Design optimization with system level adaptive optical performance

Sigmadyne

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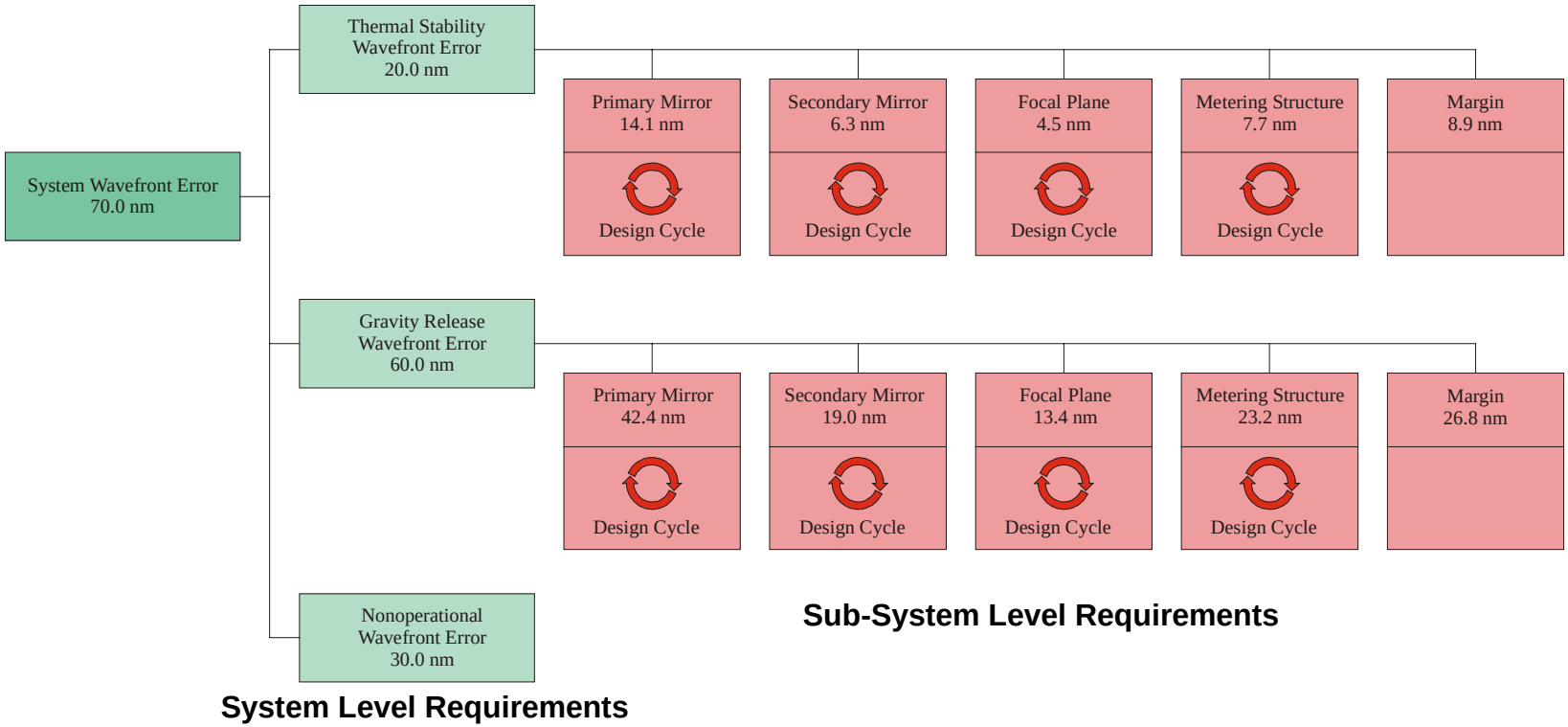
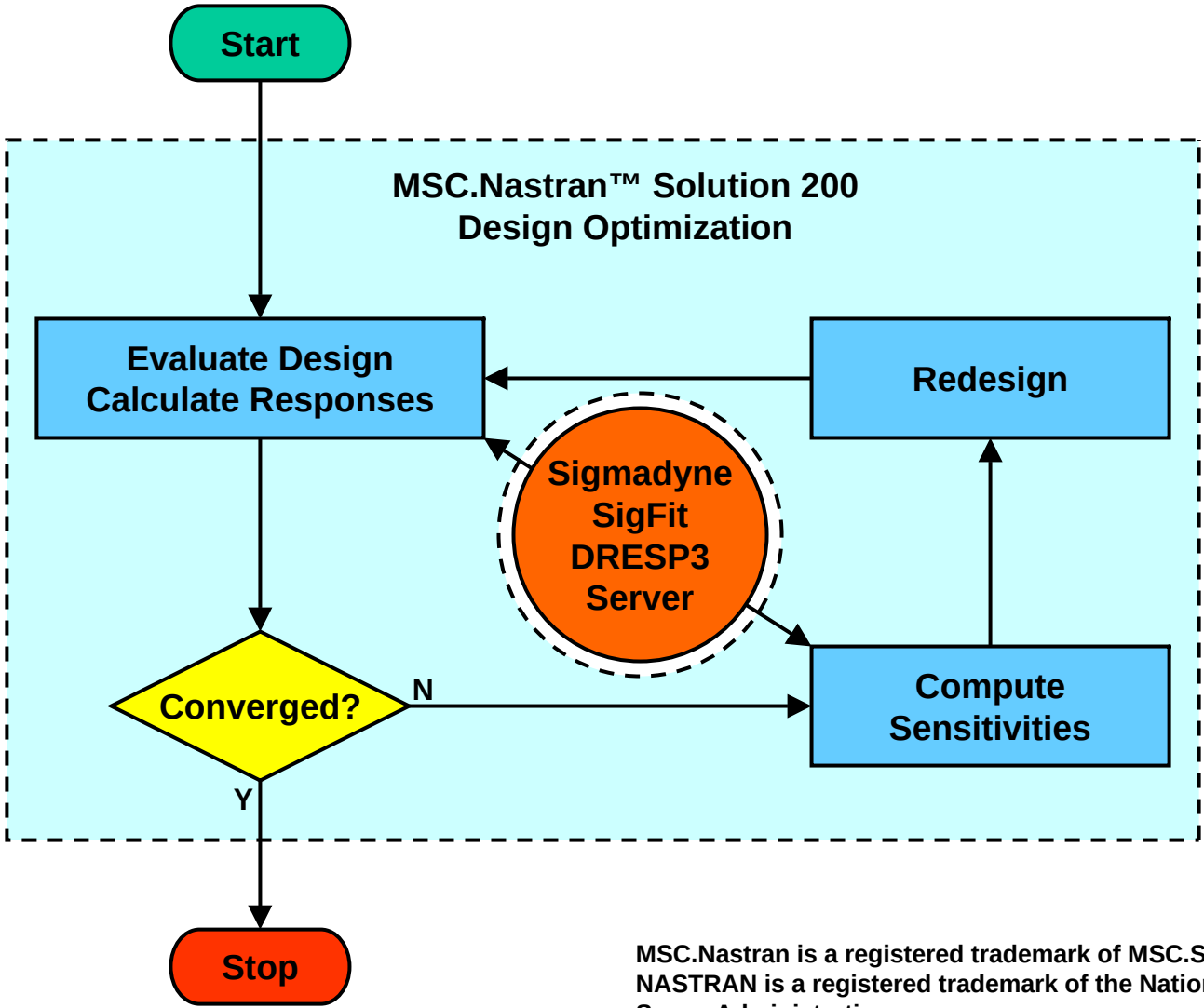
Objective

