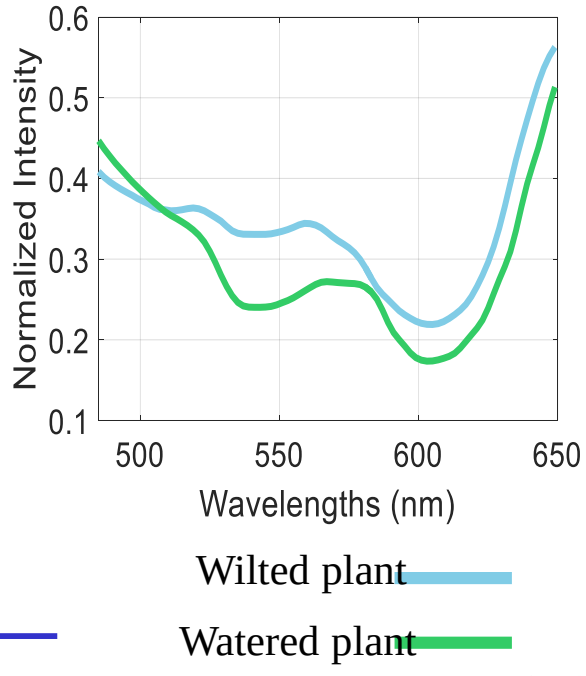
Canopy							
Specific observational targets	**Line centroid(s) [nm]**	**Sub-band [nm]**	**Spectral sampling (no of samples in sub-band)**	**Spatial resolution**	**Experiment Type**	**SNR**	**Snapshot, Tunability, and Other Features of TuLIPSS**
Leaf Chlorophyll Content at the Canopy Scale (Triangular Greenness Index-TGI)	670 550 480	630-690 520-600 450-520 or Broadband 400-700	24 32 20 100	<30	Reflectance $TGI = -0.5[(670 - 480)(R_{670} - R_{550}) - (670 - 550)(R_{670} - R_{480})]$	TBD	Spectral sampling change (Tunability) or Bandwidth Change (Tunability)

