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Analysis-Driven Systems Engineering With Cielo

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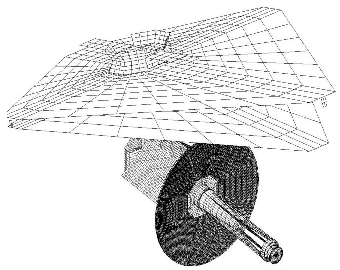
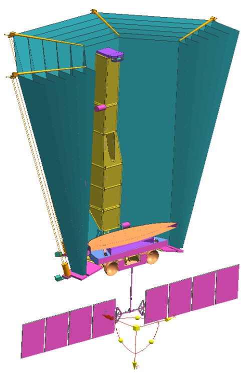
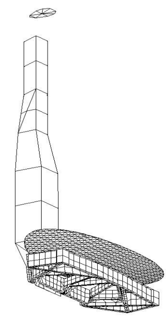
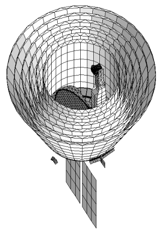
Outline

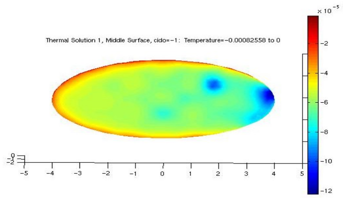
- Motivation and Challenges
- Cielo Overview: Architecture and Features
- Examples
- Summary

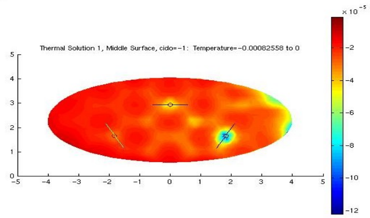


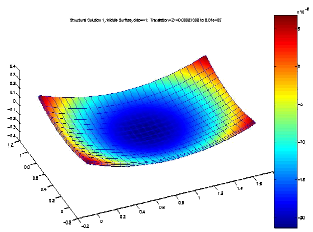


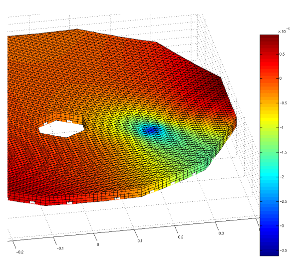












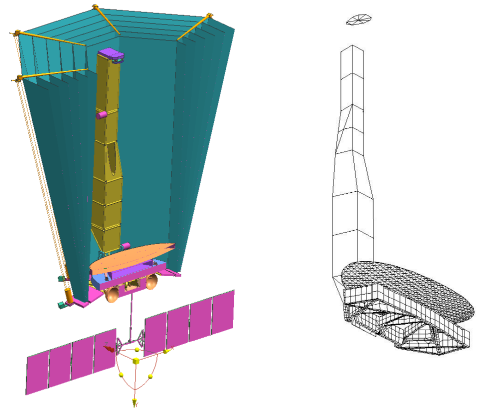
Cielo Introduction

- Goals
  - Enable “integrated modeling” via fundamentally-integrated thermal, structural, and optical aberration analytic capabilities.
  - Overcome “Commercial Off-The-Shelf” (COTS) tool limitations
  - Provide a platform for continuing methods development, vertical application development
- Status
  - Several year development effort largely by team of former MSC/NASTRAN developers
  - Common model, finite element-based code
  - MATLAB hosted, modular, large model implementation (> 1M structural degrees of freedom, tens of thousands of radiation exchange surfaces)
  - Extensible serial and parallel components (heterogeneous compute environment)
  - Under active development

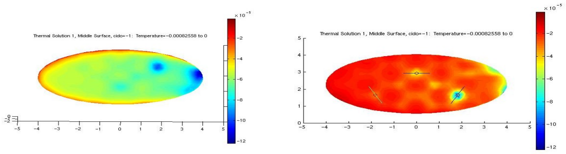
What is Cielo ?

- 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

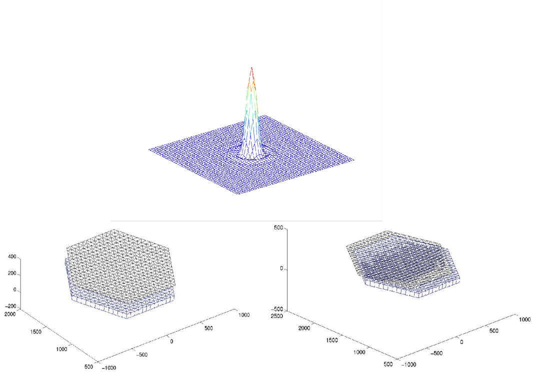
Integrated analysis capability facilitates development of detailed system- level model …



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…



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Motivation: 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

