# Advanced Mirror Technology Development (AMTD) thermal trade studies

Thomas Brooks

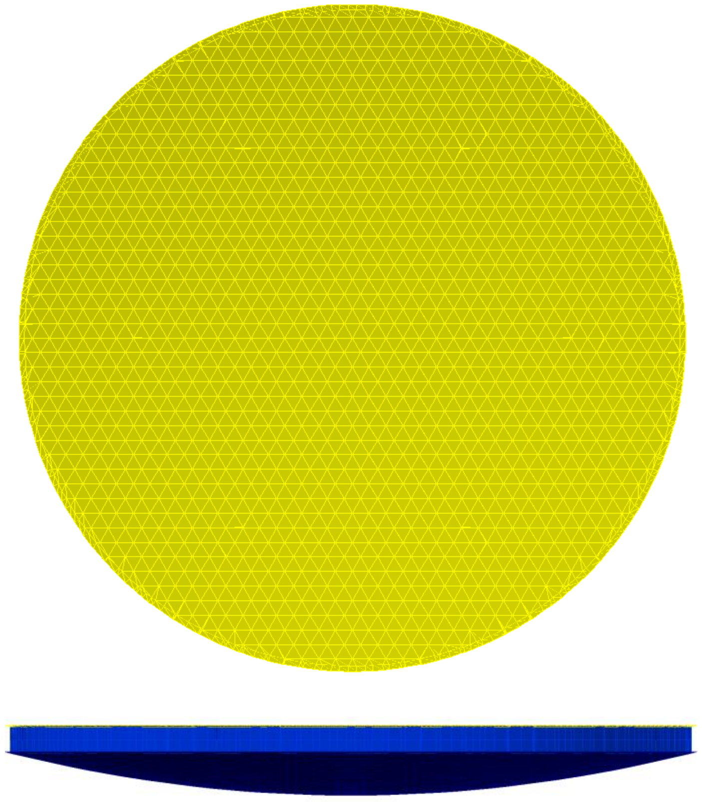
(256) 544 – 5596

thomas.brooks@nasa.gov

# Description of Primary Mirror

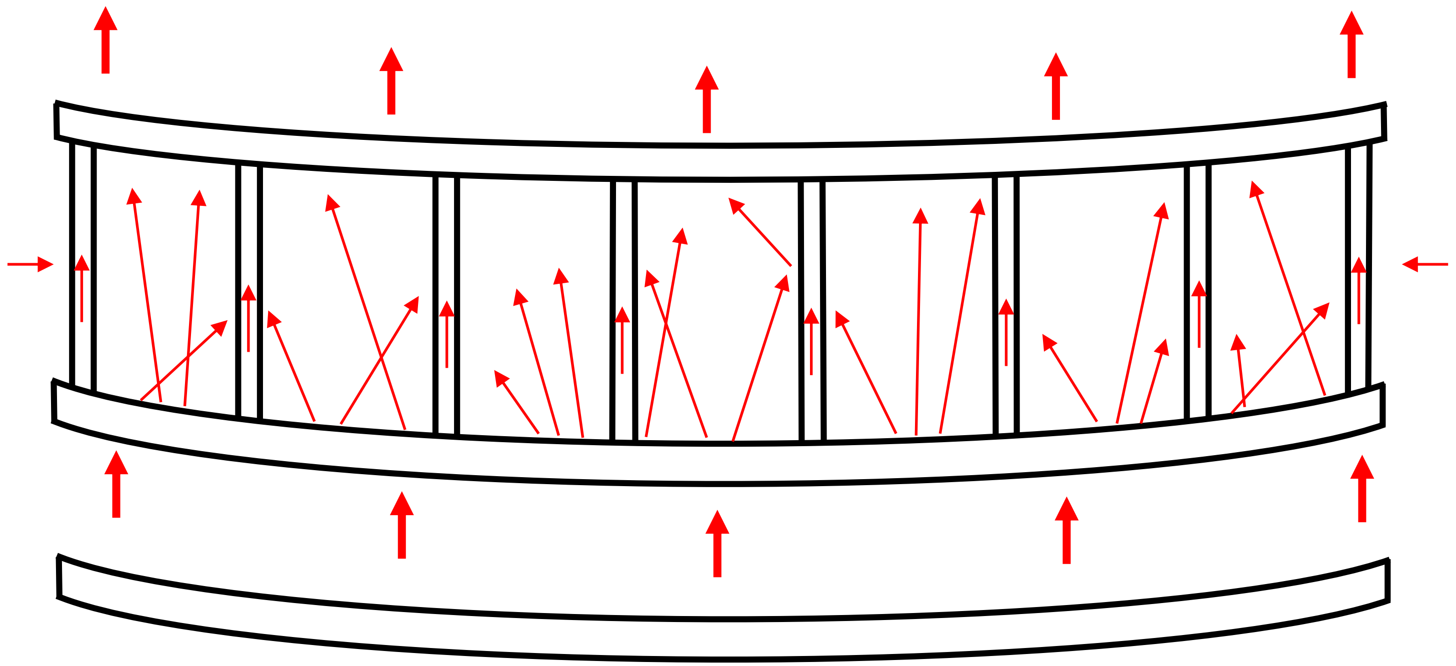
- 4m Circular Monolith
- 0.152m depth front to back
- Light-weighted with a back sheet
- Areal Density is 146 $kg/m^2$
- Optical face coated with $\varepsilon_{aluminum}=0.03$
- Fixed Mount
- Material Properties:

| Material | Conductivity [W/(m*K)] | Specific Heat [J/(kg*K)] | Density [$kg/m^3$] | Emissivity | CTE [1/K] |
|---|---|---|---|---|---|
| ULE | 1.31 | 766 | 2210 | 0.82 | $30x10^{-9}$ |
| Silicon Carbide | 180 | 750 | 3100 | 0.9 | $2.2x10^{-6}$ |
| Zerodur | 1.46 | 800 | 2530 | 0.9 | $7x10^{-9}$ |



# Heat Flow Through Mirror

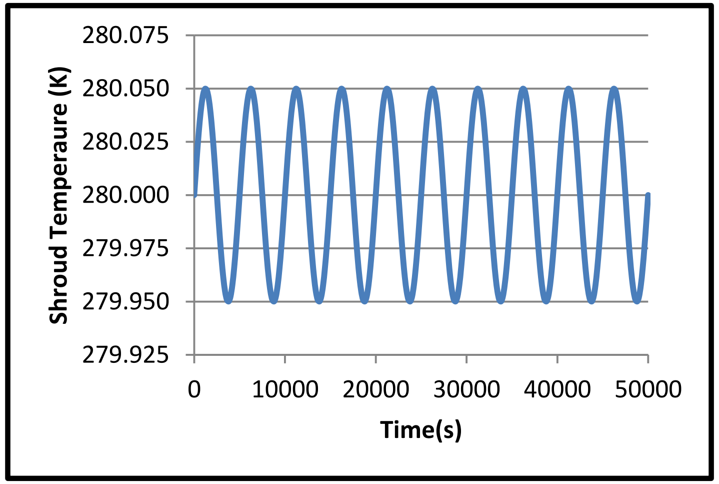
- Most heat enters the mirror from the heated plate and exits through the optical surface
- Heat is transported by radiation and conduction

