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Validation of Modeling and Simulation with Cielo using the SIM TOM3 Testbed

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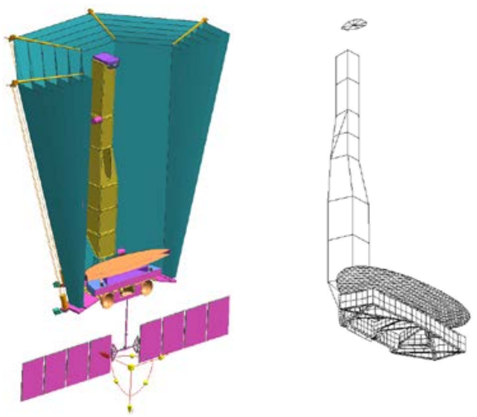
Outline

- Motivation, Physics, Solution Approach
- Scope of the Validation Exercise
- SIM TOM3 Test Bed, Experiment and Computational Models
- Creation of a Single Computational Model in Cielo
- Thermal analysis,
  view factor calculation, steady state and transient analysis
- Thermal deformation analysis,
  direct transition of temperature fields at all time steps as load cases for linear static analyses
- Optical aberration analysis,
  definition of optical element, rigid body filtering, optical aberration calculation from deformations
- Discussion of margins and uncertainties
- Summary

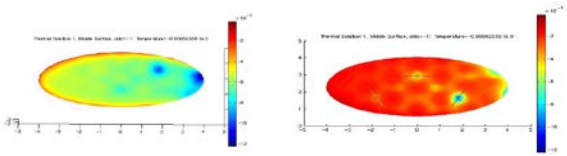
What is Cielo ?

- General-purpose finite element-based computational tool for multi-physics analysis
- Provides integrated thermal, structural and optical aberration capabilities using a common model
- Nastran input file driven
- Matlab hosted
- Running on serial and parallel machines
- Extensible object-based architecture

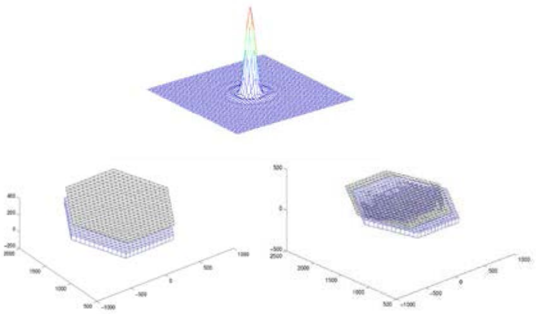
Integrated analysis capability facilitates development of detailed system-level model …



Propagates thermal, structural & dynamic effects down to optical elements and mounts …



And computes aberrations from which optical merit functions & sensitivity matrices can be assessed and optimized…



Thermal and Structural Physics

- Equations of Thermal Equilibrium: (*u(t) = temp*)

$$[B]\{\dot{u}(t)\}+[K]\{u(t)\}+[R]\{u(t)^4\}=\{P(t)\}+\{N(t)\}$$

Capacitance (Sparse)	Conductance (Sparse)	Radiation (Dense, unsymmetric)	Loads (Multiple subcases, Sparse or dense)

  - Time integration via generalized trapezoidal methods (Crank-Nicolson, etc.)
  - Nonlinear iteration via Newton-Raphson method

- Equations of Structural Dynamic Equilibrium: *(u(t) = disp)*

$$[M]\{\ddot{u}(t)\}+f\left(u(t),\dot{u}(t)\right)=\{P(t)\}$$

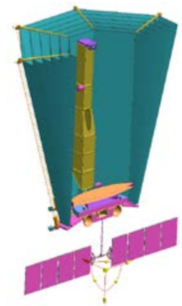
Mass, Damping, Stiffness (Sparse)	Loads (Multiple subcases, Thermal strains)

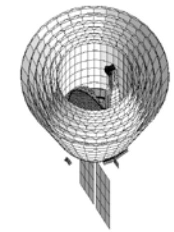
- Situation further complicated by:
  - Temperature-dependent materials
  - Radiation-material interactions
  - Microdynamic, and other geometric/strain/material nonlinearities

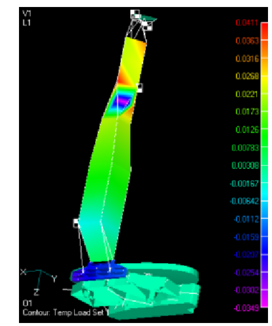
Motivation

Overcome current limitations in precision deployable structures analysis:

- COTS-based tools are domain-specific (“bucket brigade” approach)
- Pre-flight, system-level hardware testing at operating conditions is impractical
- Analysis fidelity (millikelvin, picometers) proving to be a significant challenge