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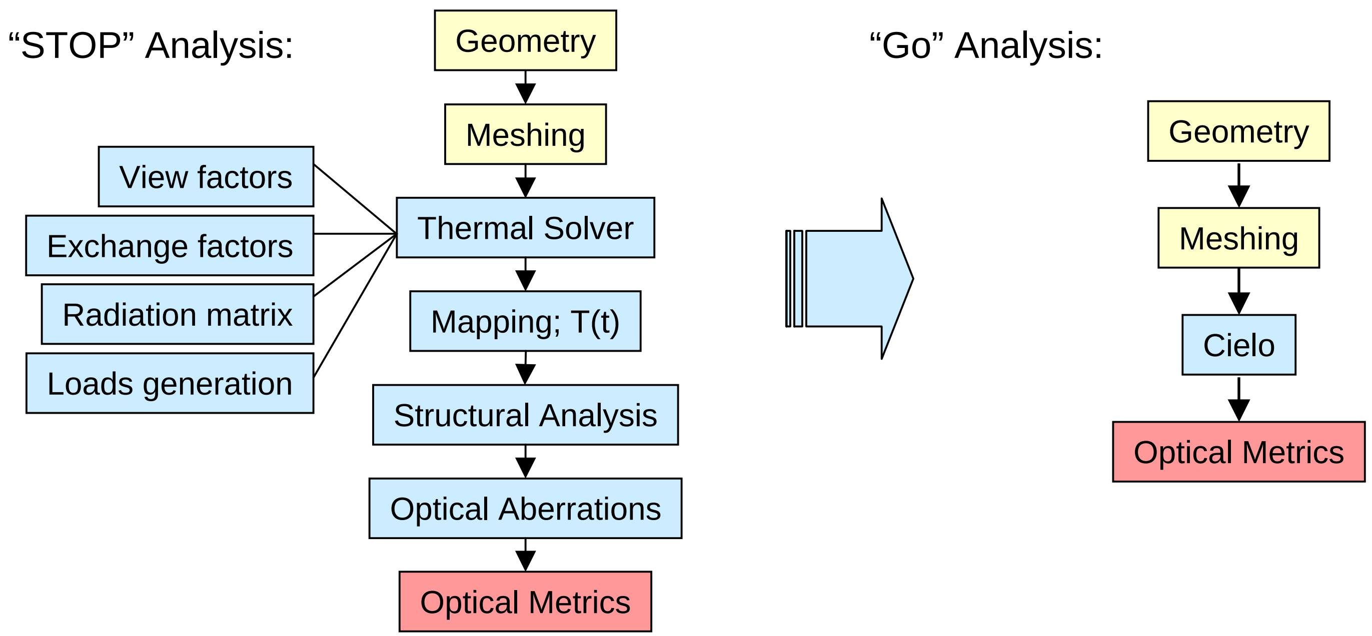
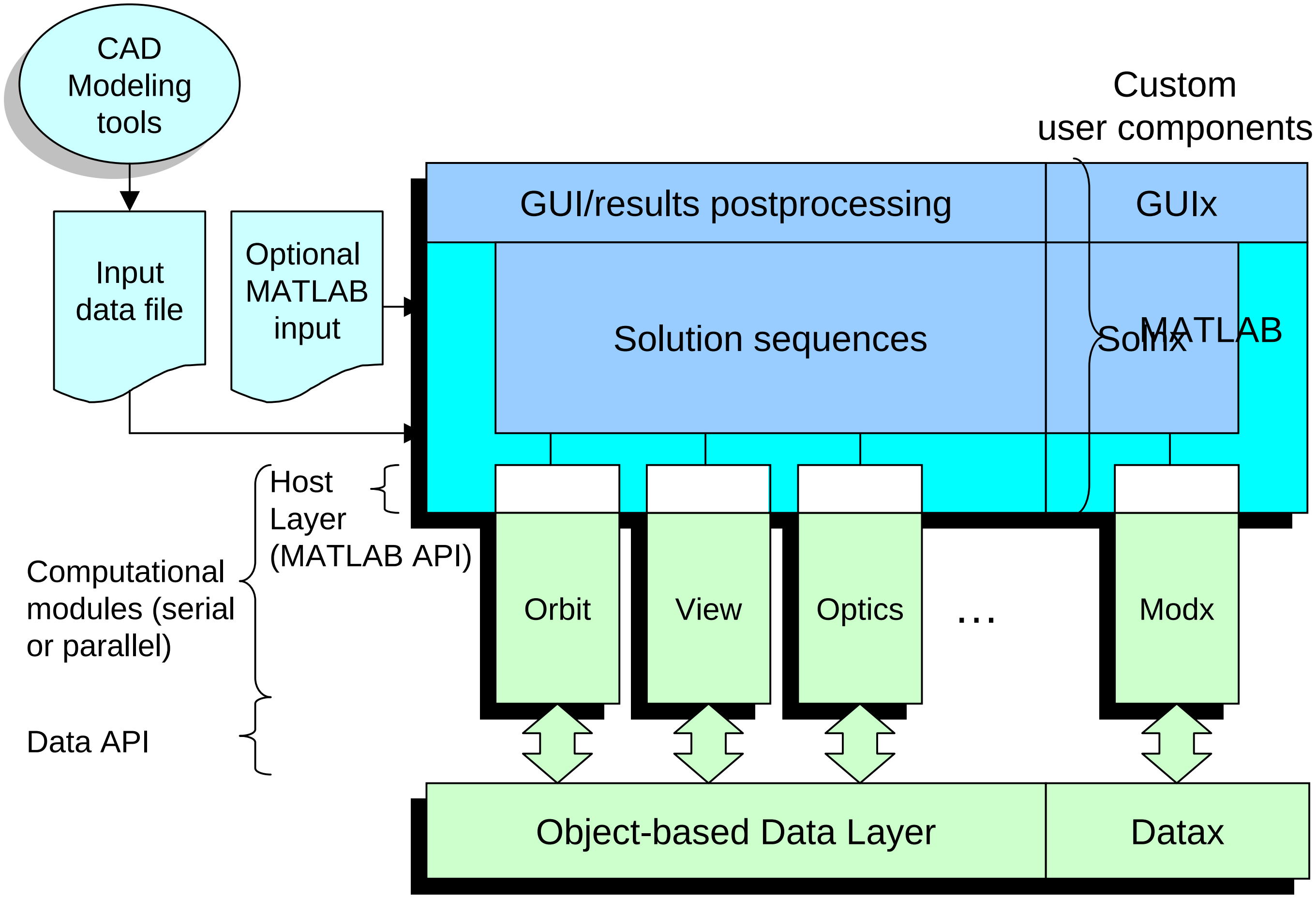
Solution Approach

