Predictive Thermal Control (PTC) Technology for Stable Telescopes

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Motivation

Exoplanet science mission concepts require **ultra-stable** telescopes for **multiple hours** exposures.

Predictive Thermal Control Study (PTCS) matures technology to **enable active thermal controlled telescopes** required to make ultra-high contrast observations of exoplanets.

PTCS started as a 4 year Strategic Astrophysics Technology (SAT) project initiated in FY17 and was converted into an Astrophysics Directed Work project.

Objectives

PTCS has 3 objectives for maturing Thermally Stable Telescope technology

1. **Validate FEM model** that predicts thermal optical performance of mirror assembly based on structural design and material properties, i.e. **CTE distribution, thermal conductivity, mass**, etc.
2. **Derive thermal stability specifications** from wavefront stability requirement.
3. **Demonstrate** Predictive Thermal Control (PTC) system to achieve **thermal stability**.

Predictive Thermal Control (PTC)

- PTC advances **active thermal control** by demonstrating a control logic called **Model Predictive Control (MPC)**.
- Adjusts heater power to **minimize thermal gradient**.
- MPC places a physics-based model into the control loop to determine control variables (heater power levels) based upon state variables (temperature measurements).
- MPC determines heater power levels using a completely different logic than proportional control.
- MPC uses a system of equations based on the governing physics to solve for heat outputs based on a desired temperature distribution.
- MPC takes into account the interdependency between all control zone’s temperatures and all control zone’s heater power.

Status

Modified the XRCF to **enable lateral and axial thermal gradient testing** of mirror systems.

Partner Harris Corp is building a **zonal actively controlled thermal enclosure** for a 1.5m ULE® AMTD-2 mirror.

Procuring a **1.2m aluminum test mirror** for preliminary tests.

Adding control hardware and software to implement PTC system with XRCF thermal environment and Harris thermal enclosure.

Milestones

PTCS has a detailed technical plan with 5 quantifiable milestones:

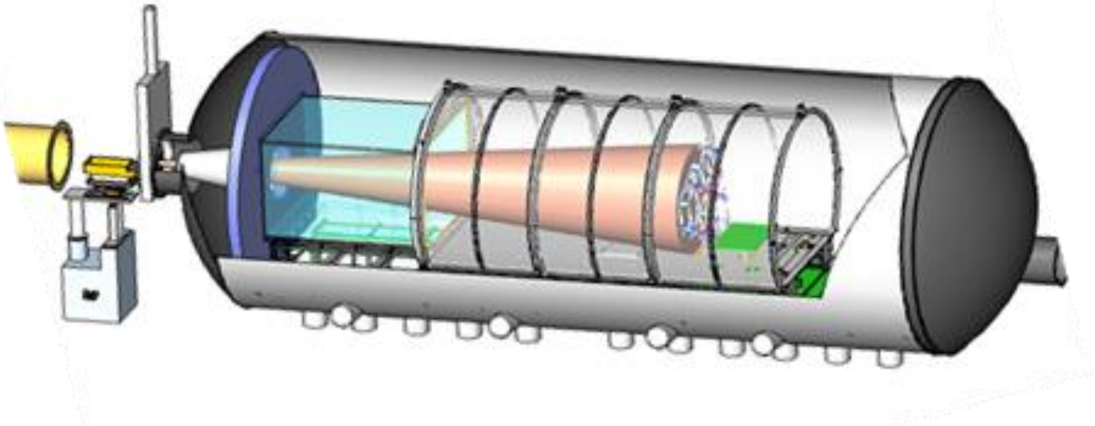
1. Develop a **FEM model of 1.5m ULE® mirror with measured CTE distribution, and reflective coating**, that predicts its optical performance response to steady-state and dynamic thermal gradients under bang/bang and proportional thermal control.
2. **Derive mirror thermal specifications** for stable wavefront.
3. **Design and build a predictive Thermal Control System** for a 1.5m ULE® mirror using commercial-off-the-shelf (COTS) components that sense temperature changes at ~1mK level and actively controls the mirror's thermal environment at ~20mK level.
4. **Validate model** by testing a flight traceable 1.5-m class ULE® mirror in a relevant thermal vacuum environment at X-ray and Cryogenic Facility (XRCF).
5. **Optimize mirror design**, material selection, mass, etc. with validated model and test data.

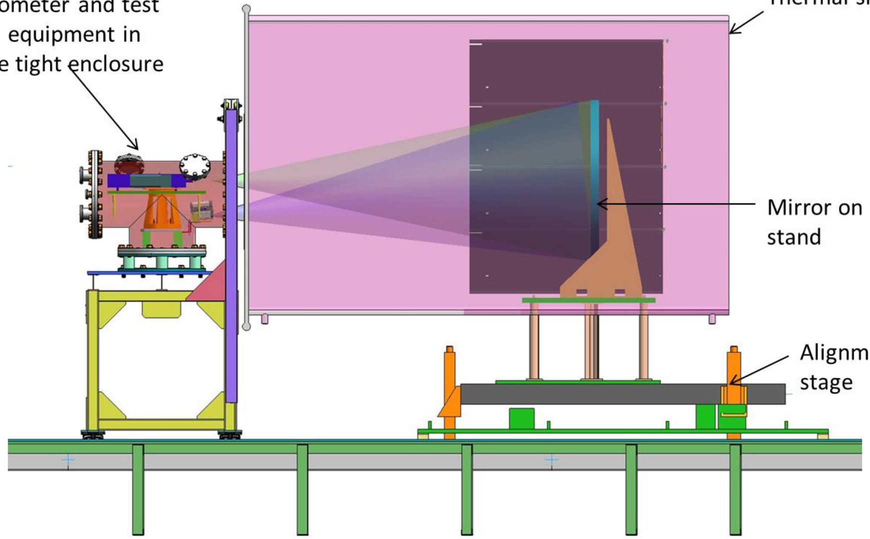
Milestone #1 Status

Develop a high-fidelity traceable model of 1.5m ULE® AMTD-2 mirror, including 3D CTE distribution and reflective coating, that predicts its optical performance response to steady-state and dynamic thermal gradients under bang/bang and proportional thermal control.

- **DONE: Developed process to correlated CTE homogeneity to measured data and demonstrated on 1.2m Zerodur Schott mirror**
- **DONE: Created high-Fidelity 'as-built' model of the 1.5m ULE® AMTD-2 mirror using MSFC x-ray computed tomography data and CTE boule data provided by Harris Corp and Corning Corp and predicted performance.**
- **IN PROCESS: Correlating mechanical properties of ULE® mirror model with 'as-measured' static cryo-deformation data.**
- FUTURE: Correlate CTE distribution in model with 'as-measured' thermal gradient data.
- FUTURE: Use correlated model to predict optical performance.

XRCF thermal optical test configurations





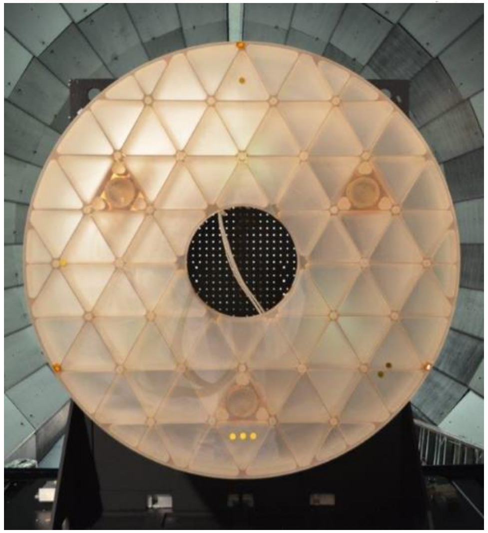
Interferometer and test support equipment in pressure tight enclosure (PTE)

