THE UNIVERSITY OF ARIZONA
Wyant College of Optical Sciences

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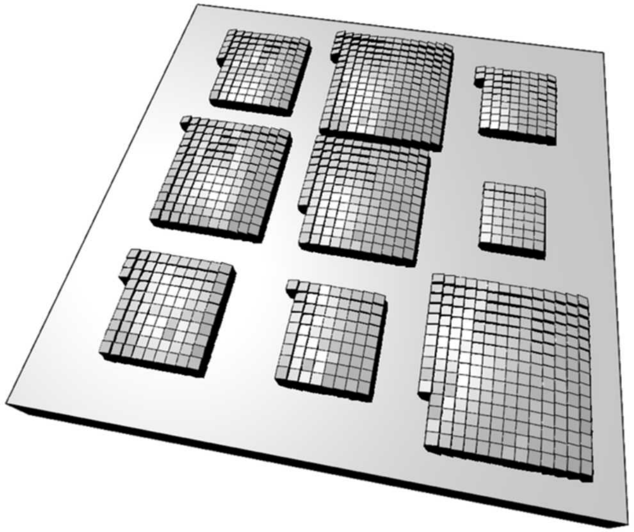
NOVEL HYBRID ANALYSIS TECHNIQUES FOR COMPLEX OPTICAL SYSTEMS

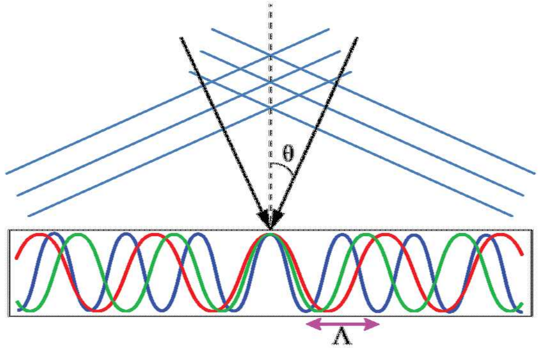
Brian Redman

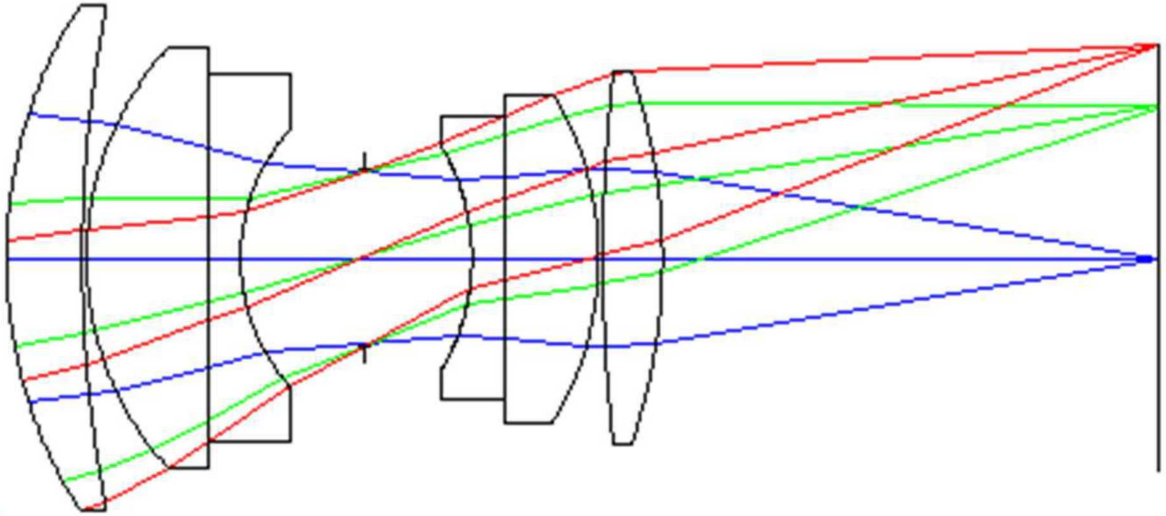
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Leveraging traditional techniques to model complex optical systems

- Extensive work optimizing modeling and measurement techniques for traditional optical systems
- New methods required for non-traditional optical systems
  - Combination of traditional processing and custom analysis techniques can be used to efficiently simulate complex optical systems







Modeling and measurements of Four optical systems

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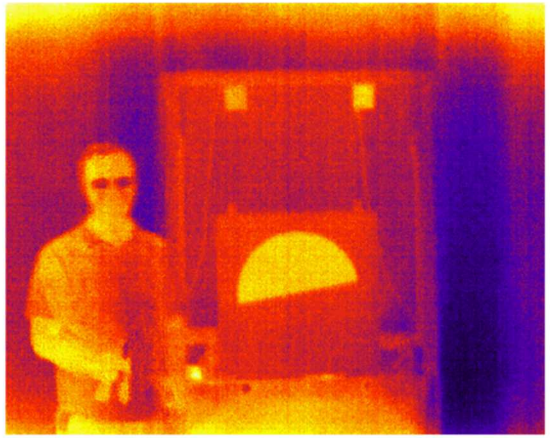
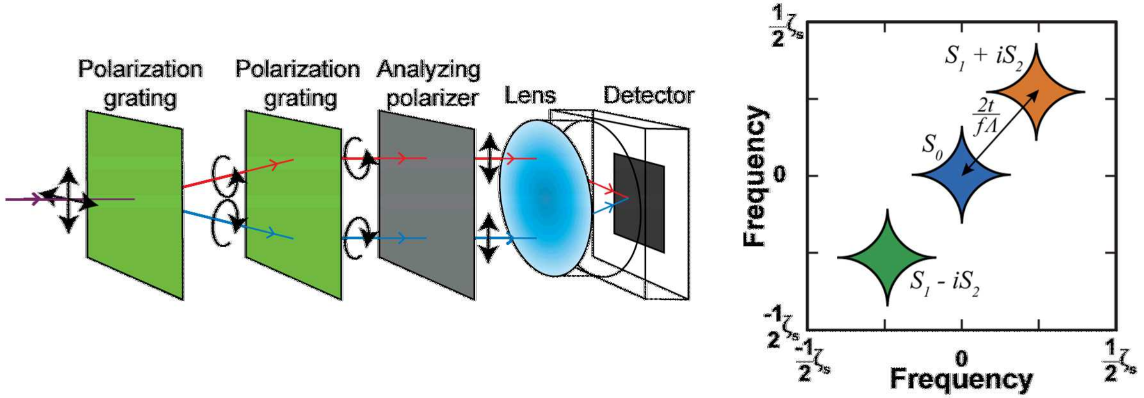
1. Long-wave infrared measurement of image degradation caused by fog



2. Channeled imaging polarimeter



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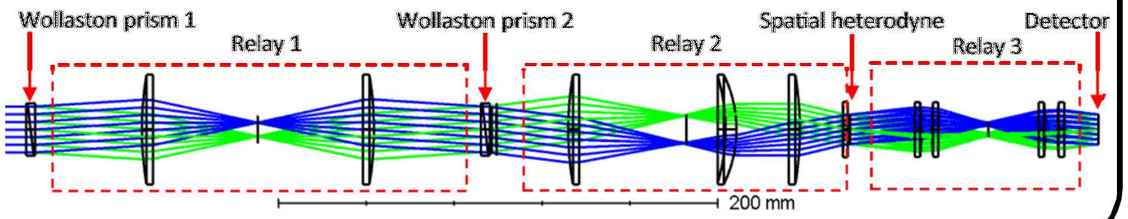
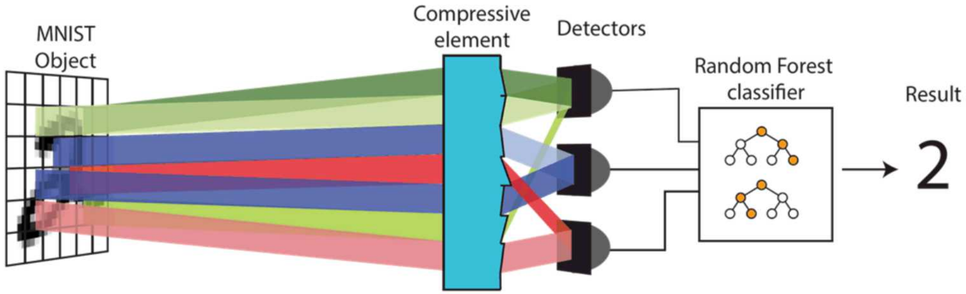


4. Compressive classification



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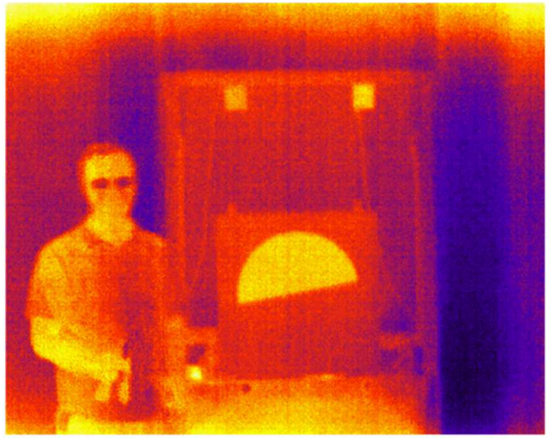

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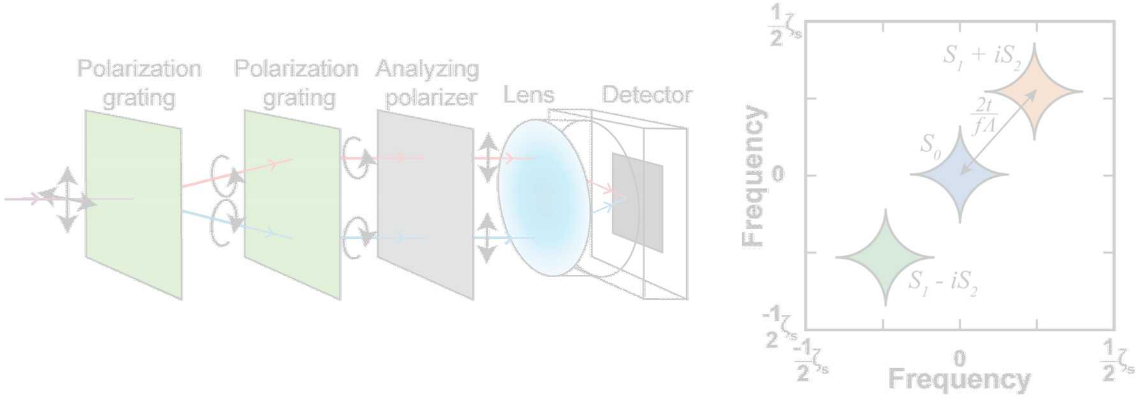

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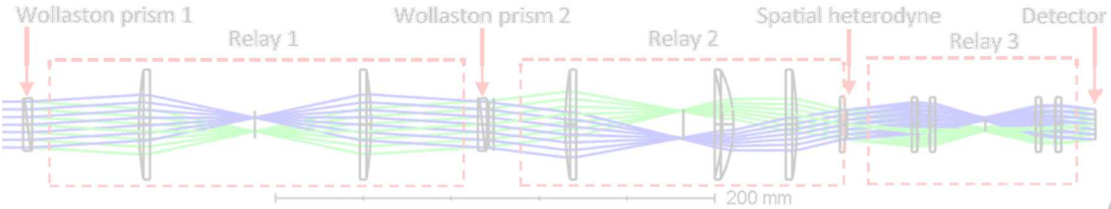
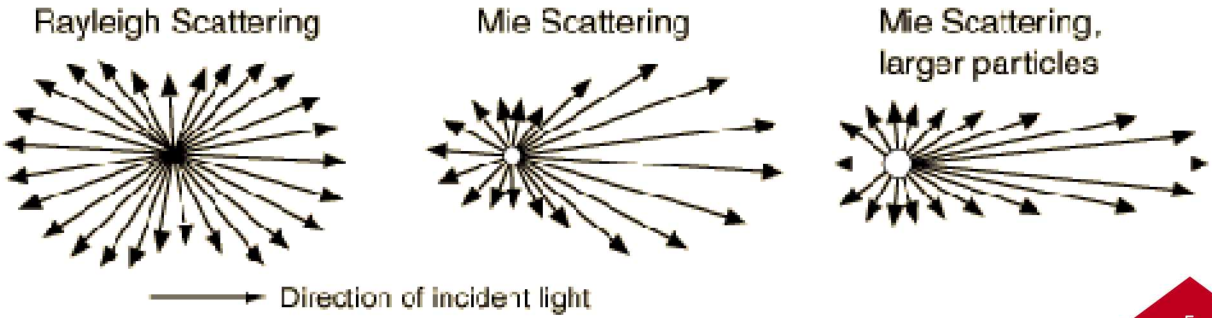
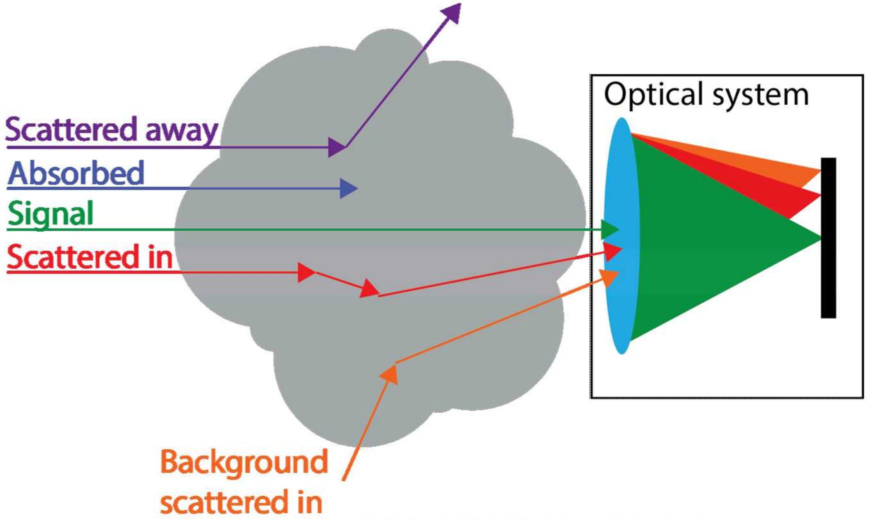


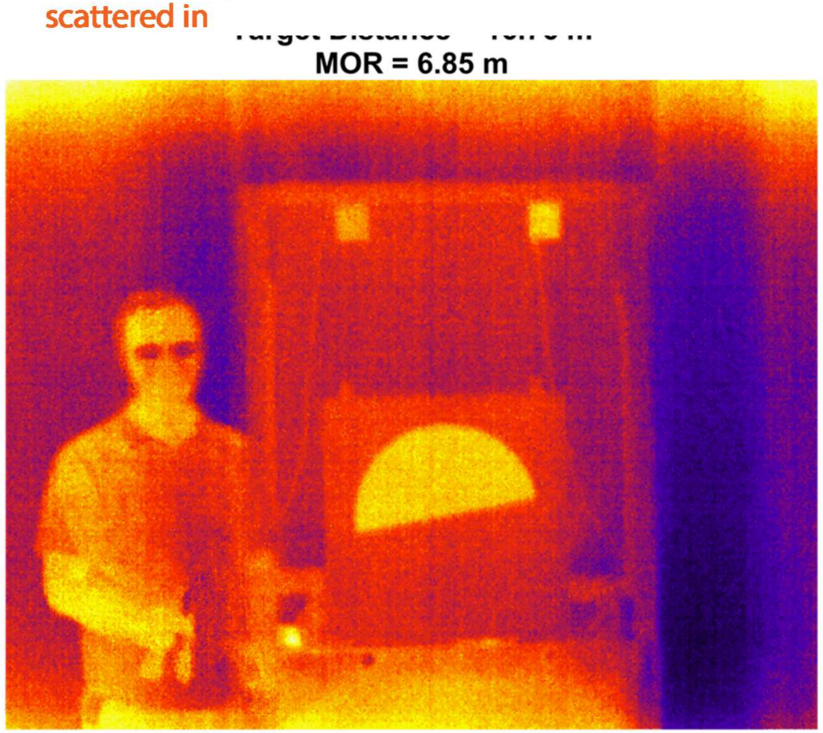
4. Compressive classification

Reduced awareness due to fog causes accidents

75-Car Pile-Up Kills at Least 3
ABC News March 31, 2013







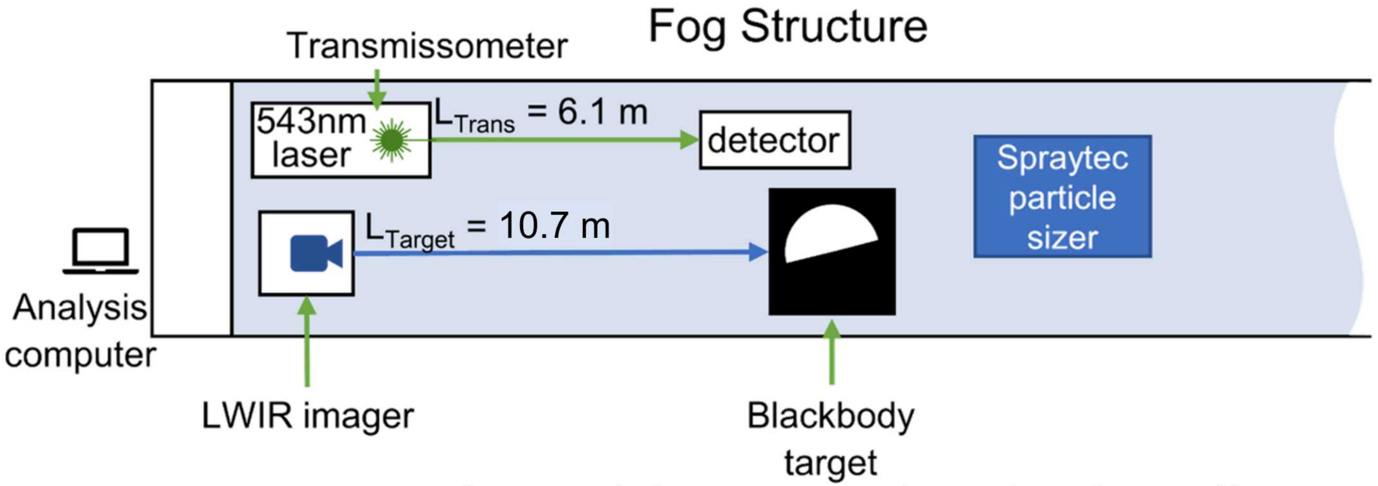
How imaging through fog is currently addressed

- Visibility
  - Distance that an object can be seen
- Koshmieder's Law
  - Dark object against light background
  - Daytime contrast against the sky
  - Approximated using transmission
- Allard's Law
  - Transmission of point source
  - Distance that a lighthouse is visible
  - Nighttime visibility of runway lights
- Meteorological optical range
  - 2,700 K lamp
  - Distance to attenuate a collimated beam
  - 5% transmission

Lighthouse - https://en.wikipedia.org/wiki/File:Pigeon_Point_Light_house.jpg

Sandia National Labs fog facility enables repeatable measurements

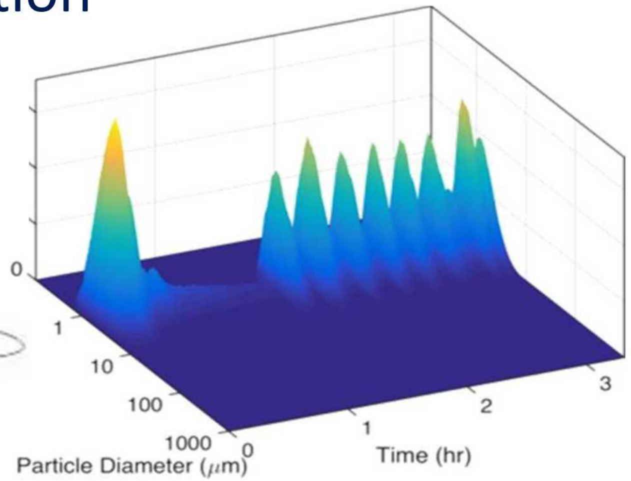
- Fog facility
  - One of the largest facilities in the world
  - 3m x 3m x 55 m
  - Extremely thick fog
  - Generation dissipation cycles
- LWIR measurements
  - Slant edge to measure MTF
  - Isolates blurring



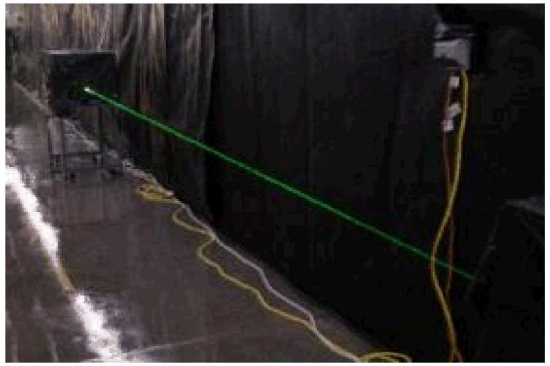
Brian J. Redman, et al., "Measuring resolution degradation of long-wavelength infrared imagery in fog," Opt. Eng. 58(5) 051806 (2019)

A combination of instruments is required to characterize the fog

Malvern Spraytec measures droplet size distribution



Transmissometer measures extinction over a long distance



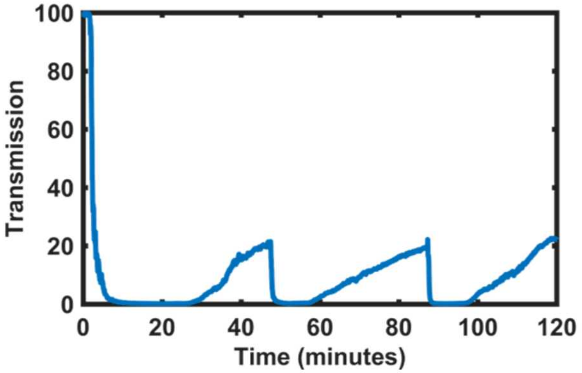
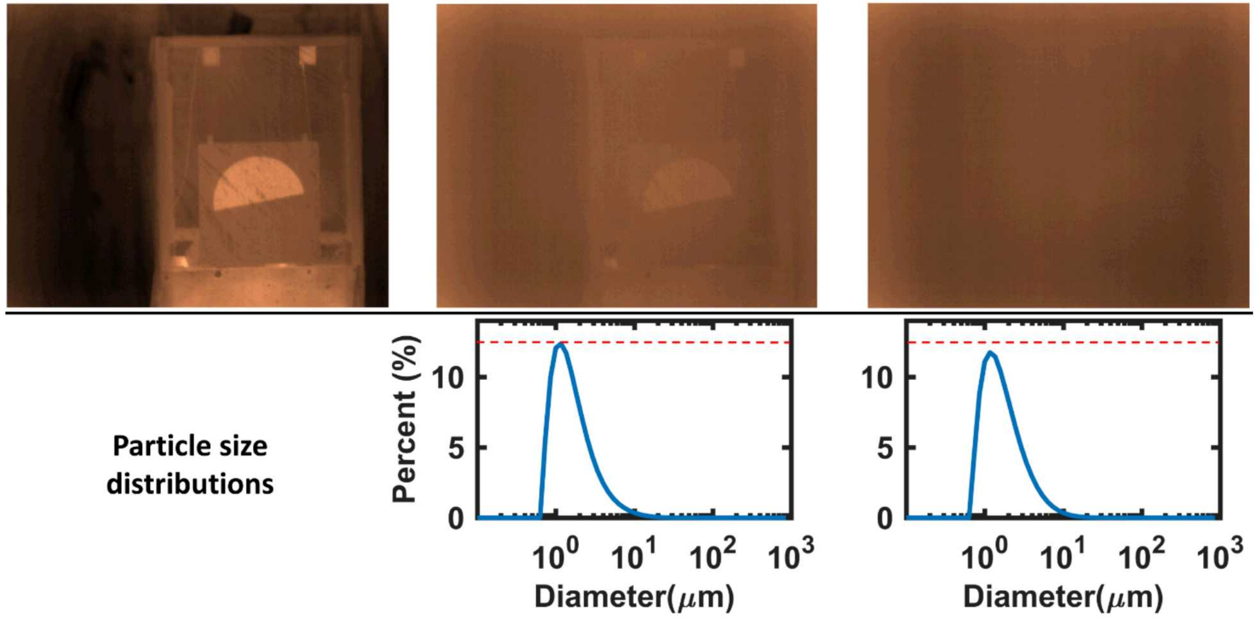