- 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

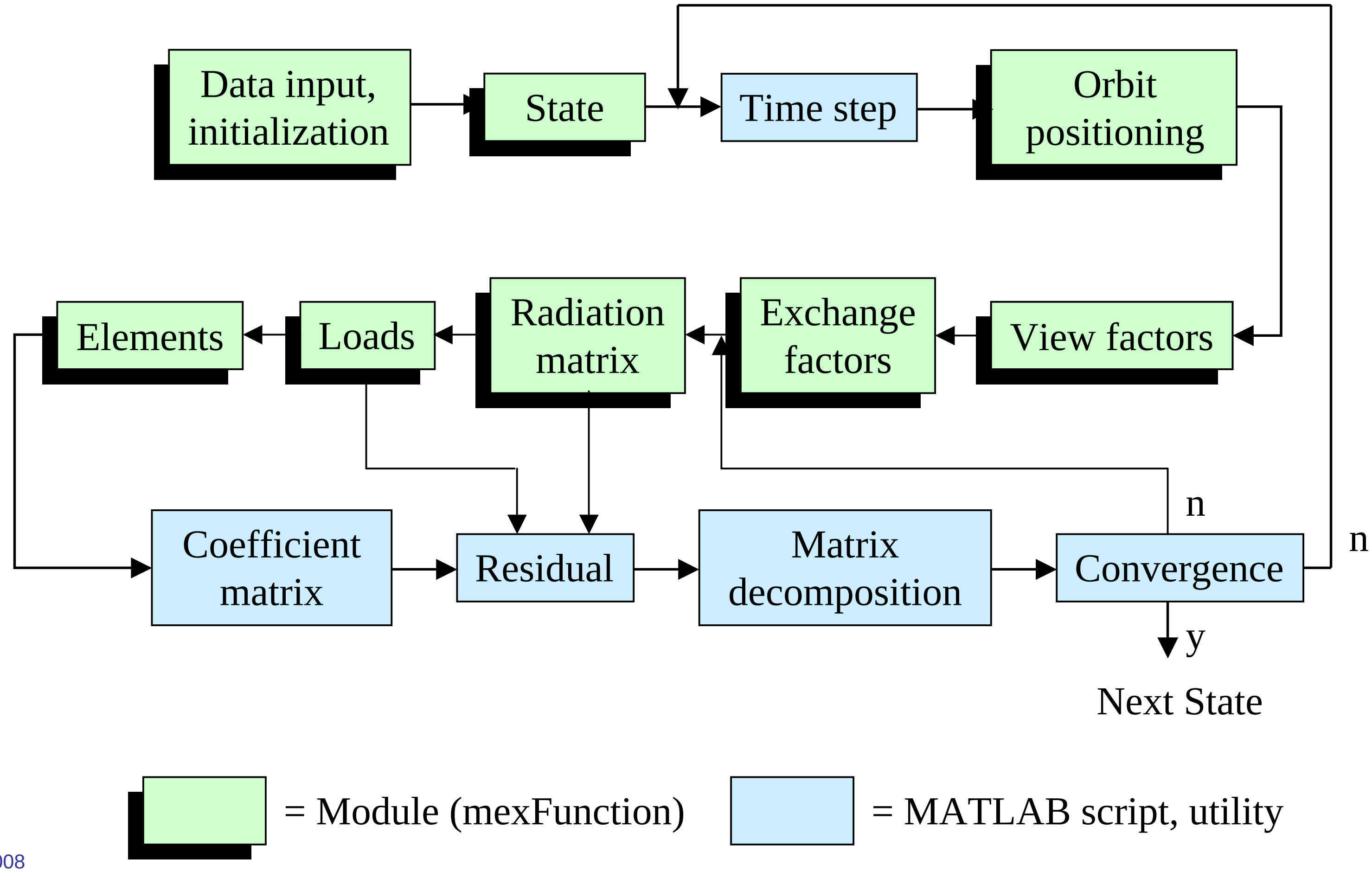


Cielo Architecture



Thermal Solution Implementation

- Solution Procedures:
  - High-level MATLAB scripts for solution control, functional module calls
  - Conceptually similar to NASTRAN's DMAP sequences
  - Natural interface to extended functionality (e.g. In-house codes, Simulink, …)