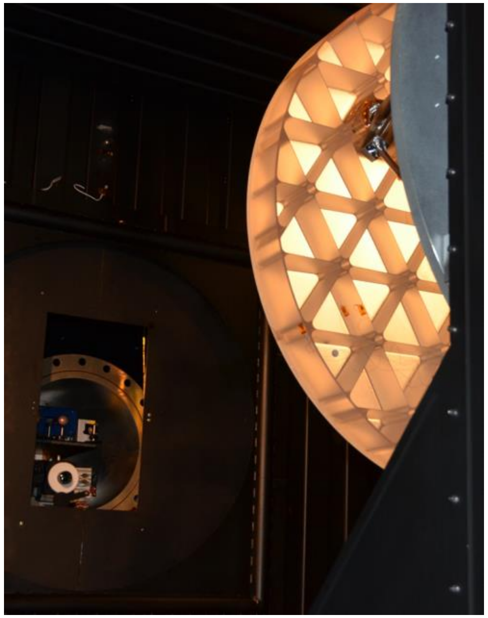
Thermal shroud

Mirror on test stand

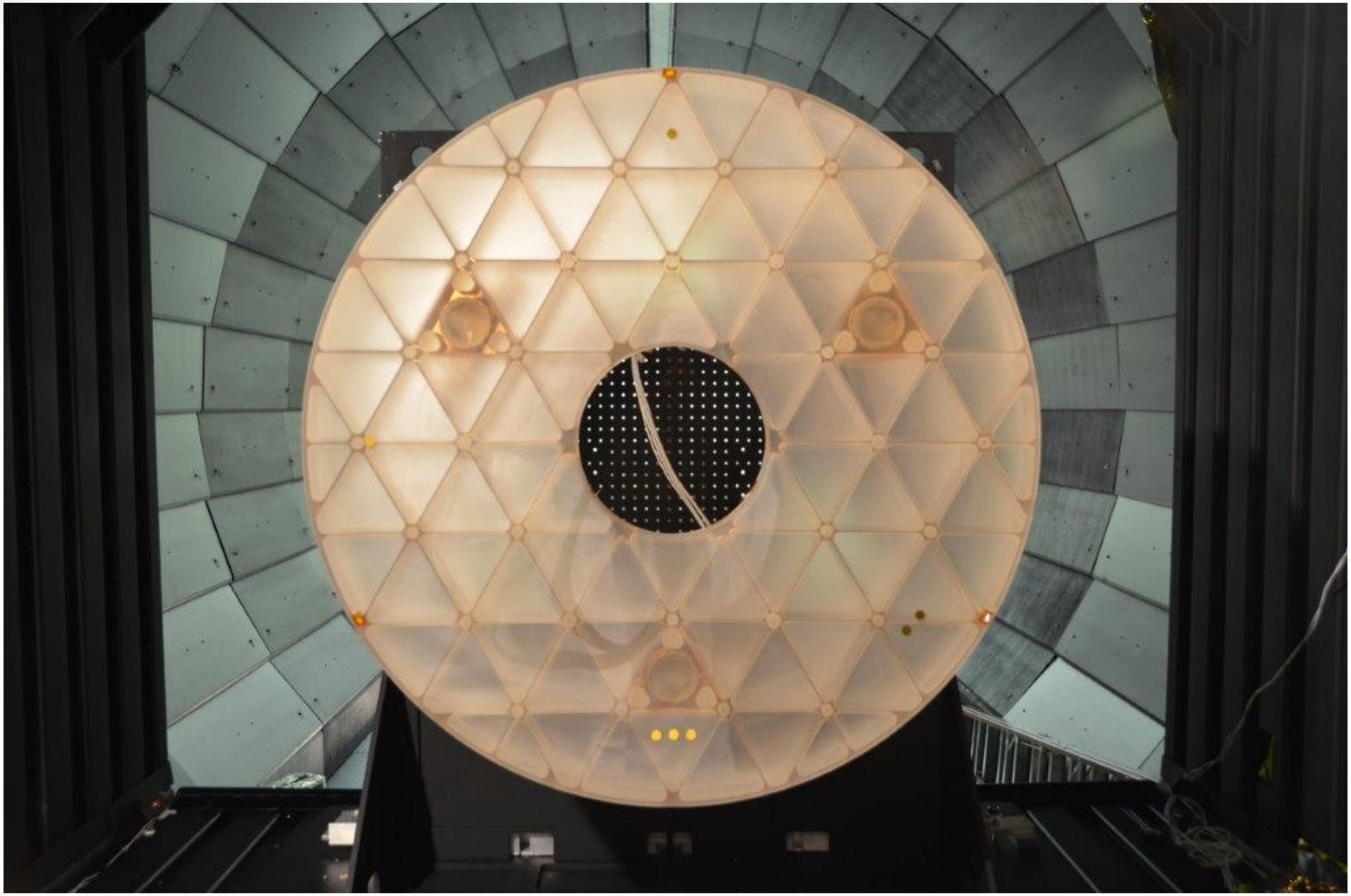
Alignment stage

AMTD-2 test configuration with PTE





Schott ELZM Model Correlation Tests



Diameter: 1.2m ROC: 3.1m Mass: 45kg; 88% lightweighted

Test Measured Data at 250K

ΔT~0.8K

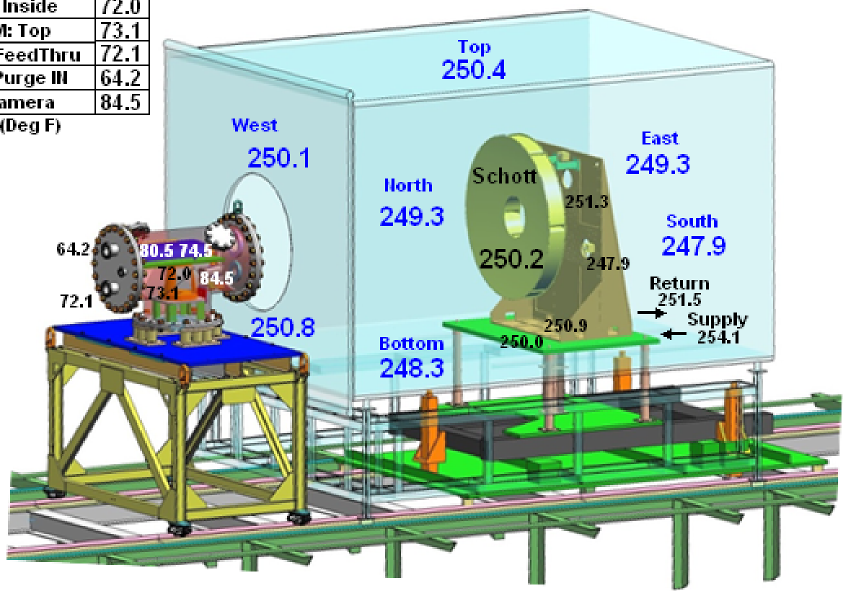
09/16/16 08:10:57

AMTD2 / Schott Cryo Test

PTE

PhaseCam East	74.5
PhaseCam West	80.5
PTE: Inside	72.0
ADM: Top	73.1
Cable FeedThru	72.1
PTE: Purge IN	64.2
IR Camera	84.5

(Deg F)

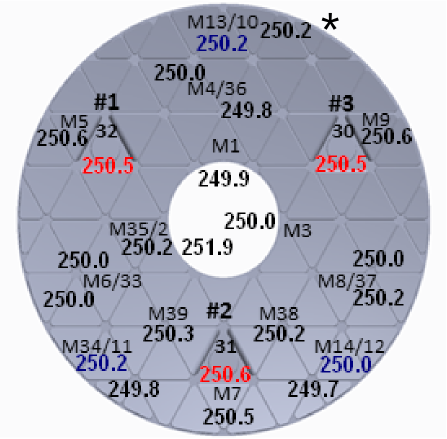


Shroud

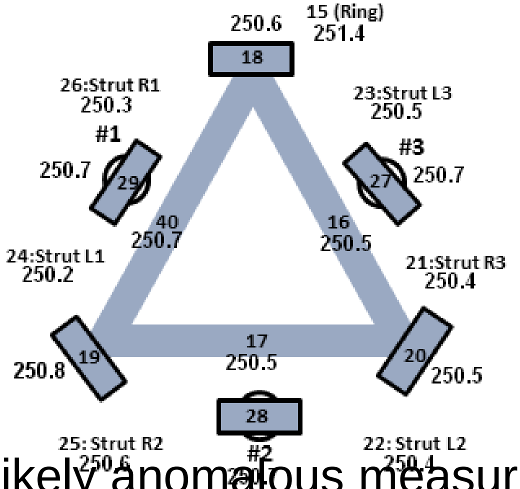
Top	250.4
North	249.3
South	247.9
Bottom	248.3
West Top	250.1
West Bottom	250.8
East	249.3

(Kelvin)

Shroud			Schott		
Average	249.4	K	Average	250.2	K
Rate	-0.1	K/HR	Rate	-0.1	K/HR
Max	250.8	K	Max	251.9	K
Min	247.9	K	Min	249.7	K
Grad	3.0	K	Grad	2.2	K



North (Front View) South



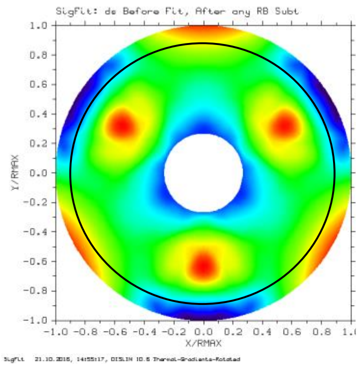
M1- Top Hole	249.9
M2 - North Hole	251.9
M3 - South Hole	250.0
M4 - 12:00	250.0
M5 - 10:00	250.6
M6 - 8:00	250.0
M7 - 6:00	250.5
M8 - 4:00	250.2
M9 - 2:00	250.3
M10- Top Edge	250.2
M11 - 8:00 Edge	249.8
M12 - 4:00 Edge	249.7
M13 - Top Front	250.2
M14 - 4:00 Front	250.0
M33 - 8:00 (w/M6)	250.0
M34 - 8:00 (w/M11)	250.2
M35 - 8:00 (w/M2)	250.2
M36 - 12:00 (w/M4)	249.8
M37 - 4:00 (w/M8)	250.0
M38 - 5:00	250.2
M39 - 7:00	250.3
30 - South Pad	250.5
31 - Bottom Pad	250.6
32 - North Pad	250.5
15 - 12:00 Ring	251.4
16 - Delta_3	250.5
17 - Delta_2	250.5
18 - Top Bracket	250.6
19 - South Bracket	250.8
20 - North Bracket	250.5
21 - Strut R3	250.4
22 - Strut L2	250.4
23 - Strut L3	250.5
24 - Strut L1	250.2
25 - Strut R2	250.6
26 - Strut R1	250.3
27 - South Mount	250.7
28 - Bottom Mount	250.7
29 - North Mount	250.7
40 - Delta_1	250.7

(Kelvin)

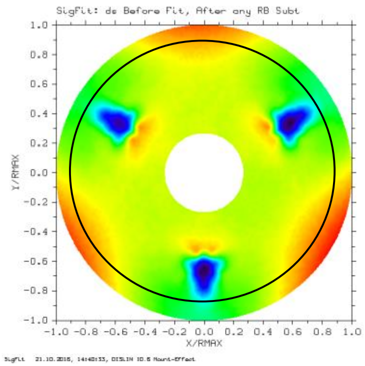
*Likely anomalous measurement ignored

Schott 1.2m ELZM Thermal Soak Correlation (294K to 250K)

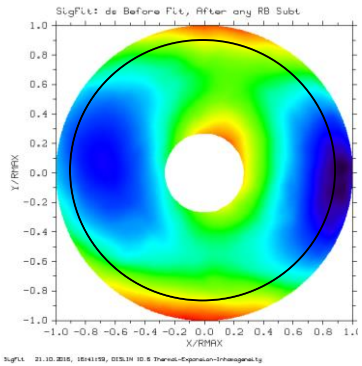
A Prior Analysis



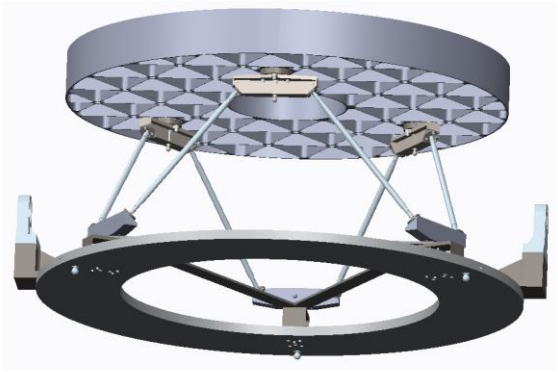
Thermal Gradients (1.28 nm RMS)



Mount Effects (0.81 nm RMS)

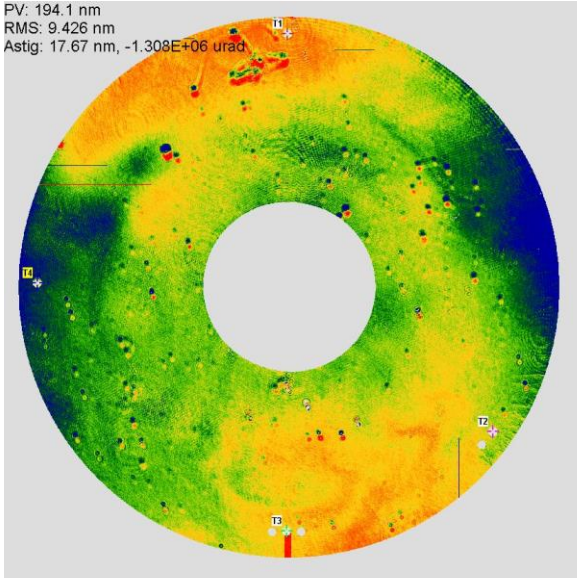


Inhomogeneity* (9.55 nm RMS)



* Random CTE map was generated with Schott specified 5 ppb/K PV homogeneity.

