# Predictive Thermal Control (PTC) Technology to enable Thermally Stable Telescopes: First Two Year Status

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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.

# History

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

# Predictive Thermal Control (PTC)

- PTC's goal is to develop an active thermal control technology that can keep mirrors at a constant temperature (< 10 mK) regardless of where the telescope points on the sky.
- PTC does this by placing a physics-based **Model Predictive Control (MPC)** logic in the control loop to determine control variables (heater power levels) based upon state variables (temperature measurements).
  - MPC uses sensors to measure the temperature distribution on the optic to estimate temperatures at unmeasured locations and determine the resulting heating profile needed to produce the desired temperature profile.
  - MPC uses sensors on the outer barrel and attitude knowledge to determine the telescope's external thermal load changes (because of a slew or roll relative to the sun) and modifies the amplitude of the enclosure's zonal heaters to compensate.

# Objectives

PTCS has 3 objectives for maturing Thermally Stable Telescope technology

1. **Validate 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** use of PTC to achieve thermal stability.

# Milestones

PTCS has a detailed technical plan with 5 quantifiable milestones:

1. Develop a high-fidelity **model of 1.5m ULE® AMTD-2 mirror with measured CTE distribution, and reflective coating**.
2. **Derive specifications** for thermal control system for wavefront stability.
3. **Design and build a predictive Thermal Control System** for a 1.5m ULE® AMTD-2 mirror that senses temperature changes and actively controls the mirror's thermal environment.
4. **Validate model** by testing 1.5-m class ULE® AMTD-2 mirror in a relevant thermal vacuum environment at X-ray and Cryogenic Facility (XRCF).
5. Use validated model to **perform Trade Studies** to optimize primary mirror thermo-optical performance as a function of mirror design, material selection, material properties (i.e., CTE) mass, etc.

# Status

MS#1: Created a high-fidelity 'as-built' FEM of 1.5-m AMTD-2 ULE® mirror including CTE distribution.

MS#2: Derived thermal control specification for HabEx baseline telescope

MS#3: Harris Corp built and delivered a 37-zone actively controlled thermal enclosure for a 1.5m ULE® AMTD-2 mirror.

MS#4: Modified the XRCF to enable lateral and axial thermal gradient testing of mirror systems.

MS#4: Adding control hardware and software to implement PTC with XRCF thermal environment and Harris thermal enclosure.

MS#4: Procuring a 1.2m aluminum mirror for preliminary tests.

MS#5: Design primary mirror for HabEx baseline telescope.

# Future Work

Test PTC control-logic in MSFC XRCF on:

- 1.2-m aluminum pathfinder mirror
- 1.5-m ULE® AMTD-2 mirror

Correlate measured test results with predicted performance.

# Objective #1

Validate model that predicts thermal optical performance of mirror assembly based on structural design and material properties, i.e. CTE distribution, thermal conductivity, mass, etc.

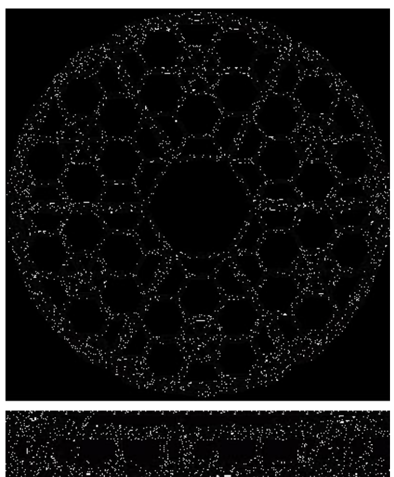
Milestones #1 and #4 support Objective #1