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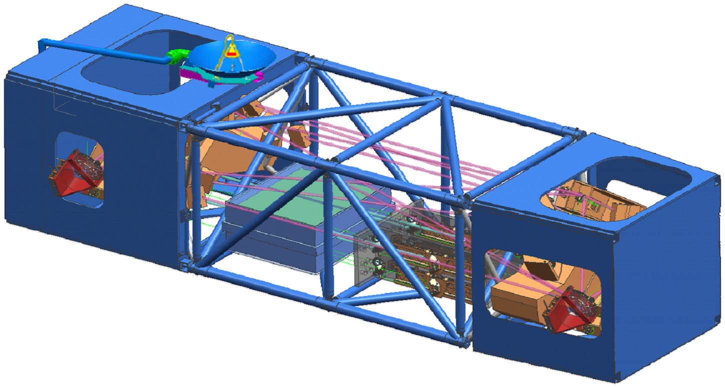
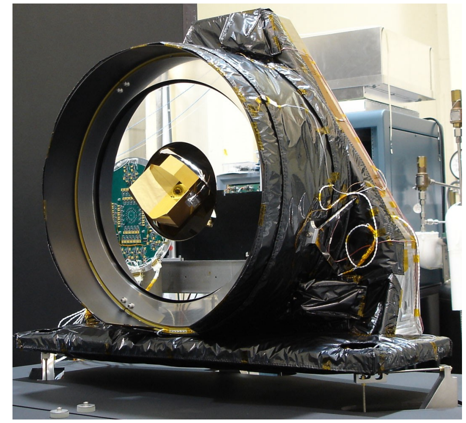
Thermal/Optical Distortion Example

- Space Interferometry Mission (SIM)
  - Precisely measure angles between stellar objects for astrometric and planet detection purposes
  - 10 meter rigid baseline interferometer
  - Flight Environment
    - Earth-trailing solar orbit
    - Benign radiation environment
- Thermal distortion analysis of Relay Optic #2B
  - Key optical element in science compressor unit
  - Transient thermal distortion analysis, corresponding surface aberrations and optical metrics
  - Geometry modeling, thermal and structural meshing in UG NX
  - UG NX TMG Thermal Analysis, temperature mapping to UG NX mesh (though thermal analysis could have been done Cielo)
  - Distortion analysis, optical aberrations in Cielo
  - Hosting, and optical response postprocessing in MATLAB

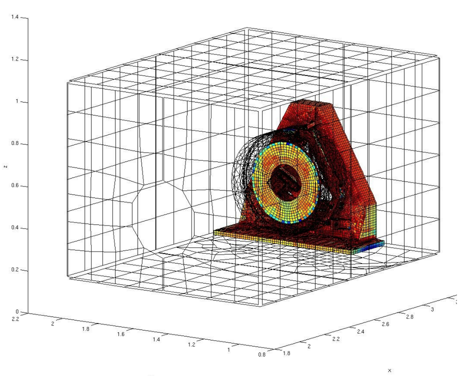


Demonstration of the Status of Cielo Validation of the SIM TOM-3 Testbed Results

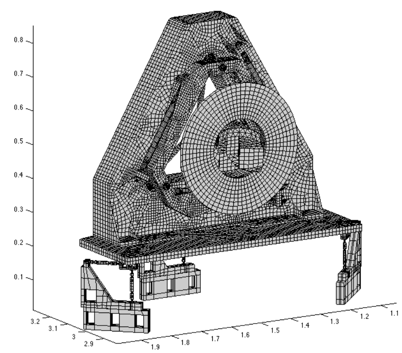
Thermo-Opto-Mechanical testbed for SIM
Measure thermally induced optical deformations of a full scale beam compressor and siderostat in flight like thermal environments



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



Box, Cans, Siderostat



Siderostat

Common high fidelity model with thermal, structural and optical attributes

- Thermal radiation surface properties, conduction and capacitance
- Structural stiffness, thermal expansion
- Optical elements for aberration

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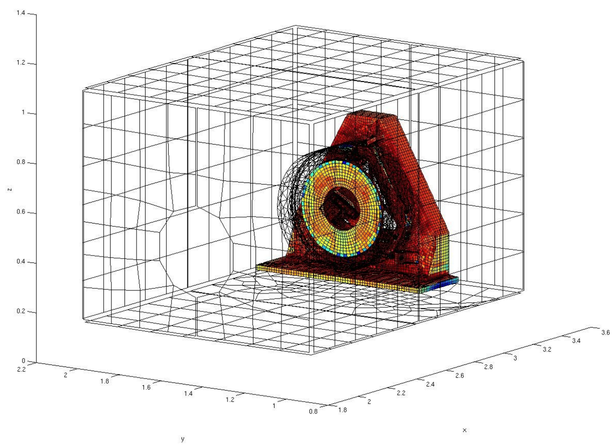
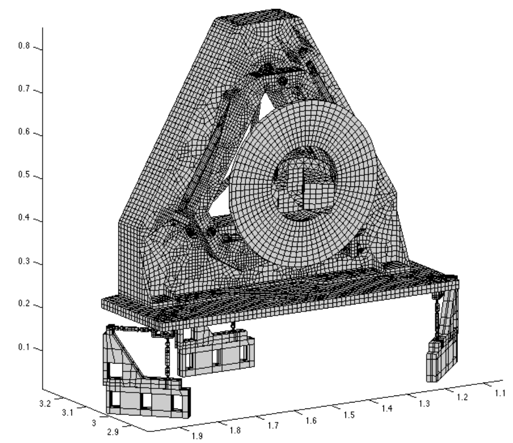
Cielo Common Model Creation