Test Results



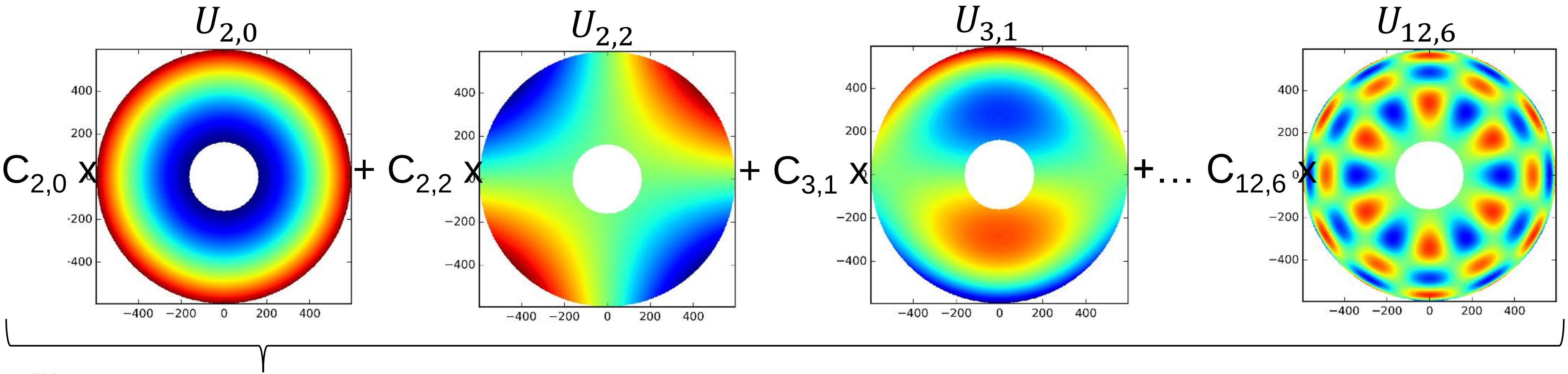
Measured SFE (9.4 nm RMS)

- **CTE drives thermal performance.**
- **Model accuracy depends on CTE knowledge.**

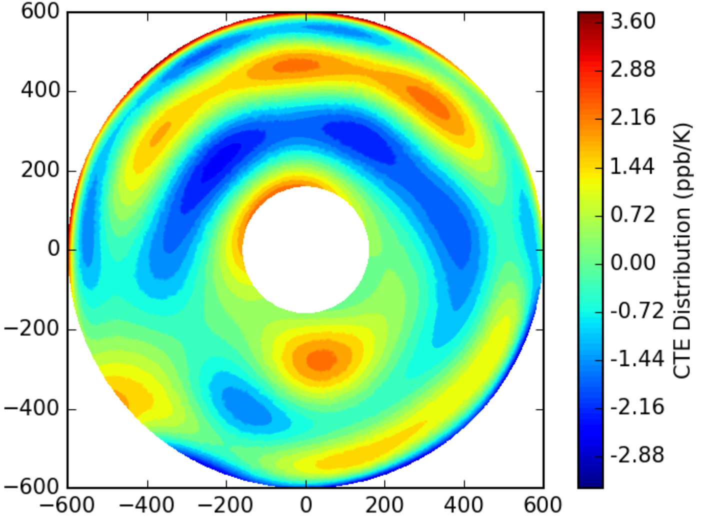
Correlation Process

Produce CTE Map from Zernike Shapes: $$[\propto_{x,y}] = \sum_{n=2}^{12} \sum_{m=0}^{n} C_{n,m} \left[U_{n,m}\right]$$

$[\propto_{x,y}]$ *is the CTE Map*

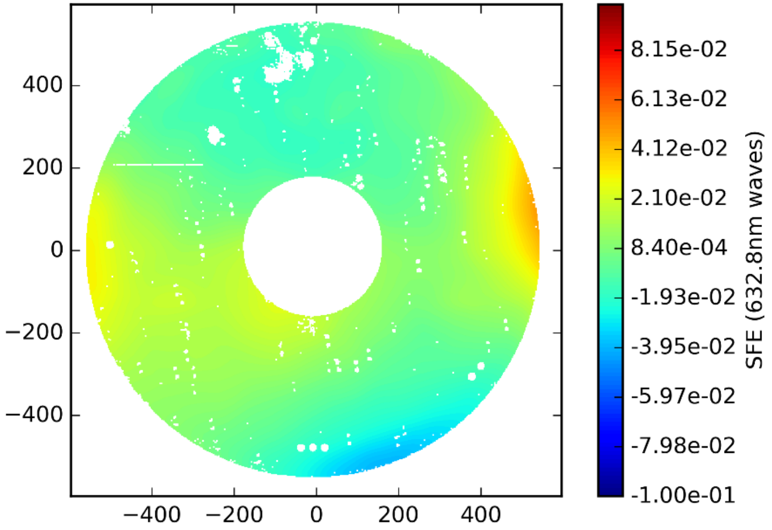


$C_{2,0}$ x $U_{2,0}$ + $C_{2,2}$ x $U_{2,2}$ + $C_{3,1}$ x $U_{3,1}$ +… $C_{12,6}$ x $U_{12,6}$