- Enable optimization with system level requirements rather than sub-system level requirements
  - Allows early feasibility studies with one system level model
  - Helps with budget flowdown for later detailed sub-system design efforts



Implementation Overview



System Adaptive Control Simulation

- Actuator influence functions Φ_m decomposed into rigid body motions and Zernike polynomials, B_{jm}, for m^{th} actuator and j^{th} rigid body motion or Zernike polynomial
- Matrix of system sensitivities, S_{kj}, transforms actuator influence surface functions, B_{jm}, to system wavefront influence functions, U_{km}

$$U_{km} = S_{kj} B_{jm}$$

- Similar transformation for i_{th} disturbance

$$Z_{ki} = S_{kj} C_{ji}$$

- Corrected system wavefront error is disturbance plus actuation

$$E = \sum_{k}^{Z} w_k \left(Z_{ki} - \sum_{m}^{M} U_{km} A_m \right)^2$$

- Minimizing E w/r to actuator input A_m gives linear equations for actuator inputs

$$[H]\{A\} = \{F\} \qquad H_{qm} = \sum_{k}^{Z} w_k U_{qk} U_{km} \qquad F_q = -\sum_{k}^{Z} w_k Z_k U_{kq}$$

Reference 1

Implementation in MSC.Nastran™ DRESP3

- MPCs compute rigid body motions and Zernike coefficients for each surface for actuator influence functions and disturbances
- Subcase specific DRESP1s reference GRID and SPOINT data
- DTABLE stores user selections, optical sensitivities, and constants
- Data passed to precompiled DRESP3 server for computation of system level corrected performance as synthetic response
- All bulk data cards written by SigFit as preprocessing step
- DRESP3 server is subroutine form of SigFit

```
grid     2000001    1000     0.0     0.0     0.0    1000
rbe3     2000001         2000001  123456 1.26938     123   10001
+        1.22097     123   10002   10007   10008   10009   10010   10011
+        0.81398     123   10003   10043   10203   10363   10523   10683
...
spoint   2001001 thru    2001037
mpc*             2000001         2001001               0 -4.39369200E-05
*                  10001               1 -3.89932992E-02
*                                  10001               2  2.25127918E-02
*                  10001               3 -1.50818754E+00
*                                  10002               1 -3.33627870E-02
....
```

```
DTABLE  ina     1.0     ns     3.0     wvl     3.9370-8izk     5.0
        nat     9.0     ndt1   1.0     ndt2    12.0    isys    1.0
        prt     3.0     ism01  3.0     nzp01   37.0
        a00001  -93.954 a00002 -93.954 a00003  4.6211+5a00004  1.0097+4
....
```

```
DRESP3   101     GRAVREL SIGFIT  SIGFRMS
         DTABLE  ina     ns      wvl     izk     nat     ndt1    isys
                 prt     ism01   nzp01   a00001  a00002  a00003  a00004
                 a00005  a00006  a00007  a00008  a00009  a00010  a00011
....
         DRESP1  101001  101002  101003  101004  101005  101006  101101
                 101102  101103  101104  101105  101106  101107  101108
....
```

