Cielo: A MATLAB®-Hosted Environment for Multidisciplinary System Analysis

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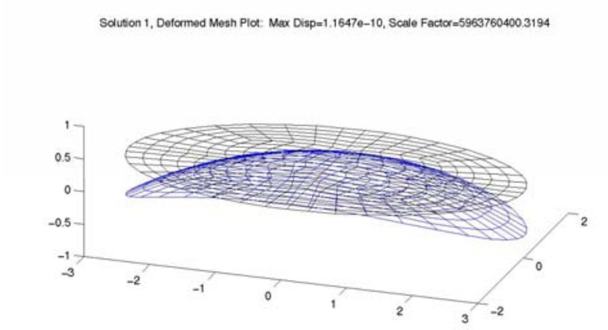
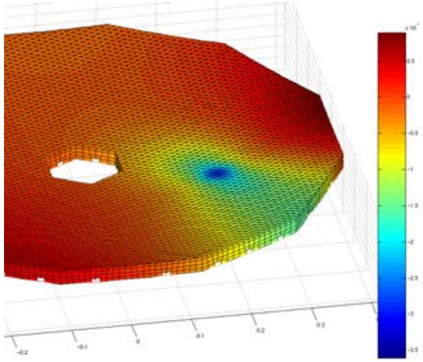
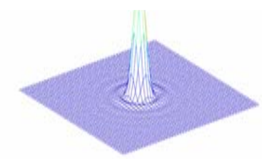
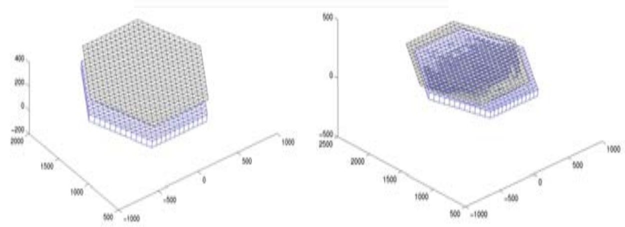
Outline

- Introduction: Motivation and Challenges
- Cielo Overview: Objectives, Approach and Enabling Technologies
- Examples
- Summary



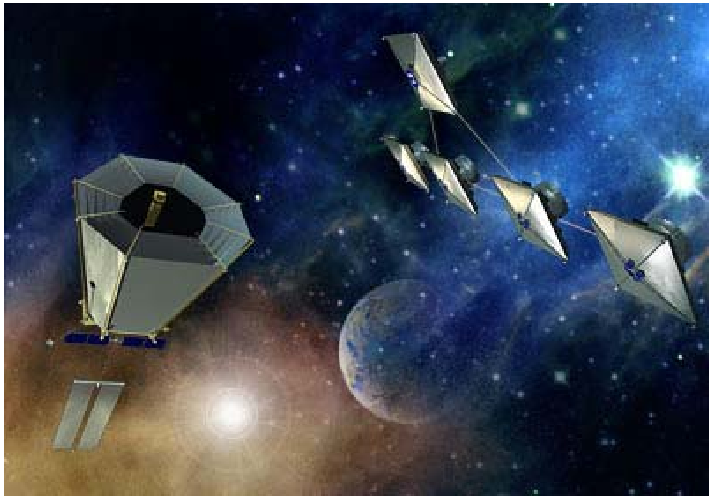




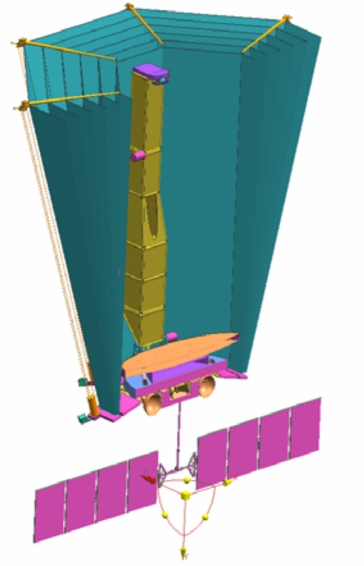


Motivation

- Case Study: Terrestrial Planet Finder – Coronagraph
  - Search for, and characterize Earth-like planets in the habitable zone around nearby stars
  - Distinguish planet light from starlight (1.0e-9 contrast ratios)
  - ~6 m class visible wavelength coronagraph operating in L2 orbit
  - Pre-flight, system-level hardware tests at operating conditions is impractical
  - Increased reliance on high-fidelity, multidisciplinary simulations.



