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**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.

**Subject Terms**: Nodal Aberration Theory, James Webb Space Telescope, Misalignment, Segmented, Mirror, Adaptive Optics, Coma, Astigmatism, Field of View, Zernike

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Misalignment-Induced Aberrations of JWST:
Isolating Low Order Primary Mirror Figure Residuals from Misalignment

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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

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

Secondary

Offset Aperture

Flat Fold Mirror

Very Thin Segmented Primary

Image

Field Bias

Tertiary

1470.59 MM

Scale: 0.02

26-Jul-09

SPIE '09 MULTIPLE TMA (SPIE 5487, 2004)

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The JWST Telescope
Field of View Limit
5th order Astigmatism

The offset field of view for the instruments of the JWST

5th order is not zero

3rd order is zero
The High Order “Boundary”

20% oversize to demonstrate The “strength” of the High order boundary

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

Field-bias ~7 arc min

ASTIGMATIC FIELD CURVES

ANGLE (deg)

FOCUS (MILLIMETERS)
Real-Ray Zernike Based FFD Analysis
Aligned JWST

Aligned RMS Wavefront Error

All Orders Astigmatic Component

All Orders Comatic Component

No other Zernike Terms Are Significant
Misalignment-Induced JWST Aberrations
3rd Order Coma

\[ W = (A_{131} \cdot \rho)(\rho \cdot \rho) \]

\[ \sum_j W_{131j} H = W_{131} H = 0 \]

\[ A_{131} = \sum_j W_{131j} \sigma_j \]

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**

Corrected For
3rd Order Misalignment Coma

\( W_{131} = 0 \)

**Misalign I**

anastigmatic

Corrected For
3rd Order Astigmatism

3rd order field-linear, field asymmetric astigmatism

\[
W = \frac{1}{2} \left[ W_{222} H^2 - 2 A_{222} H + B_{222}^2 \right] \cdot \rho^2
\]

\( W_{222} \rightarrow 0 \quad B_{222}^2 \rightarrow 0 \) misalignments small

\[
W = -(A_{222} H) \cdot \rho^2
\]


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FFD Analysis
Coma-Free Pivot
Misaligned JWST

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

Astigmatic Component
Misalignment Only
Change Dominated by 3rd Order Field-Linear, Field-Asymmetric Astig.

Comatic Component
Coma-Free Pivot

No Figure Error
Real Ray vs. Theory
Field-Linear, Field Asymmetric
3rd Order Astigmatism

Real Ray Based
FRINGE Zernike Coefficient Z5/Z6

Predicted from
Nodal Theory

X Field Angle in Object Space - degrees

Y Field Angle in Object Space - degrees
If There Were No Primary Mirror Figure Error

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”

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

Comatic Component

Astigmatic Component
Figure Error Only,
Dominantly 3rd Order
Field-Binodal Astig.
Conclusions
JWST Performance Limiting Misalignment Aberrations

- It is considered important, and readily accomplished, to report the 3\textsuperscript{rd} 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 3\textsuperscript{rd} order coma
  - field-centered, field-linear, field-asymmetric 3\textsuperscript{rd} order astigmatism
  - field-centered, field-binodal 3\textsuperscript{rd} 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.
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Recent Advances in Simulation

**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

\[ a_{131}^{AD} = H_x^{AD} + a_{131} \]

third order astigmatism

\[ a_{222}^{AD} = H_x^{AD} + a_{222} \]

fifth order coma

\[ a_{151}^{AD} = H_x^{AD} + a_{151} \]

express dependence on
misalignment parameters

\[ a_{131}^{AD} = a_{131} + H_x^{AD} \]

\[ a_{151}^{AD} = a_{151} + H_x^{AD} \]

\[ a_{222}^{AD} = a_{222} + H_x^{AD} \]

\[
\begin{align*}
   a_{222} &= \frac{1}{W_{222}} \left( W_{222,PM}^{(sph)} \sigma_{PM}^{(sph)} + W_{222,PM}^{(asph)} \sigma_{PM}^{(asph)} + W_{222,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{222,SM}^{(asph)} \sigma_{SM}^{(asph)} + W_{222,TM}^{(sph)} \sigma_{TM}^{(sph)} + W_{222,TM}^{(asph)} \sigma_{TM}^{(asph)} \right) \\
   a_{131} &= \frac{1}{W_{131}} \left( W_{131,PM}^{(sph)} \sigma_{PM}^{(sph)} + W_{131,PM}^{(asph)} \sigma_{PM}^{(asph)} - W_{131,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{131,SM}^{(asph)} \sigma_{SM}^{(asph)} + W_{131,TM}^{(sph)} \sigma_{TM}^{(sph)} + W_{131,TM}^{(asph)} \sigma_{TM}^{(asph)} \right) \\
   a_{151} &= \frac{1}{W_{151}} \left( W_{151,PM}^{(sph)} \sigma_{PM}^{(sph)} + W_{151,PM}^{(asph)} \sigma_{PM}^{(asph)} + W_{151,SM}^{(sph)} \sigma_{SM}^{(sph)} + W_{151,SM}^{(asph)} \sigma_{SM}^{(asph)} + W_{151,TM}^{(sph)} \sigma_{TM}^{(sph)} + W_{151,TM}^{(asph)} \sigma_{TM}^{(asph)} \right) 
\end{align*}
\]

Paper to be presented at
SPIE Astronomy
later this month

07 June 2010
The First Evidence of MultiNodal Aberrations
Through Focus Star Plates ‘77

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

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

\[
(FIGERR) B_{222} = 2 \left( (FIGERR) C_{5,6} \right) \exp \left[ j 2 \left( (FIGERR) \xi_{5,6} \right) \right]
\]

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

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

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

Mild Offset Subaperture Coma

Centered Subaperture Nearly Null

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