Development of Multi-Edge Slant Target for Unlocalized MTF Measurement of Airborne Imaging System Payloads

Kylel Scott
Carey Scott, Hyun Jung Kim, and Matthew Boyda

Matthew Boyda
SAMI System Engineer
NASA/LaRC

Carey Scott
SCIFLI Principal Investigator
NASA/LaRC

Hyun Jung Kim, PhD
SAMI Project Manager
NASA/LaRC

Kylel Scott
SCIFLI Research Engineer
NASA/LaRC

SCIFLI *Scientifically Calibrated In-Flight Imagery Team*

- **The Scientifically Calibrated In-Flight Imagery** (SCIFLI) **team** is a committed and close-knit group of engineers, scientists, and subject matter experts. The team has a two-decade-long proven track record of delivering flight-truth datasets, with over 60 missions ranging in complexity across all flight regimes. Our engineering datasets help investigators truly understand the behavior of vehicles under extreme flight conditions.
- **Objective**: Produce high-quality, image-based engineering data to advance the understanding of spacecraft ascent, reentry and recovery systems and hypersonic vehicle performance across diverse flight conditions
- **Mission Portfolio:**
  - Collaborations for Commercial Space Capabilities (CCSC-2)
  - Artemis Program: Orion and Space Launch System (SLS)
  - NASA Heliophysics/Science Mission Directorate
  - Hypervelocity asteroid sample return
  - Commercial Crew Program (CCP)
  - Hayabusa 2 (JAXA)
  - OSIRIS-REx
  - 2024 Chasing The Eclipse

Land and Sea-based platforms

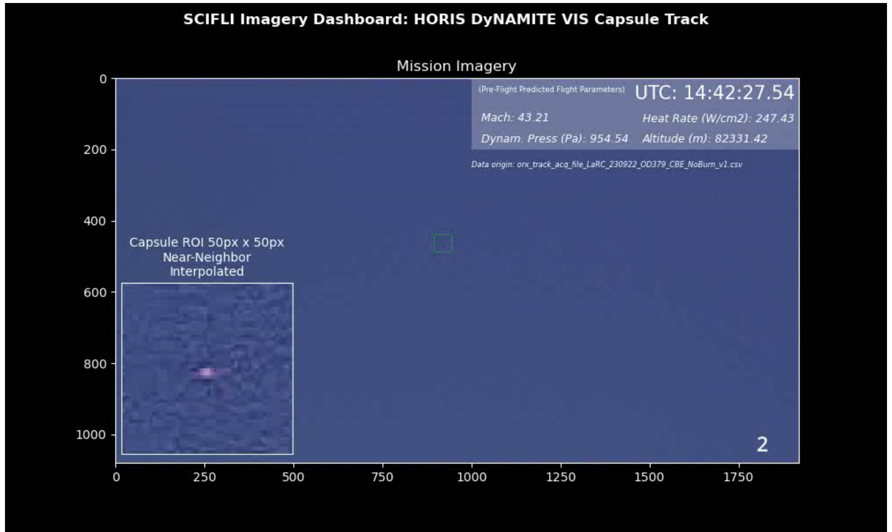
- ❑ Mobile Aerospace Reconnaissance Systems (MARS)
- ❑ Telescience Research and Technology Support (TRaTS)

Airborne imaging platforms

- ❑ WB-57 (JSC)
- ❑ Gulfstream (LaRC, JSC, AFRC)
- ❑ P-3 Orion (Navy)
- ❑ Global Hawk (AFRC)
- ❑ Boeing 777 (LaRC)

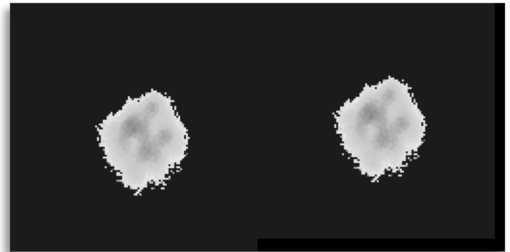
** Technical Readiness Level: in development

OSIRIS-REx
Re-Entry



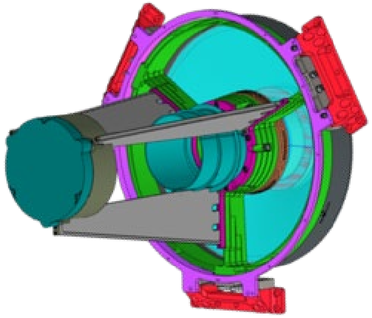
Artemis 1 On Pad

Artemis 1 BHS Calibrated Thermal
Stabilization



SAMI *SCIFLI Airborne Multispectral Imager*

A customizable & cost-effective aircraft-agnostic multispectral imaging testbed designed to collect plume and surface temperatures during Artemis I ascent.



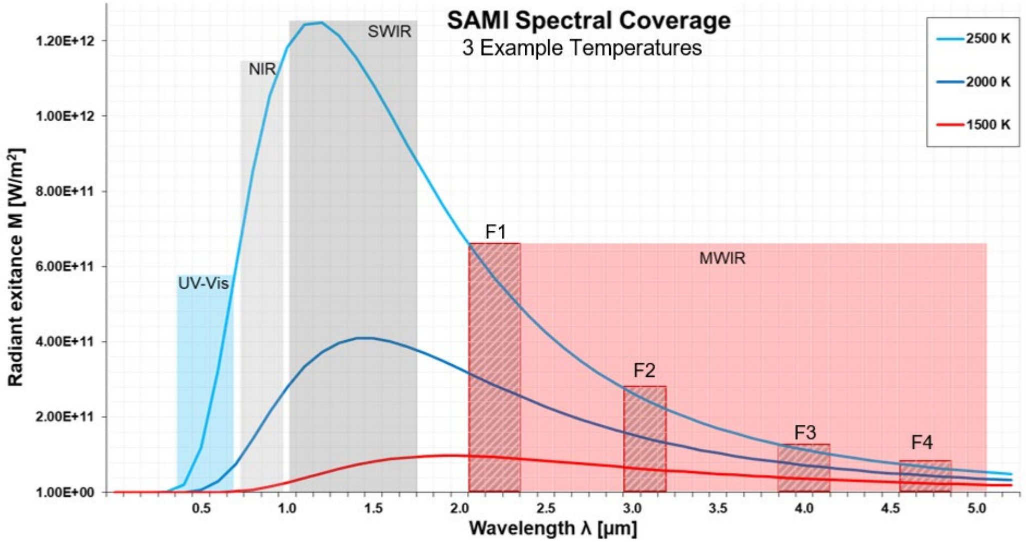
Key Capabilities

- Passive and active thermal control
- Integration within pre-existing platforms
- Multiple sensors (UV-VIS to MWIR)
- High image quality
- Semi-modular design to support mission adaptability

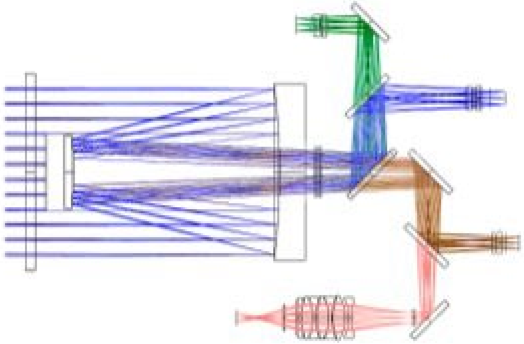
Mission Portfolio *to date*

NASA Artemis 1 Launch
SPACEX Starship Launch
SPACEX CRS-27 Return
NASA OSIRIS-REx Capsule Return

SAMI WB-57 aircraft config.



SAMI Telescope Optical Diagram



Development of Multi-Edge Slant Target for unlocalized MTF Measurement

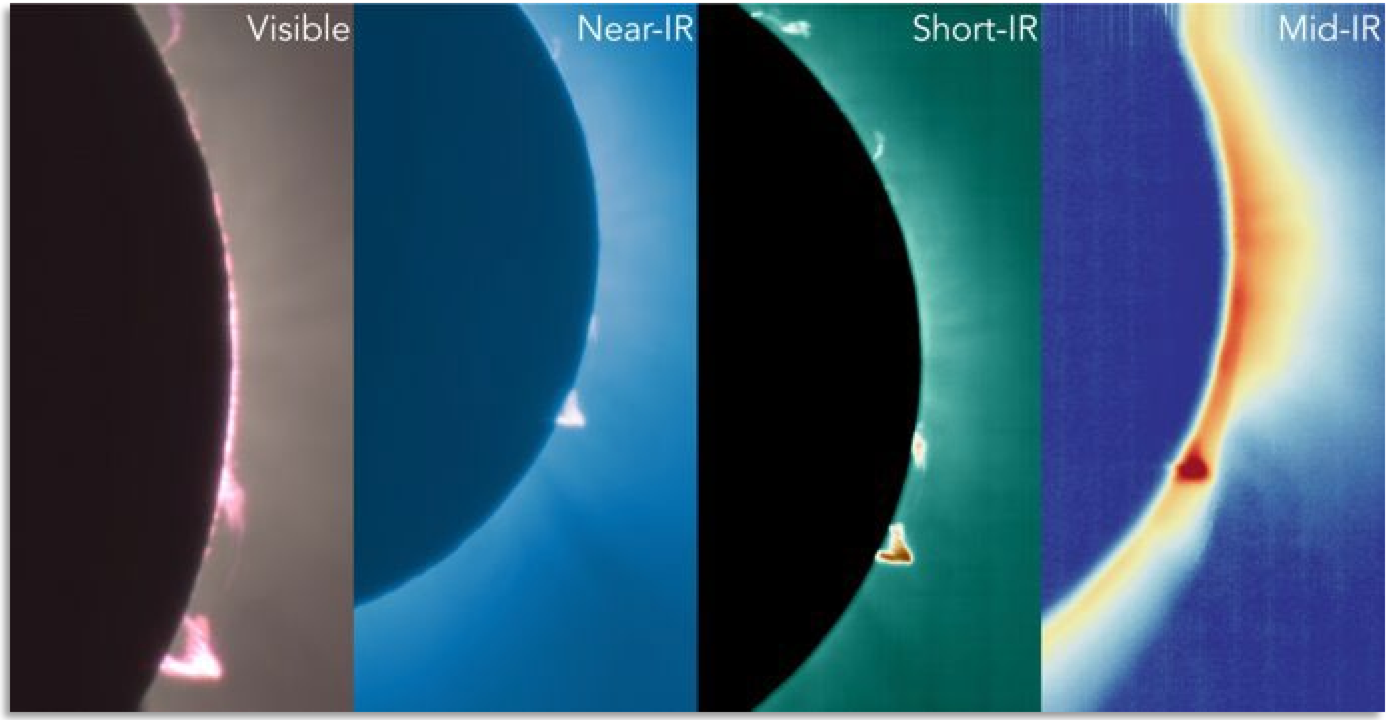
Motivation

- Desire to **validate** the **optical performance** build specifications of **SCIFLI utilized airborne imagers** (SAMI-included) and characterize spatial performance of said imagers in their flight-ready configuration for post-flight data processing and documentation

Approach

Design an approach to **experimentally characterize the Modulation Transfer Function (MTF)** of airborne **imaging assemblies** in a **lab environment**

- The resolution performance of each **band specific optical sub-assembly** of SAMI
    - Controlled wavelength and subject between sensor and optics measurements
    - Spatial consistency with respect to discrete locations on 2D image array for direct comparison of characterizations across image array



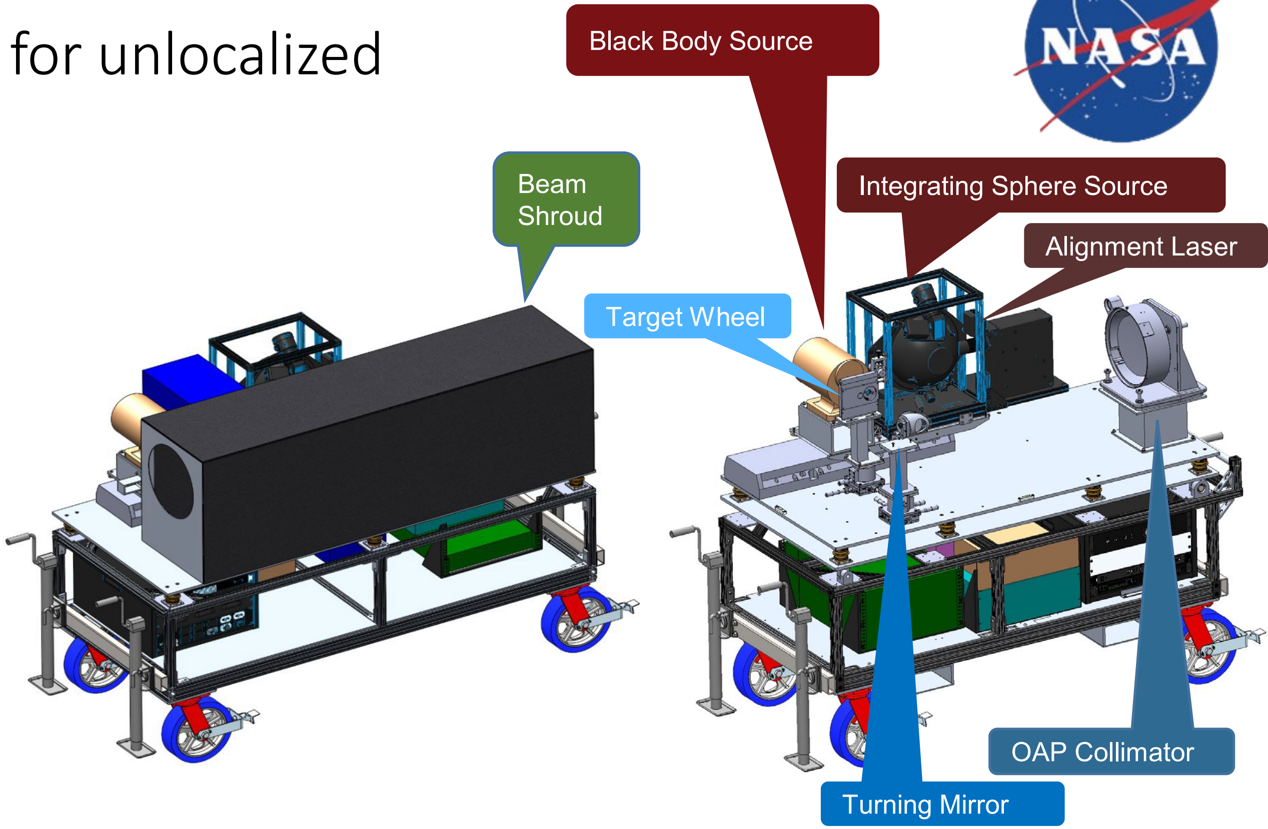
2024 Total Eclipse
SAMI Multispectral Coverage

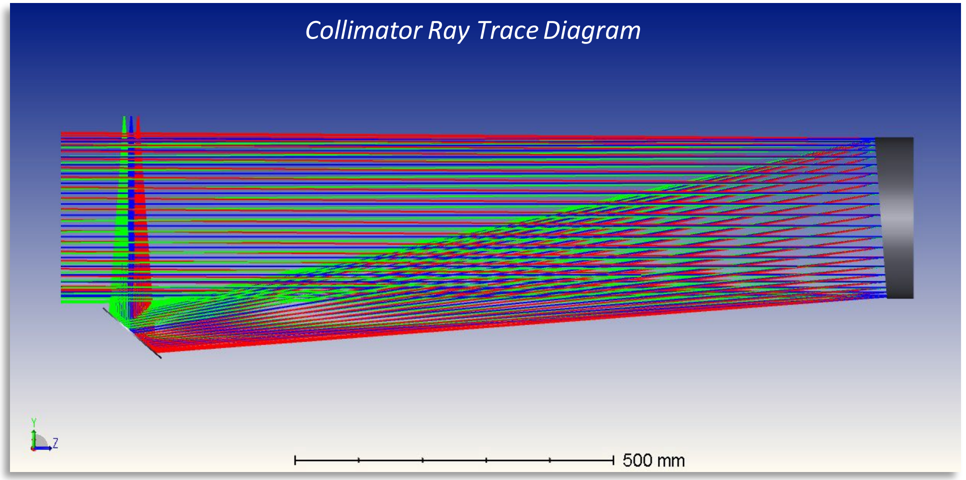
Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Background | Spectral and Spatial Calibration Capabilities

- The SAMI Calibration Cart (SCC) is a dedicated calibration system optimized to the SAMI system spectral regions of interest.
- This experimental setup allows for radiometric and spatial calibrations for long focal length (airborne) imagers to take place on the ground

- **Component Overview**
    - **Sources**. Sources cover desired spectral range for SAMI
        - One blackbody
        - One integrating sphere system
        - Alignment Laser
    - **Collimator**. Collimates light from sources and reflects it toward the sensor system
        - Off-axis parabolic (OAP) mirror
        - Fold mirror
    - **Filter wheel**. Various targets for aligning and characterizing sensors
        - Positioned with aperture at OAP focus



