Advanced Mirror Technology Development (AMTD) thermal trade studies

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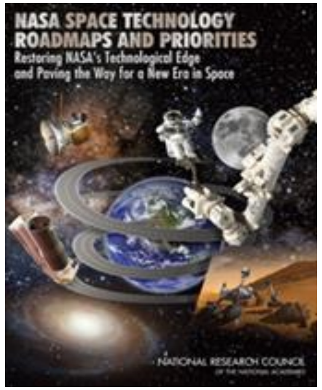
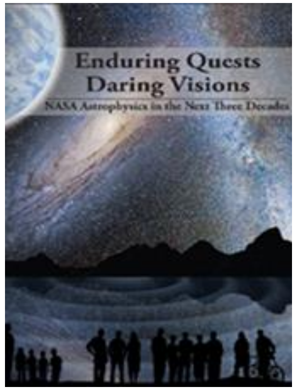
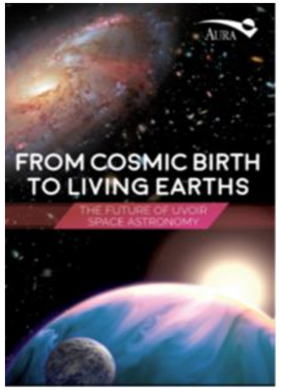
What is AMTD?

- Efforts associated with this presentation are performed as part of the Advanced Mirror Technology Development (AMTD) program
- Larger aperture space telescopes are required to answer our most compelling science questions.







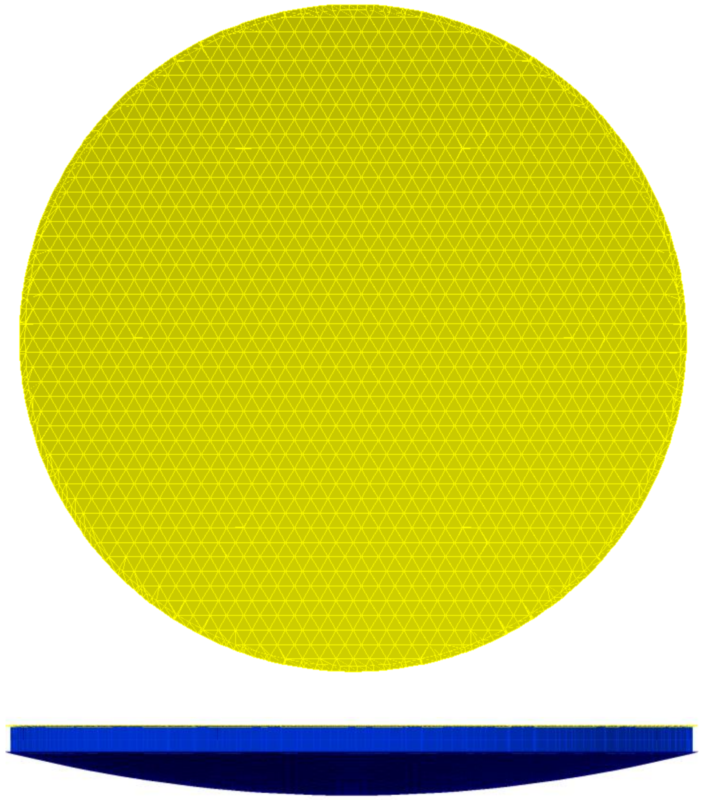
- AMTD's objective is to mature to TRL-6 critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

- To accomplish our objective, we:
    - Use a science-driven systems engineering approach.
    - Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

Description of Primary Mirror

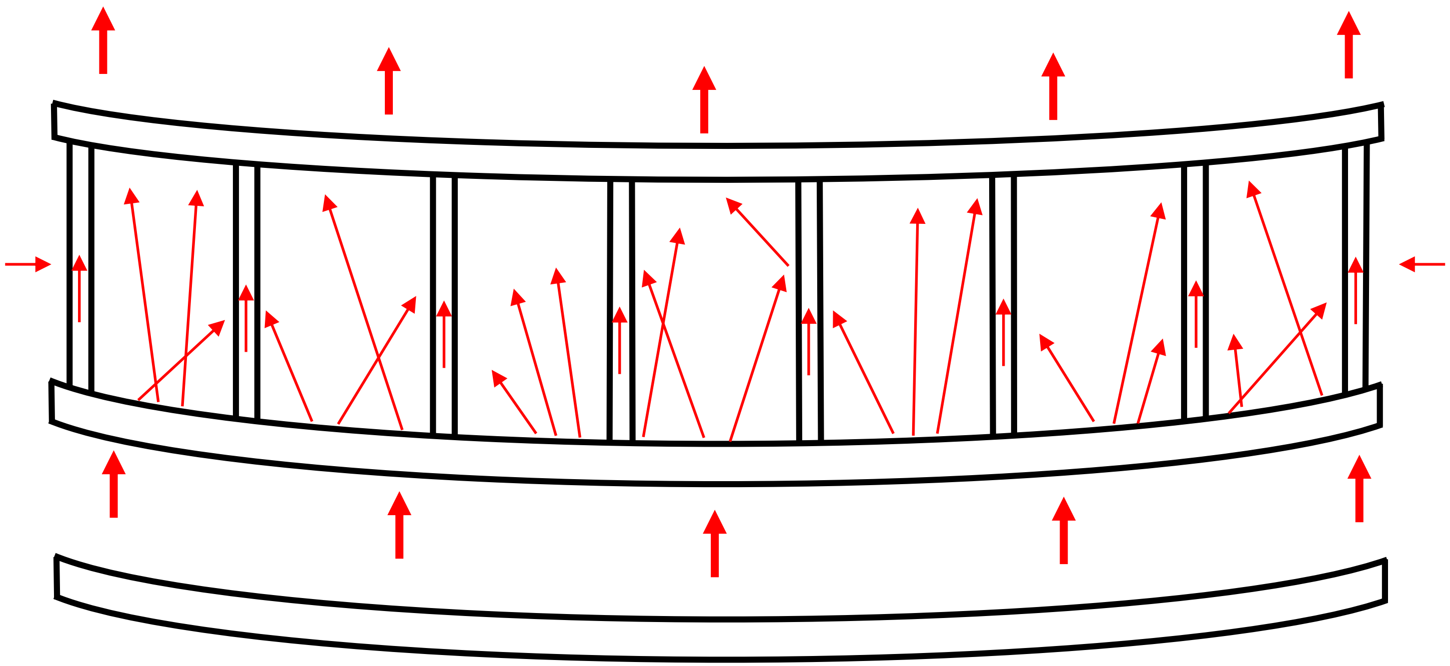
- 4m Circular Monolith
- 0.152m depth front to back
- Light-weighted with a back sheet
- Areal Density is 146 kg/m^2
- Optical face coated with $\varepsilon_{aluminum}$=0.03
- Fixed Mount
- Material Properties:

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

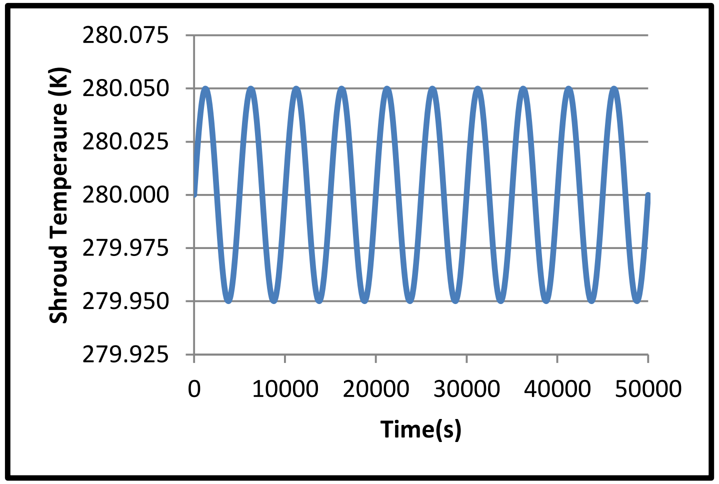
- Most heat enters the mirror from the heated plate and exits through the optical surface
- Heat is transported by radiation (56%) and conduction (44%)

