

REPORT DOCUMENTATION PAGE

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14. ABSTRACT It is important to isolate mirror shape accuracy from misalignment to maximize the ability to correct images in the James Webb Space Telescope. In this effort, nodal aberration theory was used to characterize the misalignment-induced aberration fields. This led to the discovery of a new misalignment-induced field dependence. A methodology has also been developed to integrate as-measured mirror figure errors characterized by a Zernike polynomial fit with nodal aberration theory.					
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Misalignment-Induced Aberrations of JWST:

Isolating Low Order Primary Mirror Figure Residuals from Misalignment

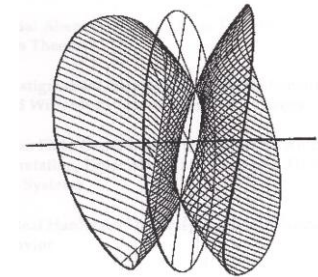
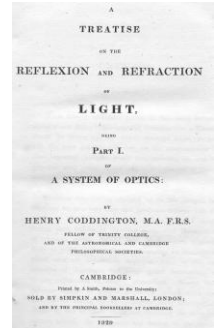
Kevin P. Thompson/ORA

Tobias Schmid/CREOL

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NASA Mirror Tech.
Boulder, CO
June 7-9, 2010



New Results in Nodal Aberration Theory Applied to JWST

- **Recent work by the authors to apply nodal aberration theory to characterize the misalignment-induced aberration fields in astronomical telescopes has led to some important new results including**
 - **A new misalignment-induced field dependence Field-Centered, Field-Asymmetric, Field-Linear Astigmatism**
 - **A methodology has been found to integrate as-measured mirror figure error characterized by a Zernike polynomial interferogram fit with nodal aberration theory (NAT)**
- **The second result allows isolating figure error from misalignment, allowing dynamic range for correction to be conserved**

Fundamentals of Misalignment Induced Aberration Fields

- A misaligned telescope (including TMA) has **no new aberration types**
- The existing aberration types often **develop new field dependencies** for the magnitude and orientation within the field of view
- The new field dependencies are best characterized by **characteristic, intrinsic nodal geometries** (aberration zero points) that are reported in K.P. Thompson, JOSA A, 2005 (3rd) and JOSA A, 2009, 2010 (5th)
- In general, once misalignment coma is removed, the remaining misalignment astigmatism is zero on-axis, but it is **NOT** field quadratic

K. P. Thompson, "Description of the third-order optical aberrations of near-circular pupil optical systems without symmetry," J. Opt. Soc. Am. A 22, 1389-1401 (2005).

Overview The JWST

Three Mirror Anastigmat (TMA)

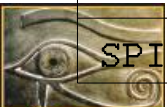
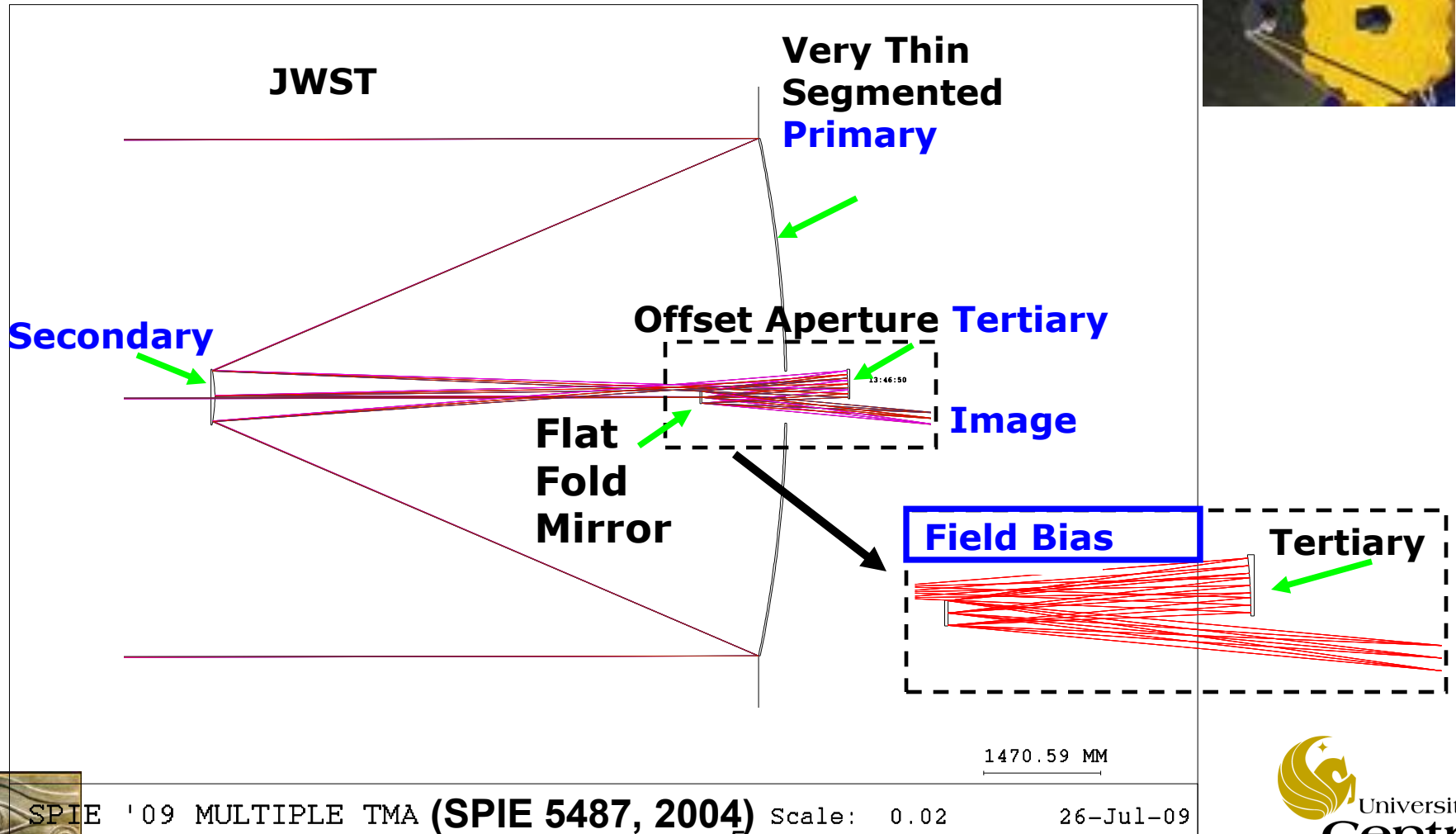


- The JWST is an **obscured aperture, field-biased** three-mirror telescope corrected for all third order aberrations, if aligned perfectly
- It has a 6.6M (segmented) aperture and a 0.33 degree Full FOV
- Like the Hubble Space Telescope, most of the instruments use portions of the field at the periphery of the field, making the overall system significantly more alignment sensitive