Wilted plant

TGI value = 12.6

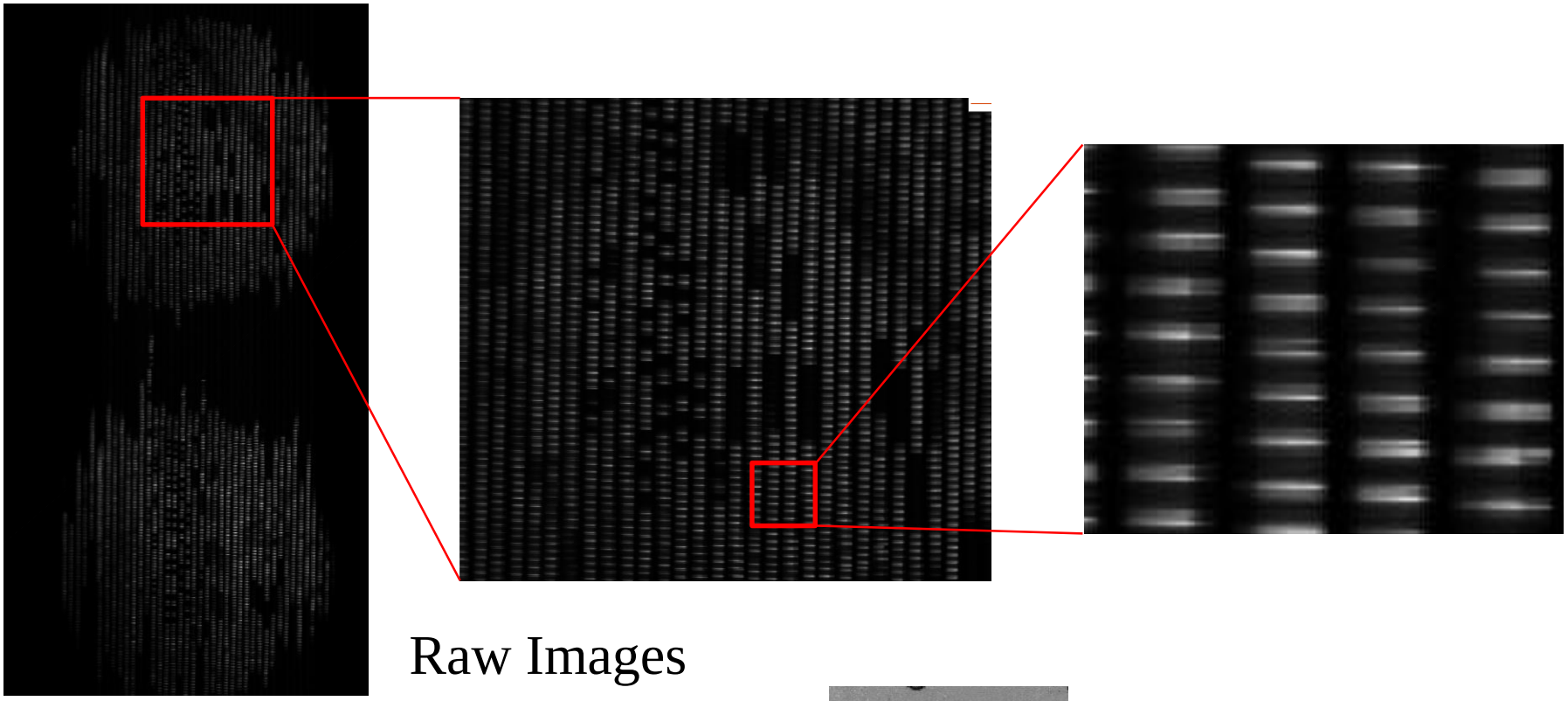
Watered plant

TGI value = 21.7

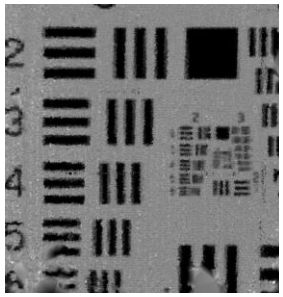


TuLIPSS Imaging

USAF 1951 Resolution Target



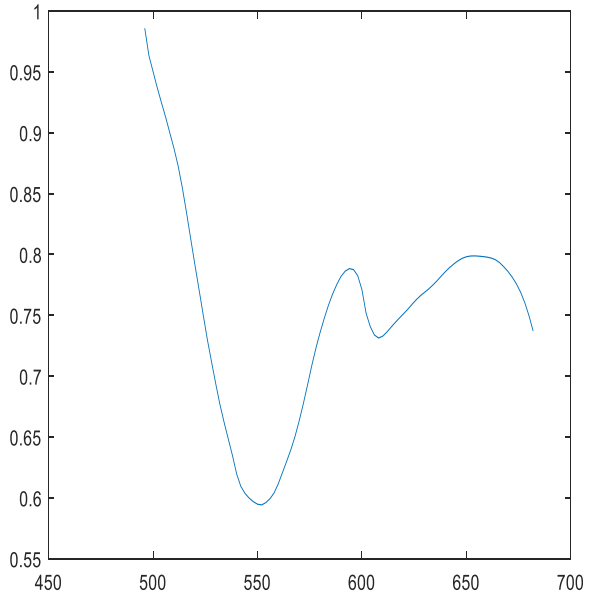
Raw Images



Reconstructed Image

TuLIPSS Imaging Results

- Leaf
  - Averaged absorbance spectrum



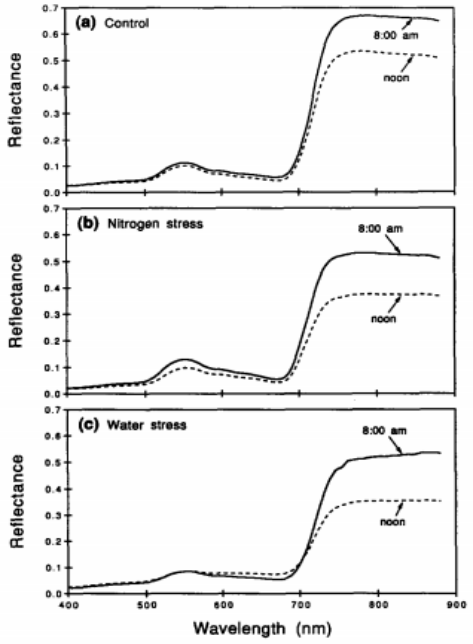
TuLIPSS Functionality vs Science Applications

Science Applications

Science: Vegetation (Land)