Image measurements synced to fog parameters



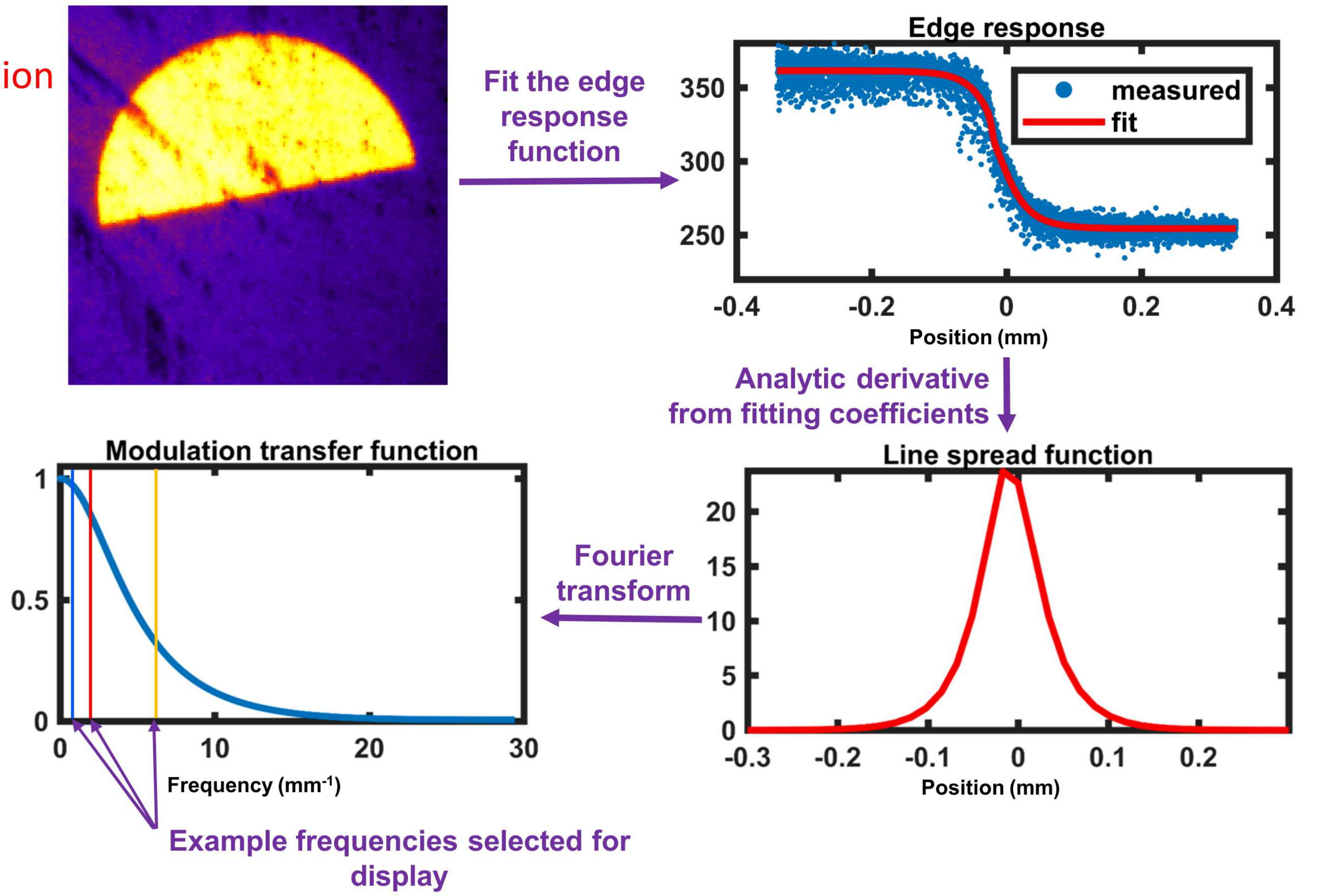
Parameters of the fog	**MOR_{543} = 6.00 m** **LWC = 0.53 g/m^3** **N_d = 78.9 × 10^3 cm^{-3}**	**MOR_{543} = 4.13 m** **LWC = 0.77 g/m^3** **N_d = 106.7 × 10^3 cm^{-3}**

Meteorological parameters derived from droplet distribution

Brian J. Redman, et al., "Measuring resolution degradation of long-wavelength infrared imagery in fog," Opt. Eng. 58(5) 051806 (2019)

Frequency measurement using edge response function

- MTF from edge response function
- Fitting edge
  - Sigmoidal functions
- Analytic derivative
  - doesn’t amplify noise
- Line spread function
  - 1D projection of point spread function
- Fourier transform gives MTF
- MTF function of fog thickness
  - Three frequencies to display trends



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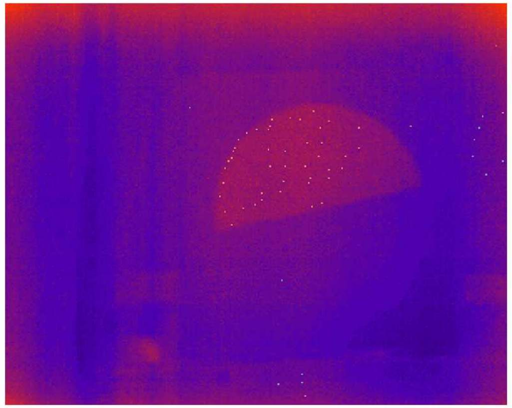
Measurements synced across instruments



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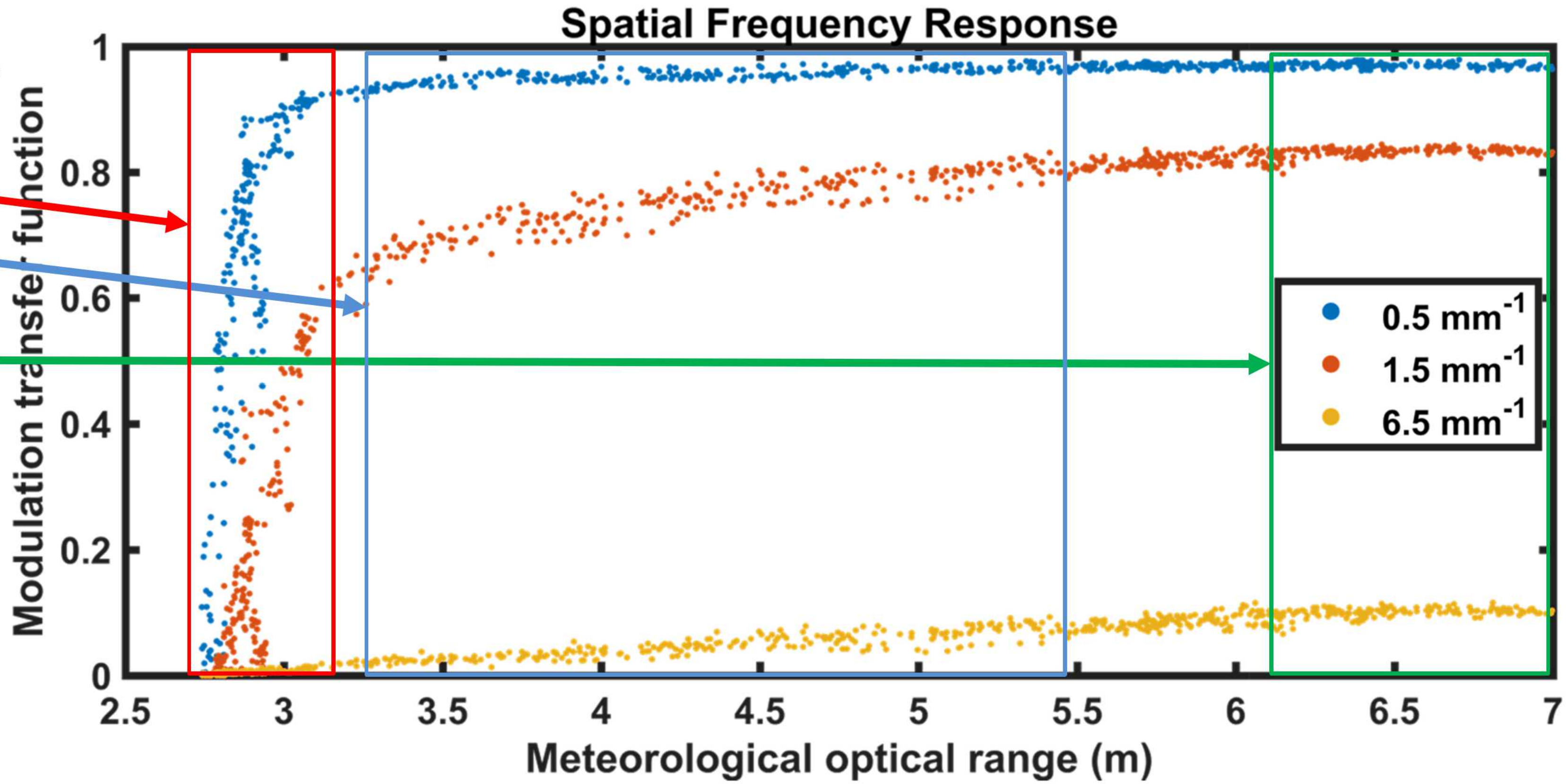
Frequency response dependent on fog thickness

- Example frequencies of the MTF vs. fog thickness
- Effective distance through 92 m MOR
- Frequency response in regions
  - Noise floor
  - Frequency recovery
    - Slope frequency dependent
  - Steady state



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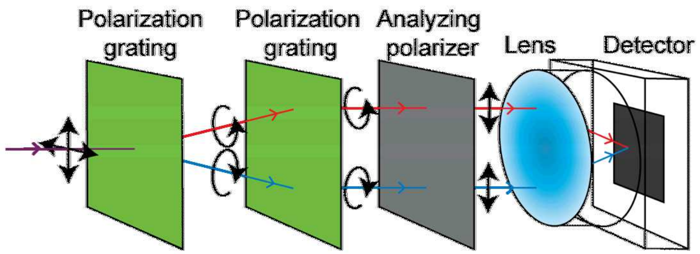

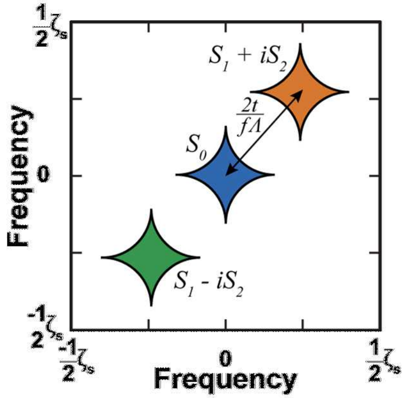

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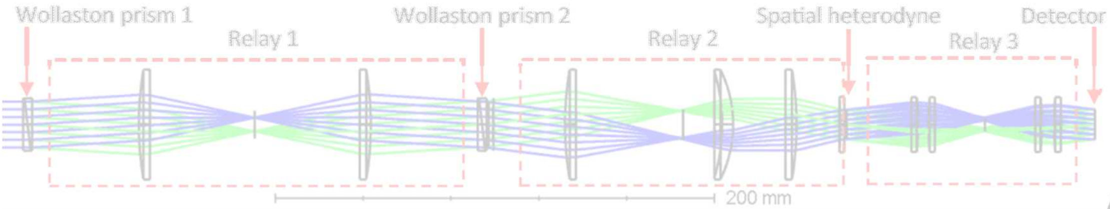
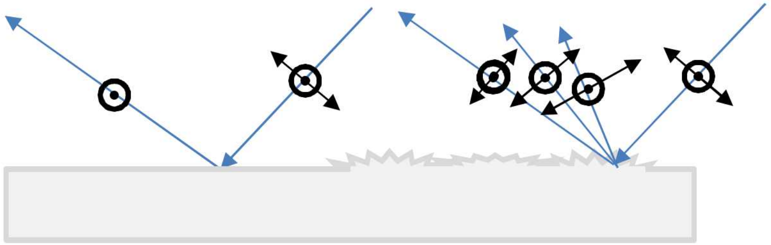


4. Compressive classification

Trading spatial resolution for polarization information

- Polarization gives information about surfaces
- Stokes polarimeter
  - – Linear Stokes
- Snapshot polarimeters
  - – High temporal resolution, decreased spatial resolution
  - – Modulated irradiance
    - Simpler fabrication

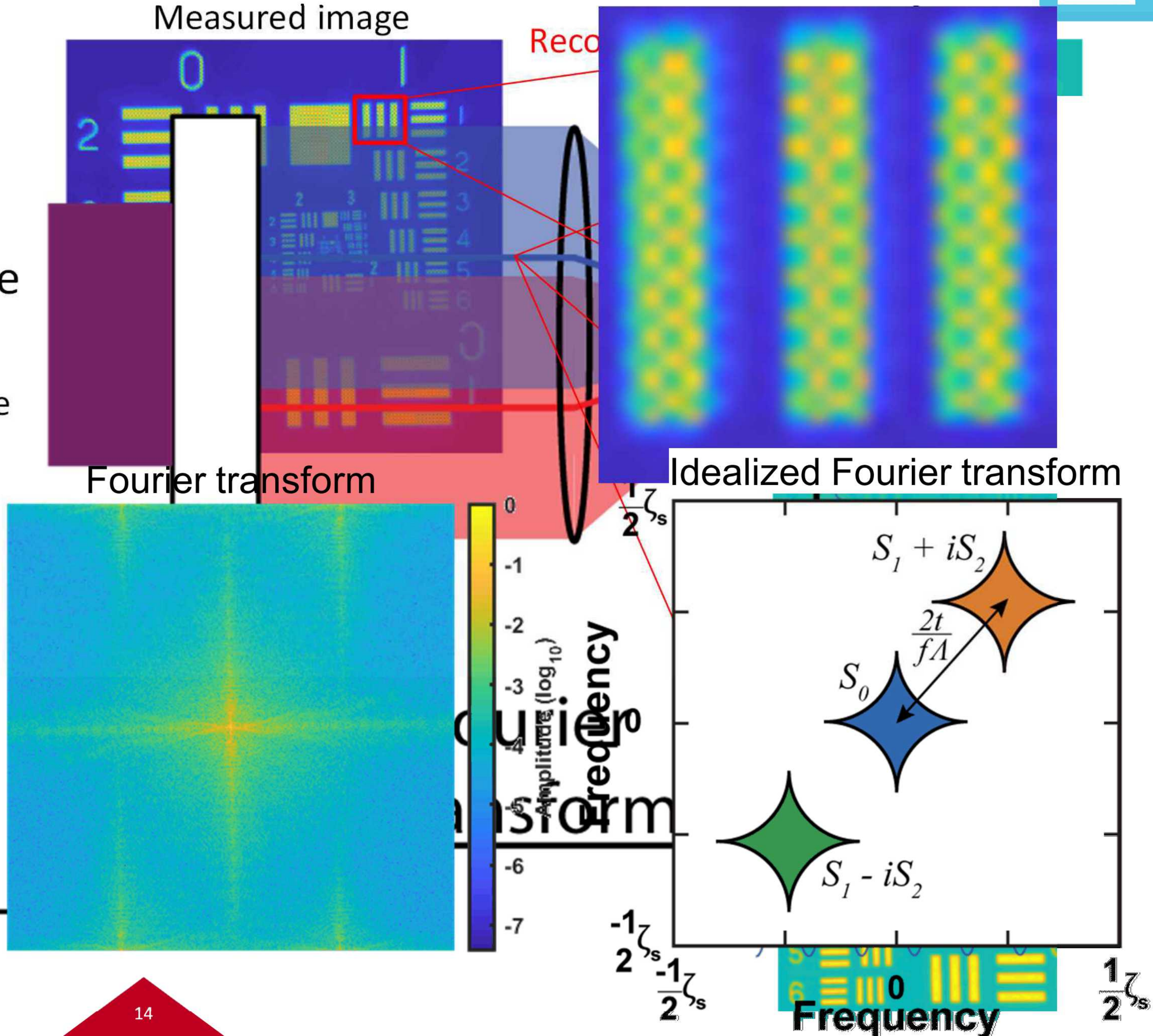


Stokes parameters

$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \Phi_{\text{total}} \\ \Phi_{\leftrightarrow} - \Phi_{\updownarrow} \\ \Phi_{\nearrow} - \Phi_{\nwarrow} \\ \Phi_{\circlearrowright} - \Phi_{\circlearrowleft} \end{bmatrix}$$

Interference to encode information into Fourier domain

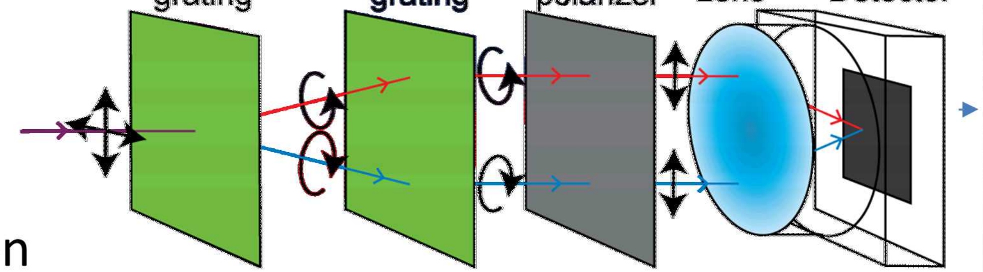
- Channeled optical systems
- Shear creates modulated irradiance
  - Visibility
    - Signal strength dependent on amplitude of modulation
- Images separated in Fourier domain
  - Channels

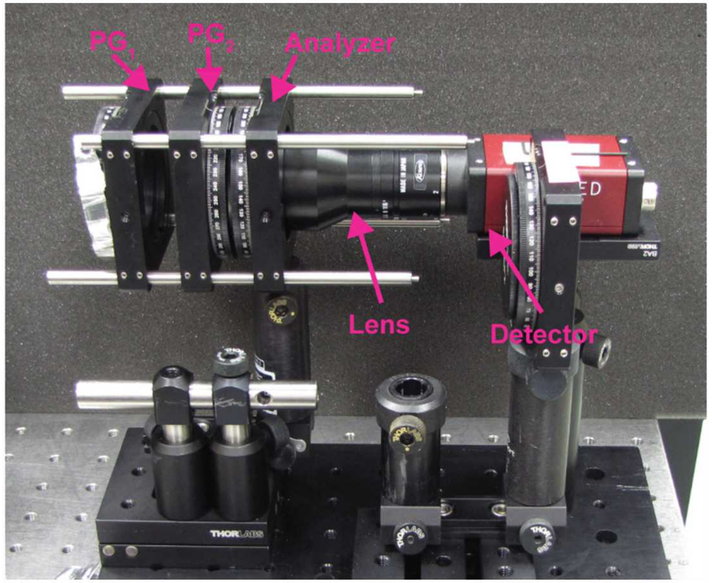


Polarization grating polarimeter optimized for maximum resolution

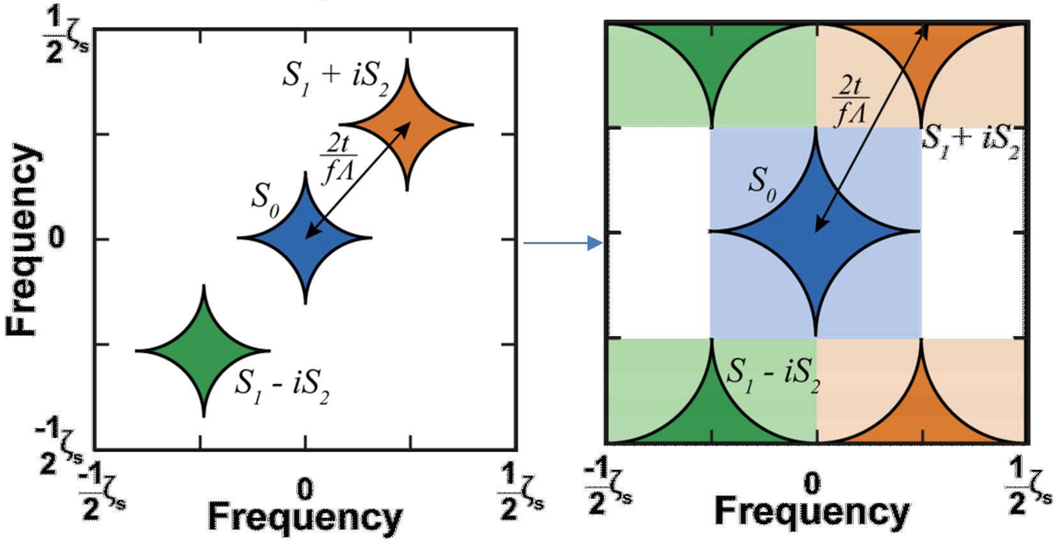
- Polarization gratings create shear
  - Diffraction grating
  - Polarization order selection
- Separation and angle set channel location
- Physical instrument created to test performance

Polarization grating polarimeter





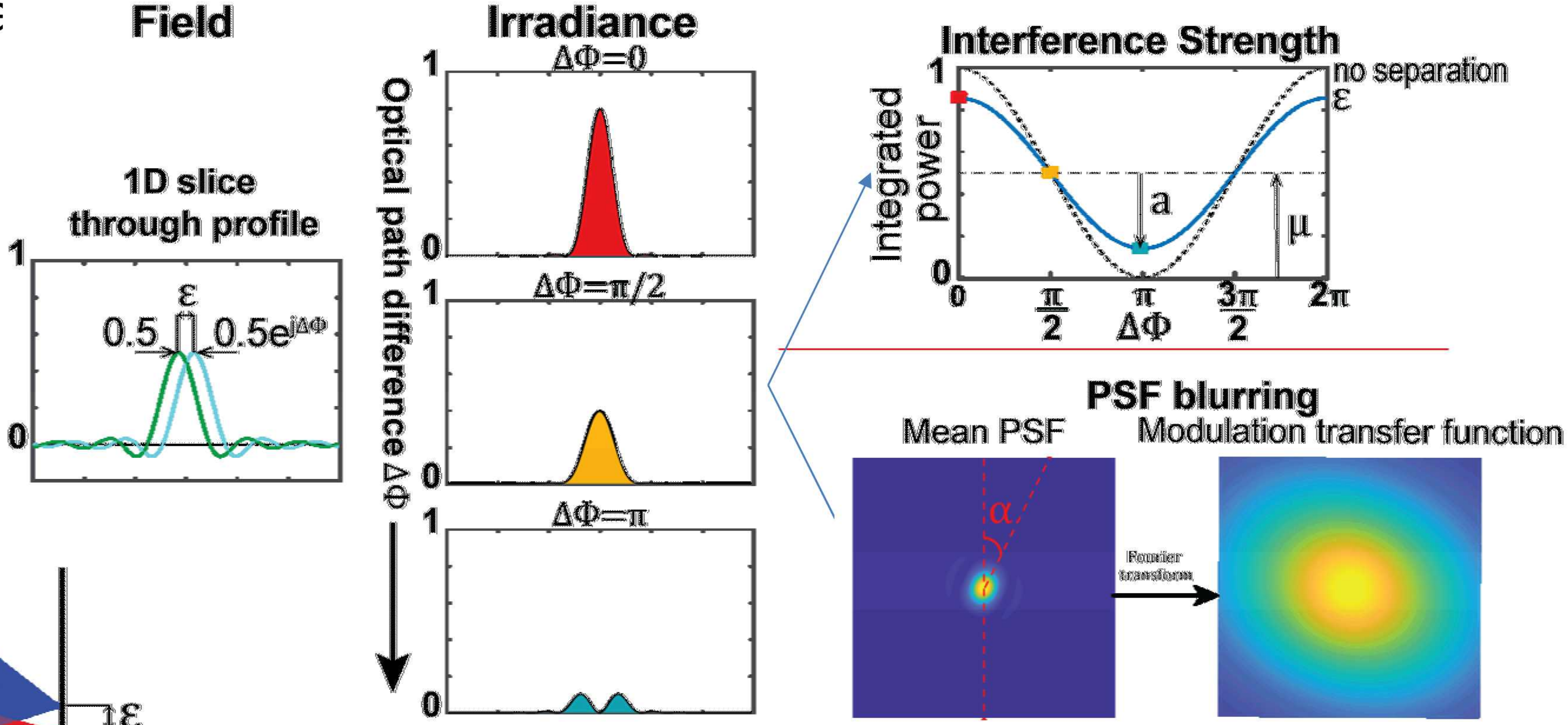
Optimized channel location

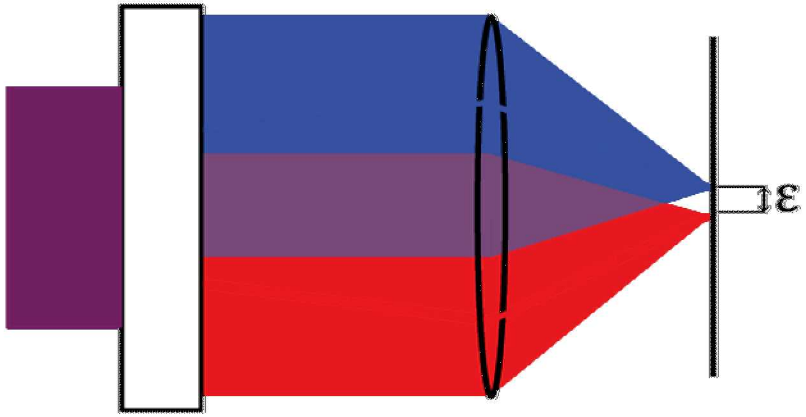


submitted: Brian J. Redman, et al., "Simulating and characterizing an optimized snapshot channeled imaging polarimeter," Optics Express

Decreased modulation amplitude due to misalignment

- Fringe visibility decrea
  - Separated PSFs
    - Interference strength
    - Blurred PSF