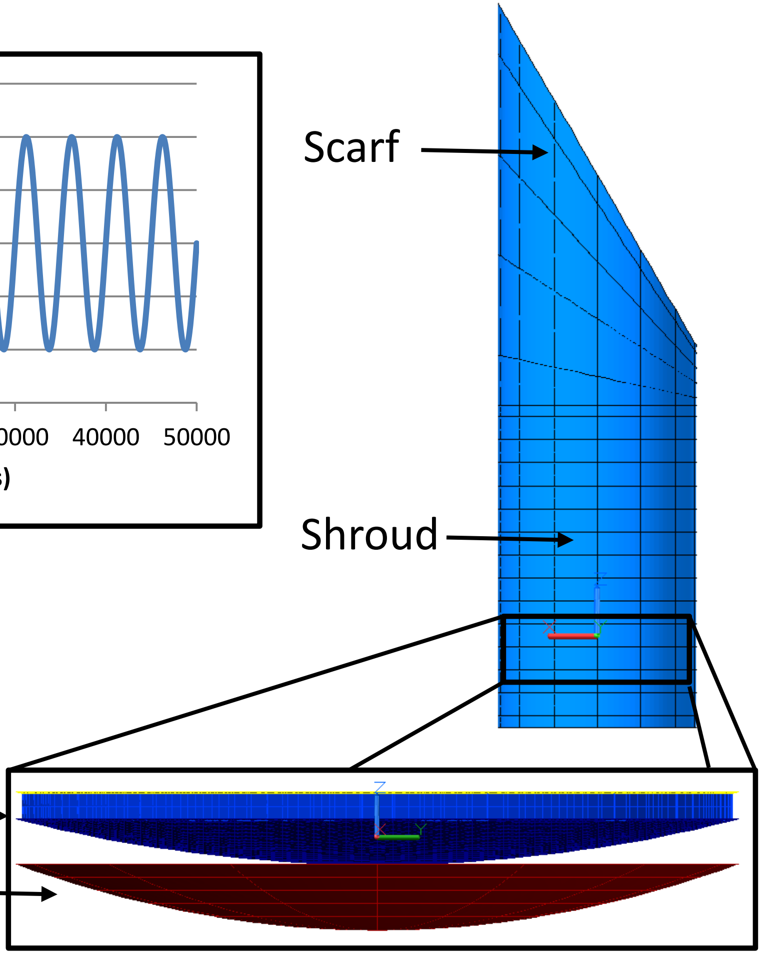


Not to scale

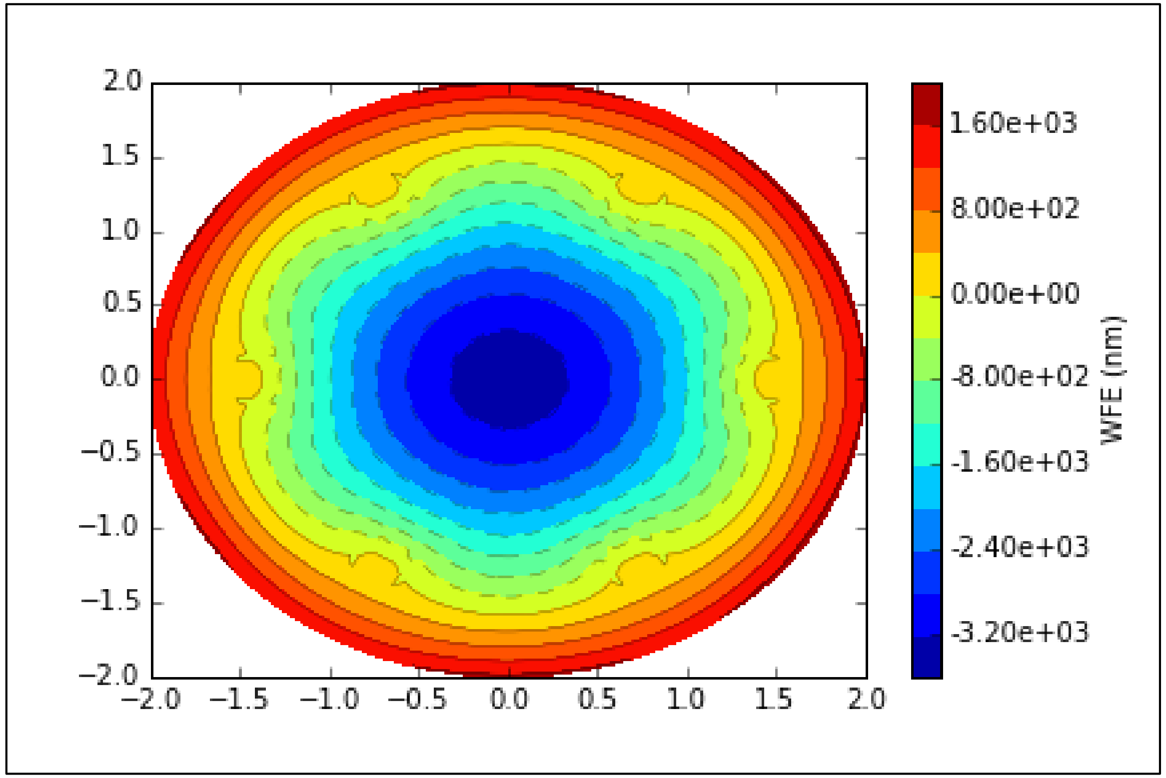
# Description of Telescope Architecture

- Cylindrical Shroud; 60˚ Scarf
- No secondary mirror or baffles
- MLI on outer surface of shroud & sides of mirror $\varepsilon^*_{MLI}=0.03$
- Inner surface of shroud painted black
- Heated plate behind mirror
- Placed at L2