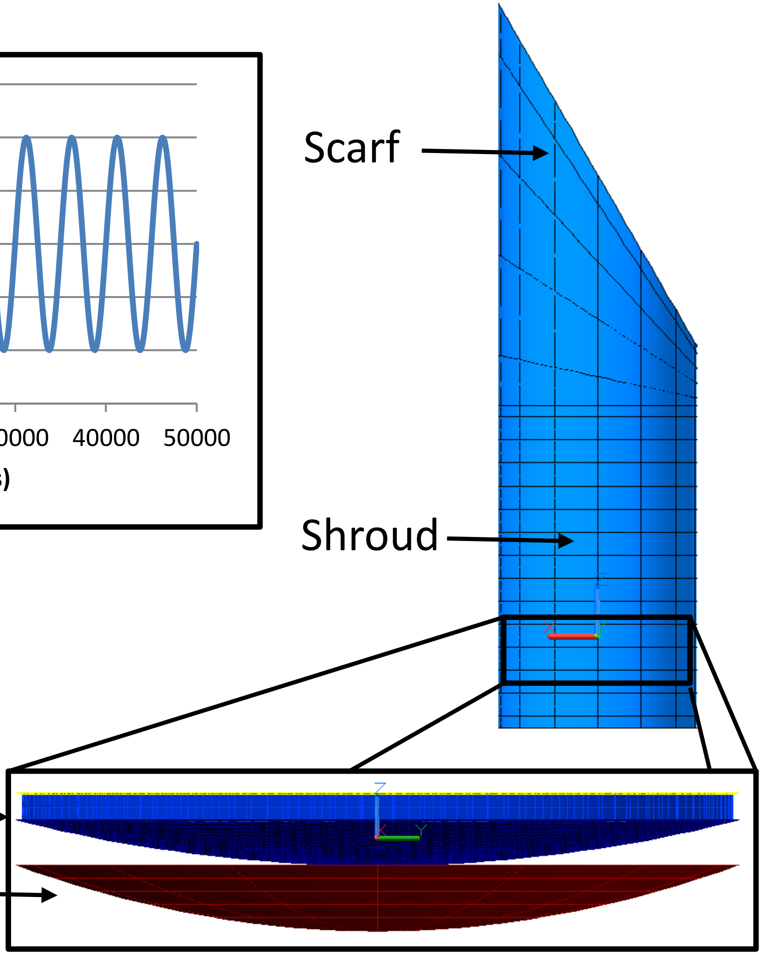


Not to scale

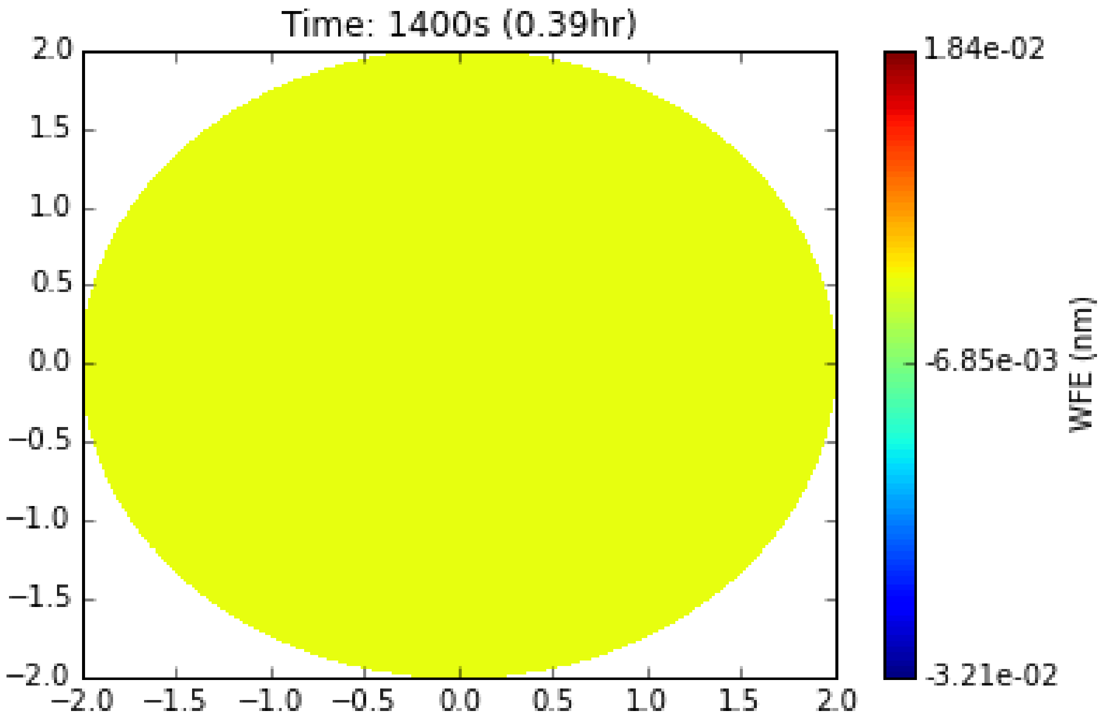
Description of Telescope Architecture

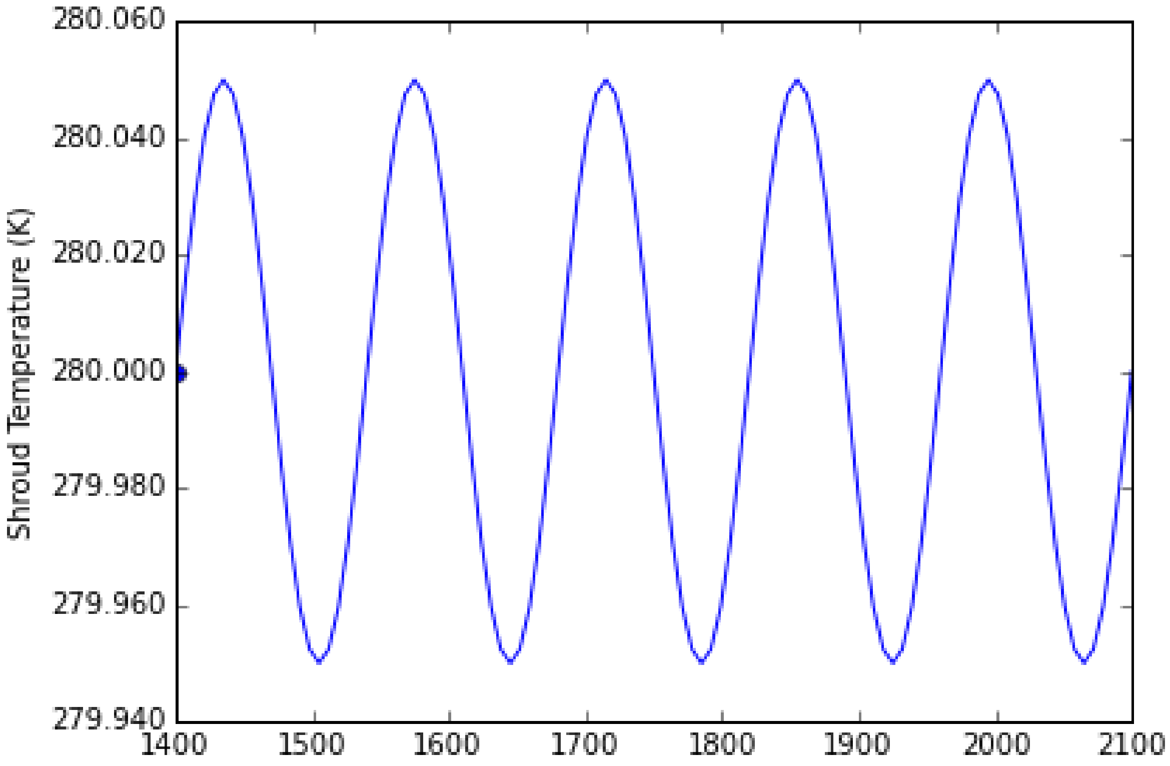
- Cylindrical Shroud; 60˚ Scarf
- No secondary mirror or baffles
- MLI on outer surface of shroud & sides of mirror $\varepsilon^*_{MLI}=0.03$
- Inner surface of shroud painted black
- Heated plate behind mirror
- Placed at L2



