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CENTER FOR FREEFORM OPTICS

New Methods for the Optical Design of Spectrometers with Freeform Surfaces

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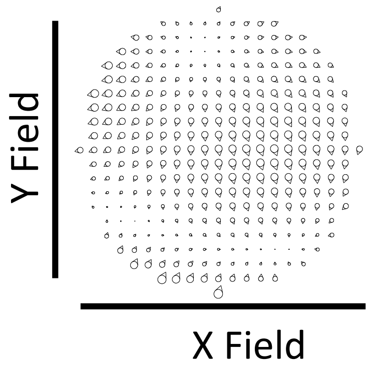
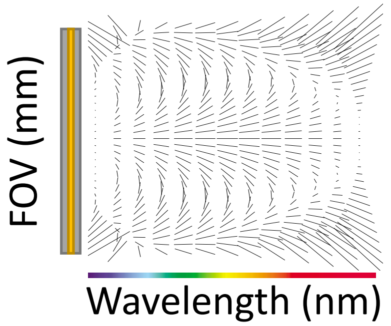
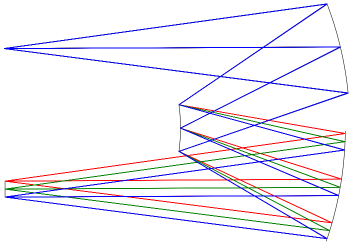
Outline



- Introduction
- Design tools for freeform surfaces



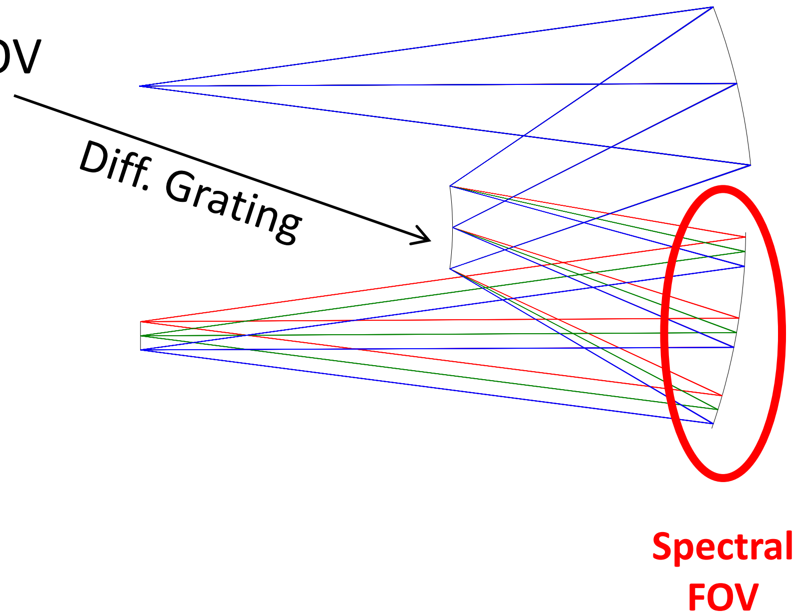
- Spectral full-field display
- Freeform spectrometer design example



- Conclusion

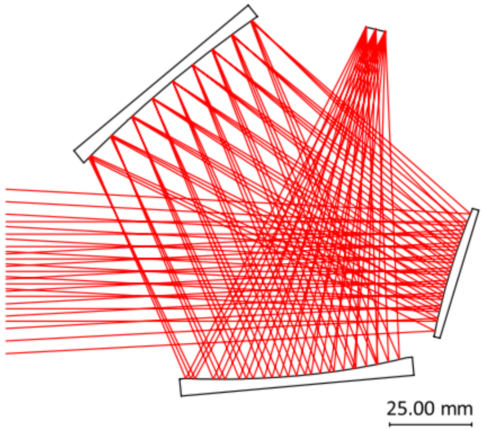
Introduction

- Designing pushbroom imaging spectrometers is challenging
  - Slit field of view (FOV)
  - Dispersive element creates spectral FOV
  - Often coupled with foreoptics

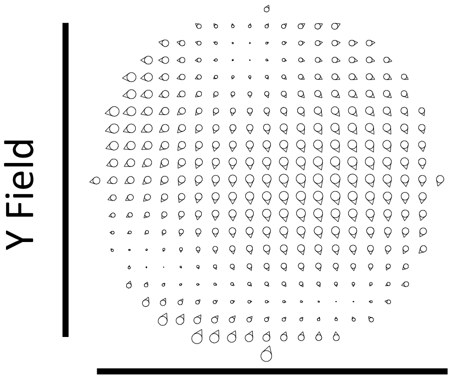


Design tools for freeform systems

- The full-field display (FFD) has been successfully utilized in the design of a LWIR freeform imager
- In the context of spectrometer design, this requires a new, spectral, full-field display (**SFFD**) to be developed
- The SFFD will enable the aberration visualization and guide the design of freeform spectrometers