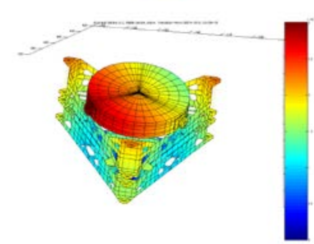






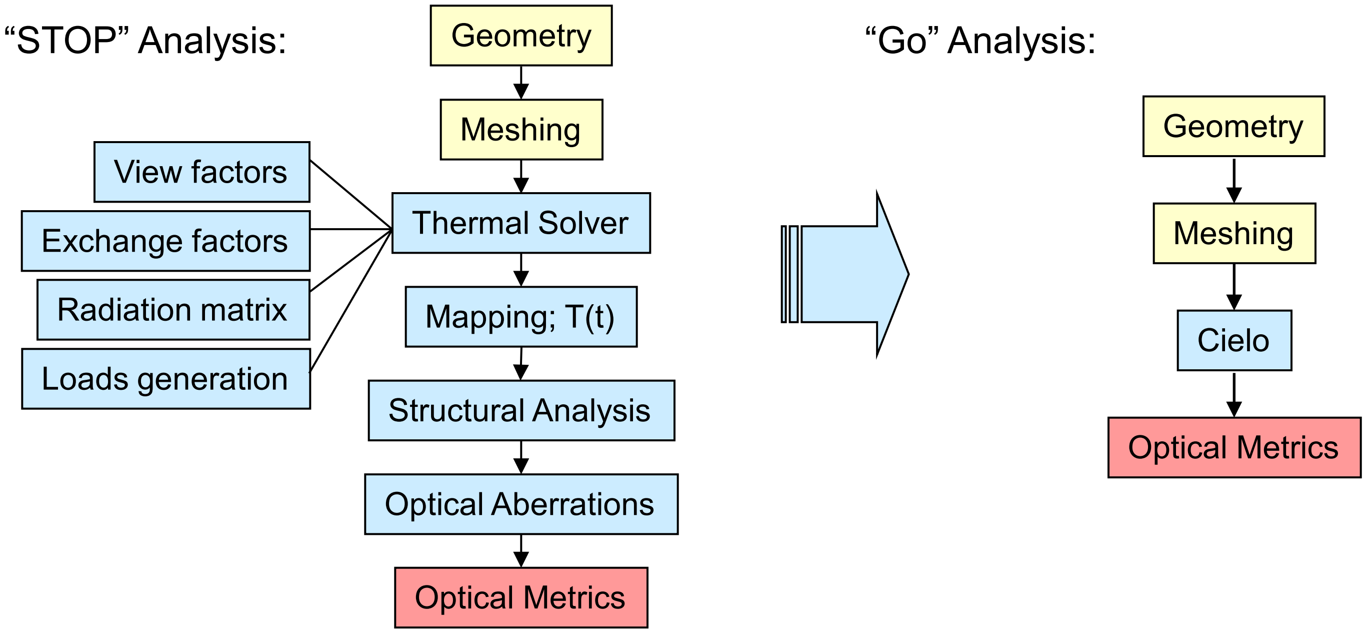
Enable analysis-driven systems engineering and design:

- Turnaround time improvement via common model approach
- Analysis fidelity via parallel computing
- Targeted methods development
- Integration with other domains (e.g. controls, optics) via MATLAB-hosting.



Solution Approach

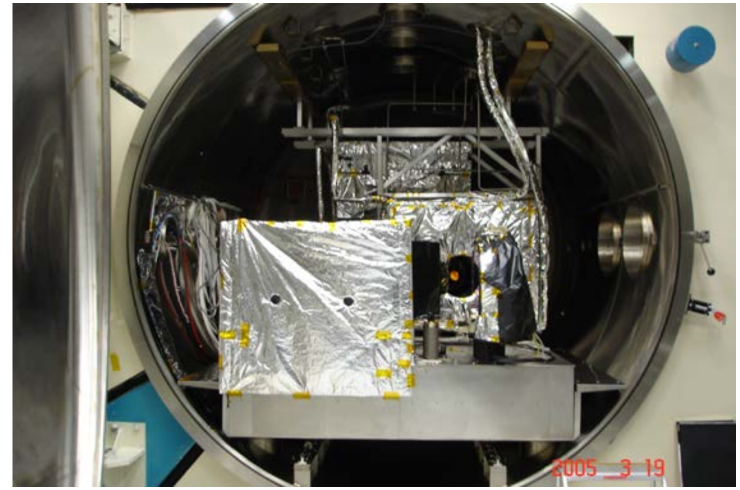
- Common finite element model representation
  - Single model with multidisciplinary attributes
  - Data-driven via augmented NASTRAN file formats
- MATLAB hosting
  - Open, extensible, scalable architecture enabled by rich MATLAB environment
  - mexFunction modules for specific, cpu-intensive phases
  - Solution control, postprocessing in MATLAB
  - Toolbox deployment



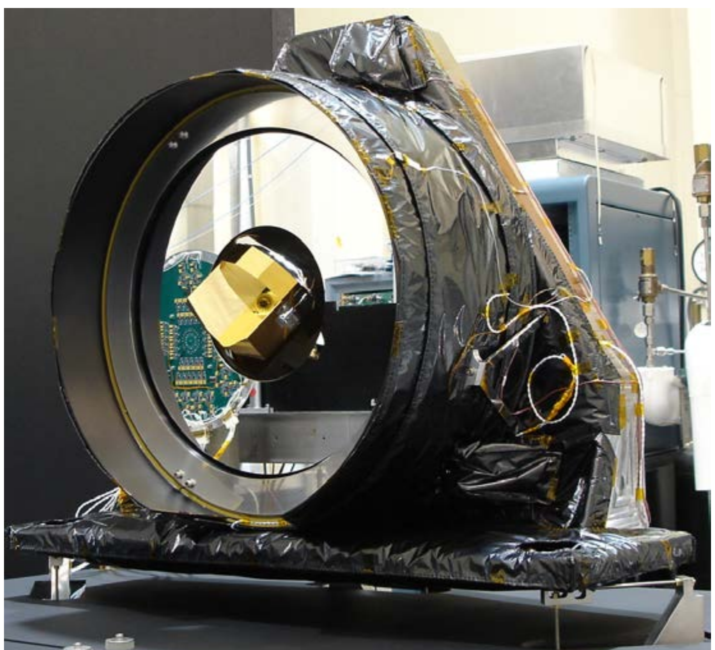
SIM TOM-3 Testbed

Space Interferometry Mission
Thermo-Opto-Mechanical Testbed
Measure thermally induced optical deformations of a full-size flight-like beam compressor and siderostat in flight like thermal environments

Fine optical path difference measurement with a common path heterodyne interferometer (COPHI)