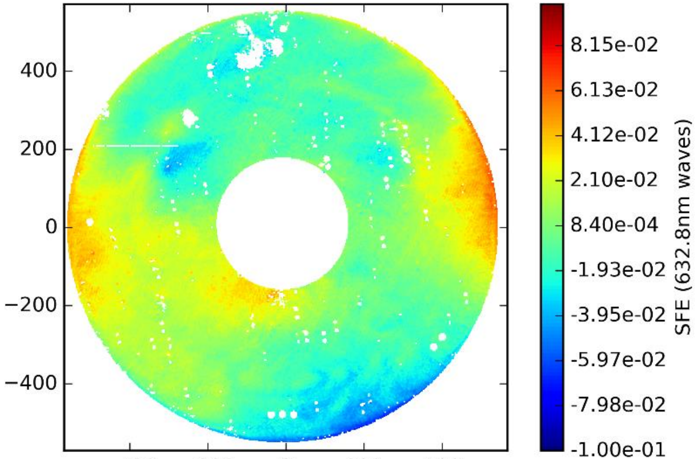
-60 ˚C Soak

Same aperture and filtering as test data

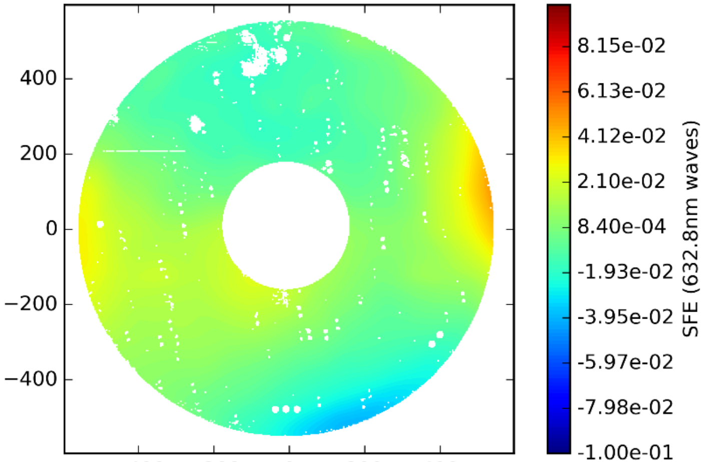


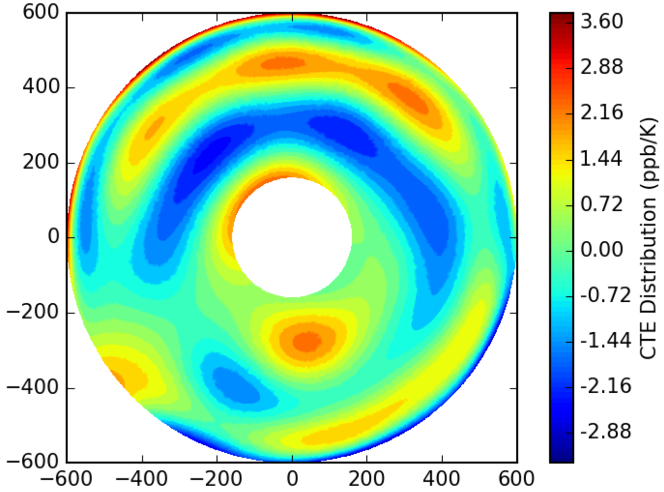
Test and Correlation Delta

Measured Soak Deformation

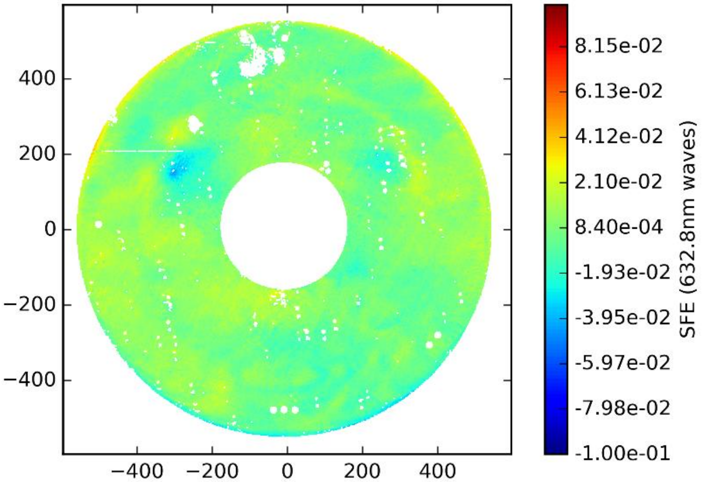


Correlated Soak Deformation





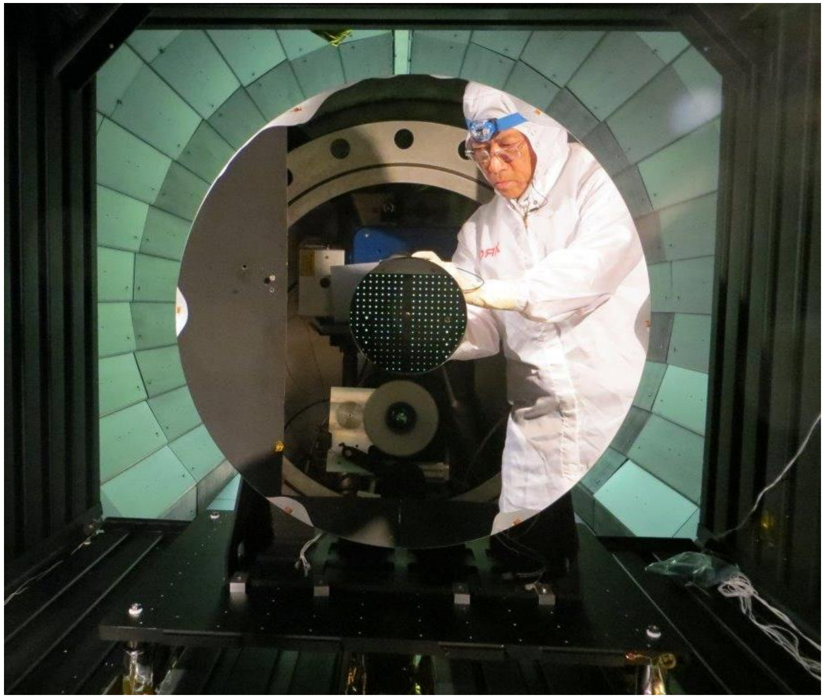
CTE Map with ~6.5ppb/K CTE homogeneity

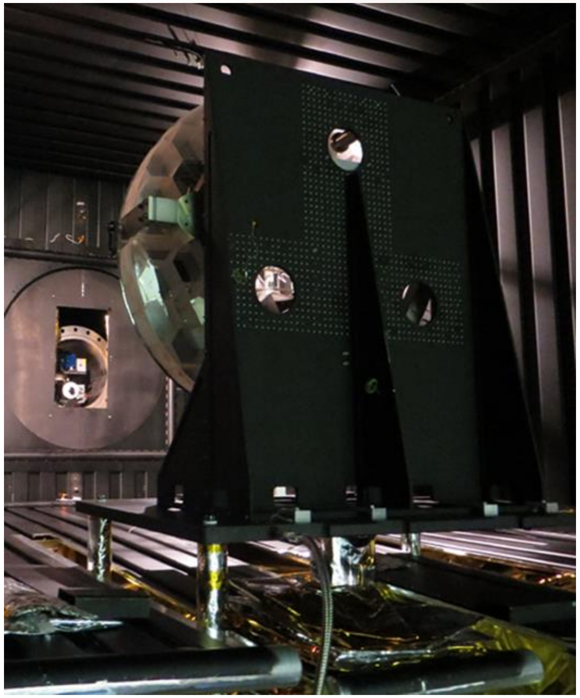


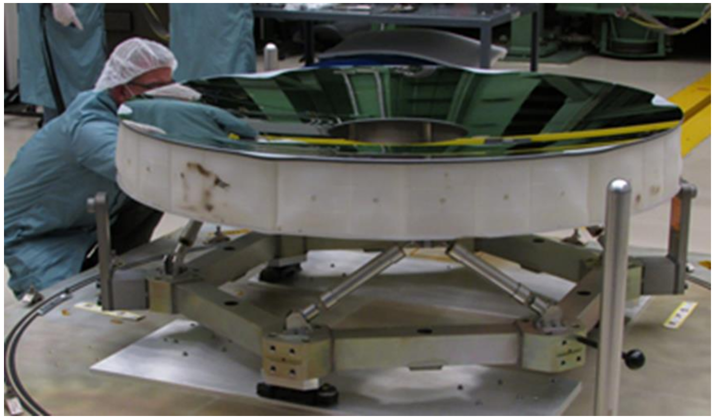
Measured – Analysis

5.9 nm < 6 nm repeatability

Harris 1.5m ULE® AMTD-2 Mirror

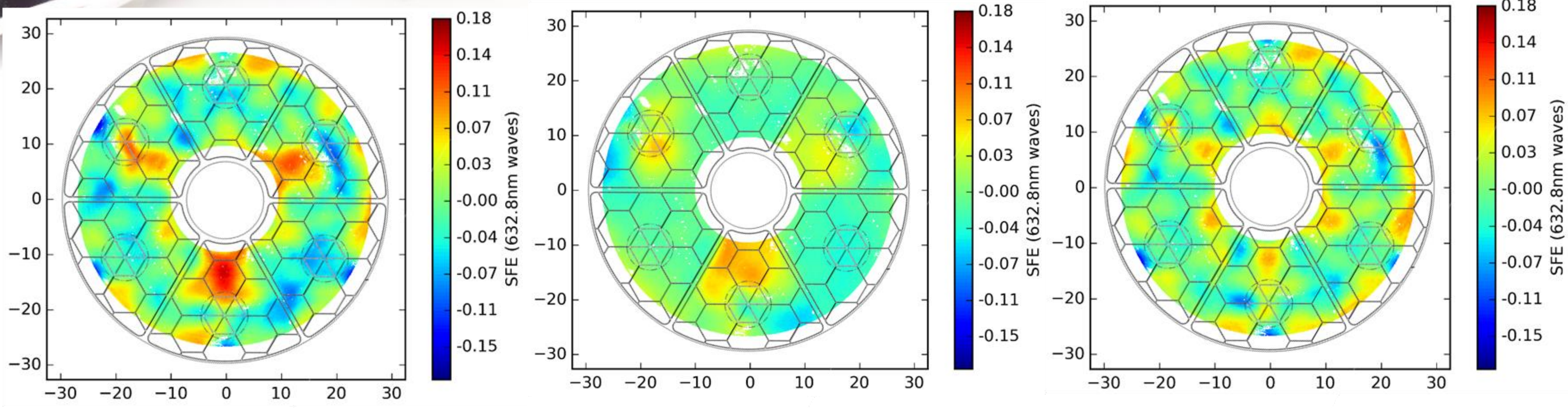






Diameter:	1.5m
ROC:	3.5m
Mass:	~50kg

Model correlation to measured data (293K – 231K)



Measured = 28.8nm rms - Model = 17.7nm rms = Residual error = 22.8nm rms

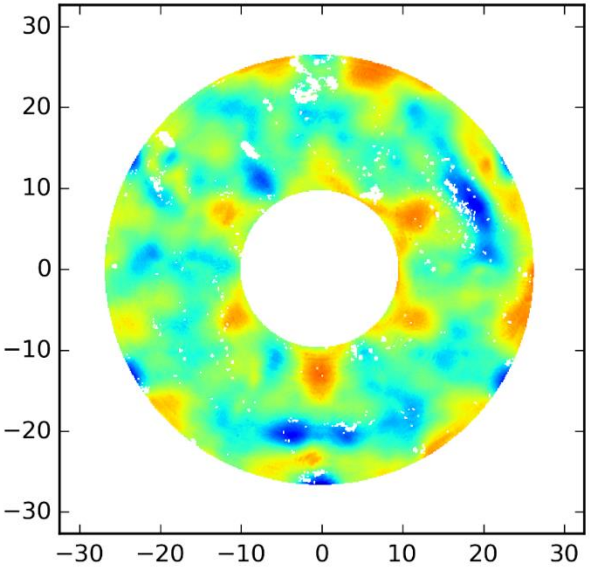
- **Model** includes prying force due to aluminum frame, mount and bond pads.
- Includes “as-built” structure & CTE.

- **Residual error** attributed to CTE inhomogeneity.
- 6-theta shape could be caused by a 6-theta temperature distribution (aligns with cores) during LTS resulting in a 6-theta CTE distribution.

CTE Correlation to Measured Data

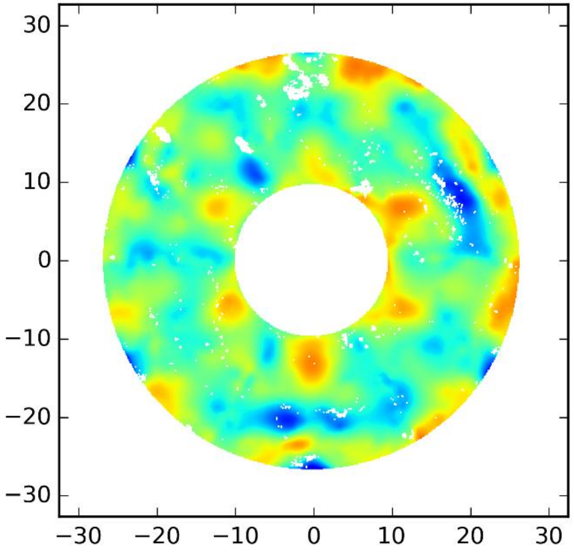
Measured SFE Change minus mount effects

RMS SFE = 22.8 nm



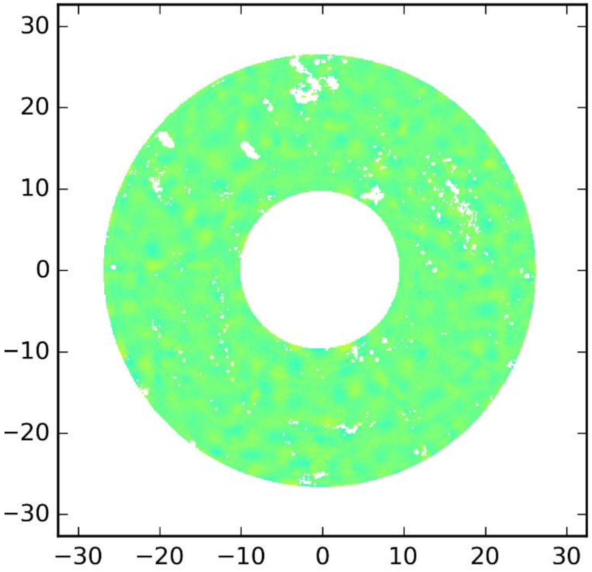
Correlated Model's Inhomogeneity Effect

RMS SFE = 22.4 nm



Test data minus correlated effects

RMS SFE = 4.4 nm



Physical mechanism that produces 'quilting' deformation is under investigation. Correlated Map was produced by introducing lateral strain difference between front/back sheets.

Milestone #2 Status

Derive thermal control system specifications for stable wavefront

DONE: HabEx program has provided tolerances for wavefront stability as a function of Zernike polynomial for the Vector Vortex Coronagraph.

- **Specification depends on spatial frequency & coronagraph:**
  - **Low-Order < 0.5 nm rms per update cycle**
  - **Mid-Spatial Frequency < 0.002 nm rms per update cycle**
- **Required Thermal Control depends on:**
  - **Mirror Thermal Sensitivity: picometers/mK**
  - **Temporal Update Cycle: 10 or 20 minutes**
  - **Thermal Controllability: 1 or 10 or 50 mK**

WFE Stability Error Budget

- Derive Tolerance for Zernike polynomials
- Sensitivities per Zernike are Fixed by Coronagraph
- Allocation Adjusted to ‘balance’ errors

$$\overset{\text{allocation}}{\epsilon_i} = \underbrace{\left(\frac{\partial \epsilon}{\partial x_i}\right)}_{\text{sensitivity}} \cdot \overset{\text{tolerance}}{\delta x_i}$$

Order				VVC-4 Sensitivity	40 ppt Allocation	VVC-4 Tolerance	PV to RMS	VVC-4 Tolerance
K	N	M	Aberration	[ppt/pm]	[ppt]	[pm PV]		[pm rms]
			TOTAL RMS		40.02	3062.6		1628.4
1	1	1	Tilt	1.96E-04	0.47	2385.6	2.00	1192.8
2	2	0	Power (Defocus)	2.44E-04	0.47	1920.1	1.73	1108.6
3	2	2	Pri Astigmatism	0.730	6.84	9.4	2.45	3.8
4	3	1	Pri Coma	0.789	7.38	9.4	2.83	3.3
5	3	3	Pri Trefoil	0.539	5.04	9.4	2.83	3.3
6	4	0	Pri Spherical	1.291	8.89	6.9	2.24	3.1
7	4	2	Sec Astigmatism	0.506	4.94	9.7	3.16	3.1
8	4	4	Pri Tetrafoil	0.527	4.94	9.4	3.16	3.0
9	5	1	Sec Coma	0.774	7.25	9.4	3.46	2.7
10	5	3	Sec Trefoil	0.547	5.12	9.4	3.46	2.7
11	5	5	Pri Pentafoil	0.680	6.37	9.4	3.46	2.7
12	6	0	Sec Spherical	1.244	8.89	7.1	2.65	2.7
13	6	2	Ter Astigmatism	1.151	8.89	7.7	3.74	2.1
14	6	4	Sec Tetrafoil	0.863	8.10	9.4	3.74	2.5
15	6	6	Pri Hexafoil	0.795	7.44	9.4	3.74	2.5
16	7	1	Ter Coma	1.577	8.89	5.6	4.00	1.4
17	7	3	Ter Trefoil	1.353	8.89	6.6	4.00	1.6
18	7	5	Sec Pentafoil	1.393	8.89	6.4	4.00	1.6
19	7	7	Pri Septafoil	1.246	8.89	7.1	4.00	1.8
20	8	0	Ter Spherical	4.338	8.89	2.0	3.00	0.7
21	8	2	Qua Astigmatism	2.078	8.89	4.3	4.24	1.0
22	8	4	Ter Tetrafoil	1.723	8.89	5.2	4.24	1.2
23	8	6	Sec Hexafoil	1.461	8.89	6.1	4.24	1.4
24	8	8	Pri Octafoil	1.533	8.89	5.8	4.24	1.4
25	9	1	Qua Coma	2.182	8.89	4.1	4.47	0.9
26	10	0	Qua Spherical	2.344	8.89	3.8	3.32	1.1
27	12	0	Qin Spherical	1.263	8.89	7.0	3.61	2.0