Box, Cans, Siderostat

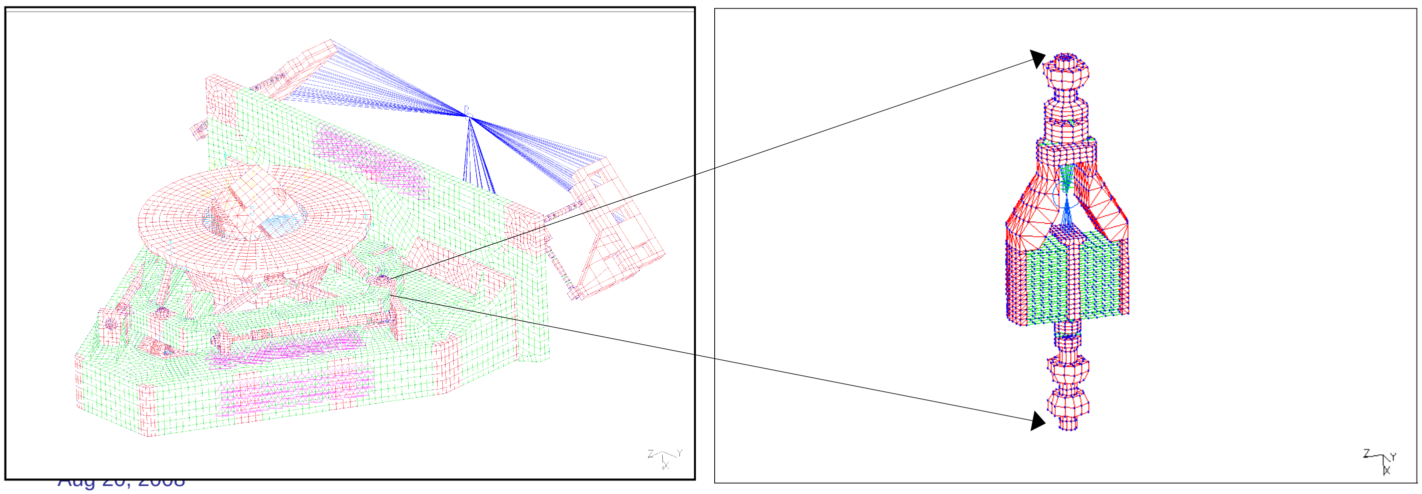


Siderostat

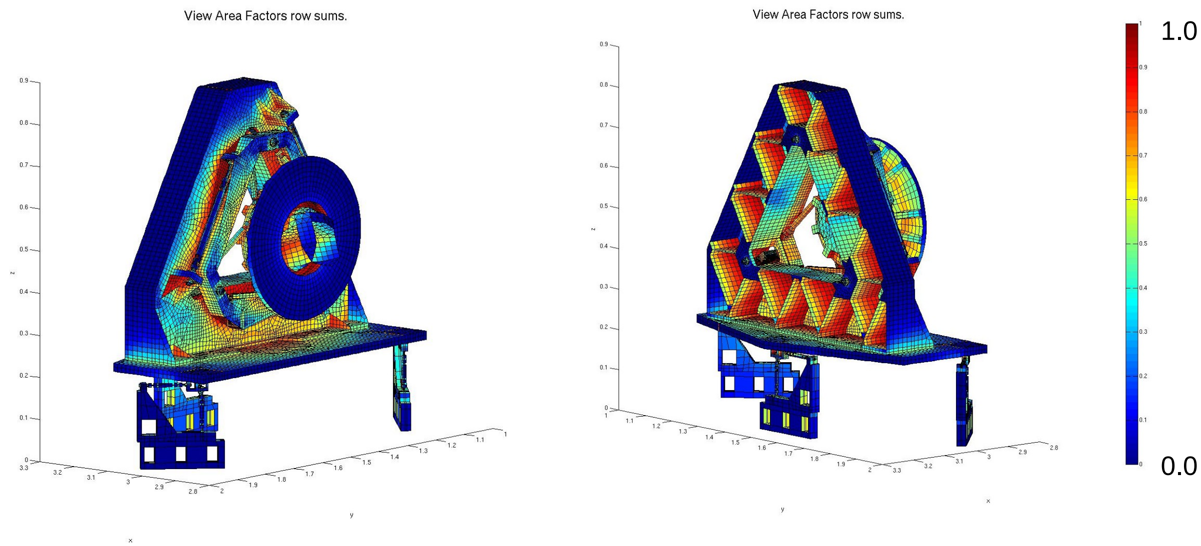


celas1	3290
chbdyg	57567
chbdyp	1
chblin	1094
chexa	14516
cord*	11
cpenta	4773
cquad4	13497
ctetra	9874
ctria3	3325
grid	48370
mat*	14
param	9
pelas	6
phbdy	1
phblin	3
pshell	26
psolid	204
radm	19
rbe3	7
rbe2	1
spc	1449
tempd	1
tstepnl	1