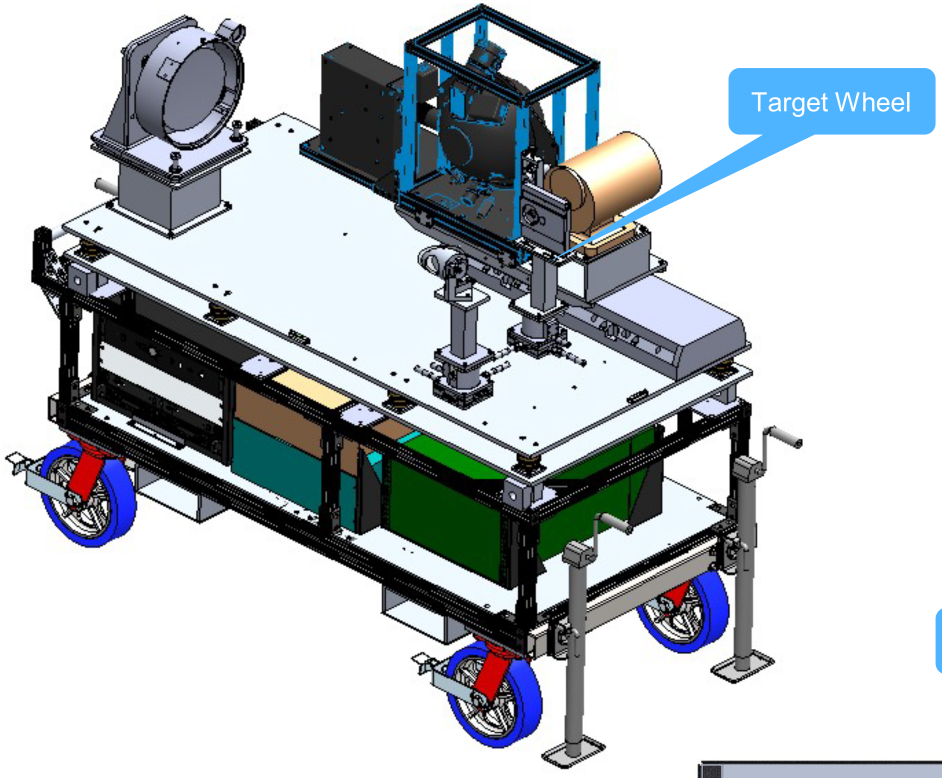


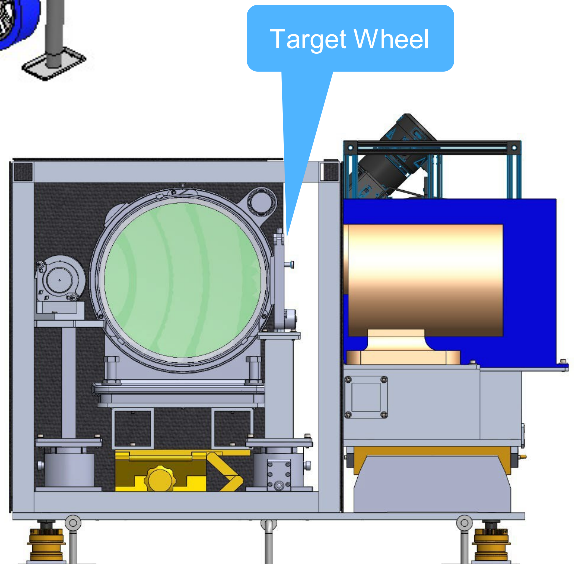
Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Background | Approach

Design Considerations

1. Calibration Cart Compatibility
    1. Utilizing the Calibration Cart would allow for lab set-up
    2. Integrating with the pre-existing Target Wheel setup would provide best repeatability
2. Assume Spatial Variance with optics
    - Compute MTF via slant edge approach
        - Allows for precise discrete sampling of MTF across the sensor plane
        - Easier to manufacture for backlit experimental setup
        - Less sensitivity to noise
3. Spectral Consistency with Target
    - Backlit experimental setup
    - Black body or Integration sphere source
    - Minimal experimental setup reconfiguration
    - Repeatability



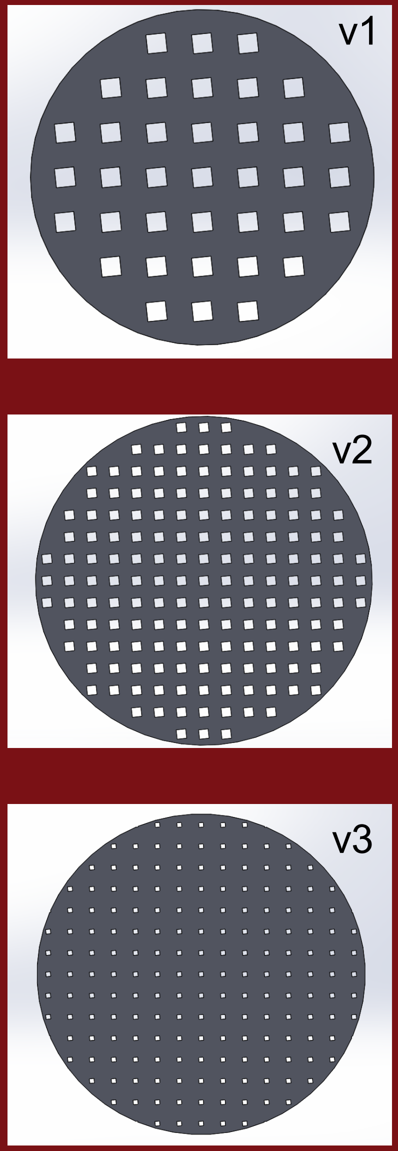


Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Plate Design

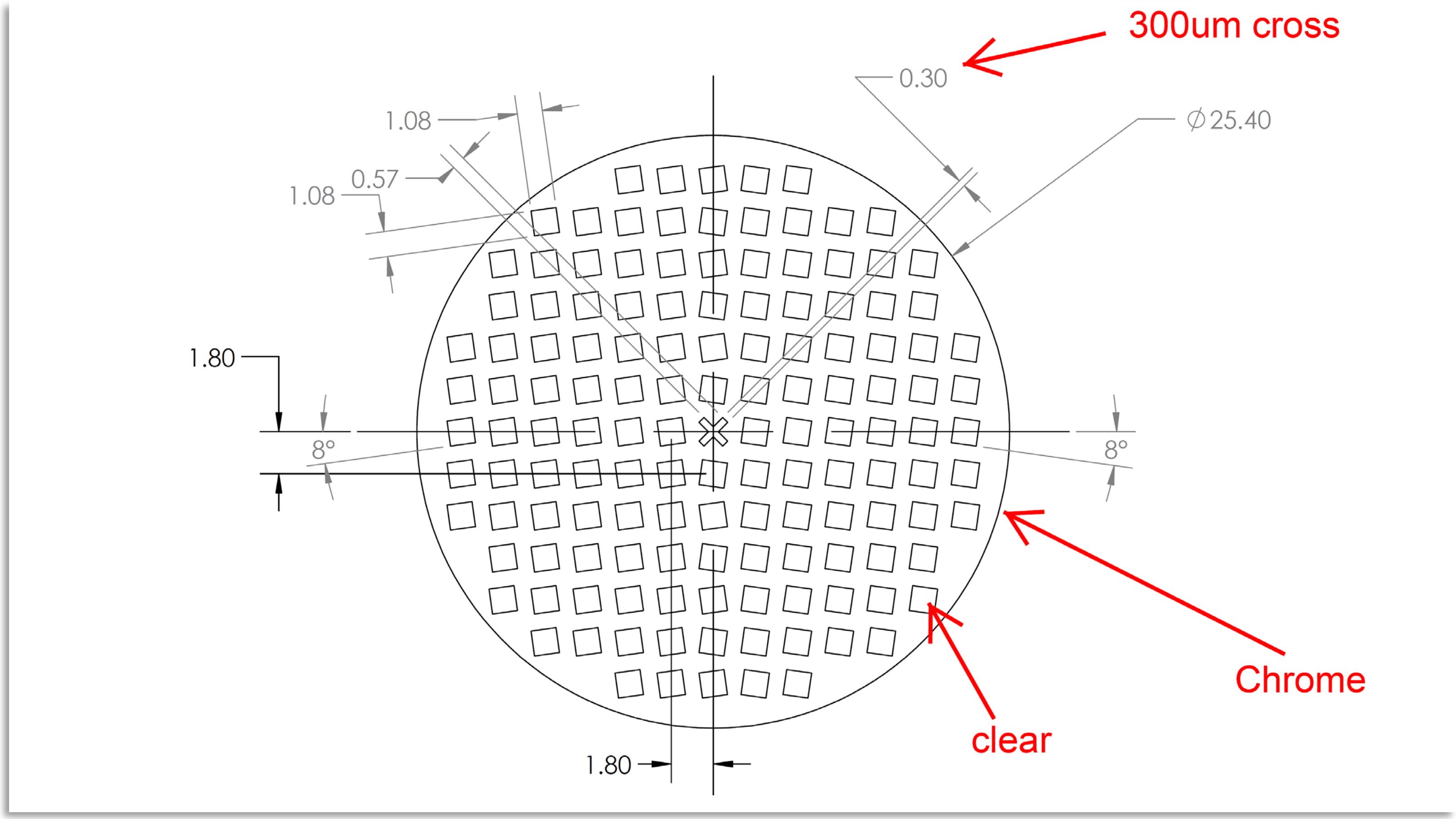
- **Custom Calibration Plate Design**
  - Provide custom target design that can be used for spatially variant MTF Analysis.
    - MTF will differ at different locations on image sensor
    - Slant Edge Method with half-moon provides 1D analysis for pixels around the edge
    - Target that provides 2D analysis is ideal for through characterization
- **Engineering Criteria**
  - 2D MTF Analysis
    - Requires Slant Edge
  - Distortion Analysis
    - Requires Grid pattern
- **Physical Constraints**
  - 1” dia. Circular part
  - Etchings/shapes < 1µm

MTF Plate Designs



Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Plate Fabrication

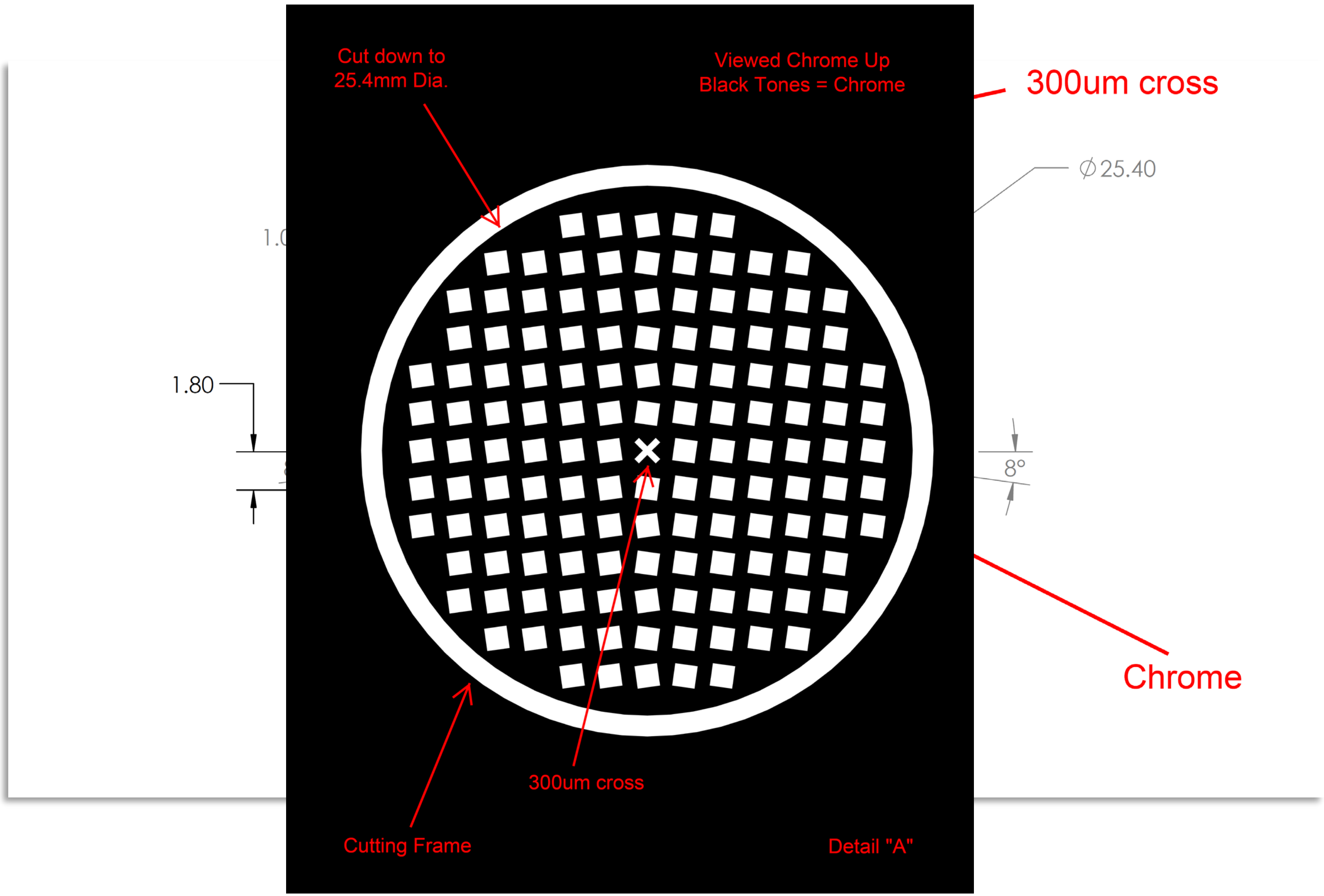


Fabrication Overview

- 1-inch size round Chrome (Cr) coated. quartz (fused silica) substrate.
- Square-shape pattern is clear (on quartz) and outside the pattern is dark (Cr coated quartz).
- Heidelberg laser lithography system (Model: DWL 66) uses for the patterning
  1. Design the MTF mask using CAD (.DXF file)
  2. Start with AZ1518 photo resist coated Cr on quartz substrate.
  3. Using the laser lithography system, exposed sample (left design), then developing, etching, and removing the photoresist
  4. The sample cuts down to 25.4 mm diameter (1” diameter)
- The pattern size tolerance is < 0.8 μm

Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Plate Fabrication



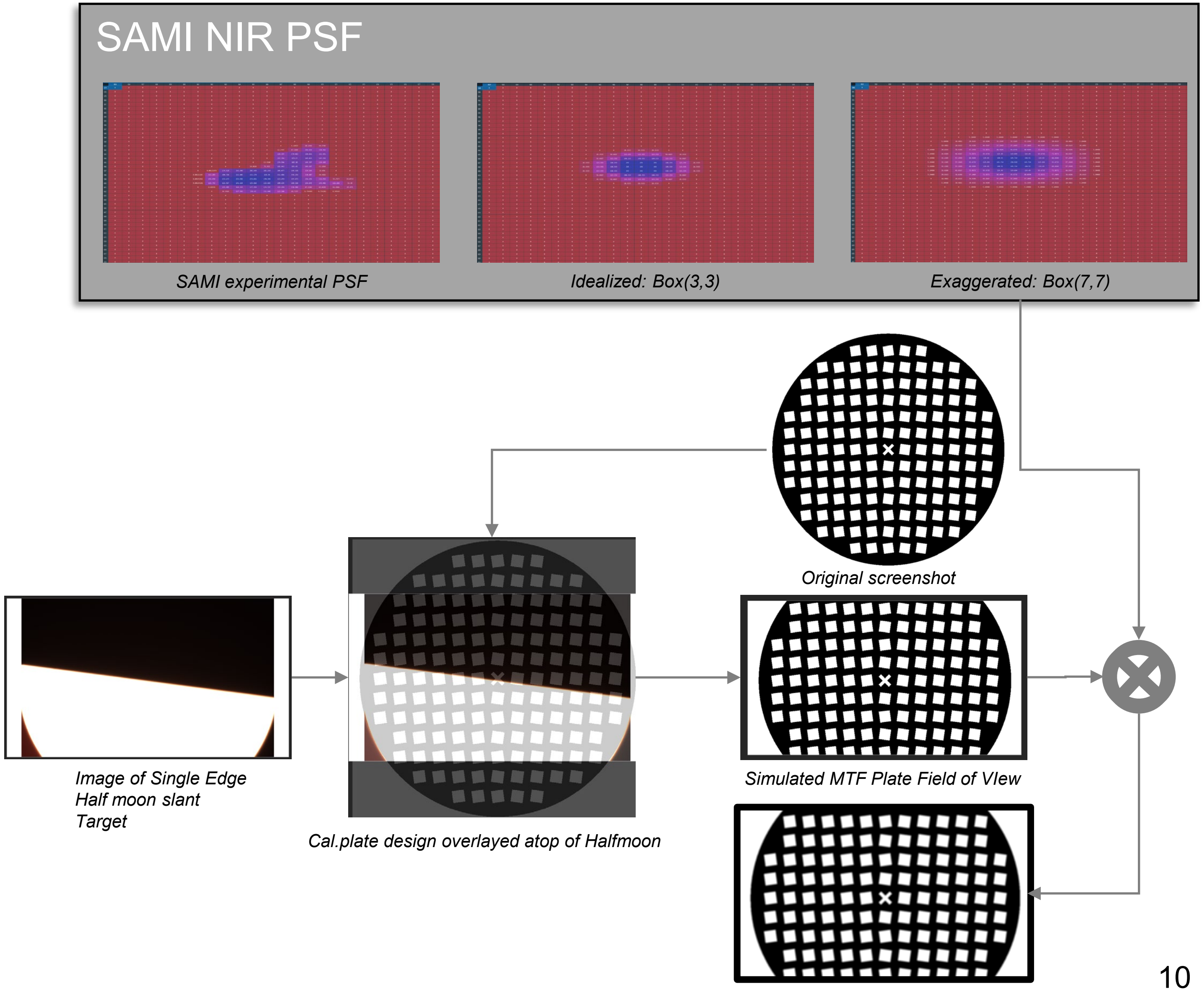
Fabrication Overview

- 1-inch size round Chrome (Cr) coated. quartz (fused silica) substrate.
- Square-shape pattern is clear (on quartz) and outside the pattern is dark (Cr coated quartz).
- Heidelberg laser lithography system (Model: DWL 66) uses for the patterning
  1. Design the MTF mask using CAD (.DXF file)
  2. Start with AZ1518 photo resist coated Cr on quartz substrate.
  3. Using the laser lithography system, exposed sample (left design), then developing, etching, and removing the photoresist
  4. The sample cuts down to 25.4 mm diameter (1" diameter)
- The pattern size tolerance is < 0.8 μm

Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Design | Validation

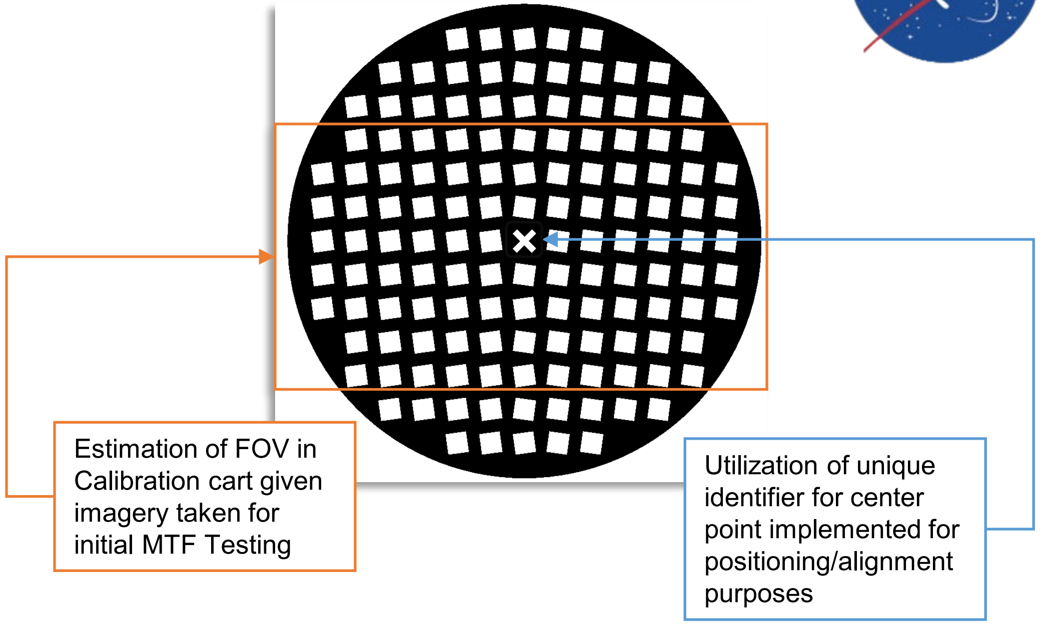
- Design Validation with Simulated Imagery
  1. PSF of SAMI was estimated, idealized, and exaggerated to assess tool on worse case scenario.
  2. Image resizing was performed based on FOV of HalfMoon imagery taken during previous testing sessions.
  3. Simulated FOV was blurred with exaggerated blur kernel to generate simulated view of calibration plate in Calibration Cart.

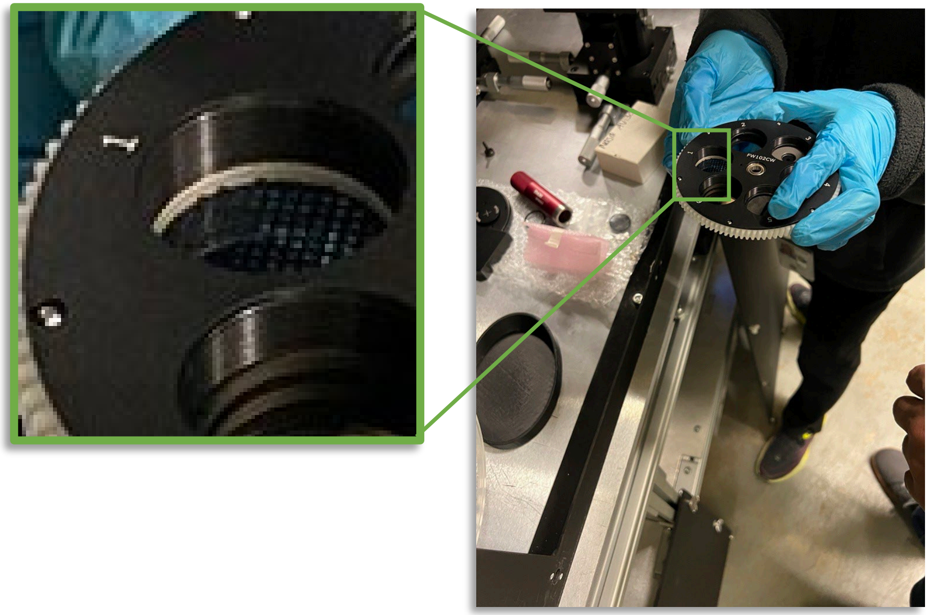


Development of Multi-Edge Slant Target for unlocalized MTF Measurement

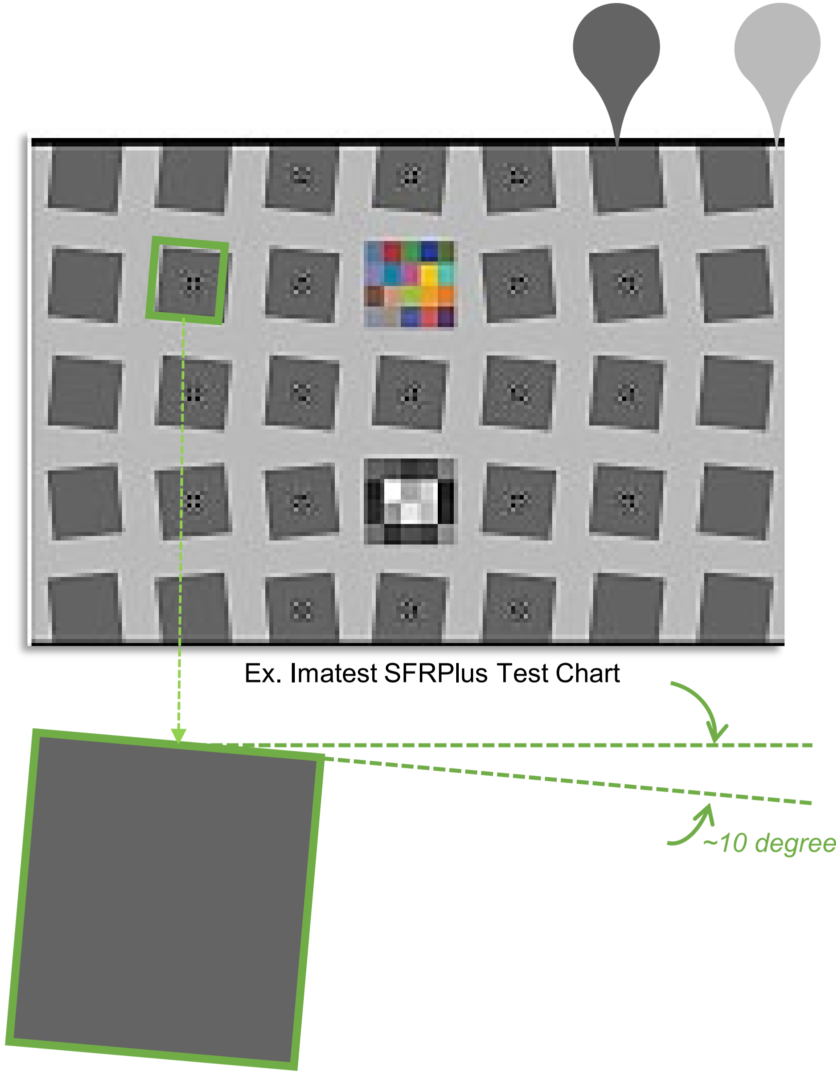
Design | Selection

- Final Plate Design
  - Pattern is suitable for MTF sampling across image sensor
  - Edge Spread Response has optimal sampling breadth and is distinguishable.
  - Super resolution: 4 adjacent columns can be used for sampling.





- Data Selection
  - Contrast
    - ISO 12233 standard of 1:4
      - Consistent with modern spatial calibration charts
      - Prevent saturation/blooming and over-estimation of MTF
  - Edge Alignment
    - Slant edge 10 degrees off-vertical/off-horizontal
    - Exclude 0 and pi/2 multiple degree angles



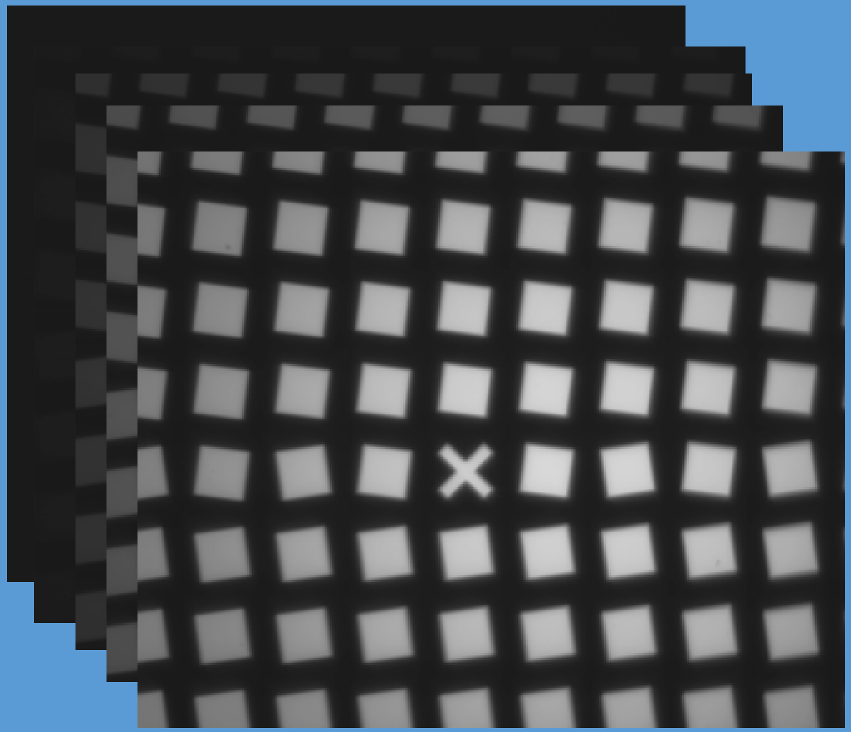
Ex. Imatest SFRPlus Test Chart

Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Procedure | Data Collection

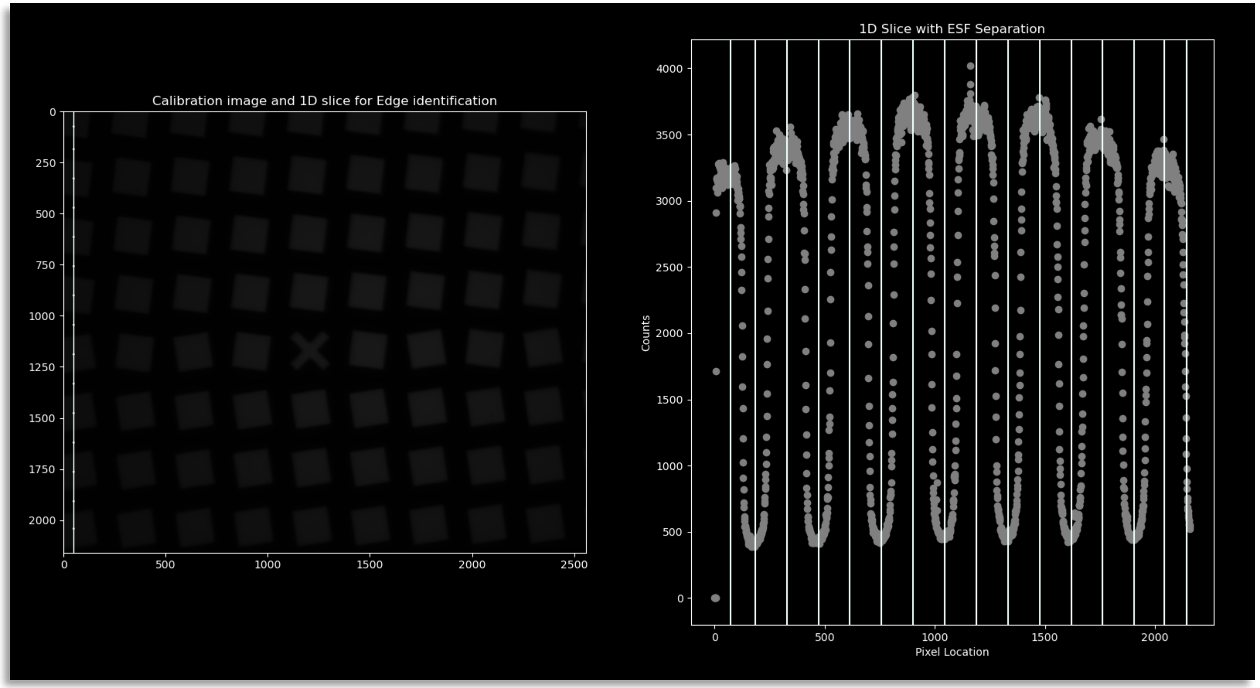
- Stills of the Calibration Target on ea. SAMI Camera at a sweep of temperature ranges
  - SAMI Sensor Under Test (SUT) edge Response
    - SAMI Cam0 (Narrow Field of View Visible)
    - SAMI Cam1 (Narrow Field of View Infrared)
    - SAMI Cam2 (Short Wave Infrared)
    - SAMI Cam3 (Mid Wave Infrared)
  - Experimental Setup Variables
    - Constant Exposure Time
    - Constant Gain
    - Temperature
      - Temperature Range: [50C - 400C] inc. 100C
      - Temperature Range: [400C – 1200C] inc. 50C

SAMI NIR Calibration Samples of MTF Target
Backlit with Black Body Source
Temp range: [50C – 1100C]



Data Processing

1. Edge detection and ESF cropping
2. Oversampling
3. Sigmoid fit for noise reduction
4. ESF to LSF via 1D derivative | LSF to MTF via FFT

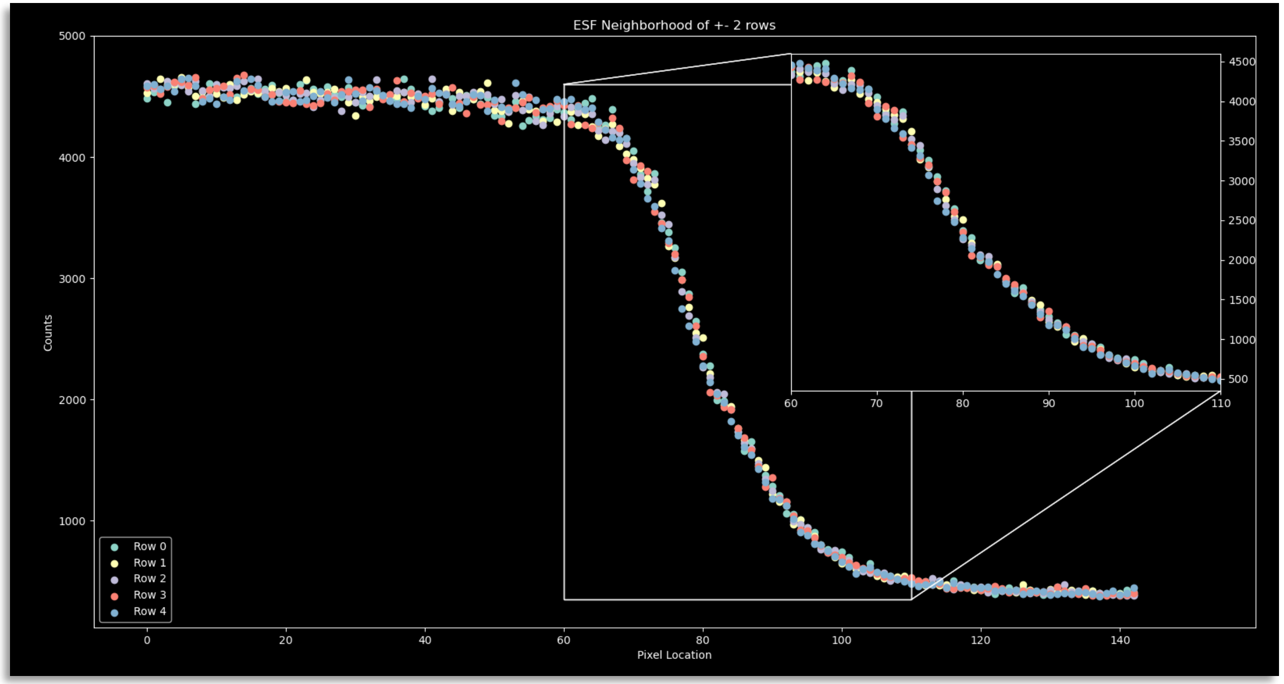


1. Edge Detection
Slices are identified in the image that intersect the quads. Edges are identified from the 1D the signal response across the slice

ESF: *Edge Spread Function*
LSF: *Line Spread Function*
MTF: Modulation Transfer Function

Data Processing

1. Edge detection and ESF cropping
2. Oversampling
3. Sigmoid fit for noise reduction
4. ESF to LSF via 1D derivative | LSF to MTF via FFT