Chlorophyll and Xanthophyll (carotenoids) monitoring via vegetation indexes

1. Precision Agriculture – Nitrogen and water stress detection within hours [ref. 1, 2, 3]
   - **TuLIPSS advantages: Tuning via band-pass filters or spectral sampling over VIS/NIR detector spectral range**
   - Centroids:
     - 539 nm (e.g. Xantophyll fluorescence - sun flower canopy) [ref. 2]
     - 690 nm, 740 nm – Chlorophyll fluorescence [ref. 3]
   - Band-pass filter bandwidth (sub-windows) ca. 100 (Xantophyll) or 200 (Chlorophyll), spectral sampling per sub-windows: 10, 20, respectively
2. Precision Agriculture – Vegetation senescence (via plant senescence reflectance index, PSRI) [ref. 4]
   - **TuLIPSS advantages: Tuning via or spectral sampling over VIS/NIR detector spectral range**
   - Centroids:
     - 678, 500, 750 nm
   - Sampling across 400 – 750 nm: 250 samples (effective spectral resolution 1.4 nm)
3. Photochemical reflectance, normalized difference vegetation and other indexes for forest canopies [ref. 5]
   - **TuLIPSS advantages: Tilting capability (snapshot) and tuning via spectral sampling across VIS/NIR**
   - **Other snapshot advantages**
     - Cross-track scanning for imaging scenes adjacent to "along-track" direction
     - Increasing survey area
   - Centroids:
     - 440, 531, 570, 680, 694, 700 , 715, 726, 734, 740, 747, 750, 760, 800 nm
   - Number of samples: 250 per 400-1000 nm



Science: Vegetation (Water)

Chlorophyll and Phycocyanin detection and measurement - Algal Blooms and Phycocyanin colonies

1. Algae identification and algae growth monitoring [ref. 6]
   - **TuLIPSS advantage: Spectral sampling change and bandwidth change (with band-pass filter) (tunability) and tilting for sun glint correction (snapshot)**
     - **Other snapshot advantages**
       - Cross-track scanning for imaging scenes adjacent to "along-track" direction
       - Increasing survey area
       - Mitigate cloud cover issues
   - centroid line: 700 nm (monitoring)
   - sub-window: 650-760 nm (w/ band-pass filter)
   - Number of samples in sub-window: 100 (ca. 1 nm effective spectral resolution)
2. Measurement of cyanobacterial phycocyanin concentration [ref. 7]
   - **TuLIPSS advantage: Bandwidth change (tunability) and tilting for sun glint correction (snapshot)**
     - **Other snapshot advantages**
       - Cross-track scanning for imaging scenes adjacent to "along-track" direction
       - Increasing survey area
       - Mitigate cloud cover issues
   - Centroids: 620, 665, and 708 nm
   - Sub-windows: +/-50nm per centroid
   - Number of samples in sub-windows spectra: 10(
     (effective resolution 1 nm)

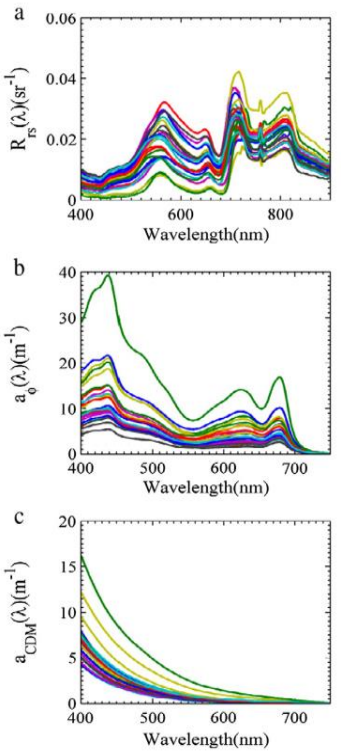
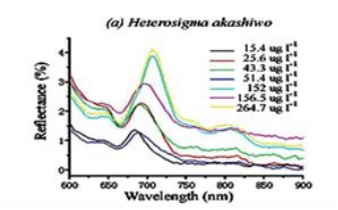
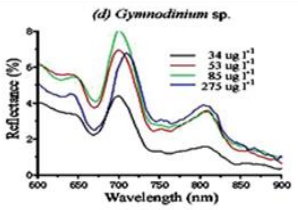
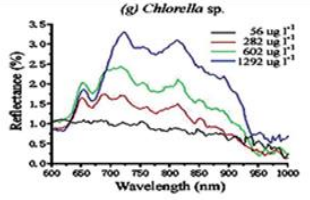


Fig. 1. (a) $R_{rs}(\lambda)$ spectra collected from aquaculture ponds in July 2010 and April 2011, (b) measured phytoplankton absorption coefficients, $a_\phi(\lambda)$, using filter-pad technique, and (c) measured $a_{CDM}(\lambda)$.







