# IDRM integrated modeling & relevance to AFTA-WFIRST

- Outline
  - Requirements review
  - Interim Design Ref. mission imager mode
  - Intro to Structural/Thermal/Optical performance (STOP) analysis
  - IDRM STOP model
  - Results with thermal control
  - Sensitivity exploration of thermal control quality
  - Conclusion
  - Backup slides

# Requirements review

- IDRM report (6/2011) had a preliminary requirements flowdown; also in DRM final report
- It was clear that the wavefront stability driver is the measurement of gravitational weak lensing (WL) through the high latitude imaging survey (HLS)
- Requirement was an <u>ellipticity stability ~5E-4 from one integration (150sec) to the next</u>
  - Details of this metric worked with C. Hirata
- Process amounts to simulating wavefront errors due to <u>thermoelastic effects from a worst-case large slew</u>

# IDRM refresher

- IDRM had a imaging channel and 2 (fixed) spectroscopy channels; stability analysis on imaging channel (ImC) only
- Note – IDRM1 ImC is VERY like DRM1 ImC; changes are in spectroscopy approach
- Materials used in IDRM, DRM1 are same as the NRO telescope [ULE fused silica mirrors; Invar mounts, composite structure];
- We must repeat this analysis as we can for the AFTA WFIRST point design , but may not be possible by 4/2013

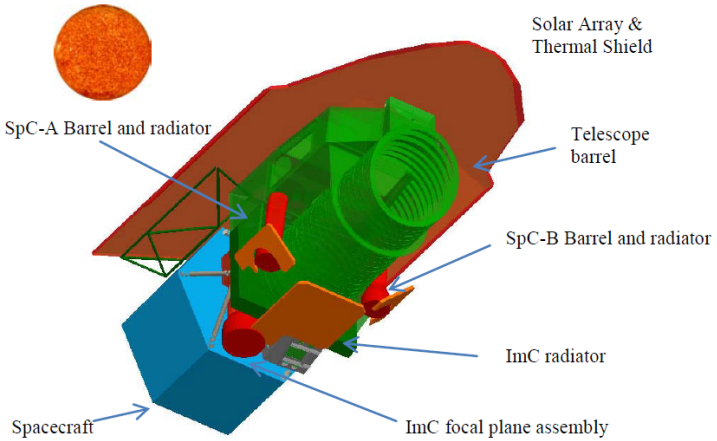
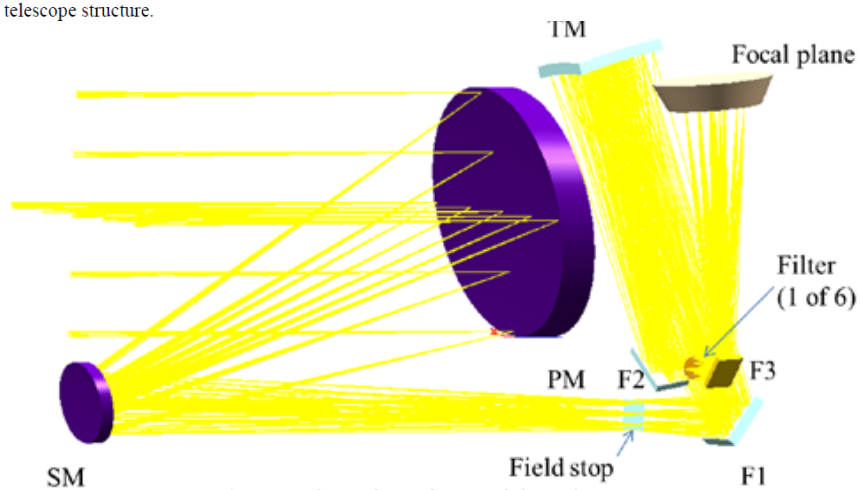



Figure 3. Observatory CAD view, looking from the anti-Sun side. Focal planes and radiators are placed facing anti-Sun and the Solar Array structure/thermal shroud shadows the payload to allow passive cooling. Each instrument channel mounts separately to the telescope structure.




Ray trace of IDRM imaging channel (ImC)

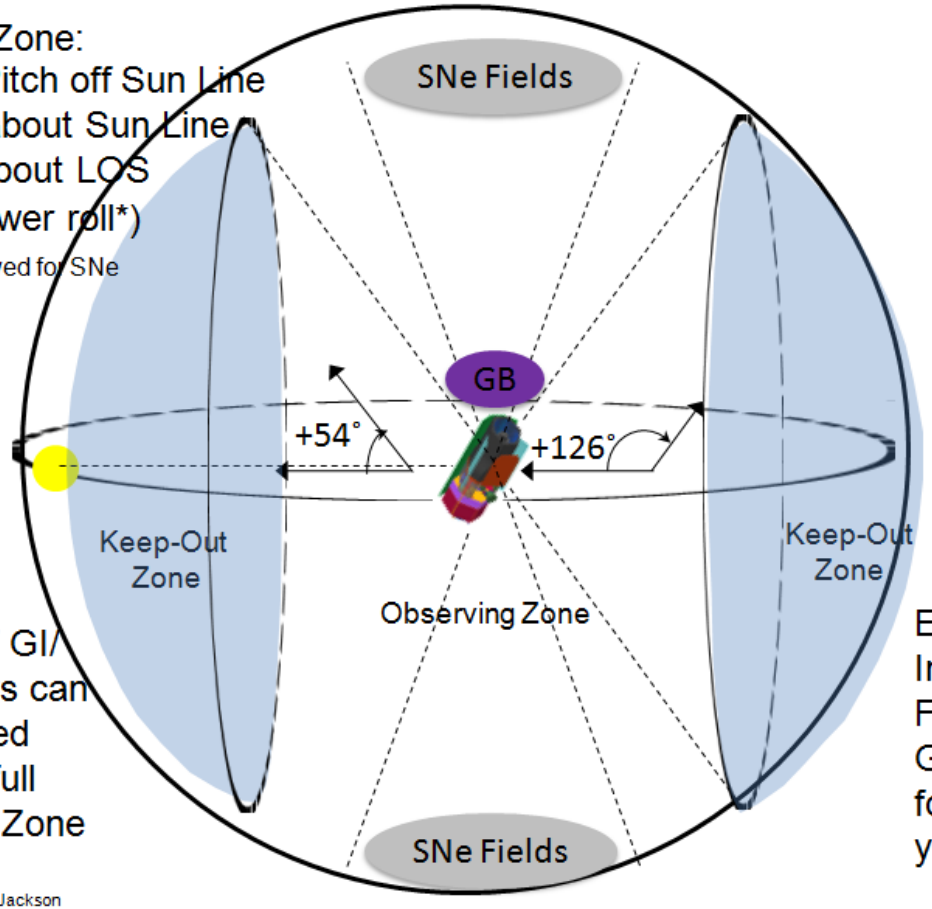
Ref: Content, D, et al SPIE 8146 (2011); Goullioud, R. et al SPIE 8442 (2012)

# WFIRST's Central Line of Sight (LOS) Field of Regard (FOR)

## Worst case thermal transient, from 0 pitch (90° to sun), 0 roll to 20 pitch, 22.5 roll

Observing Zone:
54°-126° Pitch off Sun Line
360° Yaw about Sun Line
±10° roll about LOS
(off max power roll*)

* Larger roll allowed for SNe




SNe Inertially Fixed Fields must be within 20° of one of the Ecliptic Poles, and can be rotated every ~90 days

WL/ GRS / GI/ GP Surveys can be optimized within the full Observing Zone

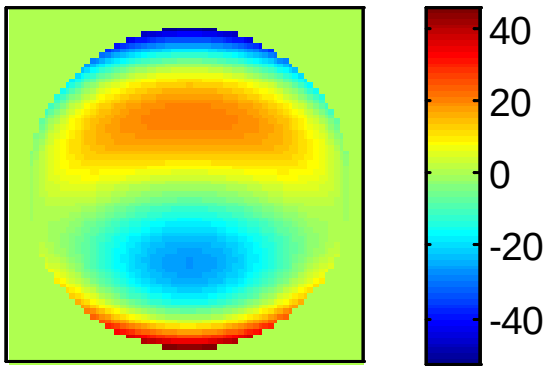
ExP can observe Inertially Fixed Fields in the Galactic Bulge (GB) for 72 days twice a year