JWST

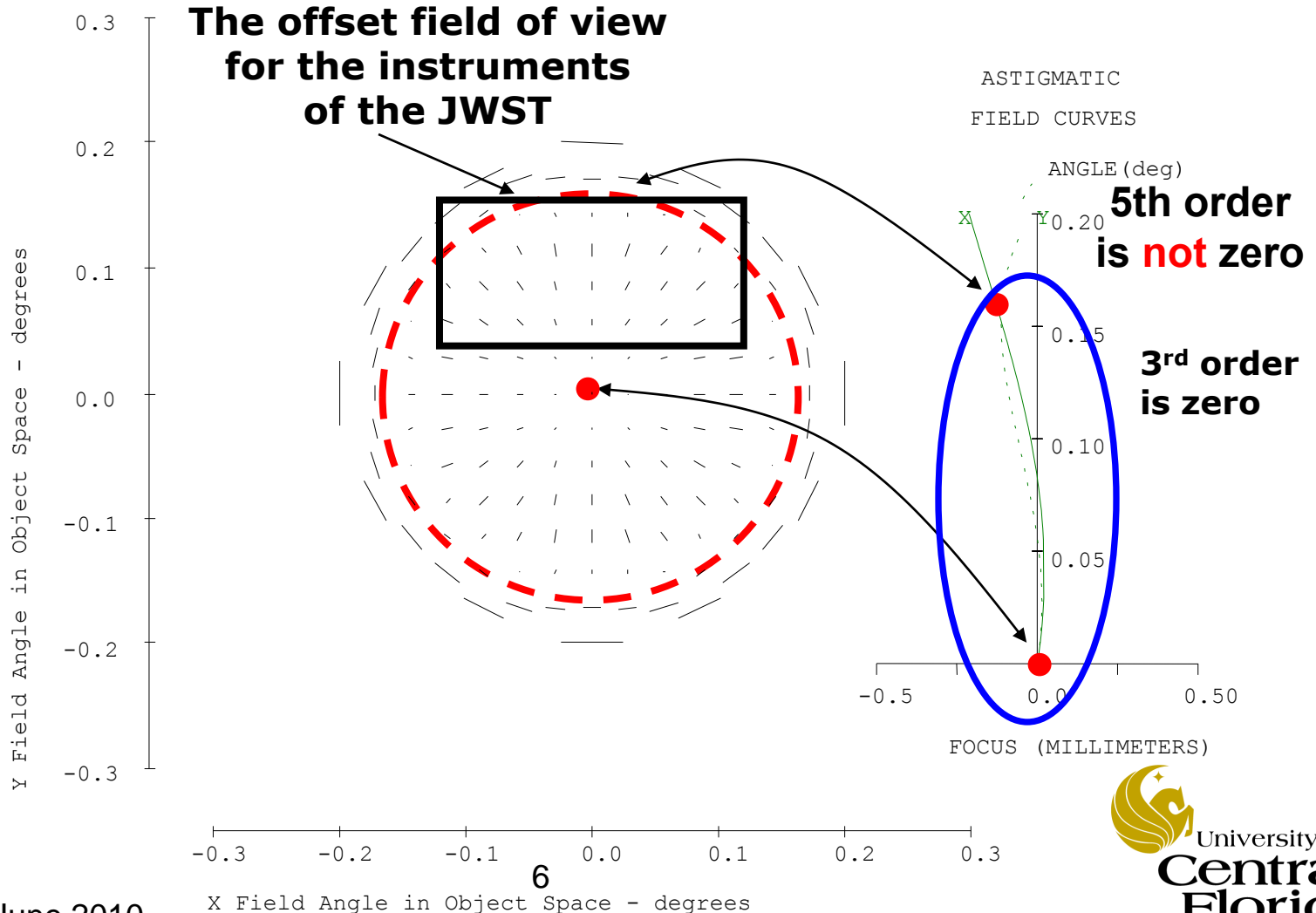
A Field Bias, Obscured TMA

17:48:16



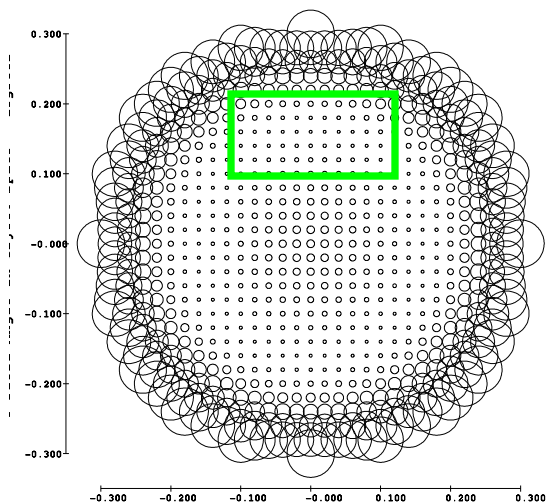
SPIE '09 MULTIPLE TMA (SPIE 5487, 2004) Scale: 0.02 26-Jul-09

The JWST Telescope Field of View Limit 5th order Astigmatism

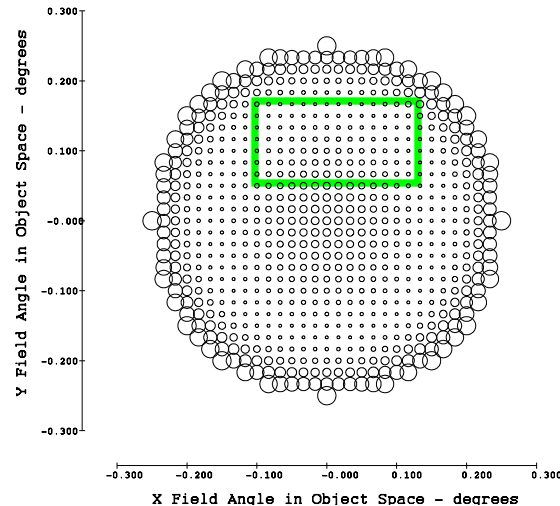


The High Order "Boundary"