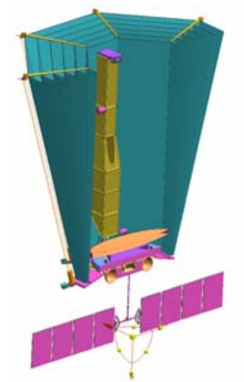
Artist's impression of the Terrestrial Planet Finder Coronagraph (TPF-C, left) and the Terrestrial Planet Finder Interferometer (TPF- I, right).



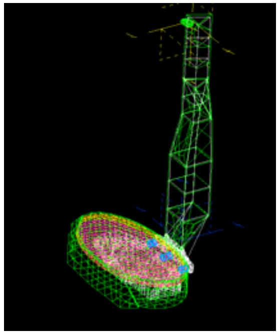
Cutaway geometric model of deployed configuration

Motivation

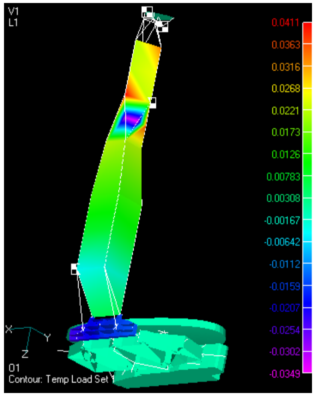
- 20° Dither Maneuver Analysis: Current State of the Art
  - Scenario: Stabilize, roll, collect data (>2 hrs) for speckle removal and planet detection
  - CAD/CAE modeling for system behavior and optical metrics using commercial tools (top row), and MATLAB hosted procedures (bottom row)

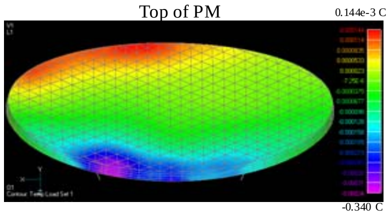


CAD model

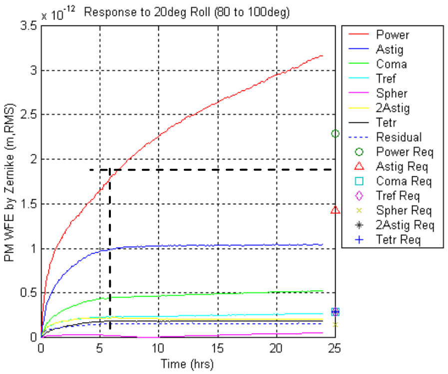


Analysis models: Thermal, mechanical, optical (common mesh)

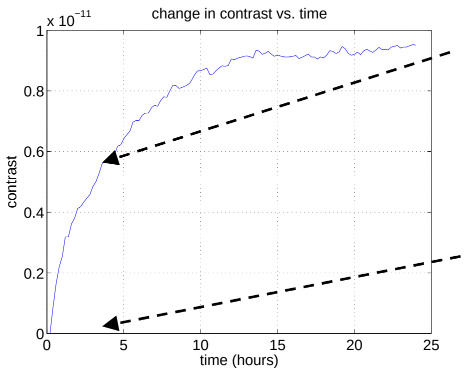




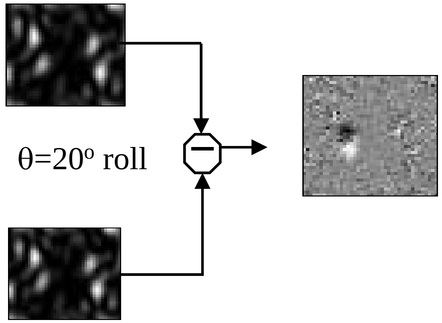
Thermo-mechanical response: Steady-state & transient



Transient WFE as Zernikes vs. Reqmts.