4

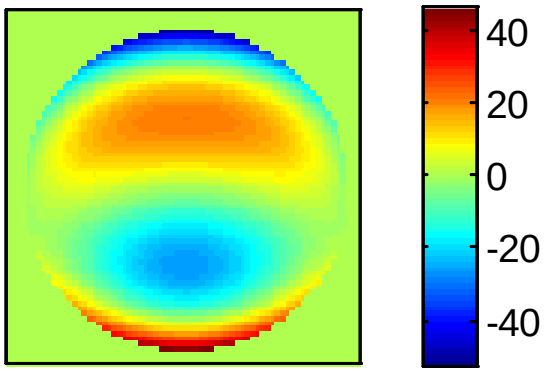
ConOps & animation credit C. Jackson

# Case B OPD Maps (Delta-Distortion)

State0 [nm] PV=98.19 RMS=14.87

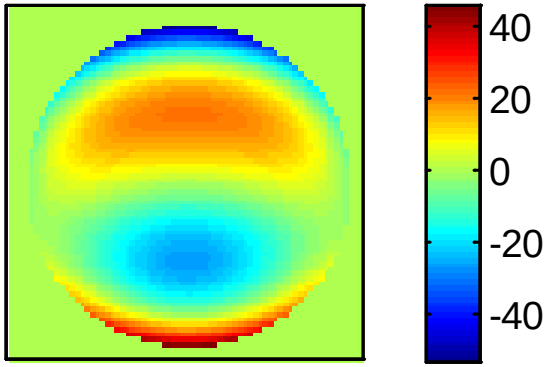



State1[nm] PV=98.46 RMS=14.92

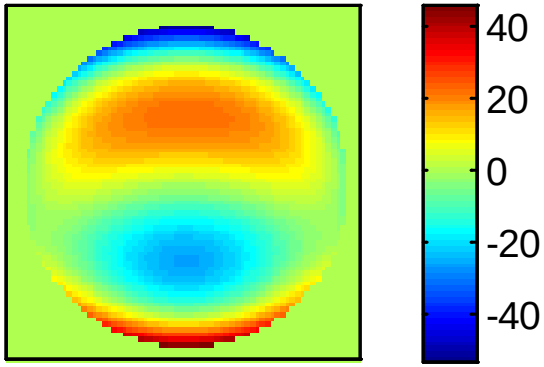



Units are nanometers

State2[nm] PV=98.74 RMS=14.97

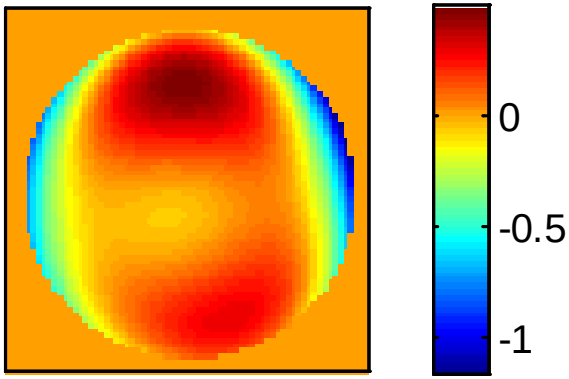



State3[nm] PV=99.02 RMS=15.04



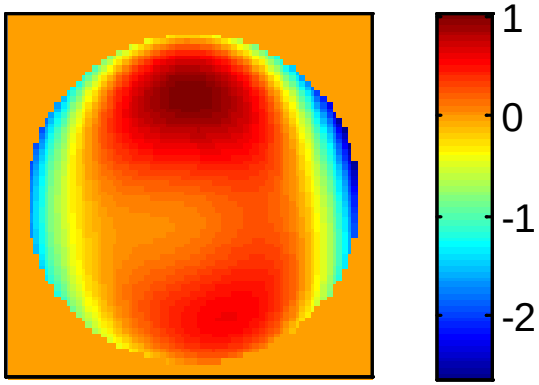
# Case B Delta-OPD Maps (Delta-Distortion)

State1-State0[nm] PV=1.64 RMS=0.28

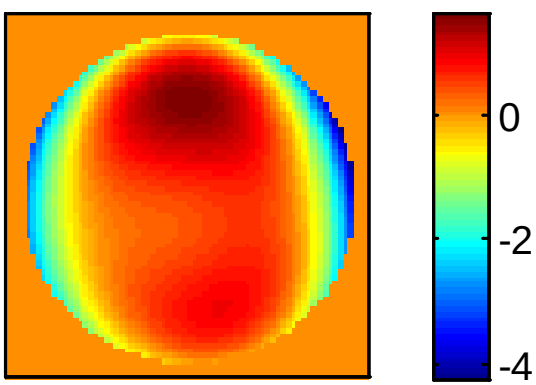



Units are nanometers

State2-State0[nm] PV=3.65 RMS=0.64




State3-State0[nm] PV=5.82 RMS=1.05

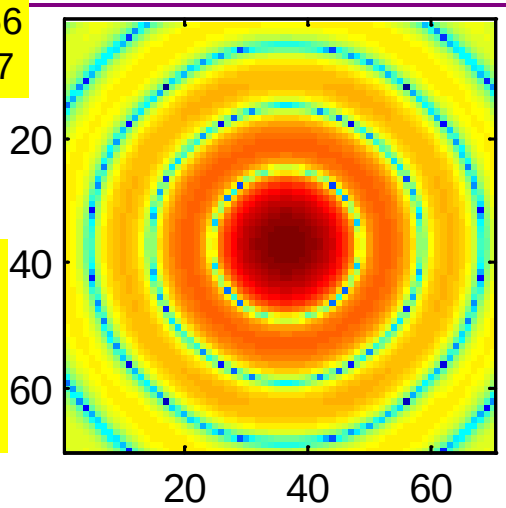


# Case B PSFs (Delta-Distortion, Delta-OPD)

log of PSF of OPD maps from previous slide,
e.g. PSF(OPD(case1)-OPD(case0))
Tip/tilt removed

State1-State0 PSF

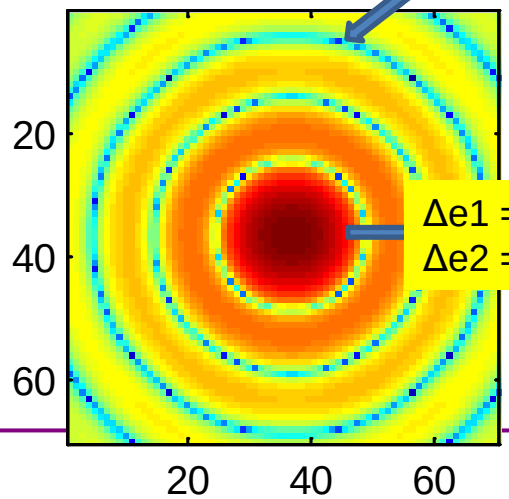
e1 = -0.0093666
e2 = -5.1617e-7




Δe1 = 7.9831e-6
Δe2 = -2.0883e-6

State2-State0 PSF

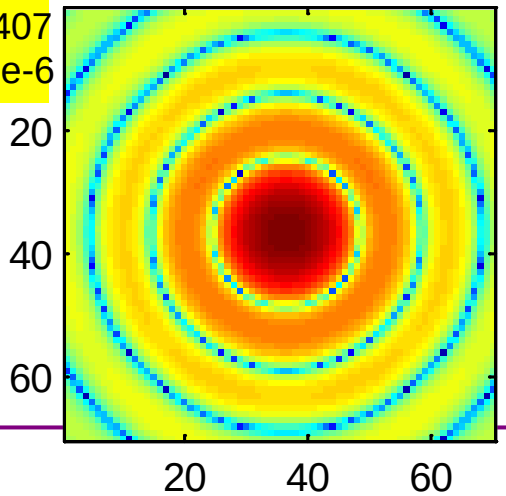
e1 = -0.0093586
e2 = -2.6045e-6




Δe1 = 1.7903e-5
Δe2 = -4.2217e-6

State3-State0 PSF

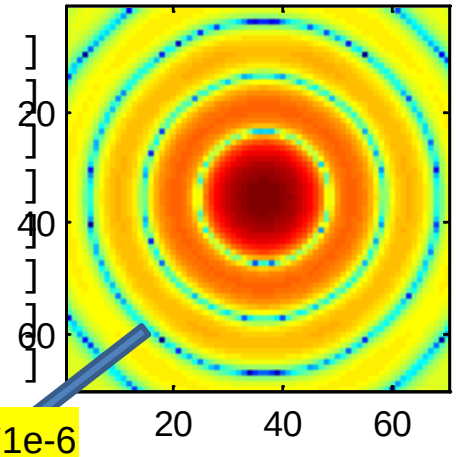
e1 = -0.0093407
e2 = -6.8262e-6



# Case B Average PSFs

| | 0-150 | 150-300 | 300-450 |
|---|---|---|---|
| xc: | 0.028691 | 0.028372 | 0.028363 |
| yc: | -0.014313 | -0.014141 | -0.014284 |
| e1: | -0.007247 | -0.0072397 | -0.0072284 |
| e2: | 4.3182e-6 | -2.1221e-6 | -5.484e-006 |
| Mxx: | 5.5439e-5 | 5.544e-5 | 5.5441e-005 |
| Myy: | 5.6249e-5 | 5.6248e-5 | 5.6248e-005 |
| Mxy: | 2.4115e-10 | -1.1851e-10 | -3.0625e-010 |
| resnorm: | 1.8926e-5 | 1.8927e-5 | 1.8927e-005 |

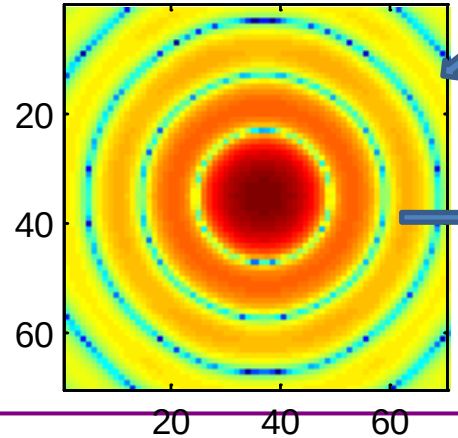
STOP avg PSF 0-150 sec




Δe1 = 7.6171e-6
Δe2 = -6.4403e-6

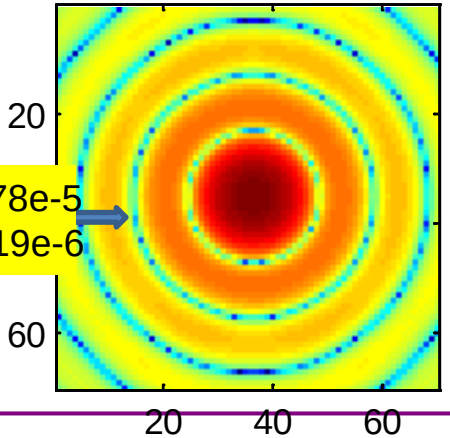
This calc is the PSF for an image (avg over 150 seconds), and includes tip/tilt. OPD(t=0) is subtracted from the OPD at each subinterval. Static tip/tilt is removed by rigid-body rotation of the telescope (with a BW of 0.02 Hz).