VVC-4 is insensitive to Tip/Tilt and Power

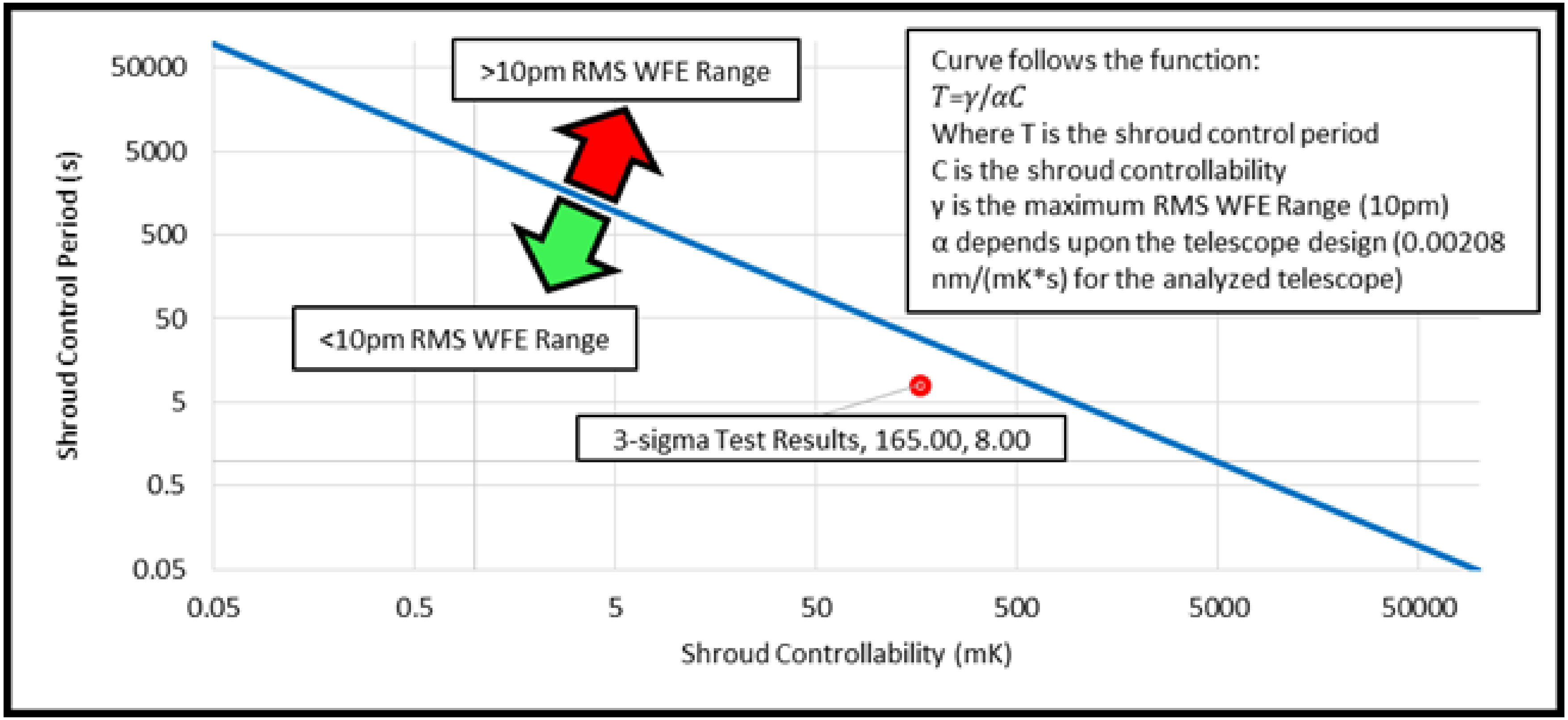
Sub-Allocation of Error Budget

Zernike terms allocation with LOS, inertial, thermal, and reserve

			RSS Allocation	100%	50%	70%	50%	10%
Order				VVC-4 Tolerance	LOS	Inertial	Thermal	Reserve
K	N	M	Aberration	[pm rms]	[pm rms]	[pm rms]	[pm rms]	[pm rms]
			TOTAL RMS	1628.4	814	1140	814	163
1	1	1	Tilt	1192.8	596.40	834.95	596.40	119.28
2	2	0	Power (Defocus)	1108.6	554.29	776.00	554.29	110.86
3	2	2	Pri Astigmatism	3.8	1.91	2.67	1.91	0.38
4	3	1	Pri Coma	3.3	1.65	2.32	1.65	0.33
5	3	3	Pri Trefoil	3.3	1.65	2.32	1.65	0.33
6	4	0	Pri Spherical	3.1	1.54	2.16	1.54	0.31
7	4	2	Sec Astigmatism	3.1	1.54	2.16	1.54	0.31
8	4	4	Pri Tetrafoil	3.0	1.48	2.07	1.48	0.30
9	5	1	Sec Coma	2.7	1.35	1.89	1.35	0.27
10	5	3	Sec Trefoil	2.7	1.35	1.89	1.35	0.27
11	5	5	Pri Pentafoil	2.7	1.35	1.89	1.35	0.27
12	6	0	Sec Spherical	2.7	1.35	1.89	1.35	0.27
13	6	2	Ter Astigmatism	2.1	1.03	1.45	1.03	0.21
14	6	4	Sec Tetrafoil	2.5	1.25	1.76	1.25	0.25
15	6	6	Pri Hexafoil	2.5	1.25	1.75	1.25	0.25
16	7	1	Ter Coma	1.4	0.70	0.99	0.70	0.14
17	7	3	Ter Trefoil	1.6	0.82	1.15	0.82	0.16
18	7	5	Sec Pentafoil	1.6	0.80	1.12	0.80	0.16
19	7	7	Pri Septafoil	1.8	0.89	1.25	0.89	0.18
20	8	0	Ter Spherical	0.7	0.34	0.48	0.34	0.07
21	8	2	Qua Astigmatism	1.0	0.50	0.71	0.50	0.10
22	8	4	Ter Tetrafoil	1.2	0.61	0.85	0.61	0.12
23	8	6	Sec Hexafoil	1.4	0.72	1.00	0.72	0.14
24	8	8	Pri Octafoil	1.4	0.68	0.96	0.68	0.14
25	9	1	Qua Coma	0.9	0.46	0.64	0.46	0.09
26	10	0	Qua Spherical	1.1	0.57	0.80	0.57	0.11
27	12	0	Qin Spherical	2.0	0.98	1.37	0.98	0.20

Thermal Stability

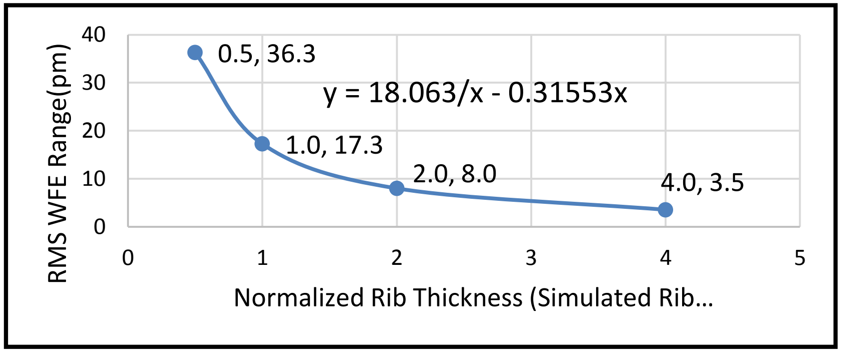
- Wavefront error meets the desired stability when the primary mirror is inside a thermally controlled environment with appropriate period and controllability performance.
- Performance trade varies as a function of specific mirror design: thermal mass, heat capacity, conductivity, CTE, etc.



Curve follows the function:
$T=\gamma/\alpha C$
Where T is the shroud control period
C is the shroud controllability
γ is the maximum RMS WFE Range (10pm)
α depends upon the telescope design (0.00208 nm/(mK*s) for the analyzed telescope)

Thermal Stability Study

- Biggest drivers for thermal stability are heat capacity and CTE
  - If all factors are constant, CTE determines error amplitude.
  - Heat Capacity determines how fast mirror responds (or does not respond) in an actively controlled thermal environment.



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

- Proposed Figures of Merit for thermally actively control mirror:
  - Massive Active Opto-Thermal Stability: MAOS=$(\rho c\_p)/CTE$
  - Active Opto-Thermal Stability: AOS=c_p/CTE

Milestone #3 Status

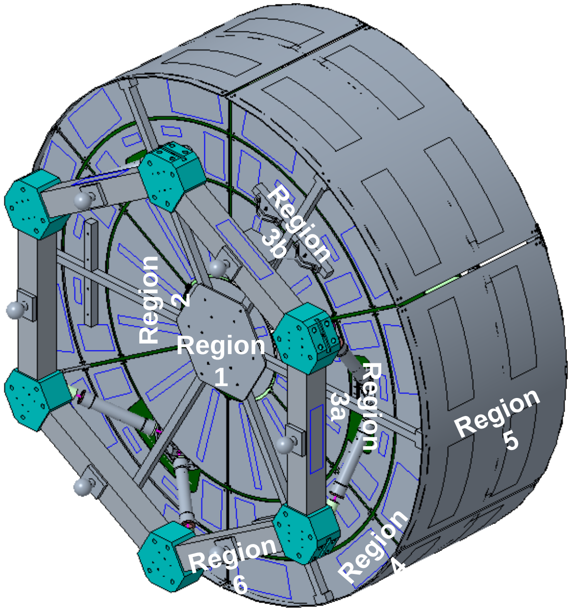
Design and build predictive Thermal Control System for 1.5m ULE® mirror with components that sense temperature changes at ~1mK level and actively control mirror's thermal environment at ~20mK level.

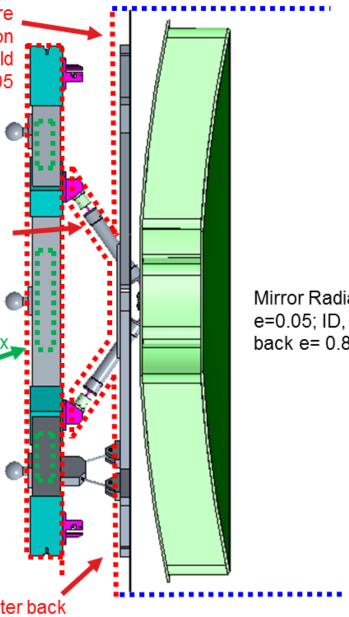
- **DONE: Defined tasks for MSFC and Harris Corp.**
- **DONE: Designed PTC system and procured components.**
- **IN-PROCESS: Integrate MSFC and Harris components of PTC system.**
- **FUTURE: Conduct test with 1.2m Aluminum mirror, and 1.5m ULE® mirror.**

Predictive Thermal Control

Multi-Zone Thermal Enclosure for 1.5m AMTD ULE® mirror.

Heat strips placed surrounding mirror and on the struts.