Transient Contrast after 20deg dither



θ=20º roll

θ=0º roll

Speckle Removal for Planet Detection

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

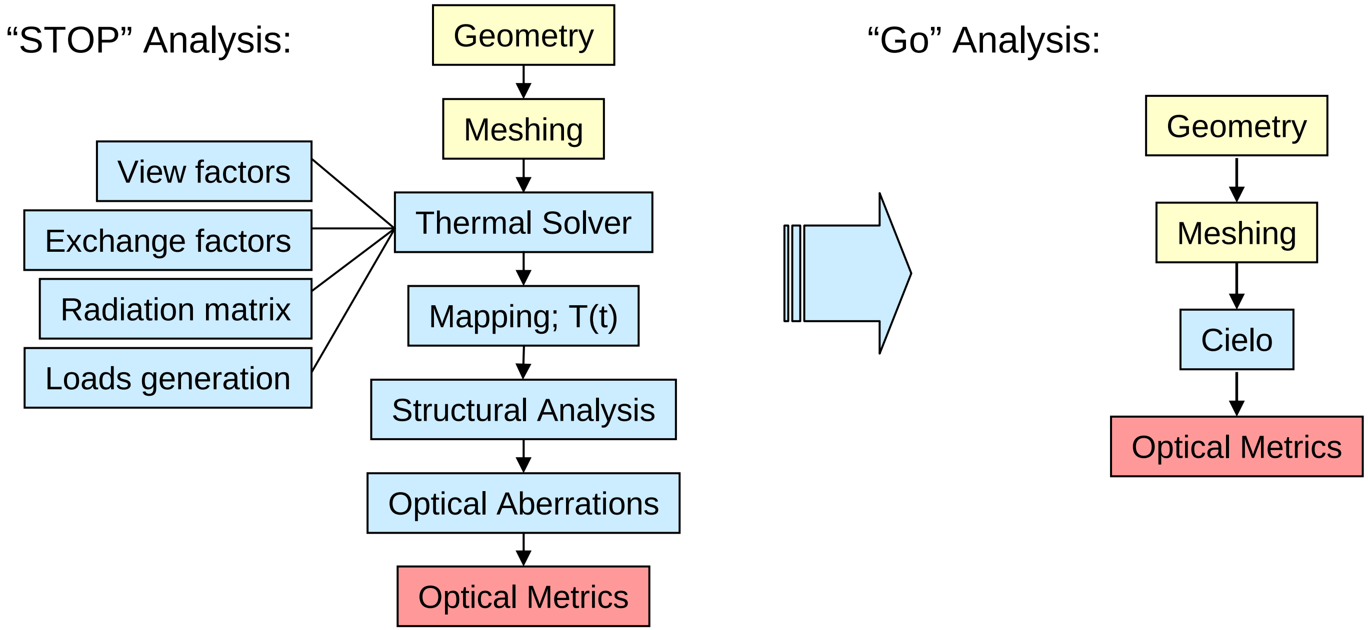
Cielo Overview

- 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
  - Five year plus development effort largely by team of former MSC/NASTRAN developers
  - 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

The MATLAB environment has proven to be an effective framework, enabling implementation, deployment, and vertical application development.