STOP avg PSF 150-300 sec




Δe1 = 1.1278e-5
Δe2 = -3.3619e-6

STOP avg PSF 300-450 sec

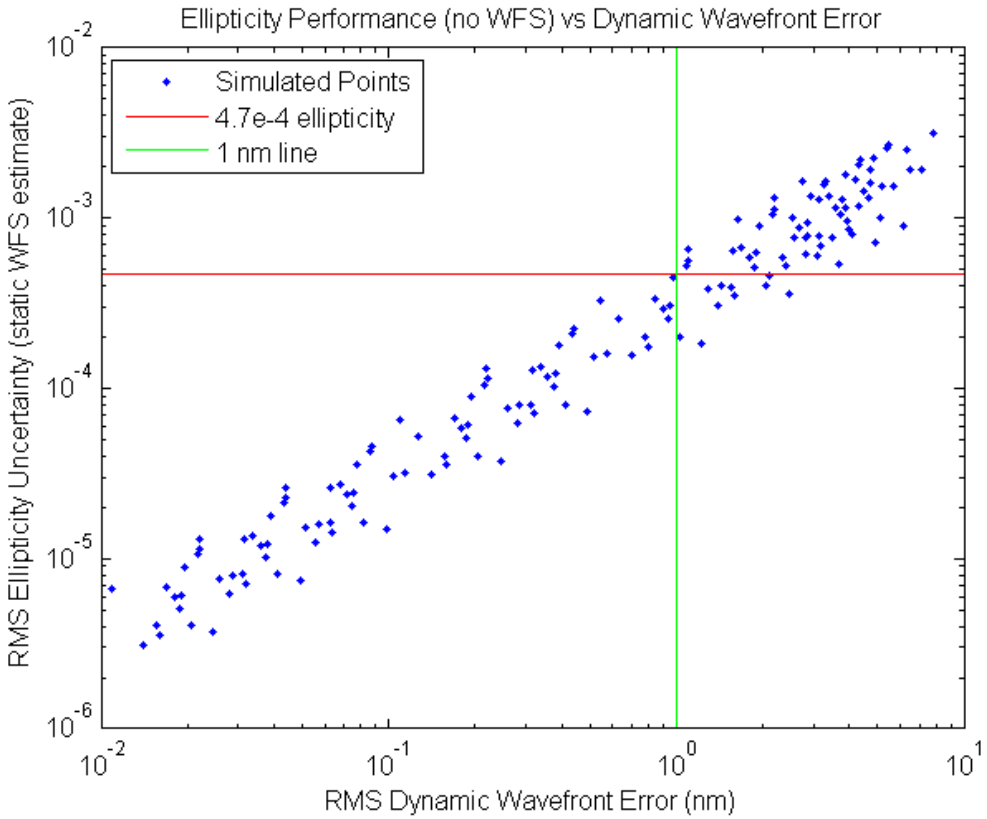


# What wavefront error does stability requirement allow?

1nm rms stability
[~70nm overall static error level]

So if wavefront error per unit thermal stability is 0.06nm/0.02K =3nm/K, IDRM needs to be thermally controlled to **0.33K**

ITT built thermal control for Chandra, controlled to ±0.1K






Ref: S. Jurling, D. A. Content, "Wavefront sensing for WFIRST with a linear optical model." *Proc. SPIE*. 8442, 844210 (2012).

# Conclusion

- 1nm derived wavefront stability met even during 1st integration time after worst-case slew
  - Quick look at thermal sensitivity (in backup) suggests 0.3K control would be adequate for this requirement
    - 0.020 K stability error produce 0.06nm rms; sensitivity coefficient 3 nm/K
    - For 1 nm stability, ~0.3K stability requirement
    - Chandra holds 0.1K, example of space telescope holding required stability

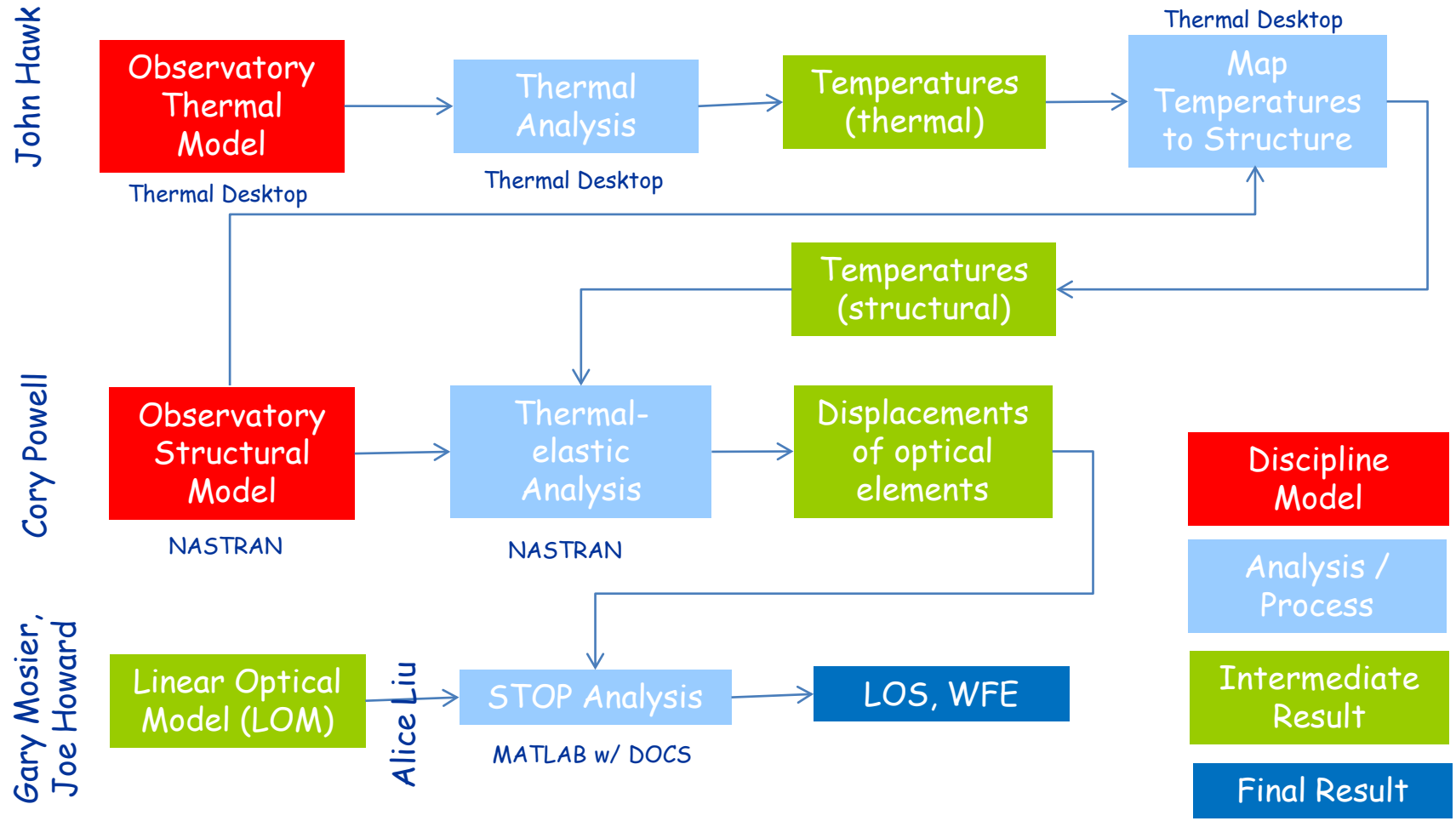
- IDRM integrated modeling team:
- GSFC: N. Armani, C. Blaurock, D. Content, J. M. Howard, J. Hawk, A. Liu, G. Mosier, C. Powell
- JPL: Z. Chang, R. Goullioud, G. Kuan, J. Moore, E. Sunada, J. Villalvazo