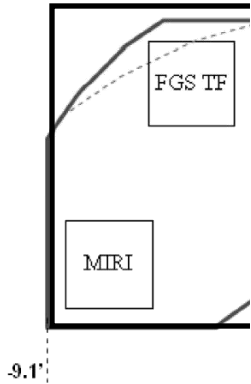
Aligned RMS Wavefront Error



Aligned RMS Wavefront Error

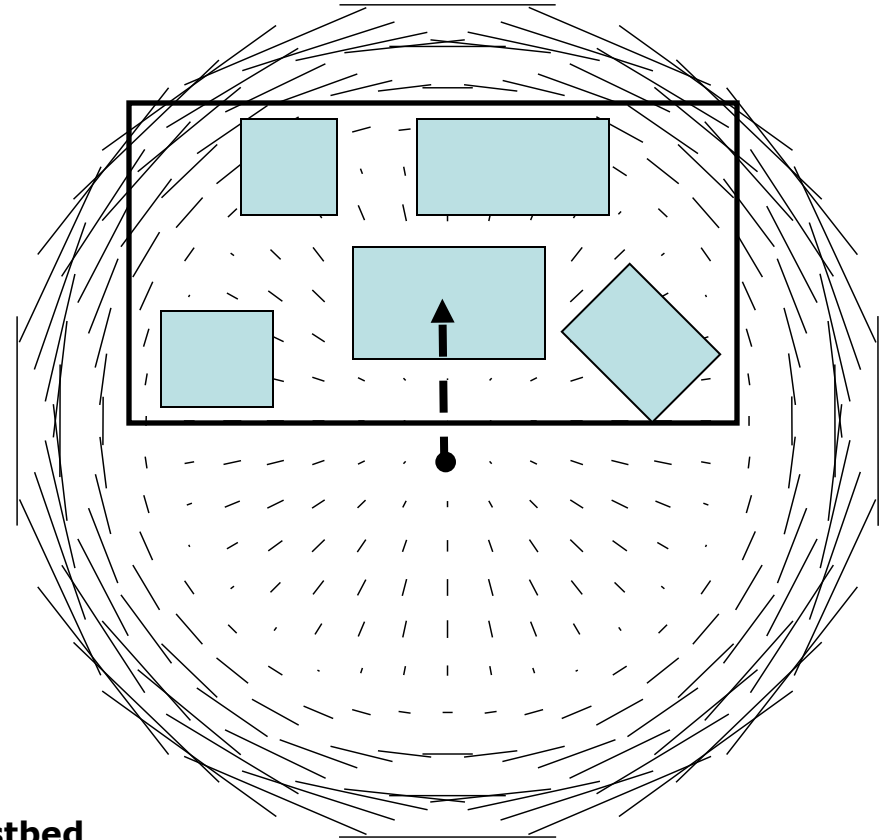


**20% oversize to demonstrate
The "strength" of the
High order boundary**



Field Angle in Object Space - degrees

0.3000
0.2000
0.1000
0.0000
-0.1000
-0.2000
-0.3000

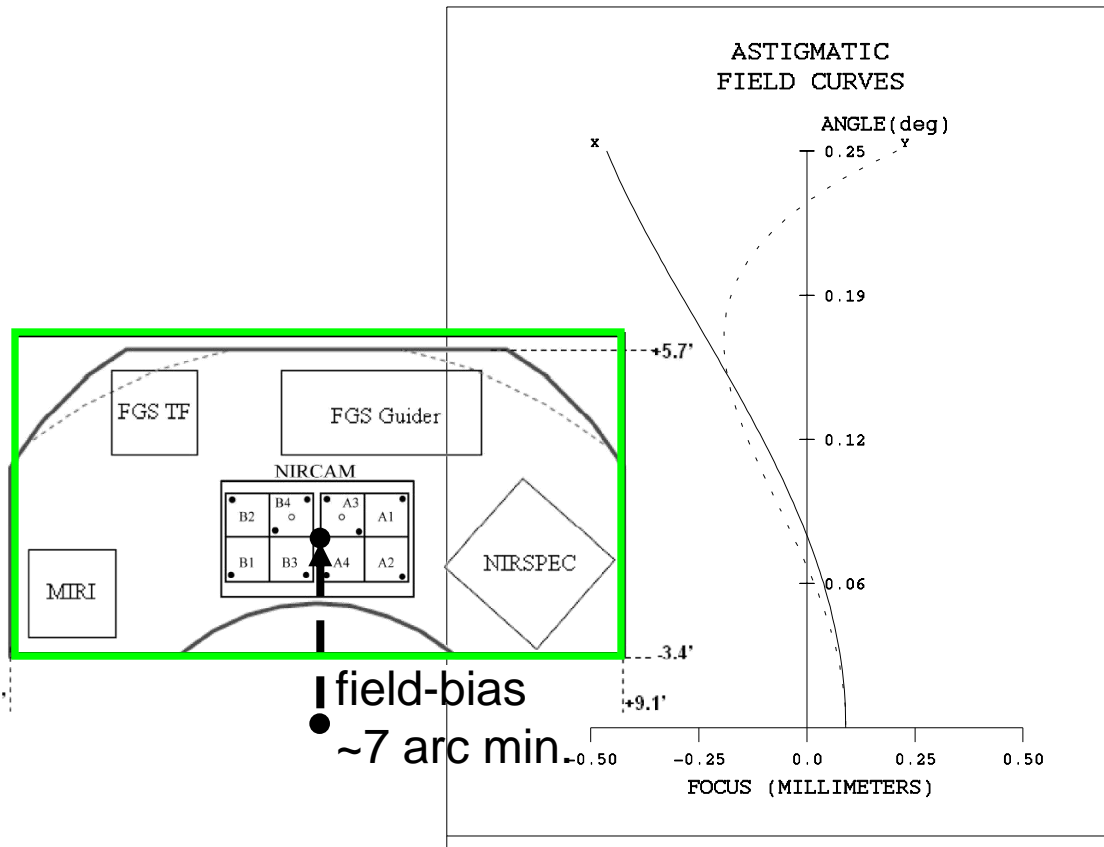
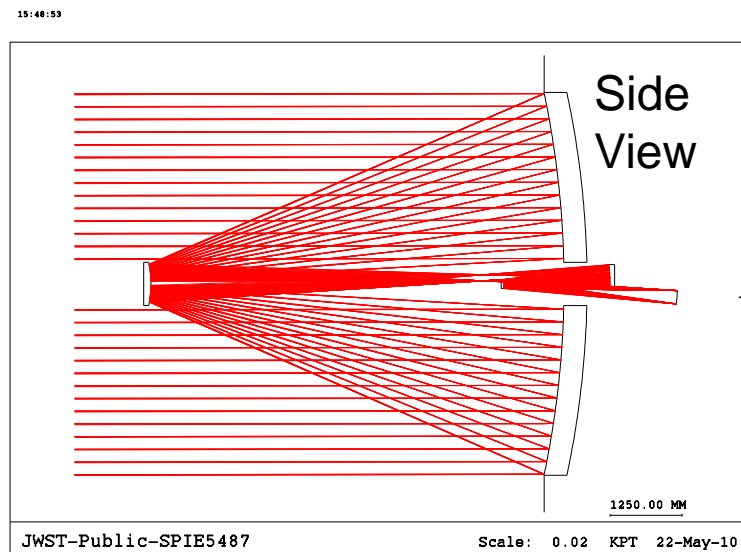
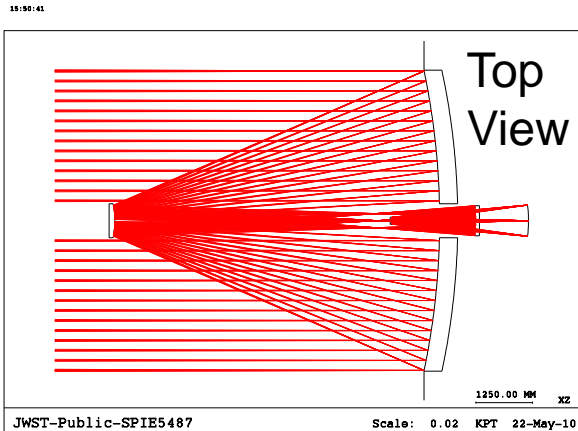


Some instruments are themselves a series of TMAs, SPIE OPTIFAB 2009

Erin Sabatke, "Using Multifield measurements to eliminate alignment degeneracies in the JWST Testbed Telescope," Ball Aerospace, Proc. of SPIE Vol. 6687 668707-1, 2007

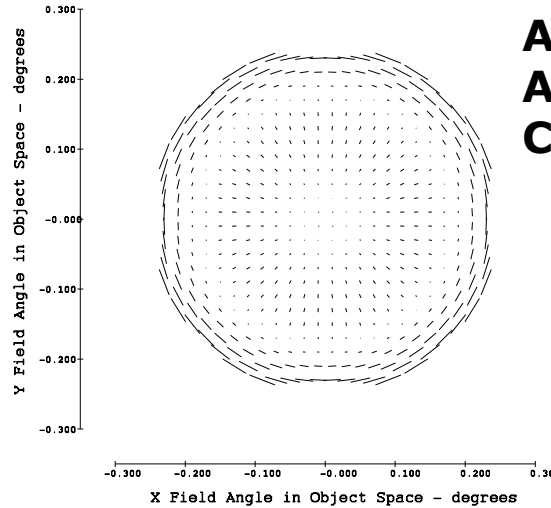
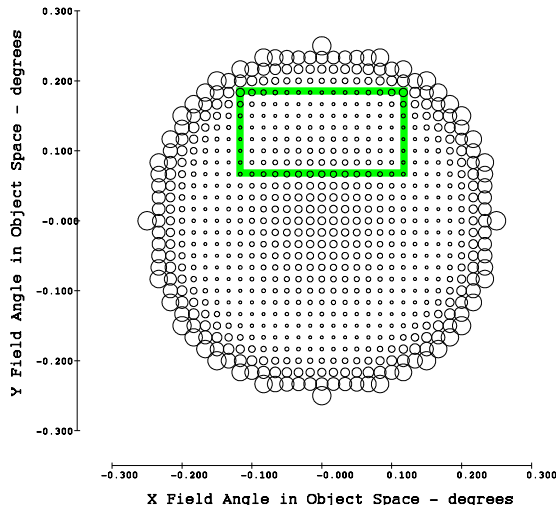


Overview of JWST FOV



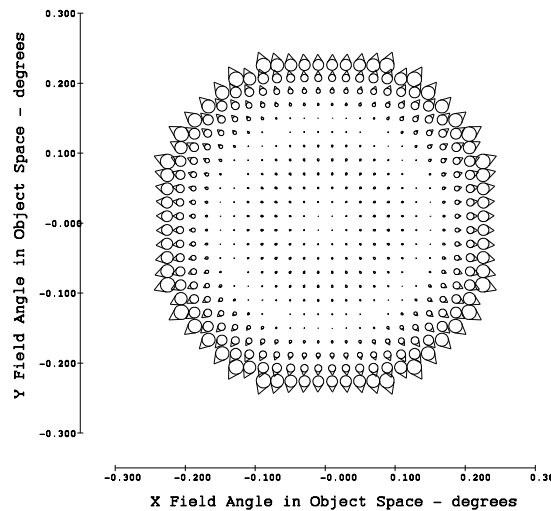
Real-Ray Zernike Based FFD Analysis Aligned JWST

Aligned RMS Wavefront Error



**All Orders
Astigmatic
Component**

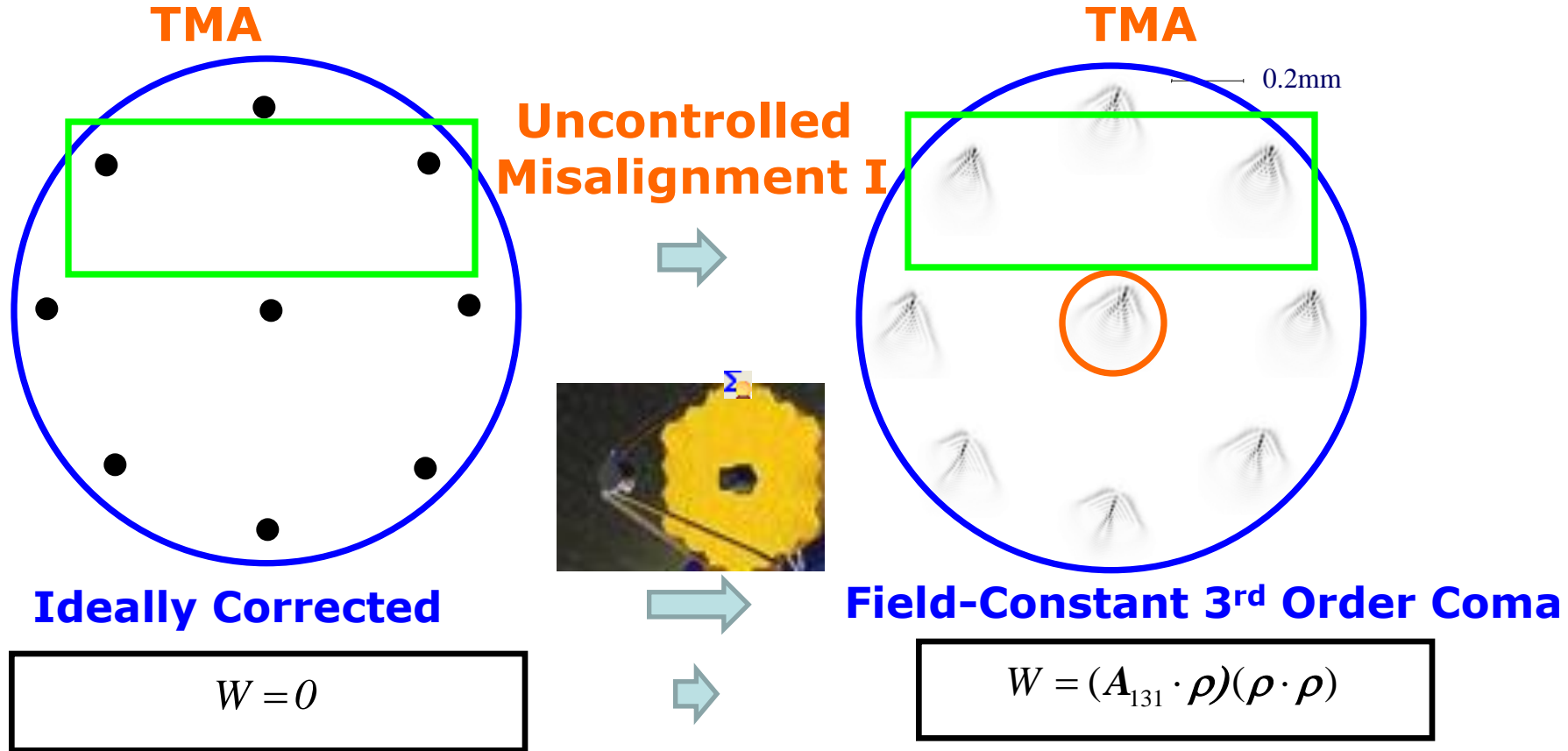
**No other
Zernike Terms
Are Significant**