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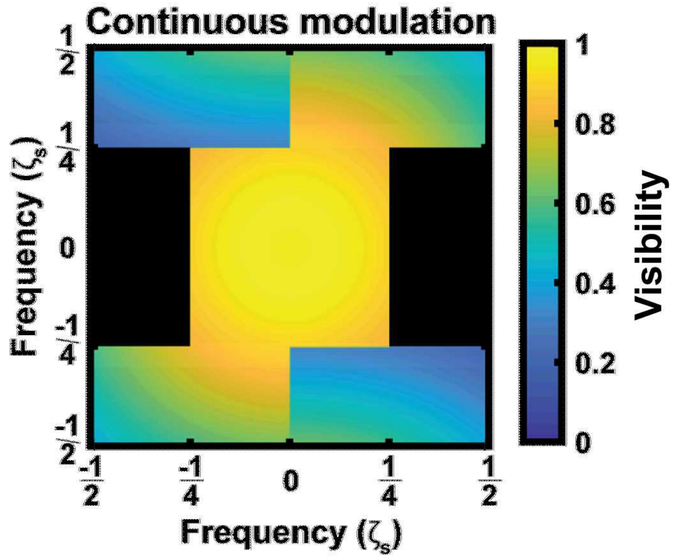
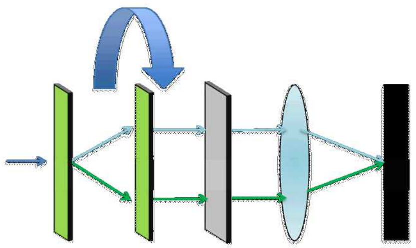
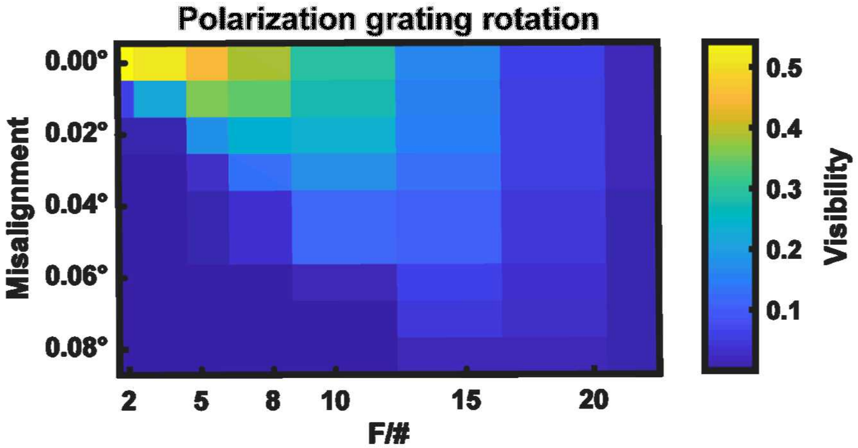
Performance of polarimeter is limited by component alignment and pixel sampling

- Pixel sampling
  - Sinc MTF
  - Modulated channels
    - High spatial frequencies
  - Fundamental limit of system
- Component misalignment
  - PSF separation and Pixel MTF
  - Highly sensitive
  - Width of PSF matters







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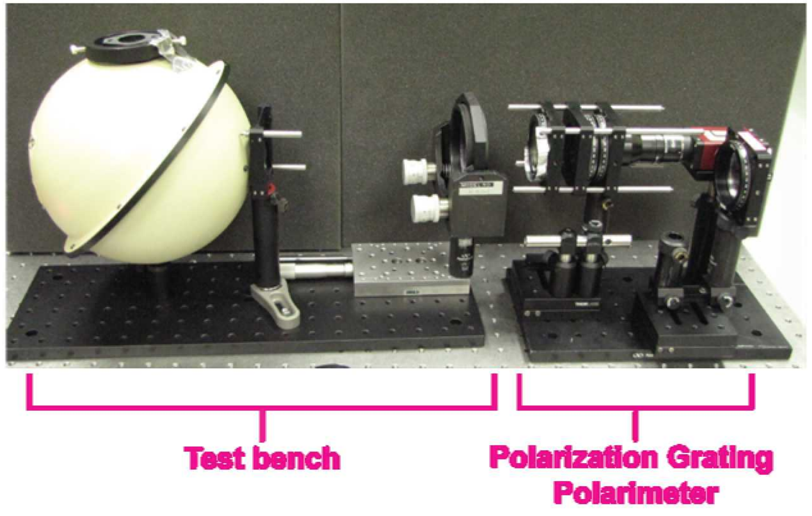
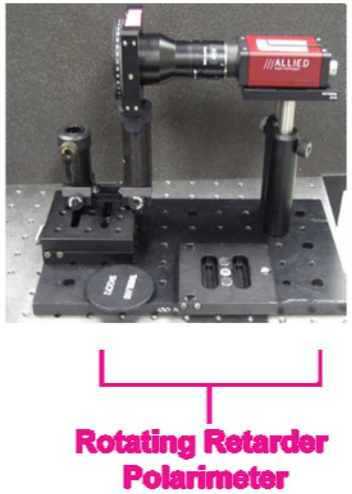
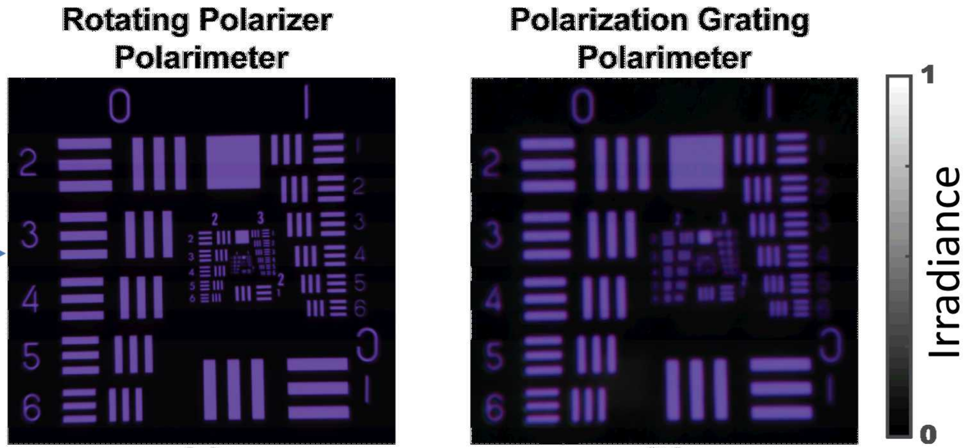
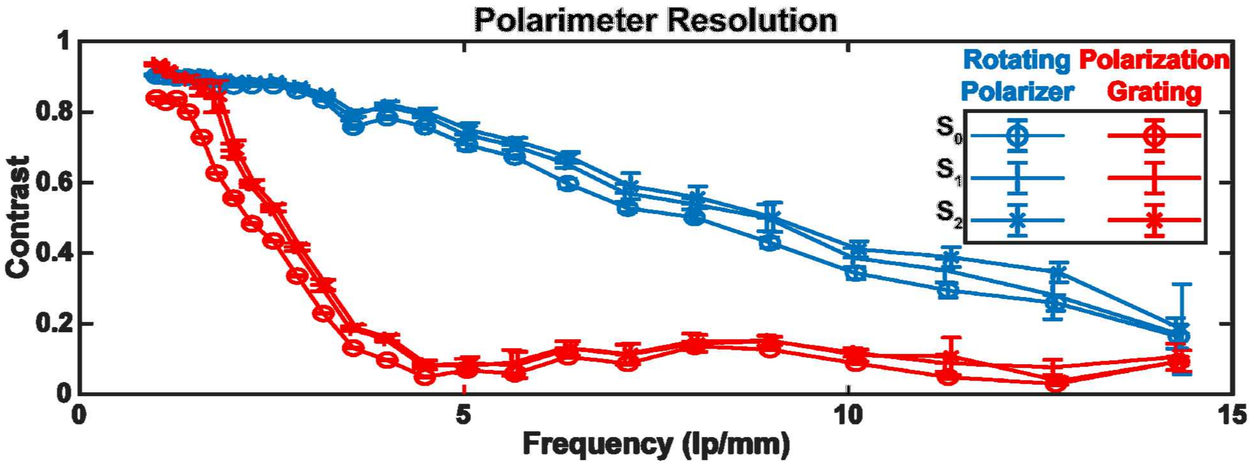
Performance of channeled polarimeter measured with resolution target



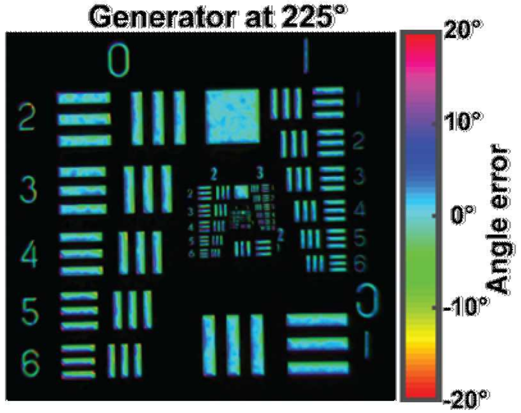




Resolution measurement



Angle measurement



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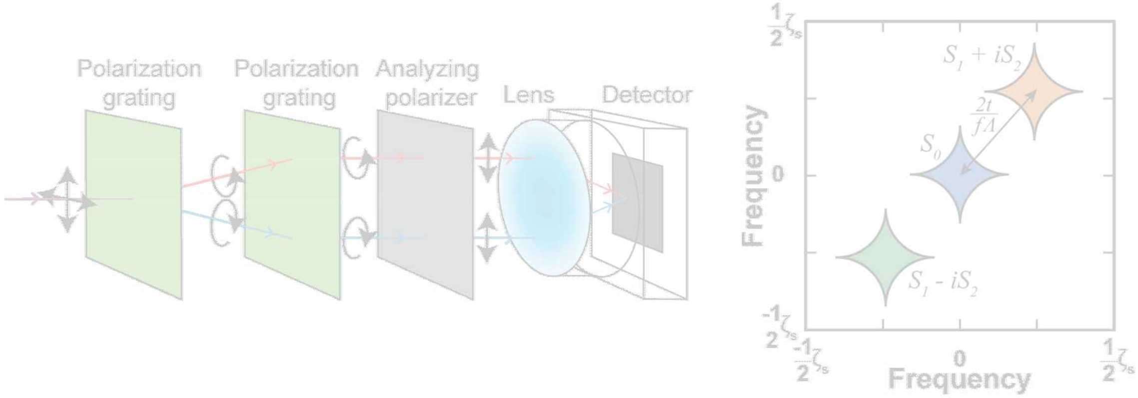

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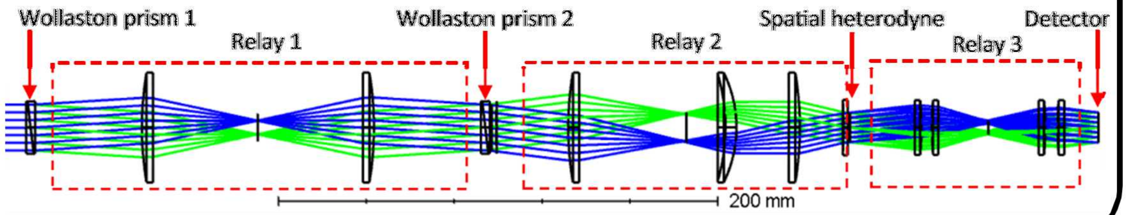
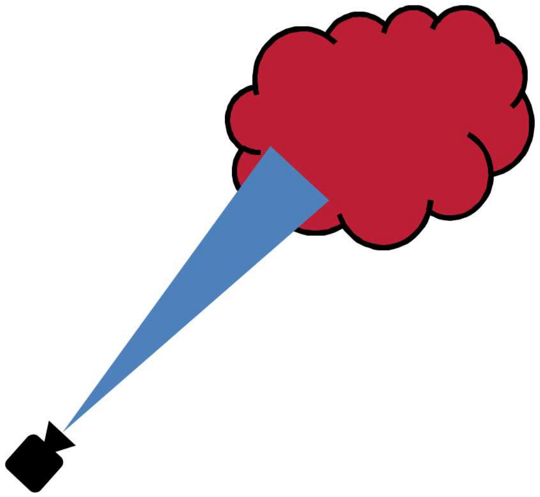
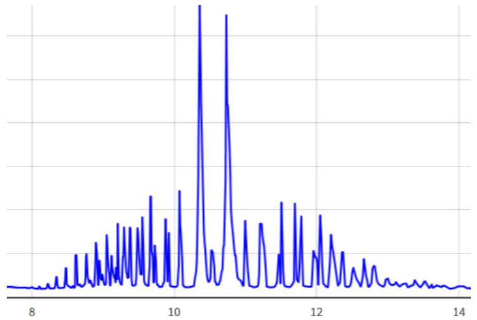


4. Compressive classification

- Non-imaging gas detection
- Spectral measurements
  - Enable material identification
  - Detection can be more important than localization
  - Instrument point and field of view
- LWIR enables passive measurements



Spectral measurement



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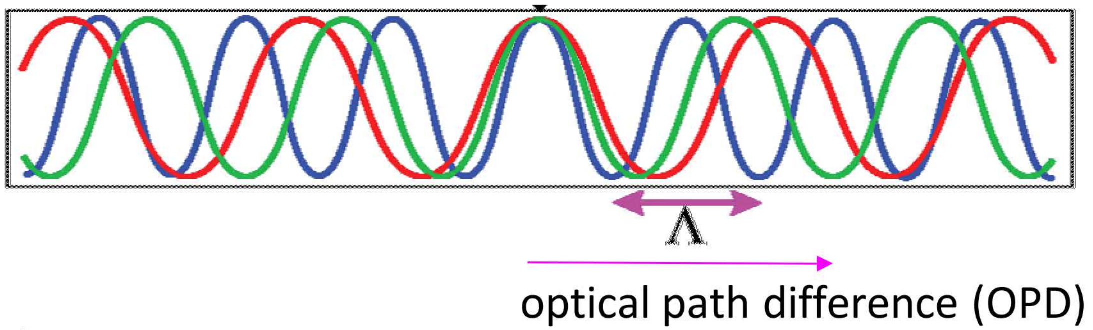
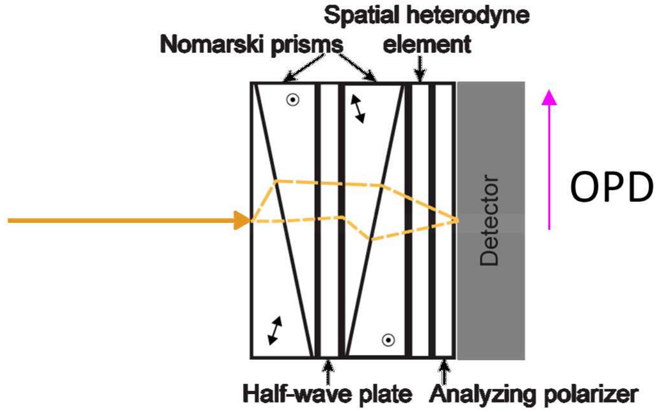
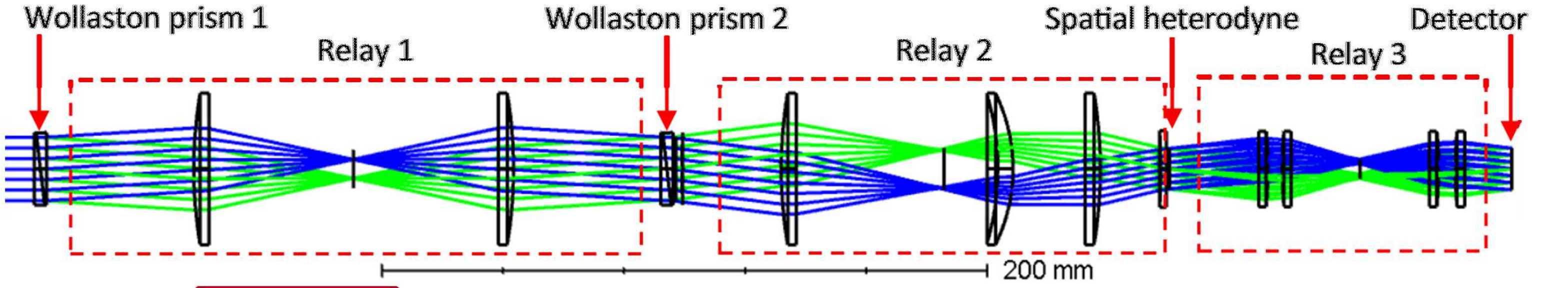
Fourier transform spectrometers (FTS) encode spectra into Fourier domain

- Interference creates a weighted sum of sinusoids
  - Fourier transform
- Can be implement as a solid state device
  - Enables hand held instrument
  - Bonded together
  - Demonstrated in the visible
- LWIR implementation more risky
  - Birefringent materials rare
  - Expanded design for proof of concept

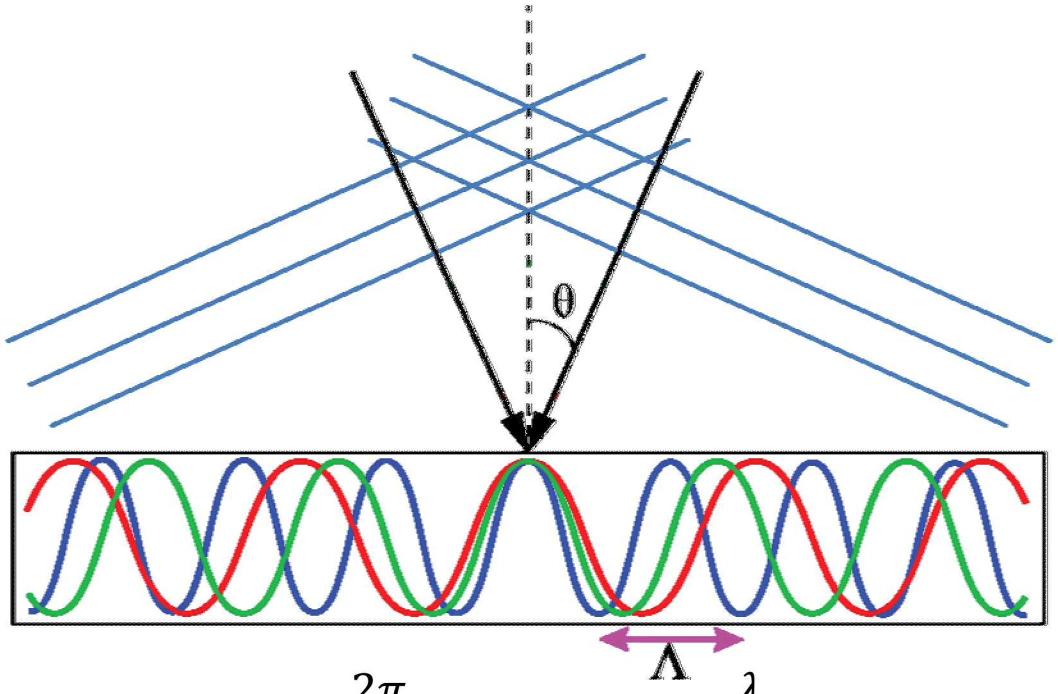






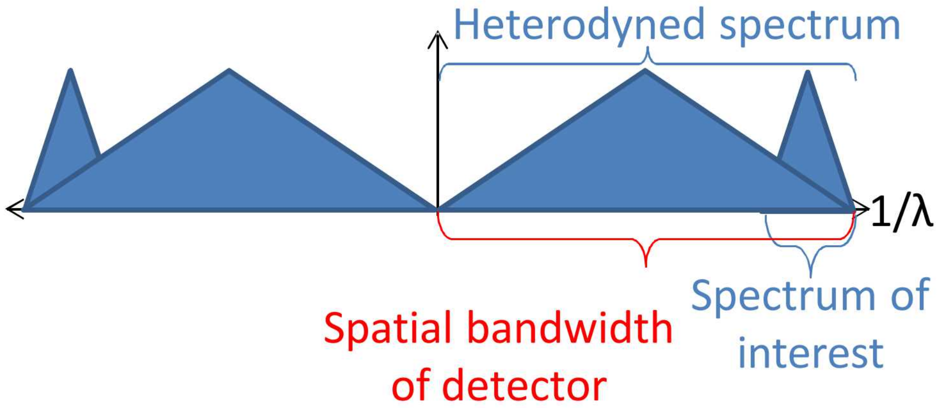
Spatial heterodyne

- Two polychromatic plane waves
  - Frequency from 0 to max frequency
  - Low resolution after Fourier transform
- Spatial heterodyne
  - Shift the spectrum lower
  - Can use spatial bandwidth of detector
- Wavelength dependence to incident angle
  - Diffractive optic

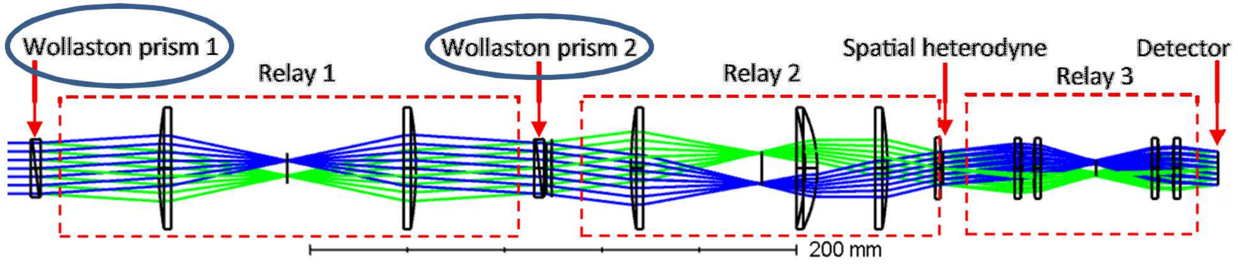


$$\Lambda = \frac{2\pi}{|\Delta \boldsymbol{k}|} \cong \frac{\lambda}{2\sin\left(\theta_0 - \sin^{-1}\left(\frac{m\lambda}{d}\right)\right)}$$

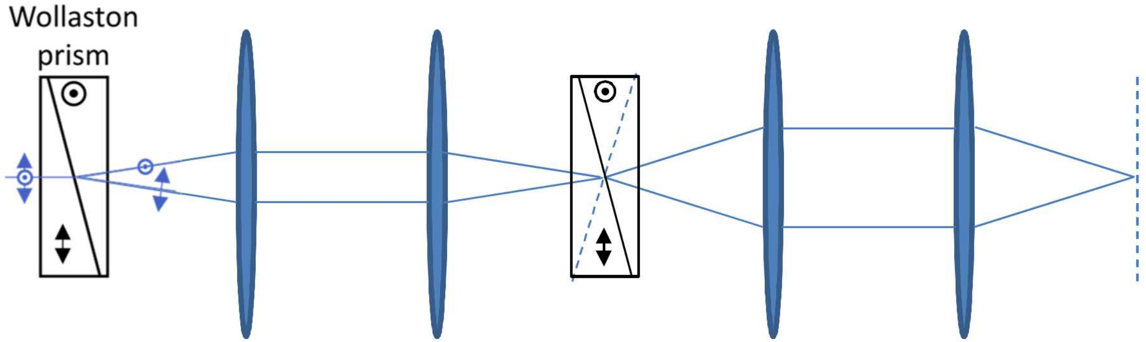
Fourier transform of interferogram



Many separate elements as proof of concept for solid state Nomarski design

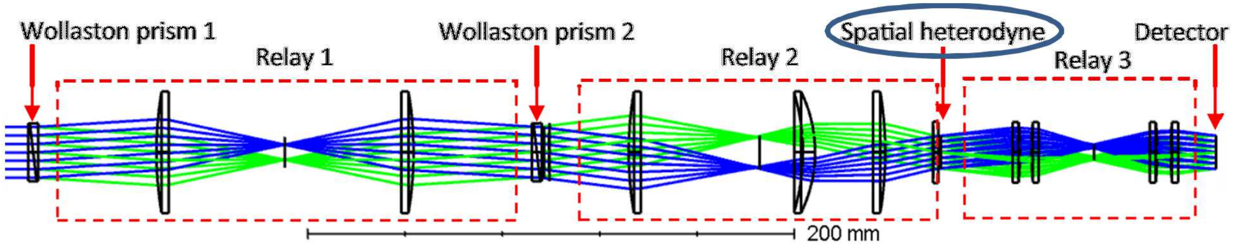


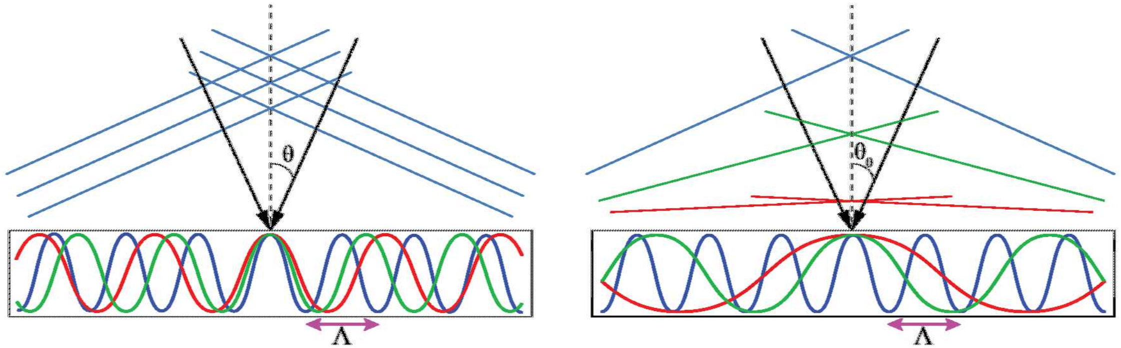
- Wollaston prism
  - Splits light
  - Slanted interference plane
- Second prism
  - Doubles angle
  - Flattens interference plane