3.3 m diameter vacuum chamber, beam compressor and shroud with siderostat inside



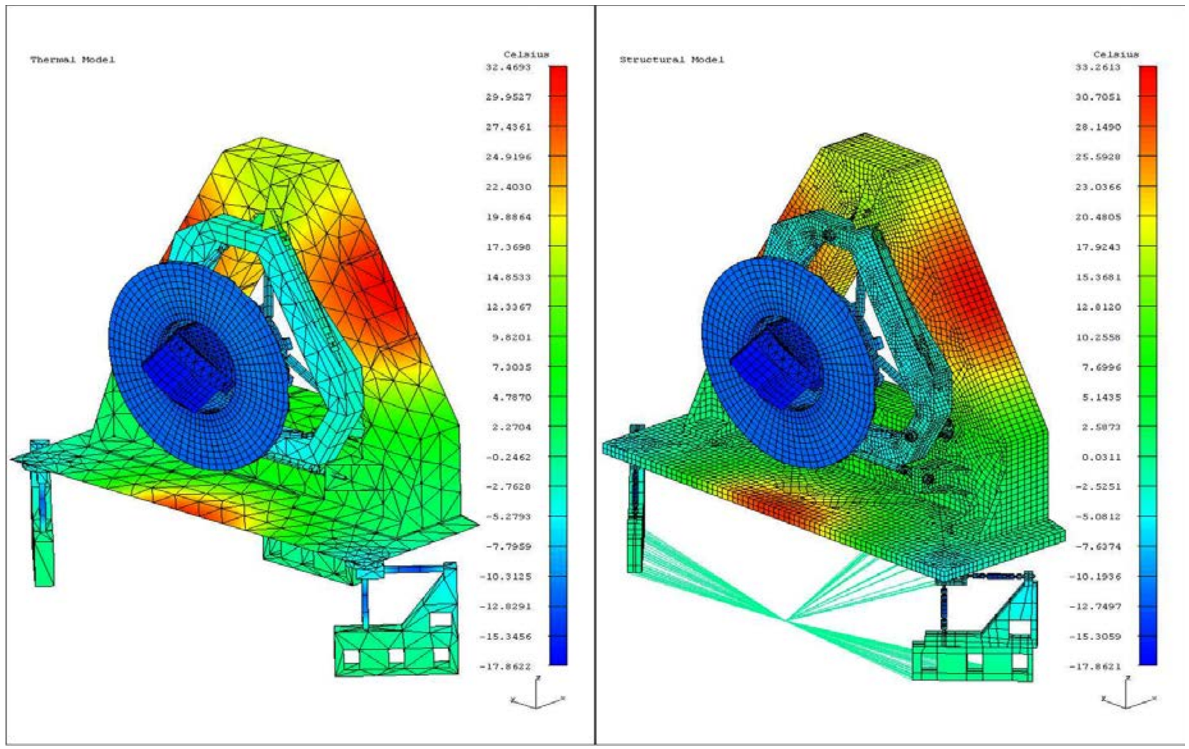
Siderostat mirror with double cube-corner including cans, yoke, and blankets

Scope of the Validation

- Demonstrate the use of a single computational model for thermal, structural and optical aberration analysis with Cielo, show high fidelity and compare with measurements of the TOM3 testbed and with results from COTS tools

- Build and validate the common model
- Compare results
  - in particular results on the siderostat mirror, steady state and transient temperatures, optical path differences (OPD)
  - Experimental results from the TOM3 test bed
  - Numerical results from TMG (temperatures) and NX/Nastran (OPD)

Existing Siderostat Models



1. Thermal Model (TMG)
2. Structural Model (NX/Nastran)
3. 20 node thermal model in Sinda for quick design studies
4. Matlab scripts extract displacements from Nastran output files, transform data for input to offline optical aberration analysis

Creation of a Common Model

- Used existing NX/Nastran structural model as a base to create a single model for thermal and structural analysis
  - Saving modeling time for this exercise was the main motivation
  - Existing quadratic elements were converted to linear elements
- Thermal attributes were added using I-deas
  - Thermal cans and box enclosure were added from the TMG model
  - Thermal surface elements were added with work-around, limited support in I-deas
  - Blankets (Chblin Elements) were added using a Matlab script
- Time dependent thermal boundary conditions were added at the Matlab script level
- Optical element was added
- Temperatures, thermal deformations and optical aberrations are all computed from single, common model