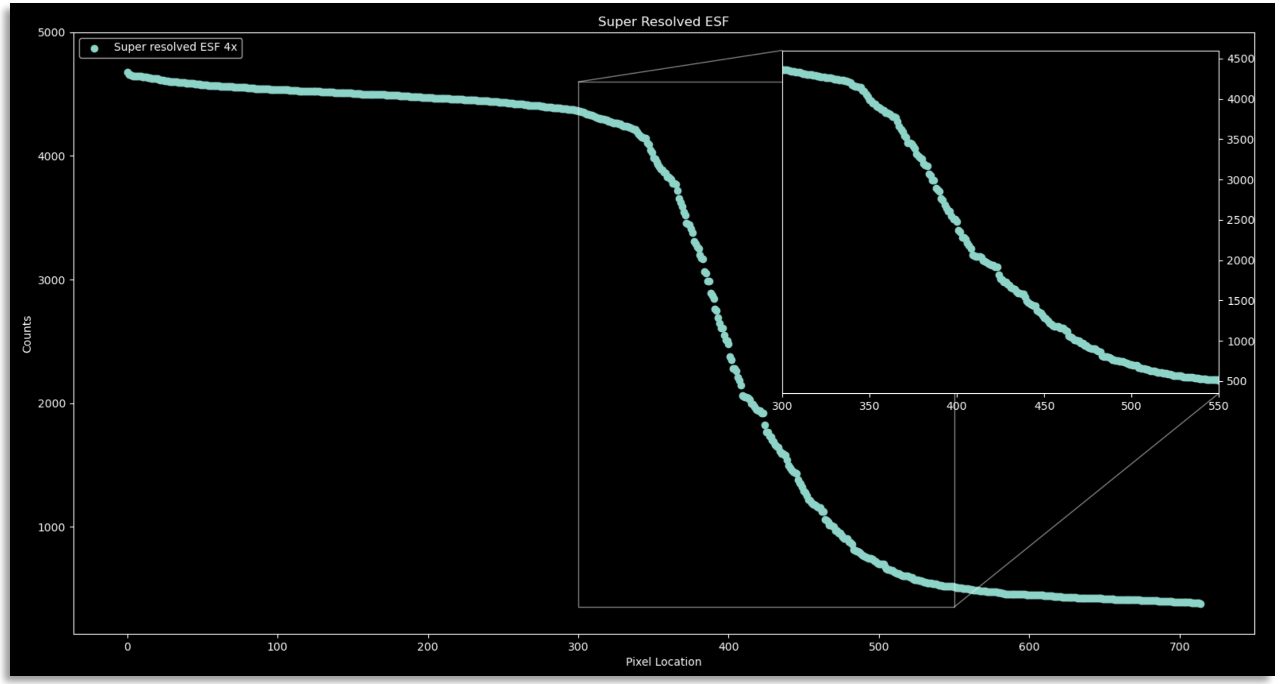


2. Oversampling
Implement binning algorithm that uses several (ISO algorithm based on 5) adjacent edge rows to create a super-resolved ESR

***ESF**: Edge Spread Function*
***LSF**: Line Spread Function*
MTF: Modulation Transfer Function

Data Processing

1. Edge detection and ESF cropping
2. Oversampling
3. Sigmoid fit for noise reduction
4. ESF to LSF via 1D derivative | LSF to MTF via FFT



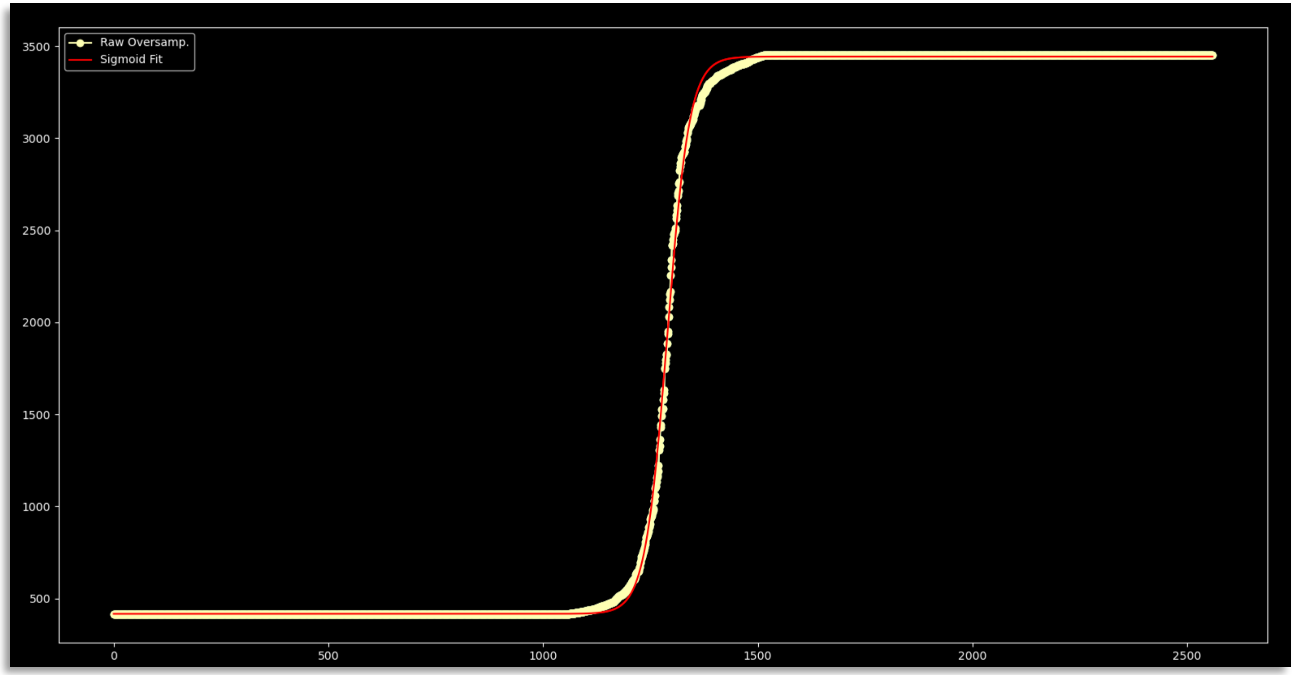
Boreman, G.D. "Point-, Line-, and Edge-Spread Function Measurement of MTF", *Modulation Transfer Function in Optical and Electro-Optical Systems*, 2nd ed., SPIE Press, 2021, pp. 81-83

2. Oversampling
Implement binning algorithm that uses several (ISO algorithm based on 5) adjacent edge rows to create a super-resolved ESR

ESF: *Edge Spread Function*
LSF: *Line Spread Function*
MTF: Modulation Transfer Function

Data Processing

1. Edge detection and ESF cropping
2. Oversampling
3. Sigmoid fit for noise reduction
4. ESF to LSF via 1D derivative | LSF to MTF via FFT



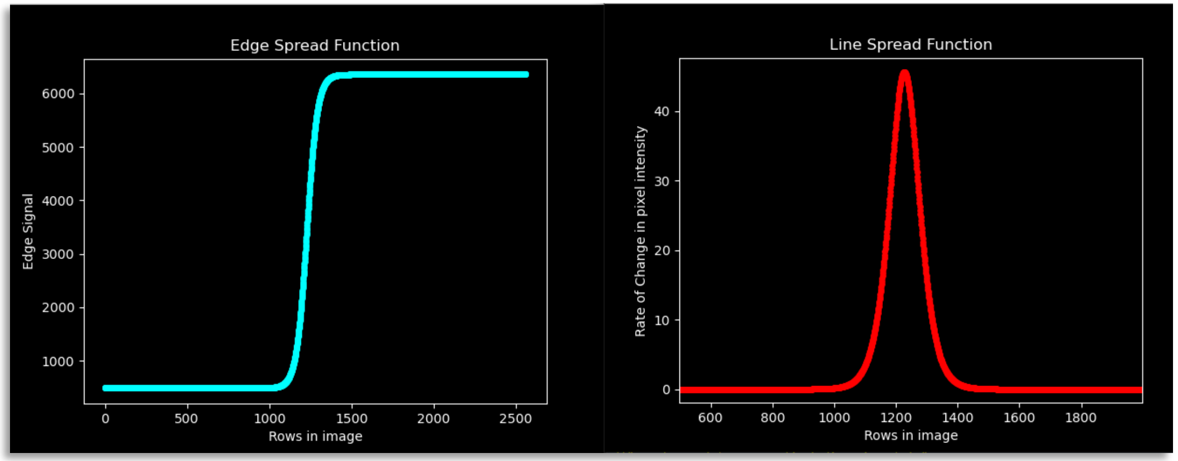
Boreman, G.D. "Point-, Line-, and Edge-Spread Function Measurement of MTF", *Modulation Transfer Function in Optical and Electro-Optical Systems*, 2nd ed., SPIE Press, 2021, pp. 81-83

3. Noise Reduction
Functional fitting reduced noise in extracted edge responses more effectively than kernel filtering while preserving signal response

ESF: *Edge Spread Function*
LSF: *Line Spread Function*
MTF: Modulation Transfer Function

Data Processing

1. Edge detection and ESF cropping
2. Oversampling
3. Sigmoid fit for noise reduction
4. ESF to LSF via 1D derivative | LSF to MTF via FFT



$$\mathrm{ESF}(x) \approx \sum_{i=1}^{\infty} \mathrm{LSF}(x - x_i).$$

$$\frac{d}{dx}\{\mathrm{ESF}(x)\} = \frac{d}{dx}\int_{-\infty}^{x} \mathrm{LSF}(x')dx' = \mathrm{LSF}(x),$$

Boreman, G.D. "Point-, Line-, and Edge-Spread Function Measurement of MTF", *Modulation Transfer Function in Optical and Electro-Optical Systems*, 2nd ed., SPIE Press, 2021, pp. 67-72

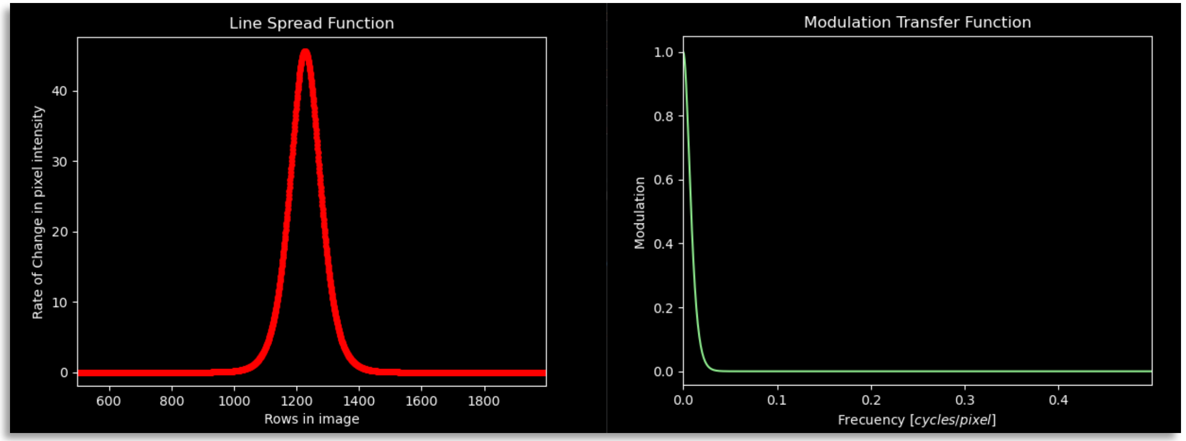
4. ESF to LSF

ESF is seen as a superposition of LSFs. Each vertical/horizontal strip on image plane produces a LSF. These LSFs integrate in the horizontal/vertical direction to form an LSF. The LSF can be derived directly from an ESF sample

***ESF**: Edge Spread Function*
***LSF**: Line Spread Function*
MTF: Modulation Transfer Function

Data Processing

1. Edge detection and ESF cropping
2. Oversampling
3. Sigmoid fit for noise reduction
4. ESF to LSF via 1D derivative | LSF to MTF via FFT



$$\left| \mathcal{F}\left\{ \frac{d}{dx} \mathrm{ESF}(x) \right\} \right| = \mathrm{MTF}(\xi, 0).$$

Boreman, G.D. "Point-, Line-, and Edge-Spread Function Measurement of MTF", *Modulation Transfer Function in Optical and Electro-Optical Systems*, 2nd ed., SPIE Press, 2021, pp. 67-72

4. LSF to MTF

The real components of the one-dimensional Fourier Transform of the LSF will yield one profile of the MTF. Any one-dimensional profile of the MTF can be derived by re-orienting the knife edge, and will vary slightly with the cosine of the angle

ESF: *Edge Spread Function*
LSF: *Line Spread Function*
MTF: Modulation Transfer Function

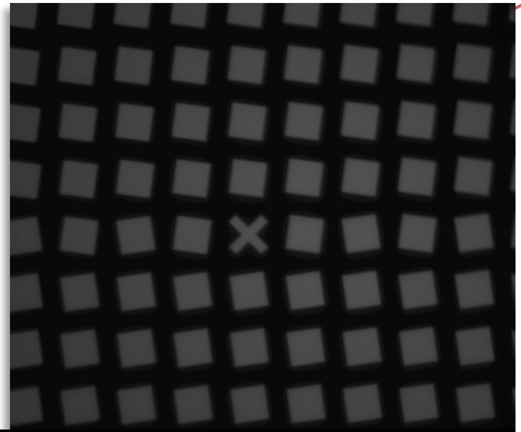
Development of Multi-Edge Slant Target for unlocalized MTF Measurement

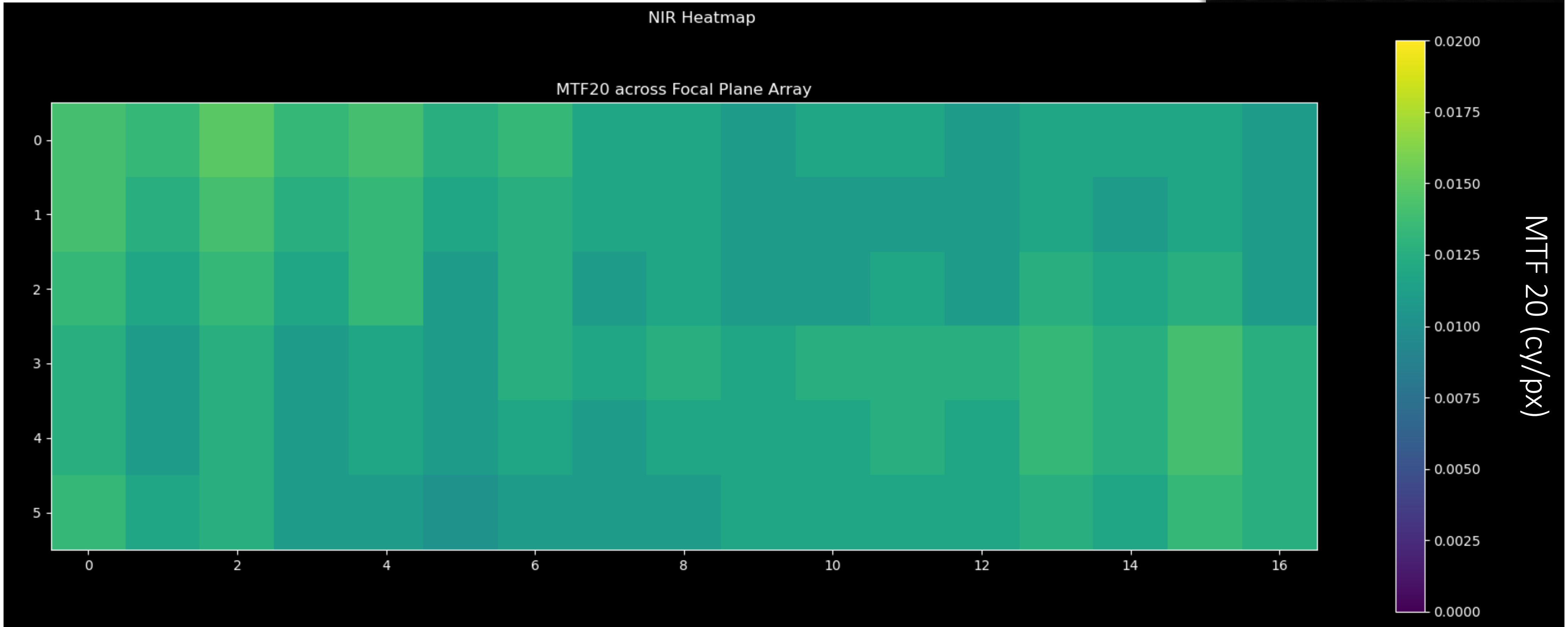
Preliminary Results NIR

Sampled MTF v. Discrete Sensor Location

- Overall uniformity across sensor
- Average:.012 cy/px | Std: .0009

Test Image





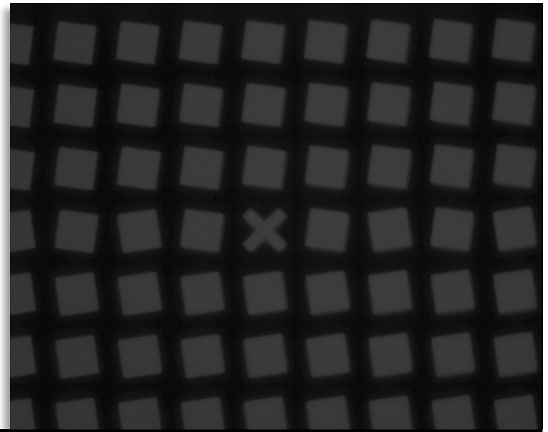
Development of Multi-Edge Slant Target for unlocalized MTF Measurement