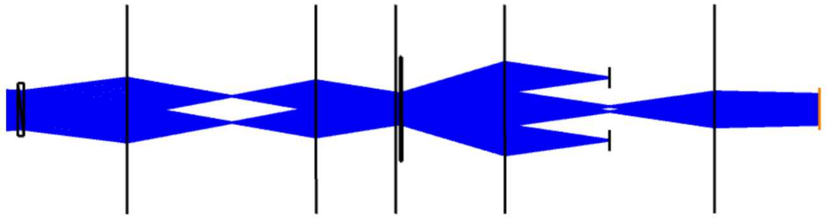


Many separate elements as proof of concept for solid state Nomarski design

- Spatial heterodyning
  - Reduce spatial frequency
- Diffractive optic
  - Change angle of plane waves
  - Fourier filter to remove unwanted orders







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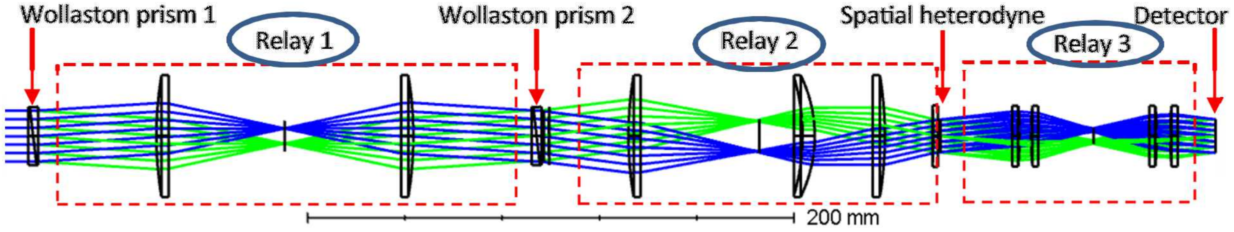
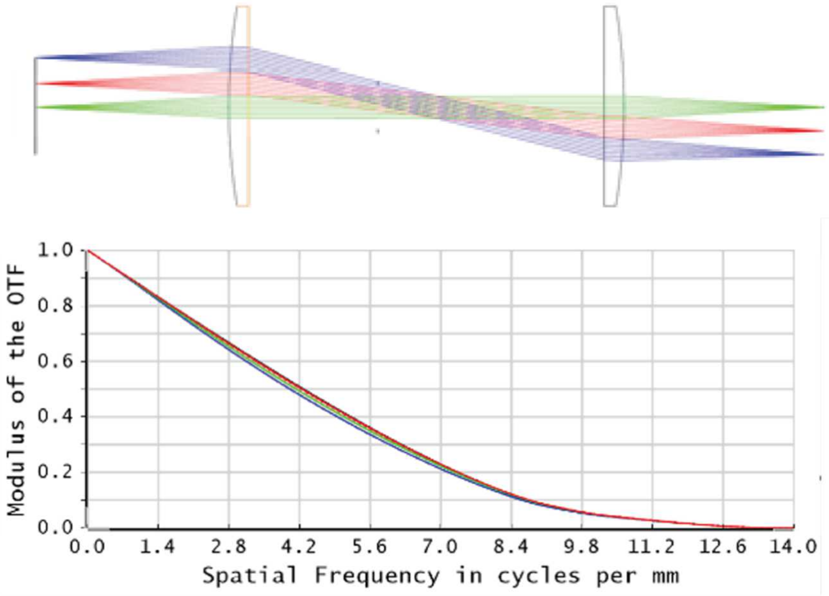
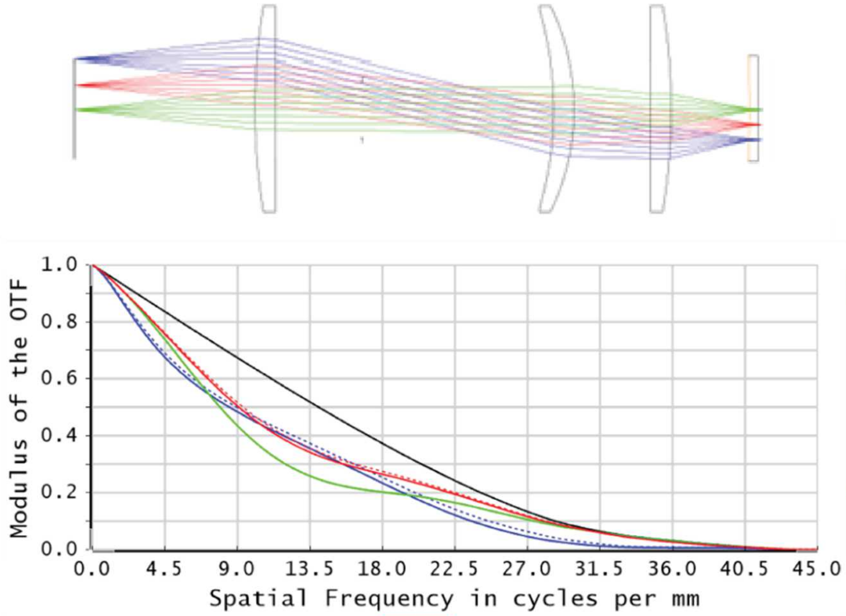
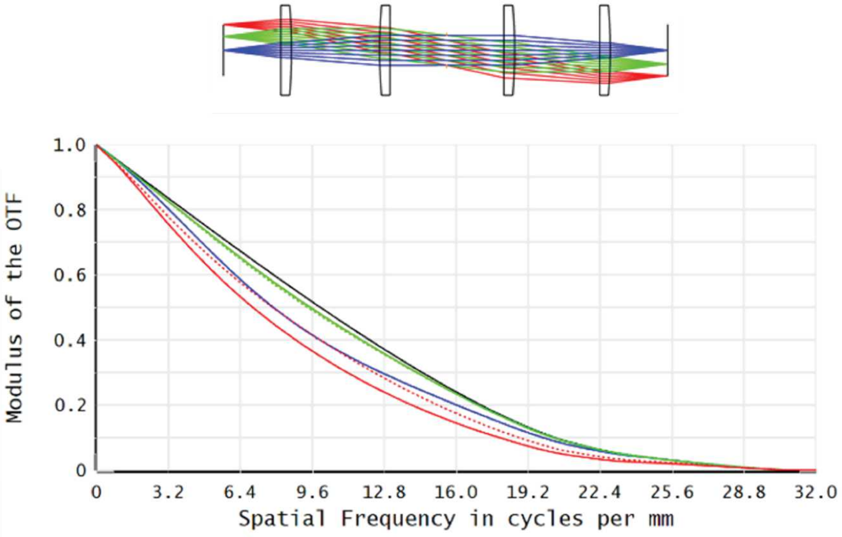


- Relays
  - Image interference plane
  - Optimized in sections
- Telecentric
  - Ray cone represents split angle

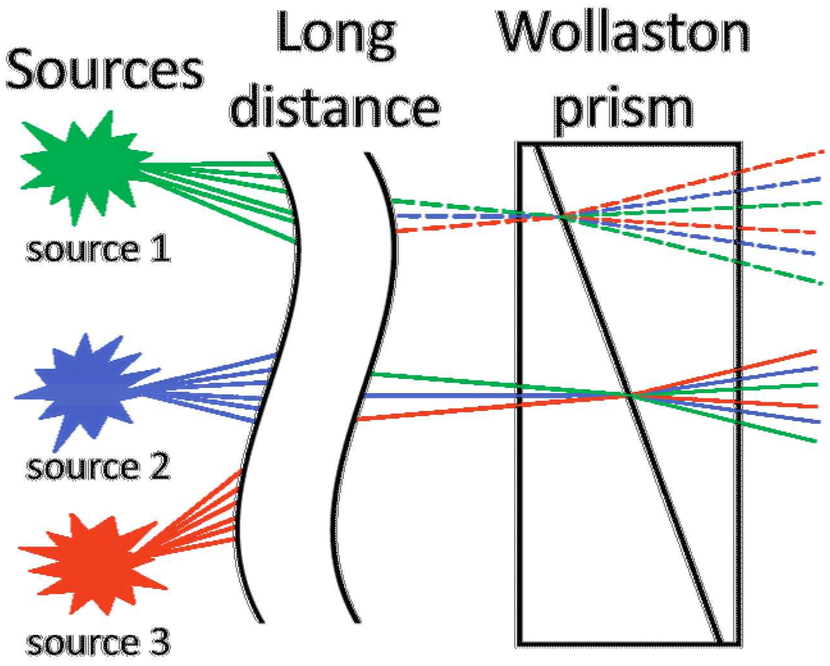






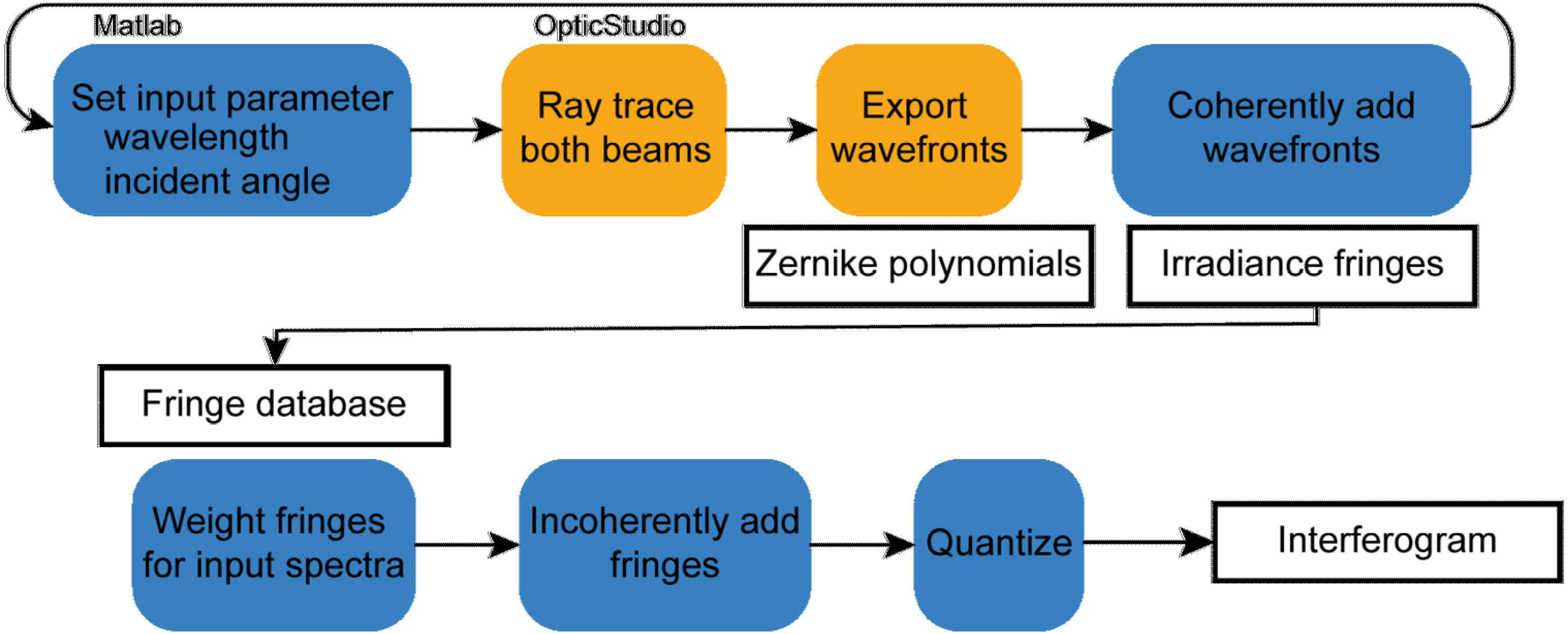
Pitfall of modeling the Fourier transform spectrometer

- Coherence
  - Crucial for simulations
  - MTF assumes coherent points



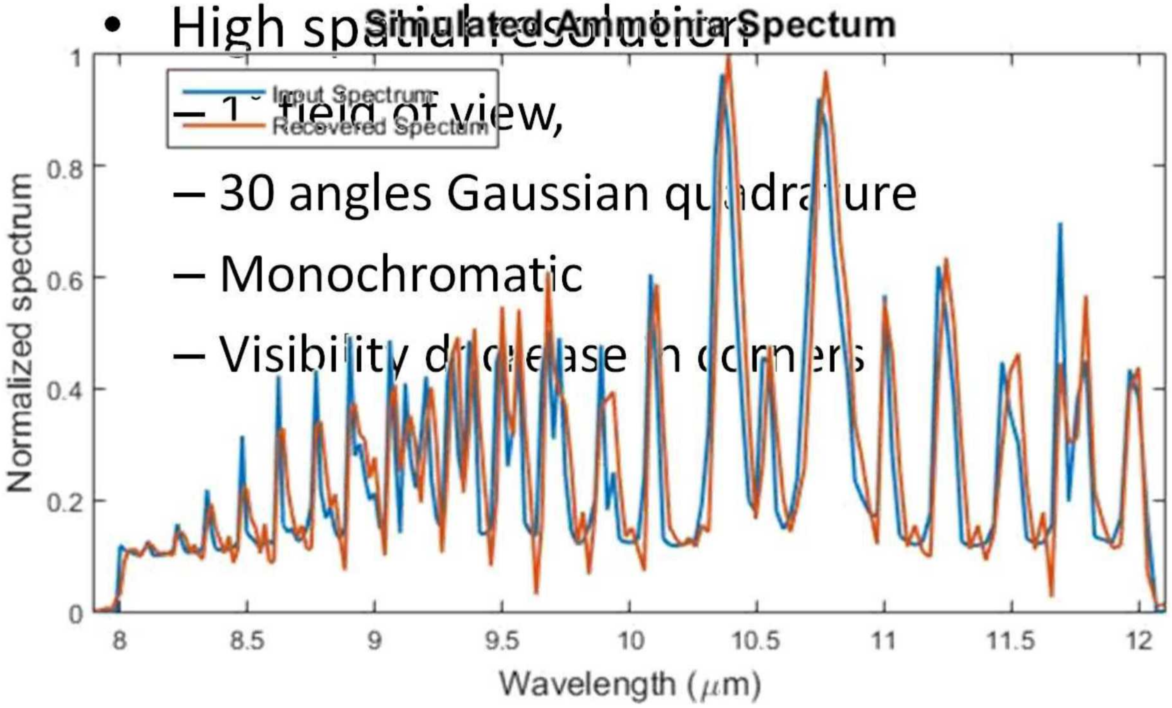
Coherence directly controlled to remove assumptions

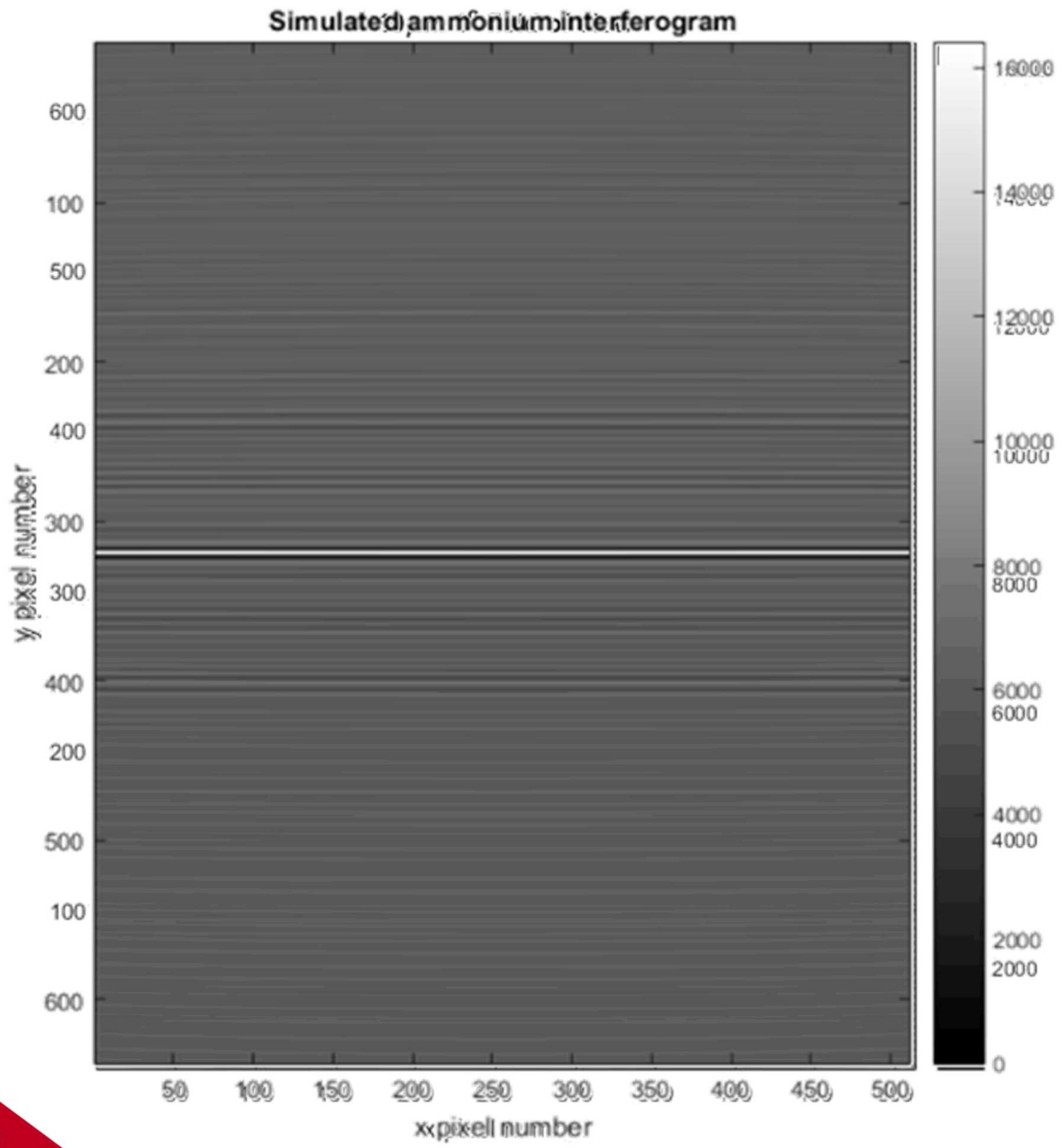
- Ray tracing efficient to estimate wavefronts
- Matlab to combine wavefronts
  - Coherently
    - Split beams
  - Incoherently
    - Input angles
    - Wavelengths



Simulation models both spatial and temporal incoherence

- High Spectral sampling
  - 400 wavelengths
  - 1˚ field of view 7 angles
  - Reconstructed
- High spatial resolution
  - 1˚ field of view,
  - 30 angles Gaussian quadrature
  - Monochromatic
  - Visibility decrease in corners

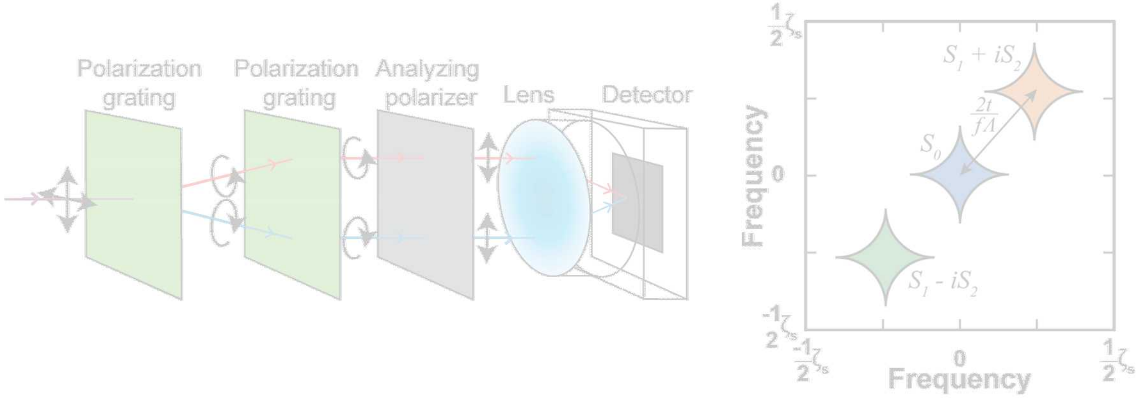




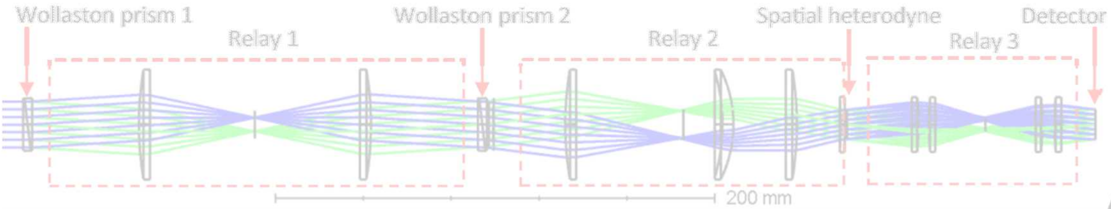
Modeling and measurements of Four optical systems

1. Long-wave infrared measurement of image degradation caused by fog

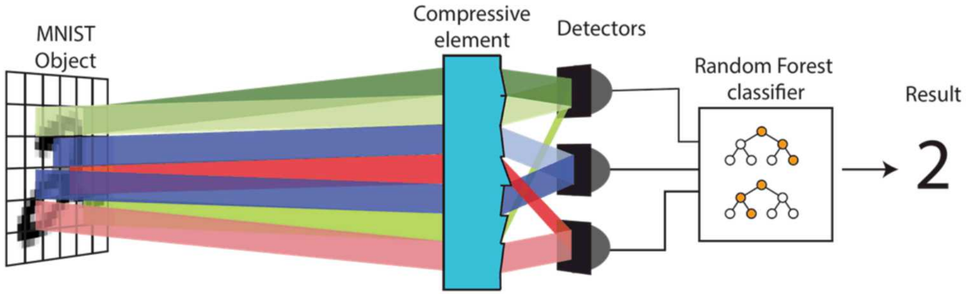
2. Channeled imaging polarimeter



3. Long-wave infrared snapshot Fourier transform spectrometer

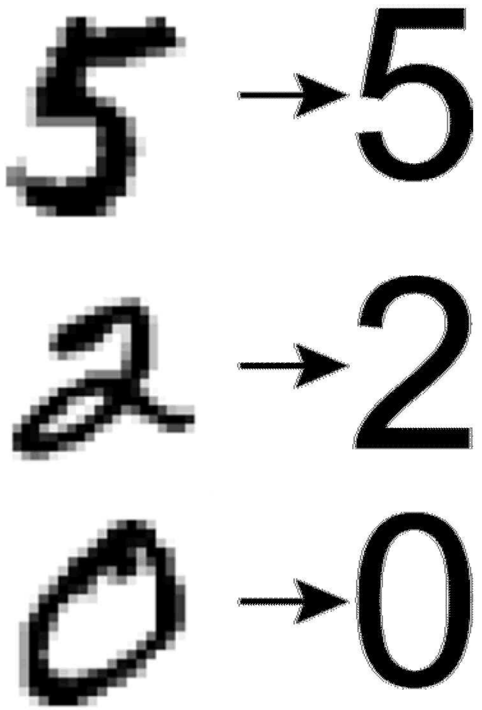


4. Compressive classification

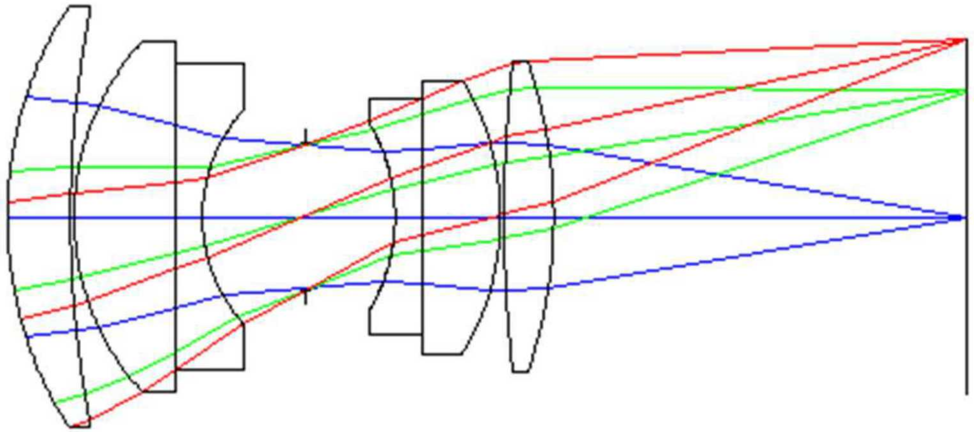


Spatial resolution not required for detection

MNIST dataset

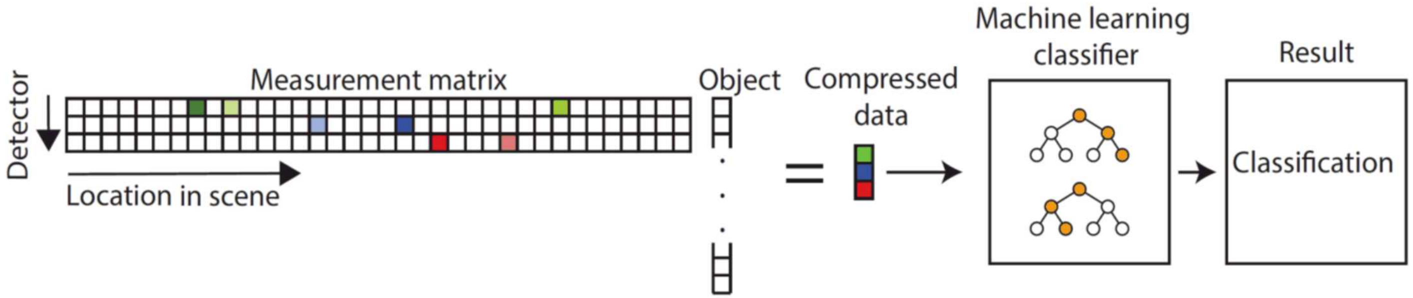


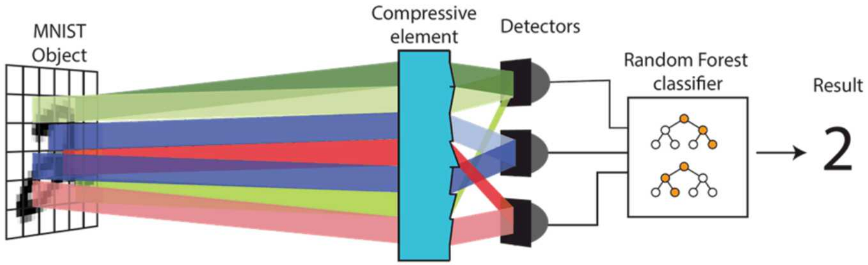
- Classification requires small subset of scene
  - Final data product class not image
  - Image processing commonly compresses high resolution images
- Imaging over constrains
  - 1:1 mapping
  - Many element optical system
- Potential to reduce size weight and power