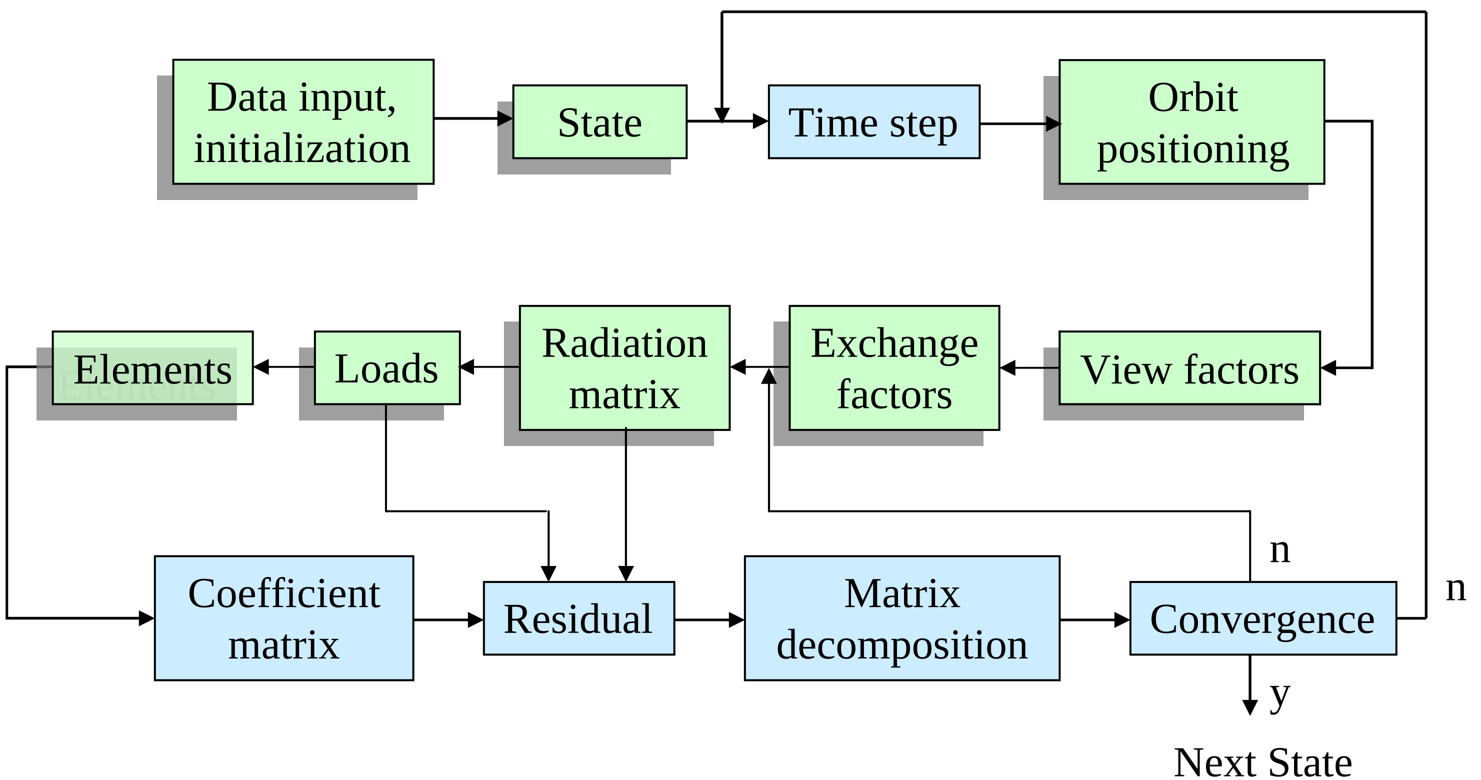
Cielo Overview

- 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