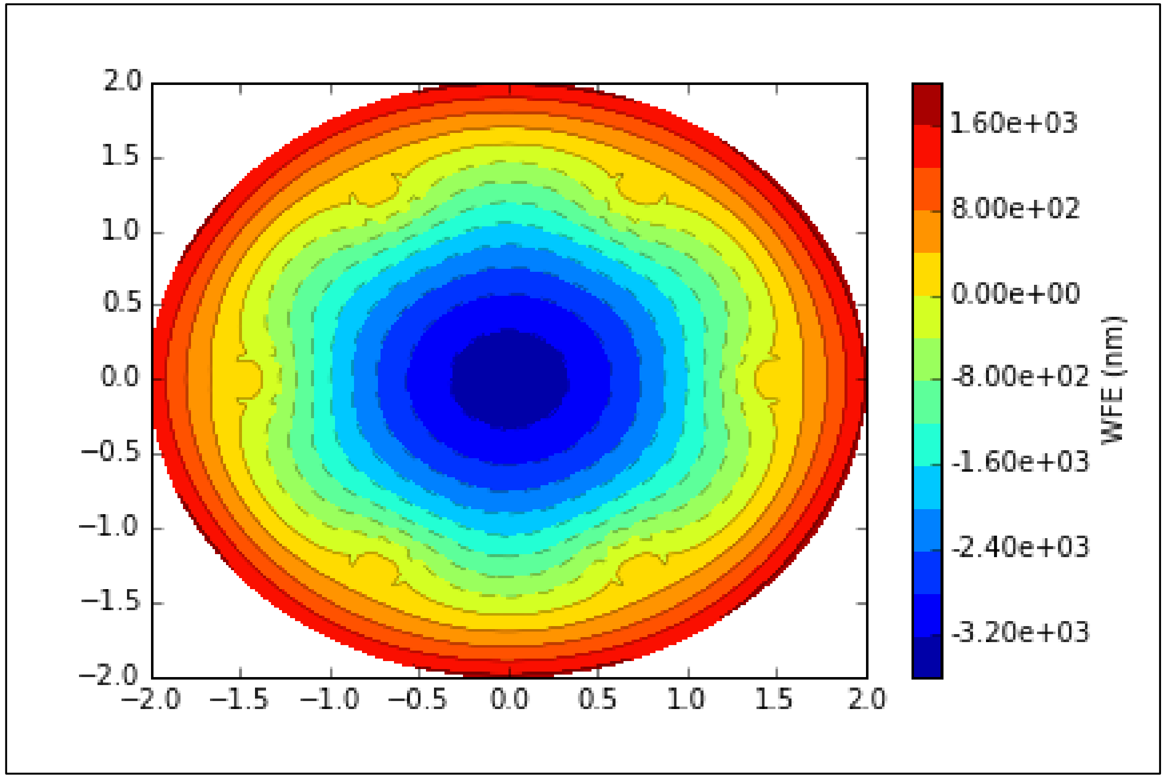


WFE Contour Video

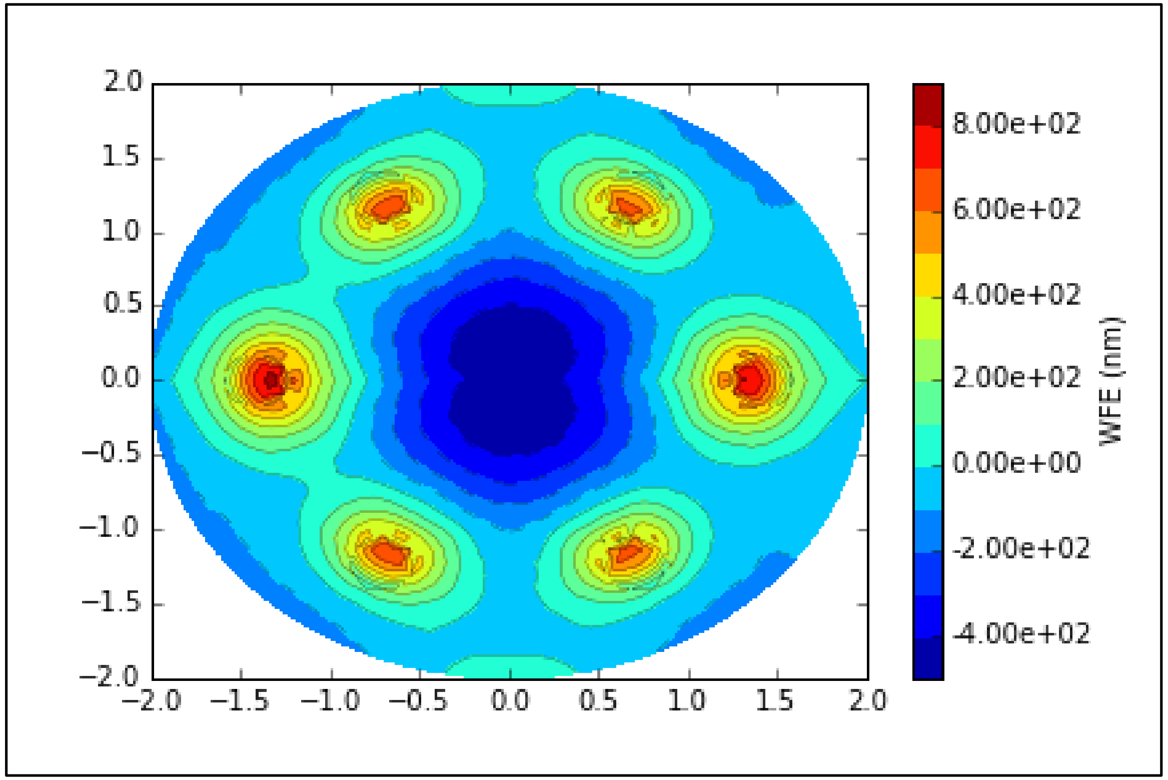




WFE Visualization



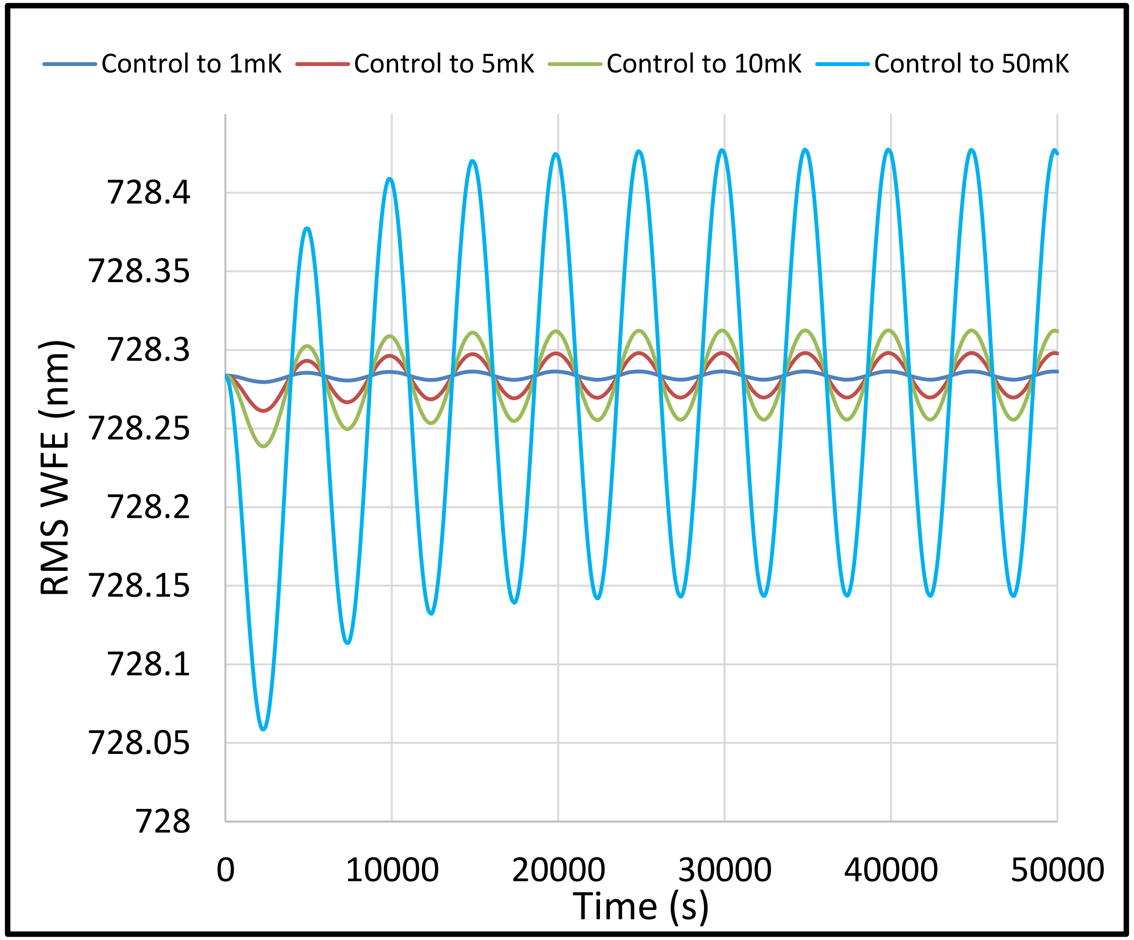