**All Orders
Comatic
Component**



Misalignment-Induced JWST Aberrations 3rd Order Coma



K. P. Thompson, T. Schmid, O. Cakmakci, and J.P. Rolland, "A real ray-based method for locating individual surface aberration field centers in imaging optical systems without symmetry," JOSA A 26, pp 1503-1517 (2009).

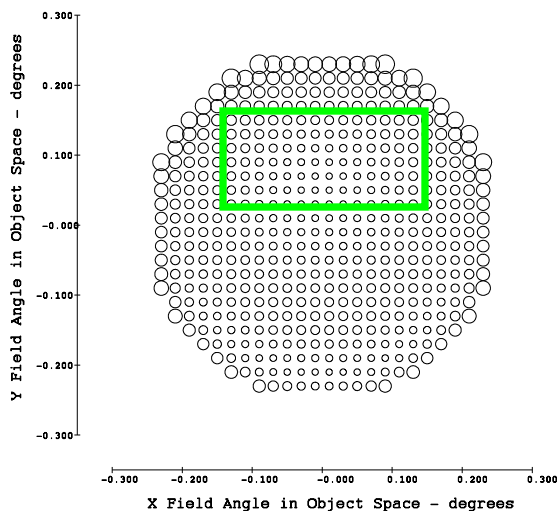
11

$$\sum_j W_{131j} H = W_{131} H = 0$$

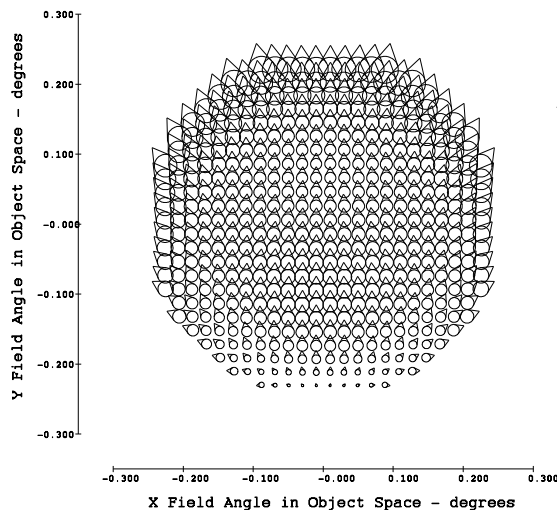
$$A_{131} \equiv \sum_j W_{131j} \sigma_j$$

FFD Analysis Misalignment Coma

Decentered Component
RMS Wavefront Error



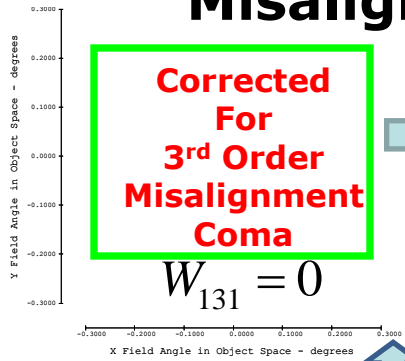
Change Dominated
by 3rd Order Field
Constant Coma



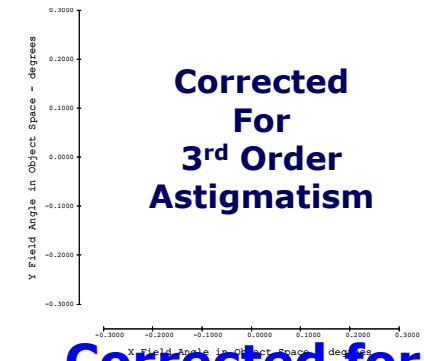
All Orders
Comatic
Component

Misalignment-Induced JWST Aberrations II 3rd Order Astigmatism

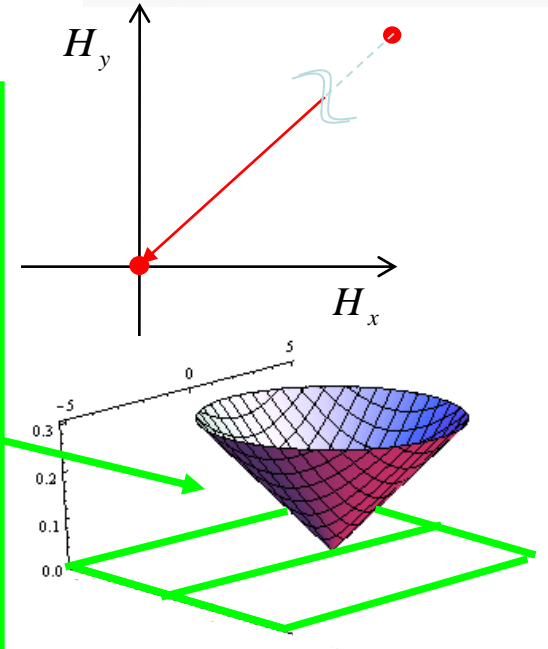
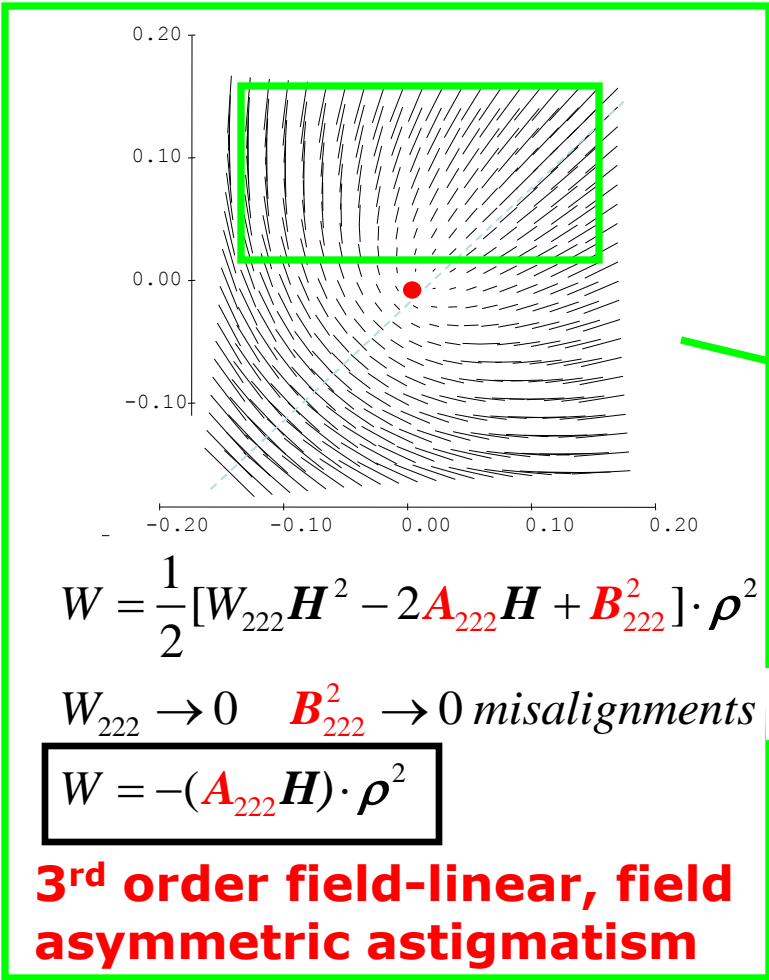
Misalign II



Misalign I anastigmatic



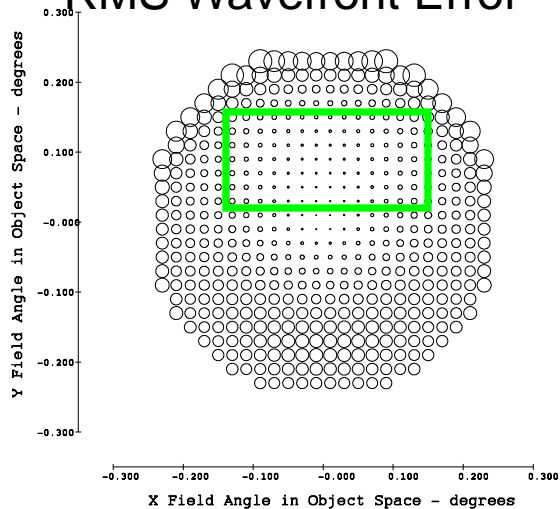
Corrected for 3rd order astig.



