Application of NASTRAN Sensitivity Coefficients To the Design of High-Performance Optical Systems

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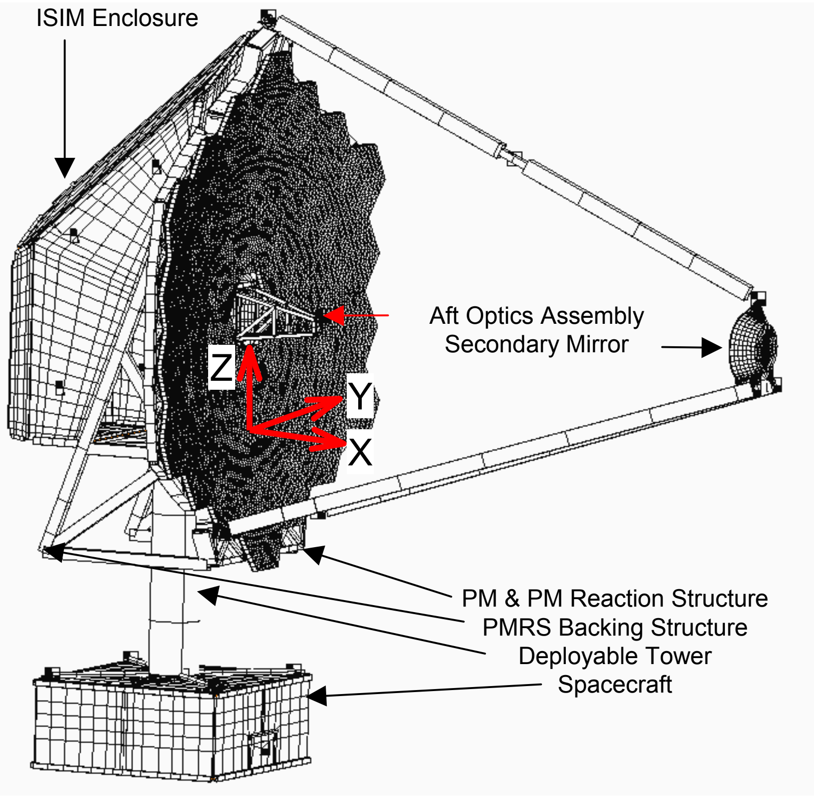
JWST Overview

- The James Webb Space Telescope (JWST) is an orbiting infrared observatory that will take the place of the HST.
  - Mass: 5400 kg (12,000 lbs)
  - Diameter of primary mirror: ~6.5 m (21.3 ft)
  - Optical resolution: ~0.1 arc-seconds
  - Wavelength coverage: 0.6 - 28 microns
  - Orbit: L2 halo orbit (1.5 million km from Earth)
  - Operating Temperature: <50 K (-370 °F)
- Major primary mirror innovations
  - Lightweight optics
  - Folding segmented mirror
  - Cryogenic actuators & mirror control

- Above information courtesy of JWST project web page (http://ngst.gsfc.nasa.gov)

NASTRAN Model

- Model logically consists of 6 sections
  - Spacecraft
  - Deployable Tower
  - PM Backplane
  - PM Segments
    - Center section
    - Two deployed wings
  - Secondary Mirror
  - Aft Optics Assembly



Analysis Technique Objective

- Observatory designed to allow required level of performance for very long exposures
  - Low-expansion materials
  - Minimize thermal gradients
  - Wavefront sensing and control
  - Traditional STOP analysis examines basic design
- Sought a fast integrated modeling procedure
  - Achieve sufficiently accurate error estimates without either NASTRAN statics or ray-tracing runs
  - Allow performance of Monte Carlo simulations or consideration of large trade spaces