Reaction structure with insulation radiates to cold enclosure e=0.05

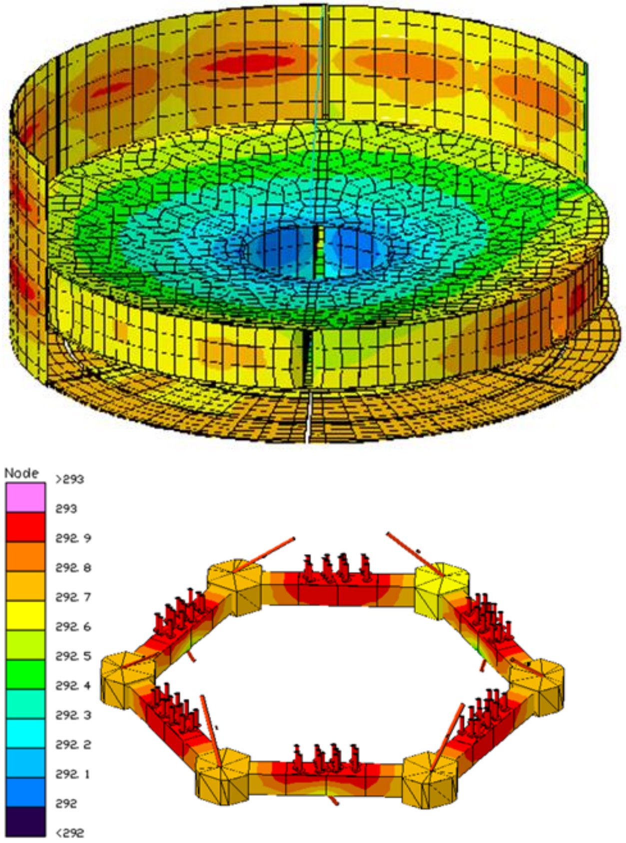
SLI encloses struts – open to warm side=0.05

Heaters on hex structure

Heater back Radiates to cold enclosure thru SLI, e=0.05

Mirror Radiation e=0.05; ID, OD, back e= 0.8

Bathtub designed with 50% SLI coverage (e=0.50 in model)



Milestone #4 Status

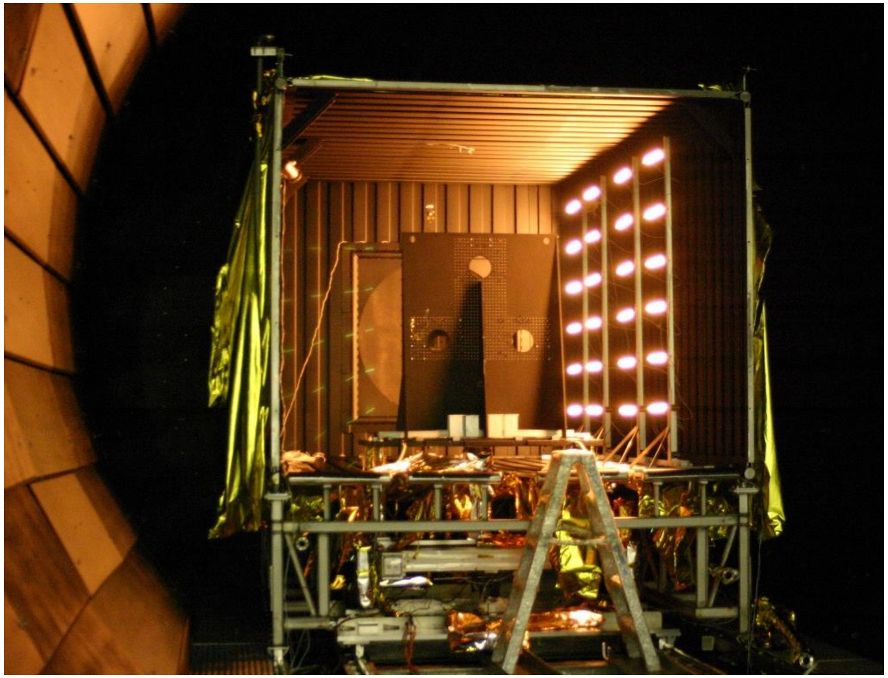
Validate model by testing 1.5-m class ULE® mirror in a relevant thermal vacuum environment in the MSFC X-ray and Cryogenic Facility (XRCF) test facility.

- **DONE: Designed and installed Solar Simulator and Cold Plate to XRCF test Capability.**
- **DONE: 'Preliminary' test of bare 1.5-m ULE® AMTD mirror (no PTC system) in XRCF at thermal soak temperature without and with solar simulator lamps.**
- **IN PROCESS: Procuring a 1.2-m Aluminum Test Mirror**
- **IN PROCESS: Correlating 'preliminary' data with model**
- FUTURE: Test 1.2m Aluminum 'test mirror' and 1.5m ULE® AMTD mirror with rear PTC system.
- OPTIONAL: Test other mirrors in XRCF/PTC configuration.

XRCF PTC test configuration

Add ability to induce axial and lateral thermal gradients onto mirror under test.

- Lateral gradient with solar lamp array.
- Axial gradient with forward cold plate.



Solar lamp array consists of 24 lamps connected in a 3-phase delta configuration (8 per phase).

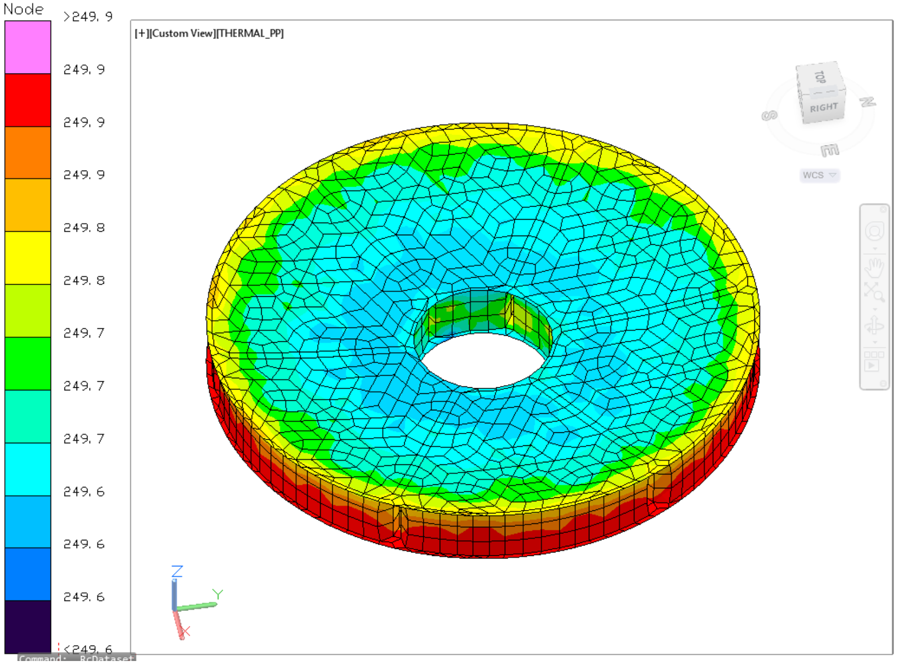
Stands designed and fabricated to provide a variety of coverage areas (i.e. 6x4, 3x8 and 2x12 etc.)

Controllable from 0 to 100% power.

Predicted Axial Performance

Predicted performance of the coated AMTD 1.5-m ULE® mirror when viewing the cold plate.

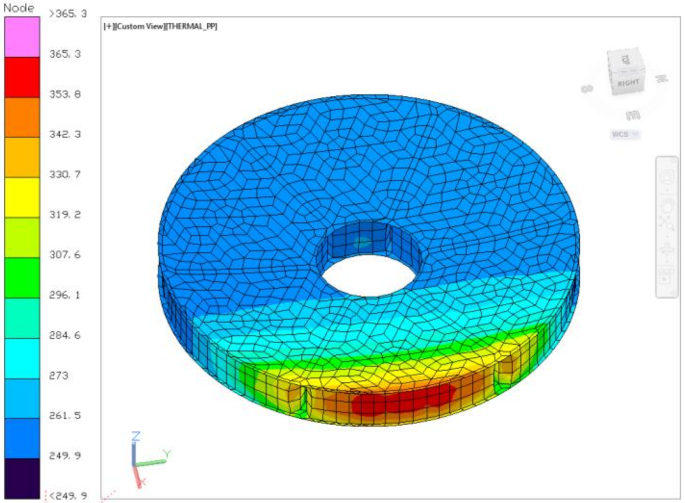
- For mirror at average temperature of 249.75K
- Cold Wall produces a small axial gradient of roughly 0.3°C.
- For uncoated mirror, predicted axial gradient is 2°C.

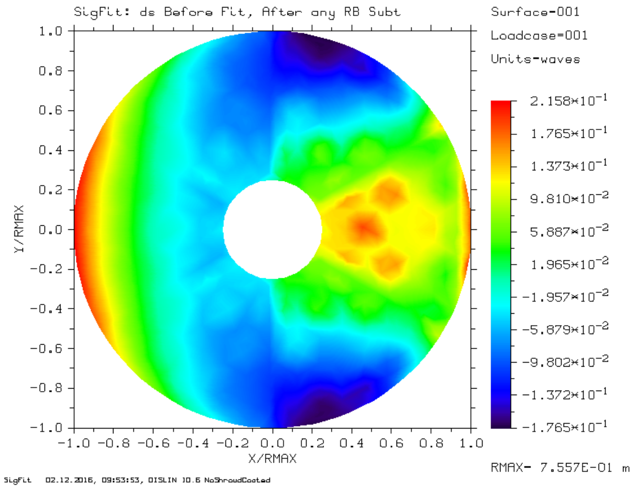


Predicted Lateral Performance

Predicted performance of the coated AMTD 1.5-m ULE® mirror when illuminated by solar simulator.

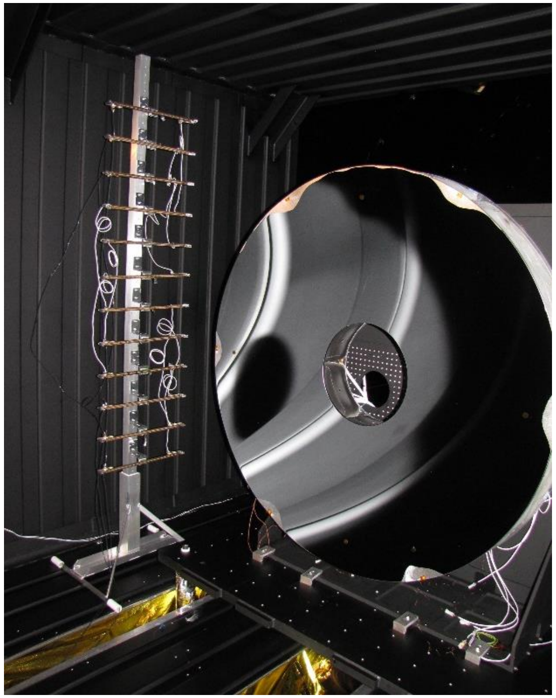
- For mirror at average temperature of 265K
- Solar Simulator produces a lateral temperature gradient of 115.4K (peak temperature of 365K)
- Predicted surface figure error is 53.5 nm rms.
- Testing a Coating Mirror is Important.
  - For uncoated mirror, predicted surface figure error is only 27 nm rms SFE because surface emissivity constrains the thermal gradient to the edge of the mirror.