Sample WFE Contour Plot (50mK, 140s Period)



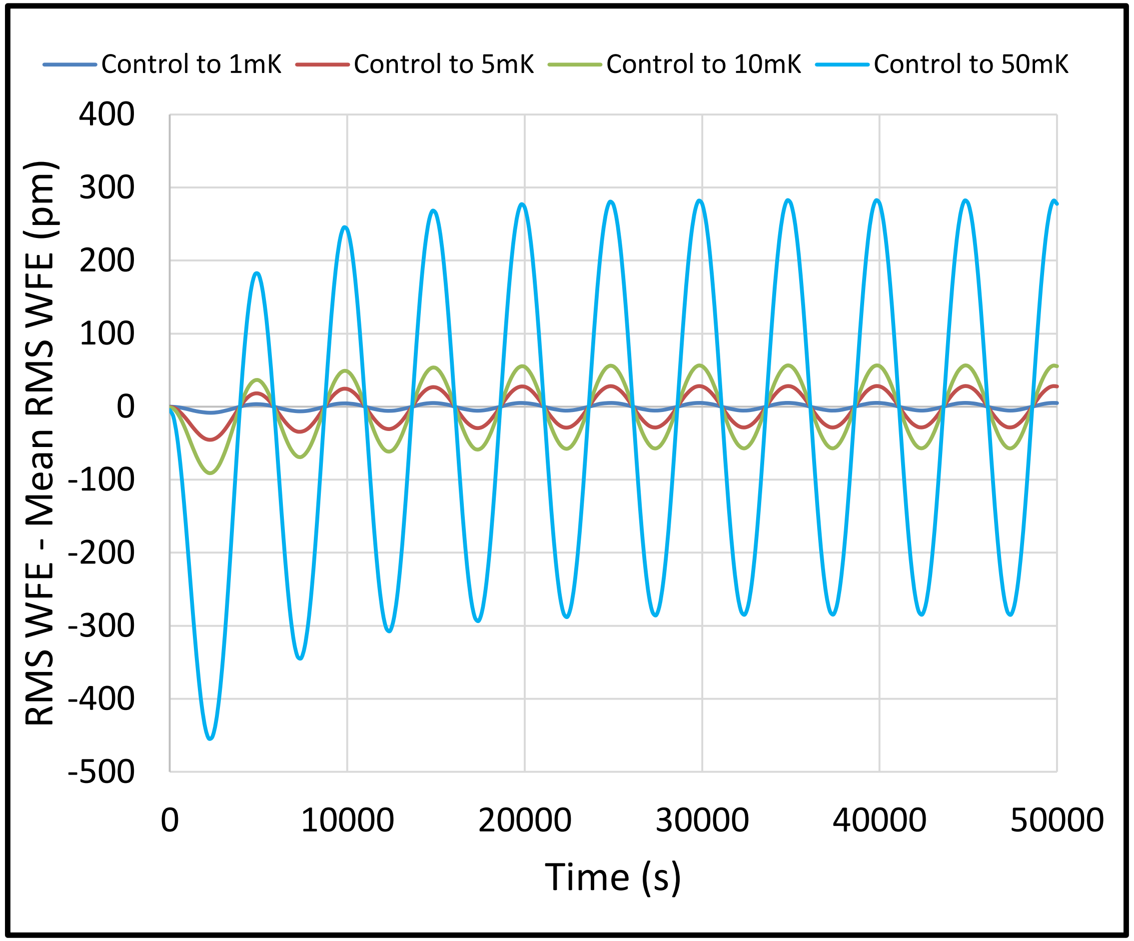
Sample WFE with Focus, Tilts, and Astigmatisms Removed (50mK, 140s Period)