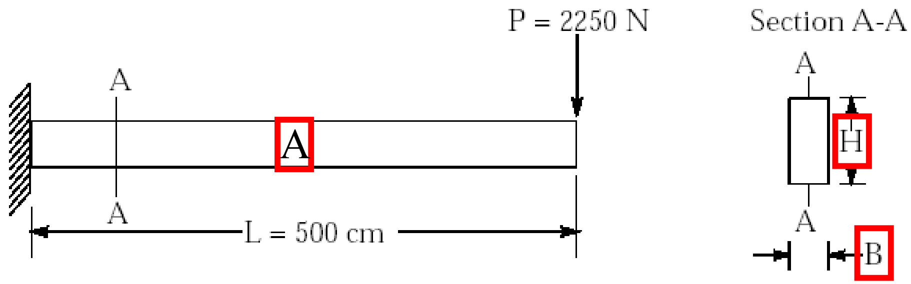
Sensitivity Coefficients

- MSC/NASTRAN Optimization approximates response quantities by a truncated Taylor Series expansion
  - Sensitivity coefficient is the constant of the Taylor series linear term
  - Sensitivity is therefore the first step in optimization
- Finds partials of response quantities, r_i, wrt design variable, x_i by means of chain rule, $\frac{\partial r_j}{\partial x_i} = \frac{\partial r_j}{\partial \{u\}} \cdot \frac{\partial \{u\}}{\partial x_i}$
  - First term is unity since we are studying displacements
  - Second term comes from static equilibrium equation,

$$[\mathrm{K}] \cdot \frac{\partial u}{\partial x_i} = \frac{\partial \mathrm{P}}{\partial x_i} \frac{|\partial \mathrm{K}|}{\partial x_i} \{u\}$$

[1]: Equations, example from NASTRAN optimization documentation

Sensitivity Analysis Example



Design Variables

- Sensitivity coefficients always computed for the design goal and constraints
  - Volume
    - $V = B\,H\,L$
    - $V \approx B_0H_0L + \mathbf{H_0L} \cdot \Delta B + \mathbf{B_0L} \cdot \Delta H + \mathbf{0} \cdot \Delta A$
  - Bending stress
    - $\sigma_{bend} = Mc/I = 6PL/BH^2$
    - $\sigma_{bend} \approx 6PL/B_0H_0^2\ \mathbf{- 6PL/(B_0H_0)^2} \cdot \Delta B\ \mathbf{- 12\,PL/B_0H_0^3} \cdot \Delta H + \mathbf{0} \cdot \Delta A$
  - Limit on thermal deflection
    - $\delta_{Therm} = AL(T_2\text{-}T_1)$
    - $\delta_{Therm} \approx A_0L(T_2\text{-}T_1) + \mathbf{0} \cdot \Delta B + \mathbf{0} \cdot \Delta H + \mathbf{L(T_2\text{-}T_1)} \cdot \Delta A$
    - Can not make CTE(T) a design variables

Linear Optical Modeling

- Joe Howard creates optical sensitivity array
  - Introduces a small motion for each optical DOF
    - Performs a ray trace
    - Recovers the OPD at the exit pupil
  - 3-D array of size 100 x 100 x 6n
    - This work considered only rigid optics
    - Exported to MATLAB
- Disturbed optical performance calculated
  - Motion of each optical DOF generated in some way
  - Array elements multiplied by calculated motion
  - Scaled arrays summed
    - Generate a single 100x100 OPD map
    - Mean despace and centroid-drift removed

Material CTE Analysis

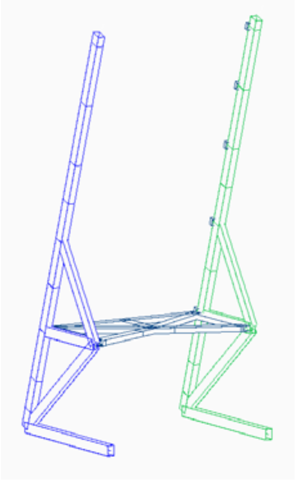
- Monte Carlo analysis used to establish probabilistic criteria for metering structure CTE
  - Determine critical parts of the metering structure
  - Create design variables for each selected area
  - Create relationships to the selected properties
  - Create design constraints of optical DOF
  - Select optimization via DSAPRT(END=SENS)=ALL
- Read coefficients into MATLAB
  - Calculate WFE using linear optics
  - Repeated these calculations thousands of times
  - Calculate mean and standard deviations of optical performance figure of merit (OPD)