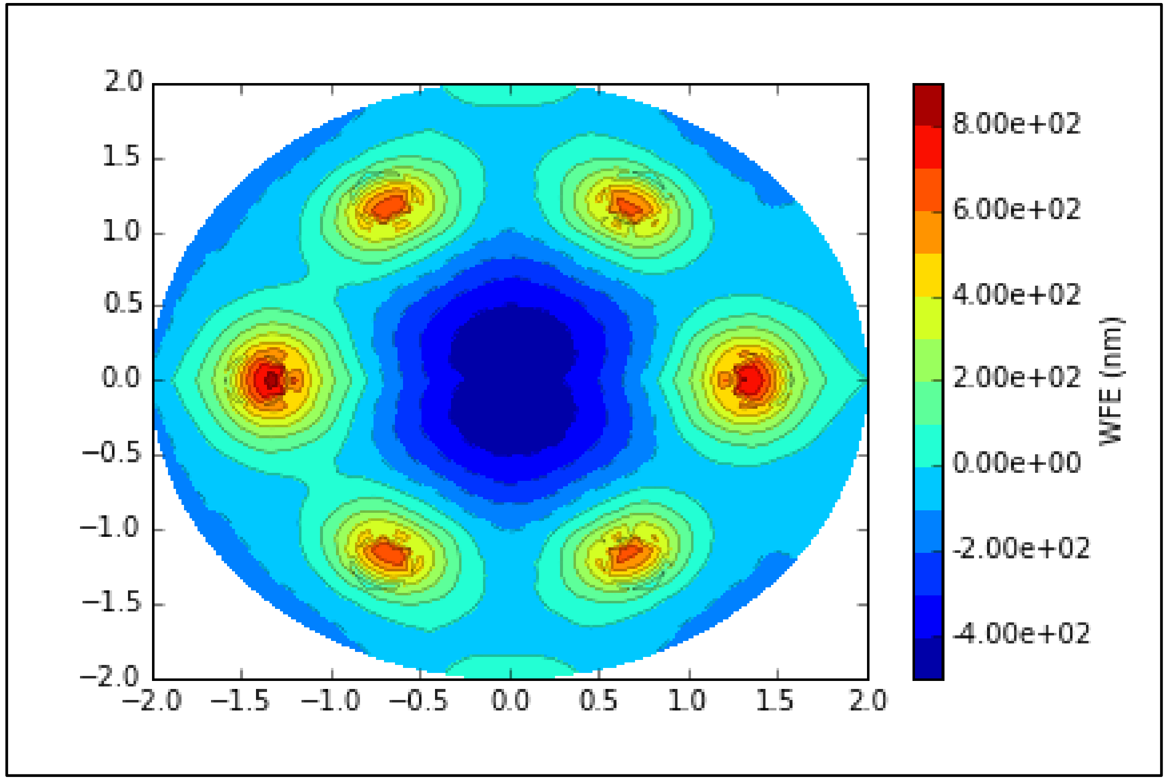


# WFE Visualization



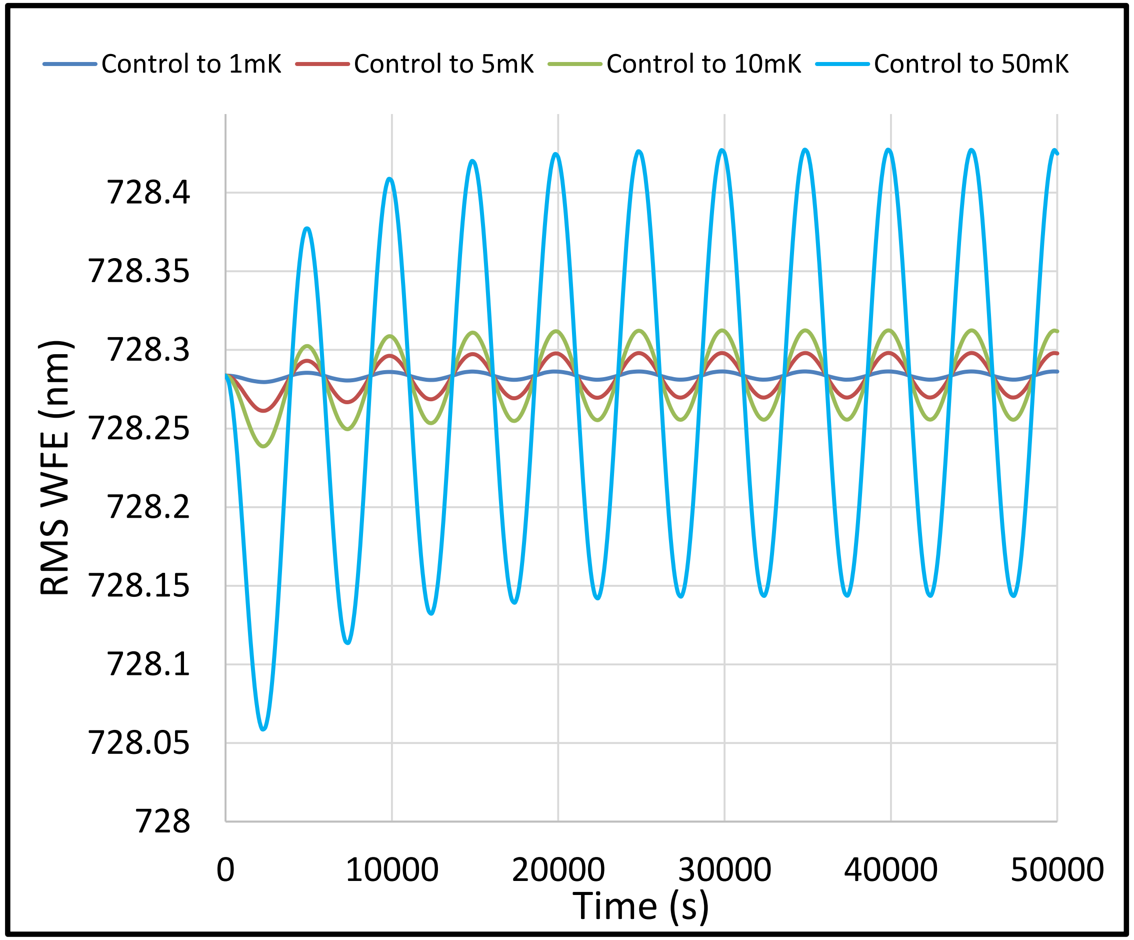

Sample WFE Contour Plot (50mK, 140s Period)