LWIR imager



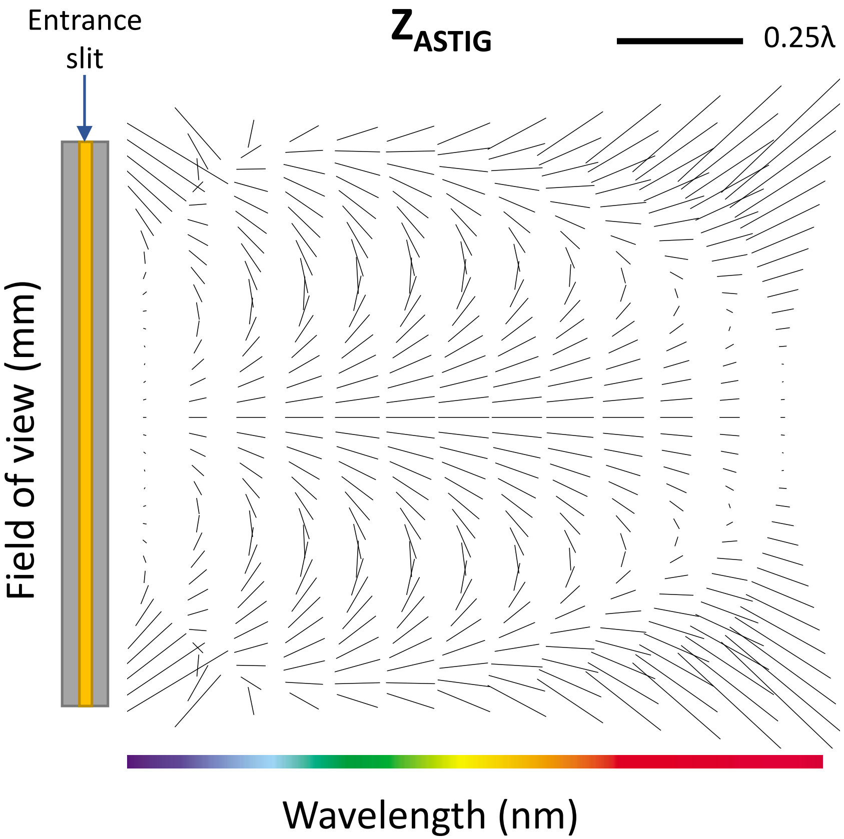
Full-field display

K. Fuerschbach, J. Rolland, and K. Rolland-Thompson, "Realizing Freeform: A LWIR Imager in a Spherical Package," in Renewable Energy and the Environment, OSA Technical Digest (online) (Optical Society of America, 2013), paper FW1B.2.

Spectral full-field display (SFFD)

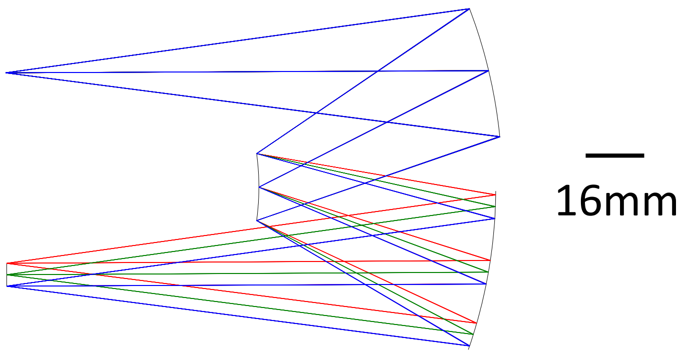
A new type of visualization for dispersive imaging systems that is:

- A plot of Fringe Zernike coefficients on field of view vs. wavelength
- Calculated on a term-by-term basis using real ray trace calculations

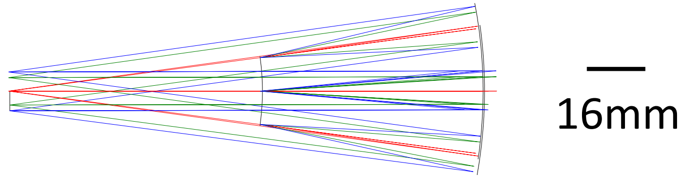


Design example using freeform optics

- Specifications:
  - F/3.8
  - 200-1500 nm spectral bandwidth
  - 10mm entrance slit length
  - 100nm/mm dispersion