Analytical Judgments

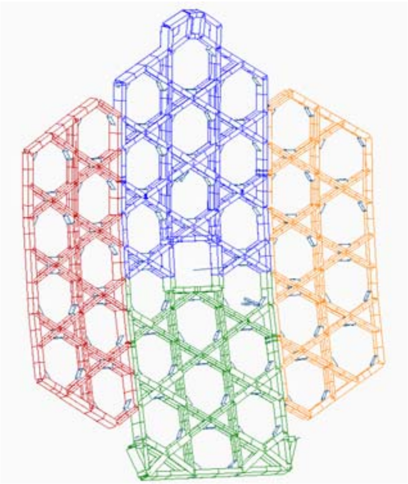
- Used contractor-delivered structural math models
  - Constrained kinematically
- Applied uniform delta-T to entire model
  - Magnitude comparable to the slew temperature changes
  - Gradients from actual temperature sets would have complicated results interpretation
    - Highest coefficients would have come from locations experiencing the greatest temperature changes during the slew
    - Would have been slew-case dependent

Structural Details

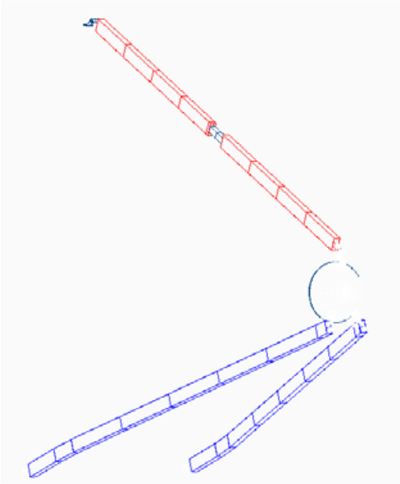
PM Support Structure

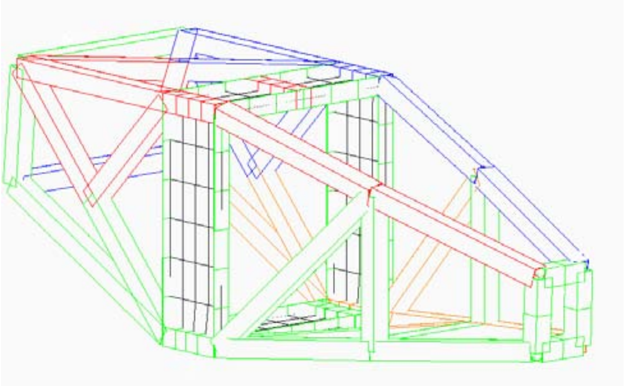


PM Backplane