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Creation of a Common Model

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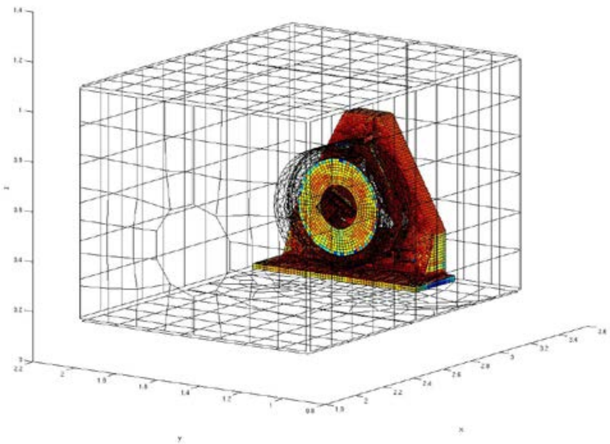
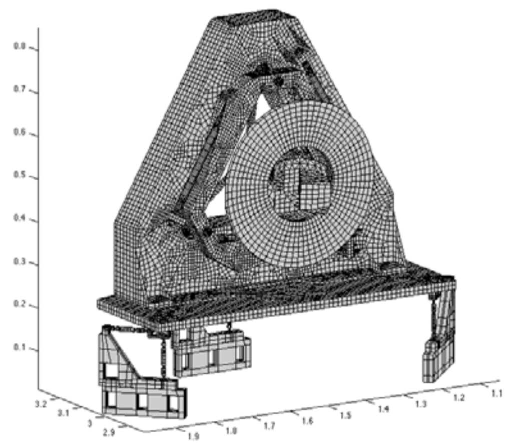
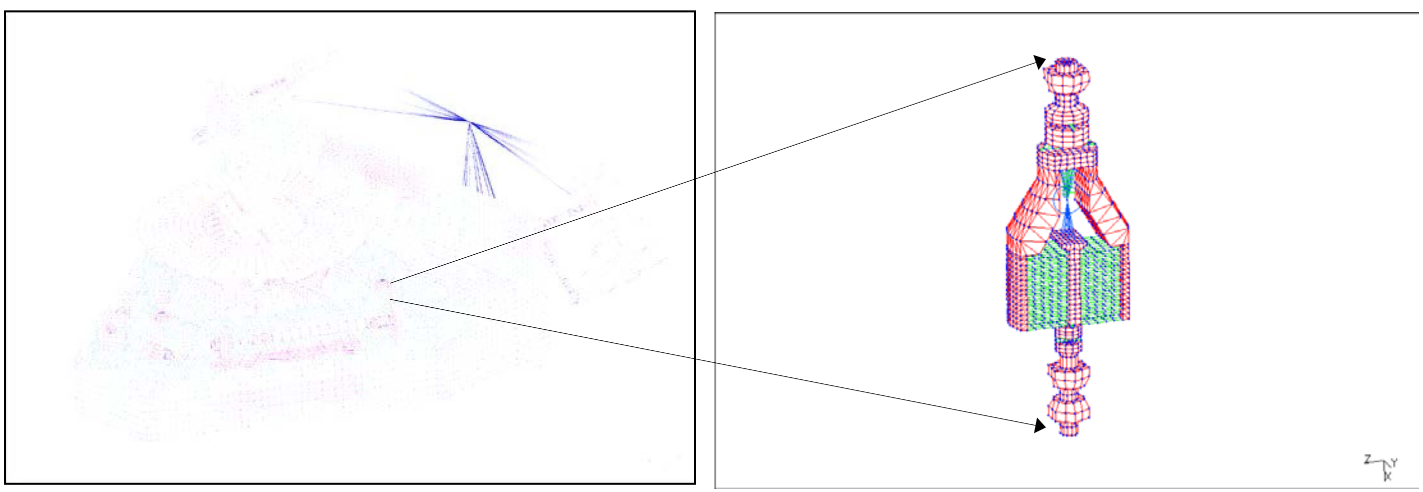
Box, Cans, Siderostat



Siderostat



Level of detail in existing siderostat model

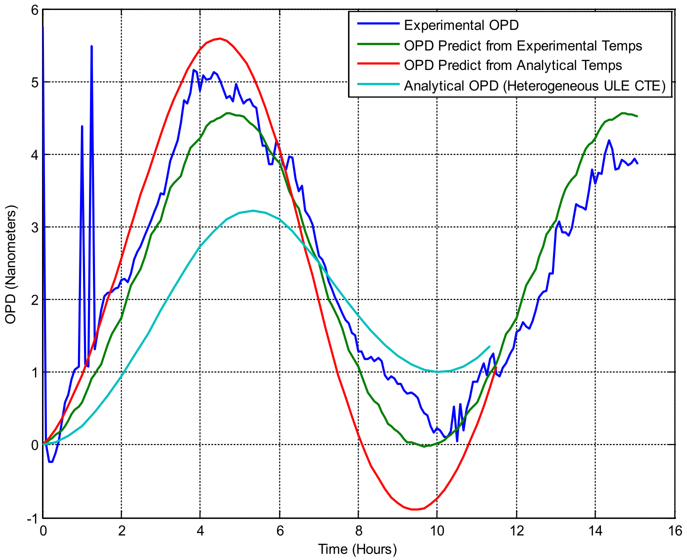


celas1	3290
chbdyg	57567
chbdyp	1
chblin	1094
chexa	14516
cord*	11
cpenta	4773
cquad4	13497
ctetra	9874
ctria3	3325
grid	48370
mat*	14
param	9
pelas	6
phbdy	1
phblin	3
pshell	26
psolid	204
radm	19
rbe3	7
rbe2	1
spc	1449
tempd	1
tstepnl	1

V&V Test Plan

Previous results from the "10X slew constant power thermal test"

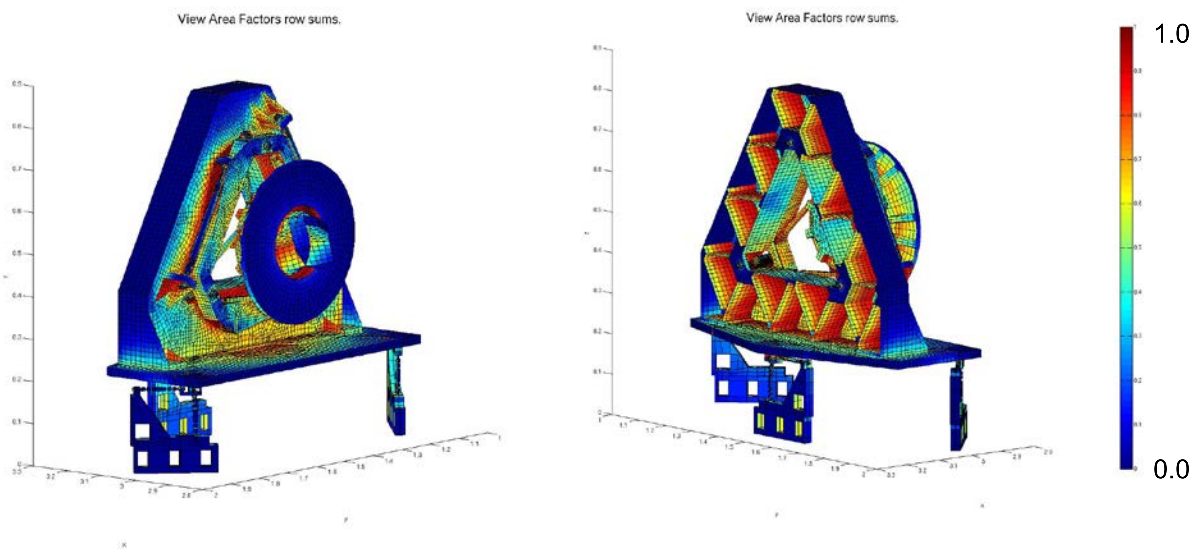
- In thermal analysis, emissivities had been tuned to get closer to measured temperatures
- In structural analysis, coefficients of thermal expansion (CTE) had been measured and tuned to get closer to the measured OPD
- Overall, OPD varied by a factor of 2 due to emissivity and CTE tuning