YZ (dispersion) plane

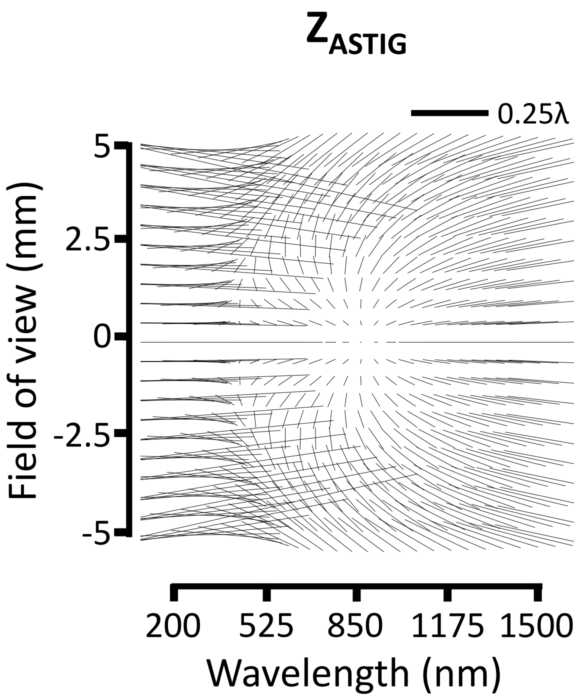


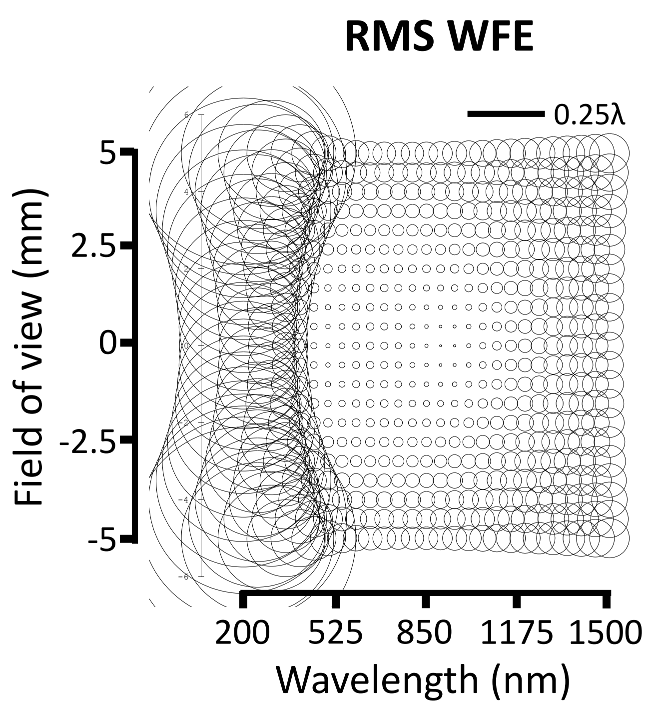
XZ (slit/field) plane

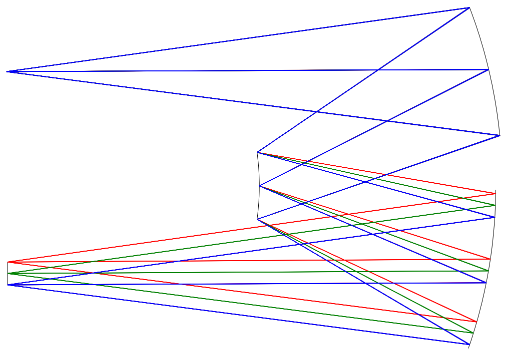
- Offner-Chrisp (OC) spectrometer
  - Concentric
    - Corrects spherical aberration
  - 1-1 magnification
    - Corrects coma and distortion
  - Limited by astigmatism
    - Ring field balance