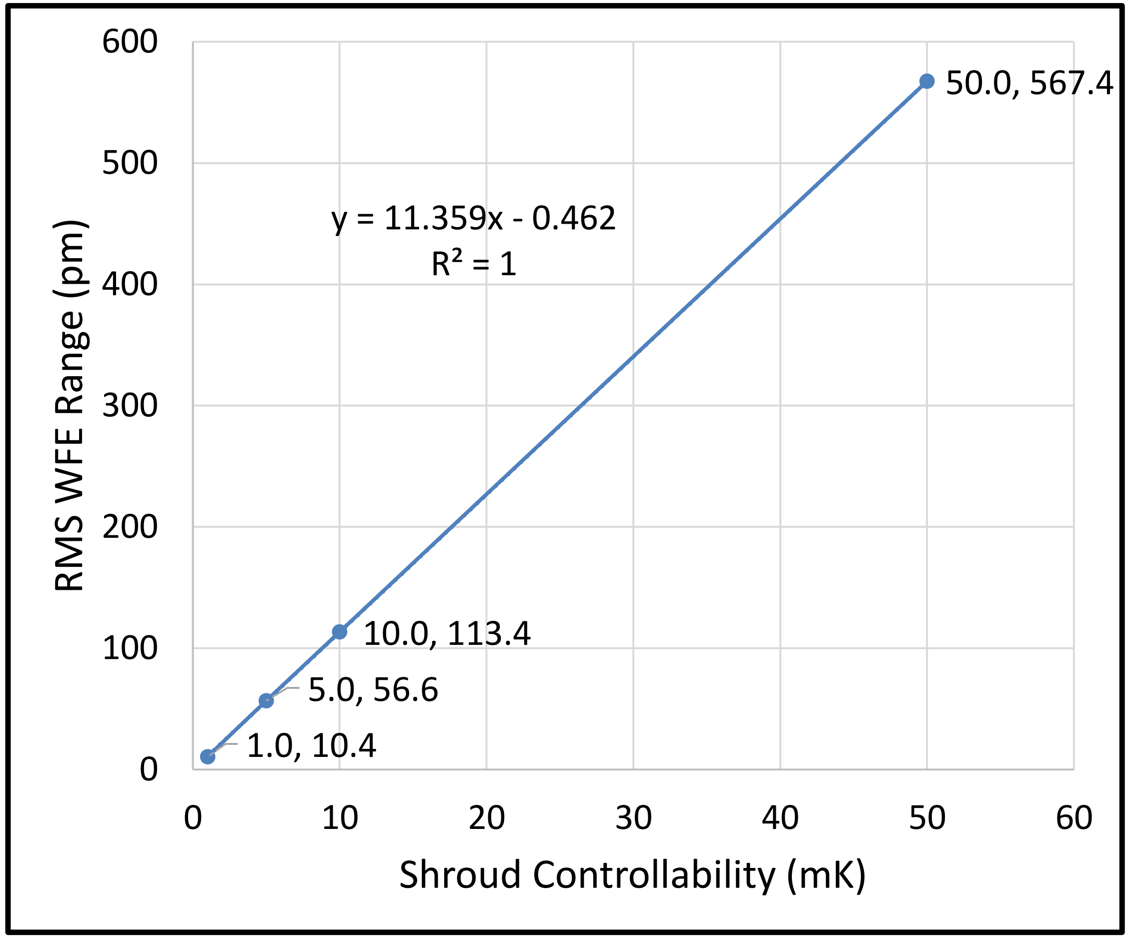
WFE Stability versus Controllability

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



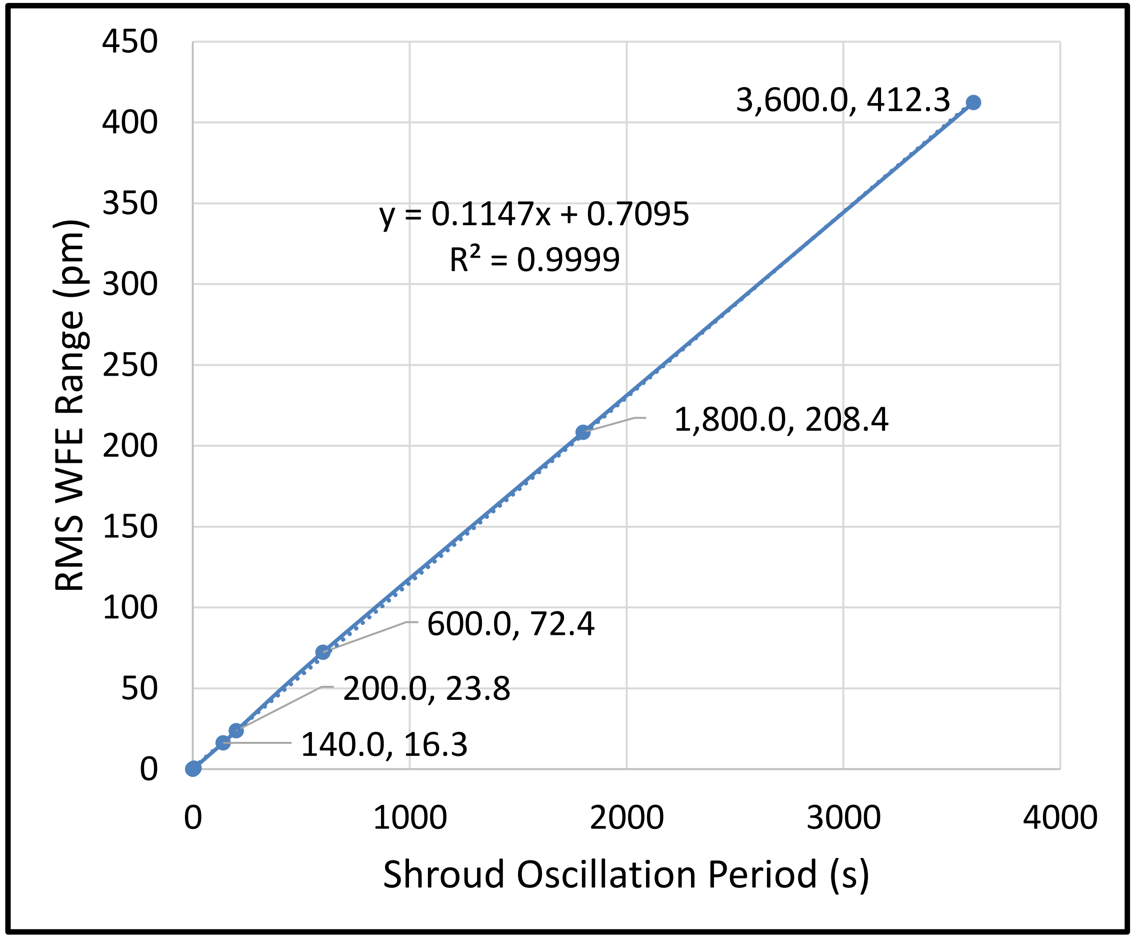
WFE Stability versus Controllability





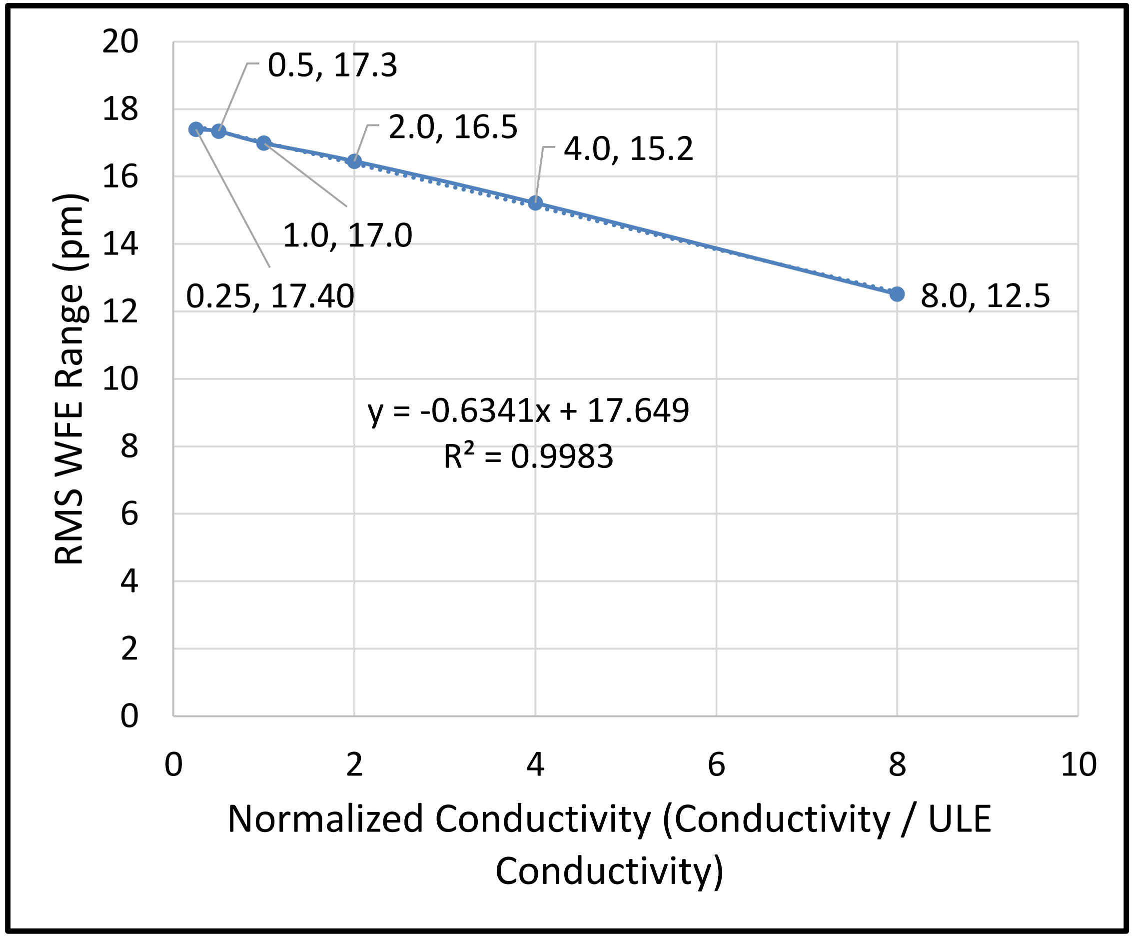
WFE Stability versus Period

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



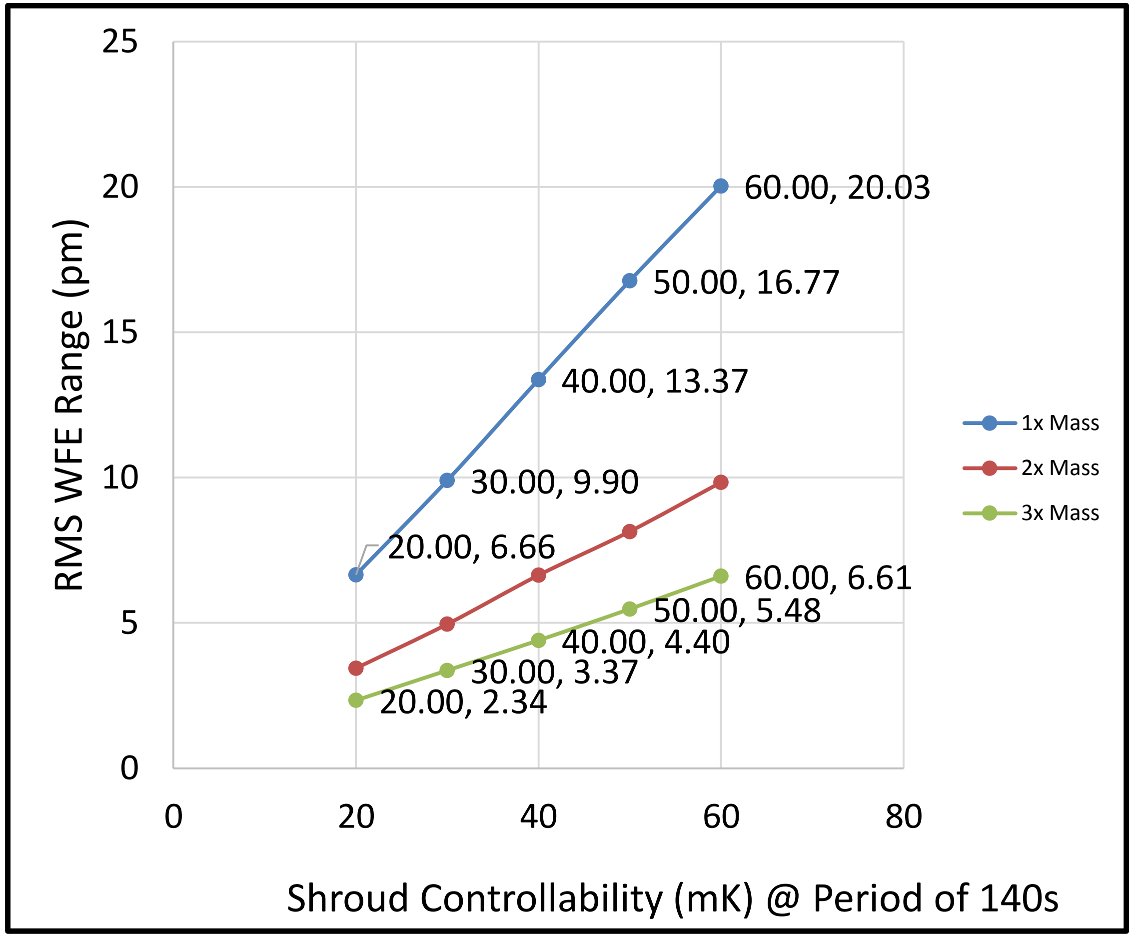
WFE Stability versus Conductivity

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



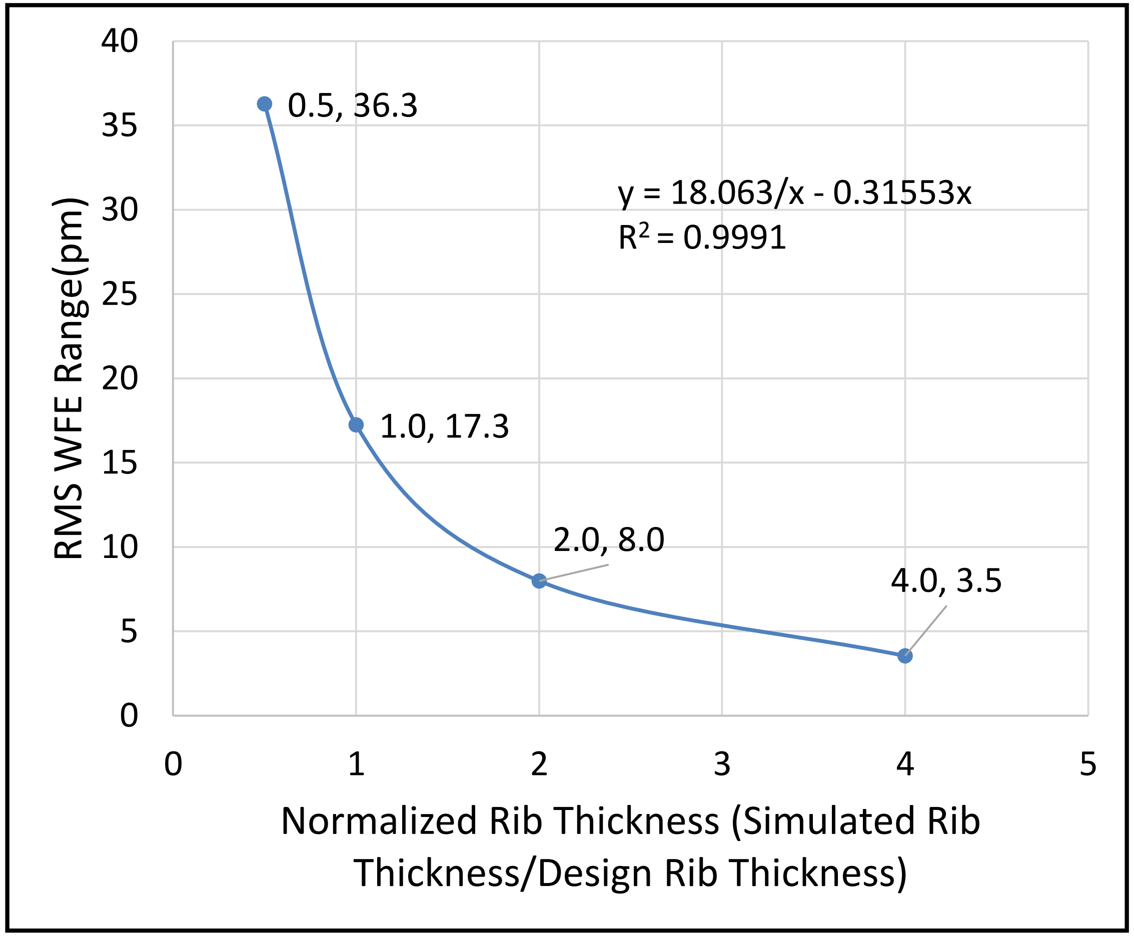
WFE Stability versus Mass and Control