Level of detail in existing siderostat model

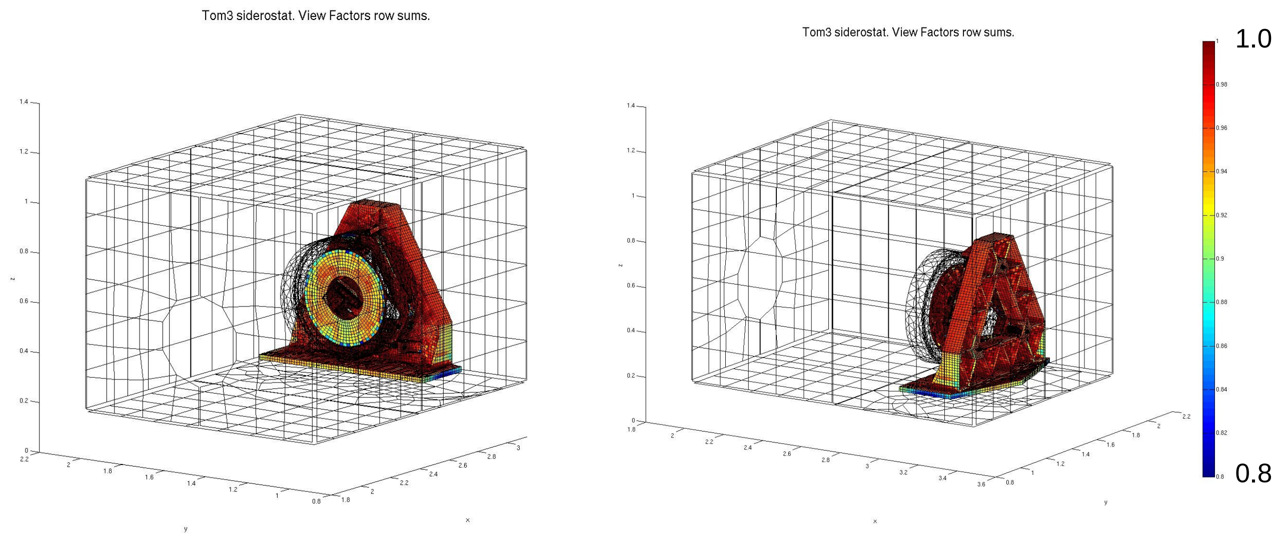


Cielo View Factor Calculation



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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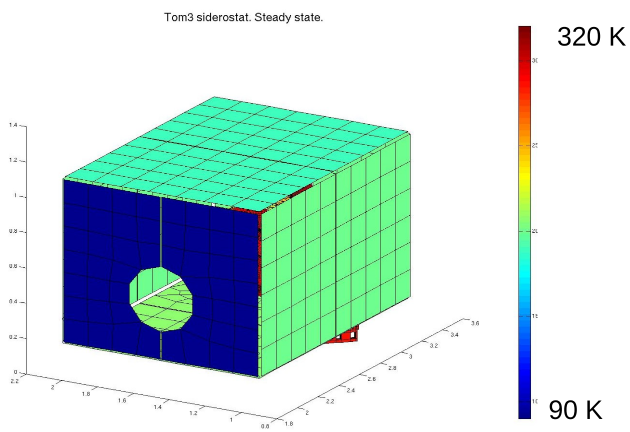
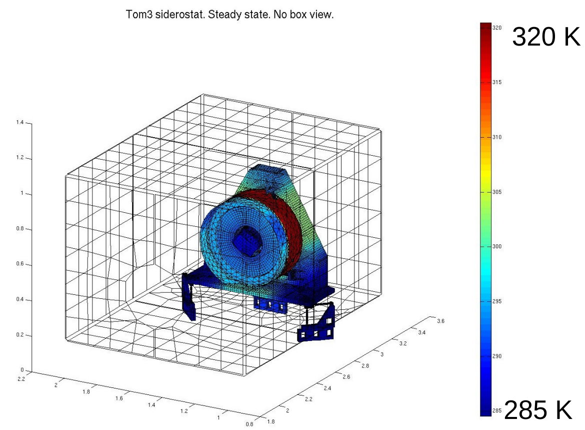
Cielo Thermal Steady State