Secondary Tower Assembly





Aft Optics Assembly

Random CTE Generation

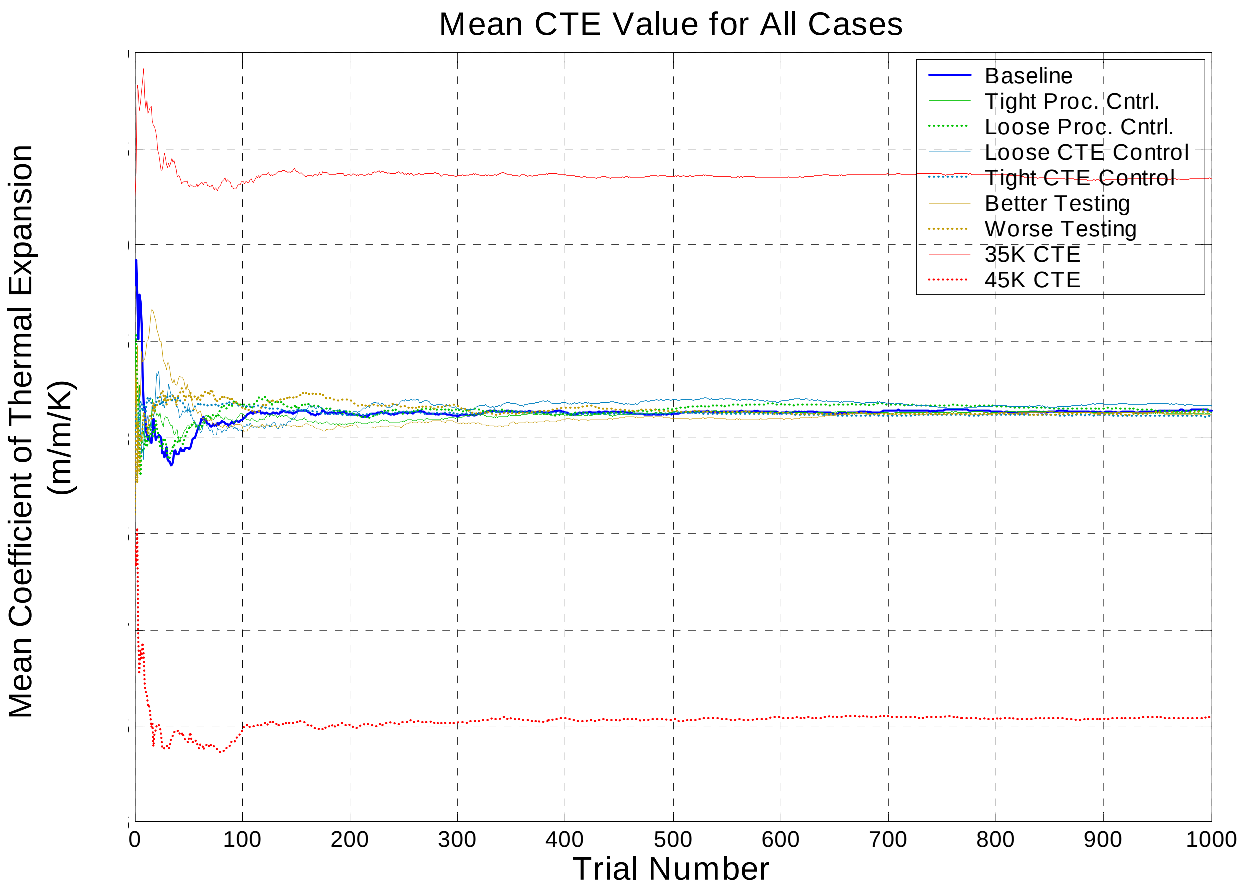
- Generated Gaussian random number
  - $\mu = 0$, $\sigma = 1$
  - Multiplied by the 1 - σ value of CTE for particular trial
    - Representing variations in manufacturing process control
  - Filtered using a trial-specific bandpass
    - Repeat process if value exceeds limits
  - Add in nominal CTE value
    - Representing variations in OTE temp. from nominal T.
- Generated random number between –1 and 1
  - Uniform distribution
  - Multiplied by a test uncertainty factor
  - Added to the value from previous step