Reference 2

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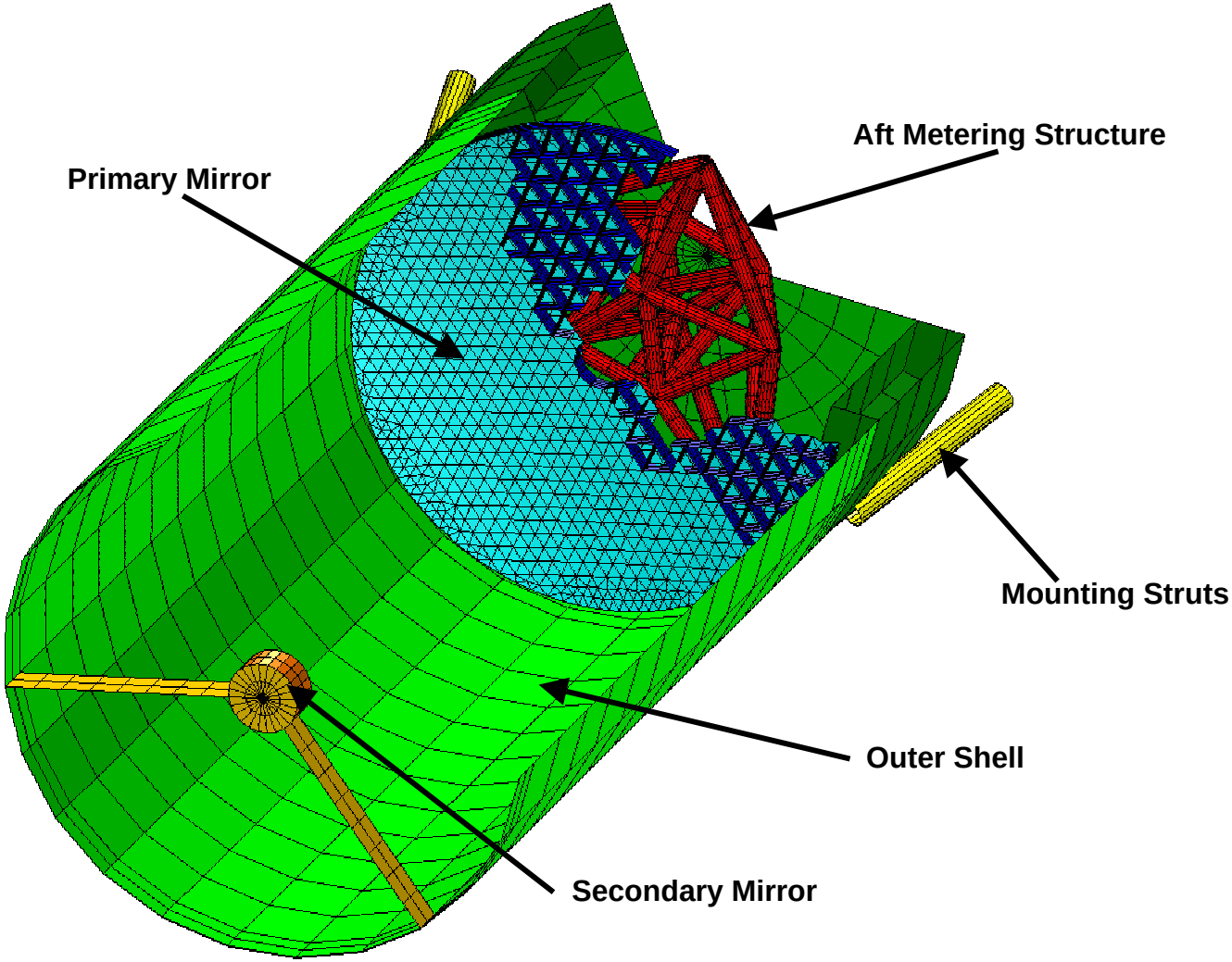
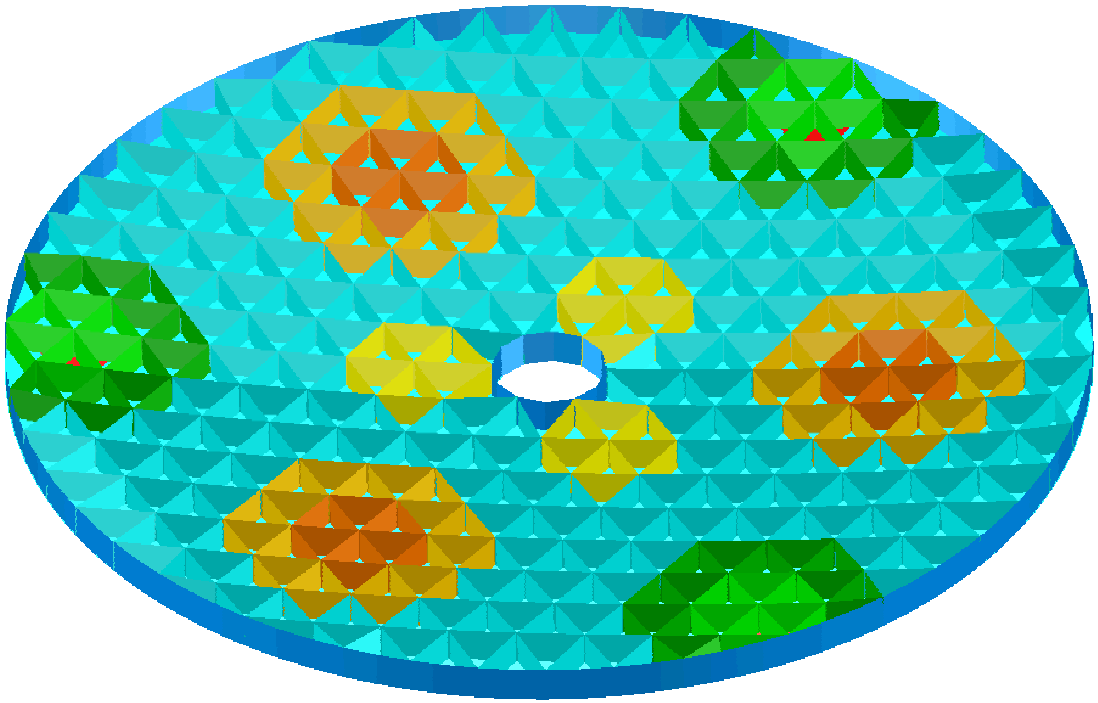
Example 1: Telescope Model