These "tuned" parameter values were taken as common model starting points in Cielo for thermal and structural analysis to make meaningful comparisons

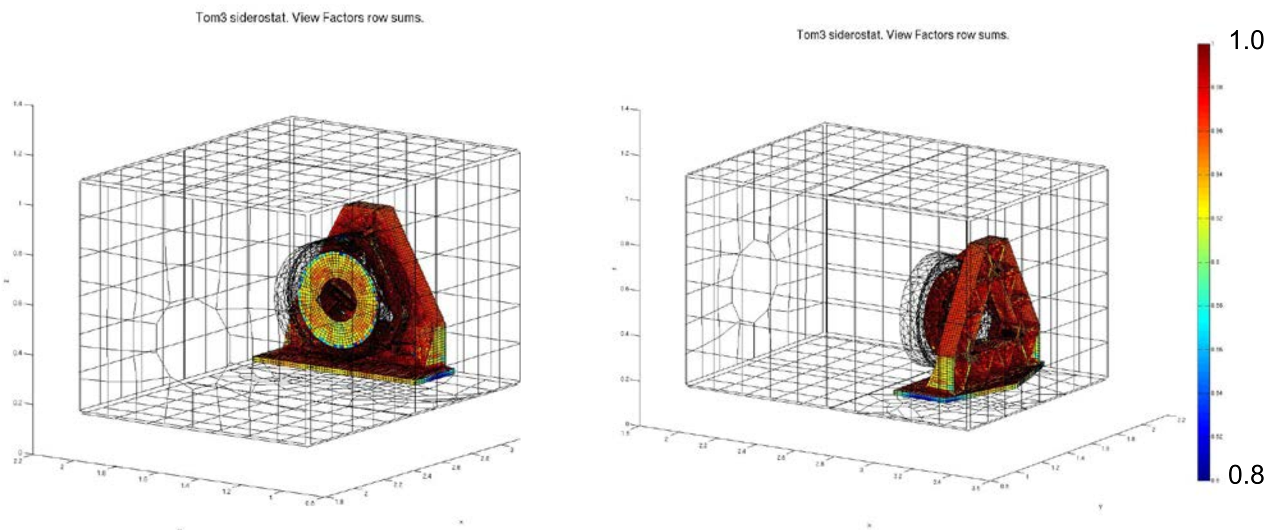
- Run steady state thermal
- Run transient thermal analysis with loads from slew maneuver
- Run static analysis for the last 70 time steps with temperature loads from the preceding thermal analysis
- Calculate OPD

View Factor Calculation



Verification of view factor calculations

Diffuse view factors of siderostat seeing space (normalized row sums)



View factors of the siderostat in the TOM3 testbed
(normalized row sums)

58,000 surface elements
(58,000 ^{2} view factors)

Wall clock time
24 hours on 256 CPUs

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Thermal Steady State

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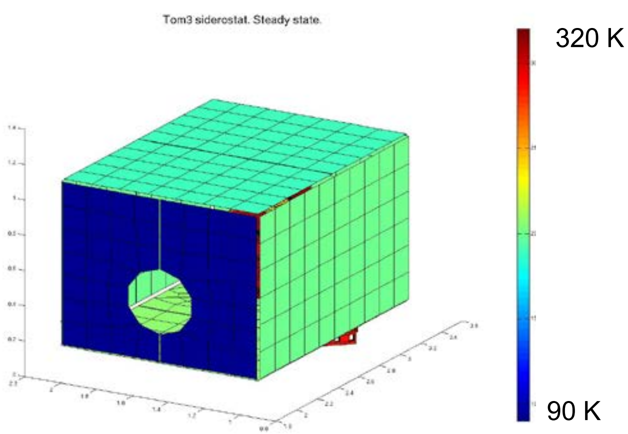
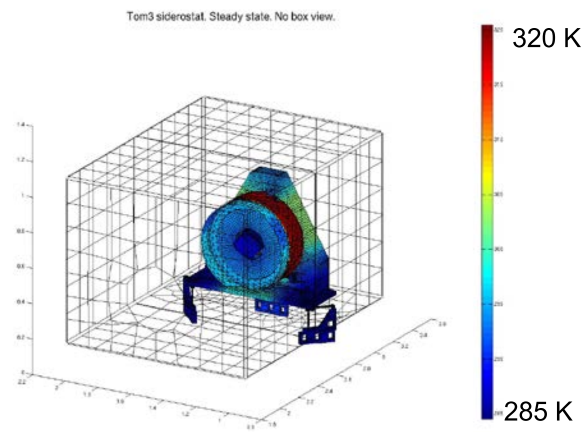
- Verification of the thermal model by running pure conduction with enforced temperature at one grid of a part
- Ran steady state thermal to reach equilibrium initial condition for transient