- 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

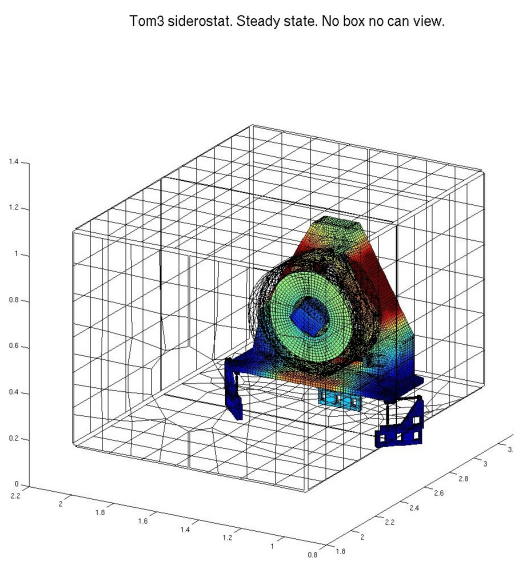


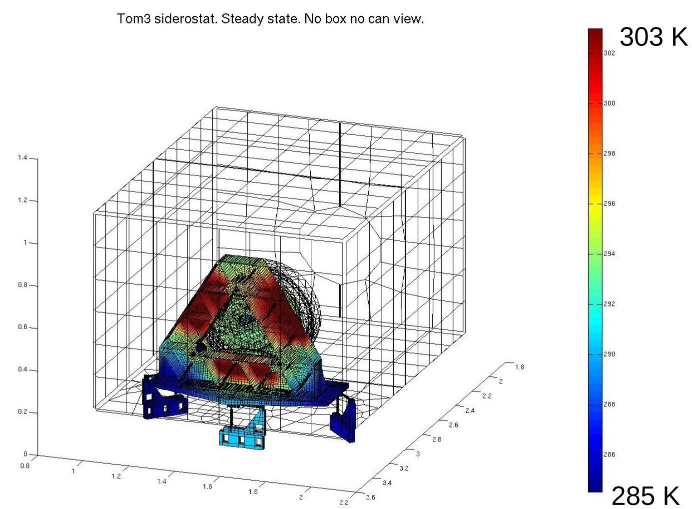


Steady state temperatures

Steady state run

1 hour on 256 CPUs





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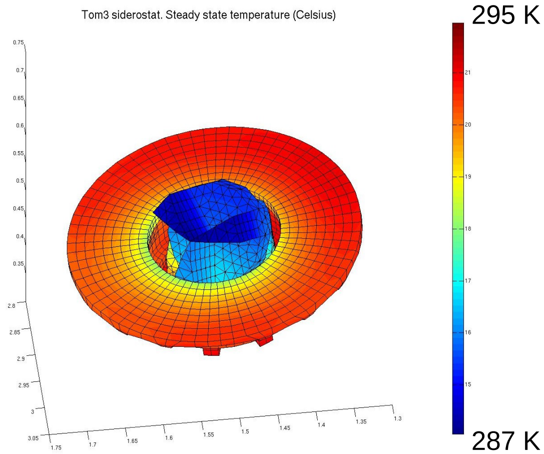
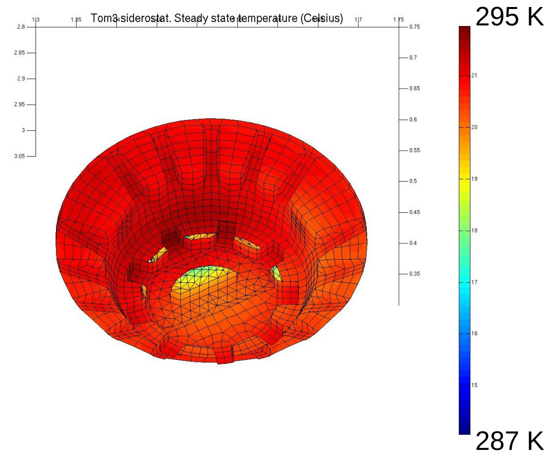
Cielo Thermal Steady State
Comparison with Test and TMG





Cielo steady state temperatures

front and back of the siderostat mirror

TMG temperatures are visually identical to Cielo

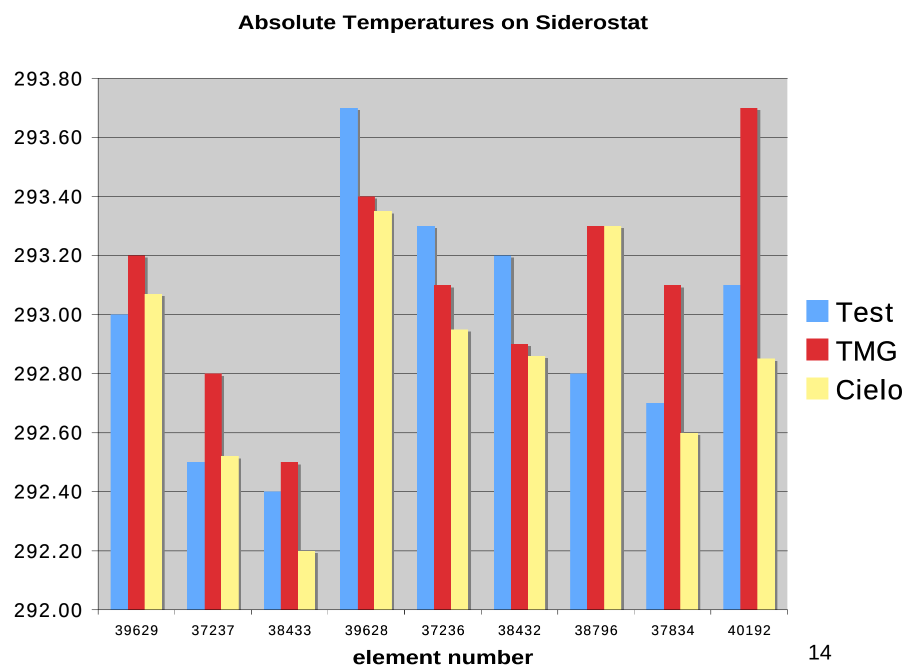
Comparison of steady state temperatures at selected elements on the mirror

Test / TMG / Cielo

Average deviation from test for 9 measured temperatures

TMG 0.32 K

Cielo 0.24 K



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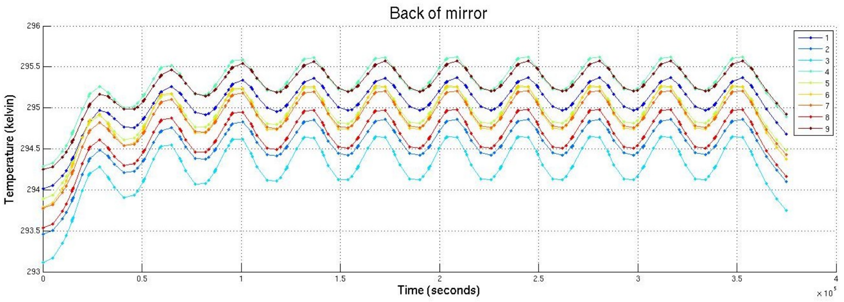
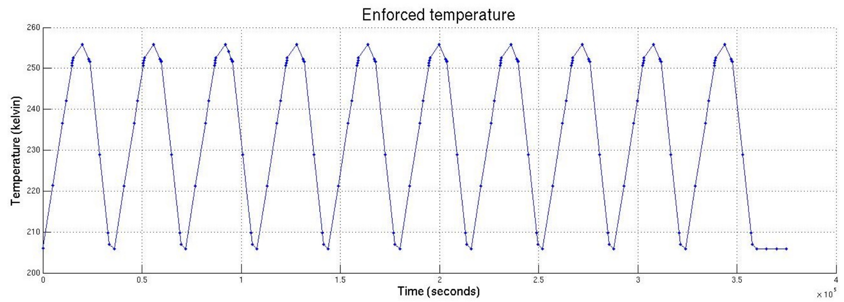
Cielo Thermal Transient Analysis