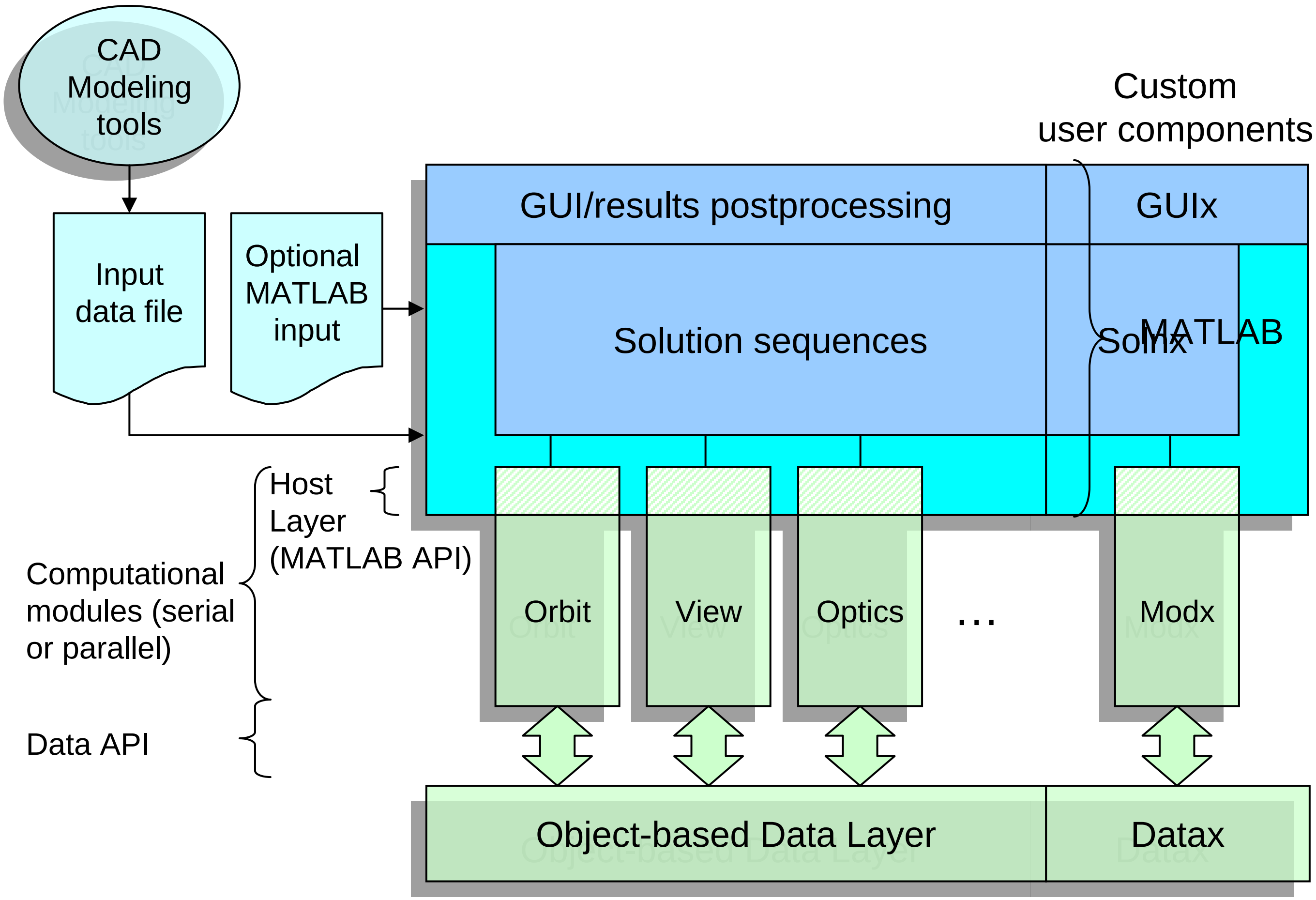
Thermal Solution Implementation

- 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, …)