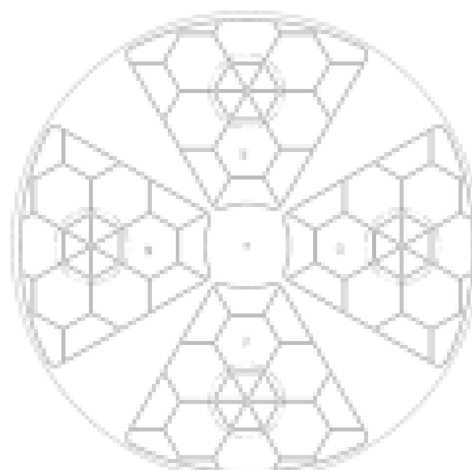
- Milestone #1 creates the high-fidelity model
- Milestone #4 validates the model

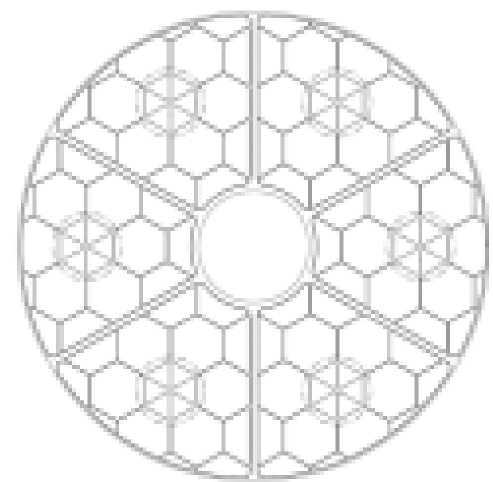
# Milestone #1 Status

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.

- **DONE: Created high-Fidelity ‘as-built’ model using MSFC x-ray computed tomography data imported into NASTRAN and Corning CTE boule data provided by Harris Corp (i.e. where each of the 18 core elements was cut from its boule and the location of that core element in the AMTD-2 mirror).**







# Milestone #4 Status

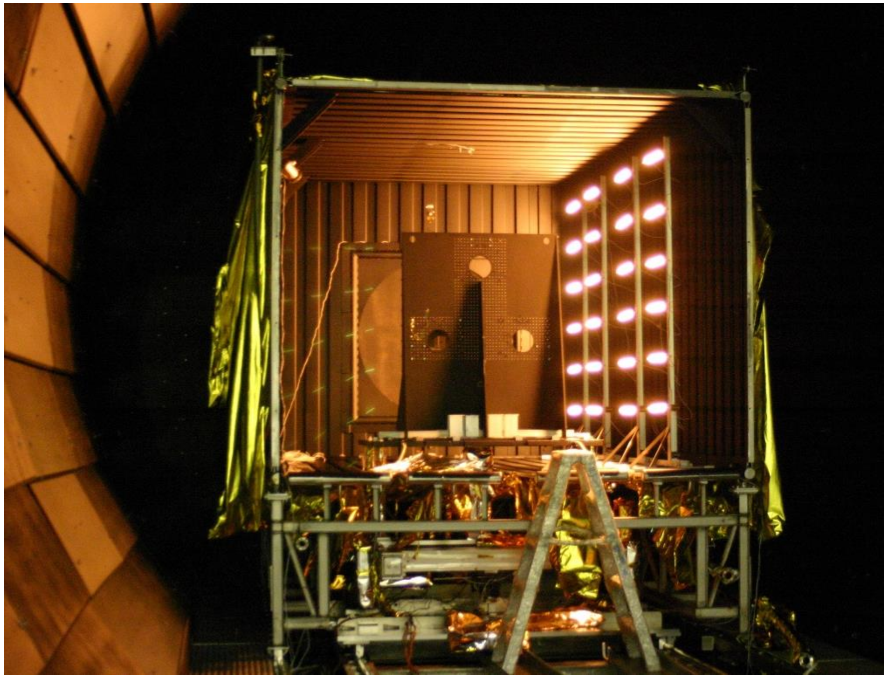
**Validate model** by testing 1.5-m class ULE® mirror in a relevant thermal vacuum environment in the MSFC X-ray and Cryogenic Facility (XRCF) test facility.