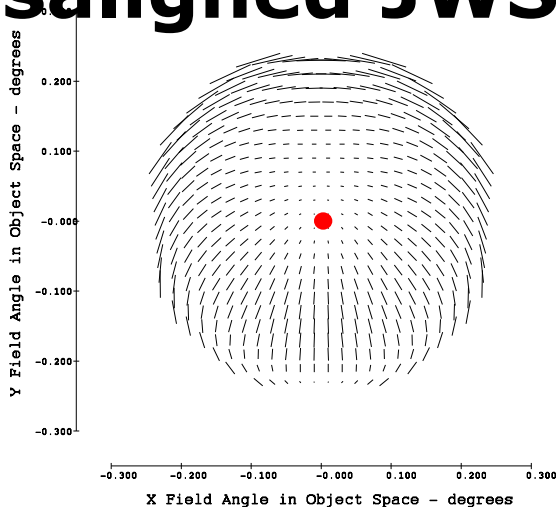
K. P. Thompson, T. Schmid, and J.P. Rolland, "The Misalignment induced aberrations of TMA telescopes," Optics Exp. 16 (25), pp 20345-20353 (2008).

FFD Analysis Coma-Free Pivot Misaligned JWST

No Figure Error
Misaligned Component
Coma-Free Pivot
RMS Wavefront Error

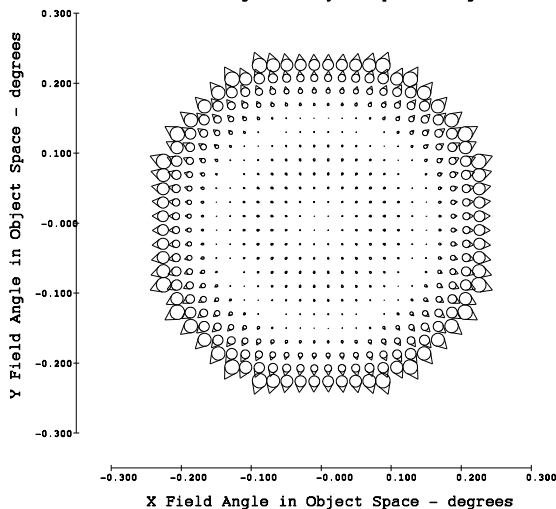


No Figure Error



Astigmatic
Component
Misalignment
Only

Change Dominated by
3rd Order Field-Linear,
Field-Asymmetric Astig.



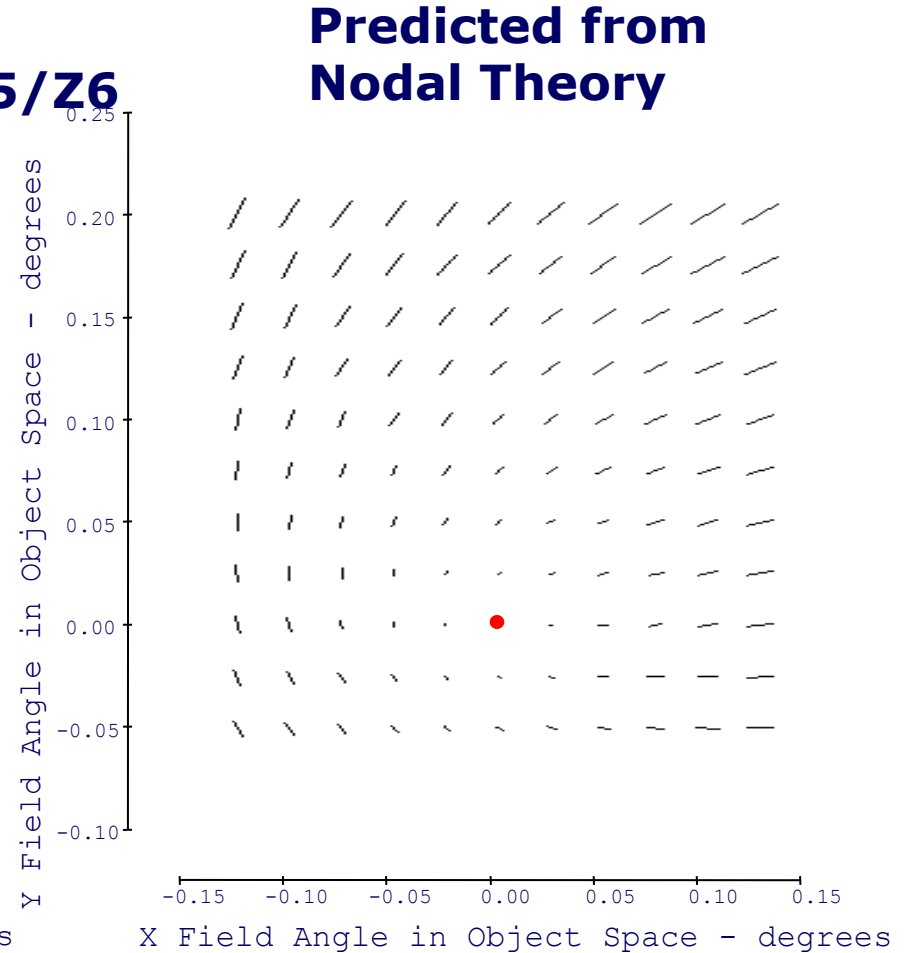
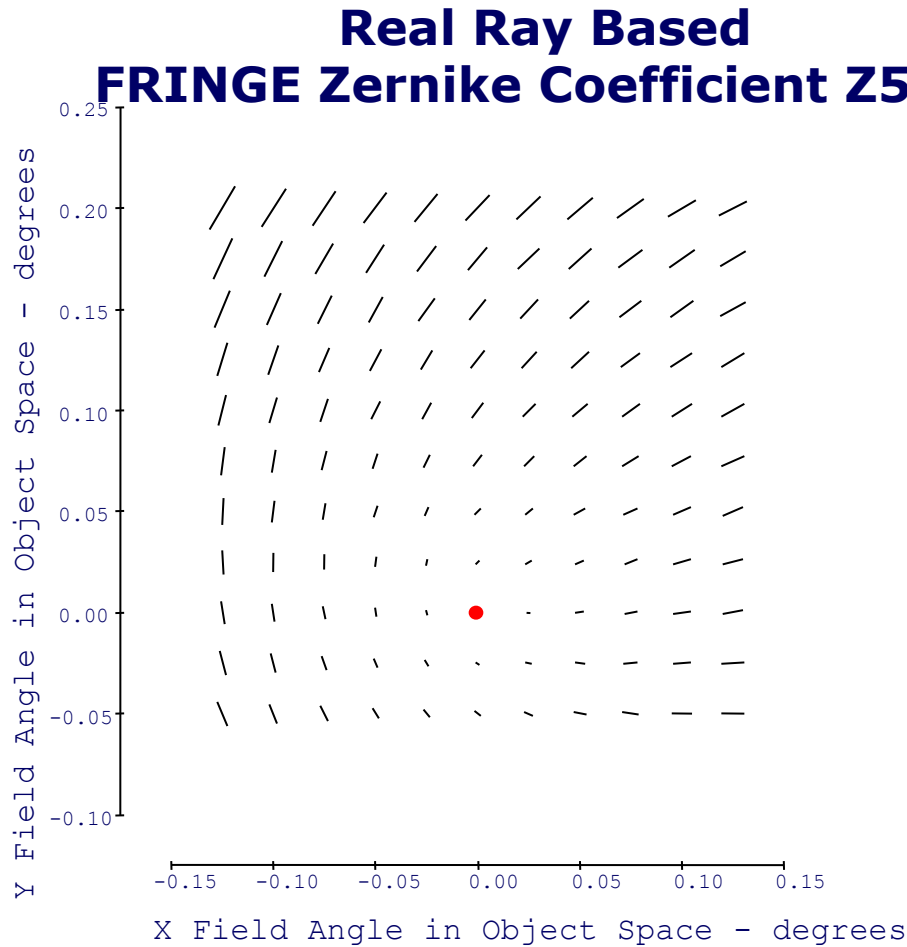
Comatic
Component
Coma-Free
Pivot