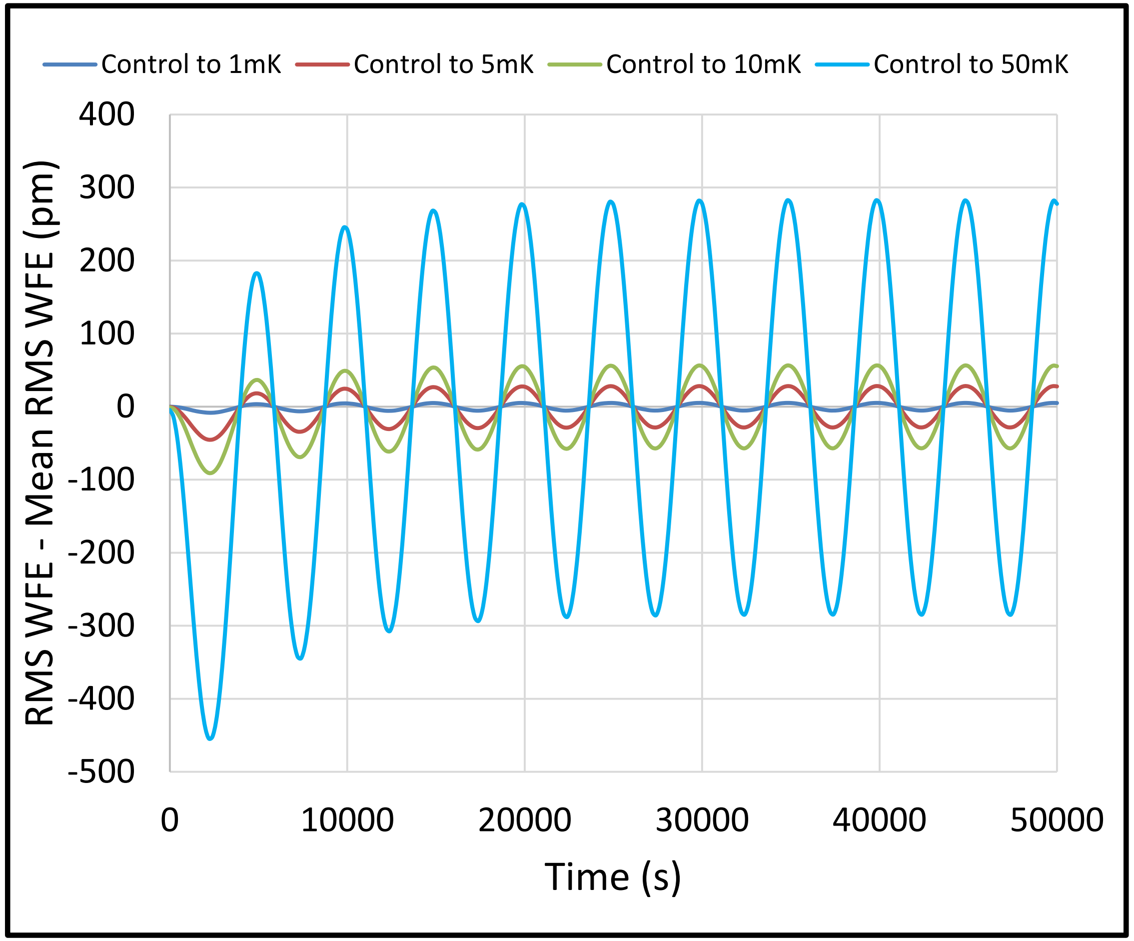

Sample WFE with Focus, Tilts, and Astigmatisms Removed (50mK, 140s Period)

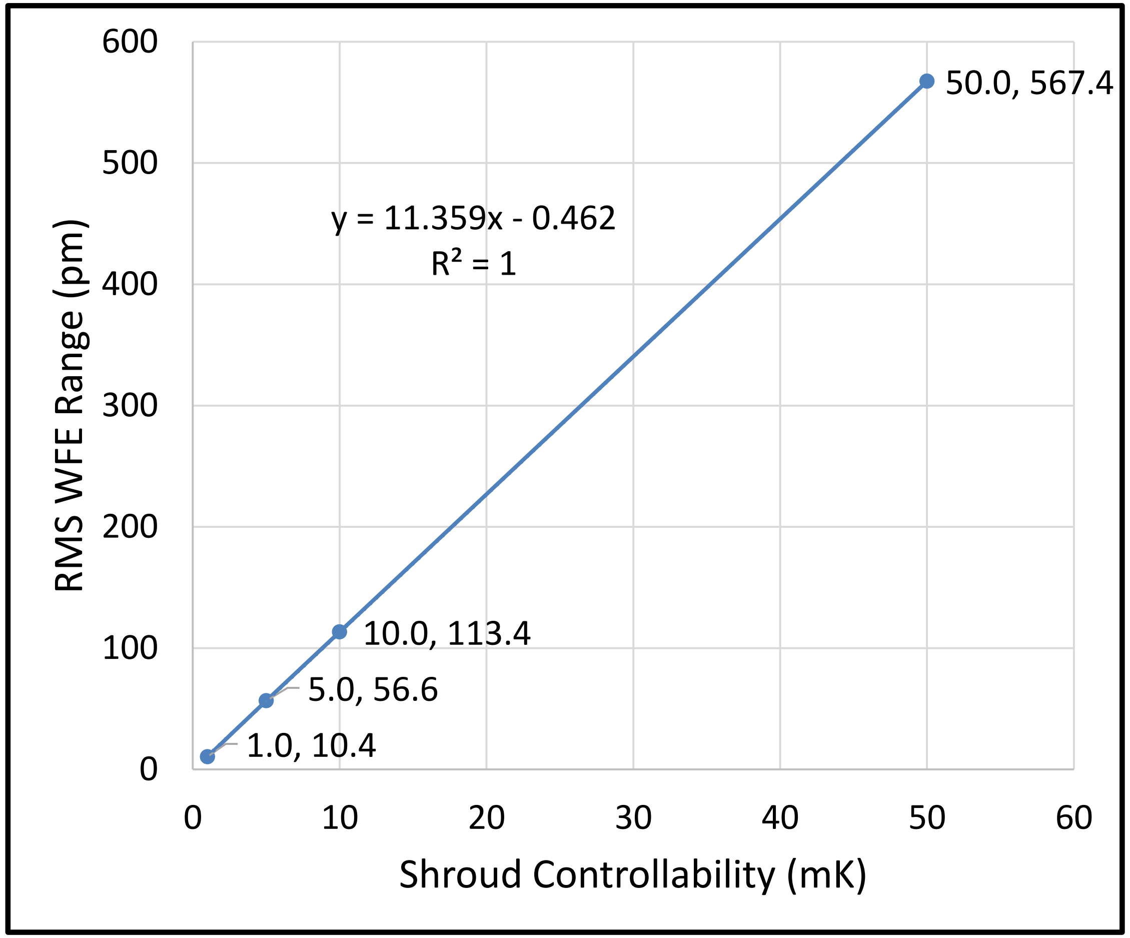
# WFE Stability versus Controllability

- Material: ULE
- Period of ACS: 5000s
- Controllability of ACS: Varied
- Density of Mirror: ULE Density
- Emissivity: 0.82
- Thicknesses: Baseline Design
- Conductivity: ULE Conductivity