- **DONE: Designed and installed Solar Simulator and Cold Plate to XRCF test Capability.**
- **DONE: Test bare 1.5-m ULE® AMTD mirror (no PTC system) in XRCF at thermal soak temperature and with thermal gradient imposed by solar simulator lamps.**
- **DONE: Correlating high-fidelity model with 'as-measured' static cryo-deformation data.**
- **DONE: Correlating high-fidelity model with 'as-measured' static thermal gradient data.**

# 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.

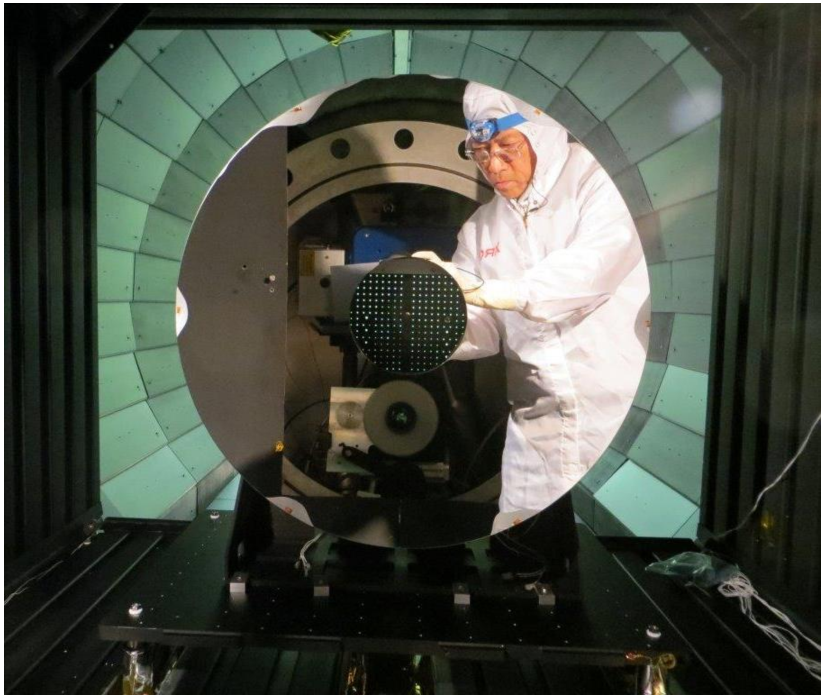


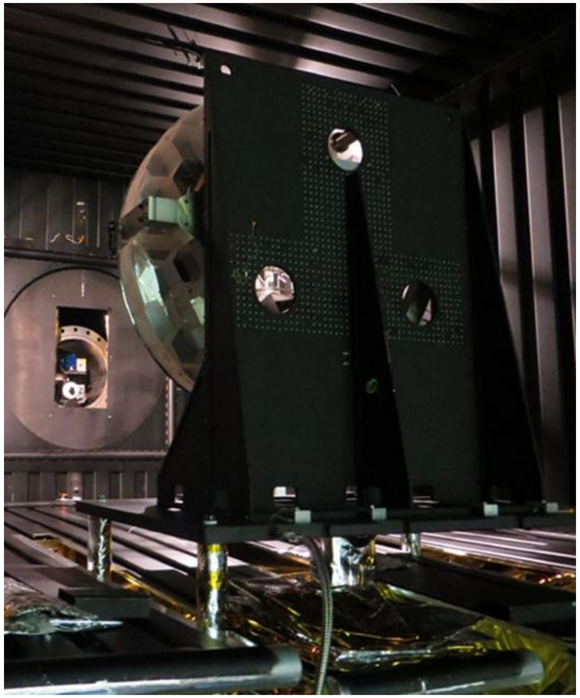
Solar lamp array consists of 24 lamps connected in a 3-phase delta configuration (8 per phase).