ESTO
Earth Science Technology Office

Science: Sediments (Water)

Total suspended solids (TSS)

1. Estimation of TSS [ref. 8]
   - **TuLIPSS advantage: bandwidth selection** [ref. 8] **and tilting for sun glint correction (snapshot)**
   - Centroids: 645 and 859 nm, sub-bands: 614 – 681 nm, 820-902 nm
   - Number of samples in sub-windows: 10 (effective resolution 8 – 9 nm)
2. Study of suspended particulate matter in rivers [ref. 9]
   - **TuLIPSS advantages: tilting capability for sun glint correction (snapshot)**
   - Centroids: 443, 483, 561, 655, 855 nm
   - Number of samples in broad band spectra: 250 (effective resolution 2.4 nm)

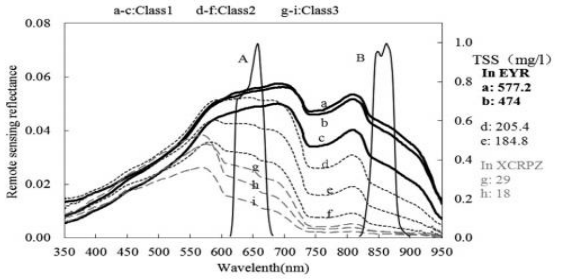


Fig. 2. The relationship between reflectance of MODIS 250-m Rrs(B1) and TSS (mg/l).The reflectance of MODIS 250-m Rrs(B1) is less than 0.025 when TSS is below ~31 mg/l ($N = 26$), and reflectance of MODIS 250-m Rrs(B1) is greater than 0.025 when TSS is above ~31 mg/l ($N = 34$).

Science: Atmosphere

Atmospheric gas measurement

1. NO3 measurement [ref. 10]
   - **TuLIPSS advantage: Bandwidth change – tunability around lines of interest (e.g. band-pass filters) and increased SNR (via pixel binning)**
   - Centroid line: 662 nm (absorption cross-section)
   - Sub-window: 640 – 680 nm
   - Number of samples in sub-window: 250 (better than 0.2 nm resolution)
2. O2 measurement [ref. 11]
   - **TuLIPSS advantage: Bandwidth change – tunability around lines of interest (e.g. band-pass filters) and increased SNR (via pixel binning)**
   - Centroid line: 760 nm [ref. 11]
   - Sub-window: 740-780 nm
   - Number of samples in sub-window: 250 (better than 0.2 nm resolution)

SWIR Applications

1. Disaster monitoring/mitigation (augmented with TIR)
   - Volcanic CO2 absorption features at 1270 nm and 1610 nm [ref. 12]
   - Tuning capability:
   - centroid wavelength and bandwidth for each absorption line (band-pass filter–based tuning – coarse tuning) - +/- 75 nm
   - number of samples – (fine tuning)
     - TuLIPSS potential: 250 samples or 0.4 nm resolution (compared to 10 nm resolution in MODTRAN simulation)

2. Synoptic Measurements in Urban Landscape: Normalized Difference Built-up Index (NDBI) [ref. 13] (augmented with TIR)
   - No centroids, sub-windows: NIR =760-900 nm and SWIR = 1550-1750 nm
   - $NDBI = \frac{SWIR-NIR}{SWIR+NIR}$

Current TuLIPSS Activities/Improvements

- Decreasing bundle dimensions (below 1 inch input) – smaller individual fiber diameter (10 microns and below)
- Optimizing throughput – fiber NA and coupling (lenslet array)
- Increasing spatial sampling (targeted 400x400)
- Elastic tuning (1-2 second mode switching) of fiber distance
  - Mechanical actuators
  - Magnetic
  - Pneumatic
- Dispersion and bandwidth tuning (selection of sub-bands and spectral sampling)
- ROI dynamic range tuning

Summary

– Field distribution techniques

- Can increase system throughput and enable fast imaging or better SNR
- Allow Optimizing DATA transfer
- They require limited data reconstruction
- Several hardware options are available for further developments

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