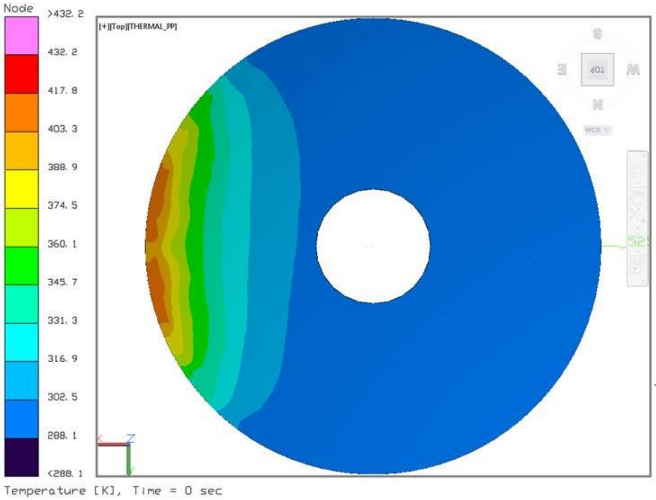


Thermal Gradient Test

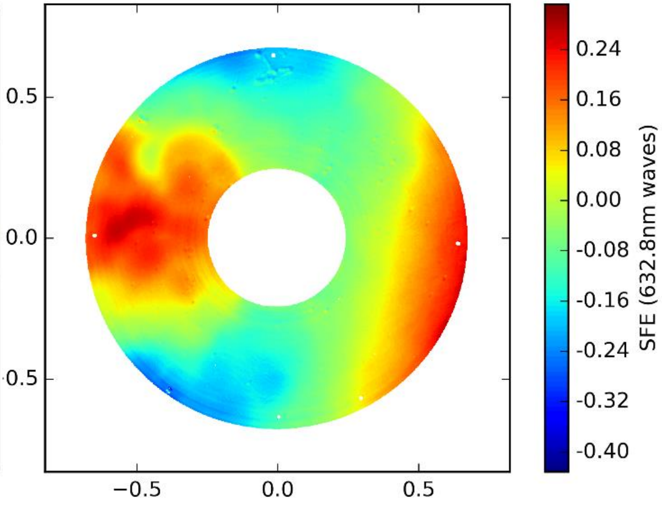
1.5m ULE® mirror tested with solar lamp array.



Thermal Gradient = 115 K



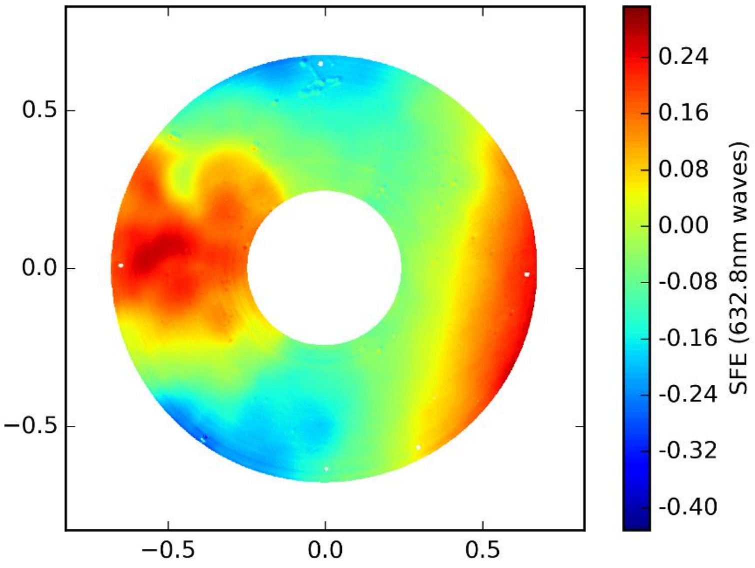
SFE = 78.7 nm rms



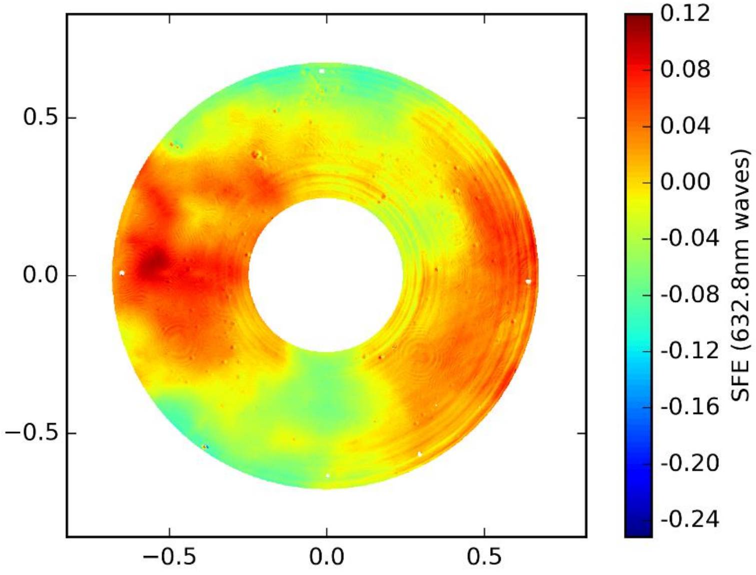
Linearity Test

Deformation of 1.5m ULE® mirror from thermal gradient is linear.

‘High’ Solar Simulator Irradiance
SFE = 78.7 nm rms

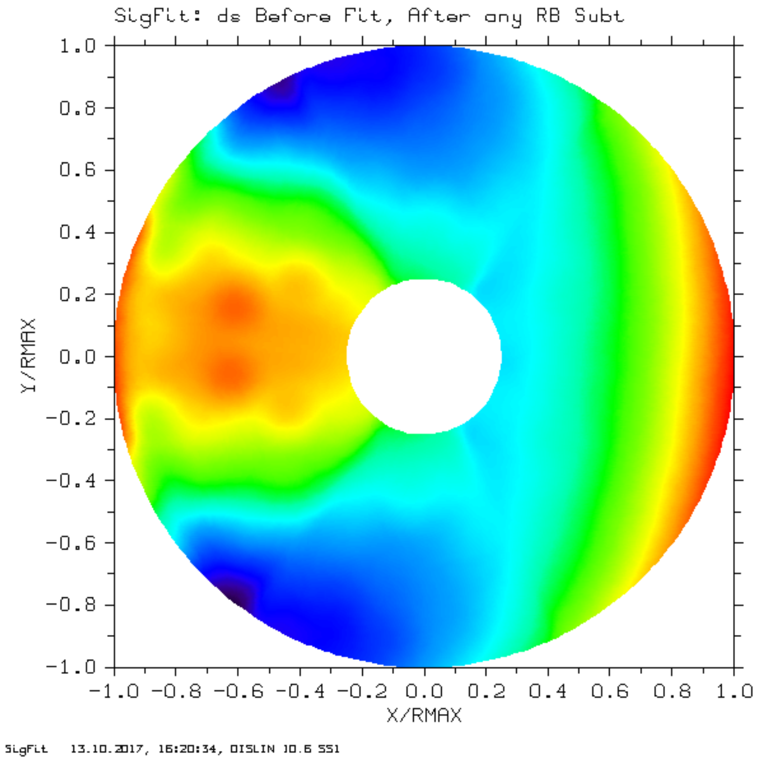


‘Low’ Solar Simulator Irradiance
SFE = 24.5 nm rms

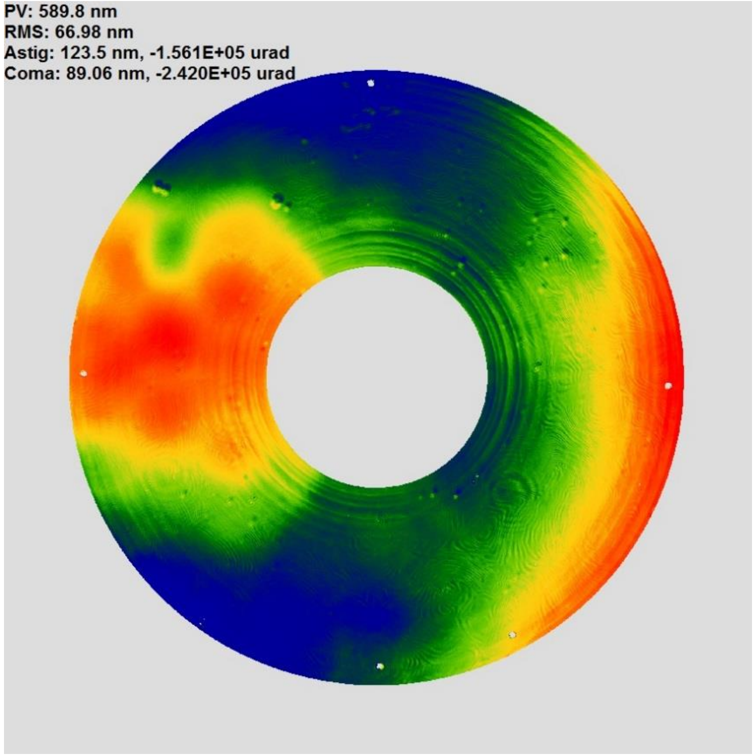


Correlated Thermal Gradient Test

Predicted SFE
12.4 nm rms



Measured SFE
67 nm rms

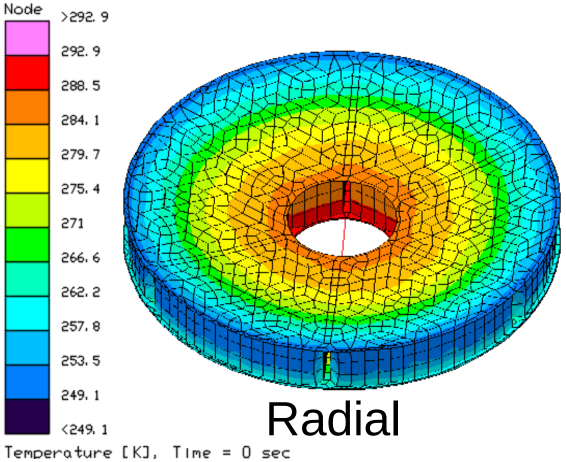


PV: 589.8 nm
RMS: 66.98 nm
Astig: 123.5 nm, -1.561E+05 urad
Coma: 89.06 nm, -2.420E+05 urad

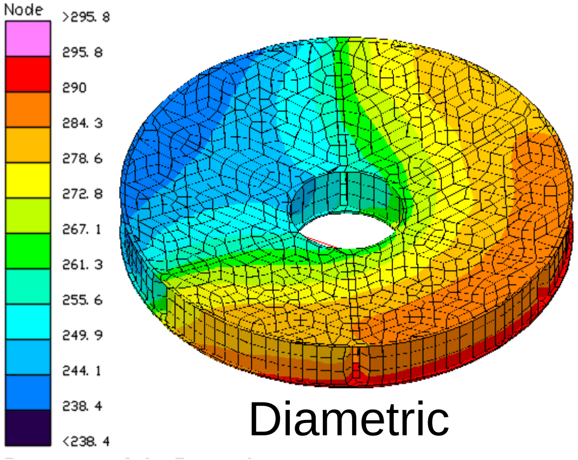
- Predicted SFE is for correlated ‘as-measured’ thermal gradient & assumes mirror has an average ‘as-built’ CTE of 4ppb/K as provided by Corning.
- (Corning Proprietary) Measured SFE requires ‘final’ CTE of ~25 ppb/K.

Active Thermal Control

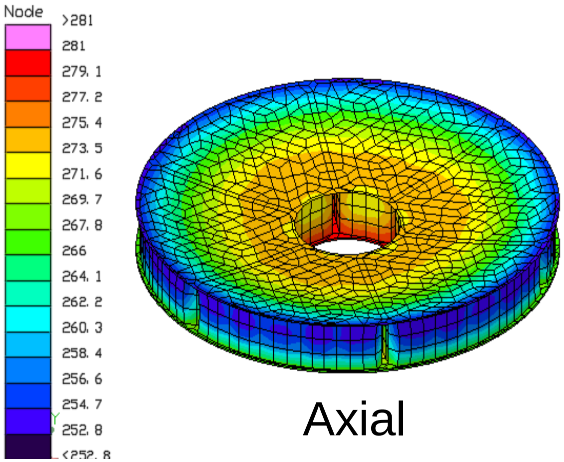
Thermal Enclosure zonal heaters are design to ‘compensate’ for environmental induced gradients by actively producing radial, axial and diametric thermal gradients in the mirror.