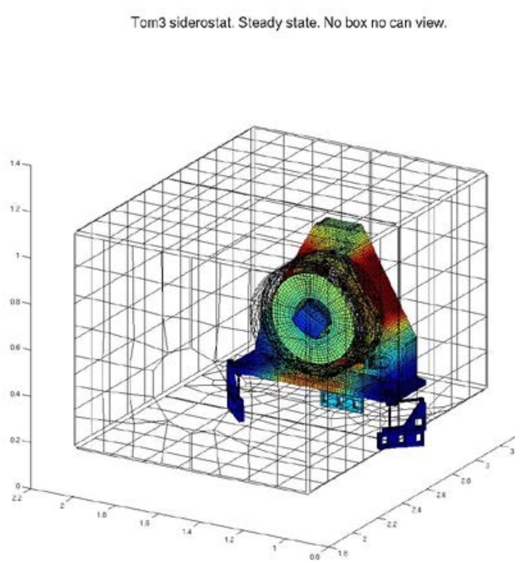


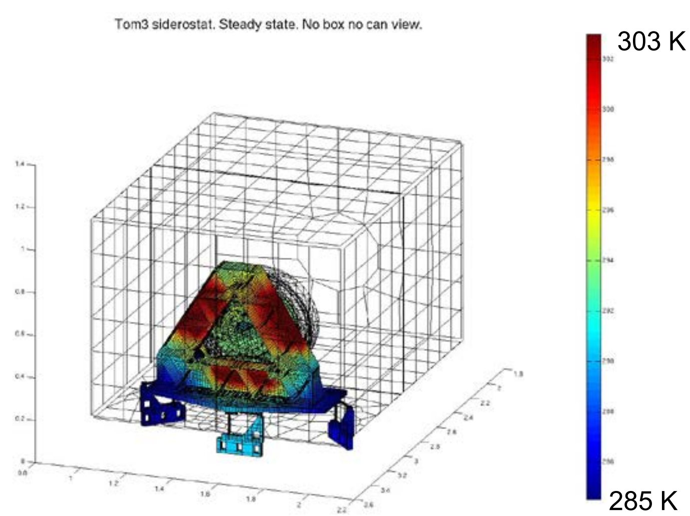


Steady state temperatures

Steady state run

1 hour on 256 CPUs





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Cielo Thermal Steady State Comparison with Test and TMG

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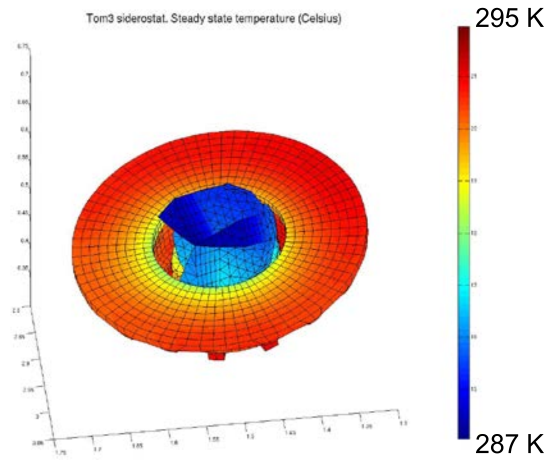
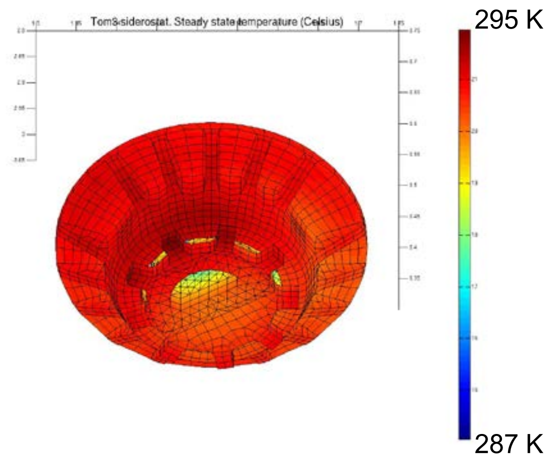




Cielo steady state temperatures

front and back of the siderostat mirror

TMG temperatures are visually identical to Cielo

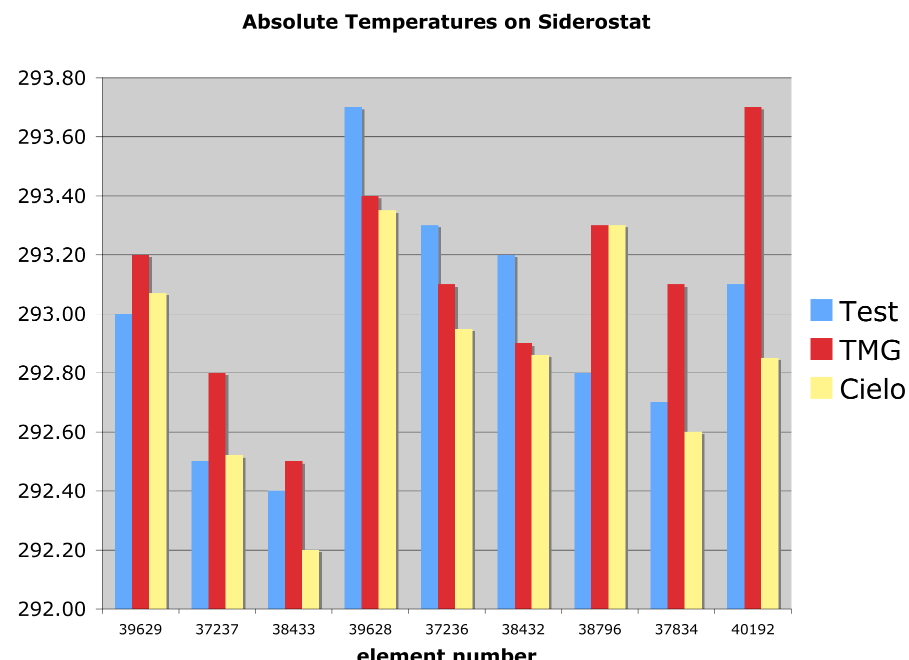
Comparison of steady state temperatures at selected elements on the mirror