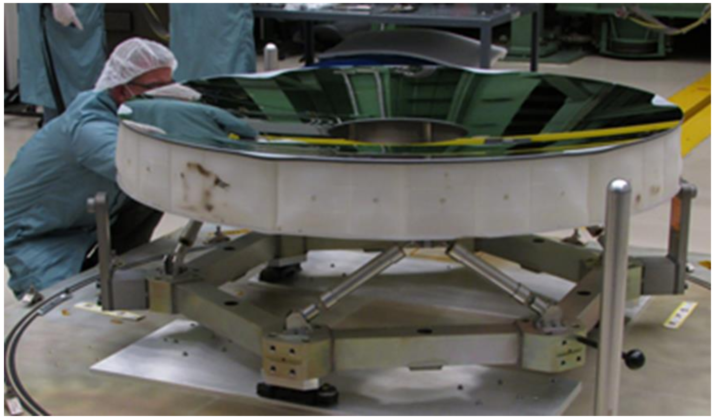
Stands designed and fabricated to provide a variety of coverage areas (i.e. 6x4, 3x8 and 2x12 etc.)

Controllable from 0 to 100% power.

# Harris 1.5m ULE® AMTD-2 Mirror







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

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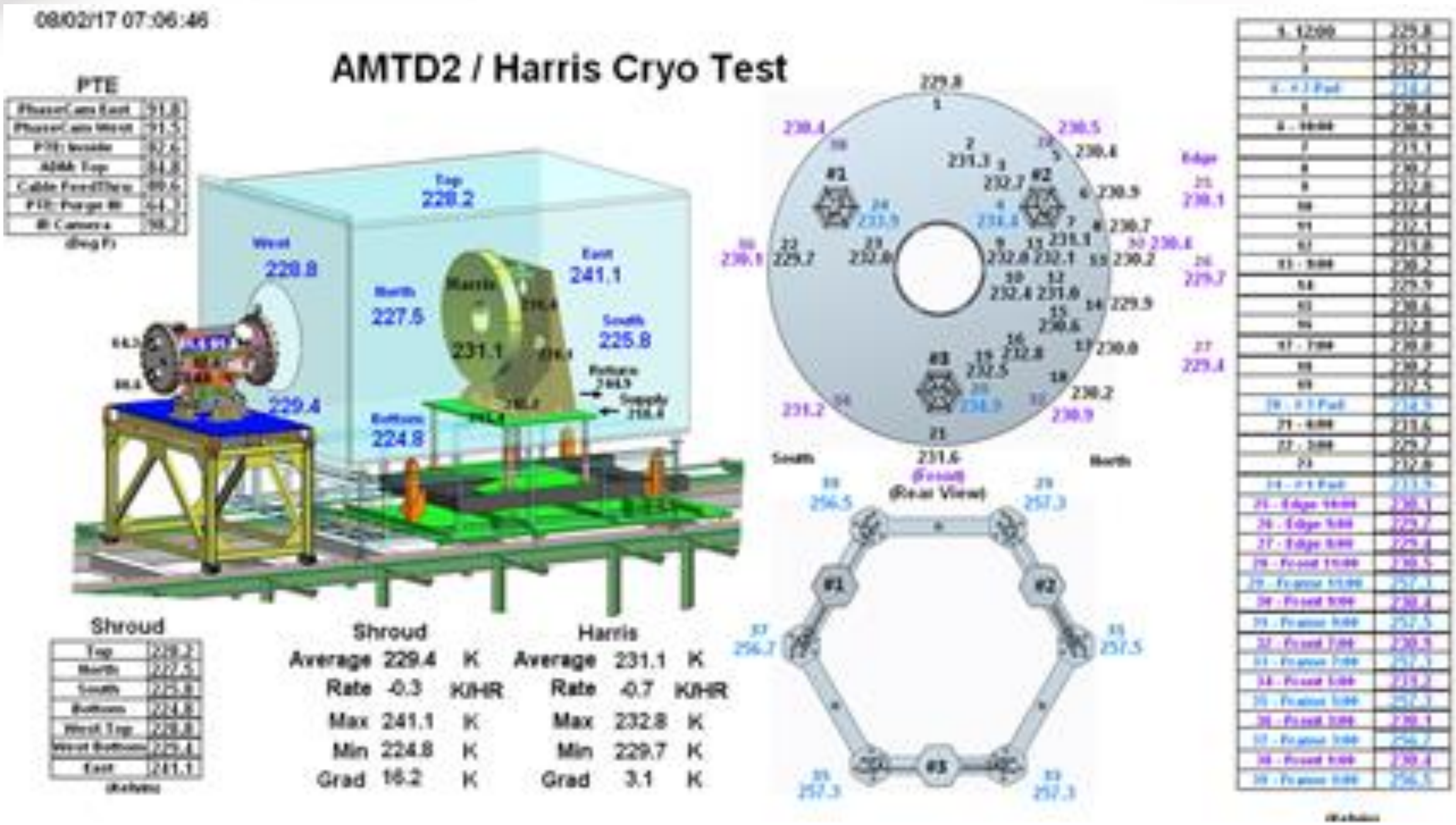
# Tested ULE® AMTD-2 Mirror to 250K