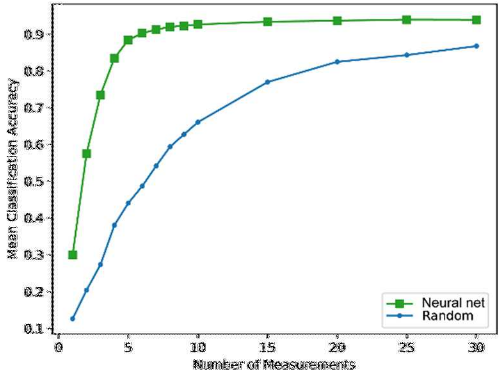


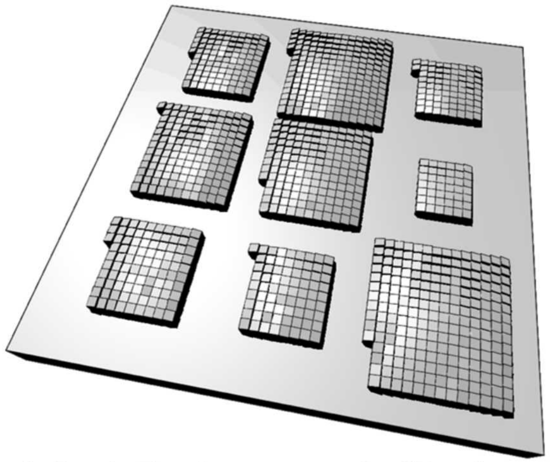
Compressive classification

- Classification algorithms compress images
  - Reduce size of dataset
    - 784 -> 9 for MNIST
  - Remove information that does not differentiate classes
  - Reduce computation requirements
- Hardware compression
  - Physical implementation of compression matrix
  - Requires multiple field angles mapped to each detector
- Prism array
  - Prism for Each non-zero entree of matrix





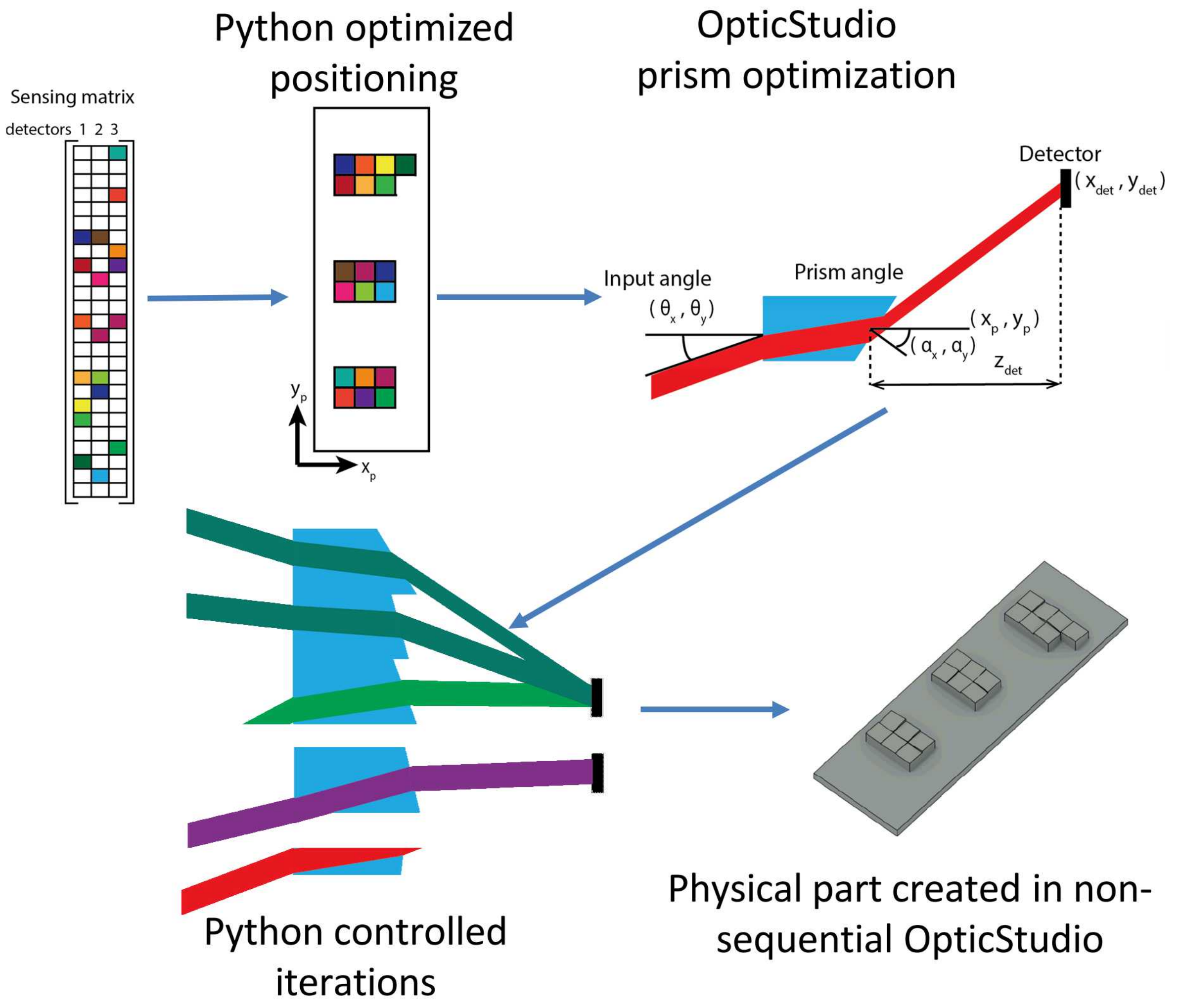


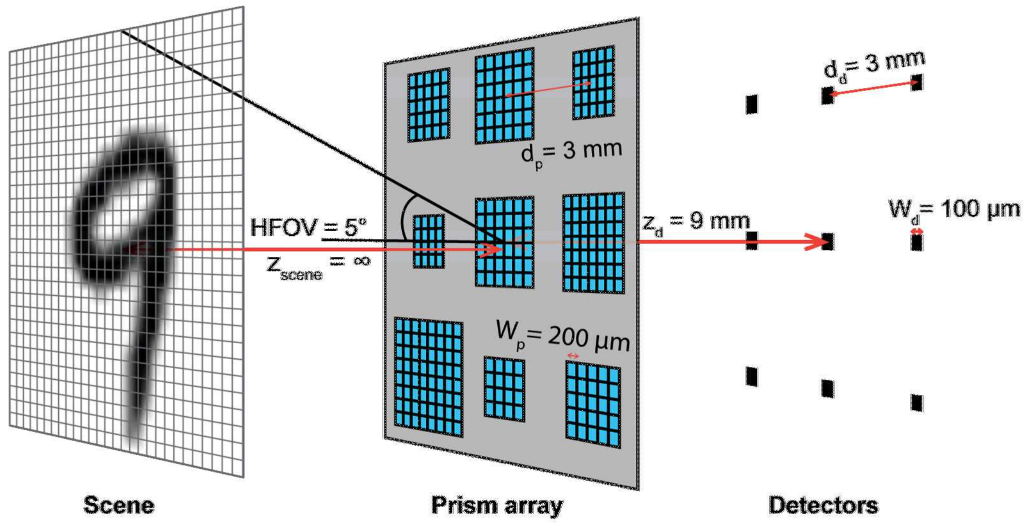


Submitted: B. J. Redman, et al., "Performance evaluation of two optical architectures for task-specific compressive classification," *Optical Engineering* **59**(5),2019.

Autonomous workflow for realizing a mathematical construct

- Assign physical parameters to dataset
- Combination of Python and OpticStudio
- Workflow independent of dataset complexity

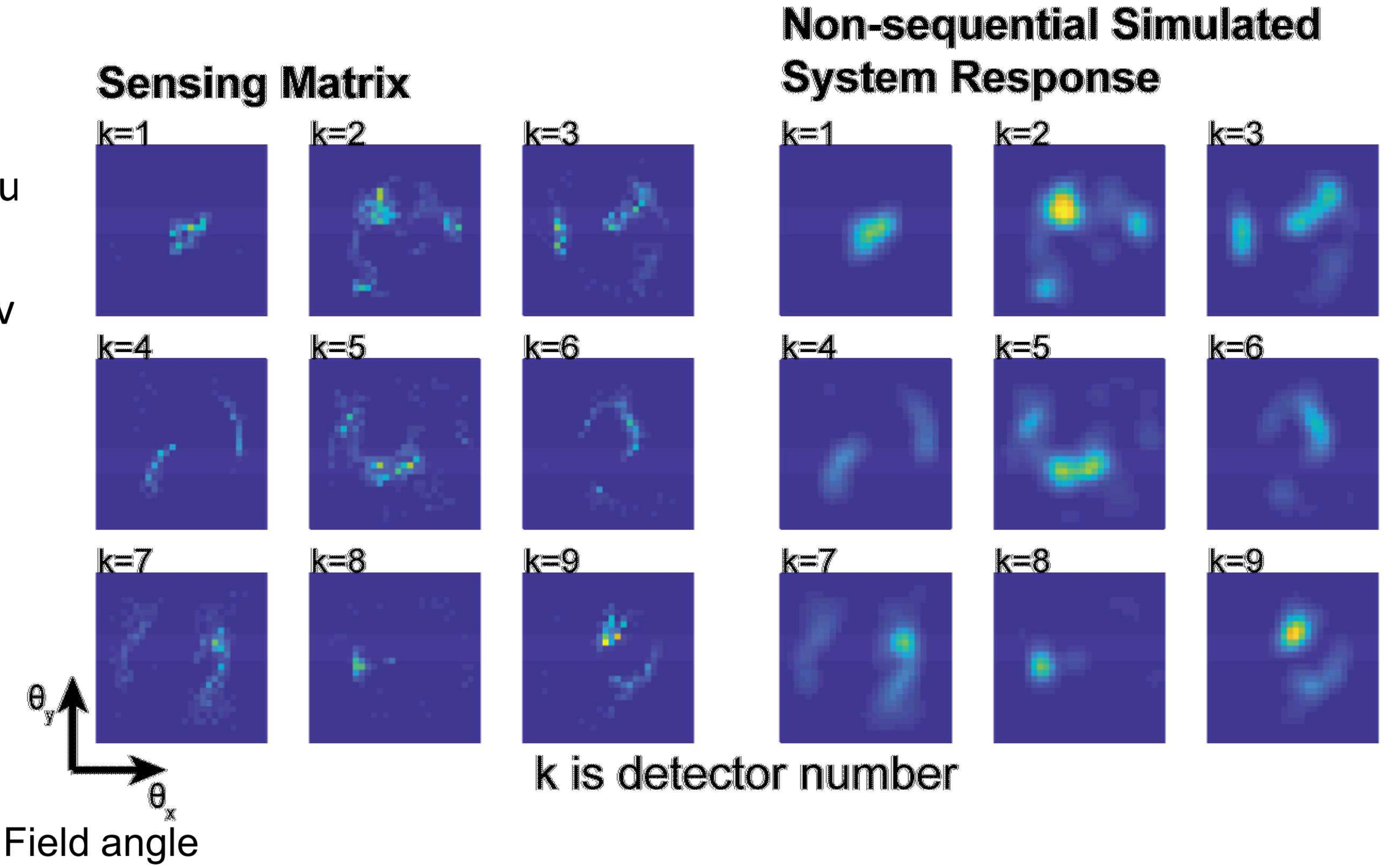




Minor revisions: B. J. Redman, et al., "Performance evaluation of two optical architectures for task-specific compressive classification," *Optical Engineering,* 2019.

Physical realization of sensing matrix

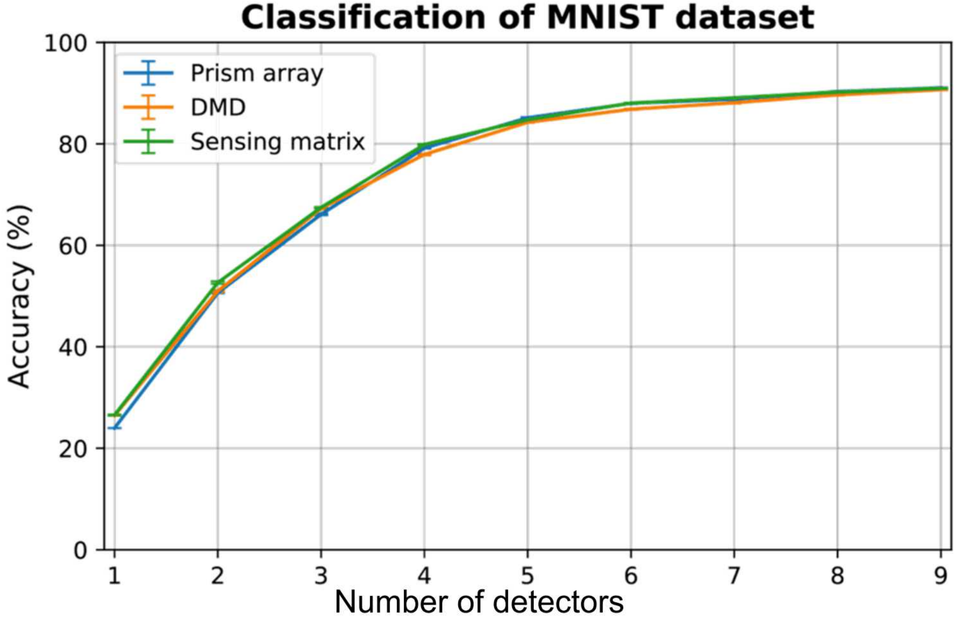
- Non-sequential ray trace
  - Separate trace for each inpu angle
  - Determine detector sensitiv
- Prism array
  - Blurring cause by prism accepting larger angle
- System response
  - Can be used to simulate performance

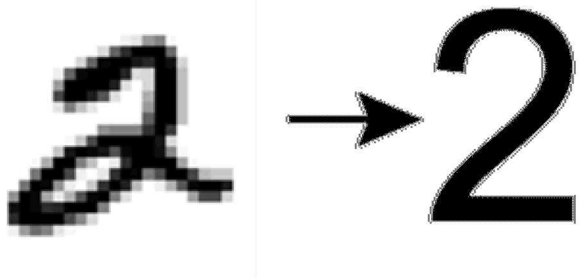


Minor revisions: B. J. Redman, et al., “Performance evaluation of two optical architectures for task-specific compressive classification,” *Optical Engineering,* 2019.

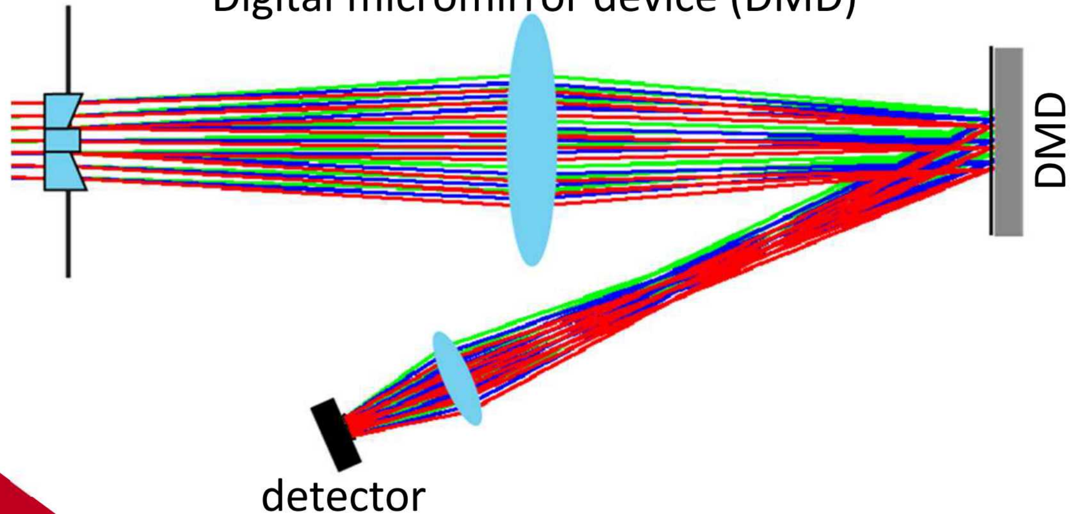
Simulations of classification accuracy to determines performance

- Sensing matrix ideal performance
- Realized with two optical architectures
  - Prism array
  - Digital micromirror device (DMD)
- Simulation uses sensing matrices
  - Nonsequential ray trace to determine sensitivity
  - Used to compress MNIST images
  - Random forest classifier



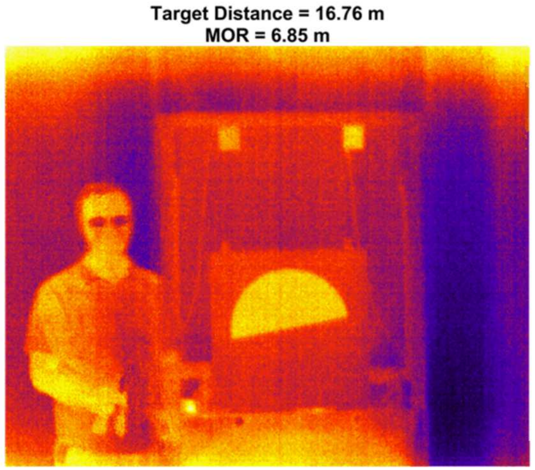


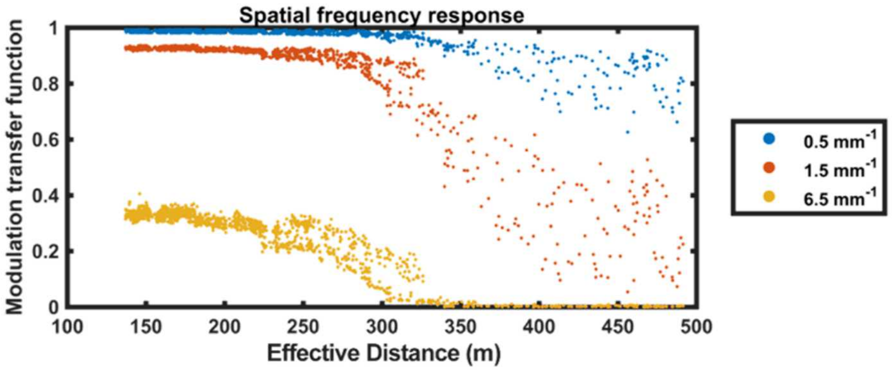
Alternate architecture
Digital micromirror device (DMD)

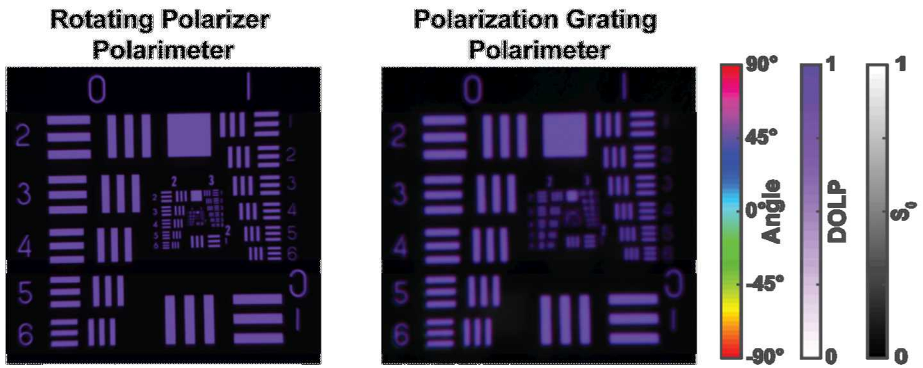


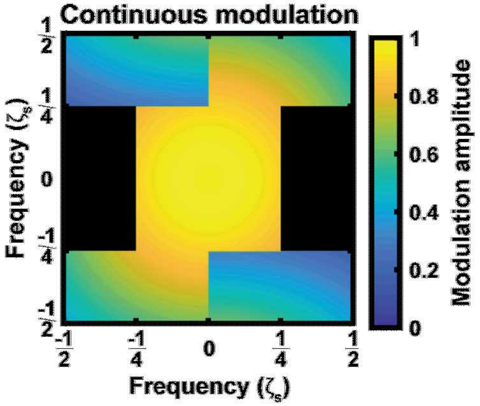
Minor revisions: B. J. Redman, et al., “Performance evaluation of two optical architectures for task-specific compressive classification,” *Optical Engineering,* 2019.

Measurement and simulation of complex optical systems

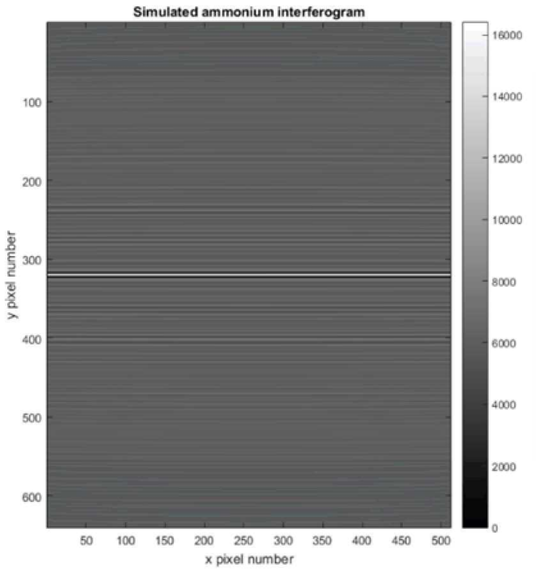


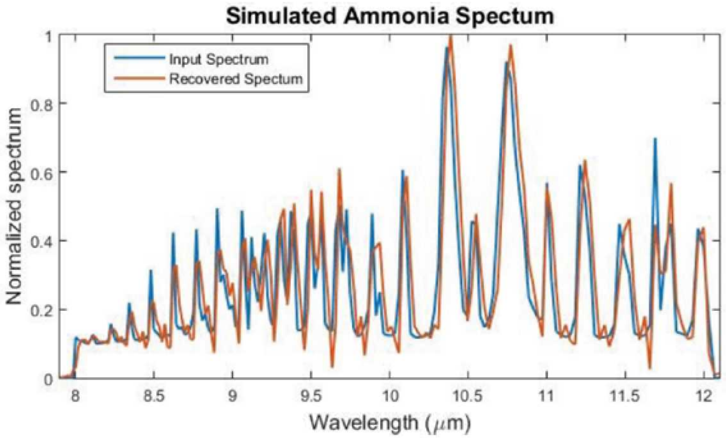


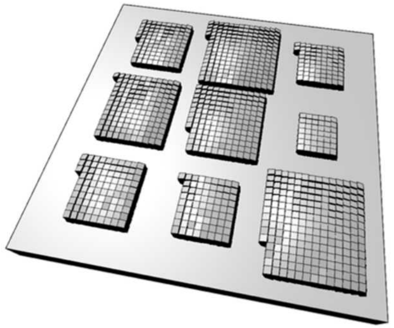


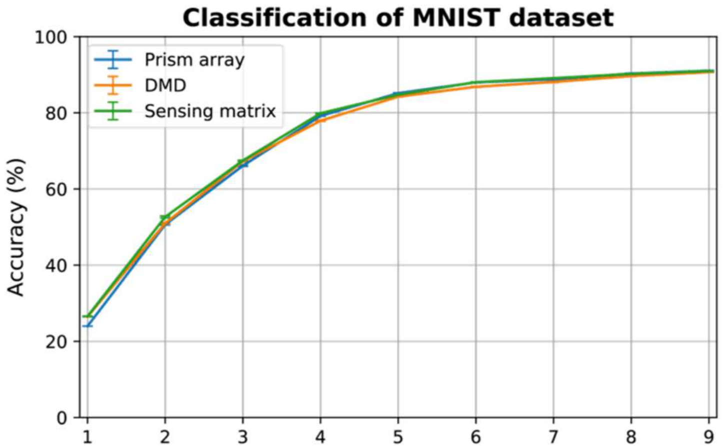


Questions?