# Backup slides

# Basics of IM

- Inputs:
  - inter-consistent model set: mechanical design (CAD), mechanical analysis (NASTRAN), optical (Zemax), thermal (thermal desktop)
    - Observatory models built at GSFC using GSFC instruments & spacecraft with JPL telescope design
  - We are using a linearized model for stability analysis, uses a linear optical model
    - Sensitivity matrix – how does system respond to perturbations
      - For this case, perturbations include both rigid body motions of optics and low order mirror shape (Zernike) deformation terms
  - Control laws (e.g. thermal, pointing)
  - Disturbances (mainly reaction wheel noise and pointing changes)
- Outputs:
  - [not included here] Pointing stability (line of sight variation)
  - Wavefront error (averaged over field or at a particular point in the field)
- Process also needs to produce models that survive launch and can achieve temperature as a preliminary milestone
- More details on STOP are in backup charts

# Thermal Distortion Analysis Process

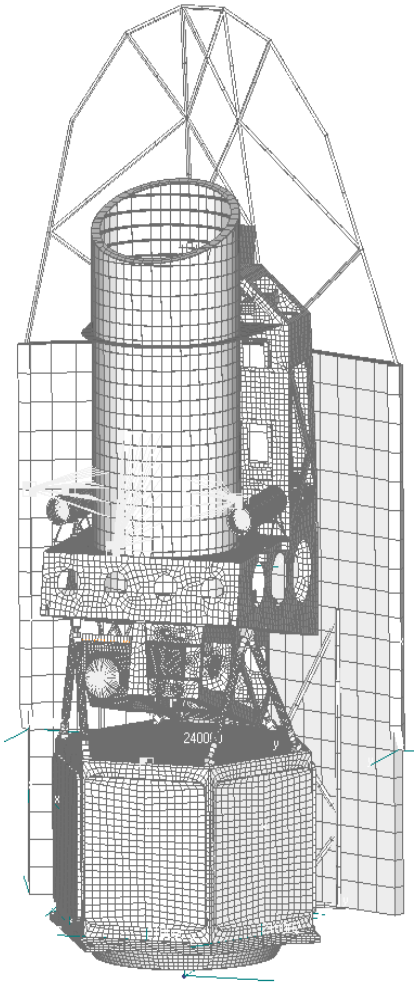


# Summary of IDRM integrated modeling results

- We meet pointing requirements up to a fairly high wheel speed of 56 rev/sec
- We meet wavefront error due to pointing to even higher speeds
- The wavefront requirements to meet WL stability are tighter than we had guessed (~1 nm v 5 nm rms)
- However we can meet this with fairly standard thermal control, at 220K (0.3K)
  - 1) meet the 1nm with active thermal control [no control errors]
  - 2) also meet with simulated inaccurate control at 0.3K level

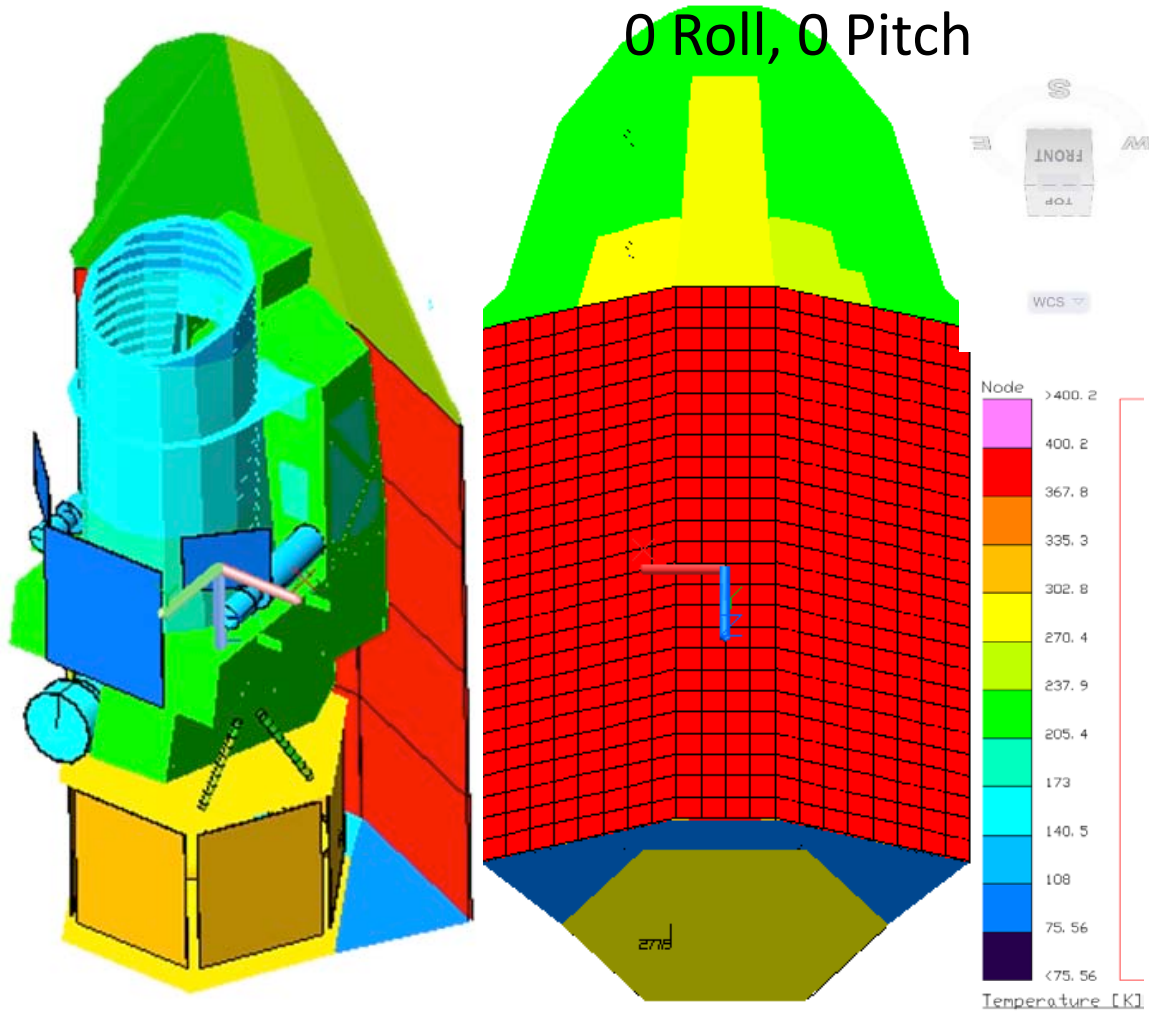
# Structural FEM –Cory Powell & Zensheu Chang

- Finite element model
  - representative materials properties
  - Telescope, then observatory level modeling
  - Stiffnesses
  - Initial use to meet launch frequency requirements
    - Done using point mass to simulate instrument
  - Refined to add instrument optics and load path
    - Enough detail to model thermoelastic deformation and rigid body motion of all optical elements
  - This 'dynamic' model used for jitter and STOP analysis
  - the model now consists of 140,606 nodes (roughly 840,000 degrees of freedom) and 246, 312 elements



# Thermal Model Description – J. Hawk, E. Sunada, J. Villalvazo

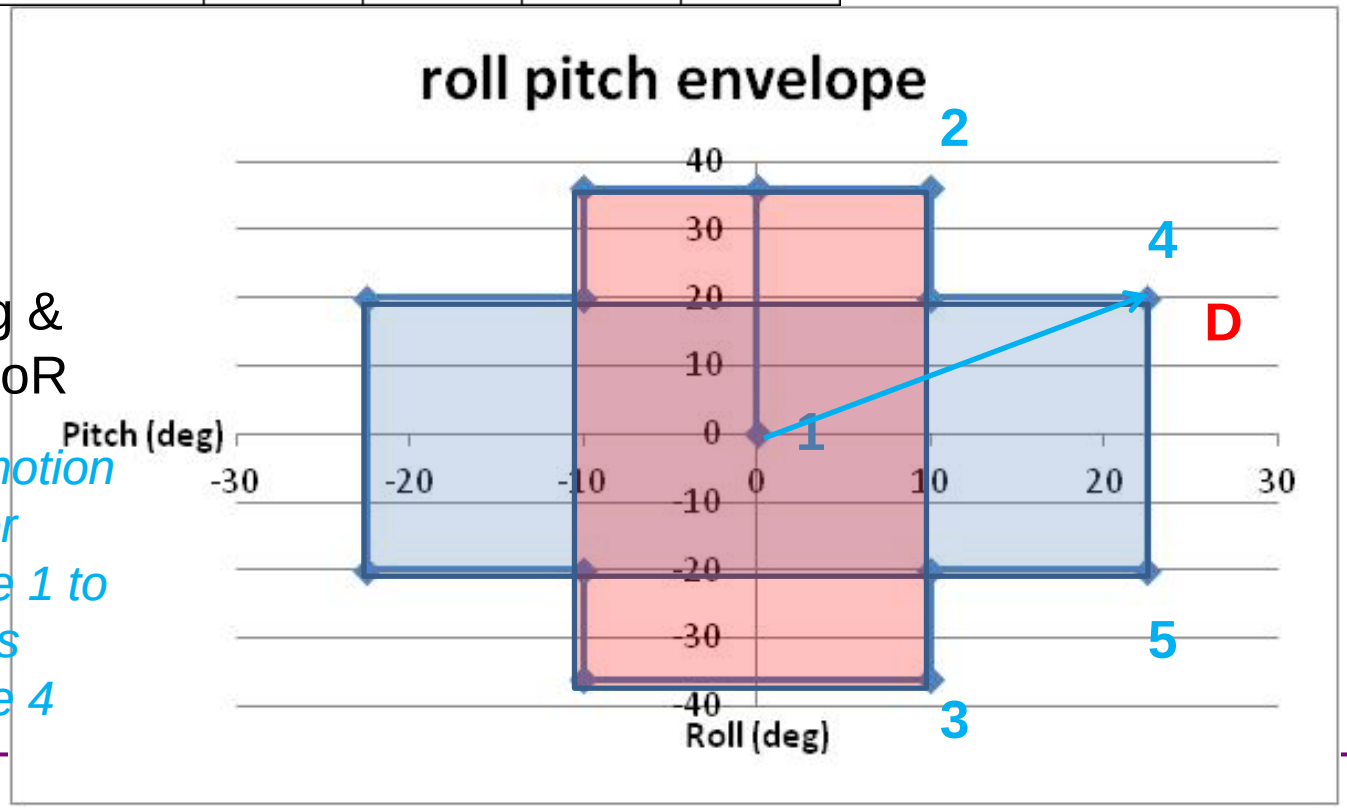
- Thermal model includes descriptions of geometry and details of conductive and radiative couplings within the observatory, and to the external environment (e.g. solar loading at SE L2, 3K background)
- Thermal equilibrium temperatures for IDRM shown