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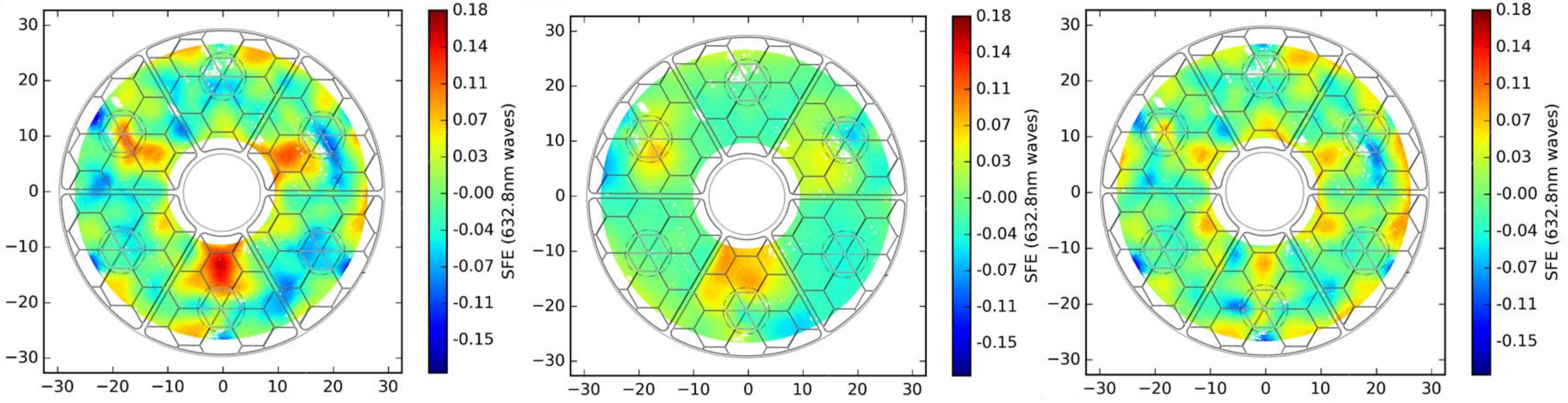
# Model correlation to measured data (293K – 231K)




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

- **Initial Model** includes:
    - prying force due to aluminum frame, mount & bond pads.
    - "as-built" structure & CTE.

- **Residual error** attributed to ULE® CTE inhomogeneity.