Publications

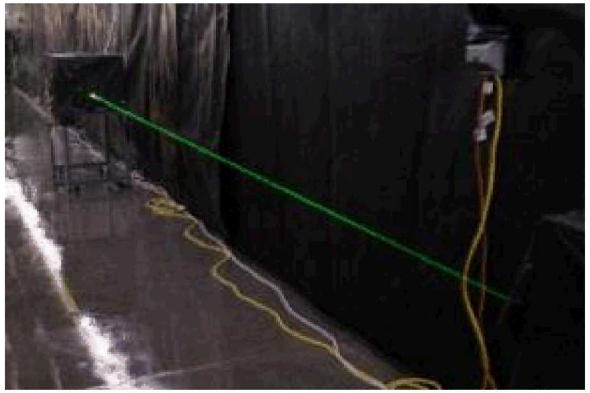
- **Publications**
  - Brian J. Redman, et al., "Measuring resolution degradation of long-wavelength infrared imagery in fog," Opt. Eng. **58**(5) 051806, 2019
- **Submitted**
  - Brian J. Redman, et al., "Simulating and characterizing an optimized snapshot channeled imaging polarimeter," *Opt. Express* , 2019
  - B. J. Redman, et al., "Performance evaluation of two optical architectures for task-specific compressive classification," *Optical Engineering*,2019.
- **Conferences**
  - B. J. Redman, et al., "Active and passive long-wave infrared resolution degradation in realistic fog conditions," in *Situation Awareness in Degraded Environments*, **11019**, SPIE, 2019.
  - B. J. Redman, et al., "Design and evaluation of task-specific compressive optical systems," in *Defense and Commercial Sensing*, **10990**, SPIE, 2019.
  - B. J. Redman, et al. "Task-specific computational refractive element via two-photon additive manufacturing," in *Optical Design and Fabrication* 2019 (Freeform, OFT), Optical Design and Fabrication 2019 (Freeform, OFT) , p. OT3A.5, Optical Society of America, 2019.
  - B. Redman, et al., "Optimizing a Compressive Imagers for Machine Learning Tasks," in *Asilomar Learning and Estimation in Imaging*, **11136**.
  - B. J. Redman, et al., "Hyperspectral vegetation identification at a legacy underground nuclear explosion test site," in *Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) Sensing XX*., **11010**, SPIE, 2019.
- **Contributing**
  - G. C. Birch, B. J. Redman, A. L. Dagel, B. Kaehr, D. Dagel, C. F. LaCasse, T.-T. Quach, and M. Galiardi, "Characterization of 3D printed computational imaging element for use in task-specific compressive classification," in *Optics and Photonics for Information Processing XIII*, **11136**, pp. 63 – 73, SPIE, 2019.
  - M. P. Thornton, K. M. Judd, A. A. Richards, and B. J. Redman, "Multispectral short-range imaging through artificial fog," *in Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXX*, **11001**, pp. 340 – 350, SPIE, 2019.
  - J. D. van der Laan, B. J. Redman, J. W. Segal, K. Westlake, and J. B. Wright, "Testing active polarimetric imagers in fog (Conference Presentation)," in *Situation Awareness in Degraded Environments*, 11019, SPIE, 2019.

The End

Auxiliary slides

Measuring fog droplet distribution

- Malvern Spratec
  - Volume distribution, $v(d)$ in %
  - Narrow separation
  - Inhalation cell
- Transmissometer
  - Transmission, T
  - Transmissometer separation, L_{trans}
  - Long distance
- Mie scattering theory
  - Wavelength dependent
  - Particle size dependent
  - Extinction coefficient due to scattering, $Q(d)$
- Products
  - Liquid water content, LWC
  - Number of droplets with given diameter, N(d)
  - Meteorological optical range, MOR



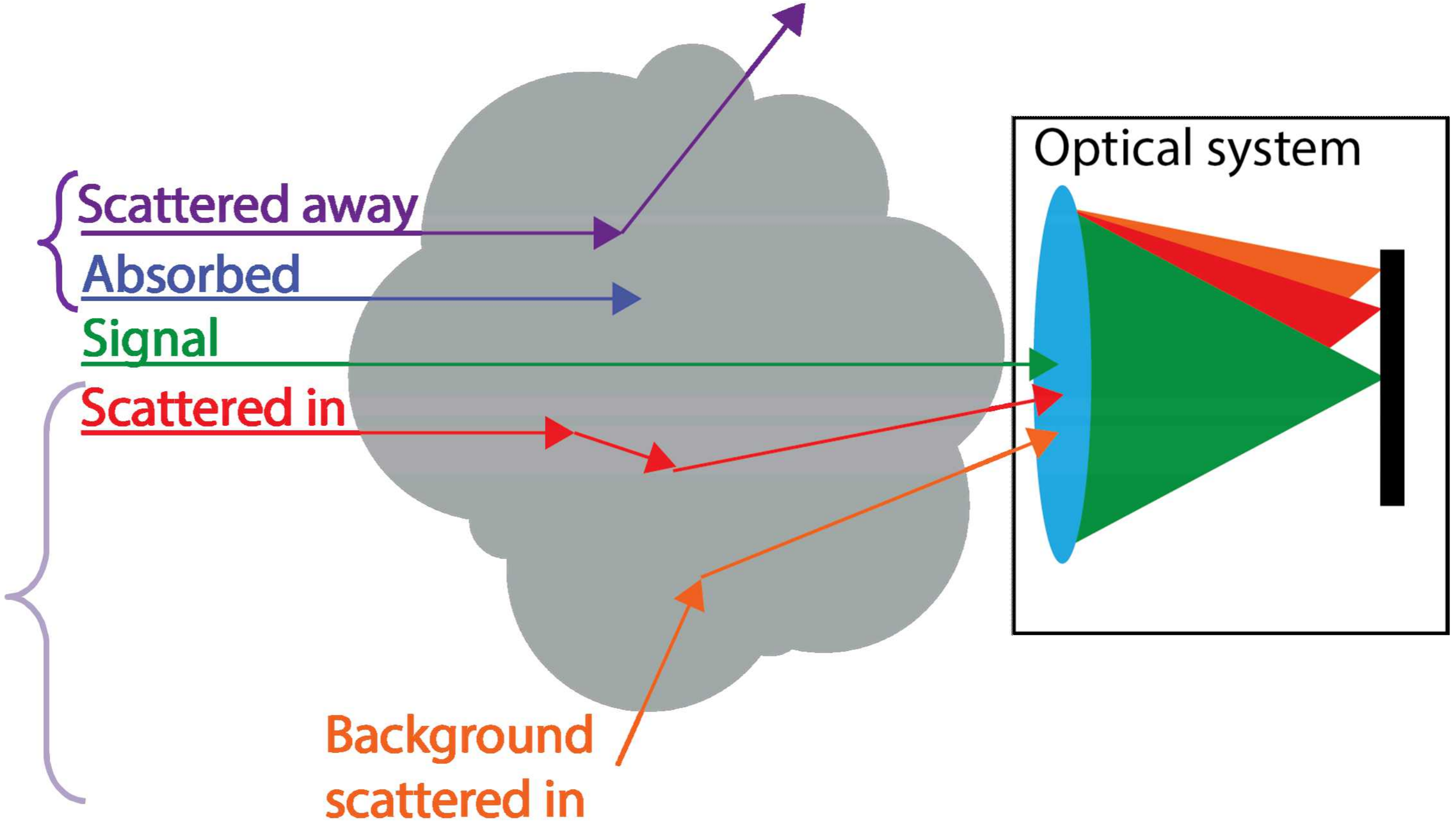
$$LWC = \frac{-2\ \ln(T)}{3\mathrm{L}_{\mathrm{trans}} \sum_i \frac{Q(d_i)\ v(d_i)}{d_i}} \rho_{water}$$

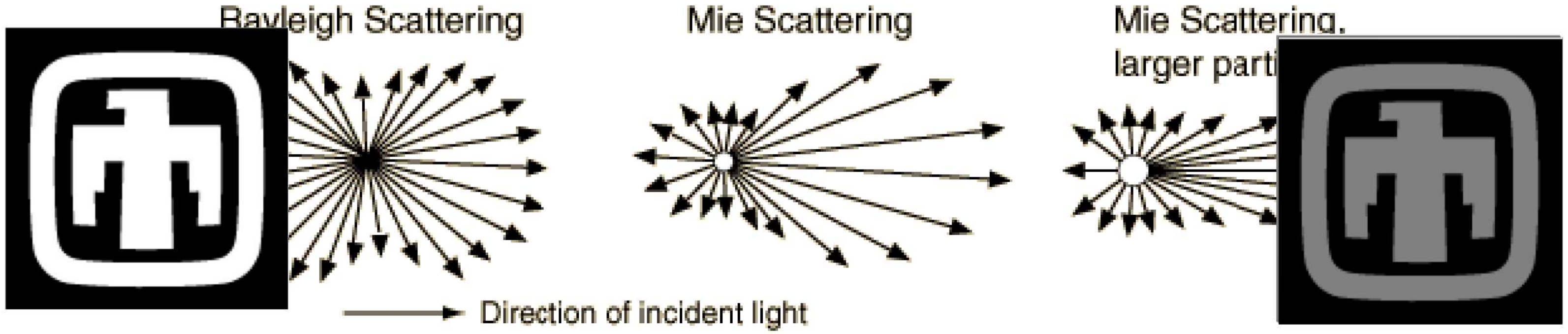
$$N(d) = \frac{\mathrm{LWC}\ v(d)}{\frac{4\pi}{3}\left(\frac{d}{2}\right)^3}$$

$$MOR = L_{trans} \frac{\ln(0.05)}{\ln(T)}$$

Multiple ways scattering degrades image quality

- Attenuation
  - Scattering
  - Absorption
- Stray light
  - Scattered from background
    - Signal independent
  - Scattered from scene
    - Causes blurring
- Dependent on fog properties
  - Particle size
  - Concentration
  - Wavelength
  - Geometry

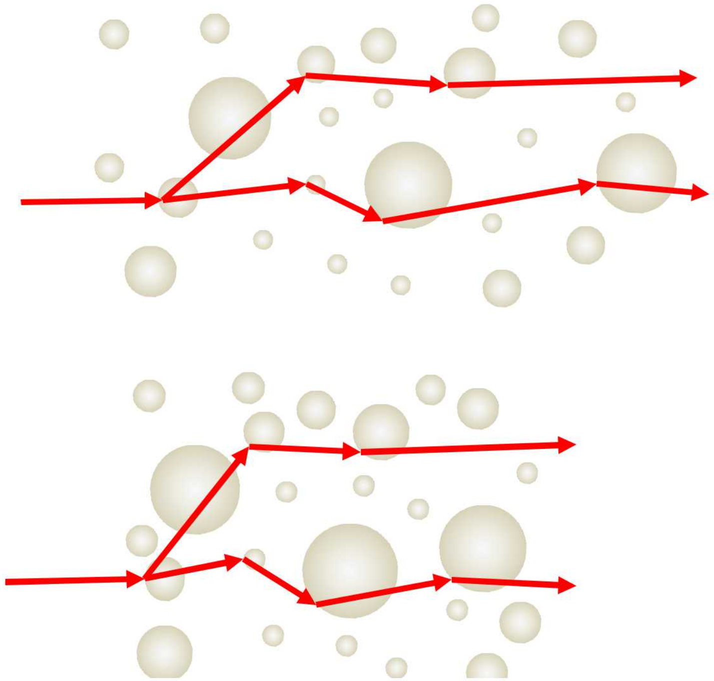




Fog affects more than transmission

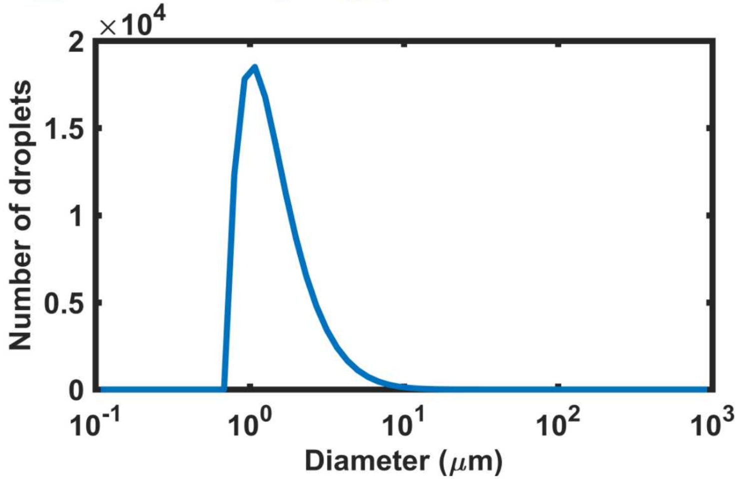
Thick fog for long distance equivalent

- Scattering probability
  - Probability of hitting a droplet
- Beer-Lambert Law
  - Optical Thickness
  - Short distance through thick fog
  - longer distance through thinner fog
- Very dense particle concentration



Equivalent distances through MOR=100m (ICAO) CATIIIc fog

Example case	Fog facility MOR (m)	Target distance (m)	Equivalent Distance to ICAO CATIIIc
Passive Imaging Discussed in this Presentation			
Thick fog	3	9 m	300 m
Moderate fog	6	9 m	150 m
Thin fog	15	9 m	60 m
Full Length of Facility			
Thick fog	3	55 m	1833 m
Moderate fog	6	55 m	917 m
Thin fog	15	55 m	367 m

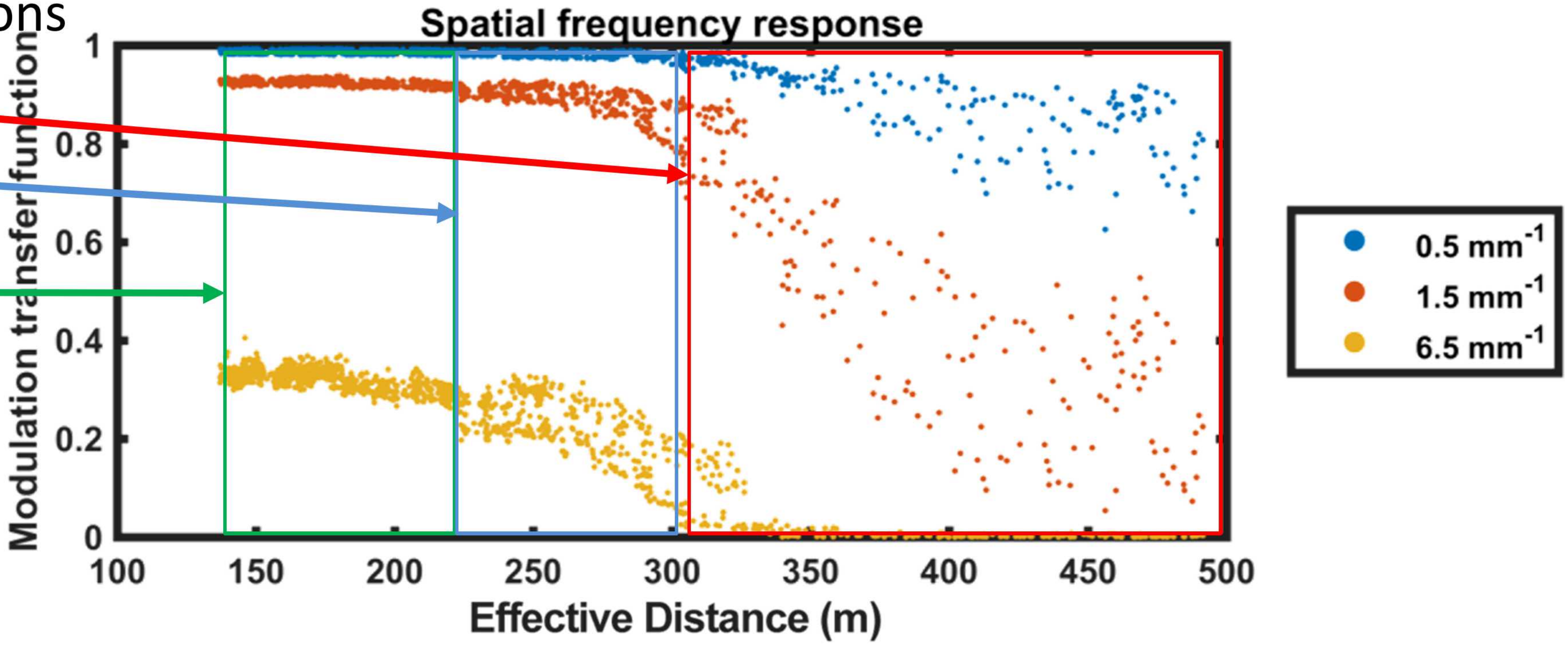


Brian J. Redman, et al., "Measuring resolution degradation of long-wavelength infrared imagery in fog," Opt. Eng. 58(5) 051806 (2019)

Capable of very long equivalent distances

Frequency response dependent on fog thickness

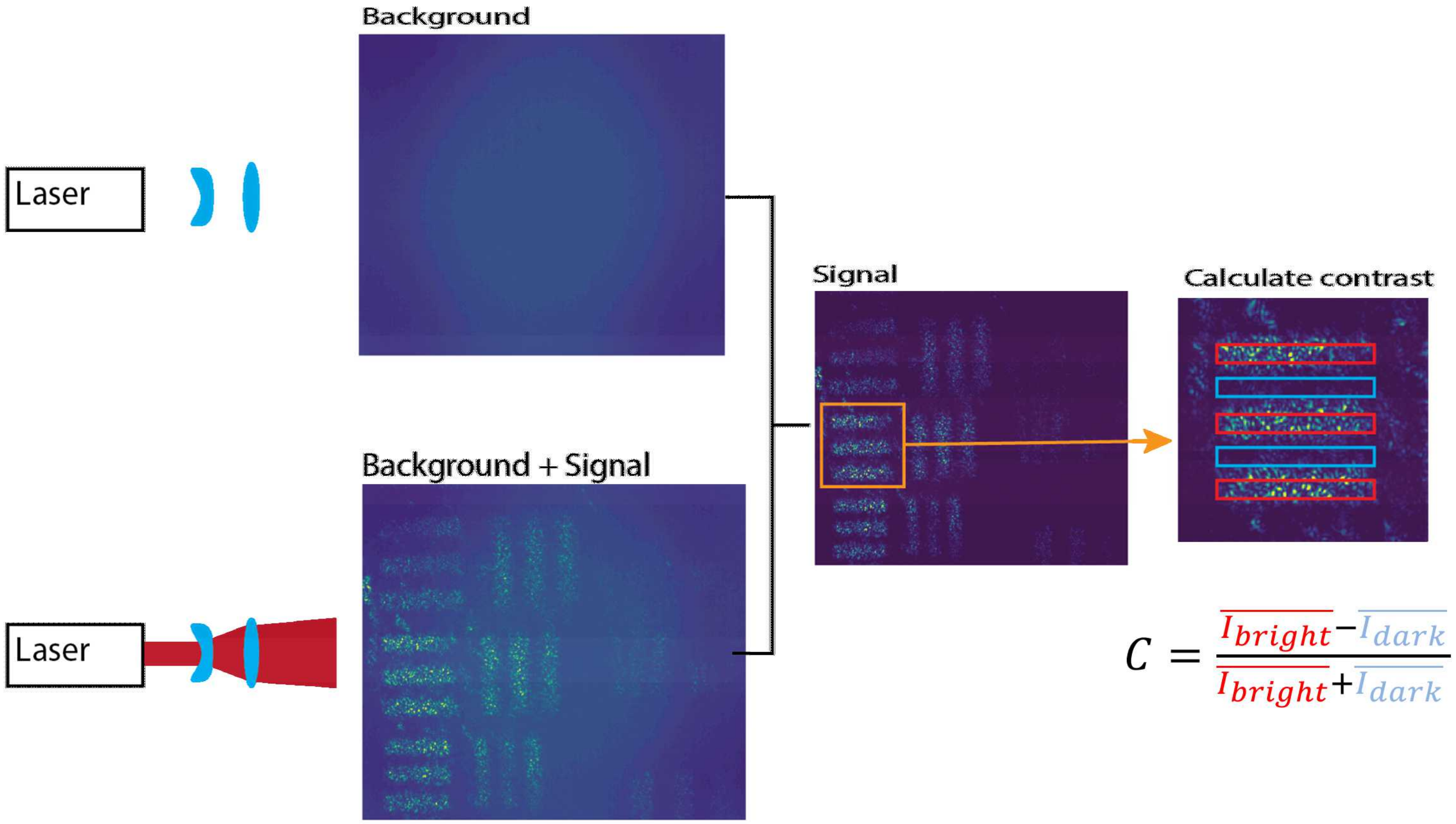
- Example frequencies of the MTF vs. fog thickness
- Effective distance through 92 m MOR
- Frequency response in regions
  - Noise floor
  - Frequency recovery
    - Slope frequency dependent
  - Steady state



Brian J. Redman, et al., "Measuring resolution degradation of long-wavelength infrared imagery in fog," Opt. Eng. 58(5) 051806 (2019)

Contrast measurement using active illumination

- Laser illumination
  - Speckle
  - Fourier analysis less effective
- Contrast transfer function
  - Averaging to reduce noise
- Shuttering
  - remove background

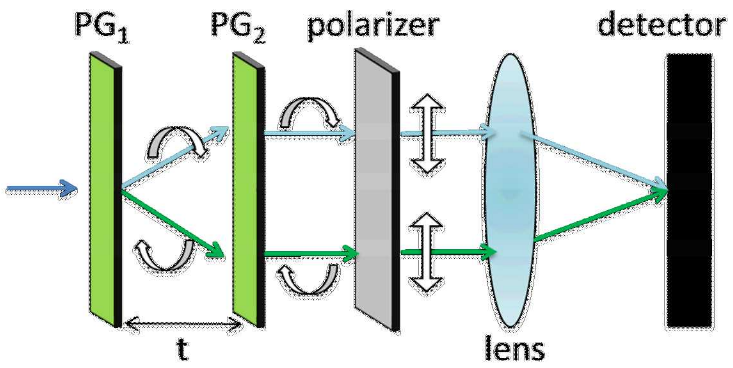


$$C = \frac{\overline{I_{bright}} - \overline{I_{dark}}}{\overline{I_{bright}} + \overline{I_{dark}}}$$

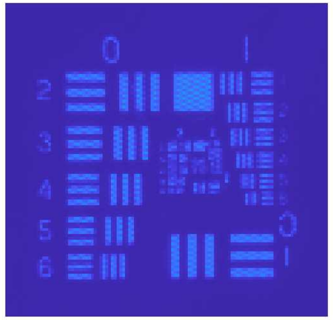
Contrast of speckle image requires averaging submitted: Brian J. Redman, et al., “Simulating and characterizing an optimized snapshot channeled imaging polarimeter," Optics Express

Snapshot polarimeter

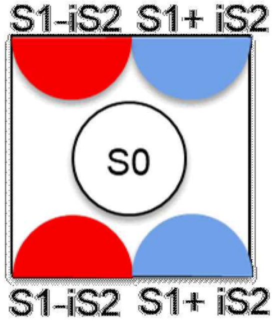
Polarimeter



Example image

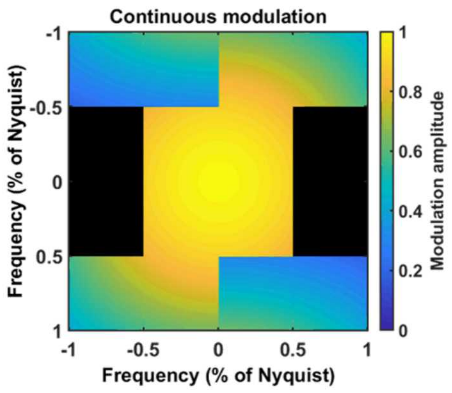


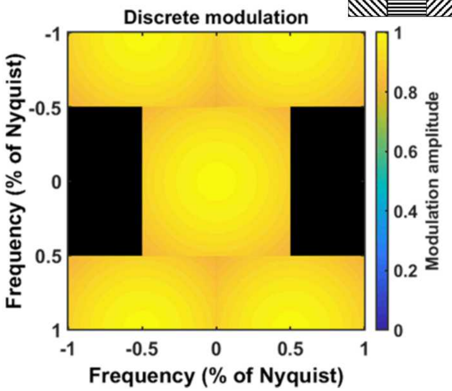
Fourier plane



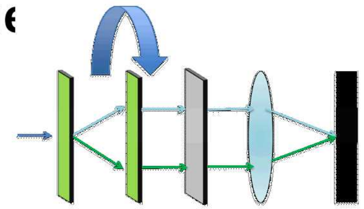
Simulations

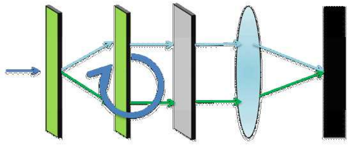
Visibility reduction due to pixel sampling