# transient cases – case D is the case with maximum change in required heater power (worst case thermal stability)

| transient cases | | | | | |
|---|---|---|---|---|---|
| label | description | start roll | start pitch | end roll | end pitch |
| A | extreme UL slew | -10 | -36 | 10 | 36 |
| B | extreme SN slew | -22.5 | -20 | 22.5 | 20 |
| C | extreme SN to Survey | -22.5 | -20 | 10 | 36 |
| D | center to SN +corner | 0 | 0 | 22.5 | 20 |

| Roll | Pitch | Heater Power(W) |
|---|---|---|
| 0 | 0 | 217.3 |
| 22.5 | 20 | 199.8 |




SN FoR

uLensing & survey FoR

*Note: this is a motion from attitude for equilibrium case 1 to same attitude as equilibrium case 4*

# Transient Analysis Approach

- In order to analyze the transient cases statically, the case was broken up as follows:
  - State 0: Room temperature to Steady State (SS) temperature prior to slew.
  - State 1: Room temperature to 150 seconds after slew is completed temperature profile.
  - State 2: Room temperature to 300 seconds after slew is completed temperature profile.
  - State 3: Room temperature to 450 seconds after slew is completed temperature profile.
- To analyze the stability between states, the following operations are performed:
  - SS to first 150 sec stability = State 1 – State 0
  - 150 sec to 300 sec stability = State 2 – State 1
  - 300 sec to 450 sec stability = State 3 – State 2

# Optical model and linear optical model

- Zemax optical design
  - Off axis PM,SM, TM; 3 fold flats; filter (flat fused silica) wheel
    - Very nearly achromatic image quality, by design
  - Mirror are conic sections
- Linear optical model
  - Numerical differentiation of wavefront at each of 25 field points with respect to rigid body and Zernike (15 term) deformation errors of each optic
    - More discussion in backup charts
  - Sensitivity matrix; Matlab used
  - Also used for line of sight (LOS) errors

# Outputs From Structural FEM to Optical Analyst

- The structural model predicts surface deflection, rigid body motion of the optics
- These files are read into matlab
- Matlab calculates wavefront by multiplying LOM sensitivity matrix by rigid body + Zernike perturbation vector

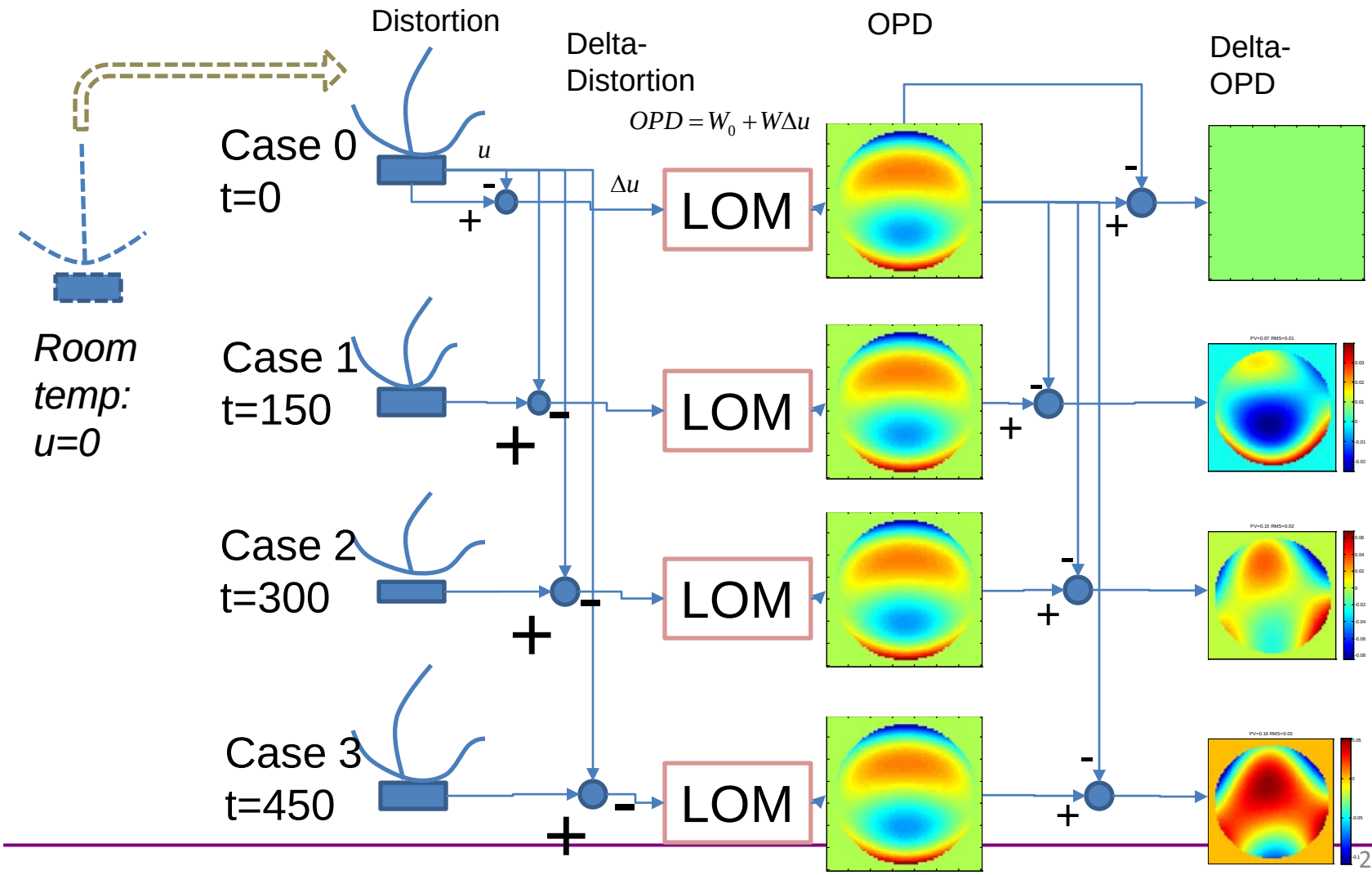
# Analysis Assumptions (Case D)

- Case B: From 0 roll/pitch to +22.5 roll/ +20 pitch
- Treat State 0 as a reference
  - Time 0: u = u_State0 – u_State0 = 0
  - Time 150: u = u_State1 – u_State0
  - Time 300: u = u_State2 – u_State0
  - Time 450: u = u_State3 – u_State0
- Treat static OPD as a reference
  - Subtract OPD(t=0) from OPDs for t=150,300,450

u=mechanical displacement, rigid-body optics motion plus figure

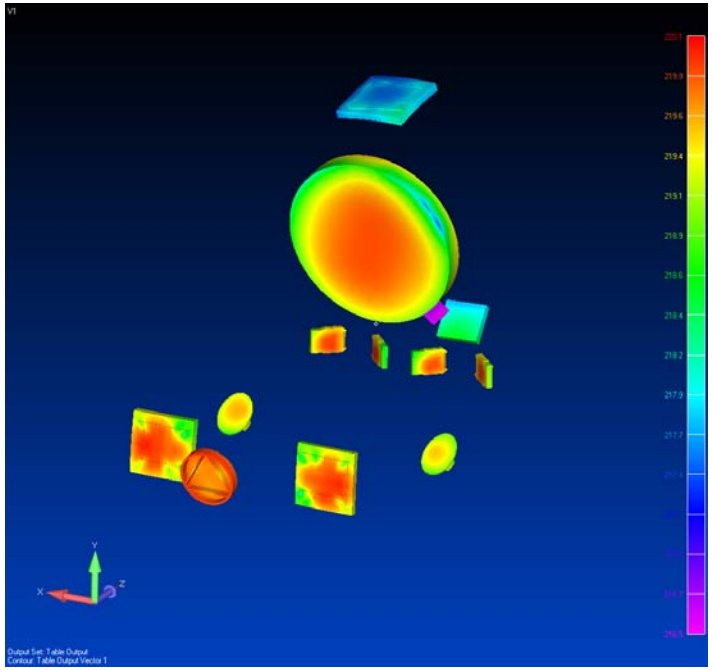
State0: wfirst-C2B-STOP-CaseD-State0-V1.pch
State1: wfirst-C2B-STOP-CaseD-State1-V1.pch
State2: wfirst-C2B-STOP-CaseD-State2-V1.pch
State3: wfirst-C2B-STOP-CaseD-State3-V1.pch