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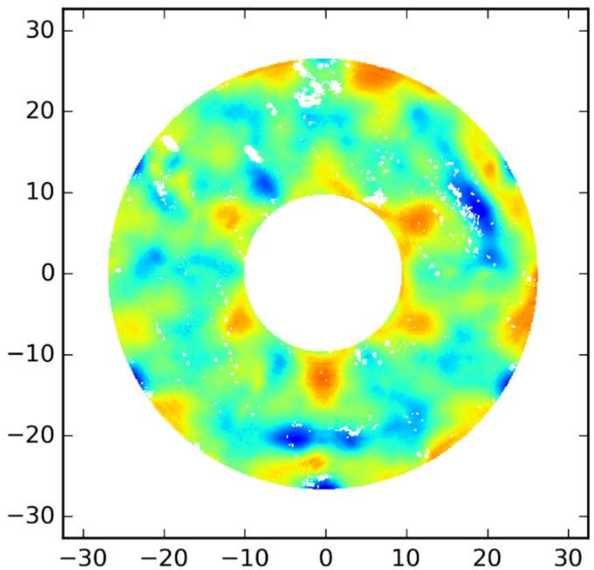
# CTE Correlation to Measured Data

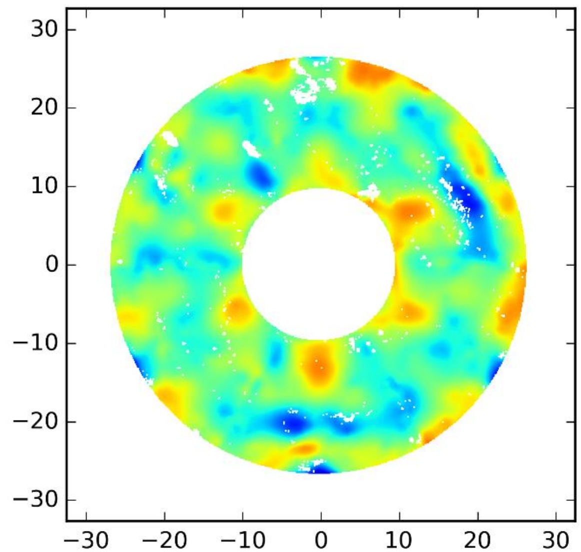
Measured SFE Change minus mount effects

RMS SFE = 22.8 nm



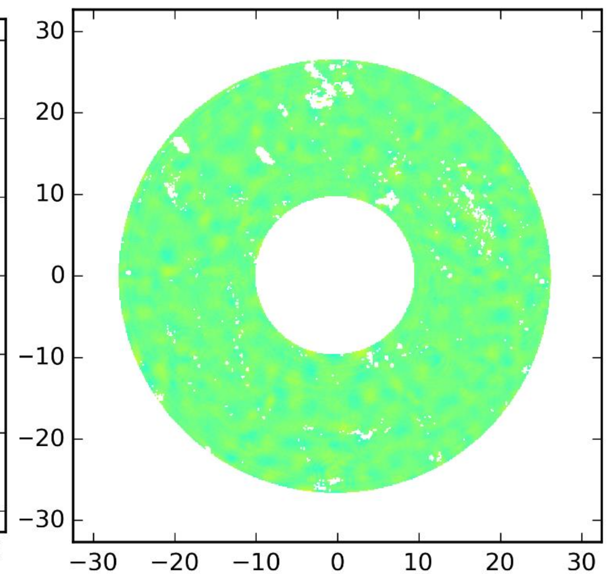

Correlated Model's Inhomogeneity Effect