M. Chrisp, "Convex diffraction grating imaging spectrometer," US Pat. 5,880,834 (1999).

OC spectrometer - All spherical performance







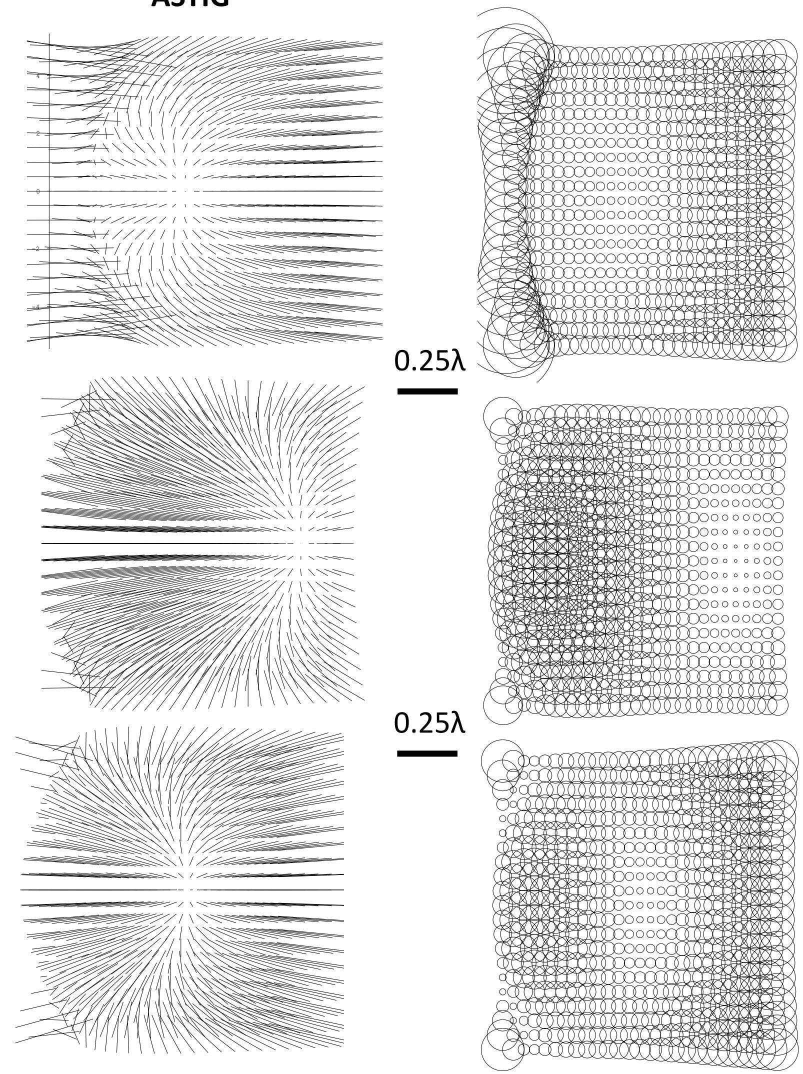
The maximum/average RMS WFE was calculated for all fields and wavelengths for comparison

All spherical surfaces:

Max RMS WFE: 0.731λ
Avg. RMS WFE: **0.097λ**

Benchmarking with coaxial aspheres

Z_{ASTIG} **RMS WFE**



All surfaces aspheric (A-D):

Max RMS WFE: 0.427λ
Avg. RMS WFE: **0.091λ**

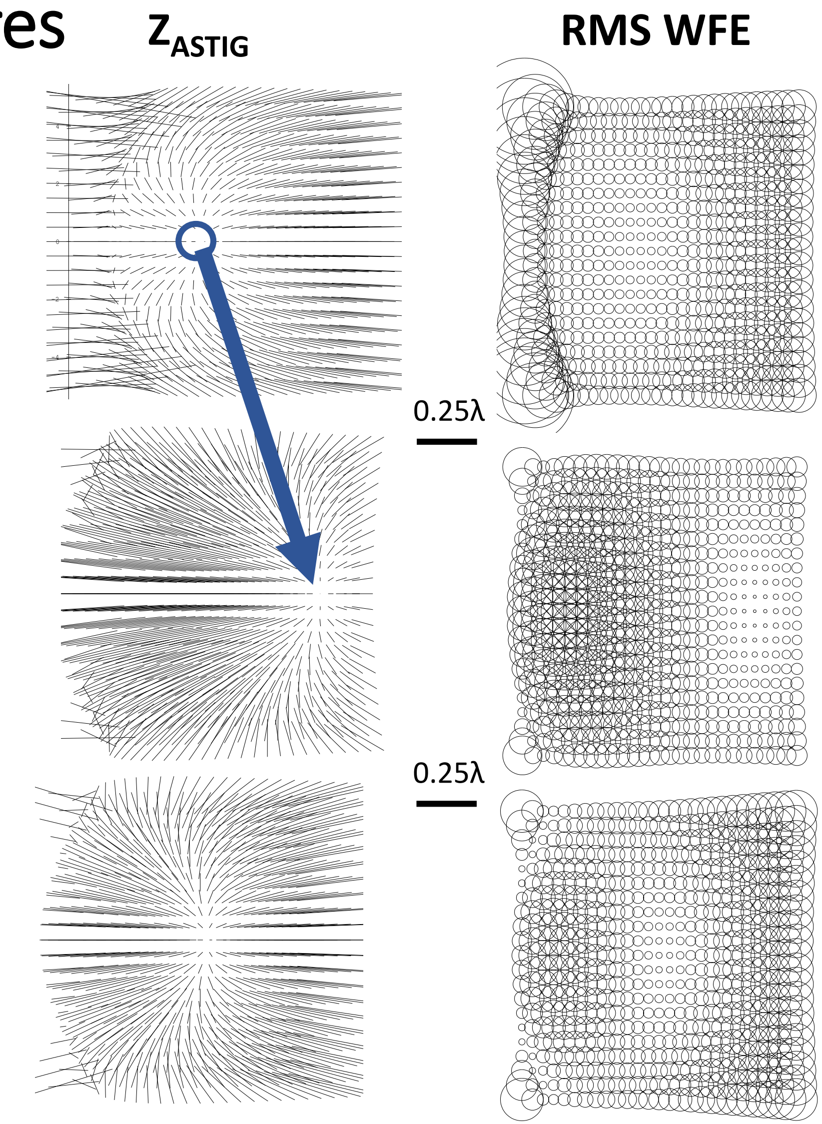
All aspheric surfaces
with astigmatic node shift:

Max RMS WFE: 0.205λ
Avg. RMS WFE: **0.096λ**

Anamorphic aspheric surfaces:

Max RMS WFE: 0.186λ
Avg. RMS WFE: **0.092λ**

Benchmarking with coaxial aspheres



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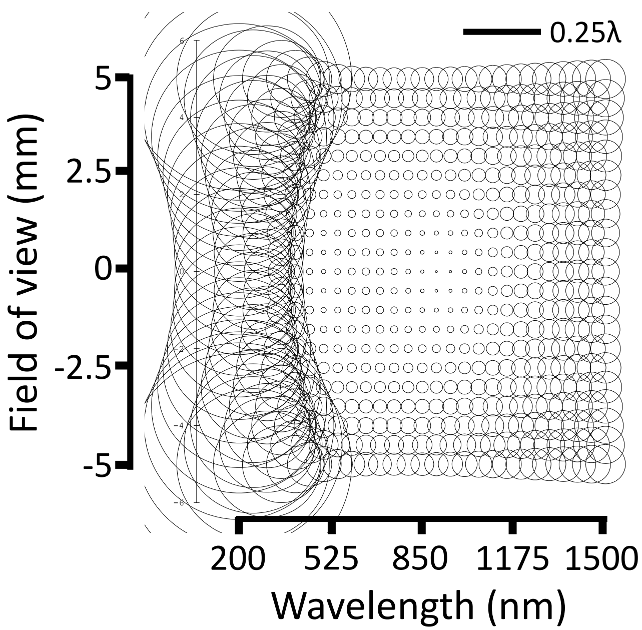
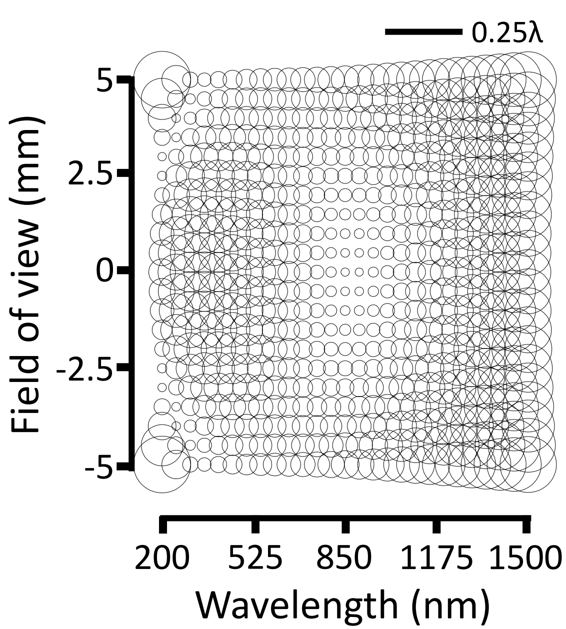
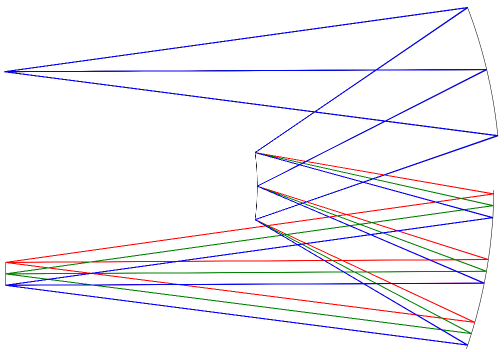
Summary of benchmarking aspheres