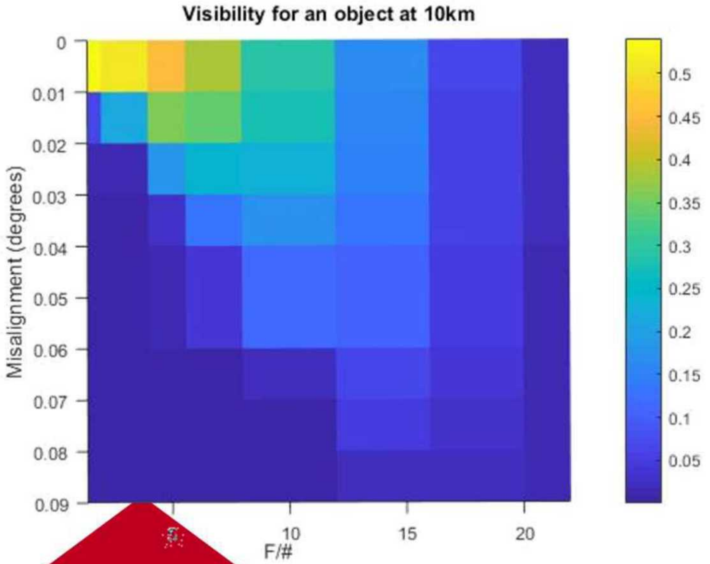


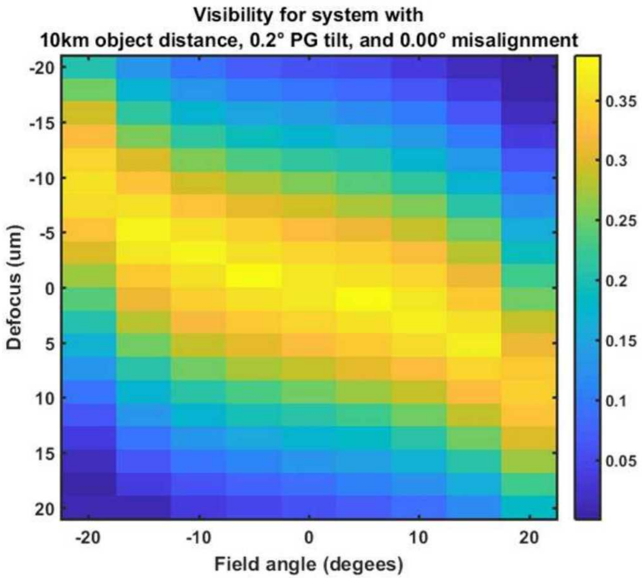


Visibility reduction due to misalignment



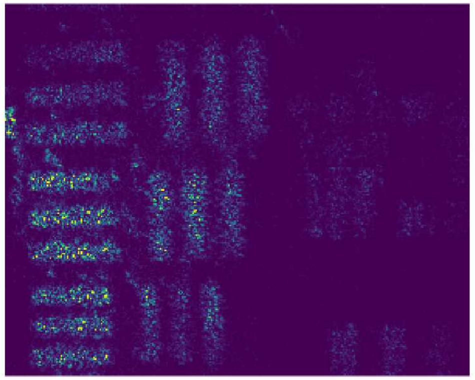


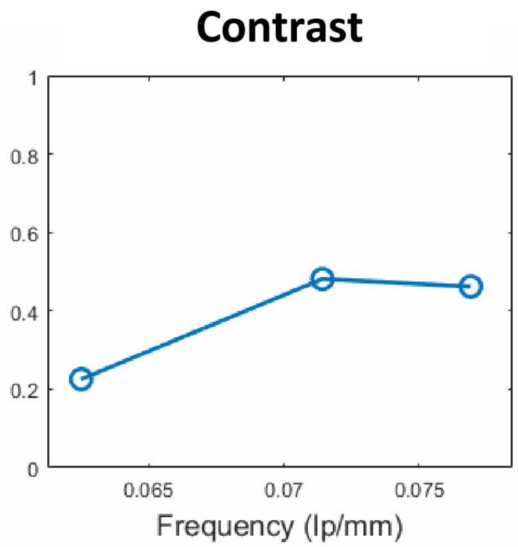


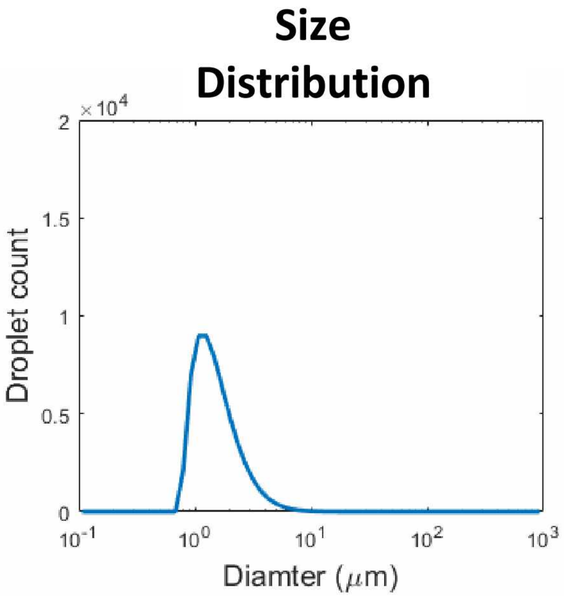


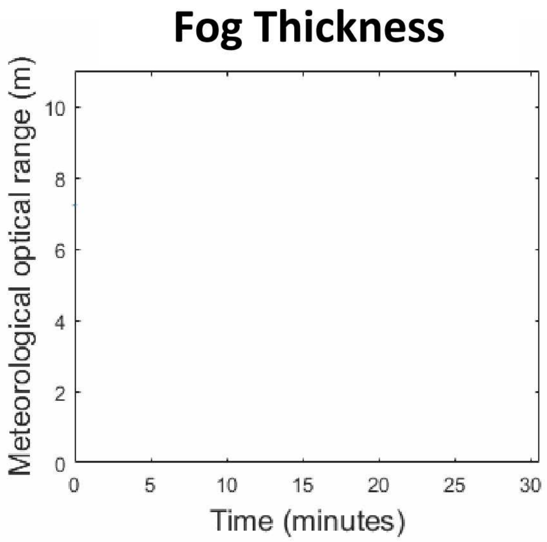
Example active collect

- Target distance 3.0 m
- 1 generation cycle



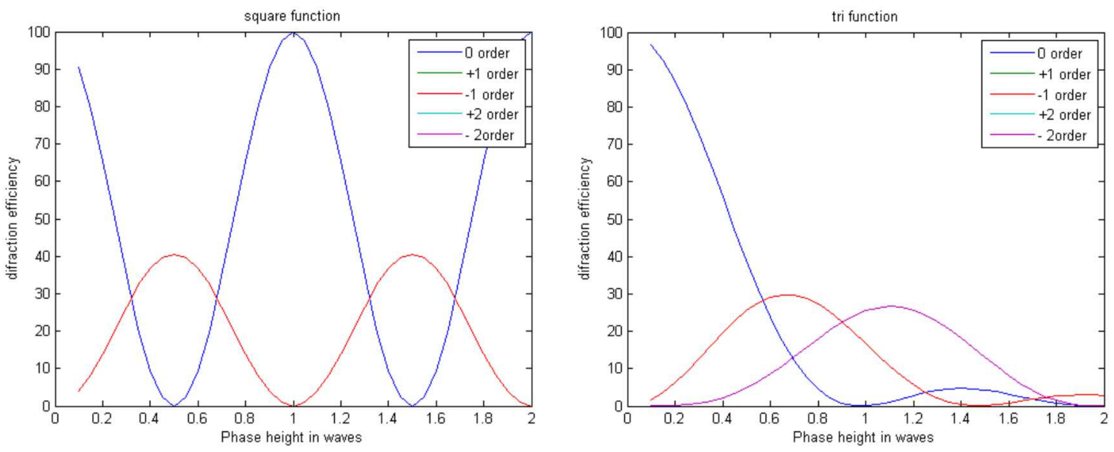




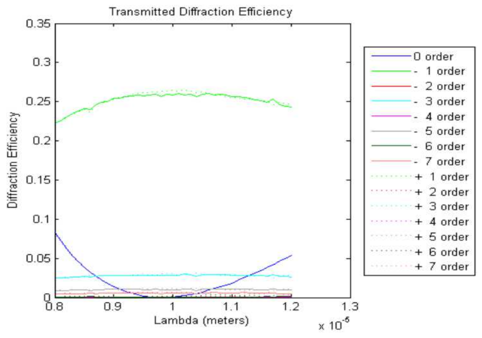


Diffractive optic investigation

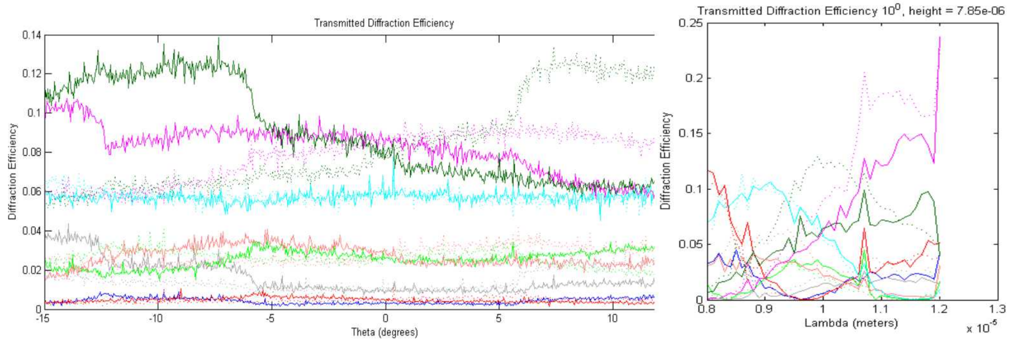
- Simulated the grating performance for
  - thin and thick
- Binary grating, and triangle profile
- RCWA for thick analysis



RCWA Binary

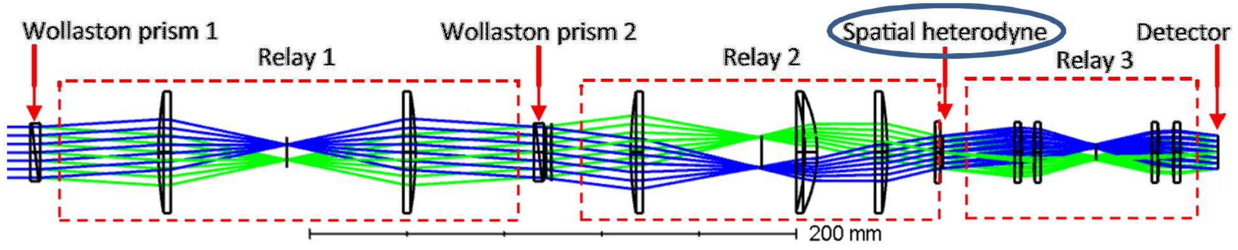


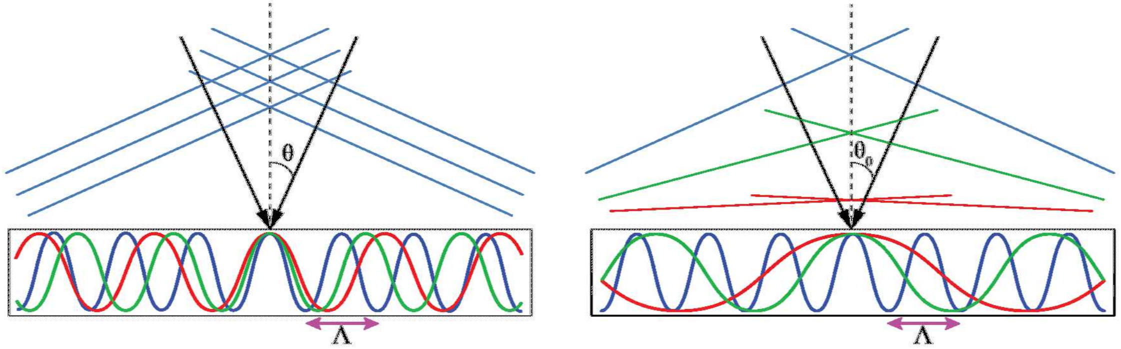
RCWA Tri

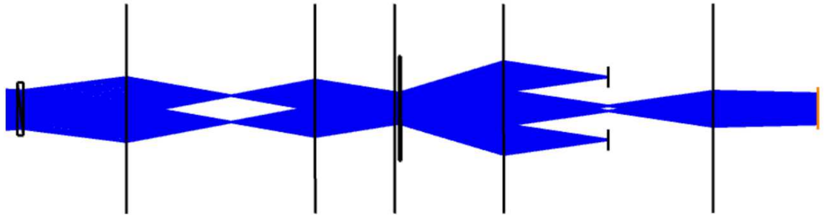


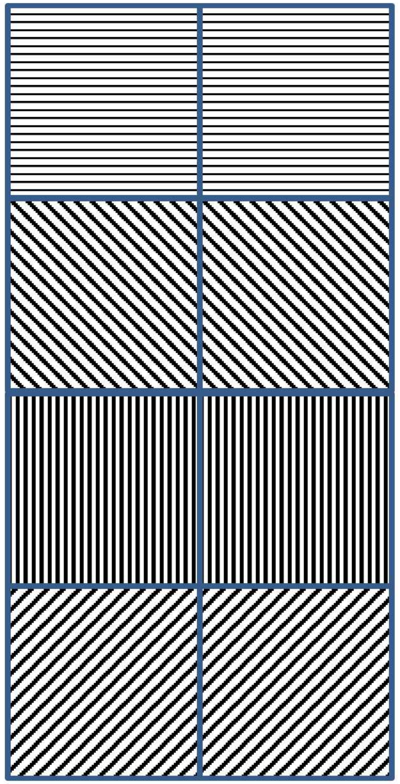
Many separate elements as proof of concept for solid state Nomarski design

- Spatial heterodyning
  - Reduce spatial frequency
- Diffractive optic
  - Change angle of plane waves
  - Fourier filter to remove unwanted orders
- Patterned polarizer
  - Linear change of polarization angle
  - Multiply irradiance by sinusoid
  - Similar to AM radio demodulation



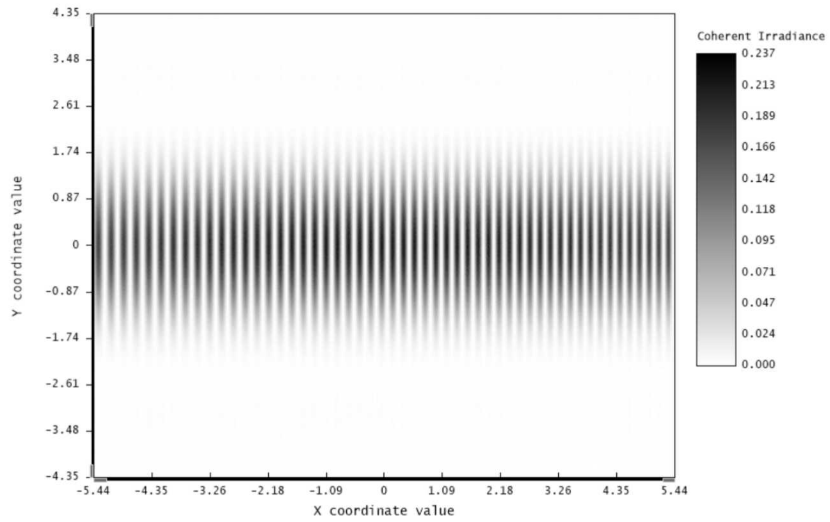


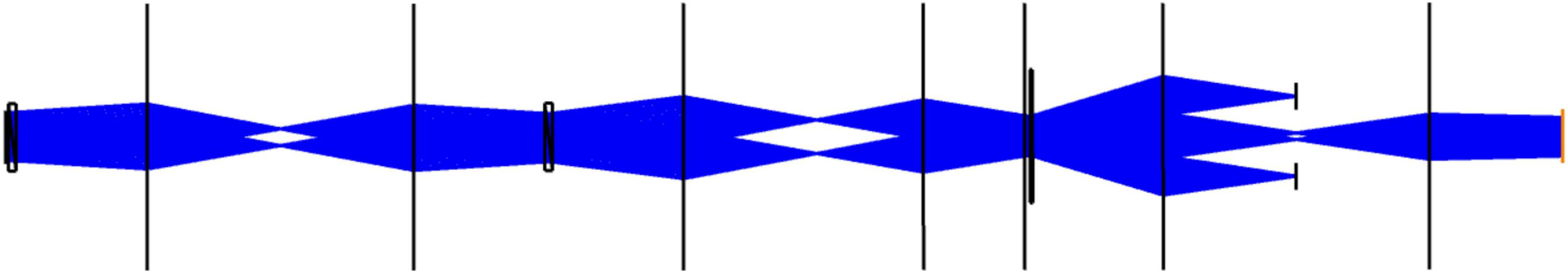




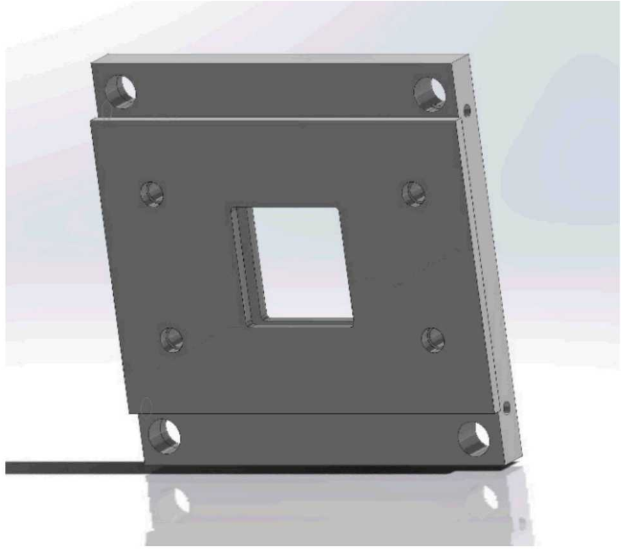
Nonsequential Simulation

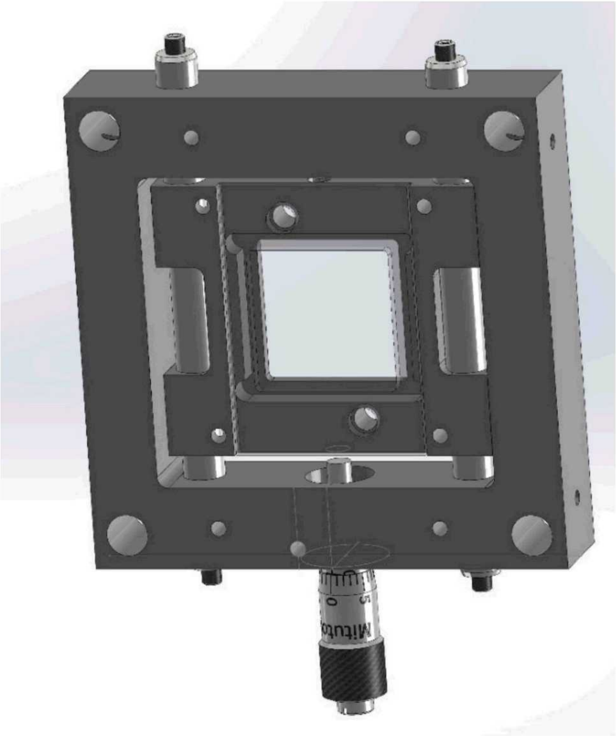
- Nonsequential OpticStudio ideally could simulate interferogram from multiple input angles without the need for Matlab
- Ideal on axis configuration gave an interferogram which seemed to have errors.

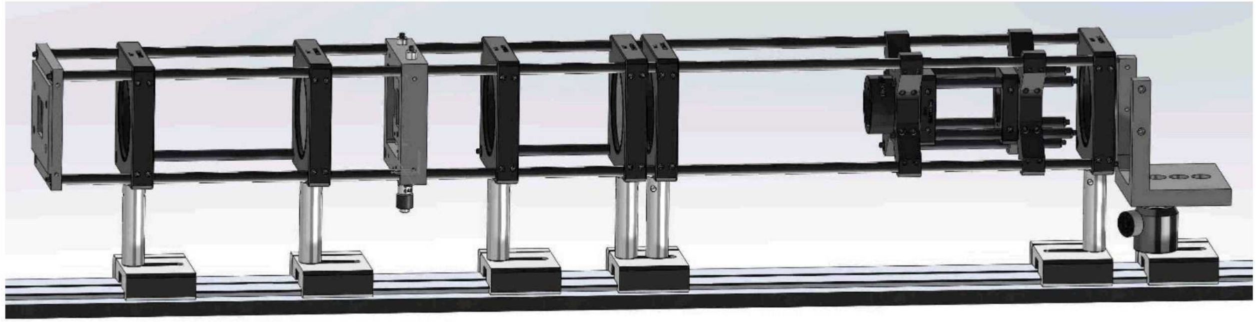




Physical design

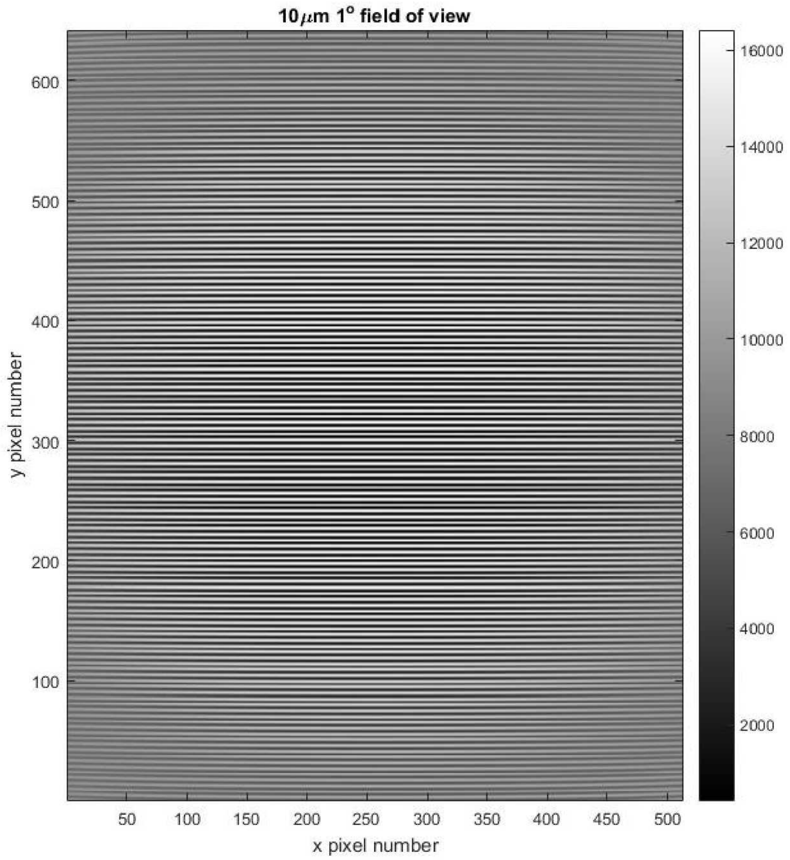


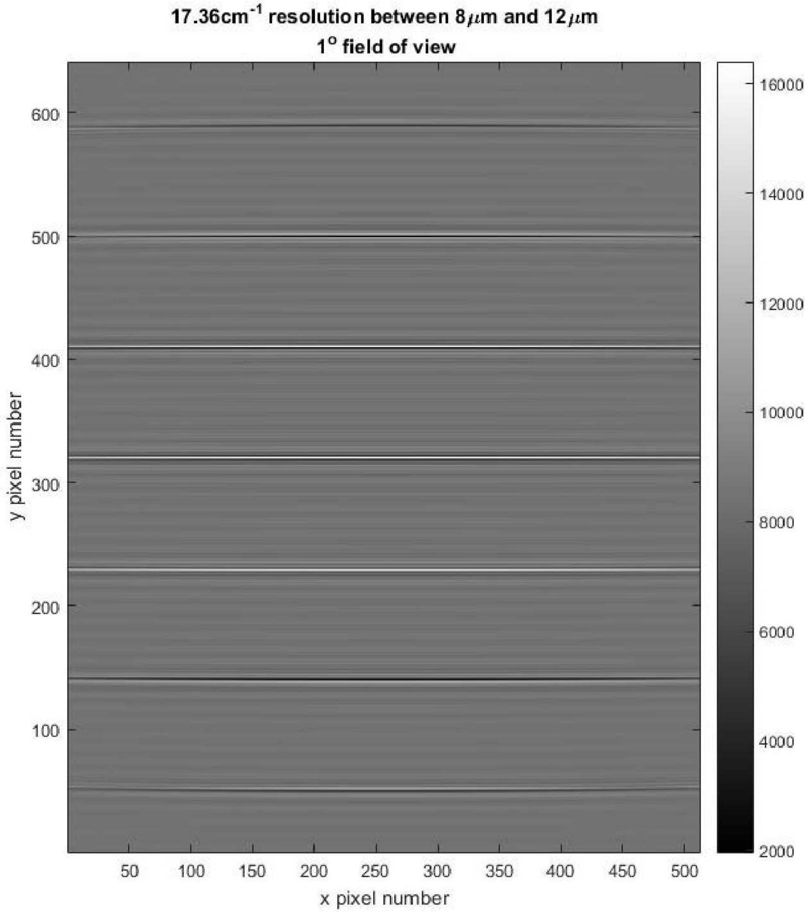




Simulation of Interferogram

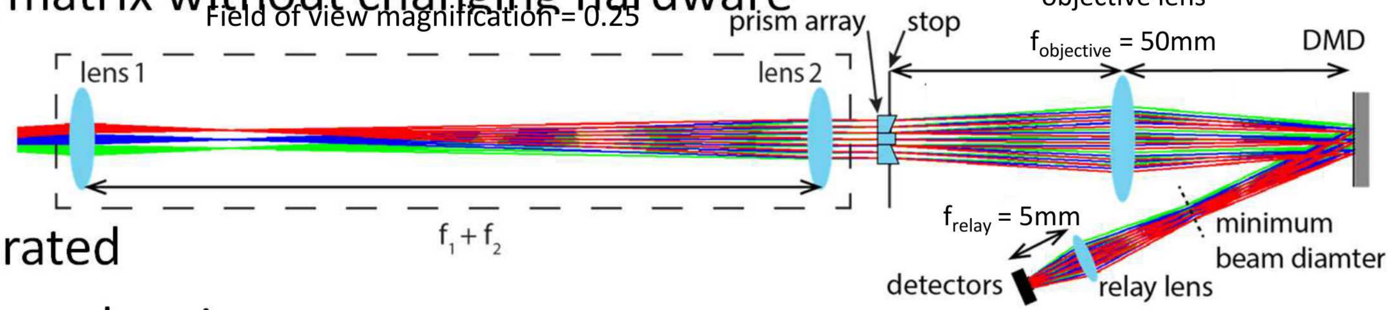
- A single wavelengths shows the slight blurring at the edges due to spatial incoherence
- Increasing the number of wavelengths dropped the visibility faster