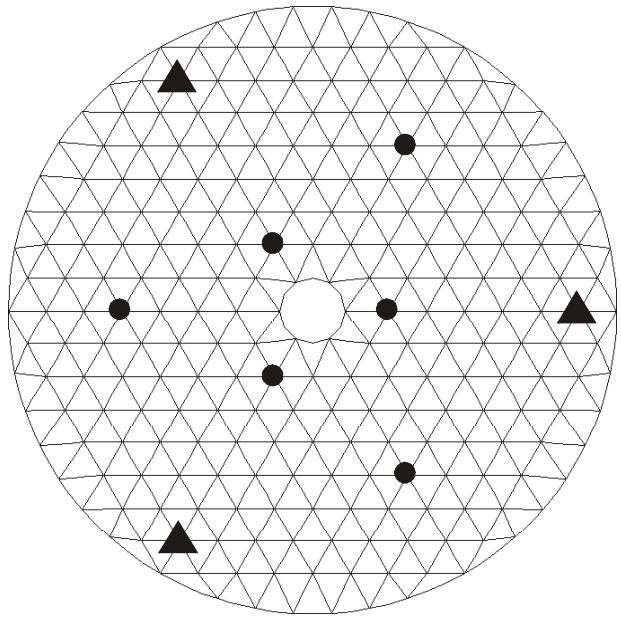


Example 1: Primary Mirror Model

- Core wall thicknesses allowed to vary near mounts and force actuators



Plot of PM FEM with front faceplate erased
Colors show different core wall thicknesses



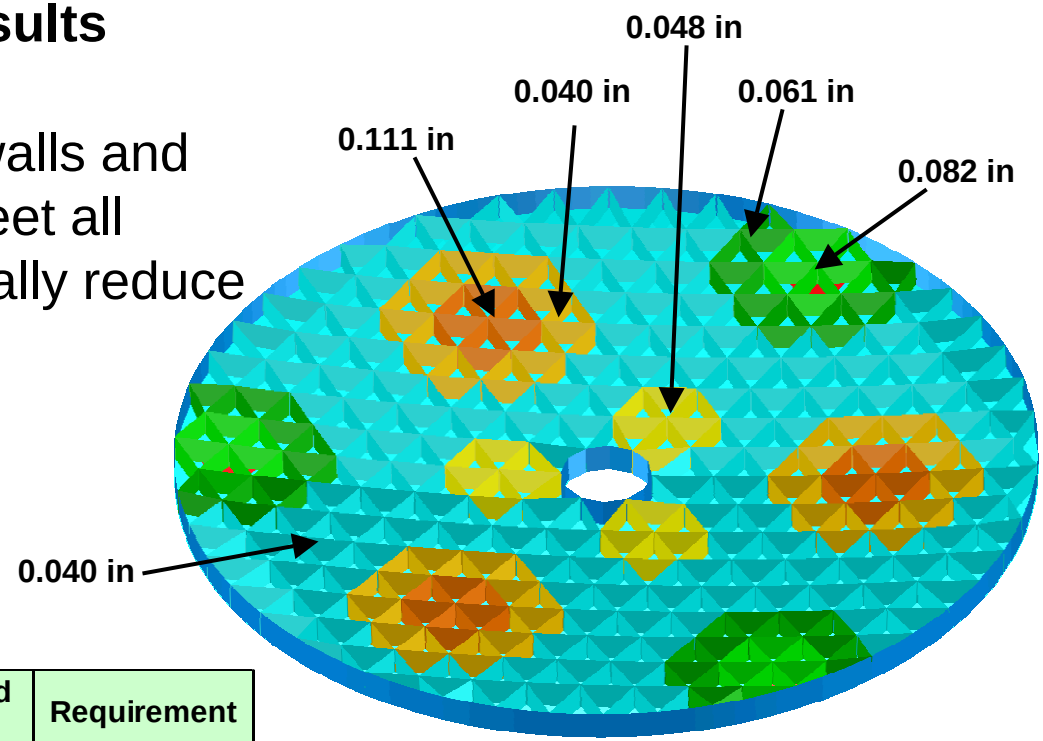
Plot of PM core layout with actuator locations shown
Triangles: Displacement actuators
Circles: Force actuators