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



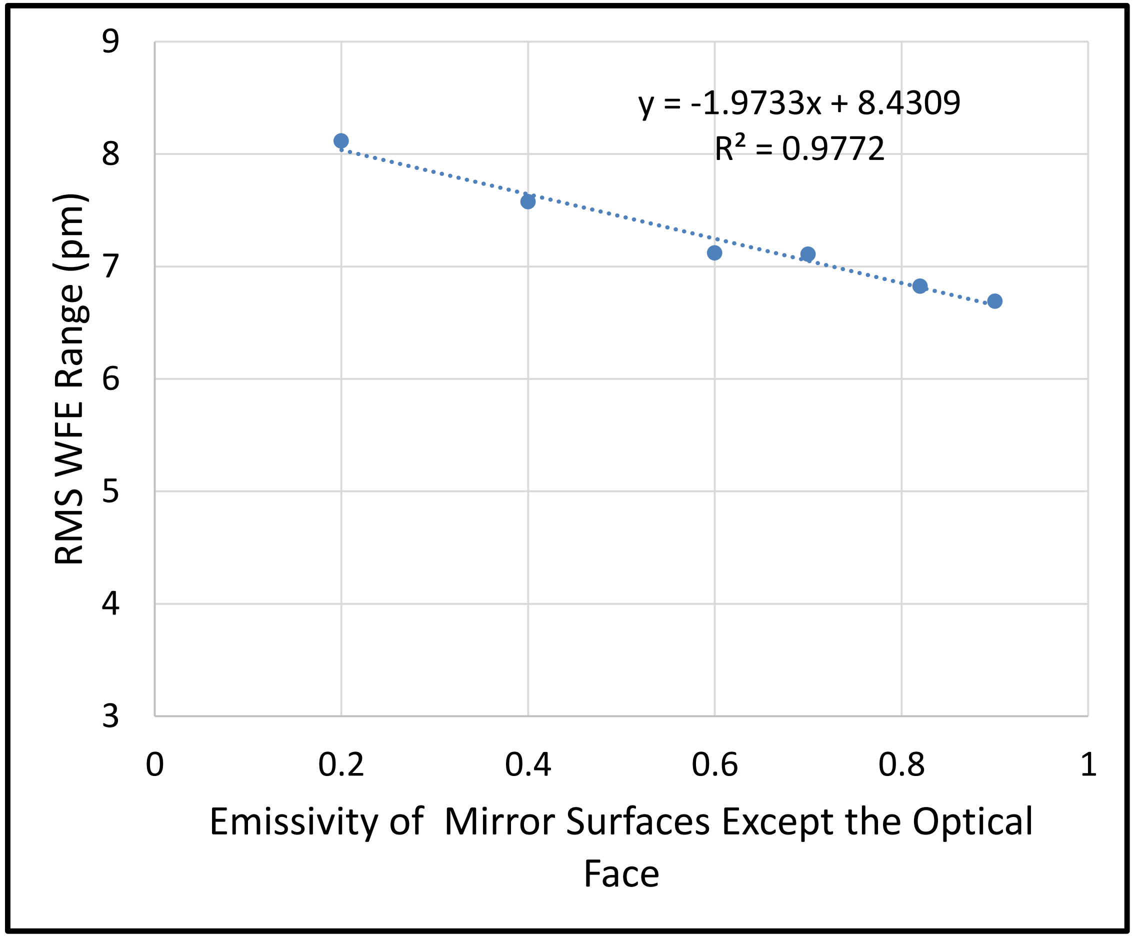
WFE Stability versus Thicknesses

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



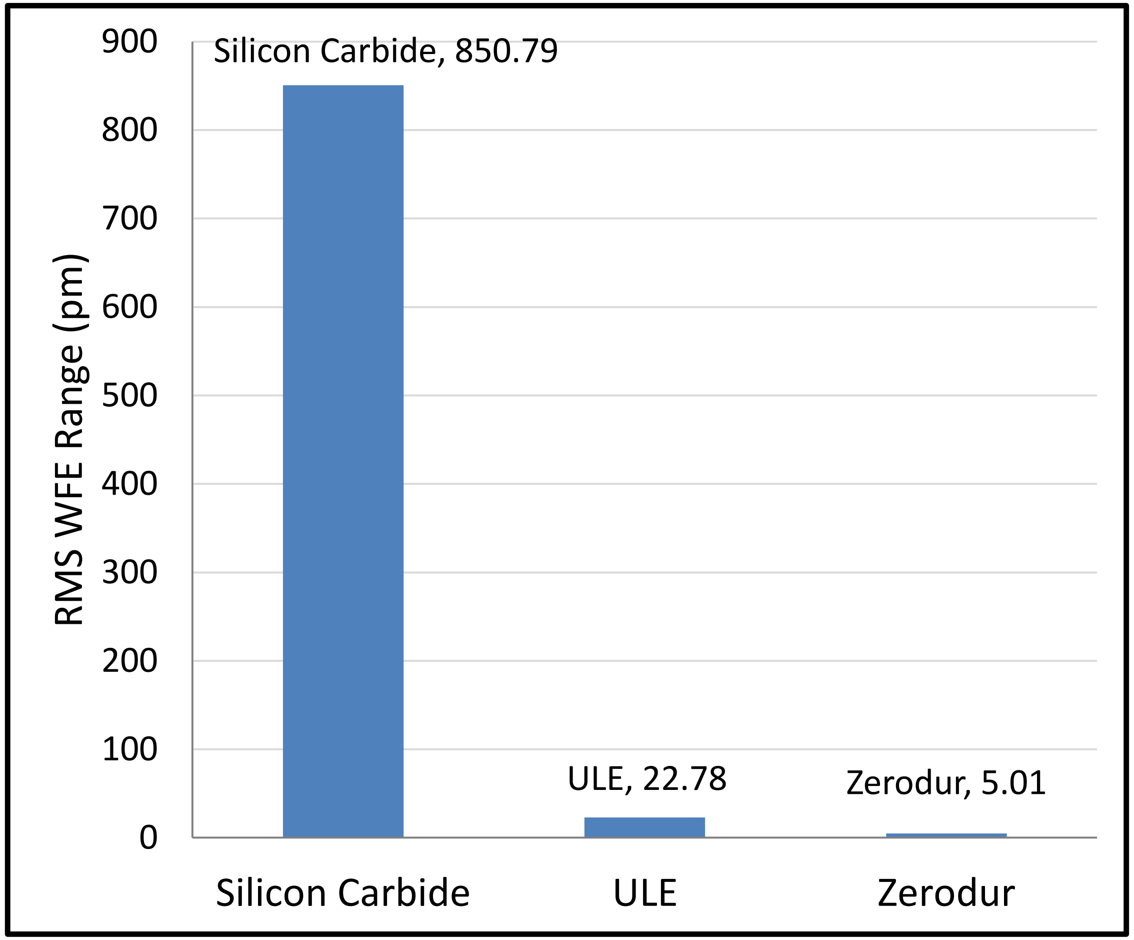
WFE Stability versus Emissivity

- 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 transfer in and out of the rod
- Equation 2 describes linear thermal expansion
- Algebra and calculus then Equation 5
- Equation 4 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)

$$\frac{dQ}{dt} = \rho V c_p \frac{dT}{dt} \qquad \text{Equation 1}$$