RMS WFE



RMS WFE





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<u>Anamorphic asphere:</u>

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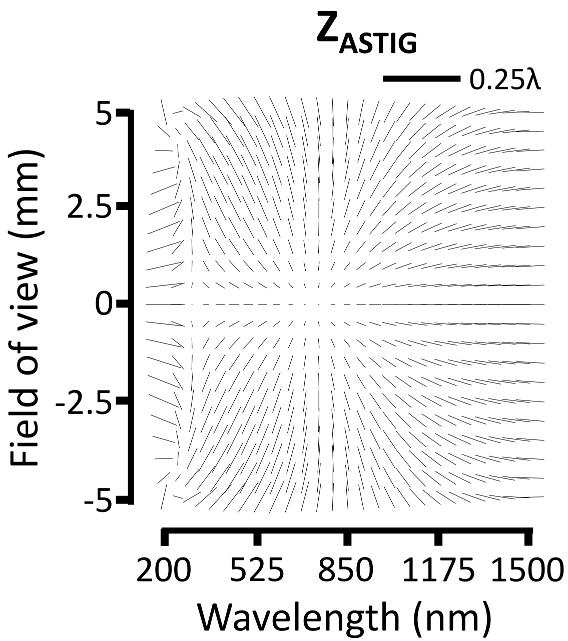
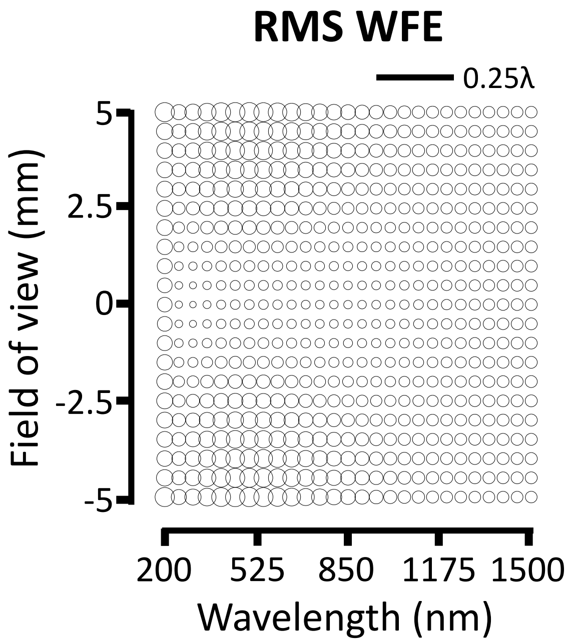
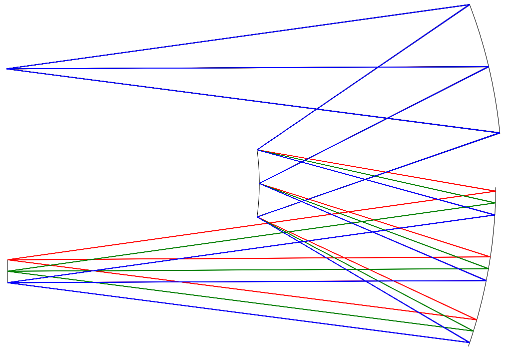
Note: Avg. RMS WFE does not decrease appreciably