Example 1: Optimization Statement

- MINIMIZE: Primary mirror weight
- DESIGN VARIABLES:
  - Optical facesheet thickness: 0.18 inch < t_f < 0.25 inch
  - Back facesheet thickness: 0.10 inch < t_b < 0.25 inch
  - Interior core wall thicknesses: 0.04 inch < t_c < 0.25 inch
  - Inner and outer core wall thicknesses: 0.08 inch < t_c < 0.25 inch
  - Core depth: 0.25 inch < t_c < 5.0 inch
- SUBJECT TO:
  - Thermally induced system wavefront error < 20 nm RMS
  - Gravity release induced system wavefront error < 60 nm RMS
  - Peak launch induced stress in PM < 1000 psi
  - First mounted PM natural frequency > 200 Hz

Example 1: Optimization Results

- Optimization adjusts core walls and faceplate thicknesses to meet all requirements and dramatically reduce weight

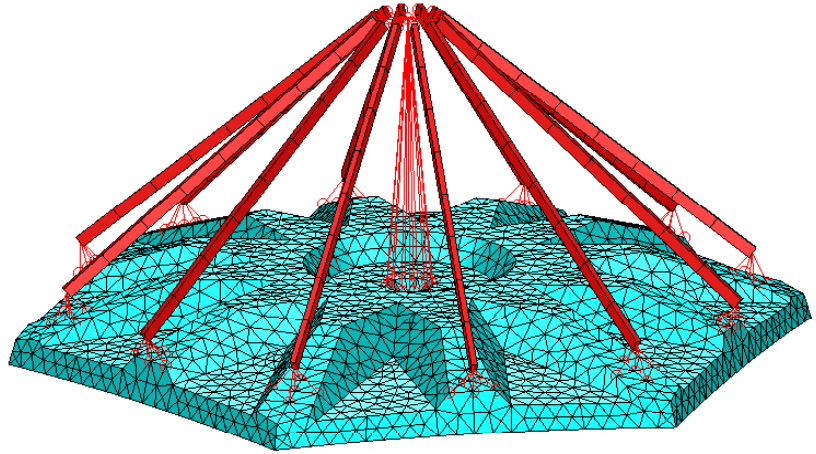


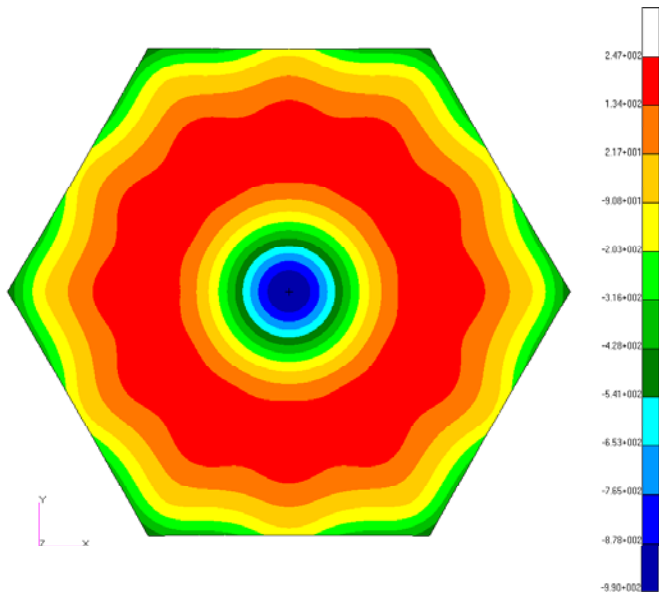
Core wall thicknesses of optimized design

Response	Initial Design	Optimized Design	Requirement
Thermally Induced Wavefront Error	9 nm	20 nm	20 nm
Gravity Release Induced Wavefront Error	54 nm	60 nm	60 nm
Peak Launch Stresses	1000 psi	1000 psi	1000 psi
First Natural Frequency	231 Hz	221 Hz	200 Hz
Weight	20.8 kg	9.9 kg	Minimum
Areal Density	53.0 kg/m^2	25.2 kg/m^2	Minimum