Analysis Cases

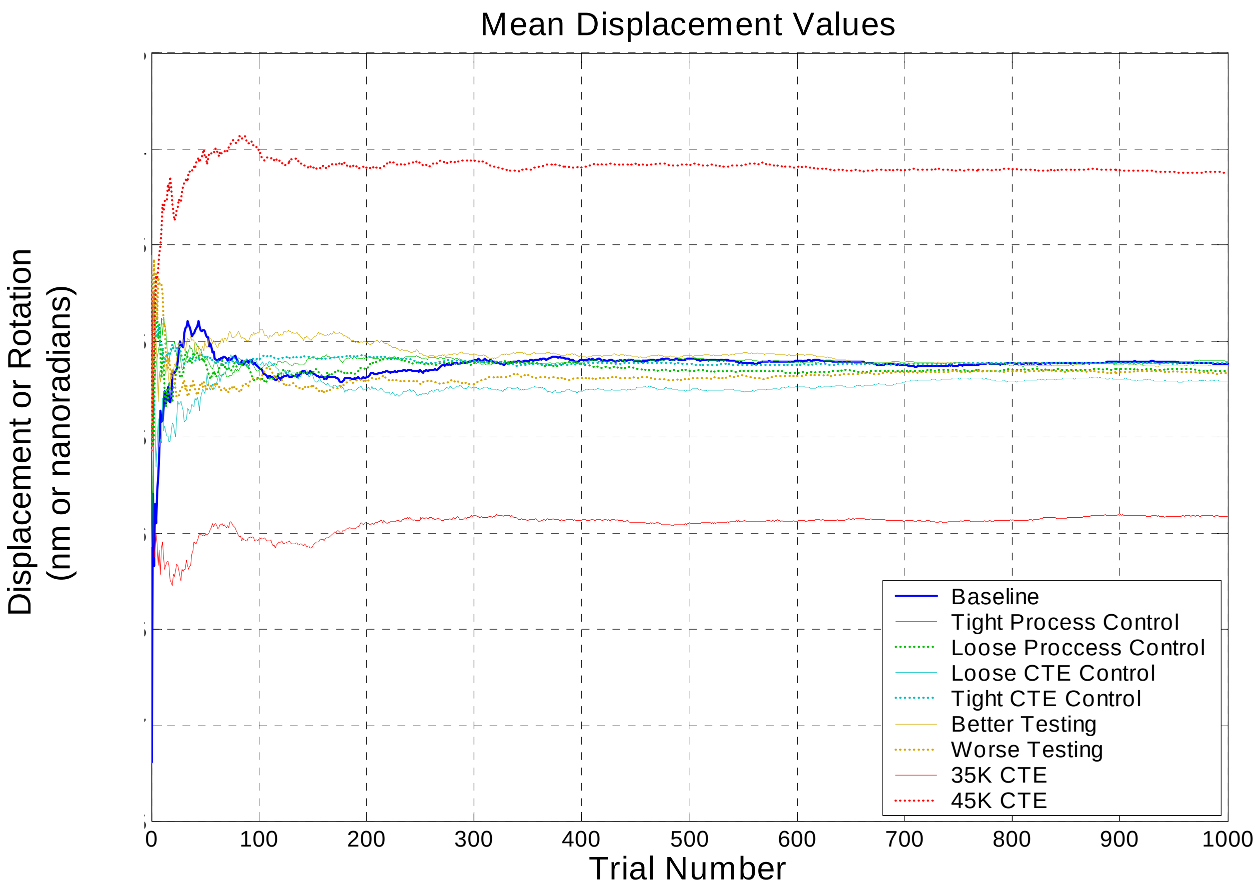
Case	1 Stnd. Deviation (ppb/K)	Bandpass Filter (ppb/K)	Test Uncertainty (ppb/K)	Reject Rate (%)	Mean CTE (ppb/K)	Comments
1	σ	± ω	± β	20	α	Baseline Case
2	.78σ	± ω	± β	10	α	Narrow CTE Spread
3	1.9σ	± ω	± β	50	α	Wide CTE Spread
4	σ	± .40ω	± β	61	α	Tighter CTE control
5	σ	± 2.0ω	± β	1.4	α	Looser CTE control
6	σ	± ω	± .50β	20	α	Better CTE testing
7	σ	± ω	± 2.0β	20	α	Worse CTE testing
8	σ	± ω	± β	20	1.15α	35K Nominal Temp
9	σ	± ω	± β	20	.805α	45K Nominal Temp