# Delta-Distortion / Delta-WFE



# Thermal Mapping

- Thermal analysis and mapping was performed by John Hawk with Thermal Desktop.
- Thermal Desktop relies on linear interpolation to map temperatures of the grids in the thermal model to the nodes in the structural model. It does so on a sliding scale; e.g. first it looks for all coincident grids and nodes and maps them, then it goes to nodes within a mm of the grid, then 2, then 5, etc. etc. This limits potential bleed-over between structures of contrasting temperatures.
- Large temperature differences exist between the structures: SASS 373K, Bus 313K, Telescope 220K, Imager 175K. In order to prevent any bleed-over between these structures, the model was broken up into 6 groups for mapping: SASS, Bus, Imager and Spectrometers, Telescope Strongback and Rear Enclosure, Telescope Baffle, and the Optics.
- With the models broken up into these groups, a full map can be completed with no bleed-over, eliminating the need for the structural engineer to complete the map through the NASTRAN thermal analyzer.
- Maps were verified by John Hawk to be accurate.



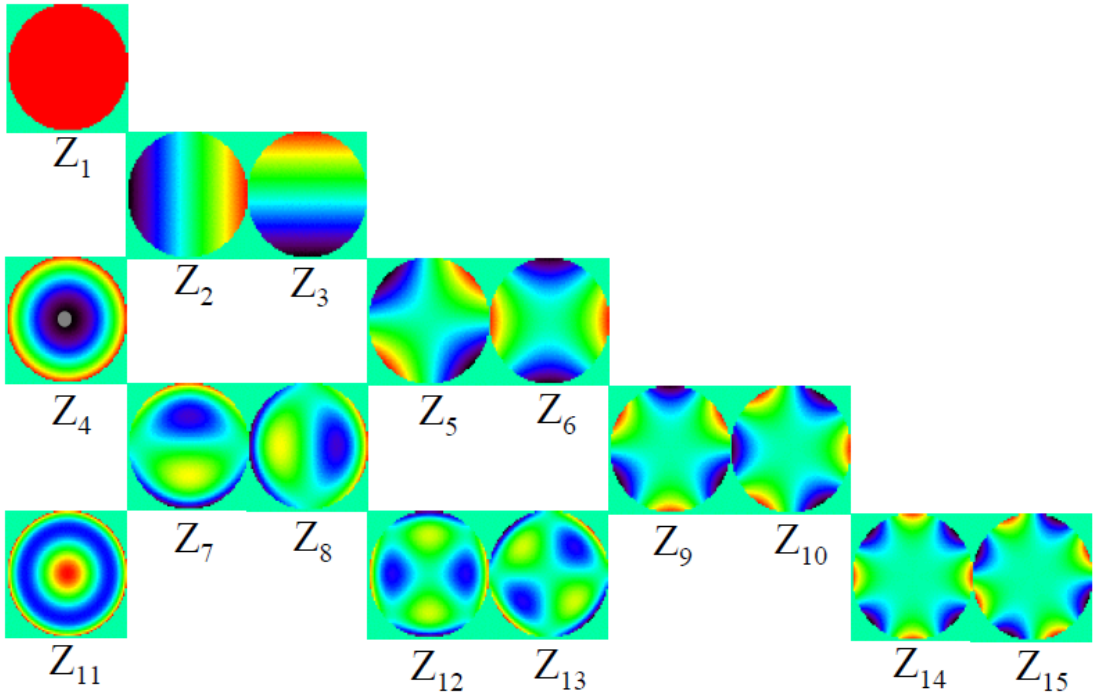
**Example of thermal mapping on the Optics group.**

Ref: J. M. Howard SPIE 2003; note however that IDRM LOM includes 15 Zernike deformation terms on each optic, new feature

## Linear Optical Model (LOM)

- Provides a readily available tool to generate relatively accurate RMS wavefront errors for *residual*, *transient*, and *image motion* integrated modeling analyses
- Runs in Matlab, so interaction with optical design software is not necessary … no ray tracing is required after initial setup
- Easy to use, so non-optical engineers (i.e. mechanical structures folks) can generate first-order results of their perturbation analyses, e.g jitter and thermal distortions, without constantly bothering an overworked, underpaid, optical analyst (other than the occasional spot check)

# Zernike terms: form orthonormal basis set for deformations on a unit circle




Noll, RJ. Zernike polynomials and atmospheric turbulence. J Opt Soc Am 66; 207-211 (1976).

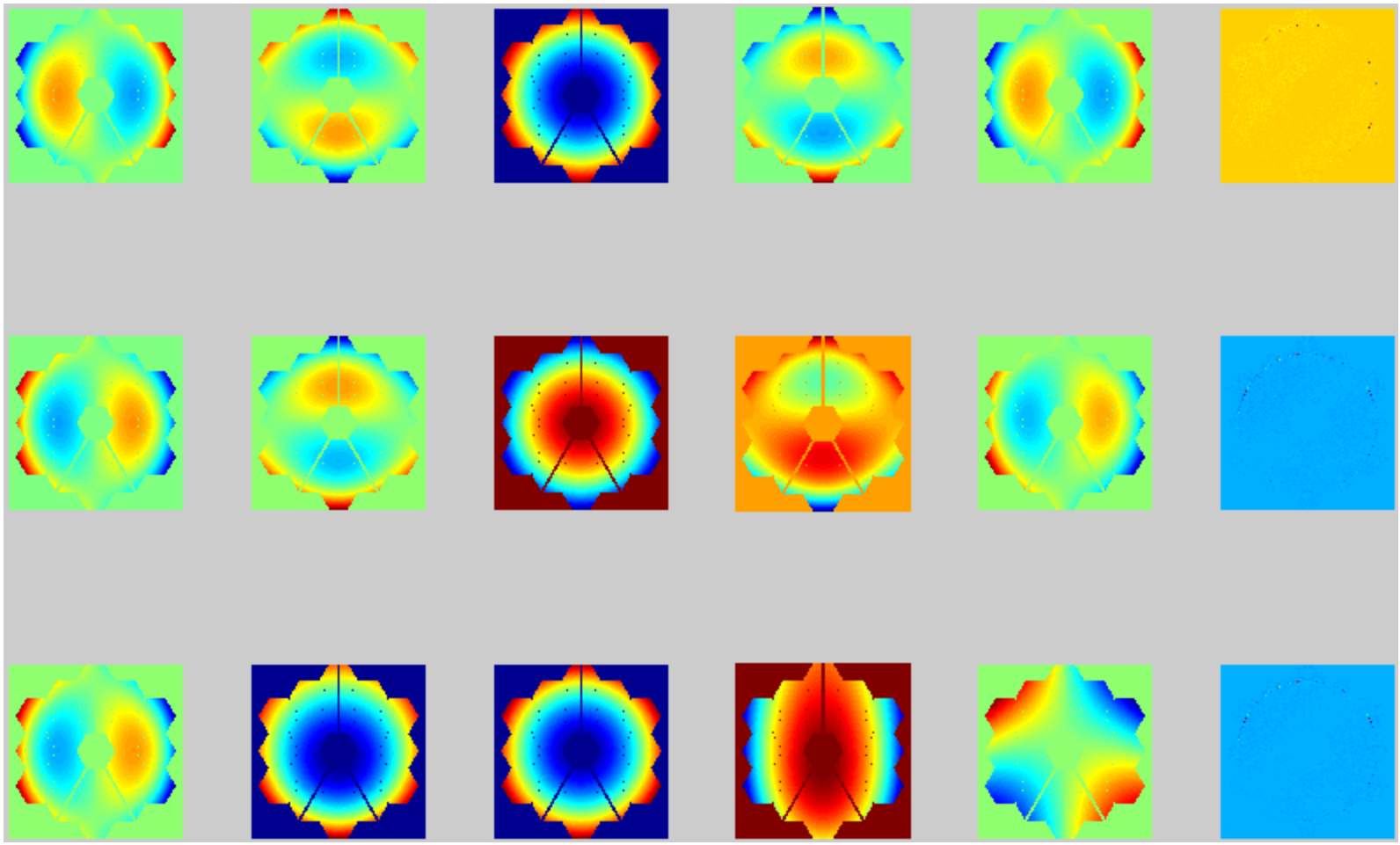
# Example of LOM {rigid body, JWST OTE}

X Y Z rot X rot Y rot Z

PM

SM

TM



# Method for creating a Linear Optical Model

1. Using raytracing software, generate an exit pupil OPD wavefront map with no perturbations, i.e. the “design residual” error. Note that all wavefronts have **no** adjustments to remove tilt or focus, and units are in microns. The reference ray (i.e. chief ray) and reference sphere should remain stationary for all perturbation calculations, to properly account for jitter affects on the wavefront.
2. Start with first node, decenter in X by $\Delta x$, generate exit pupil wavefront map, reset segment to nominal position.
3. Repeat step 2 by decentering in Y, then Z.
4. Repeats step 2 and 3 but apply $\Delta$ tilts about X, Y, and Z axes at the node.
5. Repeat steps 2-4 (i.e. 6 DOF perturbations) for each primary mirror segment, then the secondary mirror, tertiary, FSM, and Image surface for telescope.
6. Subtract “design residual” error from all perturbed OPD wavefront maps.