RMS SFE = 22.4 nm




Test data minus correlated effects

RMS SFE = 4.4 nm

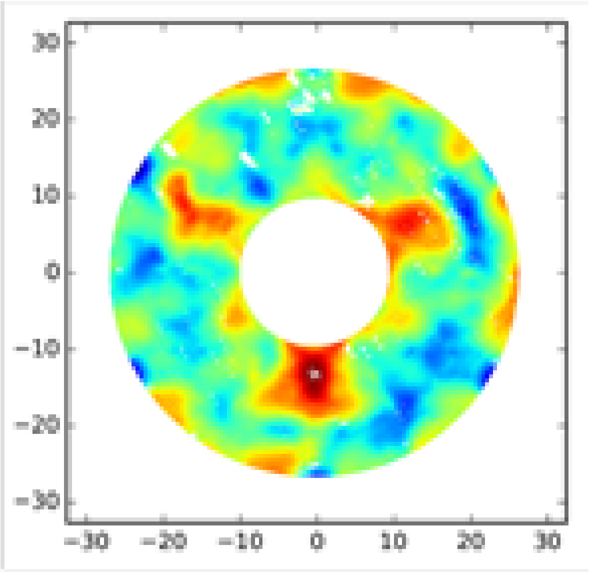



Correlated Map was produced by introducing lateral strain difference between front/back sheets.

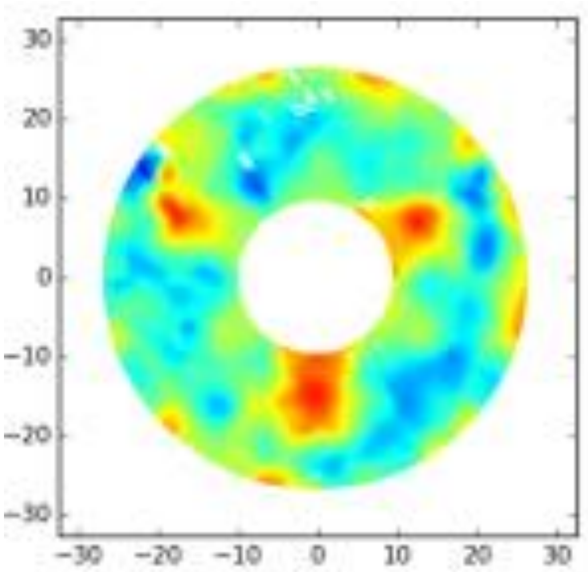
# Predicted vs Measured Cryo-Deformation