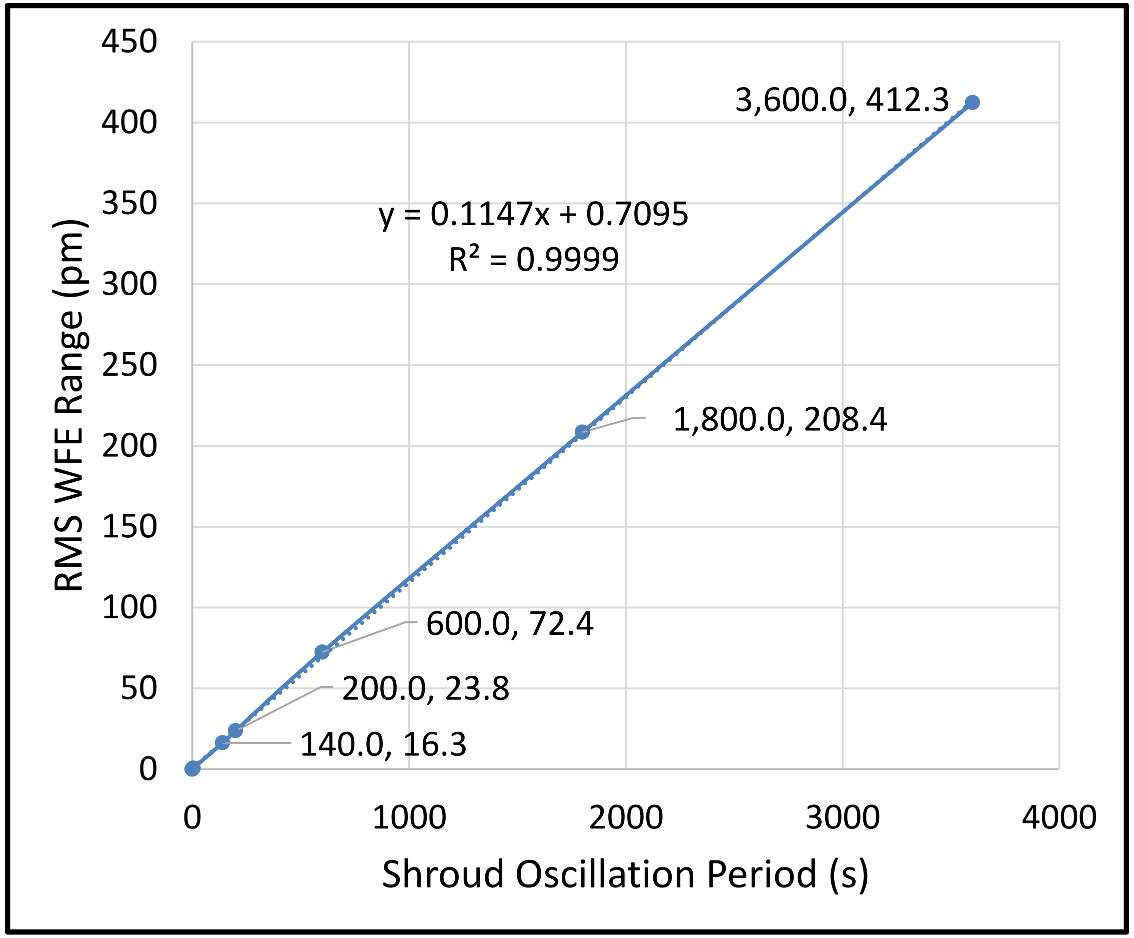
# WFE Stability versus Controllability



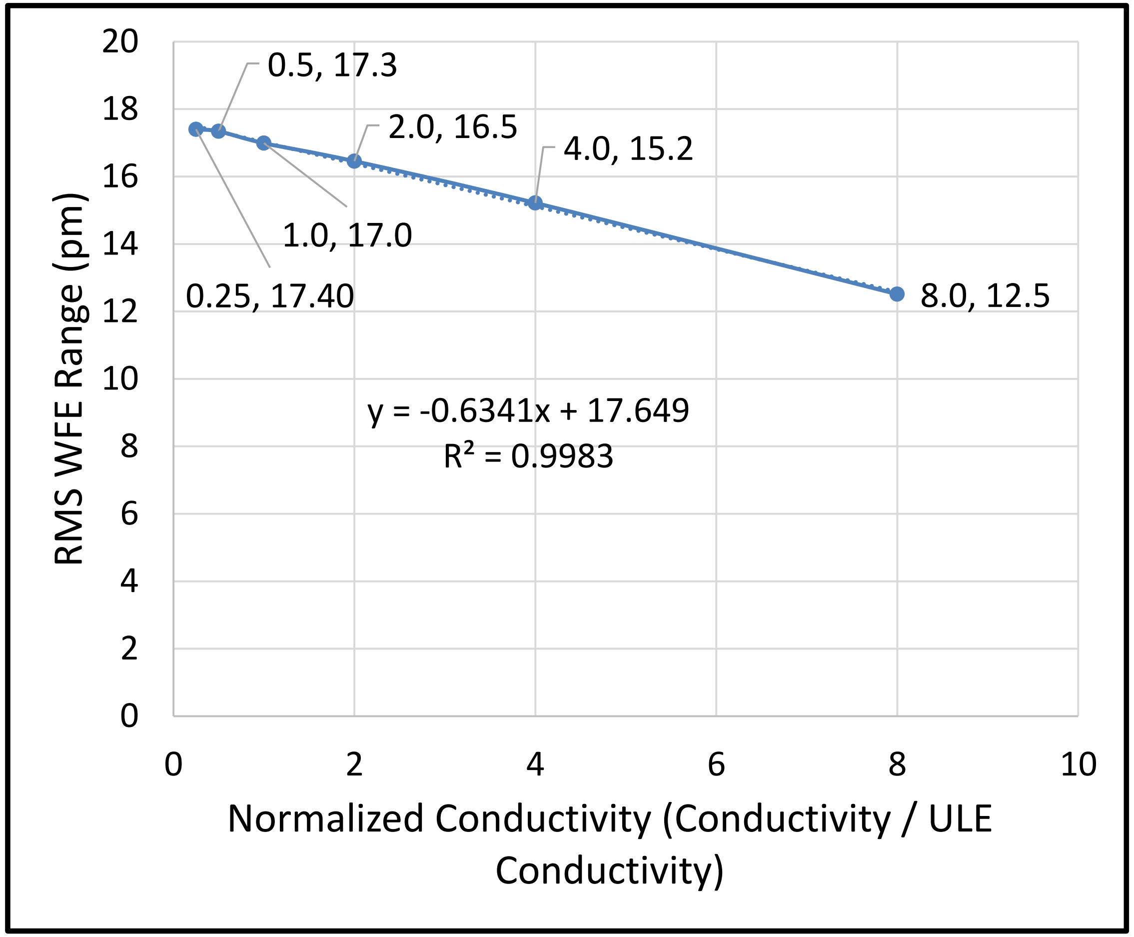
# WFE Stability versus Period

- Material: ULE
- Period of ACS: Varied
- Controllability of ACS: 50mK
- Density of Mirror: ULE Density
- Emissivity: 0.82
- Thicknesses: Baseline Design
- Conductivity: ULE Conductivity