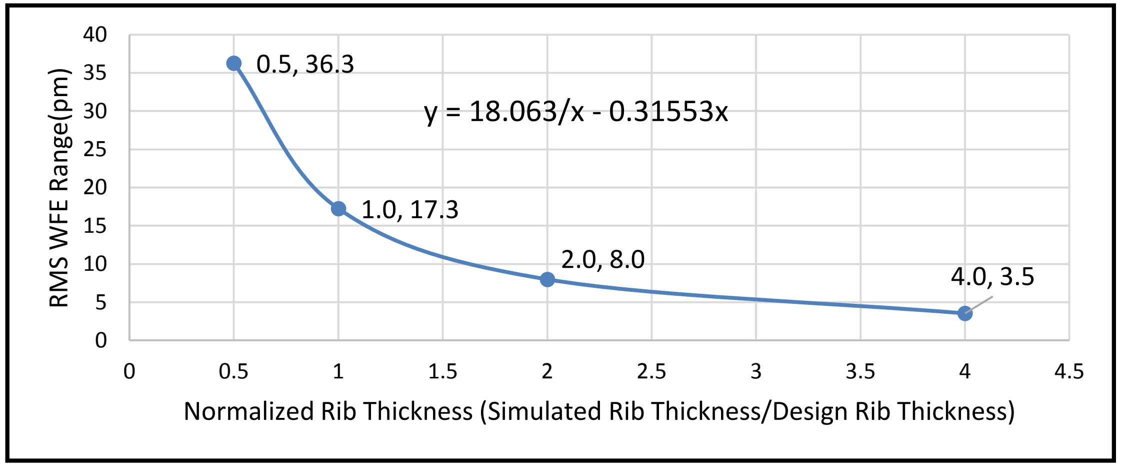
$$(\mathrm{CTE}) L \Delta T = \Delta L \qquad \text{Equation 2}$$

$$\frac{dT}{dt}(\mathrm{CTE}) L = \frac{dL}{dt} \qquad \text{Equation 3}$$

$$\frac{dL}{dt} = \frac{(\mathrm{CTE}) L}{\rho V c_p} \frac{dQ}{dt} \qquad \text{Equation 4}$$

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/m^3)	Active Optothermal Stability (GJ/kg)	Specific heat (J/kg/K)	Density (kg/m^3)	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?

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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.