Test / TMG / Cielo

Average deviation from test for 9 measured temperatures

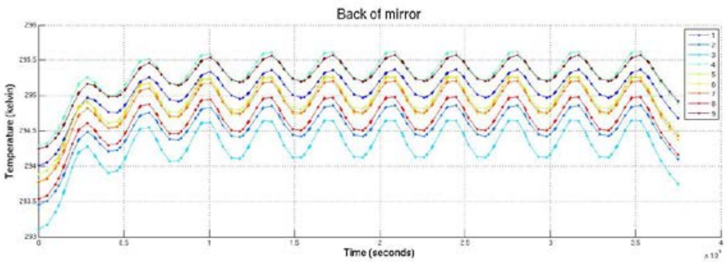
TMG 0.32 K

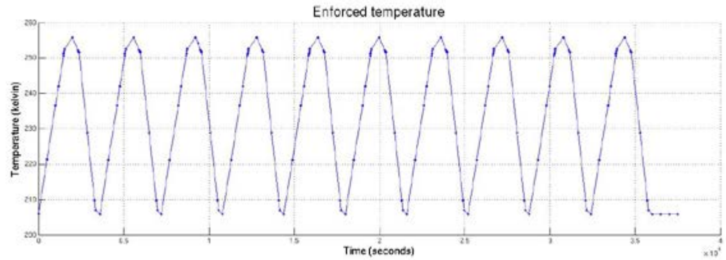
Cielo 0.24 K



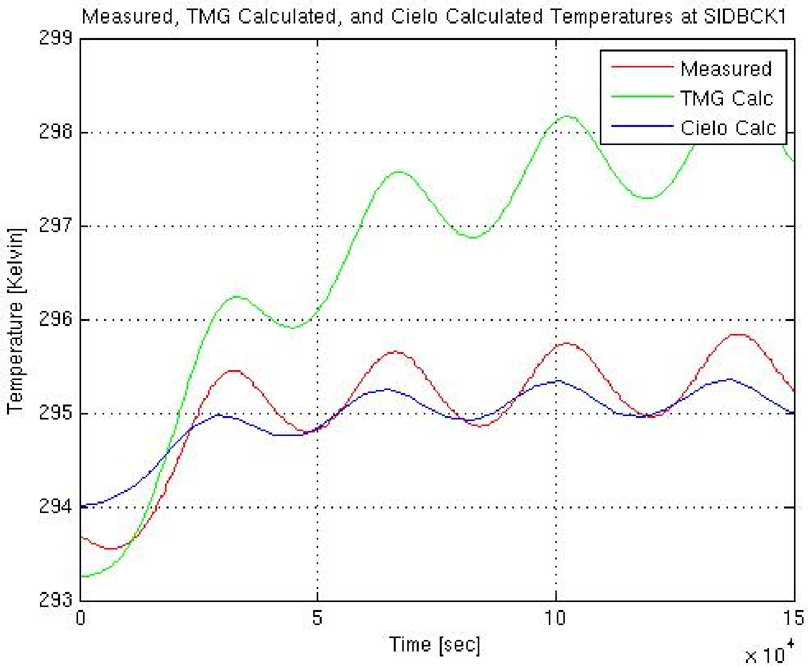
Thermal Transient Analysis

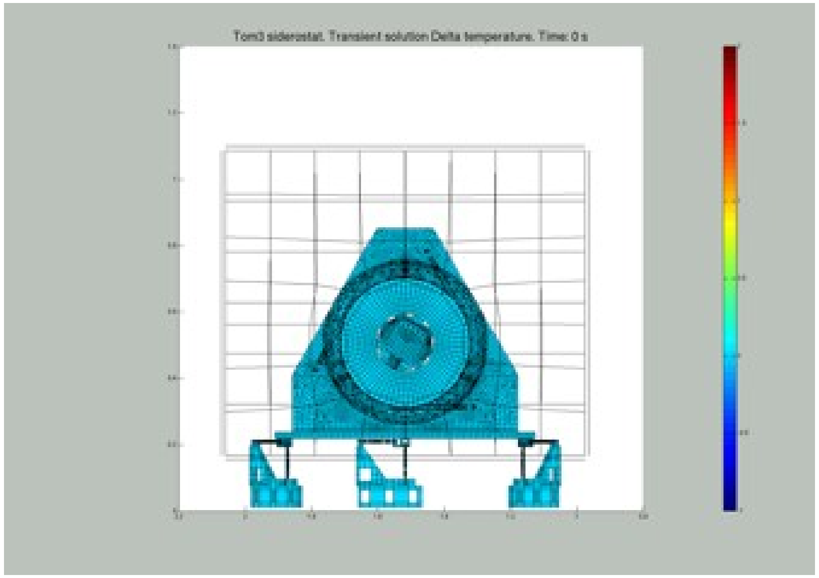
- Starts from steady state equilibrium
- Implicit time step integrator, mid-point alpha method, with time step control
- Enforced temperature boundary conditions at the box walls
- 18 hours wall clock time on 256 CPUs to calculate 10 cycles





Comparison Test / TMG / Cielo





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Cielo Thermal Deformations and Optical Aberrations

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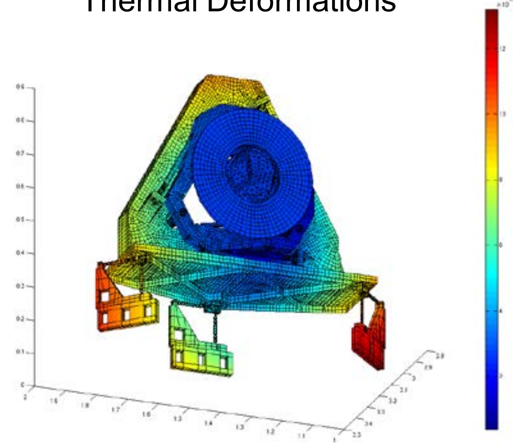
- Verified structural analysis by comparison with NX/Nastran