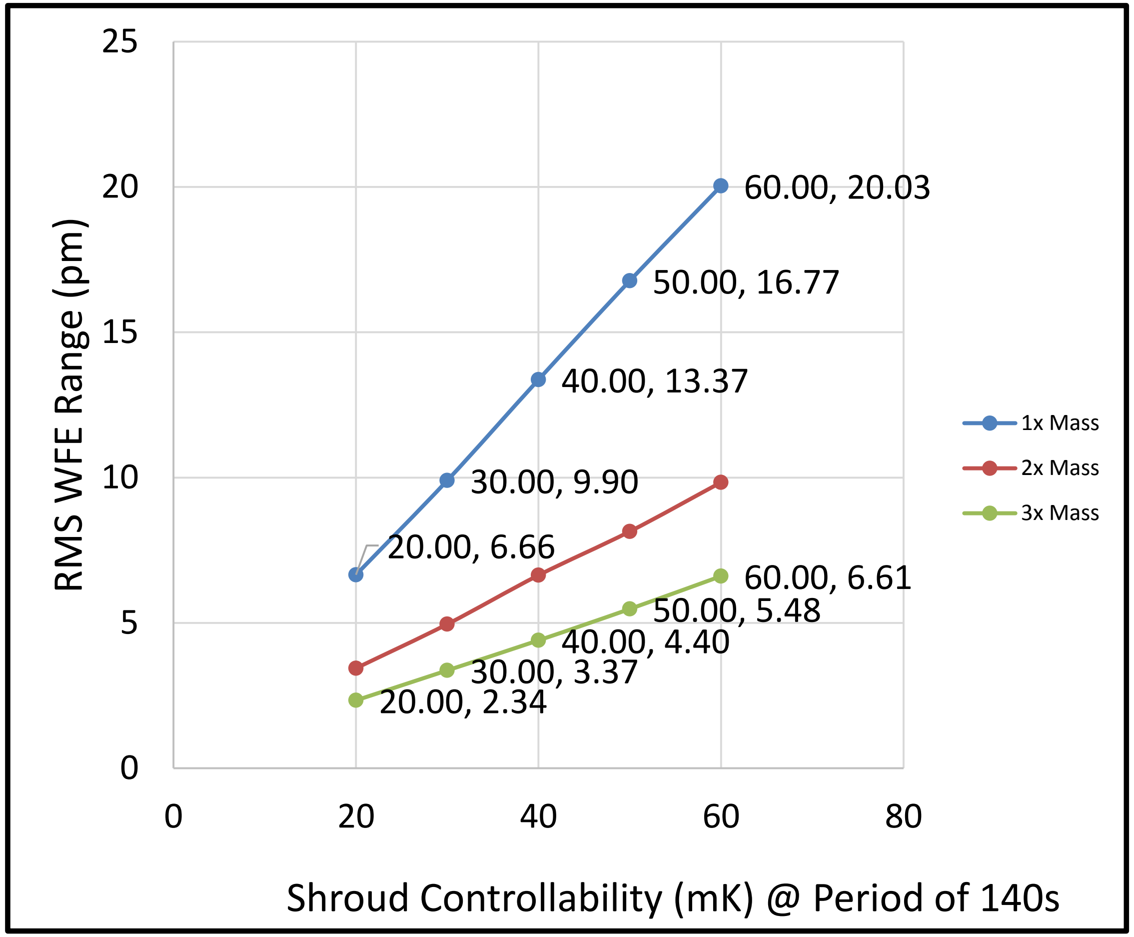
# WFE Stability versus Conductivity

- Material: ULE
- Period of ACS: 140s
- Controllability of ACS: 50mK
- Density of Mirror: ULE Density
- Emissivity: 0.82
- Thicknesses: Baseline Design
- Conductivity: Varied



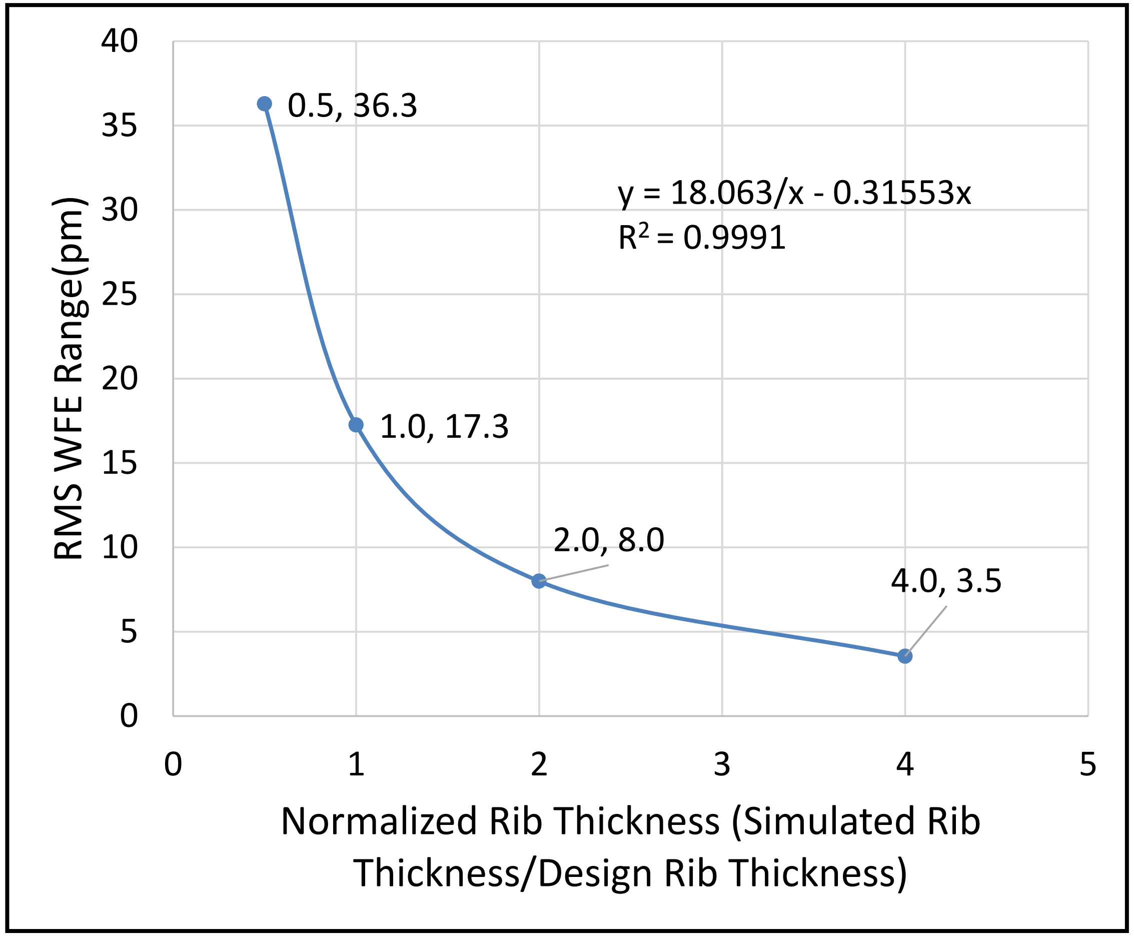
# WFE Stability versus Mass and Control

- Material: ULE
- Period of ACS: 140s
- Controllability of ACS: Varied
- Density of Mirror: Varied
- Emissivity: 0.82
- Thicknesses: Baseline Design
- Conductivity: ULE Conductivity