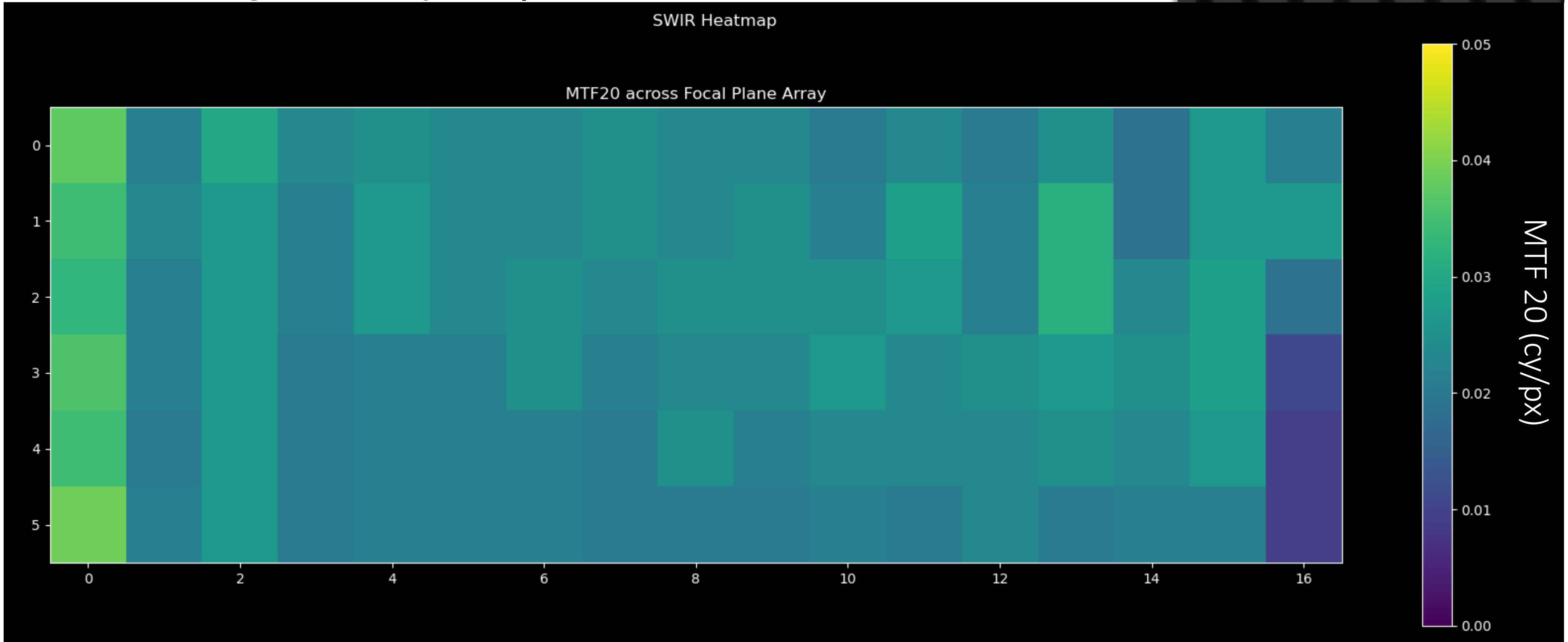
Preliminary Results SWIR

Sampled MTF v. Discrete Sensor Location

- Lateral non-uniformity observed
- Average: .02 cy/px | Std: .005

Test Image





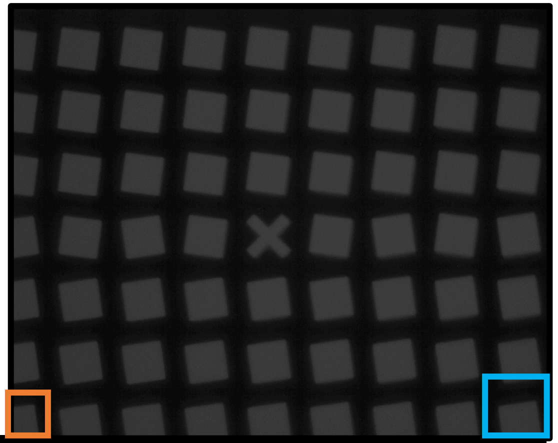
Development of Multi-Edge Slant Target for unlocalized MTF Measurement

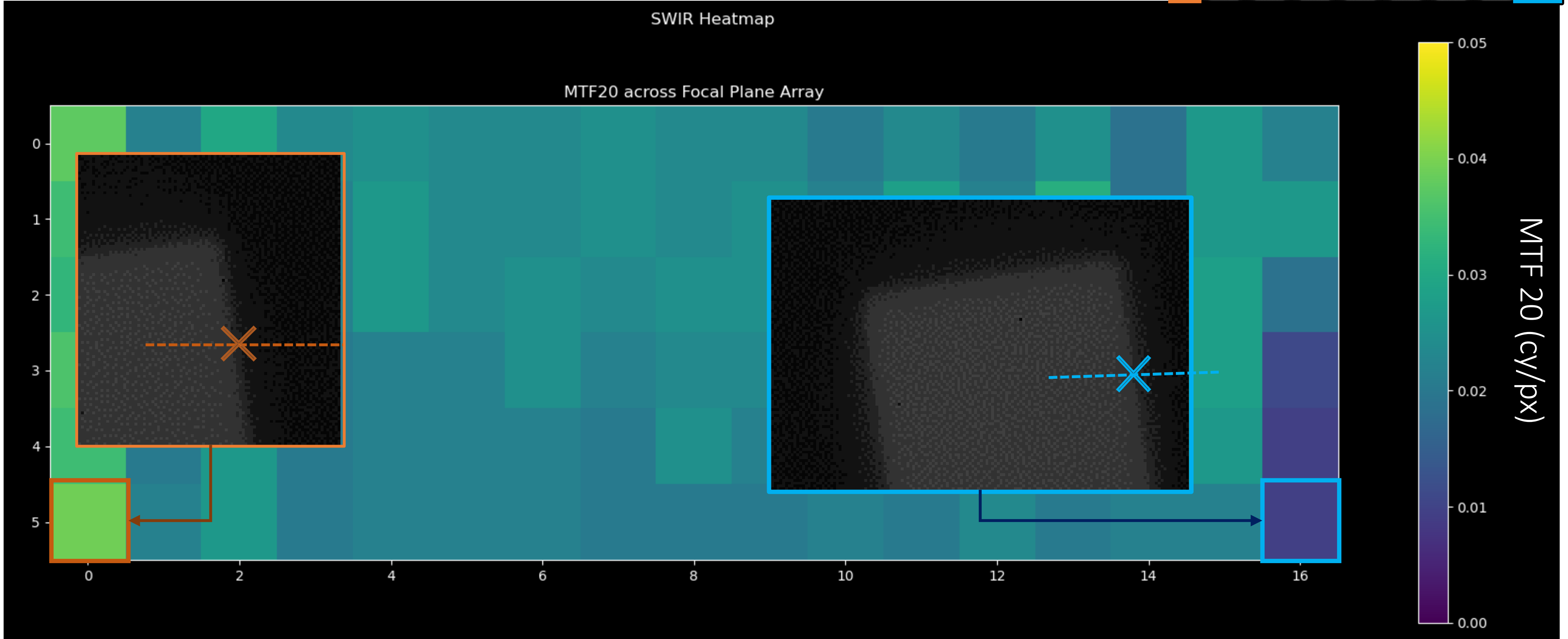
Preliminary Results SWIR

Sampled MTF v. Discrete Sensor Location

- Lateral non-uniformity observed
- Average: .02 cy/px | Std: .005

Test Image

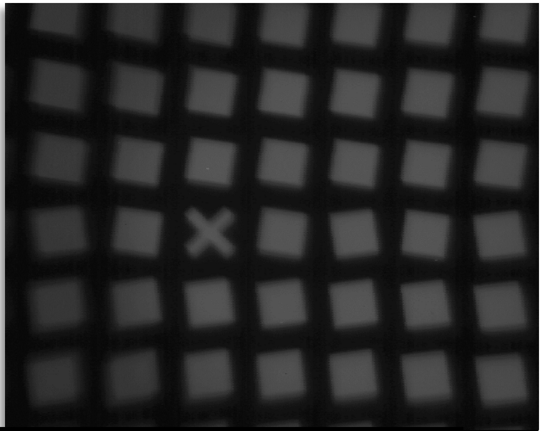


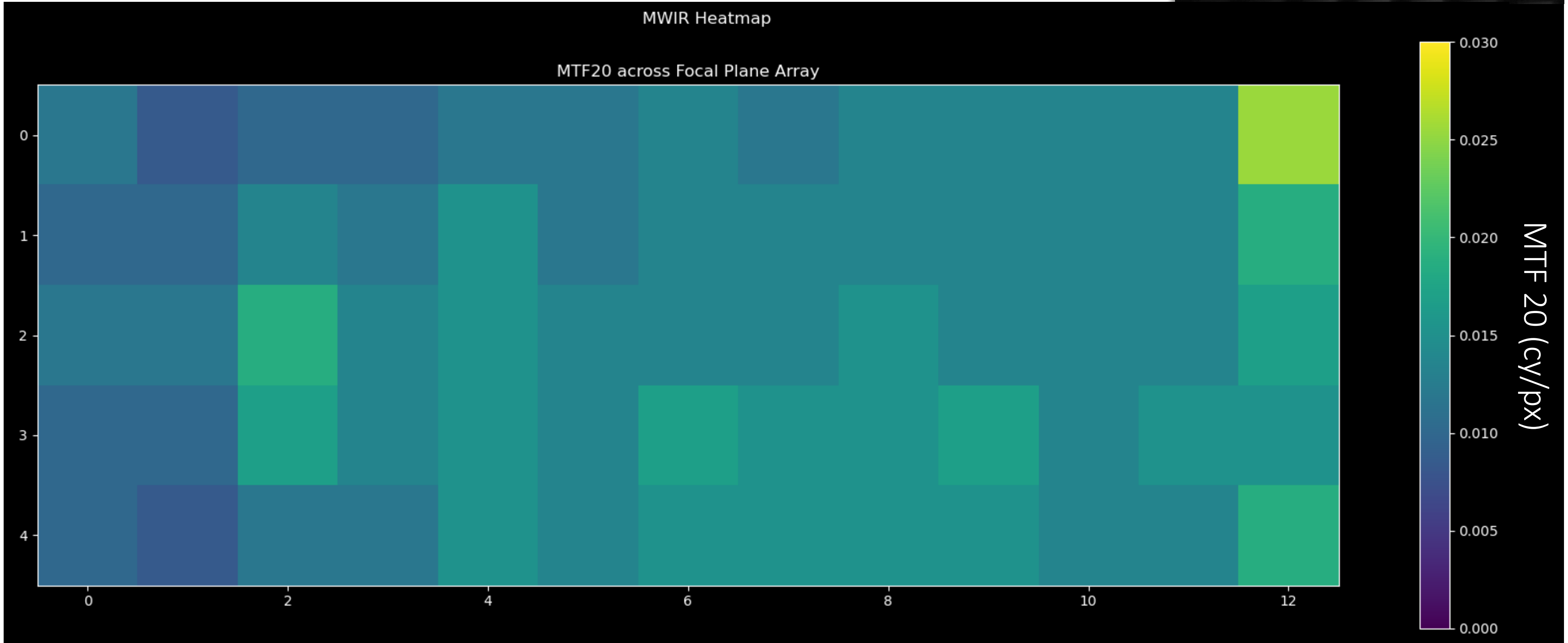


Sampled MTF v. Discrete Sensor Location

- Lateral non-uniformity observed
- Average: .013 cy/px | Std: .002

Test Image





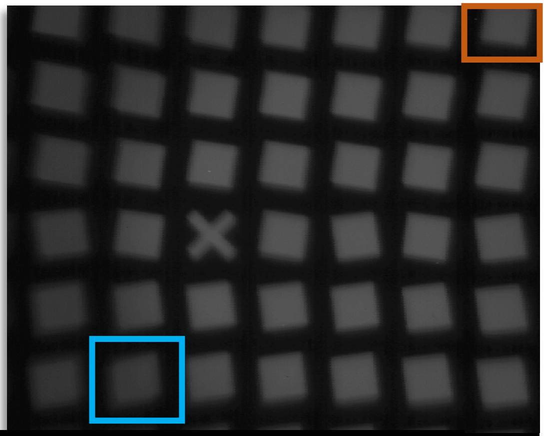
Development of Multi-Edge Slant Target for unlocalized MTF Measurement

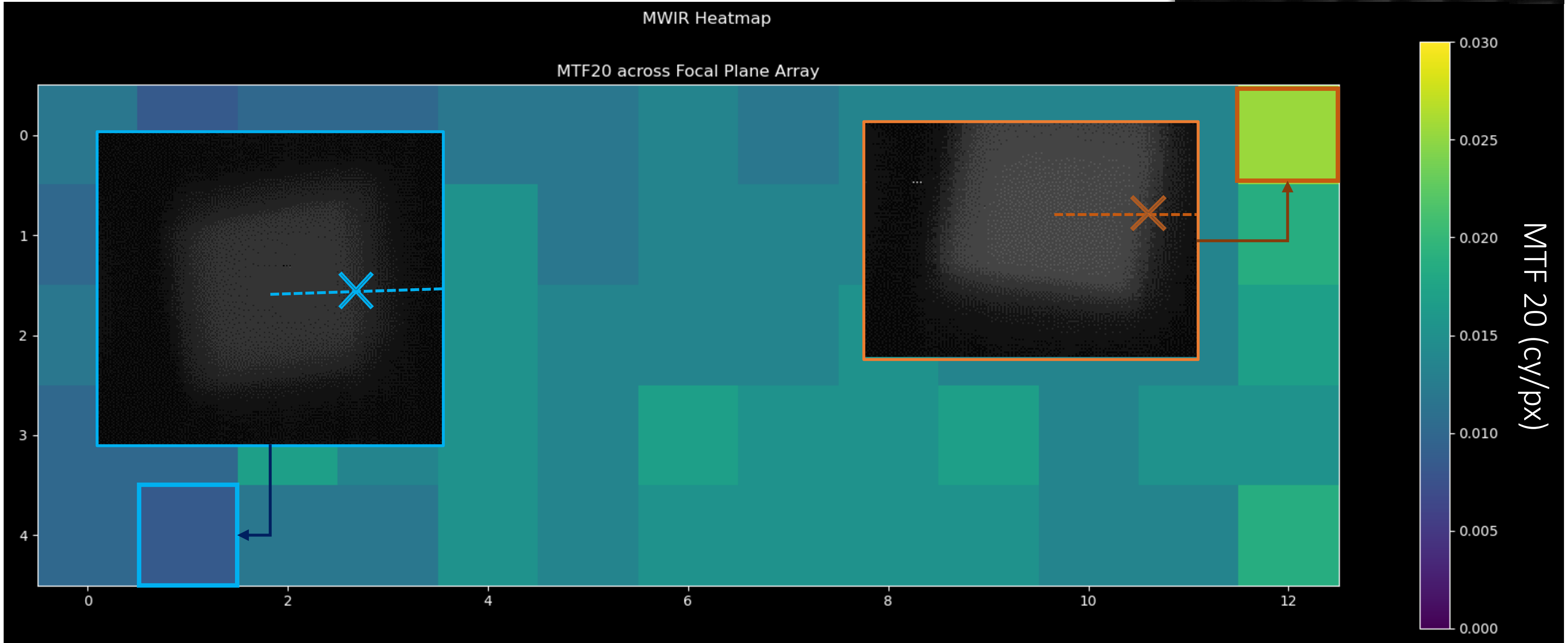
Preliminary Results MWIR

Sampled MTF v. Discrete Sensor Location

- Lateral non-uniformity observed
- Average: .013 cy/px | Std: .002

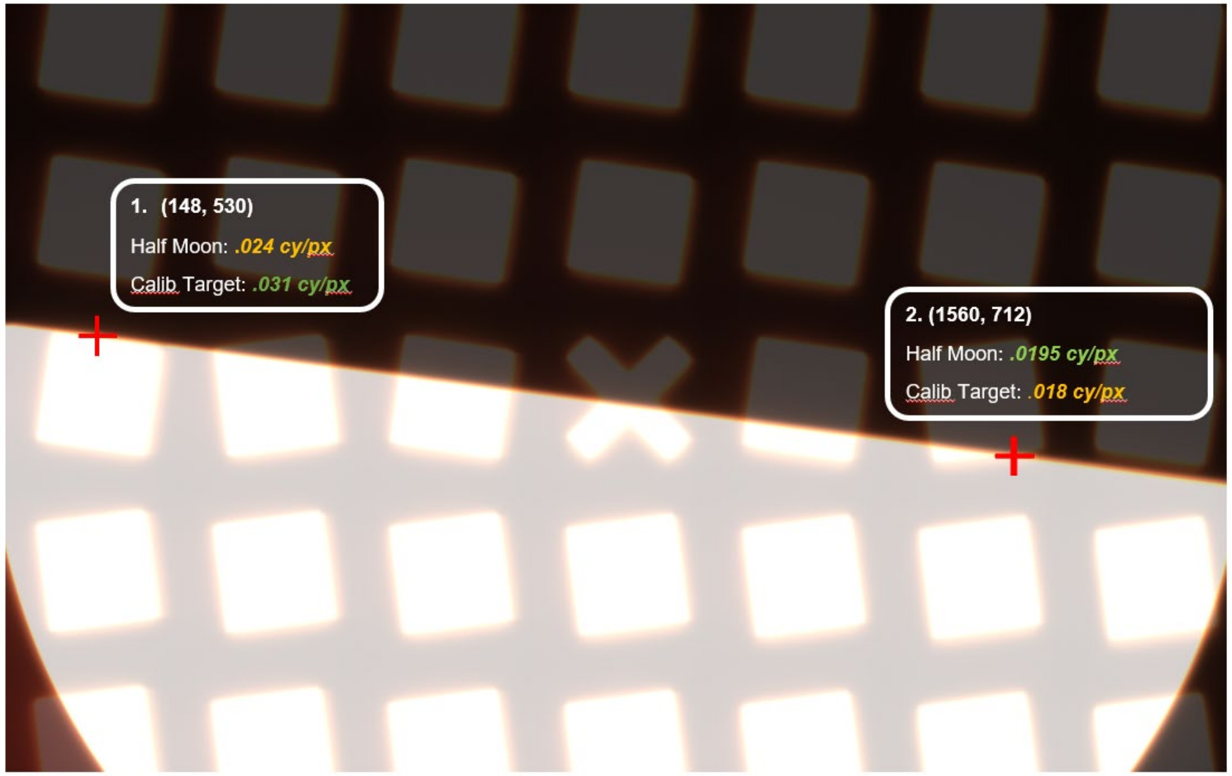
Test Image





Measurement Validation

- Validation with Single Edge Calibration Cart Target
  - MTF Measurements with calibration plate and halfmoon target agree
  - Great validation example of prototype calibration plate design