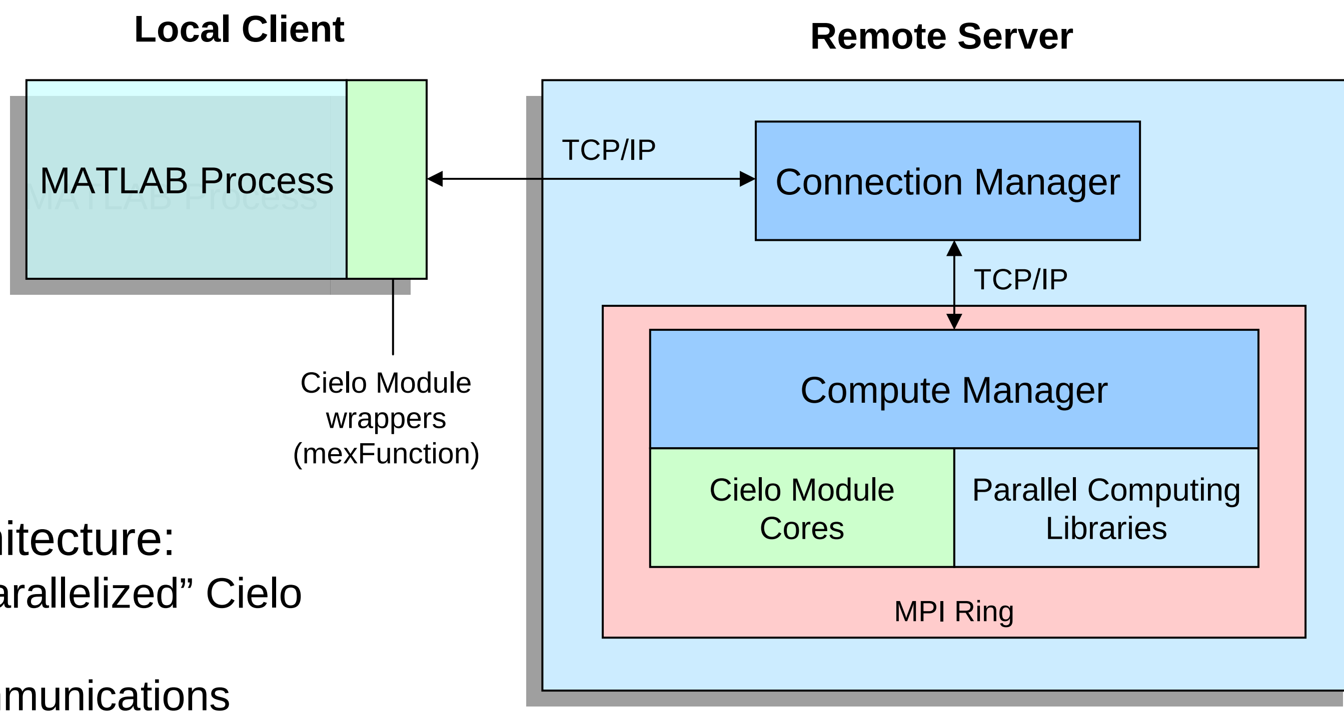


= Module (mexFunction) = MATLAB script, utility

Cielo Architecture



Parallel Architecture

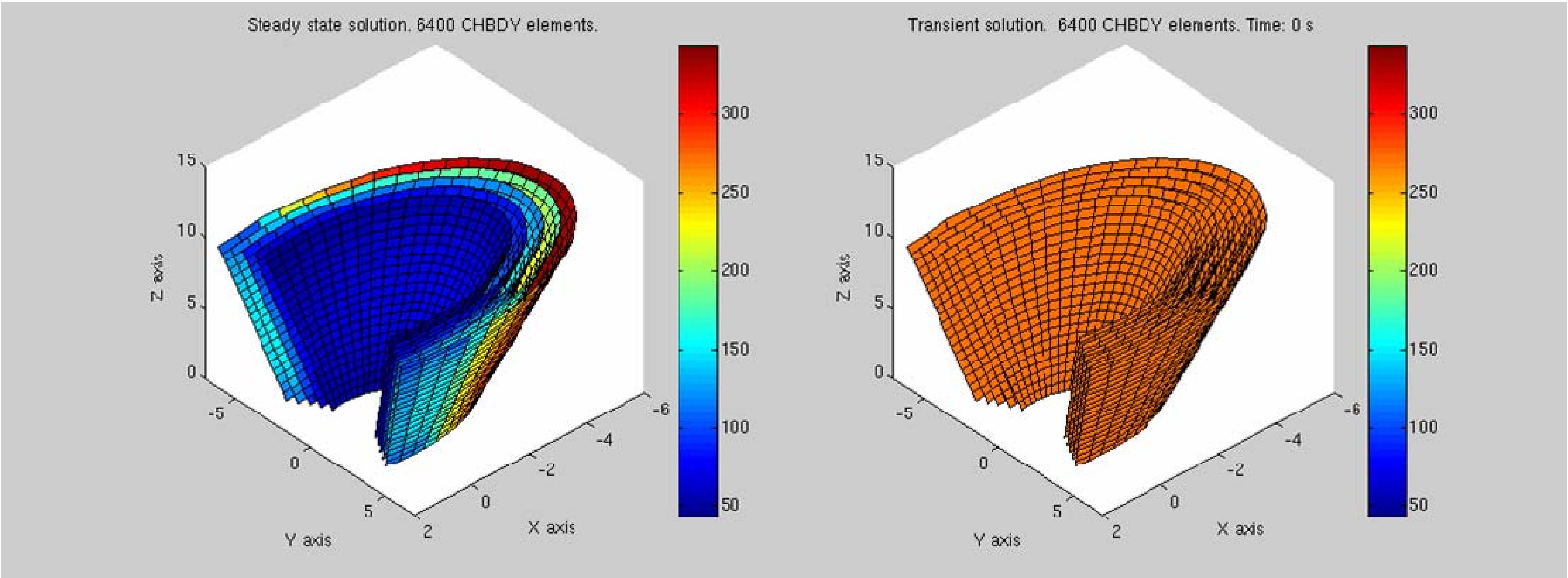


Client/Server Architecture:

- Enables calls to “parallelized” Cielo modules
- TCP/IP-based communications
- Remote Server operations driven by local MATLAB process
- Extended Parallel Compute Library interface (PETSc, Plapack, etc.)

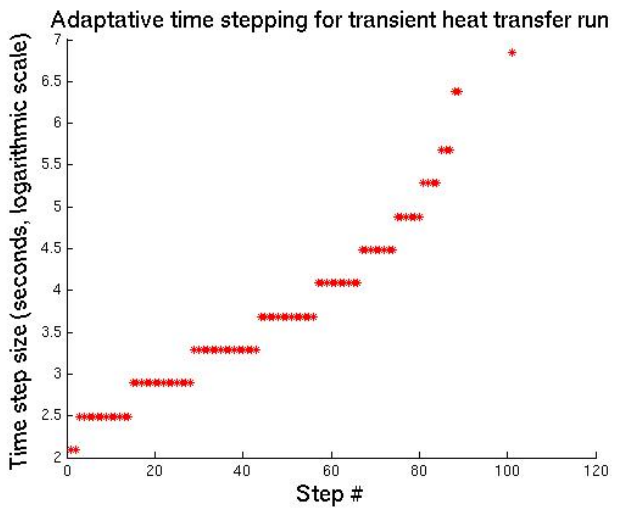
Distributed Computing Example