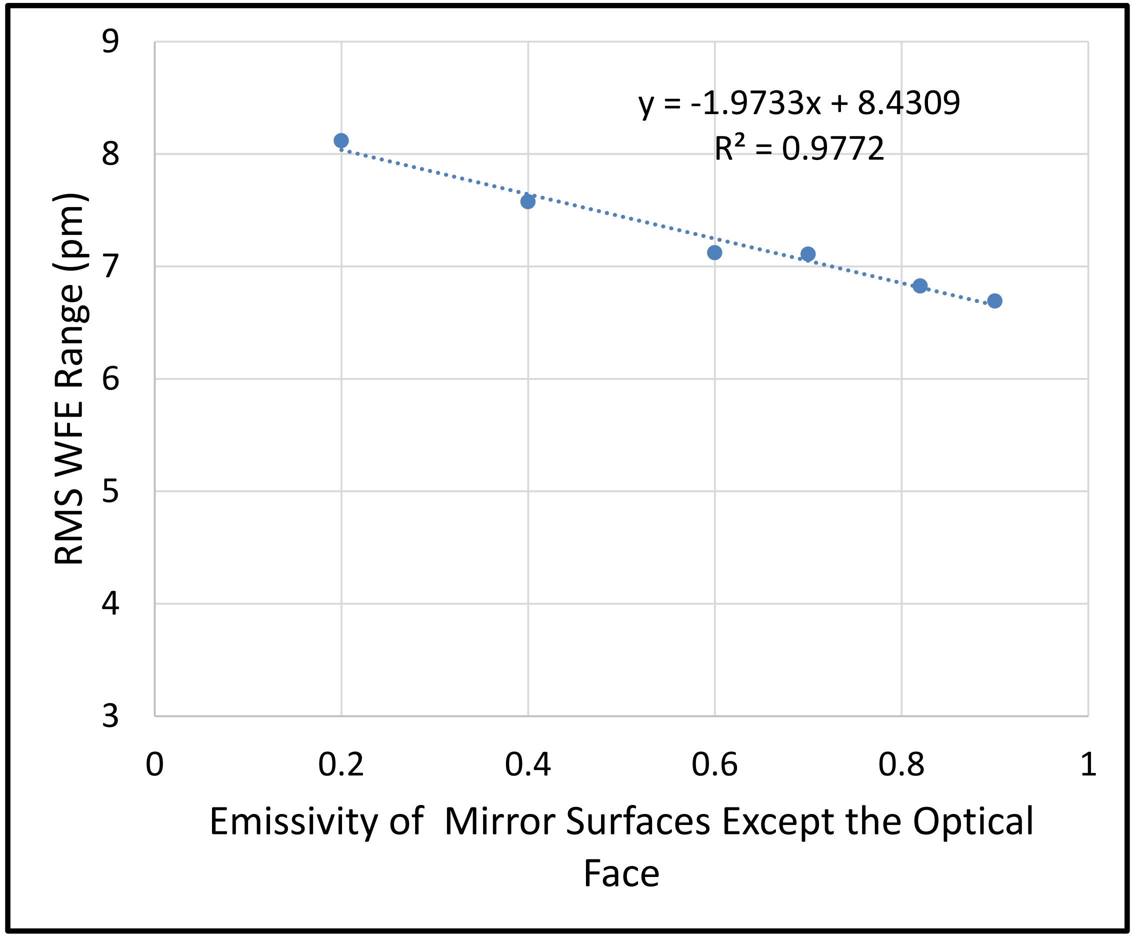
# WFE Stability versus Thicknesses

- Material: ULE
- Period of ACS: 140s
- Controllability of ACS: 50mK
- Density of Mirror: ULE Density
- Emissivity: 0.82
- Thicknesses: Varied
- Conductivity: ULE Conductivity



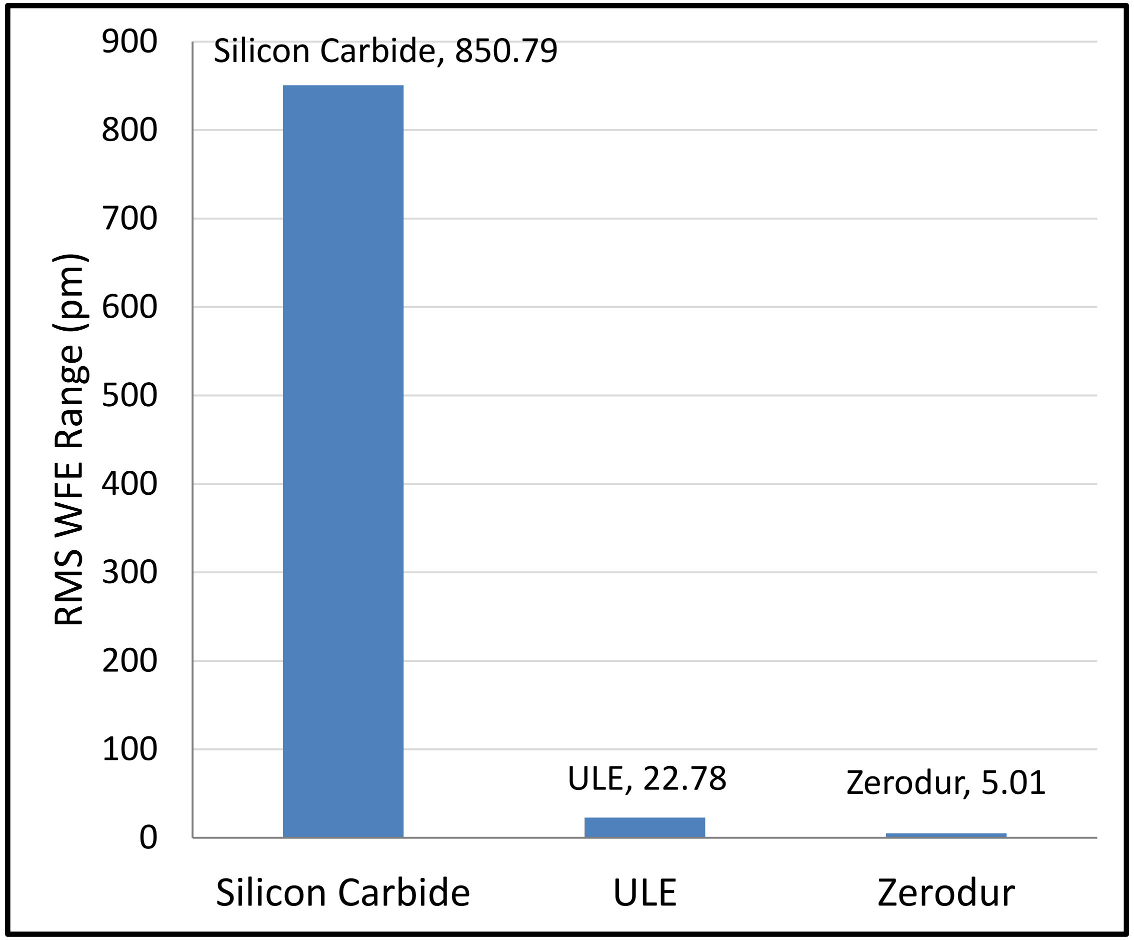
# WFE Stability versus Emissivity

- Material: ULE
- Period of ACS: 140s
- Controllability of ACS: 20mK
- Mirror Density: ULE Density
- Emissivity: Varied
- Thicknesses: Baseline Design
- Conductivity: ULE Conductivity