Radial



Diametric



Axial

Aluminum Test Mirror

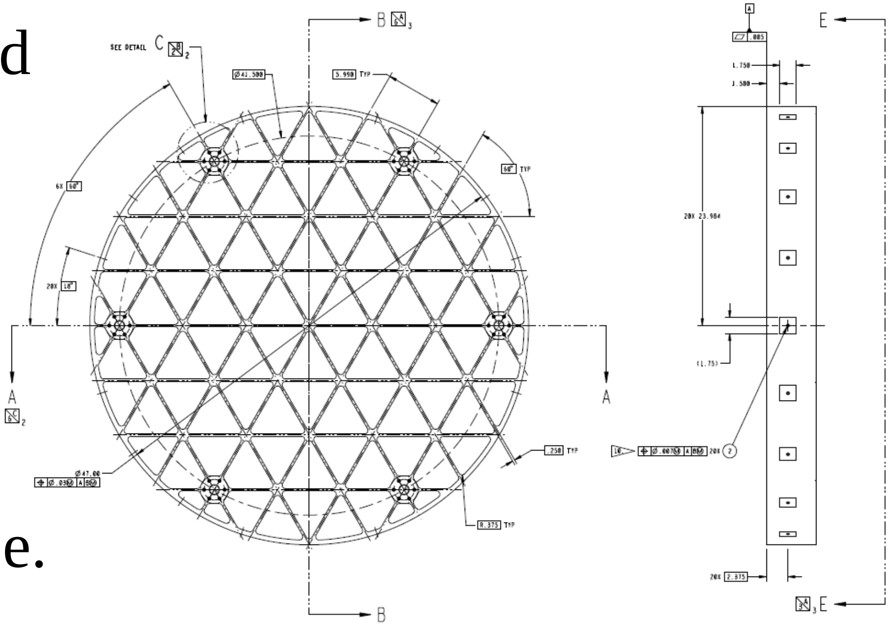
Because ULE® CTE is small, it takes a large thermal gradient to produce a measurable effect.

Therefore, PTCS is procuring a 1.2m Aluminum Mirror to use as a pathfinder test article.

Mirror struts/mounts are design to fit PTC Thermal Enclosure

For testing, MSFC will diamond turn as spherical surface.

Additionally, MSFC plans to cryo-null figure mirror as a technology demonstrator for a potential Far-Infrared Mission such as Origins Space Telescope.



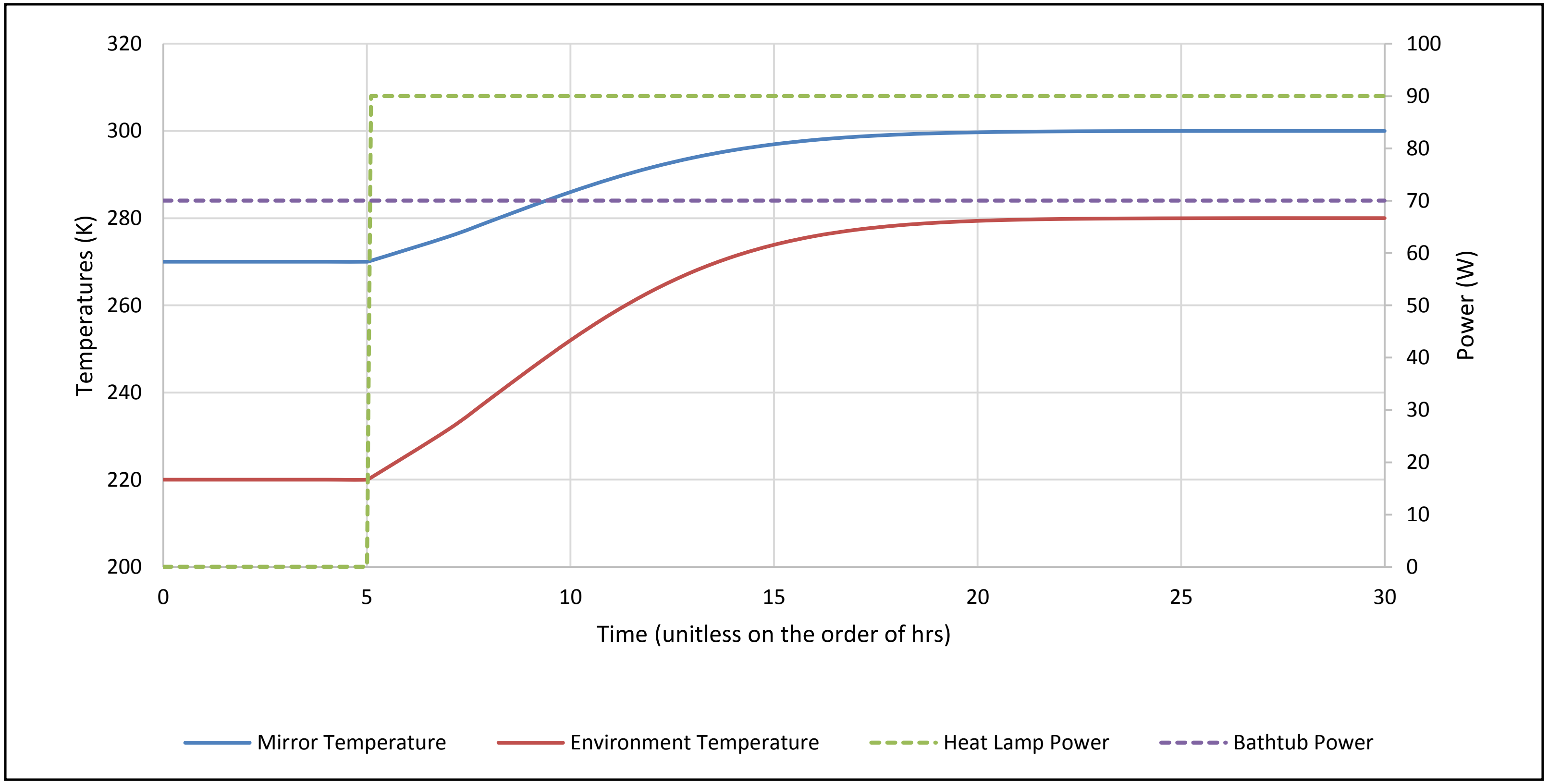
Milestone #5 Status

Use a validated model to perform trade studies to determine how thermo-optical performance can be **optimized as a function of mirror design, material selection, mass,** etc.

- **DONE: Preliminary trade studies conducted including initial assessment of HabEx Baseline Design**
- FUTURE: Trade Studies for potential mirror systems for HabEx, LUVOIR and/or OST.

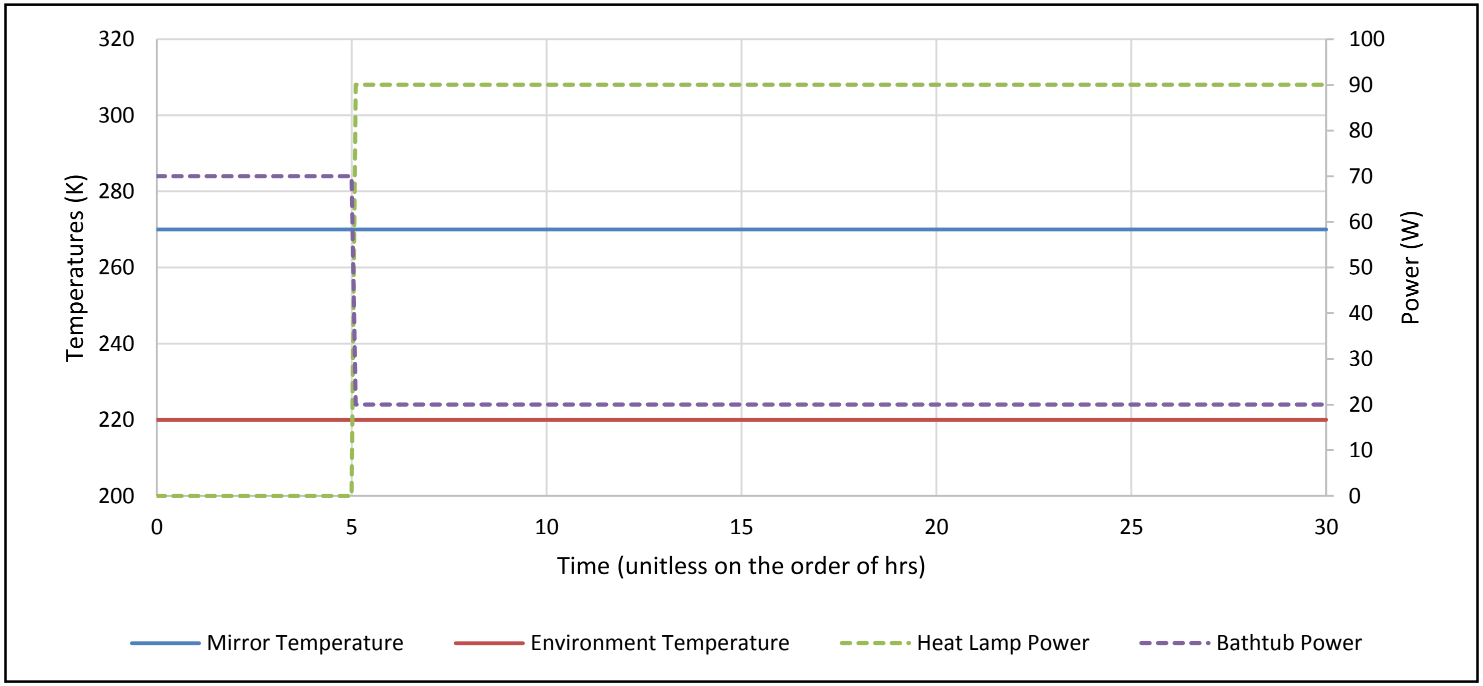
PTC passive thermal test

- This is the control case for the experiment.
- The mirror is at steady state at ~270K.
- The environment is at a temperature (T_E) and the thermal enclosure is at power (Q_B).
- Increase heat lamp power (Q_H) at time “5” and monitor mirror surface figure.
- The aluminum hexagonal backplane’s temperature is maintained at ~270K.



PTC active thermal test

- This is an active case that tests the thermal control. The performance of thermal control is judged by how well it reduces transient SFE response relative to passive test.
- The initial conditions are the same as the initial conditions in the passive test.
- The heat lamps turn on and the bathtub/rear heater thermal control system responds, ideally in a way that maintains the mirror temperature at constant temperature.
- The aluminum hexagonal backplane's temperature is maintained at ~270K throughout the test.



PTC active thermal test

- Measure heat lamp (Q_H) output and thermal enclosure heat output (Q_B) that can be removed by the refrigeration system.

- Find the combination of T_E and Q_B that:

1. Controls the mirror at ~270K during the passive test
2. Allow the mirror to stay at 270K when the heat lamps turn on by reducing the heater power on bathtub/heater panels

Conclusion

PTCS uses Science-Driven Systems Engineering methodology to mature technology for thermally stable telescopes.

PTCS has three objectives:

1. Validate models that predict thermal optical performance of real mirrors and structure based on their structural designs and constituent material properties, i.e. coefficient of thermal expansion (CTE) distribution, thermal conductivity, thermal mass, etc.
2. Derive thermal system stability specifications from wavefront stability requirement.
3. Demonstrate utility of a Predictive Control thermal system for achieving thermal stability.

Predictive thermal control has the potential to solve the thermal stability problem for exoplanet searching telescopes and will be tested on flight traceable hardware to determine its efficacy.

PTCS has made significant progress on its 5 Milestones in 2018.