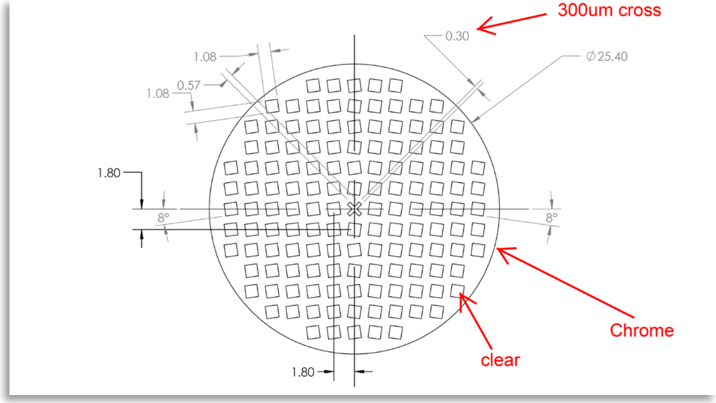


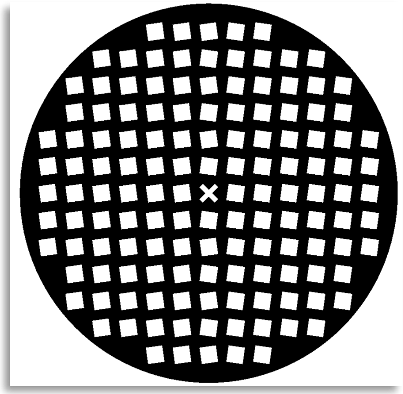
Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Summary

Conclusions

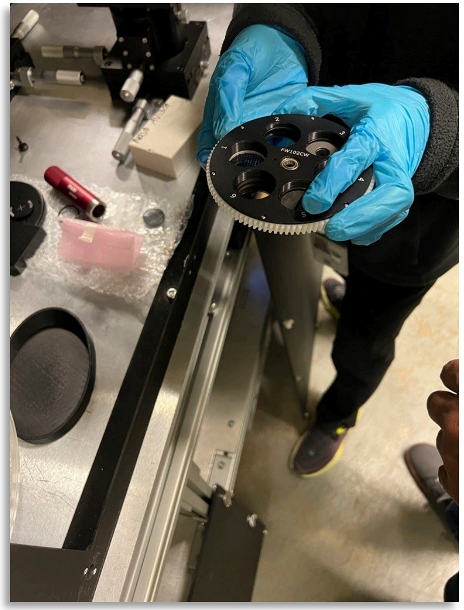
- The spatial non-uniformity across the SWIR and MWIR sensors is currently being investigated further
  - Impact on radiometric data collect is minimal, but the team seeks to fully understand the characteristics of the SAMI payload
- Additional processing is to be done for other SCIFLI airborne imaging assets



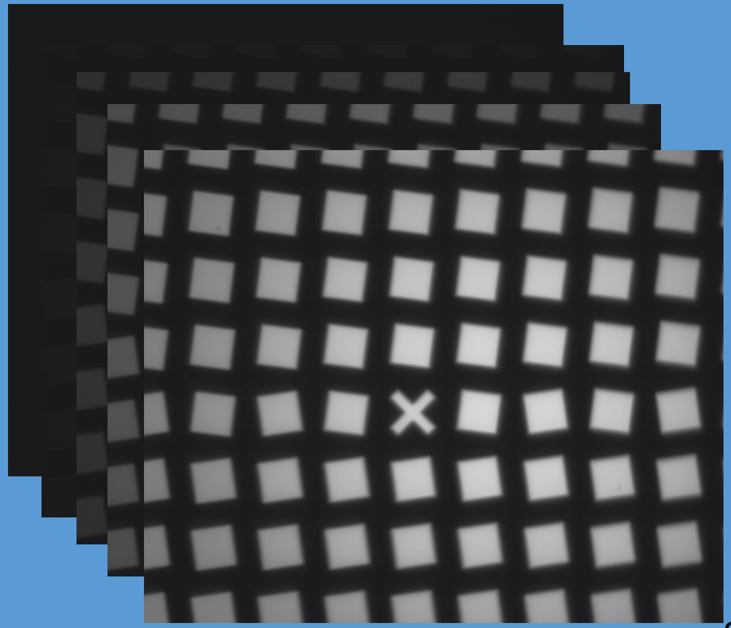


Summary

- A calibration target was designed to measure MTF via. Slant edge across image plane
  - Customized for compatibility with SAMI Calibration Cart
  - Designed for repeatability and consistency with multispectral imager
  - Fabricated to be utilized in Target Wheel and backlit with radiometric source
- The measurements taken with the custom target agree with measurements from off-the-shelf solutions
- The utility of the novel approach is demonstrated
  - Provide more complete characterization of sensor across the image plane
  - Allows for utility outside of slant edge analysis (grid extraction, image plane spatial response uniformity, image sensor placement and optical-axis alignment verification)



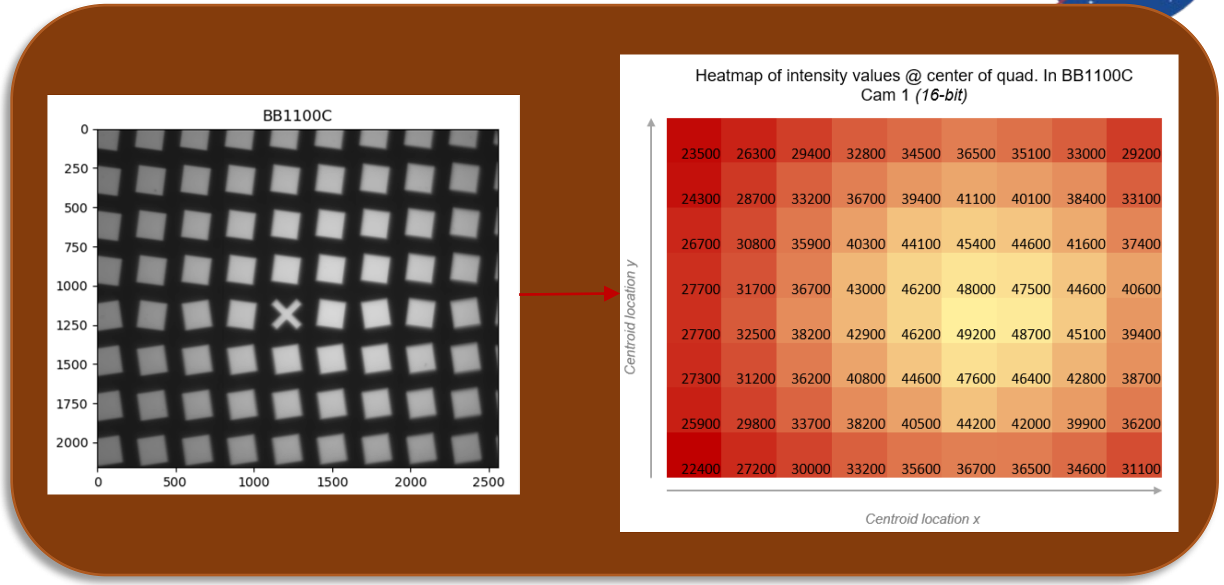
SAMI NIR Calibration Samples of MTF Target
Backlit with Black Body Source
Temp range: [50C – 1100C]

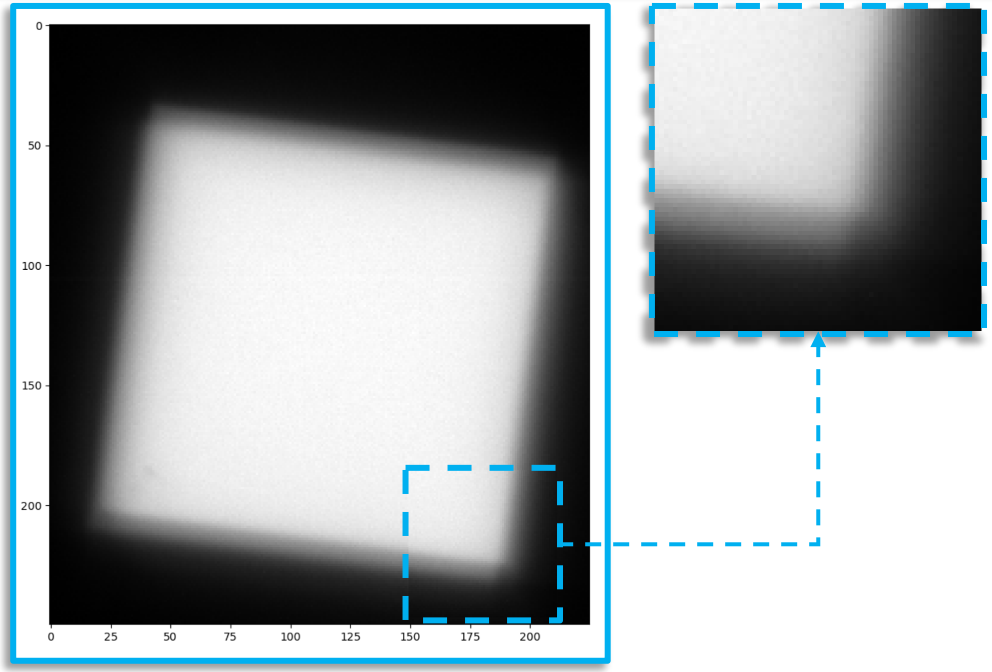


Development of Multi-Edge Slant Target for unlocalized MTF Measurement

Improvements and Next steps

- Experimental Set-up
  - Better precision with source settings for appropriate contrast
  - Spatial non-uniformity in source back-lighting contributing to irregular contrast at edges across plate
- Manufacturing
  - Improving ESF linear transition region
    - Potential inter-reflections creating second edge from occluded to non-occluded regions in high-contrast regions
- Data Processing
  - Validation with captured flight data
  - Utilize Spatial Calibration Plate to characterize the following:
    - Blooming dynamics as a function of Radiance, ET, and Gain
    - Temperature/Radiance Dependent Non-Localized axis-symmetric 2D PSF Estimation

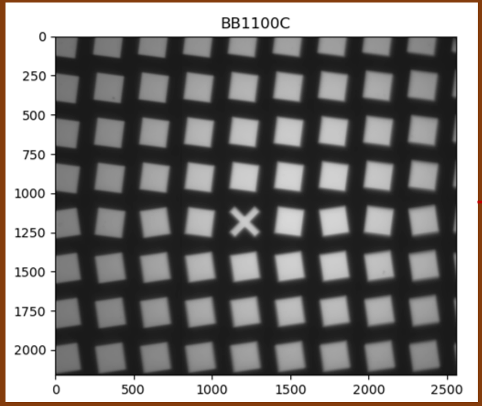


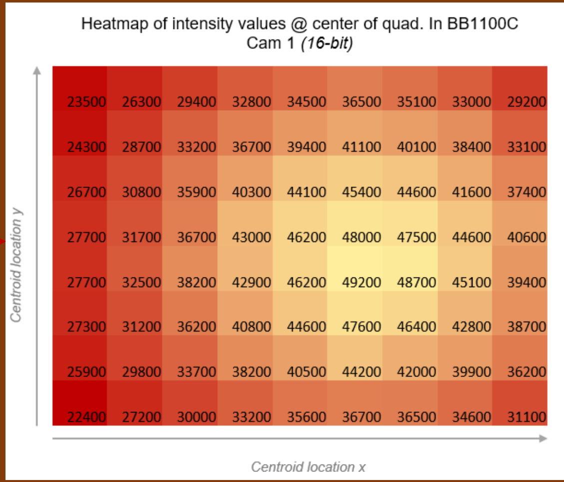


Development of Multi-Edge Slant Target for unlocalized MTF Measurement

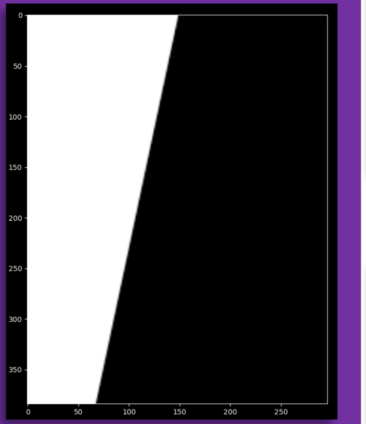
Improvements and Next steps

- Experimental Set-up
  - Better precision with source settings for appropriate contrast
  - Spatial non-uniformity in source back-lighting contributing to irregular contrast at edges across plate
- Manufacturing
  - Improving ESF linear transition region
    - Potential inter-reflections creating second edge from occluded to non-occluded regions in high-contrast regions
- Data Processing
  - Validation with captured flight data
  - Utilize Spatial Calibration Plate to characterize the following:
    - Blooming dynamics as a function of Radiance, ET, and Gain
    - Temperature/Radiance Dependent Non-Localized axis-symmetric 2D PSF Estimation

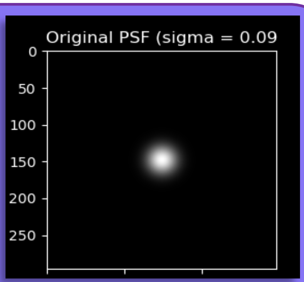




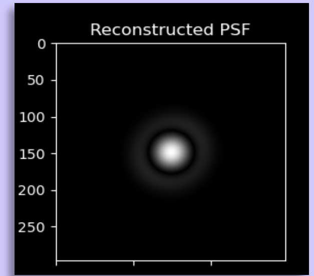
Input Image



Blur image with gaussian kernel $G(\sigma)$



Reconstruct 2D axis-symmetric PSF from MTF



Development of Multi-Edge Slant Target for unlocalized MTF Measurement

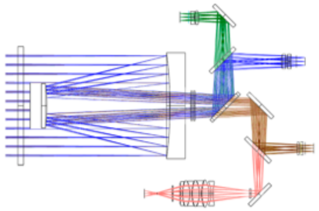
SCIFLI Talk Tomorrow

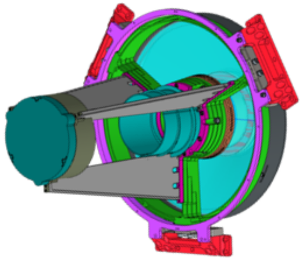
SAMI

SCIFLI AIRBORNE MULTISPECTRAL IMAGER

NASA SCIFLI's Calibrated Missions Portfolio

Matthew Boyda
Carey Scott, Hyun Jung Kim, and Kylel Scott





Matthew Boyda
SAMI System Engineer
NASA/LaRC

Carey Scott
SCIFLI Principal Investigator
NASA/LaRC

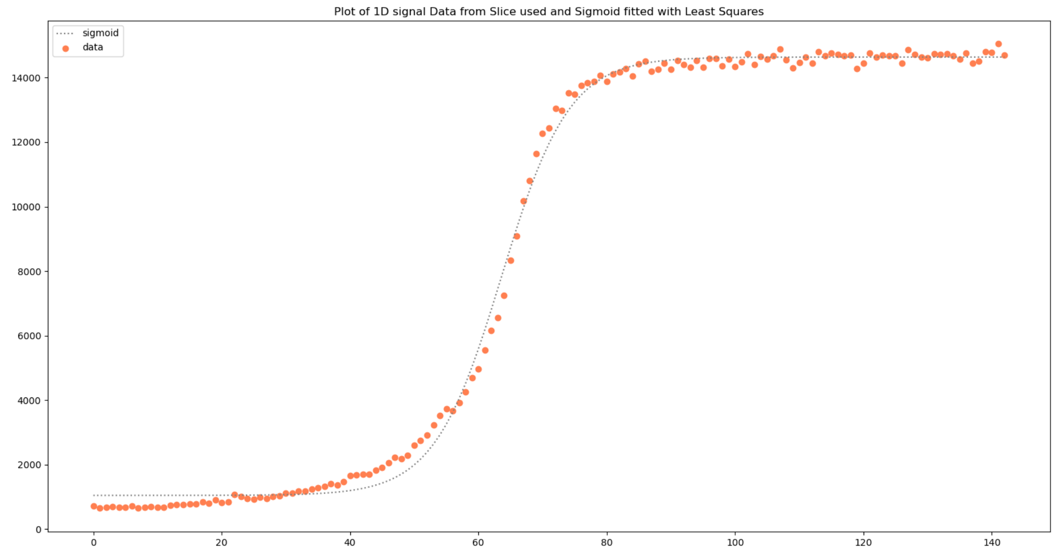
Hyun Jung Kim, PhD
SAMI Project Manager
NASA/LaRC