- 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





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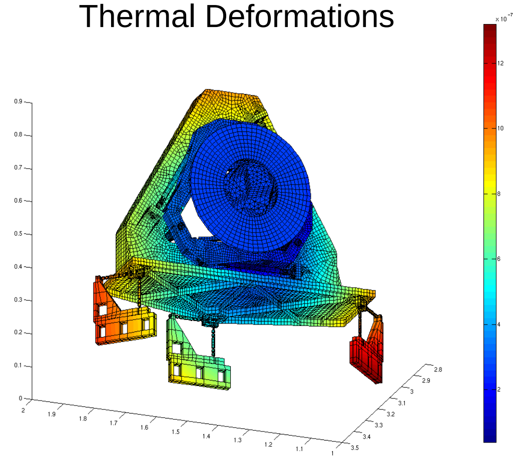
Cielo Thermal Deformations and Optical Aberrations

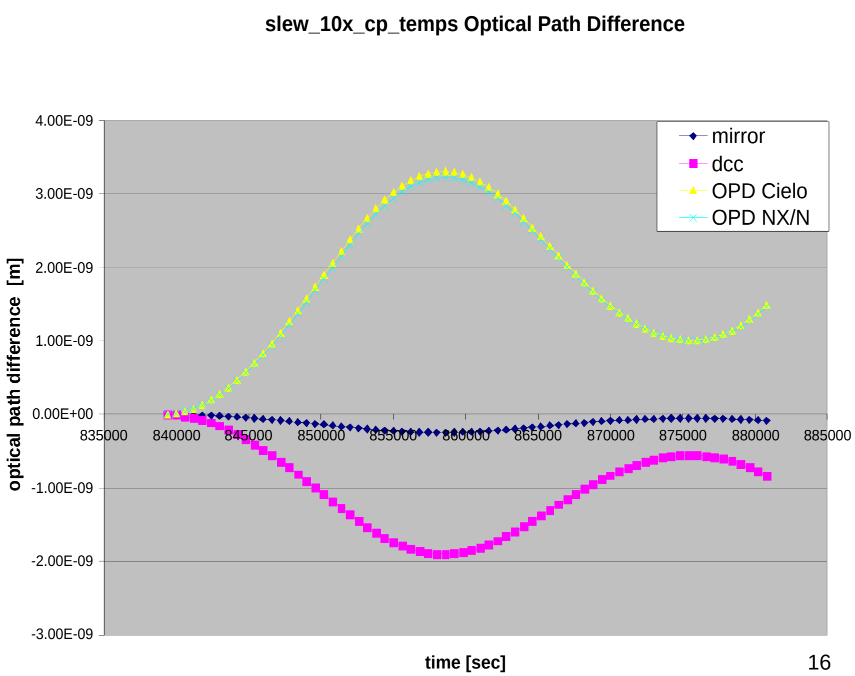
- Verified structural analysis by comparison with NX/Nastran

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



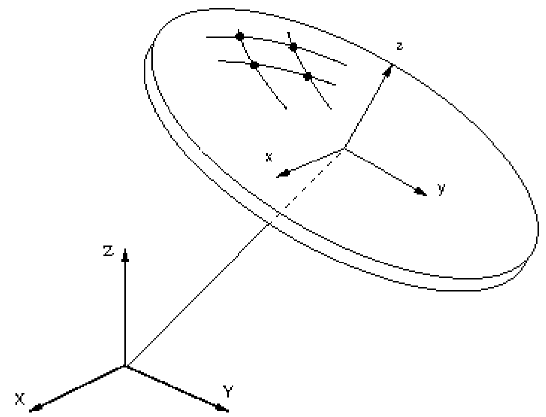


- 70 temperature fields for one cycle are read from the data base or are resident in the Matlab workspace
- 70 subsequent linear static analyses each followed by optical aberration calculations based on user specified optical elements
- 15 min. run time on our new SUN machine (in serial) to produce all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

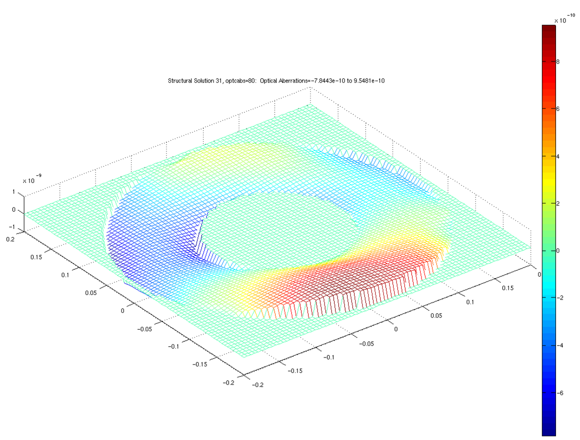
Computing Optical Aberrations from Thermal Deformations in Cielo

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



Summary

Cielo effectively implements thermal, structural, and optical aberration analyses in an open, extensible manner.

"Integrated modeling" can be a natural conclusion if the analytical capabilities are themselves fundamentally integrated.

Unique "predictive engineering" capability presented via common-model approach, Cielo capabilities, MATLAB integration.

Analytical, experimental validation results in excellent agreement.