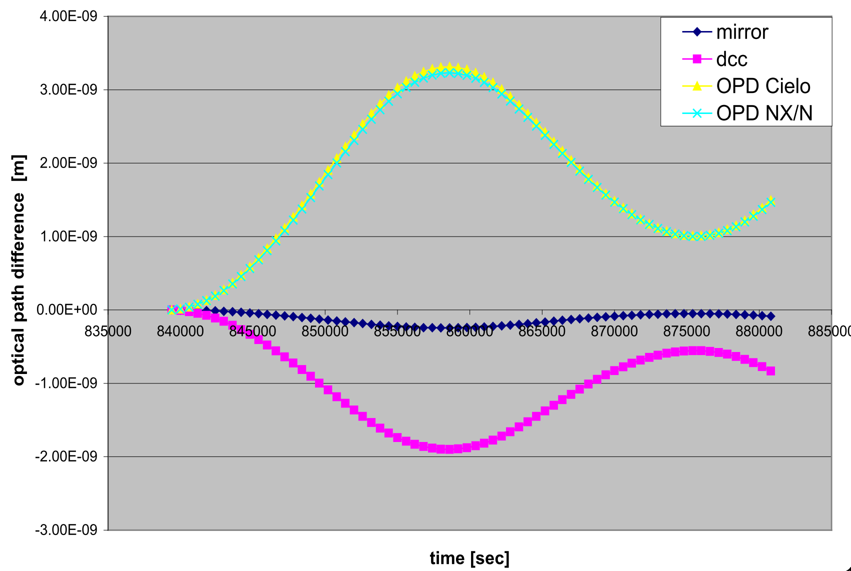
  Maximum displacement normal to the mirror

Code/ Elem.	NX Q9/T6	NX Q4/T3	Cielo Q4/T3
d max [m]	1.100e-11	1.090e-11	1.084e-11
delta	0.0%	1.0%	1.6%

Thermal Deformations



slew_10x_cp_temps Optical Path Difference

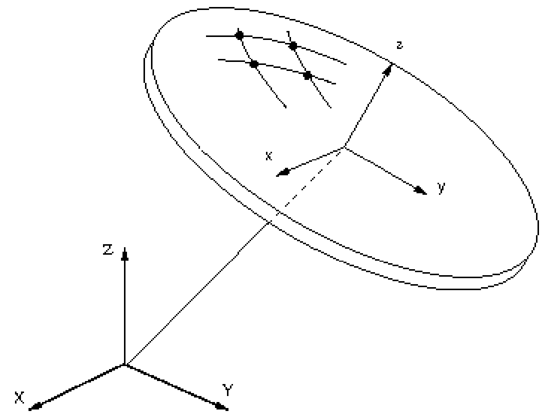


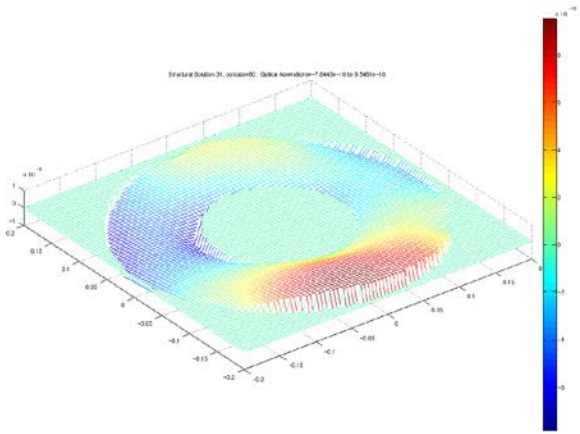
- 70 temperature fields for one cycle are read from the data base or are resident in the Matlab workspace
- 70 subsequent linear static analyses each followed by optical aberration calculations based on user specified optical elements
- 15 min. run time on our new SUN machine (in serial) to produce all thermal deformations and optical aberrations over time

Computing Optical Aberrations from Thermal Deformations in Cielo

For every optical element, for every load case,

- Partition displacement solutions to optical degrees of freedom
- Transform displacements to optical coordinate system
- Compute best-fit rigid body components with respect to optical coordinate systems
- Construct deformed optical surface with, or without rigid-body contributions
- Use underlying finite element interpolation functions to compute aberrations as differences between deformed, undeformed surfaces at interferogram locations





- XYZ – finite element basic coordinate system
- xyz – local optical coordinate system shared with MACOS, CODE V, et al.
- COPTC – optical element definition (surface degree-of-freedom associativity, local coordinate system specification)
- OPTCABS – subcase-dependent data recovery requests

Discussions of Margins and Uncertainties

- Physics
  - Assumption of diffuse radiation
- Material Parameters
  - **Emissivities** of surfaces, especially for the cans are the most uncertain parameters and to make matters worse, they are also the most sensitive in this radiation dominated problem
  - Effective emissivities for the blankets are uncertain and sensitive as well
  - Conductivity and capacitance are available with sufficient accuracy
  - Young's moduli for structural analysis are available with sufficient accuracy
  - **Coefficients of thermal expansion** (CTE) are uncertain and sensitive
- Accuracy in modeling and simulation for thermal analysis
  - Growth in temperature response in the TMG solver ?

- In the previous TOM3 test report, it was concluded that the variations in OPD predictions by a factor of 2 are within the required margins
- Questions remain about uncertainties in sensitive parameters like emissivities and CTEs
- A tool like Cielo can make the necessary parameter studies in a reasonable time frame provided that sufficient computer wall clock time is available

Summary

- The common model approach reduces turn around time by at least a factor of 3 compared to the standard approach
- Cielo is able to produce high fidelity thermal results by allowing model sizes which can not be handled by COTS tools
- Run times for view factors and thermal transient analysis are within acceptable range assuming access to a cluster with 256 nodes
- Run times for linear static analysis are not critical
- Higher fidelity in values of emissivity and coefficient of thermal expansion is necessary
- Computer time must be further reduced to make parameter studies feasible