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

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

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

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: $0.731\lambda$
Avg. RMS WFE: $0.097\lambda$
Benchmarking with coaxial aspheres

All surfaces aspheric (A-D):

Max RMS WFE: \(0.427\lambda\)
Avg. RMS WFE: \(0.091\lambda\)

All aspheric surfaces with astigmatic node shift:

Max RMS WFE: \(0.205\lambda\)
Avg. RMS WFE: \(0.096\lambda\)

Anamorphic aspheric surfaces:

Max RMS WFE: \(0.186\lambda\)
Avg. RMS WFE: \(0.092\lambda\)
Benchmarking with coaxial aspheres

All surfaces aspheric (A-D):
Max RMS WFE: 0.427\lambda
Avg. RMS WFE: 0.091\lambda

All aspheric surfaces with astigmatic node shift:
Max RMS WFE: 0.205\lambda
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Anamorphic aspheric surfaces:
Max RMS WFE: 0.186\lambda
Avg. RMS WFE: 0.092\lambda
Summary of benchmarking aspheres

All spherical surfaces:
Max RMS WFE: $0.731\lambda$
Avg. RMS WFE: $0.097\lambda$

Anamorphic asphere:
Max RMS WFE: $0.186\lambda$
Avg. RMS WFE: $0.092\lambda$

Note: Avg. RMS WFE does not decrease appreciably
OC spectrometer - freeform performance

All spherical surfaces:
Max RMS WFE: 0.731\lambda
Avg. RMS WFE: 0.097\lambda

Anamorphic asphere:
Max RMS WFE: 0.186\lambda
Avg. RMS WFE: 0.092\lambda

Surfaces are of the \phi-polynomial (Fringe Zernike) type

All freeform surfaces: Diffraction limited for all fields and wavelengths

Max RMS WFE: 0.063\lambda
Avg. RMS WFE: 0.041\lambda
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

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

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
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