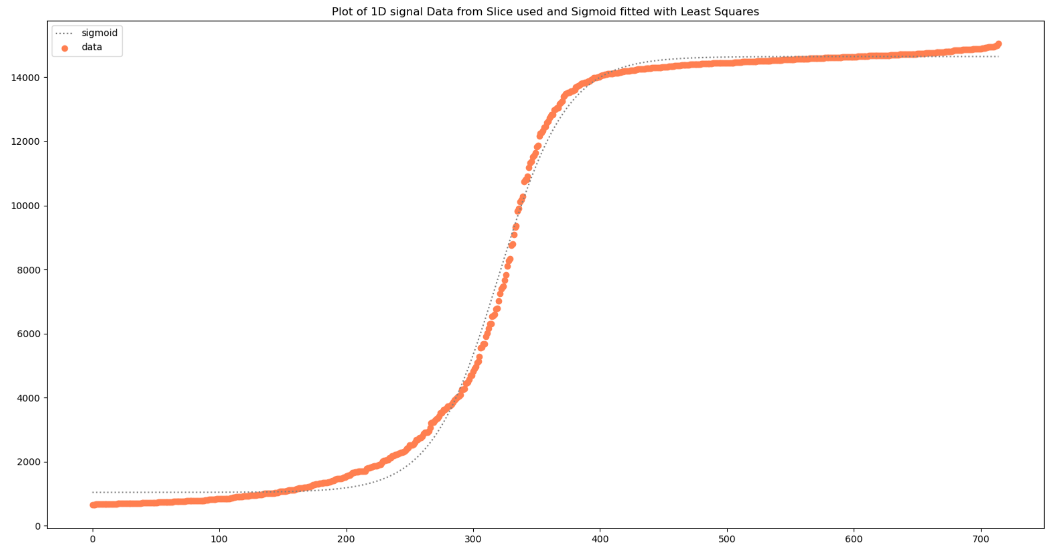
Kylel Scott
SCIFLI Research Engineer
NASA/LaRC

Backup

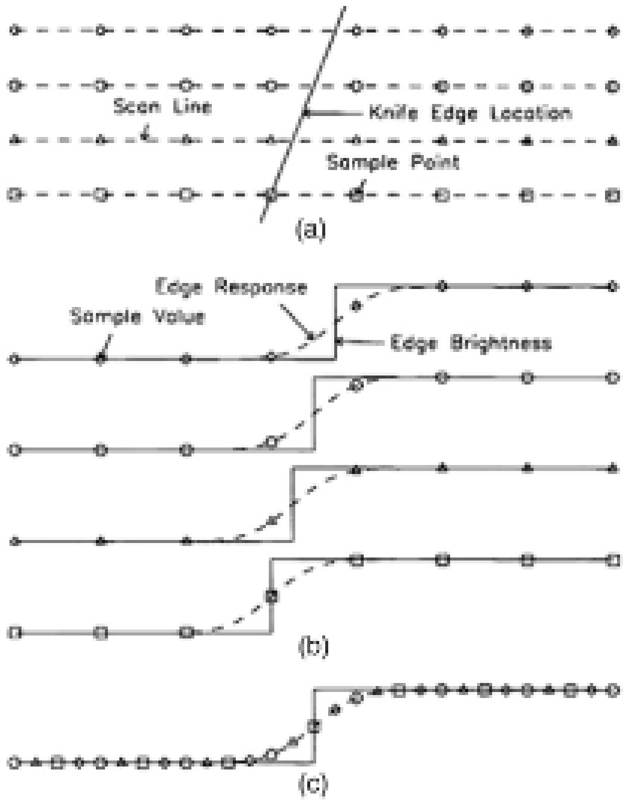
MTF Characterization Analysis

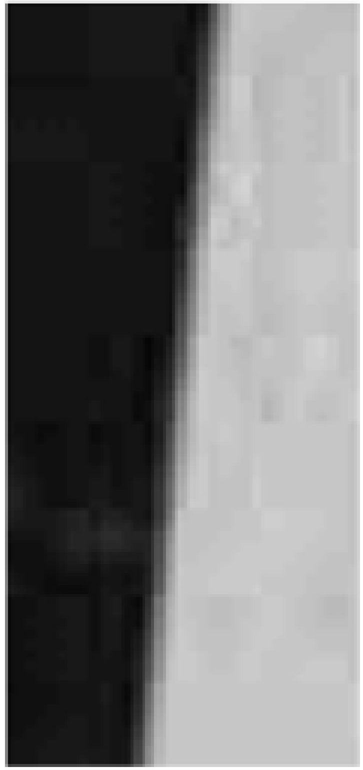
- Oversampling Results
  - Super-sampling of ESF for better MTF extraction
    - Using edge rows/cols +- 2 pixels from row/col of interest
  - Automated Edge position localization from row signal





- Oversampling Results
  - Oversampling of ESF for better MTF extraction
    - Using edge rows/cols +- 2 pixels from row/col of interest
  - Registered scans across edge are combined in successive order
    - a) Scan grid across rows of image sampling knife edge
    - b) Registered scans and relative pixel signal at specific grid location
    - c) Combination of successive scans for oversampled edge response

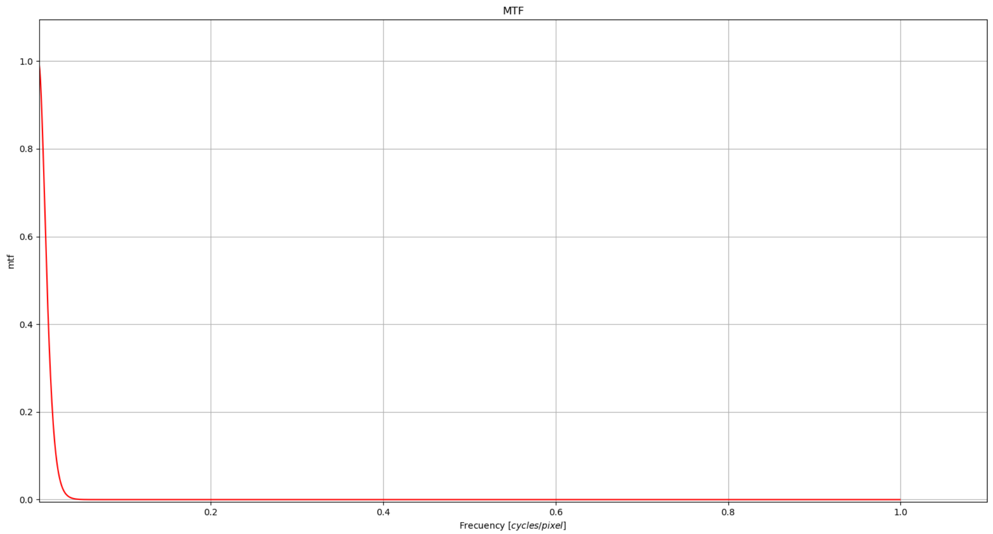


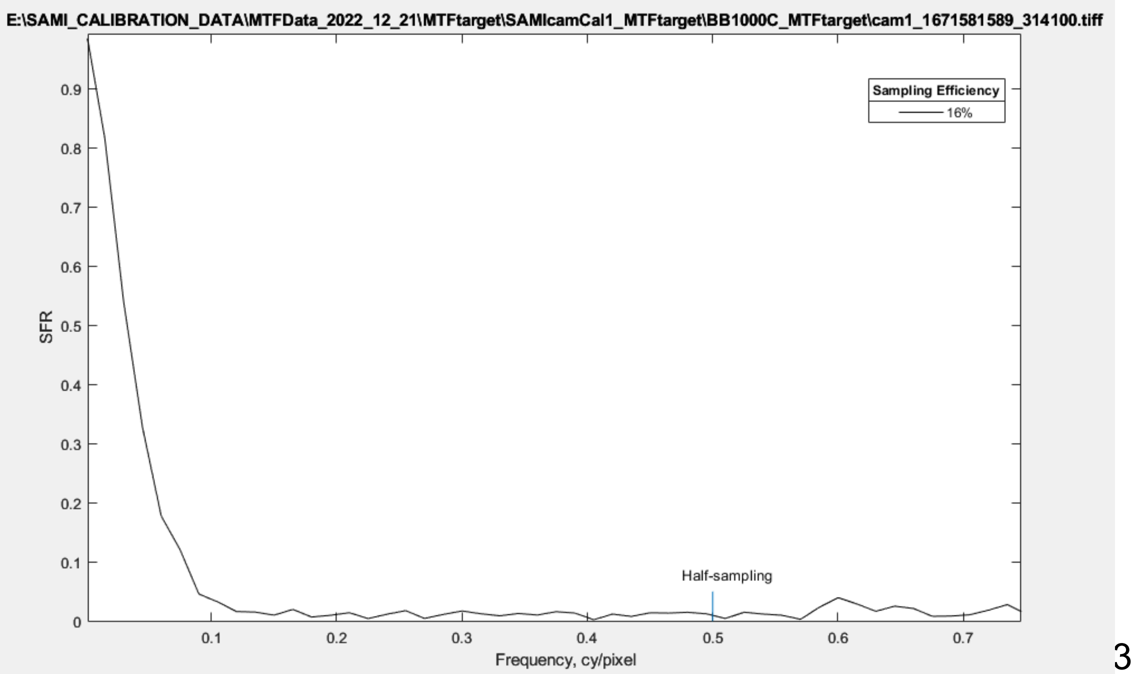


Boreman, G.D. "Point-, Line-, and Edge-Spread Function Measurement of MTF", *Modulation Transfer Function in Optical and Electro-Optical Systems*, 2nd ed., SPIE Press, 2021, pp. 67-72

32

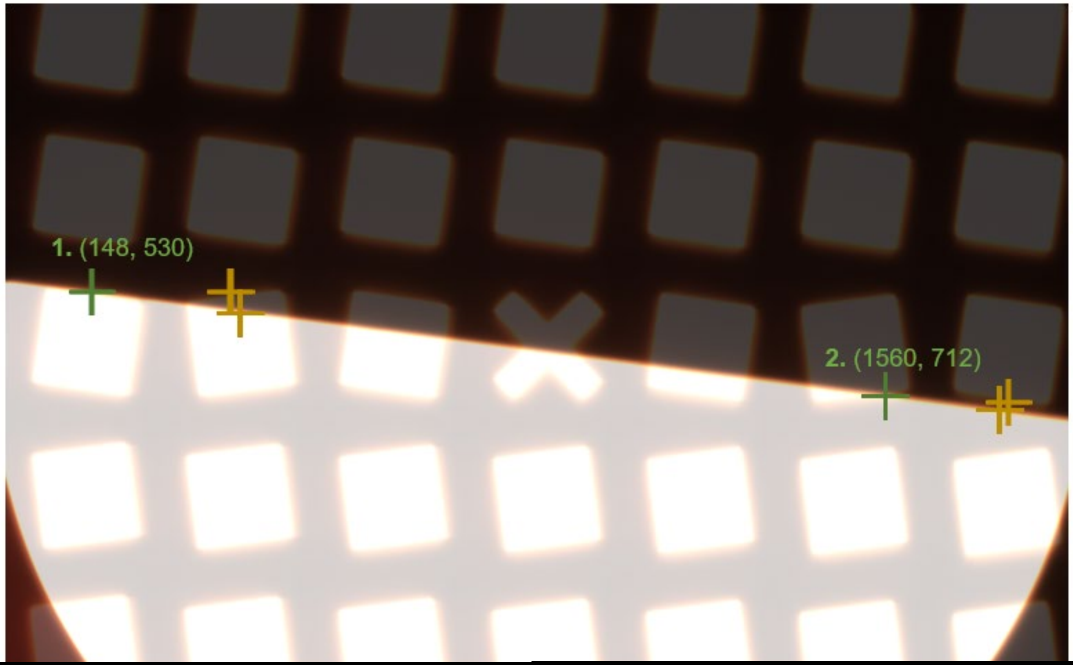
- MTF Validation
  - Super-sampling of ESF for better MTF extraction
    - Using edge rows/cols +- 2 pixels from row/col of interest
  - Automated Edge position localization from row signal
  - Tool verification with ***sfrmat3*** MATLAB application

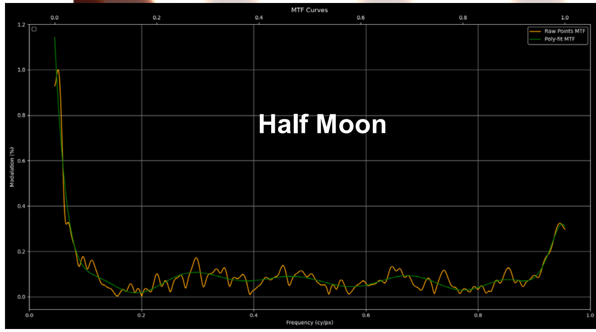


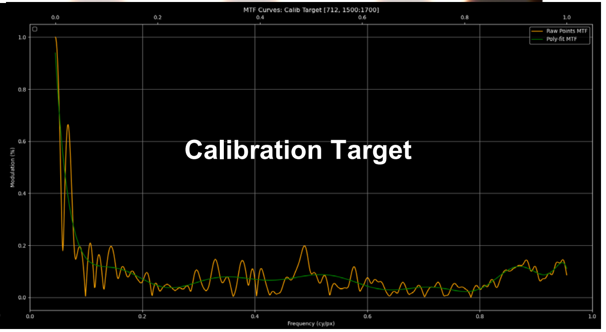


MTF Characterization Analysis

- Target Comparison
  - MTF Measurements with calibration plate and halfmoon target are comparable
  - Great validation example of prototype calibration plate design