Example 2: SPOT Optimization

- Objective
  - Develop a back surface profile to allow optimum correction of ±2 mm change in radius-of-curvature
  - Residual surface error of 5 nm RMS desired
- Baseline Design
  - 225 nm RMS corrected surface
  - Relatively good control of azimuthally varying residual error
  - Considerable primary spherical in the residual error
  - Primary spherical can be substantially removed with proper profile

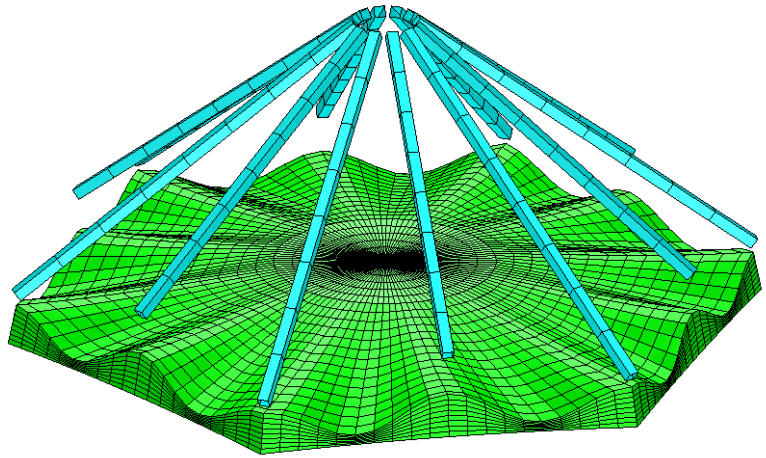




Courtesy NASA Goddard Space Flight Center

Corrected Surface Error of Baseline Design

Example 2: SPOT Optimization



- Optimized Design
  - Coefficients of two-dimensional polynomials used as shape design variables

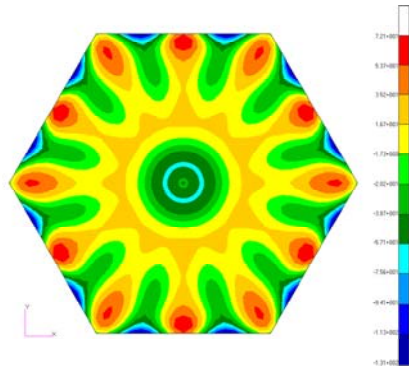
$$f(r,\theta) = a_0 \quad r \le 127\ mm$$

$$f(r,\theta) = a_0 + a_1\frac{(r-127)}{310.728} + a_2\left[\frac{(r-127)}{310.728}\right]^2 + a_3\left[\frac{(r-127)}{310.728}\right]^3 + a_4\left[\frac{(r-127)}{310.728}\right]^4 +$$

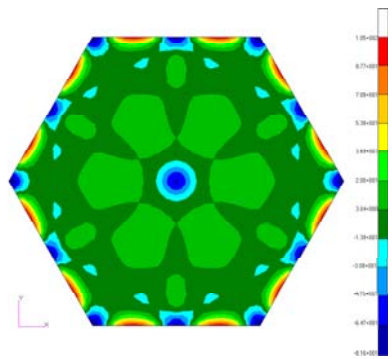
$$b_1\left[\frac{(r-127)}{310.728}\right]\cos(6\theta) + b_2\left[\frac{(r-127)}{310.728}\right]^2\cos(6\theta) + b_3\left[\frac{(r-127)}{310.728}\right]^3\cos(6\theta) + b_4\left[\frac{(r-127)}{310.728}\right]^4\cos(6\theta) +$$

$$c_1\left[\frac{(r-127)}{310.728}\right]\cos(12\theta) + c_2\left[\frac{(r-127)}{310.728}\right]^2\cos(12\theta) + c_3\left[\frac{(r-127)}{310.728}\right]^3\cos(12\theta) + c_4\left[\frac{(r-127)}{310.728}\right]^4\cos(12\theta)$$

  - Central flat area required for processing
  - 33 nm RMS corrected surface down from 225 nm RMS
  - 21 nm RMS corrected surface with no central flat
  - Residual surface contains high-order deformations driven by only local actuator attachment behavior