OC spectrometer - freeform performance







Surfaces are of the φ-polynomial (Fringe Zernike) type

<u>All spherical surfaces:</u>

Max RMS WFE: 0.731λ
Avg. RMS WFE: **0.097λ**

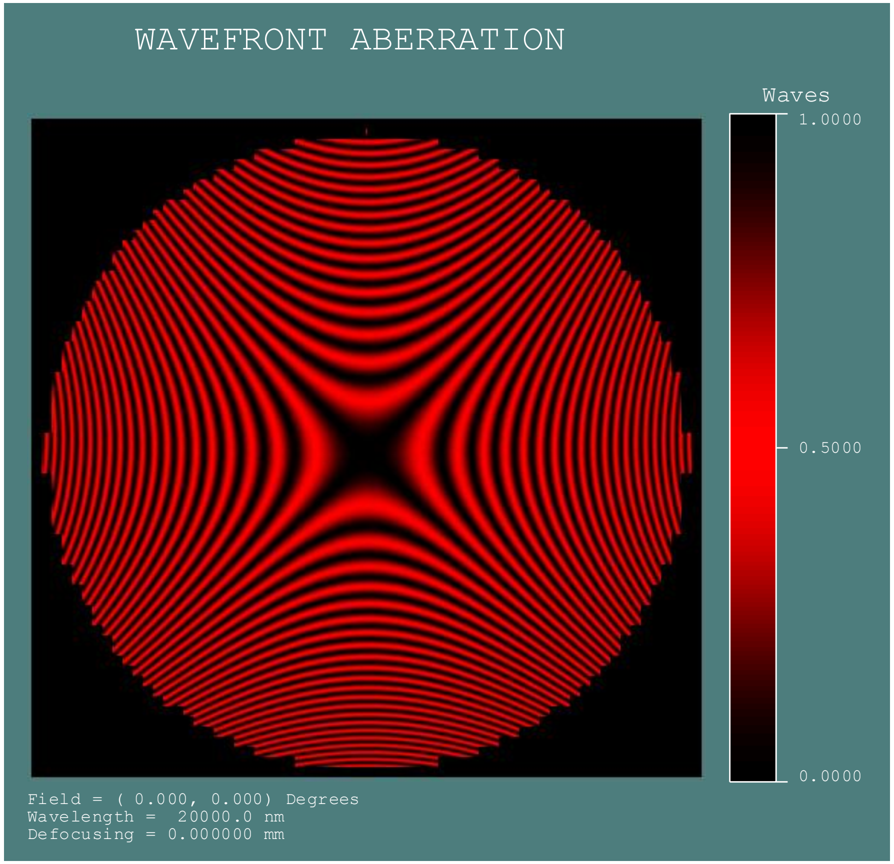
<u>Anamorphic asphere:</u>

Max RMS WFE: 0.186λ
Avg. RMS WFE: **0.092λ**

<u>All freeform surfaces:</u>
Diffraction limited for all fields and wavelengths

Max RMS WFE: 0.063λ
Avg. RMS WFE: **0.041λ**

Freeform surface departures

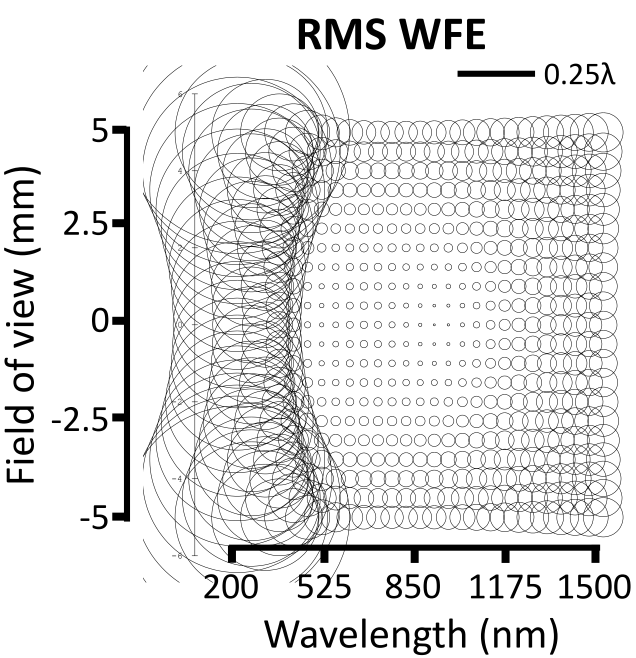


Tertiary – largest departure

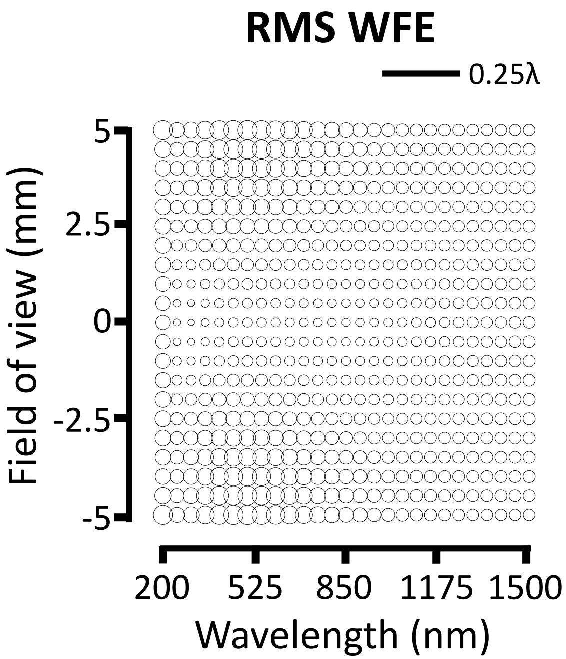
PV 833 µm
Exact shape may vary

Common to all surfaces:
Dominated by Astigmatism
< 1000 µm departure

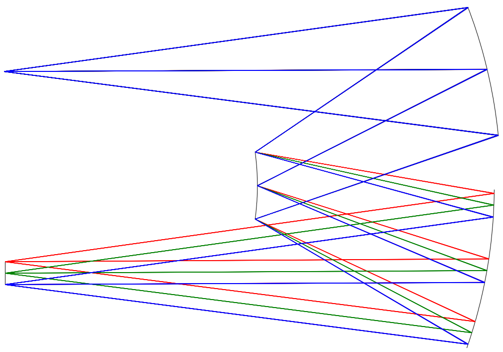
Spherical vs. freeform OC spectrometer



Spherical



Freeform



Avg. RMS WFE:

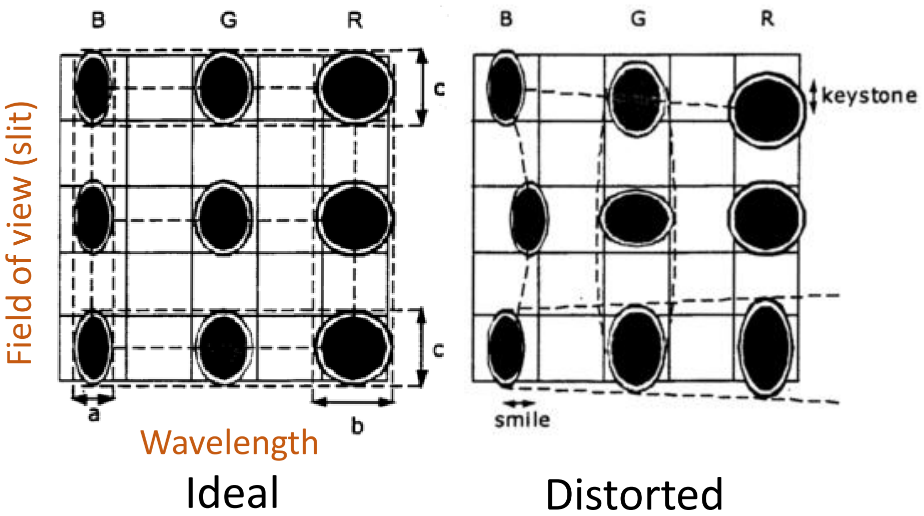
Spherical → asphere
6% decrease

Spherical → anamorphic asphere
5% decrease

Spherical → freeform
58% decrease

Simultaneous achievement of optical performance and distortion correction

- Imaging spectrometers have two types of distortion
  - Spectral smile
    - Typically want to be <1% of a pixel
  - Spatial keystone
    - Typically want to be <5% of a pixel
  - Measured the deviation with respect to the centroid of each wavelength or field
- Distortion and imaging performance are a design trade-off for spectrometers consisting of all-spherical surfaces