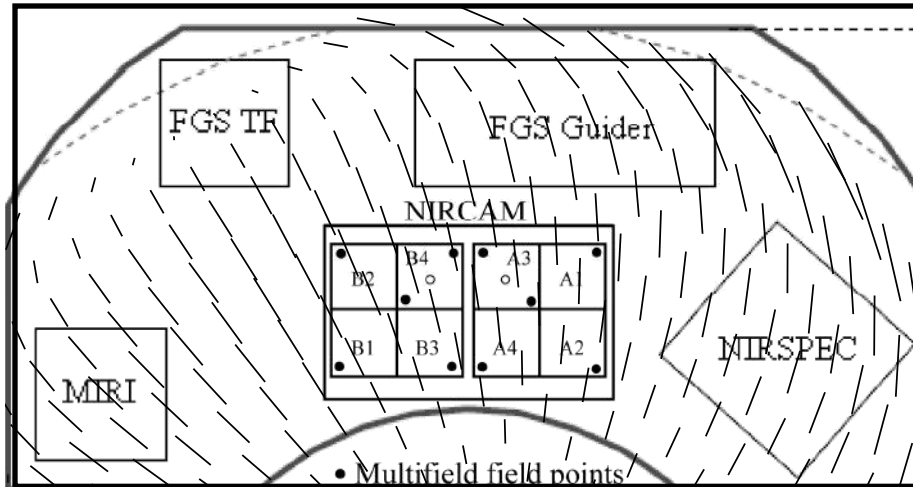
Real Ray vs. Theory

Field-Linear, Field Asymmetric

3rd Order Astigmatism



If There Were No Primary Mirror Figure Error

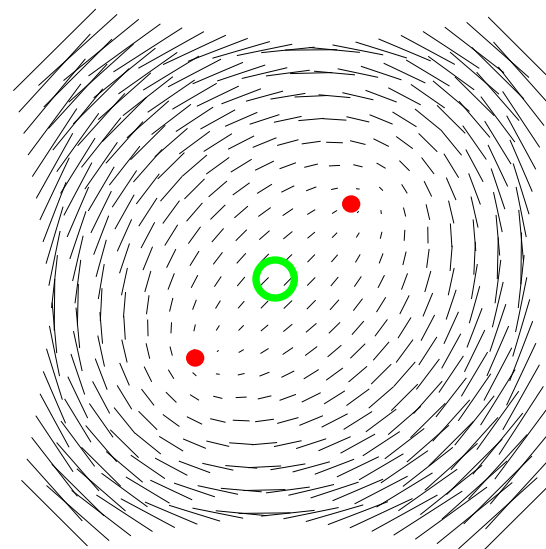
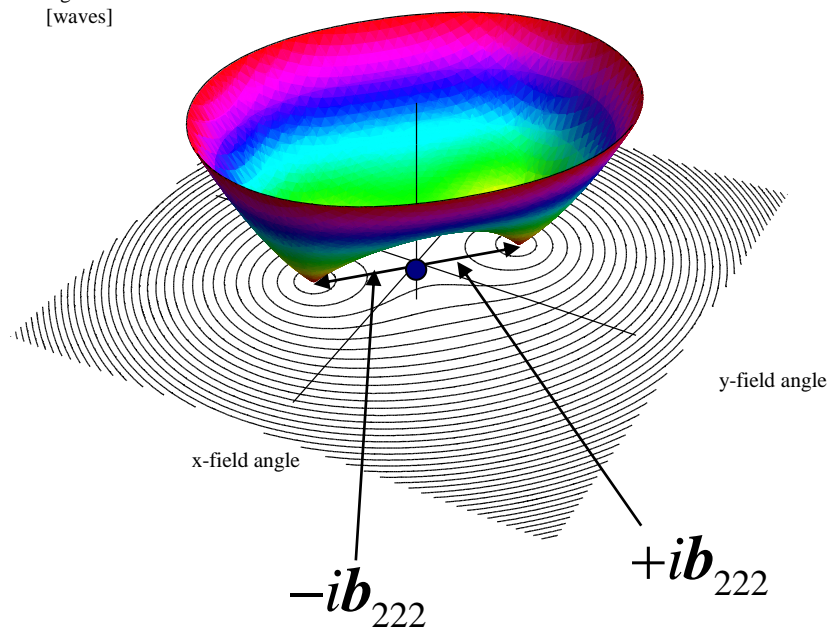


+5.7 Without the insight of misalignment induced aberration theory, the rotation of astigmatic images can appear complex, they are simply binodal fields interacting with a boundary

Because the Phase Diversity measurements are made at the backend of instruments that are themselves complex, some with multiple TMAs, understanding the nodal signatures of the instruments, before their data is used to predict the state of the telescope would be leveraged as a basis to create a highly accurate analytic model for support during alignment

The Astigmatic Field with Primary Mirror "Figure Error"

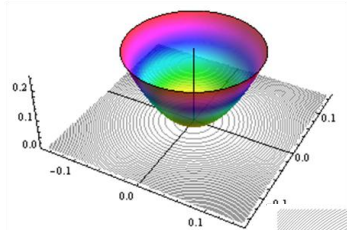
Astigmatism
[waves]



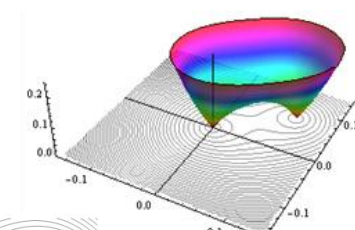
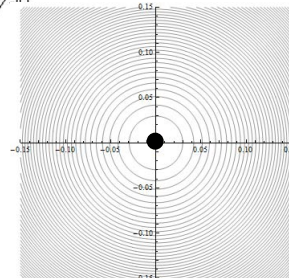
(a)

Unlike misalignment which create field-centered, field-linear, field-asymmetric astigmatism, **primary mirror figure error creates field-centered, field-binodal, field-plane-symmetric astigmatism**

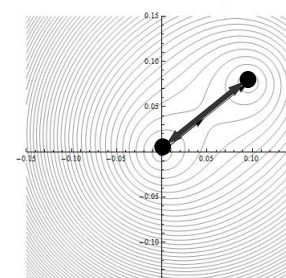
Astigmatic Nodal States of Coma-Aligned JWST Including Figure Error



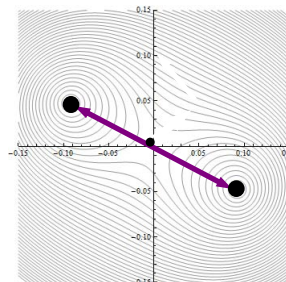
**Aligned
And
No Figure Error**



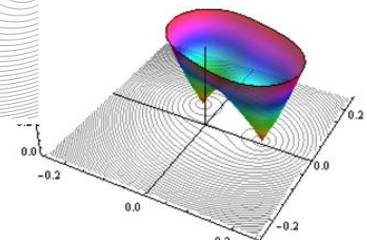
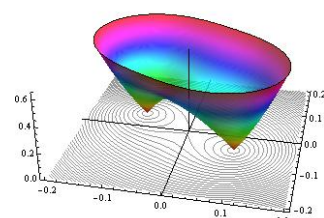
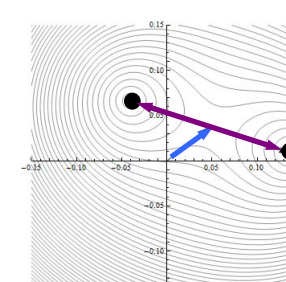
**Misalignment
But
No Figure Error**



**Aligned
But
With Figure Error**

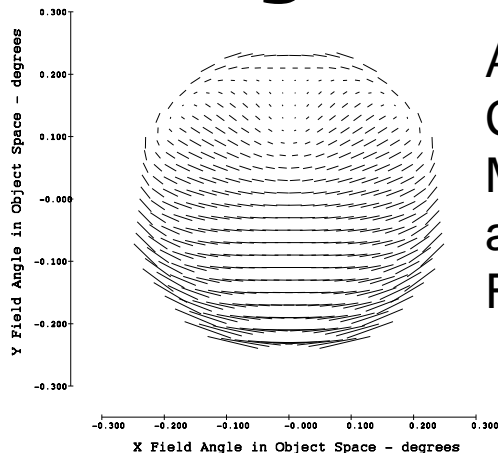
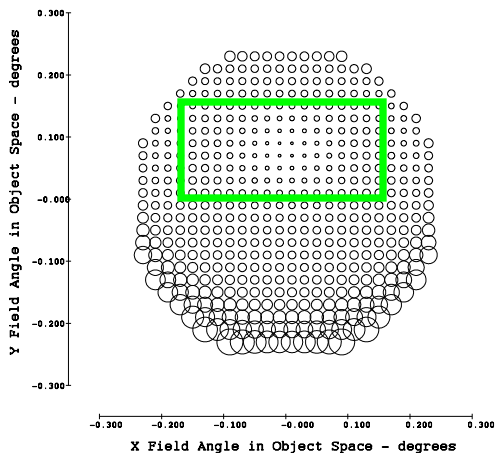