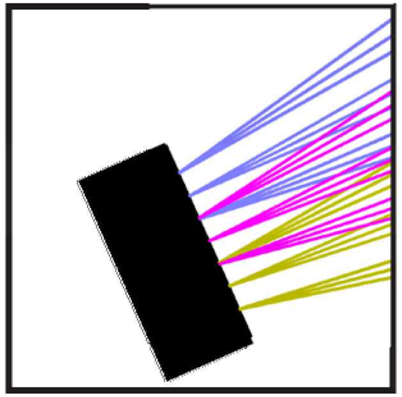


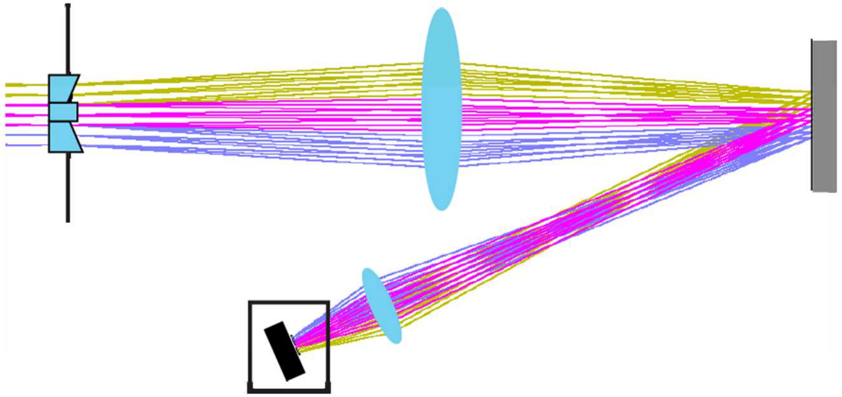


Weighting implemented using a DMD

- Digital micromirror device (DMD)
  - Allows for dynamically setting sensing matrix without changing hardware
  - At image plane
- Separating information
  - DMD - channels separated, fields separated
  - Detectors - channels separated, fields overlapping
- Optimizing throughput
  - Maximize magnification of detector
  - Maximize field of view
  - Constrained by DMD size
  - Constrained by realistic lenses

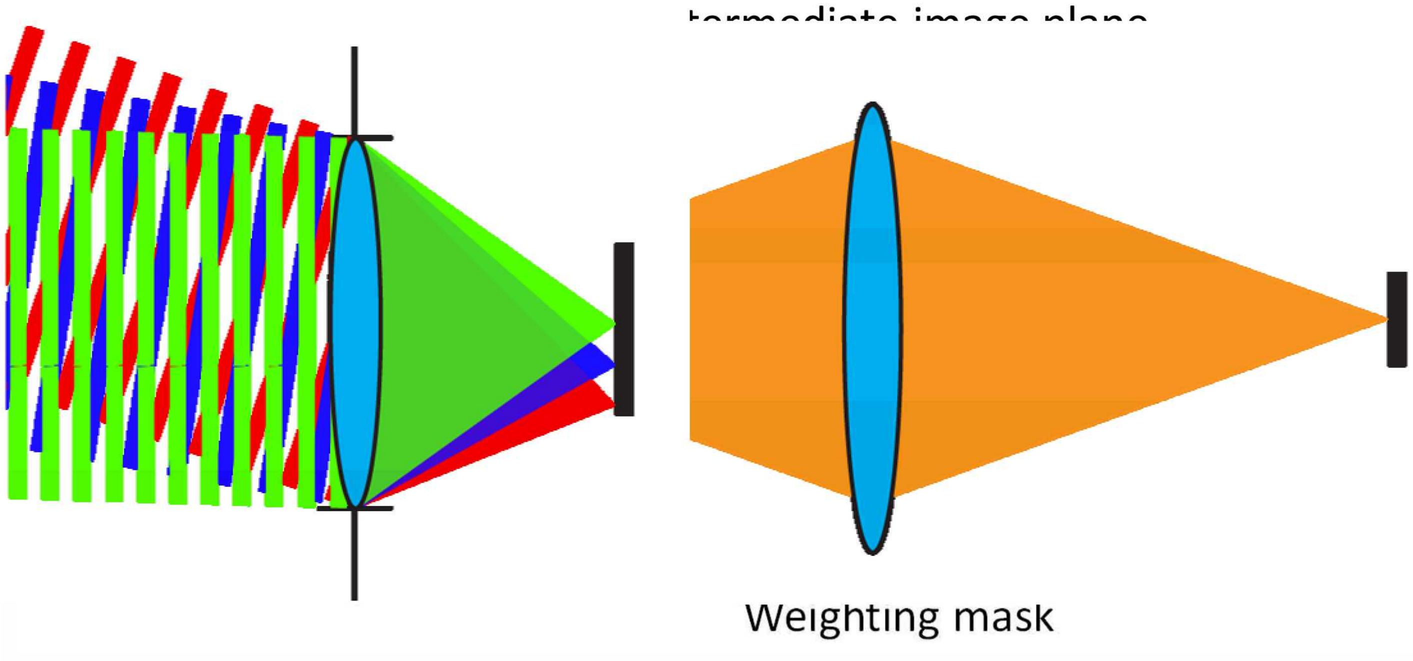




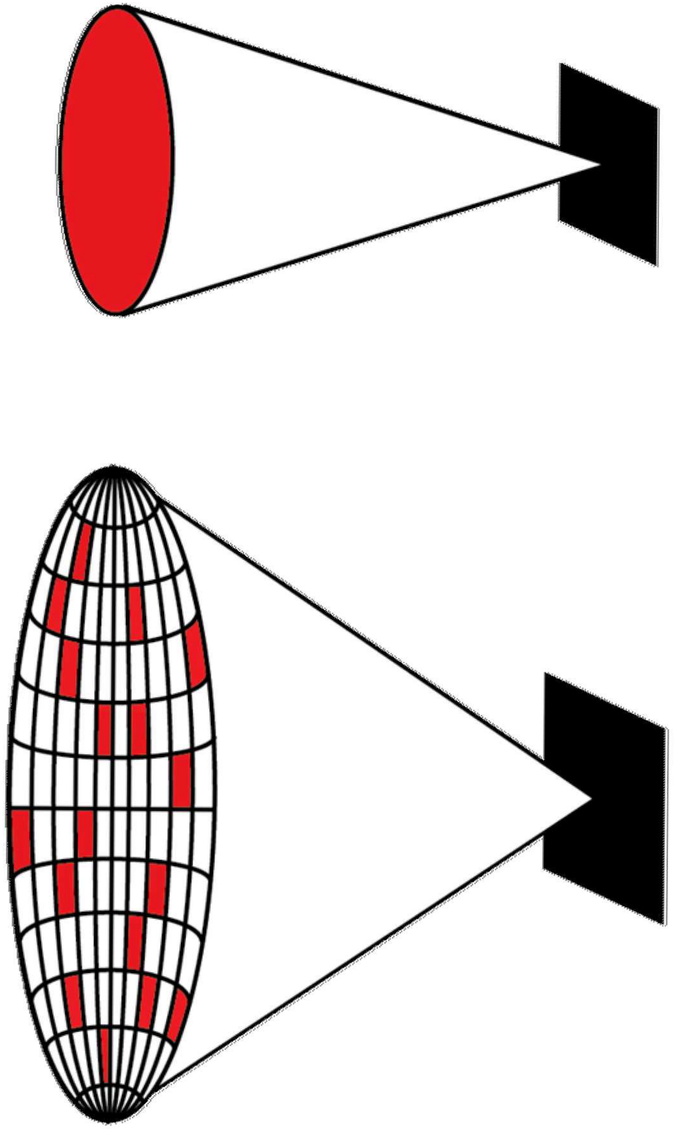


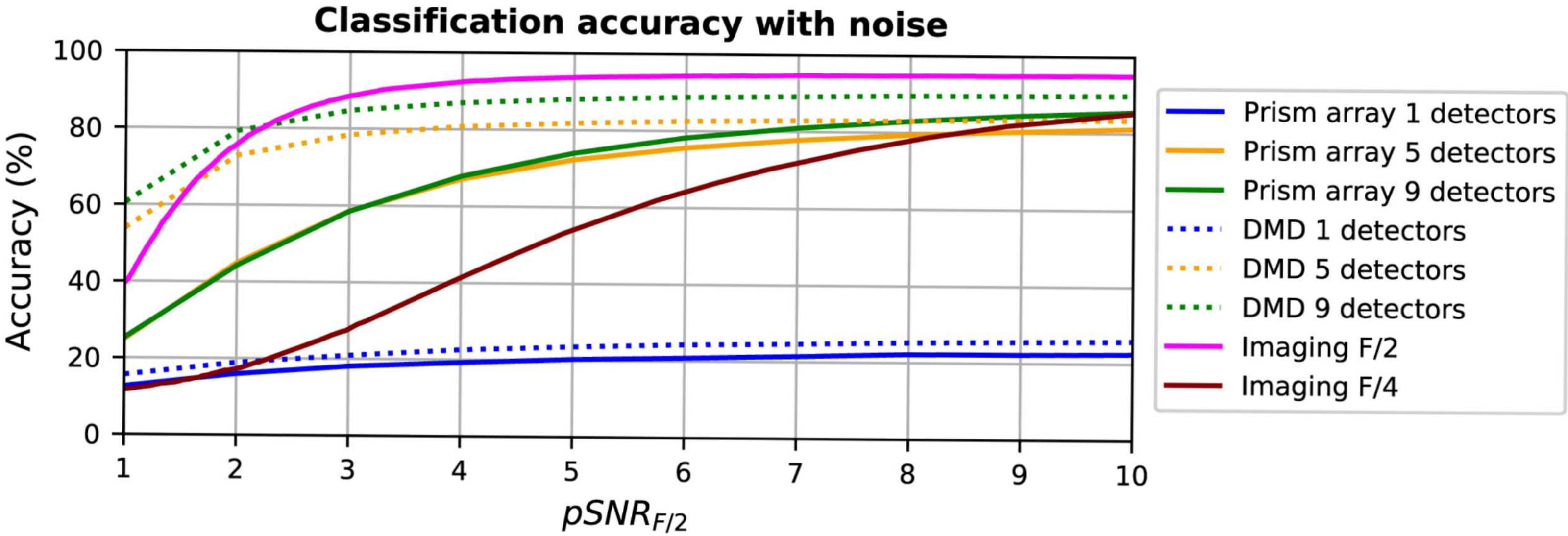
Parallel measurements conventional optics

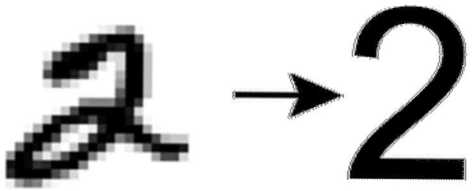
- Direct imaging
  - 1:1 mapping
- Image stop
  - Uniform irradiance at detector
- Telecentric
  - Intermediate image plane
  - Magnification independent of lens separation
- Division of aperture
  - Fields separated at intermediate image plane
  - Parallel measurements



Radiometric modeling to compare performance between architectures

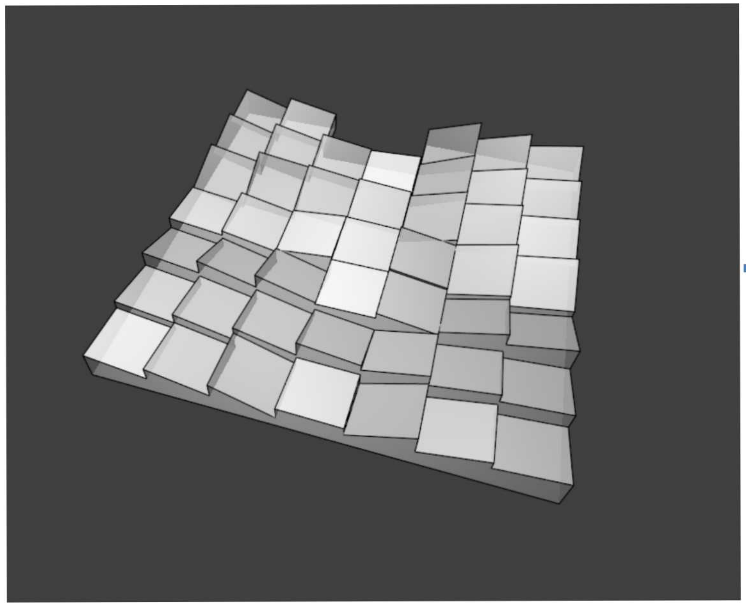




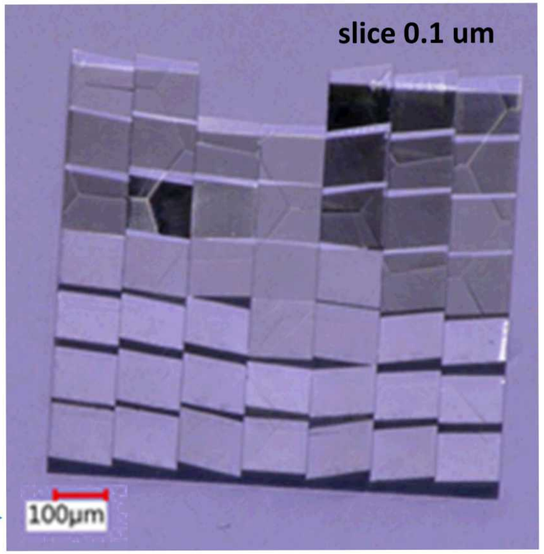


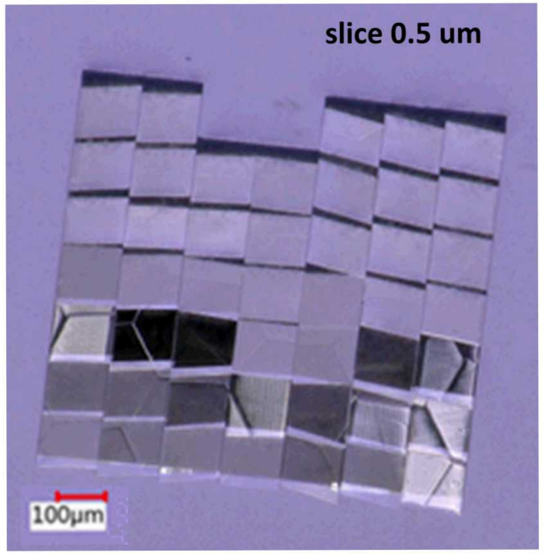
Additive manufacturing of nontraditional component

Design of refractive optic
- Sharp edges
- Not feasible using traditional manufacturing



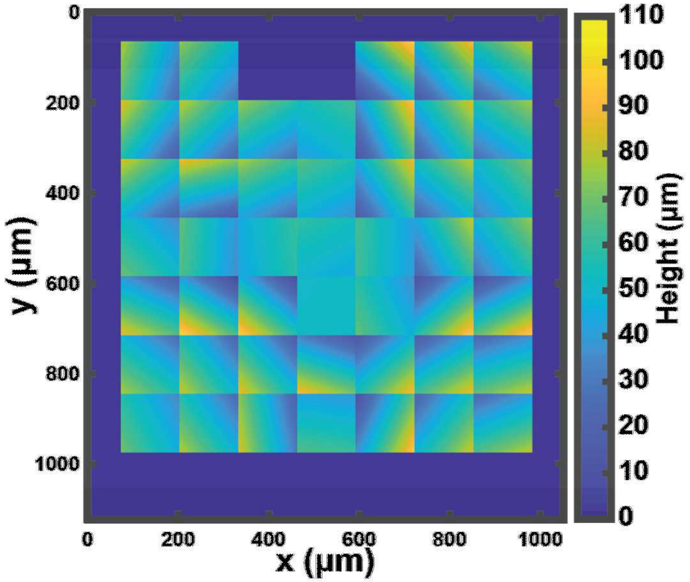
Nanoscribe
- 3D printer
- Two photon polymerization

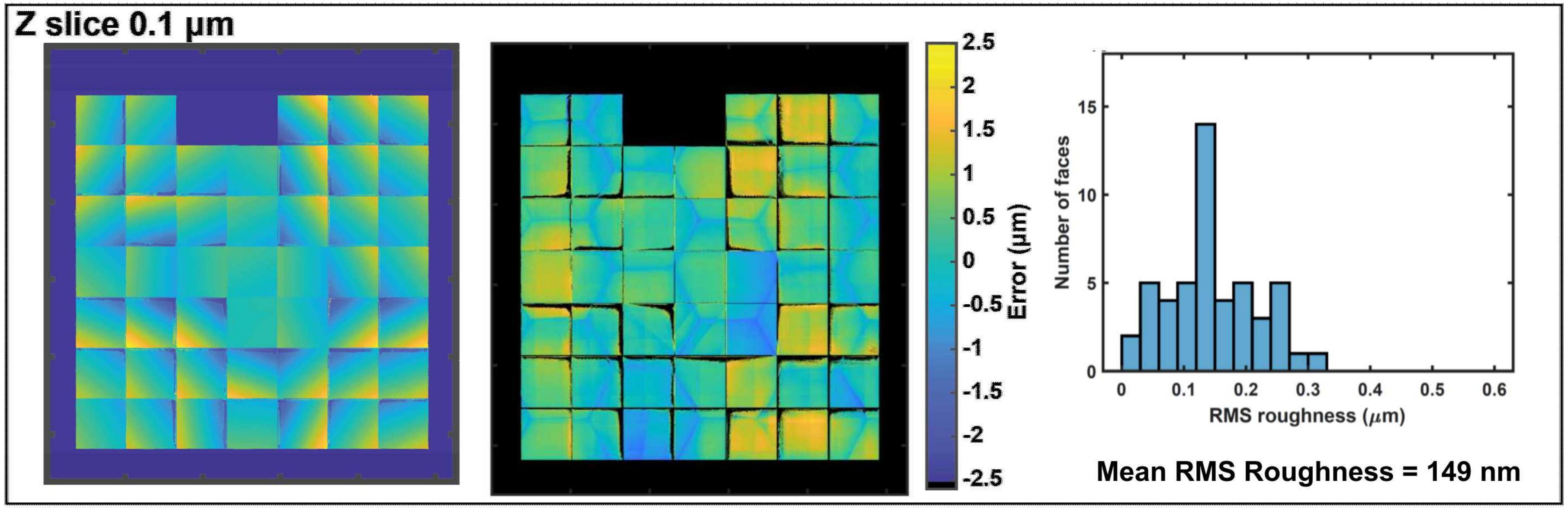


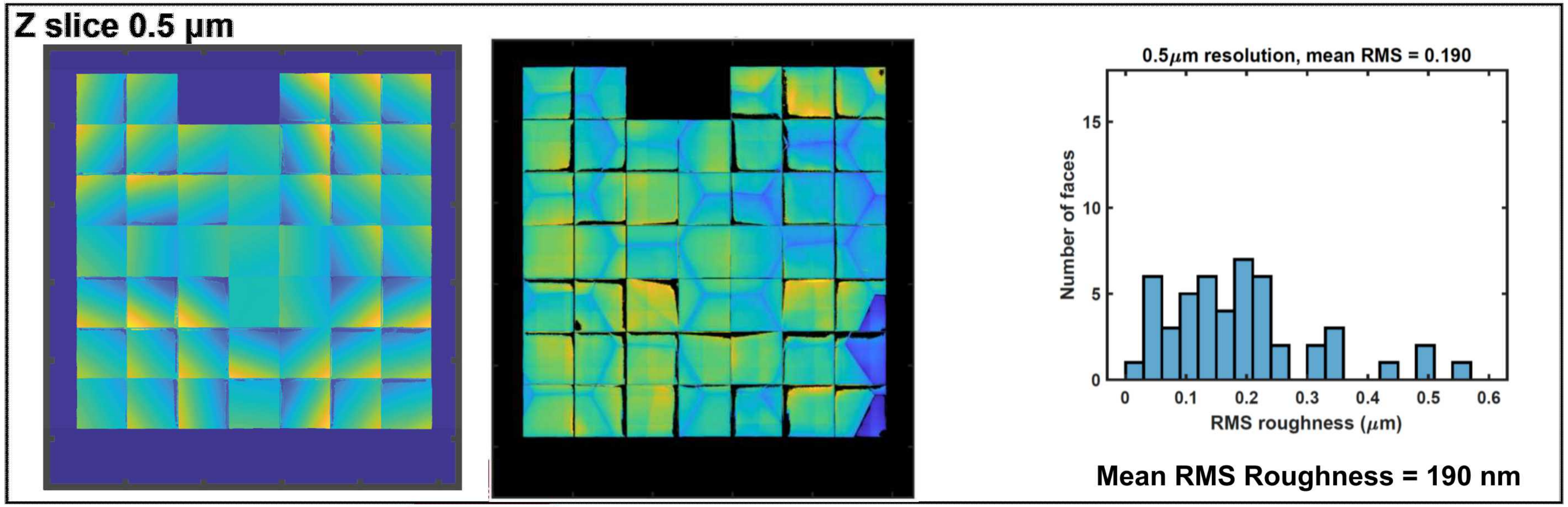


Surface characterization – Binary Arrays

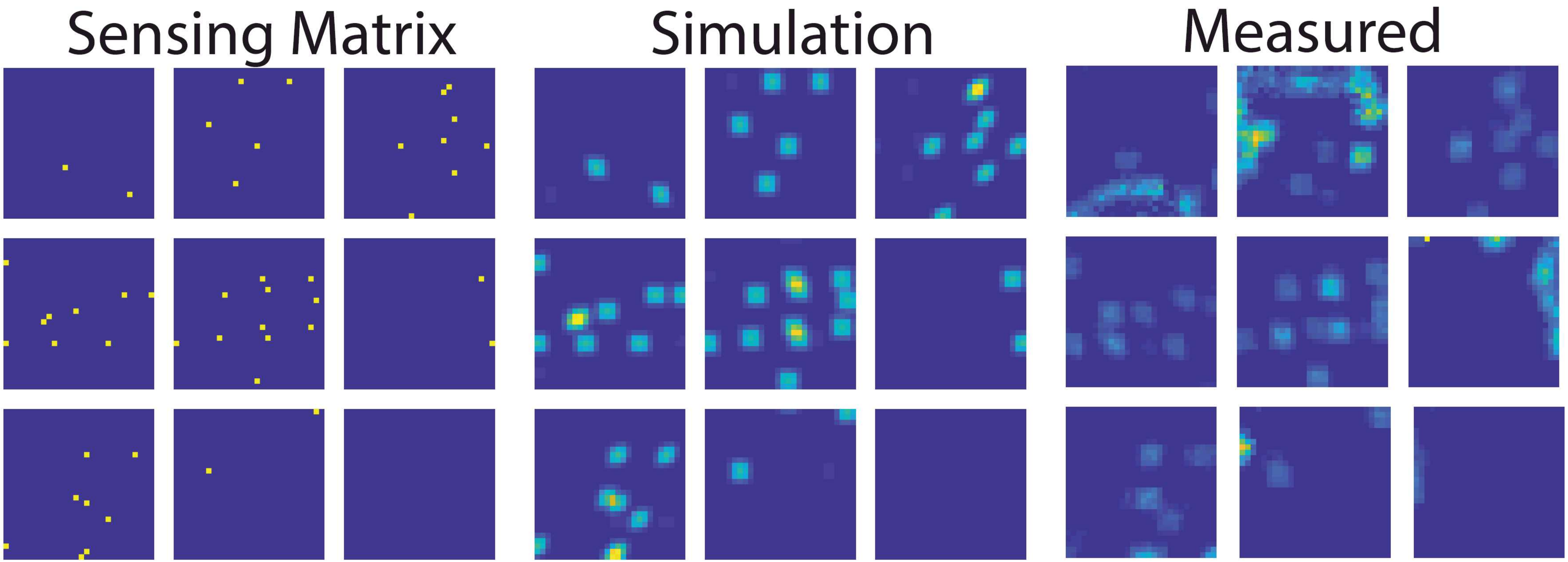
Design | **Measurement** | **Deviation from design** | **Surface roughness**







Future Work – Complete system characterization



Example printed prism

- Skirt to decrease masking requirements
- Multiple prisms to implement weighting
- Alignment pillars