- Cases should be considered as four pairs to be compared to the baseline

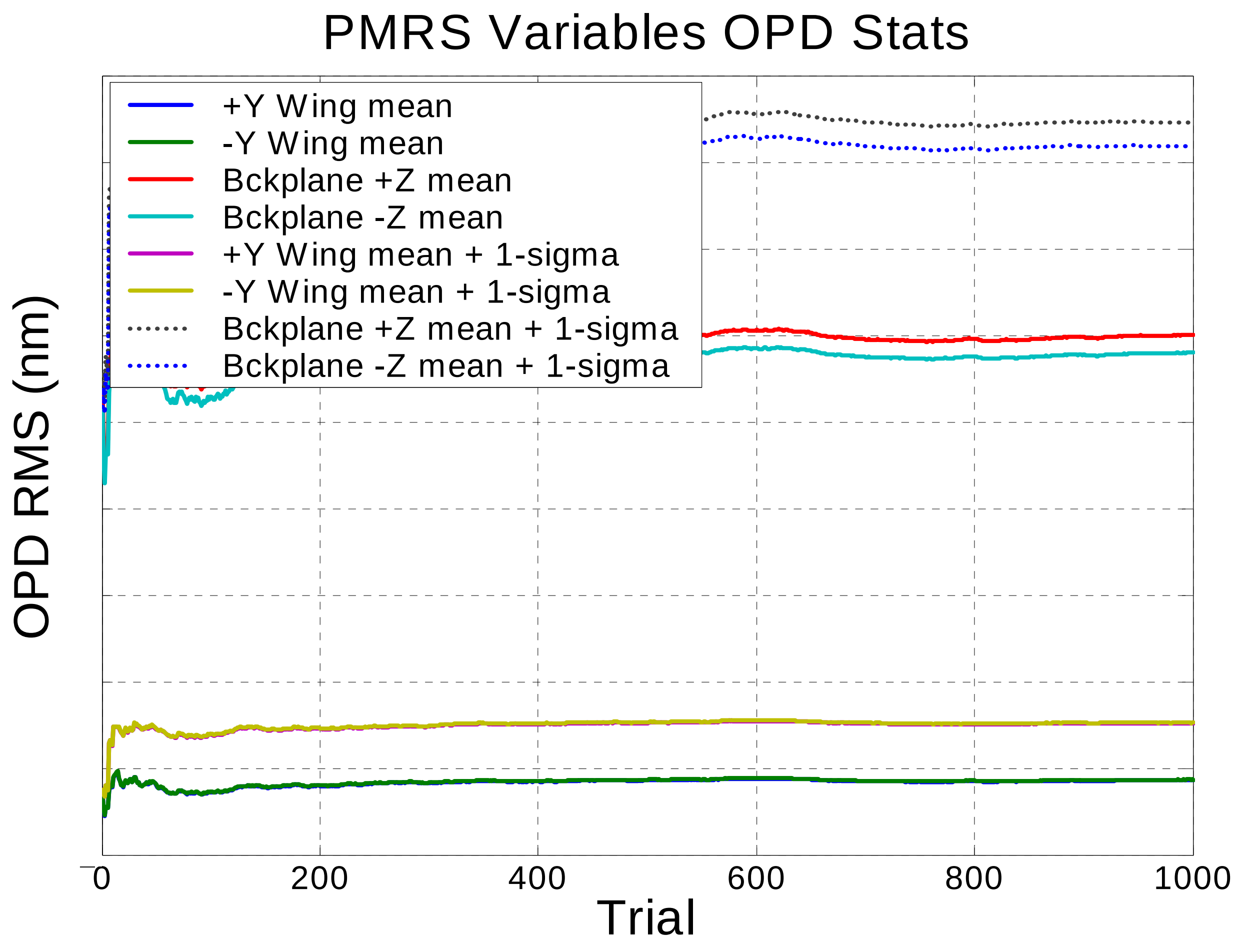
Mean CTE Convergence (All Trials)



Mean Displacement Convergence (All Trials)



Design Variable Error Contributions (Nominal Case)



Conclusions

- Detailed multi-disciplinary analyses can be augmented with sensitivity coefficient-based analysis
- NASTRAN models can generate linear estimations of the effect of changes in structural parameters
- Optical analysis tools can create similar linear models of wavefront error
- Eliminates thousands of NASTRAN model runs and equal numbers of ray-tracing runs