*MTF50: **.0195 cy/px***

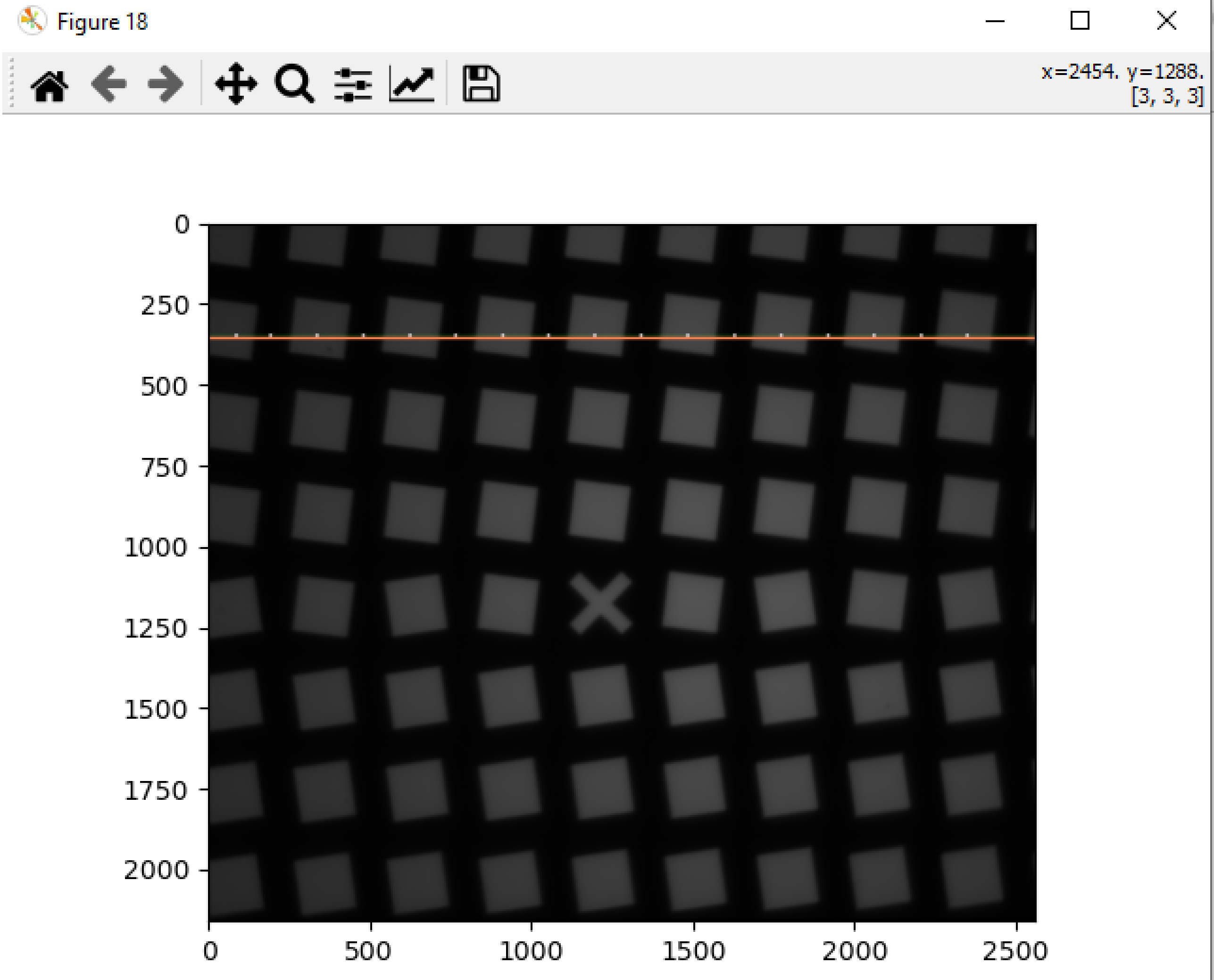
*MTF20: **.0422 cy/px***

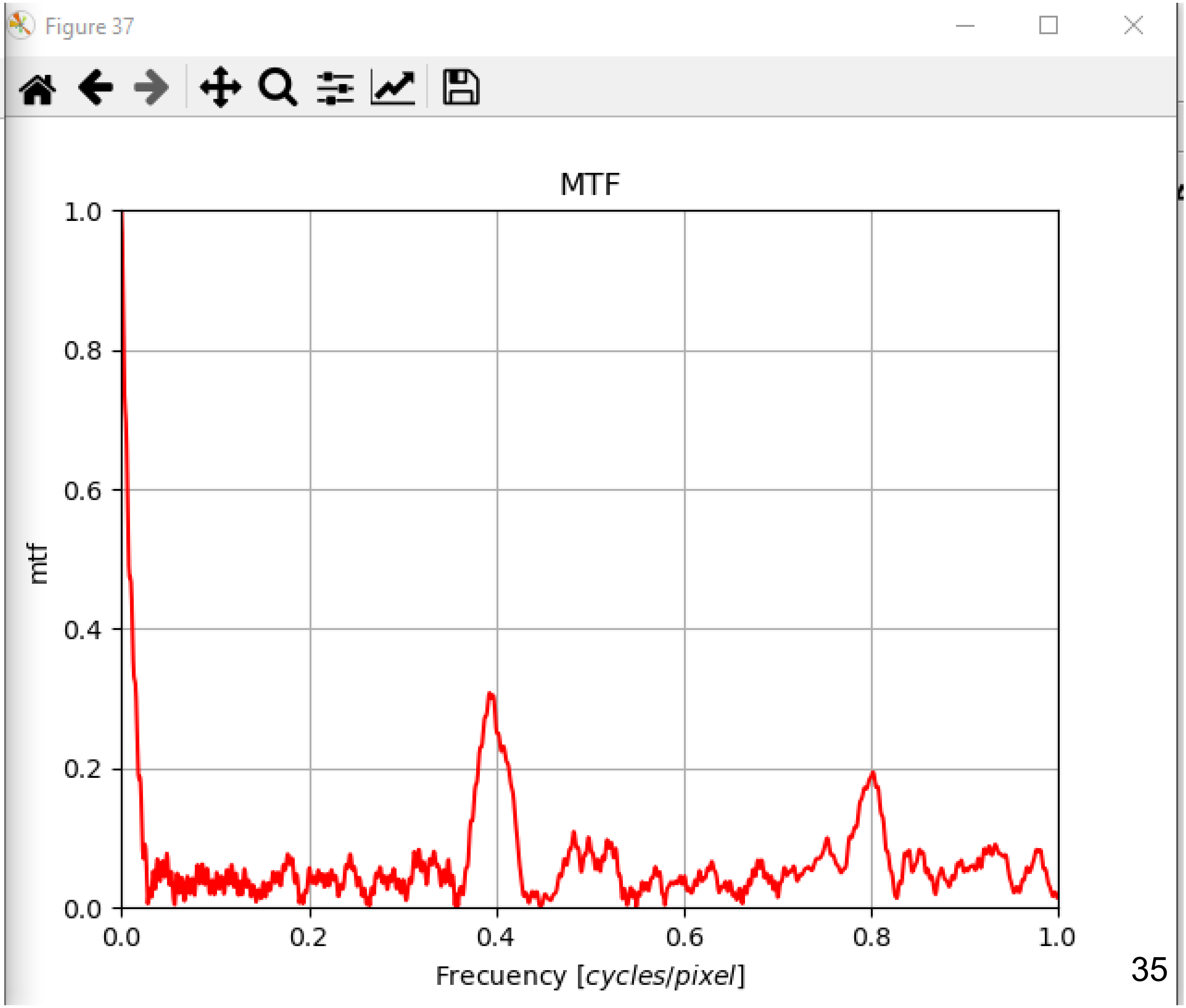
*MTF50: **.018 cy/px***

*MTF20: **.047 cy/px***

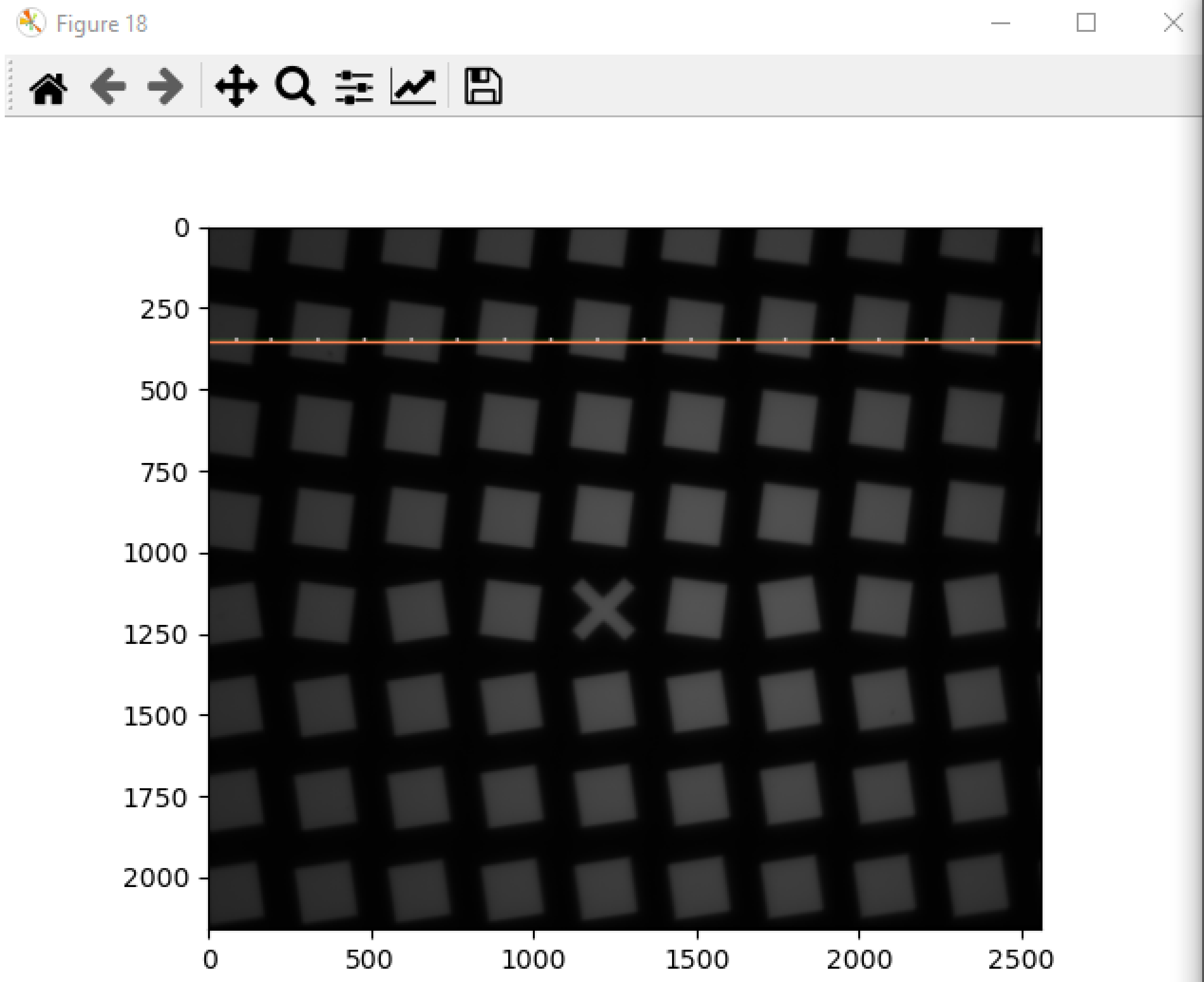
34

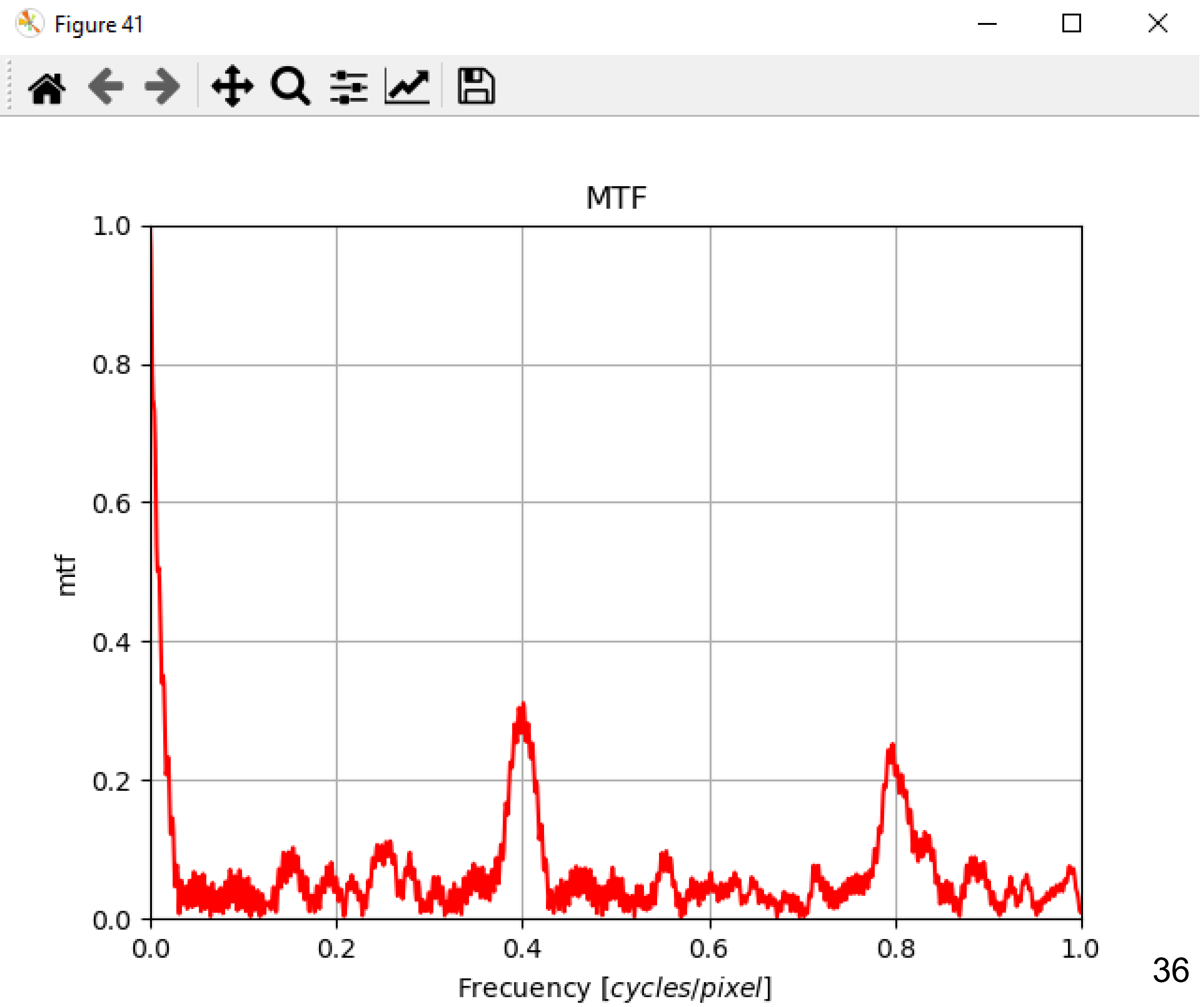
MTF edge_idx=2



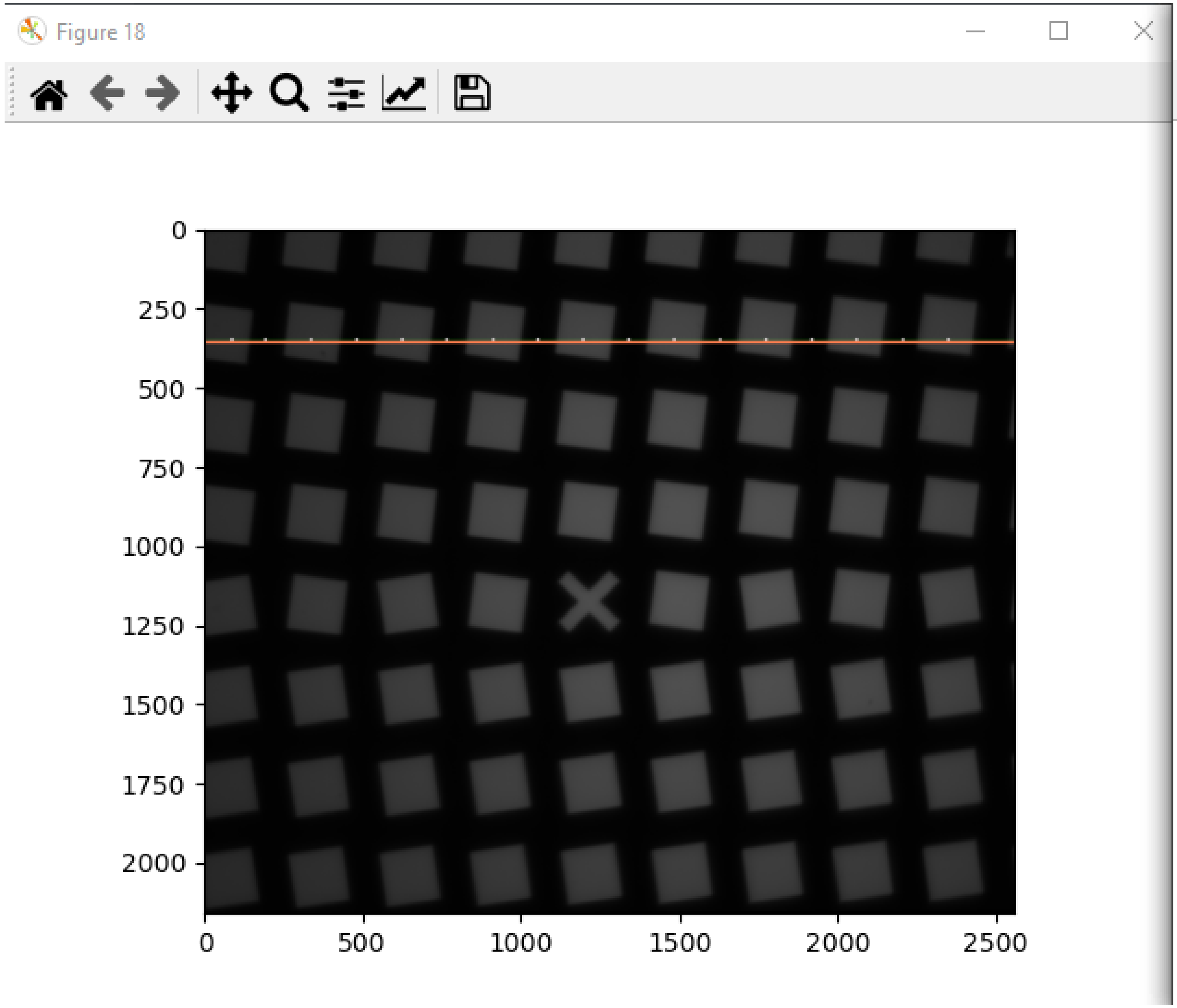


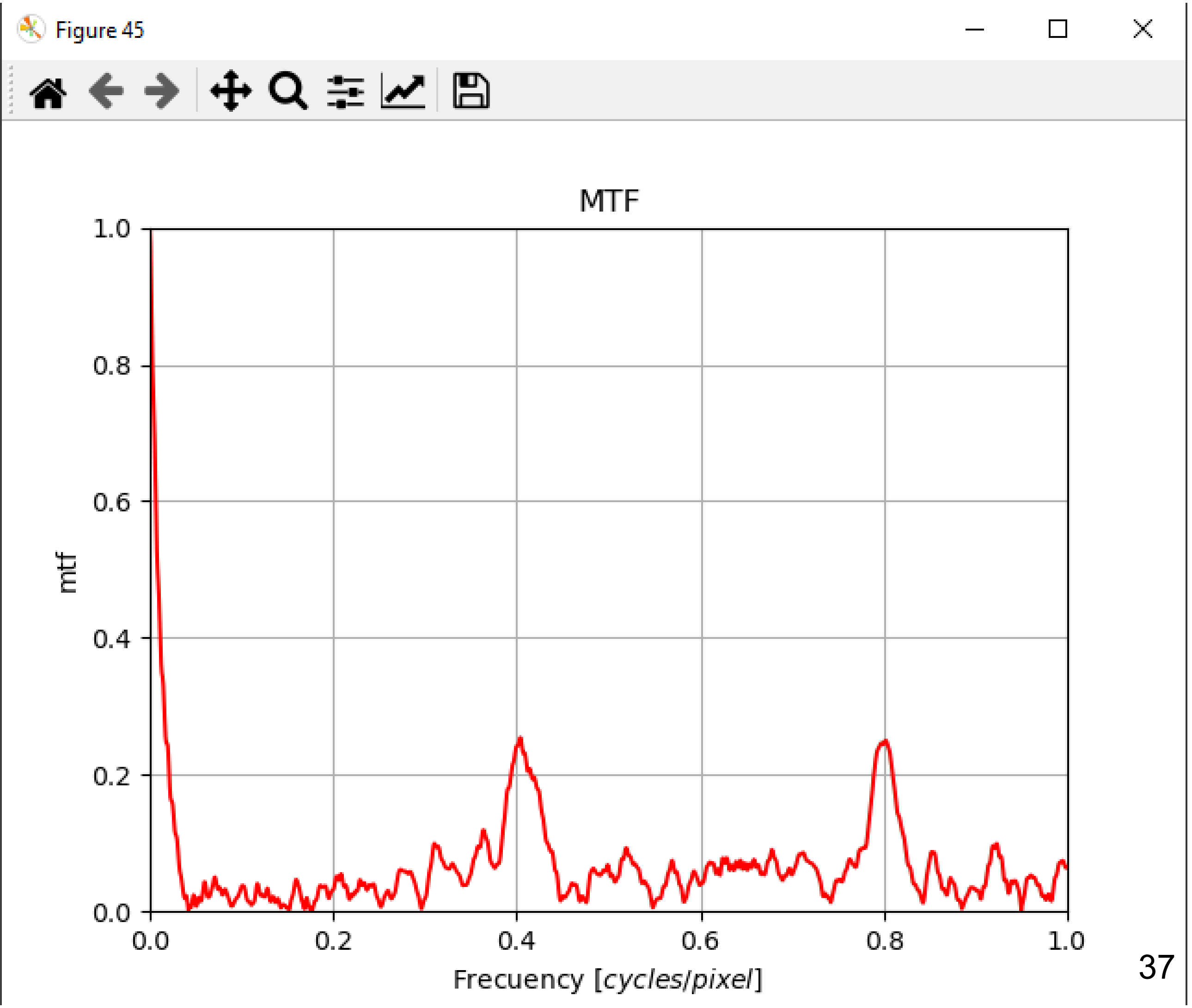
MTF edge_idx=6





MTF edge_idx=10





MTF edge_idx=14