  - Freeform corrects smile/keystone while retaining diffraction limited performance in the Offner-Chrisp



Spectral broadened Offner-Chrisp was analyzed to have max 0.1µm smile and 0.08µm keystone which for a 10µm pixel is 1% and 0.8% respectively

P. Mouroulis, R. O. Green, and T. G. Chrien, "Design of pushbroom imaging spectrometers for optimum recovery of spectroscopic and spatial information.," Appl. Opt. **39**, 2210–20 (2000).

Summary

- The SFFD calculates the magnitude and direction of Fringe Zernike coefficients and plots them on field of view vs. wavelength axes
- The SFFD assists the designer in the design of spectrometers
- Insights provided by nodal aberration theory and the SFFD motivate novel compact high performance freeform spectrometers
- The use of freeform surfaces in an Offner-Chrisp spectrometer enables a much wider spectral bandwidth than spherical or aspheric designs due to correction of the astigmatic field as seen using the SFFD
- Leveraging freeform in an Offner-Chrisp facilitates simultaneous optical performance and distortion correction

Acknowledgements

- NSF I/UCRC Center for Freeform Optics (**CeFO**)
  Ball Aerospace & Technologies Corp.; OptiPro Systems, LLC; PerkinElmer; PolymerPlus LLC; Rochester Precision Optics; SCHOTT North America, Inc.; Air Force Research Laboratory; Zygo Corporation; ARRI.
- Peter Marasco and Dennis Yates for the stimulating discussions
- Synopsys Inc. for the student license of CODE V