**Misalignment
And
Figure Error**

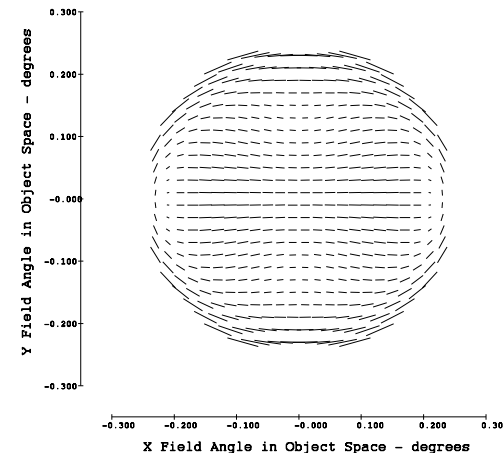


FFD Analysis Coma Corrected Misaligned JWST With Figure Error

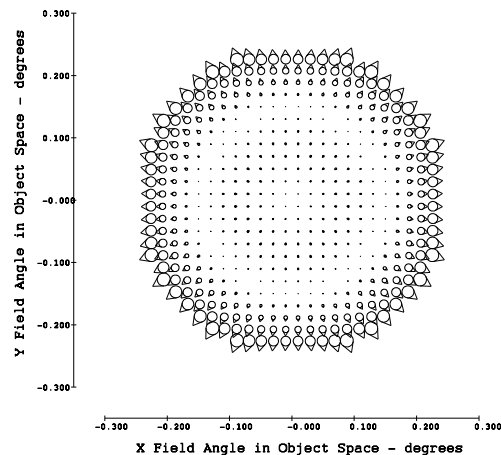
With Figure Error
Misaligned Component
Coma-Free Pivot
RMS Wavefront Error



Astigmatic
Component
Misalignment
and
Figure Error



Astigmatic Component
Figure Error Only,
Dominantly 3rd Order
Field-Binodal Astig.



Comatic
Component

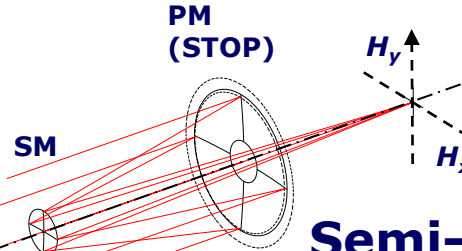
Conclusions

JWST Performance Limiting Misalignment Aberrations

- It is considered important, and readily accomplished, to report the 3rd order misalignment aberration fields of the instruments to be used in collecting Phase Diversity data
- The aberrations to concentrate on at final alignment are
 - field-constant 3rd order coma
 - field-centered, field-linear, field-asymmetric 3rd order astigmatism
 - field-centered, field-binodal 3rd order astigmatism
- Separating the misalignment and figure error components makes best use of compensating dynamic range - Phase Diversity measurements from at least two and preferably three instruments allow distinguishing these two components

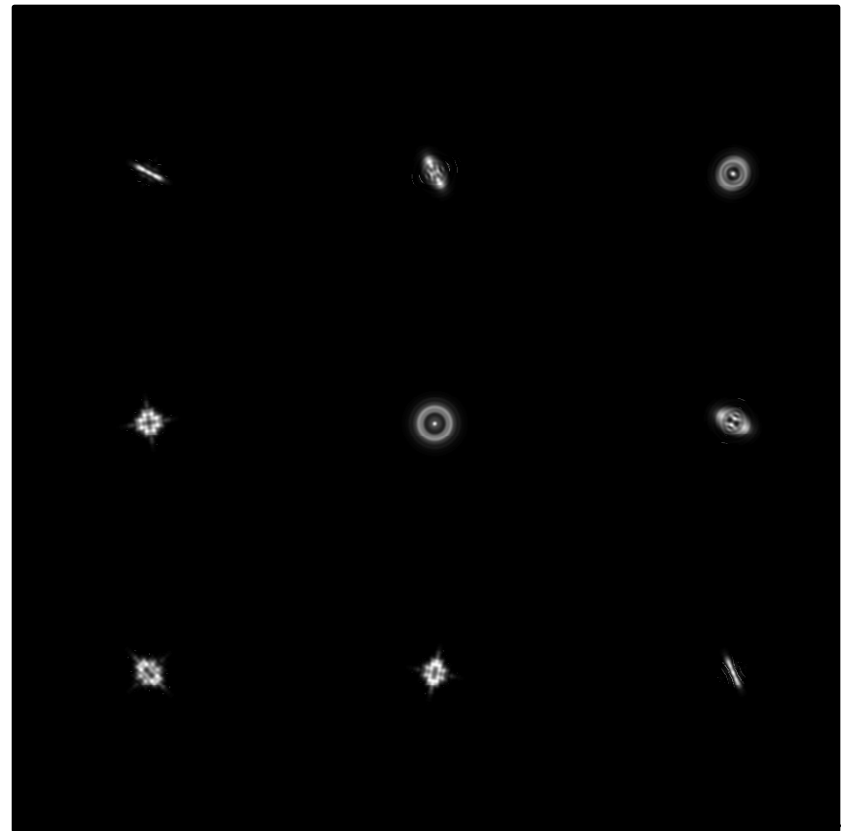
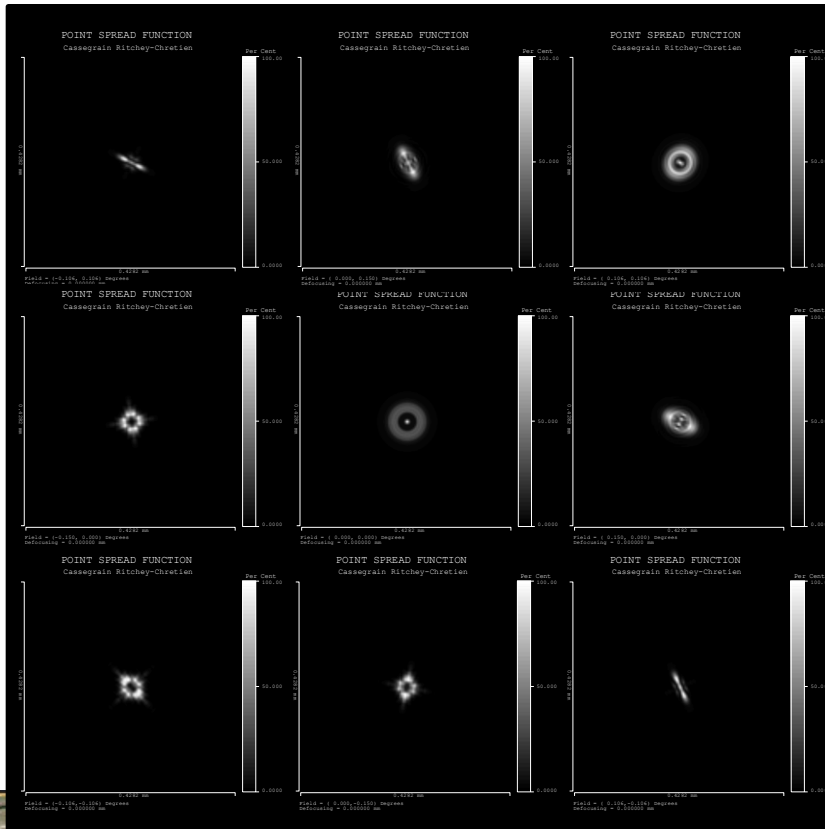
Acknowledgements

- **This work was and is supported by,**
 - **the Florida I-4 Corridor program,**
 - **the University of Rochester,**
 - **Optical Research Associates**



PSF computed with Raytracing Software

Semi-Analytical PSF utilizing Nodal Aberration Theory



Application to the LSST is more complex Alignment Strategy based on Z5/6, Z7/8, and Z14/15

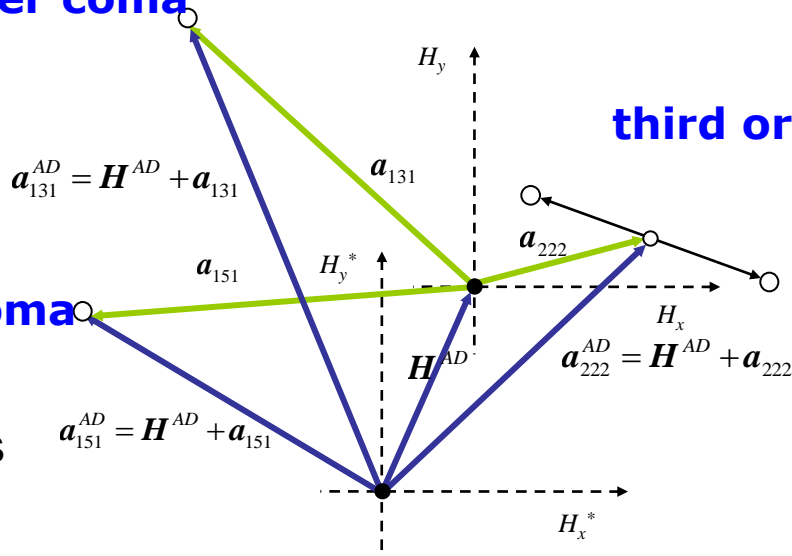
third order coma

third order astigmatism

fifth order coma

Paper to be
presented at
SPIE Astronomy
later this month

express dependence on
misalignment parameters



$$a_{131}^{AD} = a_{131} + H^{AD}$$

$$a_{151}^{AD} = a_{151} + H^{AD}$$

$$a_{222}^{AD} = a_{222} + H^{AD}$$

$$a_{222} = \frac{1}{W_{222}} \left(W_{222,PM}^{(sph)} \sigma_{PM}^{(sph)} + W_{222,PM}^{(asph)} \sigma_{PM}^{(asph)} + W_{222,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{222,SM}^{(asph)} \sigma_{SM}^{(asph)} + W_{222,TM}^{(sph)} \sigma_{TM}^{(sph)} + W_{222,TM}^{(asph)} \sigma_{TM}^{(asph)} \right)$$