# Method for using a Linear Optical Model

1. Determine the 6 DOF motions $d_j$ for each optical node $i$. Motions can be due to thermal gradients on structure, CTE variations, reaction wheel vibrations, segment misalignments, etc.
2. Multiply motions $d_{ij}$ by each applicable matrix.
3. Sum all matrices to create an OPD map at the exit pupil.

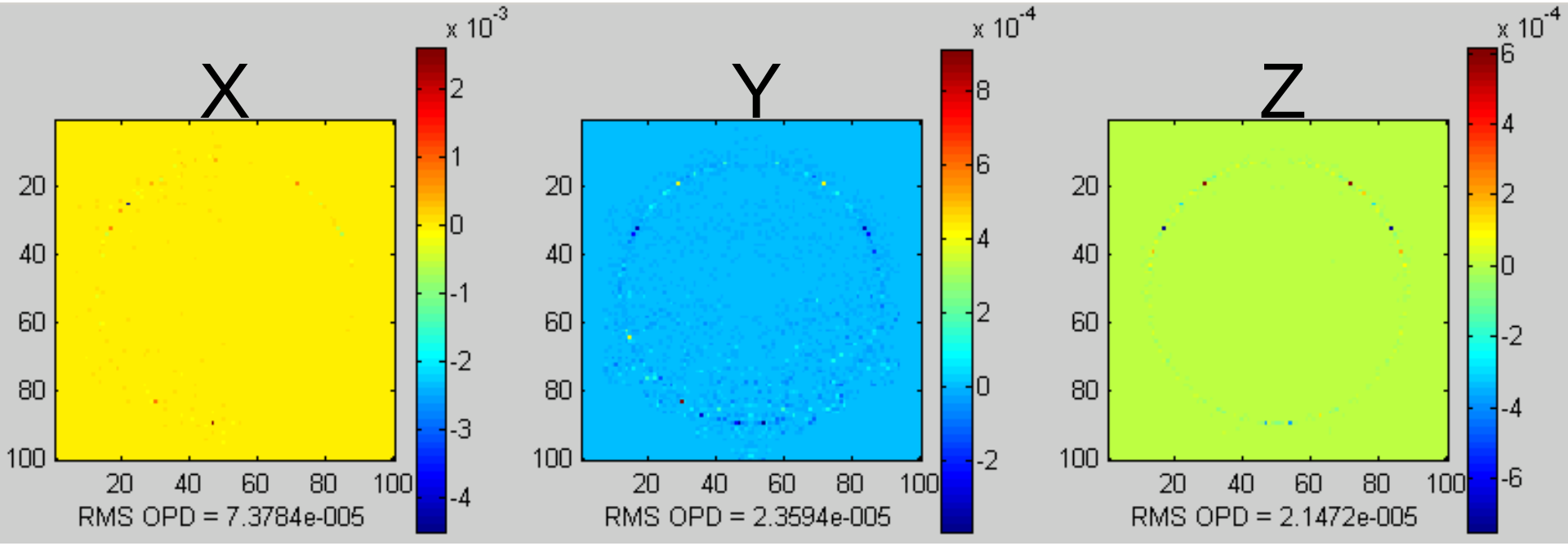
$$OPD = \sum_i \frac{\partial W}{\partial u_j} d_{ij}$$

$i$ = node, $j$ = DOF

4. Determine RMS wavefront error from OPD. Remove tilt as applicable. Note: Image motion centroids must be calculated on a segment basis across the aperture, a global tilt cannot be used.

# **Linear Optical Model Global Check**:

Decenter all nodes together by the same amount, and and generate OPD map by summing the matrices. The result should be zero.



## Linear Model Accuracy Test (for Primary Mirror)

1. Randomly perturb all 6 DOF for each segment, 99 runs with increasing STD DEV of variations. Range = 10 nm/nr to 1000.0 nm/nr
2. Generate exit pupil wavefront opd's using raytrace software, subtract "design residual"
3. Generate exit pupil wavefront using Linear Model
4. Compare the exit pupil wavefronts

# LOM or direct integrated modeling?

- Linear optical model:
  - Pro: fast, quick to use
  - Con: limited to perturbations, small changes
  - Con: limited to low order deformation terms and rigid body
- Direct modelling
  - Pro: not limited to perturbations
  - Pro: not limited to low order shape perturbations
- For (e.g.) cooldown effects over wide temperature range, mount, 1g distortions, probably should use direct modeling
- For stability, use LOM

# Comments on thermal control

- Simulated transient above does not include any thermal sensing or control errors
  - In this area it may be optimistic
  - Exploring how to add realistic (worst case) errors to add realism
- JPL telescope team did a sensitivity analysis, below

# Summary of Heater Sensitivity Analysis

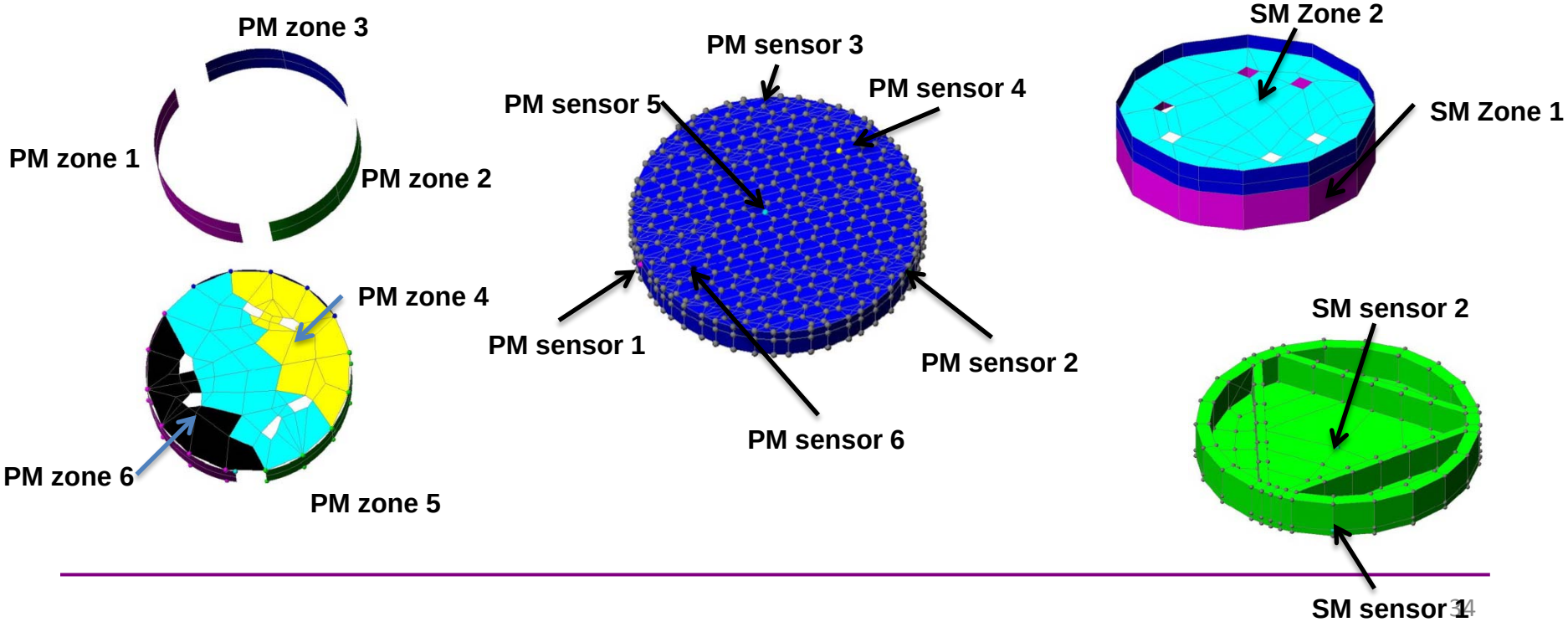
- Performed heater set-point sensitivity analysis on primary and secondary mirrors for the nominal orientation.
- Assumed one heater control zone set-point controlling at 20mK less than the other zones.
- Two cases were analyzed:
  - Case 1:PM heater zone 5 & SM zone 2 set-point at 20mK less than the other zones
  - Case 2:PM heater zone 3 & SM zone 1 set-point at 20mK less than the other zones