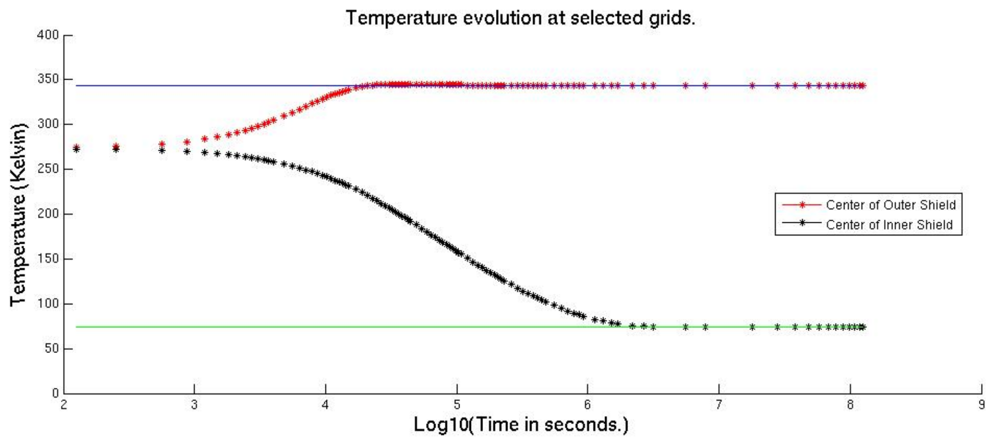
- TPF-C Alternative Sunshade concept:
  - Study heat dissipation effects from “open” sunshade (packaging, deployment concerns)
  - Multi-layer sunshield treated as diffusely exchanging surfaces (first approximation)
  - Investigate steady-state and short- and long-term transient solutions
- Computationally:
  - Numerical conditioning, adaptive time-stepping, numerical stability for low-capacitance systems (and other extreme cases, as in high-capacitance tests shown here)