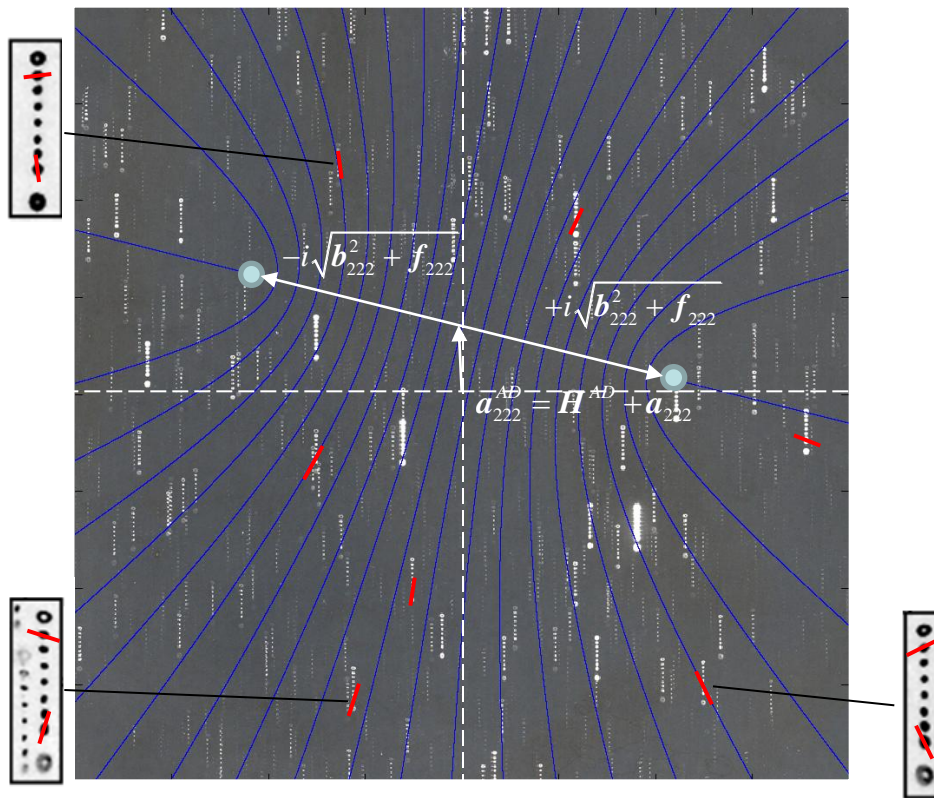
$$a_{131} = \frac{1}{W_{131}} \left(W_{131,PM}^{(sph)} \sigma_{PM}^{(sph)} + W_{131,PM}^{(asph)} \sigma_{PM}^{(asph)} + W_{131,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{131,SM}^{(asph)} \sigma_{SM}^{(asph)} + W_{131,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{131,SM}^{(asph)} \sigma_{SM}^{(asph)} \right)$$

$$a_{151} = \frac{1}{W_{151}} \left(W_{151,PM}^{(sph)} \sigma_{PM}^{(sph)} + W_{151,PM}^{(asph)} \sigma_{PM}^{(asph)} + W_{151,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{151,SM}^{(asph)} \sigma_{SM}^{(asph)} + W_{151,TM}^{(sph)} \sigma_{TM}^{(sph)} + W_{151,TM}^{(asph)} \sigma_{TM}^{(asph)} \right)$$

The First Evidence of MultiNodal Aberrations

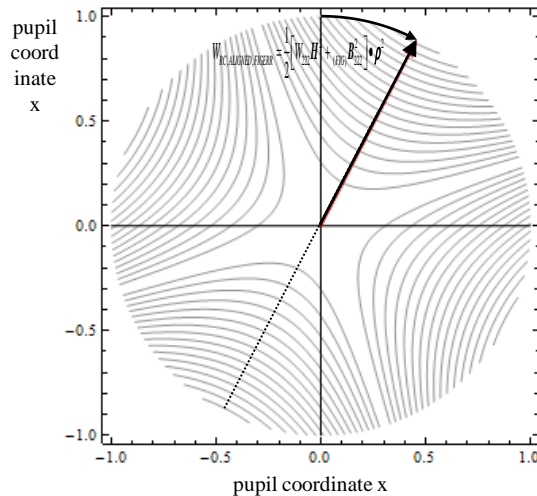
Through Focus Star Plates '77

● Astigmatic
Nodes



Through focus
photographic plate taken
with the 90" telescope of
the Steward observatory,
located on Kitt Peak. This
plate was taken in the 70's
before the theoretical
developments that led to
nodal aberration theory
and provided the first
physical confirmation of
the validity of this theory

Characterizing Figure Error as a Zernike Coefficient Interferogram



**Primary Mirror
Figure Error
Characterized as
C5/C6 Zernike Fit**

$$W_{RC,ALIGNED,FIGERR} = \frac{1}{2} [W_{222} H^2 + (FIG) B_{222}^2] \cdot \rho^2$$

$$(FIGERR) B_{222}^2 \equiv 2 \left((FIGERR) C_{5,6} \right) \exp \left[j2 \left((FIGERR) \xi_{5,6} \right) \right]$$

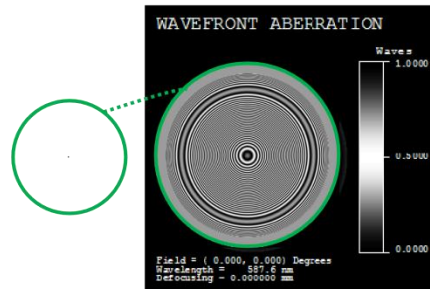
$$(FIGERR) C_{5,6} = \sqrt{\left((FIGERR) C_5 \right)^2 + \left((FIGERR) C_6 \right)^2}$$

$$(FIGERR) \xi_{5,6} = \frac{1}{2} \text{ArcTan} \left(\frac{-\left((FIGERR) C_6 \right)}{\left((FIGERR) C_5 \right)} \right)$$

T. Schmid, K.P. Thompson, and J.P. Rolland, "Separation of the effects of astigmatic figure error from misalignments using Nodal Aberration Theory (NAT)," submitted to Optics Express (May 2010)

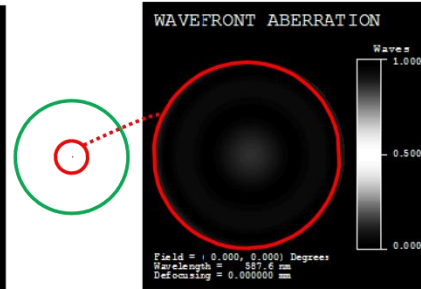
The "portal" for combining Zernike coefficient interferograms with nodal aberration theory

Full Aperture Aspheric Mirror Spherical



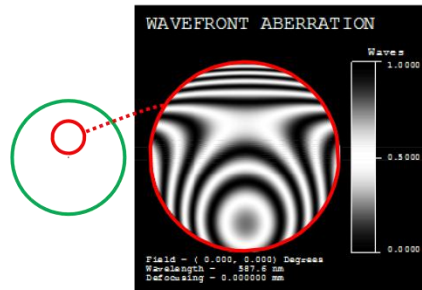
(a)

Centered Subaperture Nearly Null

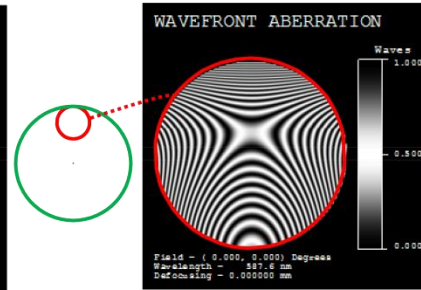


(b)

Mild Offset Subaperture Coma



Strong Offset Subaperture Astigmatism And some coma



Offset aperture aspheres were included in the original nodal work in the 70s – this path can be exploited as a path to introduce mirror figure error, for mirrors at the aperture stop/pupils