# Primary and Secondary Mirror Heaters

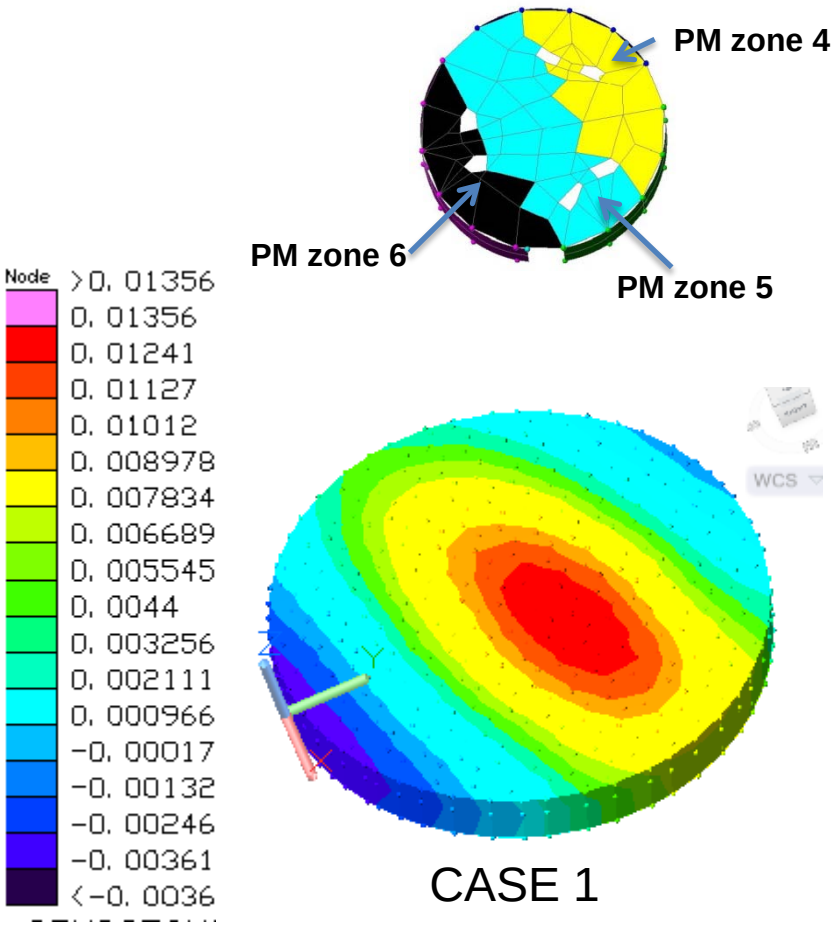
- Analyses uses Proportional heaters (On temp 219K, off temp 220K) temperature is controlled to midpoint with operation logic

**Primary mirror**
**six thermostatic heater control zones with sensor points on mirror**

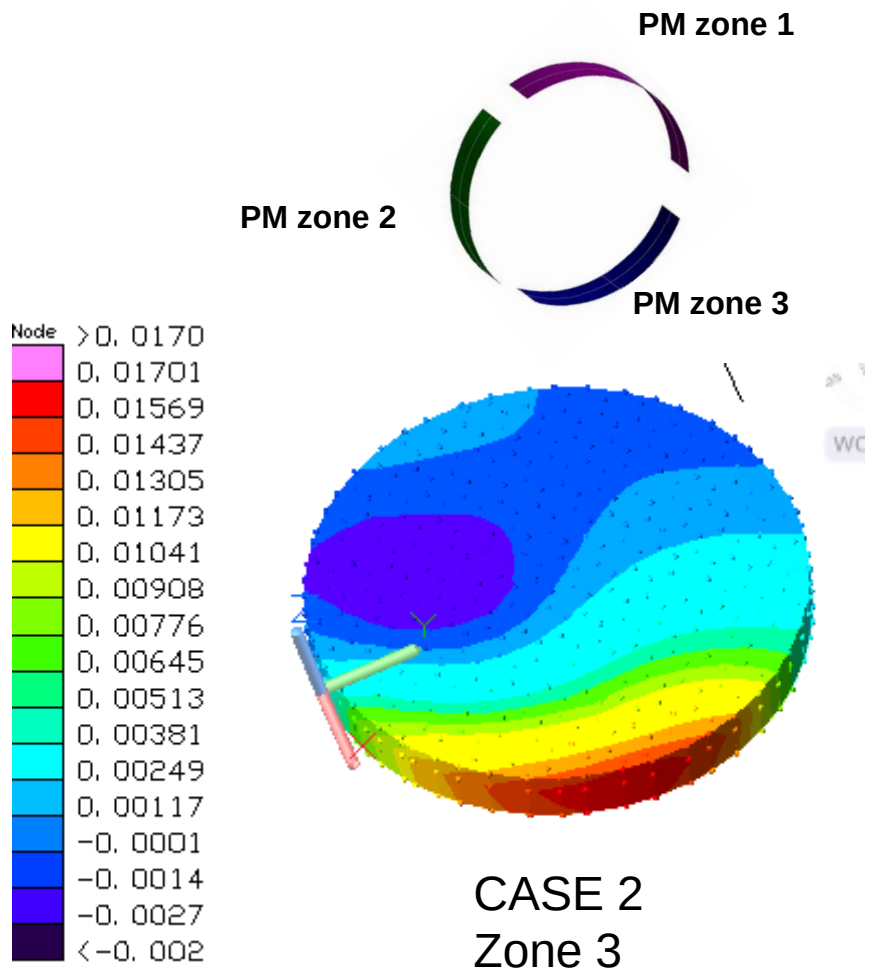
**Secondary mirror**
**two thermostatic heater control zones with sensor points on mirror**



# Primary Mirror Temperature Change ΔT(T_reference-T_sensitivity)



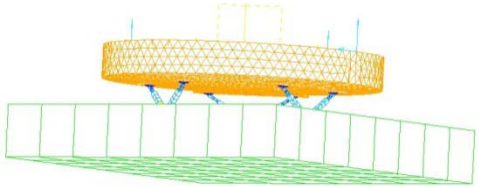

CASE 1
Zone 5

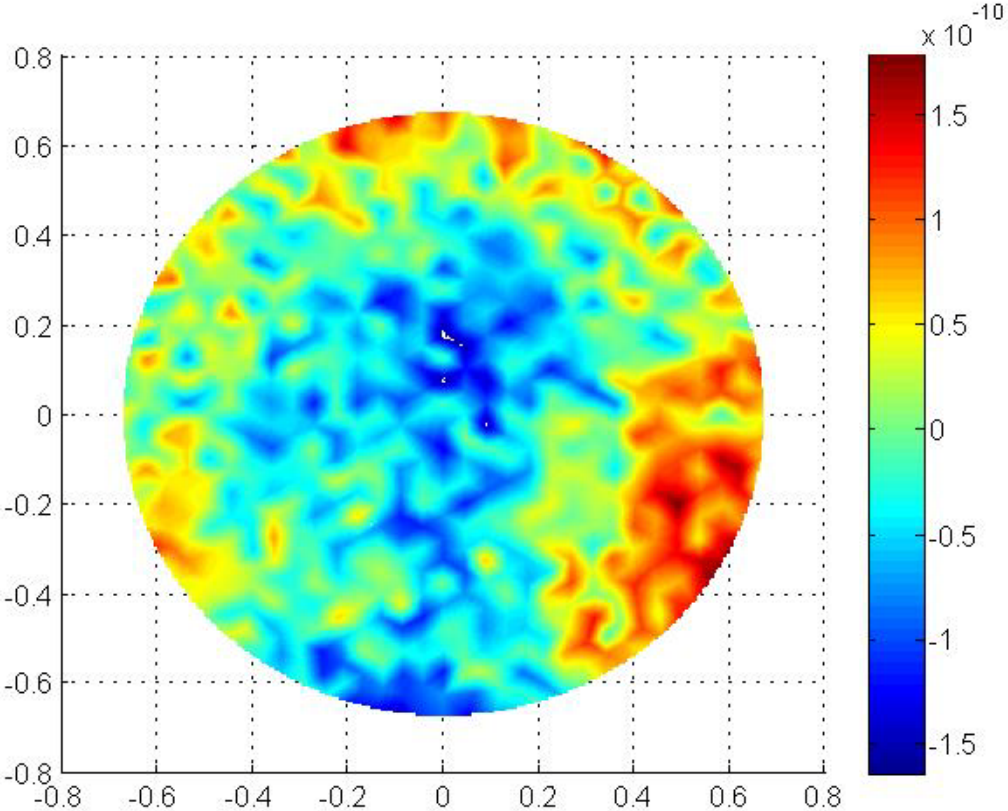



CASE 2
Zone 3

# Primary Mirror – Standalone Model With M55J Box

- Standalone Model
- M55J Box
- Difference between 2 flight thermal cases
- Invar pads
- Adhesive CTE = 110 ppm/$^0$K
- Titanium bipods






RMS = 0.061771 nm P2P = 0.34304 nm

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  http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST_SDT_Final_Report.pdf
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