Distributed Computing Example

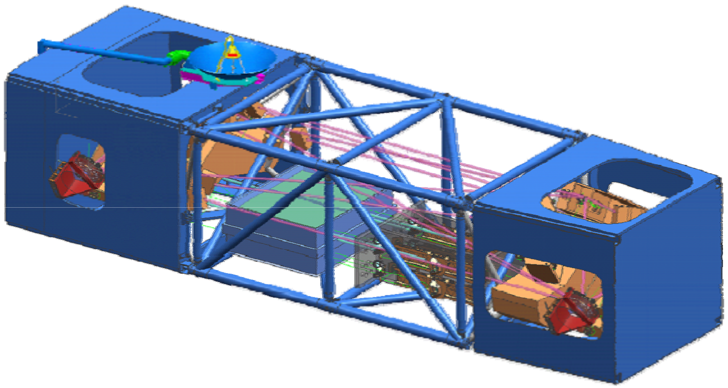
- MATLAB hosted implementation allows:
  - Client process interaction with local, and remote modules
  - Remote "embarrassingly parallel" computations, with results sets returned to the client workspace
  - Data postprocessing, user-level interaction within consistent, familiar MATLAB environment





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



Thermal/Optical Distortion Example

Thermal Solutions (UG NX TMG)

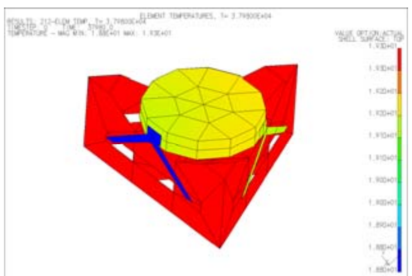
- 5 steady-state cases
- 2 transient (655 total time steps, ~21 hrs of transient phenomena)
- Temperature mapping in I-deas

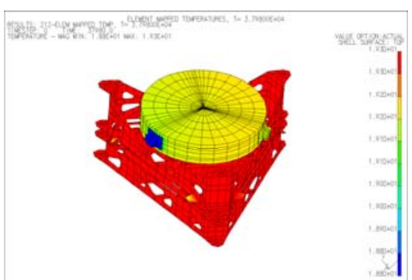
Thermal Distortion (Cielo)

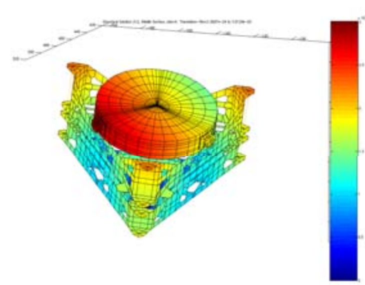
- Normal modes model verification
- Transient distortions in single runs (414 time steps in TC11, 241 in TC12)

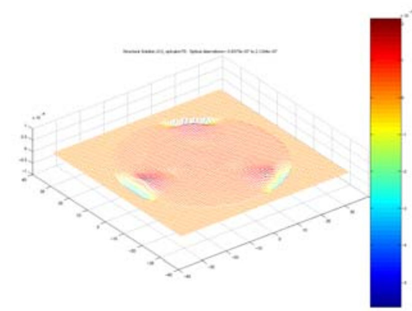
Optical Aberrations (Cielo)

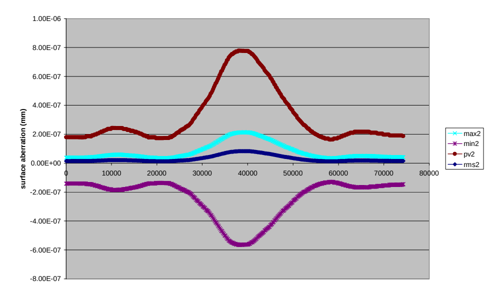
- Optical element definition as part of structural model
- Aberrations/interferogram file generation in Cielo
- Visualization, optical metrics, data postprocessing in MATLAB











"External" Analysis Phase

MATLAB hosted Analyses

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.

MATLAB provides a rational environment for complex solution procedure development and deployment.

Current, future work in areas of:

- Specular exchange, transmissive, specular effects
- Nonlinear characterizations
- Design sensitivity and optimization
- Vertical application development, Simulink integration