# WFE Stability versus Material

- Material: Varied
- Period of ACS: 140s
- Controllability of ACS: 50mK
- Mirror Density: Material Based
- Emissivity: Material Based
- Thicknesses: Baseline Design
- Conductivity: Material Based



# Quick Review

- RMS WFE Range is directly proportional to the ACS’s controllability and period.
- RMS WFE Range is inversely proportional to the mirror’s heat capacity and has a weak, negative linear relationship with conductivity and emissivity.
- For the material properties used, Zerodur causes the easiest to meet requirements on an active control system, followed closely by ULE, and distantly by Silicon Carbide

# 1-D Rod Closed-Form Model

Rod with a mass, specific heat, thermal energy, temperature and coefficient of thermal expansion of m, $c_p$, Q, T, and CTE respectfully

Length of rod, L

- Equation 1 describes heat storage in the rod
- Equation 3 describes linear thermal expansion
- Algebra and calculus then Equation 5
- Equation 5 shows variables that affect thermal strain rate
  - Geometry dependent: L, V, dQ/dt (surface area)
  - Material dependent: CTE, ρ, $c_p$, and dQ/dt (emissivity and absorptivity)

$$Q = \rho V c_p T \quad \text{Equation 1}$$

$$\frac{dQ}{dt} = \rho V c_p \frac{dT}{dt} \quad \text{Equation 2}$$

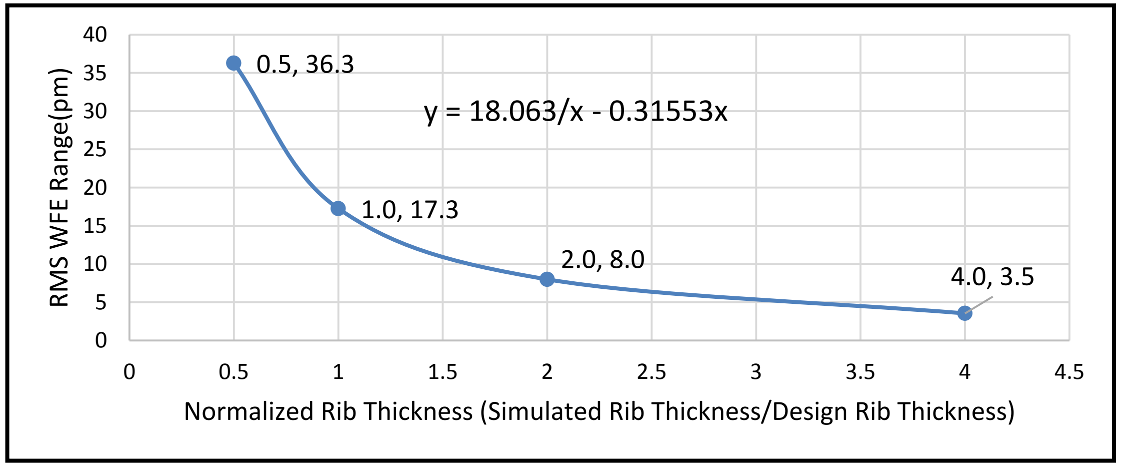
$$(\mathrm{CTE}) L \Delta T = \Delta L \quad \text{Equation 3}$$

$$\frac{dT}{dt}(\mathrm{CTE}) L = \frac{dL}{dt} \quad \text{Equation 4}$$

$$\frac{dL}{dt} = \frac{(\mathrm{CTE}) L}{\rho V c_p} \frac{dQ}{dt} \quad \text{Equation 5}$$

# Summary

- Numerical and analytical models agree that heat capacity and CTE have very strong affects on thermal deformation rates.




$$\frac{dL}{dt} = \frac{(\mathrm{CTE})L}{\rho V c_p}\frac{dQ}{dt}$$

- For an actively controlled substrate, the following figures of merit are proposed:

$$\text{Massive Active Optothermal Stability, MAOS} = \frac{\rho c_p}{CTE}$$

$$\text{Active Optothermal Stability, AOS} = \frac{c_p}{CTE}$$

# Summary Continued

## A data table of potential substrate materials is provided*

| Material | Massive Active Optothermal Stability (TJ/m³) | Active Optothermal Stability (GJ/kg) | Specific heat (J/kg/K) | Density (kg/m³) | Coefficient of thermal expansion (1/K) |
|---|---|---|---|---|---|
| **Fused silica** | 2.91 | 1.32 | 741 | 2202 | 5.60E-07 |
| **ULE 7971** | 112 | 51.1 | 766 | 2200 | 1.50E-08 |
| **Zerodur** | 83.1 | 32.8 | 821 | 2530 | 2.50E-08 |
| **Cer-Vit C-101** | 140 | 56.0 | 840 | 2500 | 1.50E-08 |
| **Beryllium I-70A** | 0.298 | 0.161 | 1820 | 1850 | 1.13E-05 |
| **Aluminum 6061-T6** | 0.113 | 0.042 | 960 | 2710 | 2.30E-05 |
| **Silicon Carbide CVD** | 0.936 | 0.292 | 700 | 3210 | 2.40E-06 |
| **Borosilicate crown E6** | 0.595 | 0.255 | 830 | 2330 | 3.25E-06 |

* Data in this table is compiled from Yoder, P.R., *Opto-Mechanical Systems Design*, 2nd ed., Marcel Dekker, New York, NY (1993).

# Any Questions?

Contact Information

Email: thomas.brooks@NASA.gov

Phone Number: (256) 544-5596

# Methodology

Thermal Analysis done in Thermal Desktop → Write NASTRAN input file → Run Thermal Deformation Analysis in NASTRAN → Post Processes Data for Optical Analysis

- Tasks boxed in red are handled entirely with a program written in Python.
- Program saves weeks of work per analysis.
- Program has been used to determine relationships between the telescope’s characteristics and technical performance parameters like stability.