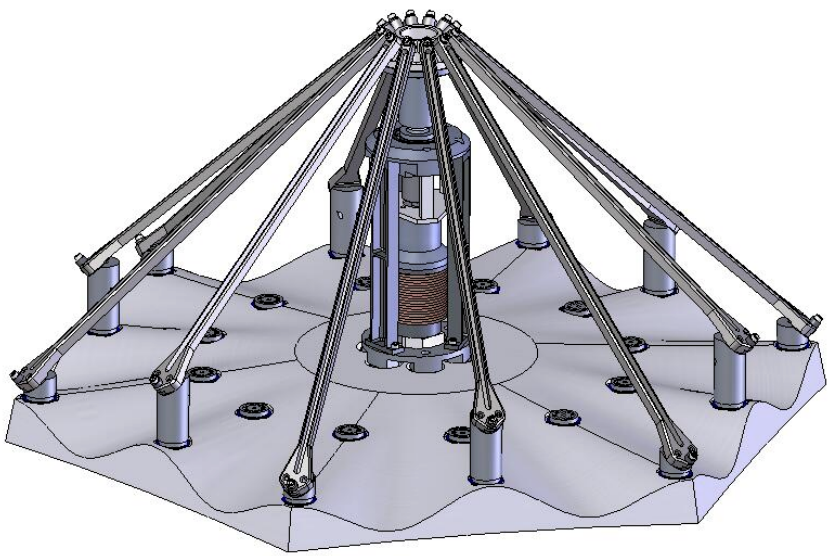
Corrected Surface Error of Optimized Design

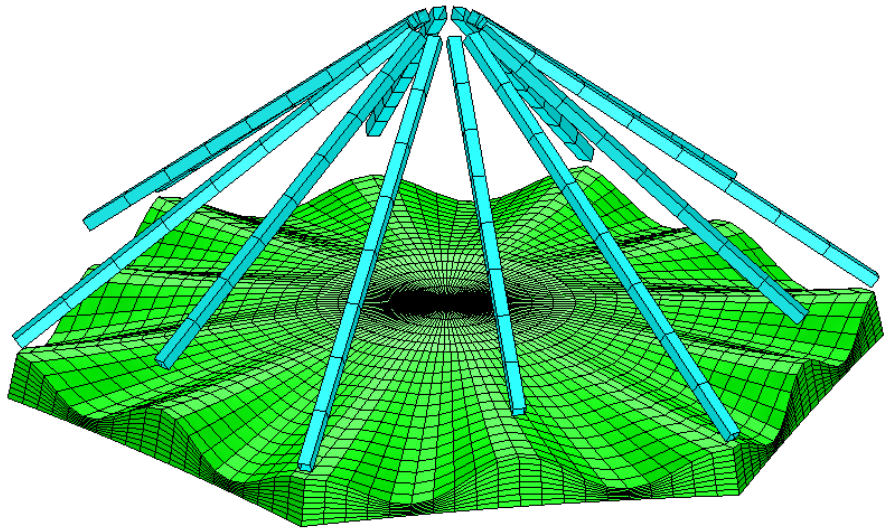


Corrected Surface Error of Optimized Design with No Central Flat

Courtesy NASA Goddard Space Flight Center

Example 2: SPOT Hardware





Courtesy NASA Goddard Space Flight Center

Reference 5

Summary

- MSC.Nastran™ DRESP3 allows optimization using higher level optical performance metrics
  - Early trade studies compare concept optimums vs. point designs
  - Error budget and rough design flow down to sub-assemblies based on true combined optical and mechanical behavior; not guesswork and prior experience
  - Optimizations take advantage of system level interactions
- Implemented in next SigFit version (Summer 2005)

References

1. K. Doyle, V. Genberg, G. Michels, "Integrated optomechanical analysis of adaptive optical systems", SPIE Vol. 5178 (5), San Diego, CA, August, 2003.
2. **MSC.NASTRAN™ 2004 Design Sensitivity and Optimization User's Guide**, MSC.Software, Santa Ana, CA, 2003.
3. Doyle, Keith B., Victor L. Genberg , Gregory J. Michels, **Integrated Optomechanical Analysis**, SPIE Press, Bellingham, WA (2002).
4. Michels, Gregory J. et. al., "Design optimization of system level adaptive optical performance", SPIE Vol. 5867 (25), San Diego, CA, August, 2005.
5. Budinoff, Jason, "Design & Optimization of the Spherical Primary Optical Telescope (SPOT) Primary Mirror Segment", FEMCI Poster Session, May 2005.