Revised Model for Thermal Soak of 293K to 231K

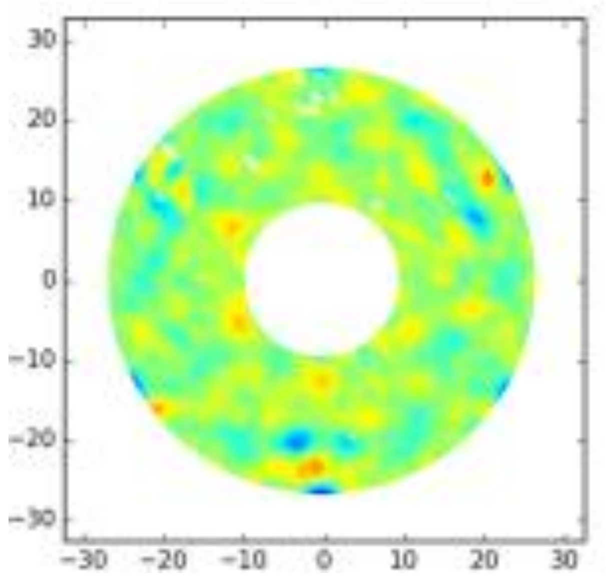
Measured
28.8 nm rms




Predicted
24.7 nm rms



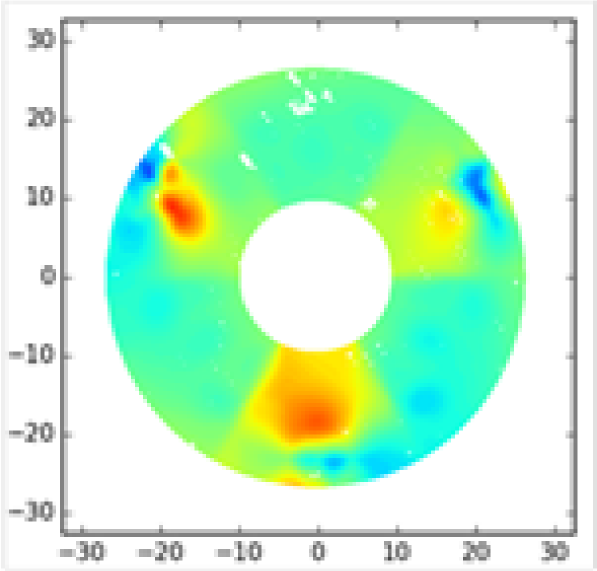

Difference
13.4 nm rms



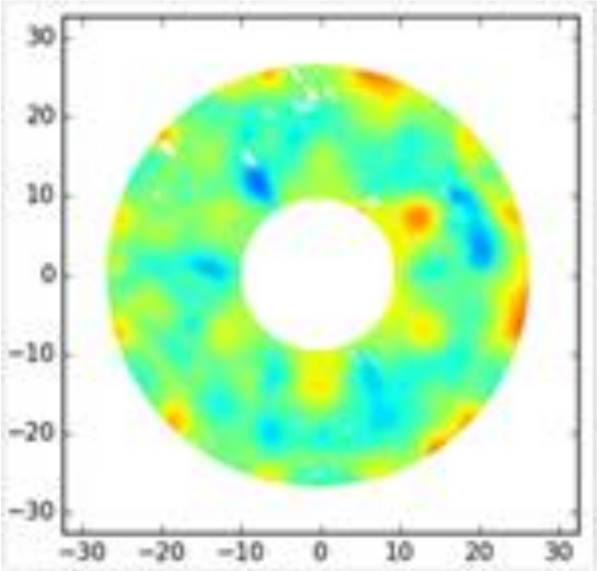
# High-Fidelity Model

High-fidelity model predicted cryo-deformation based on mounting to aluminum backplane and CTE mapping.

Predicted Mount Deformation
18.9 nm rms

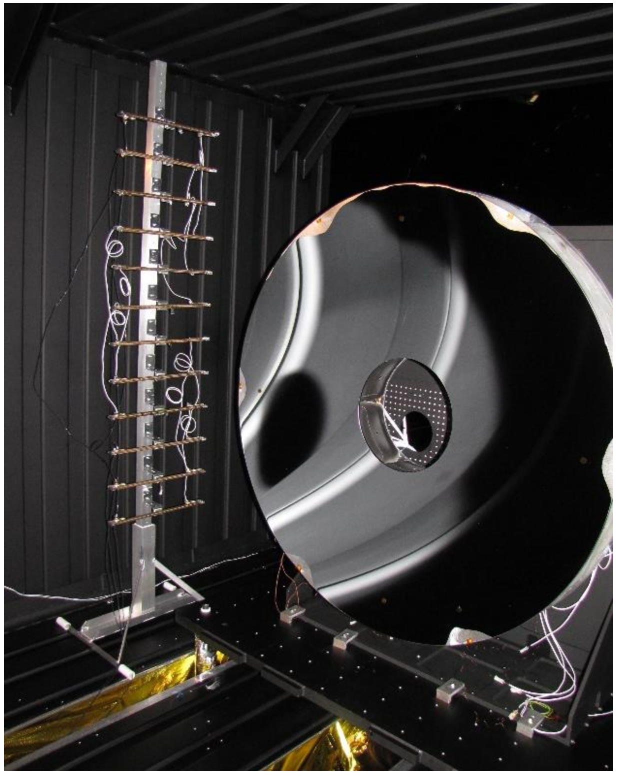



Predicted CTE Deformation
16.6 nm rms



# Thermal Gradient Test

To further validate high-fidelity model, measured 1.5-m ULE® AMTD-2 mirror's response to a static lateral thermal gradient imposed by solar lamps



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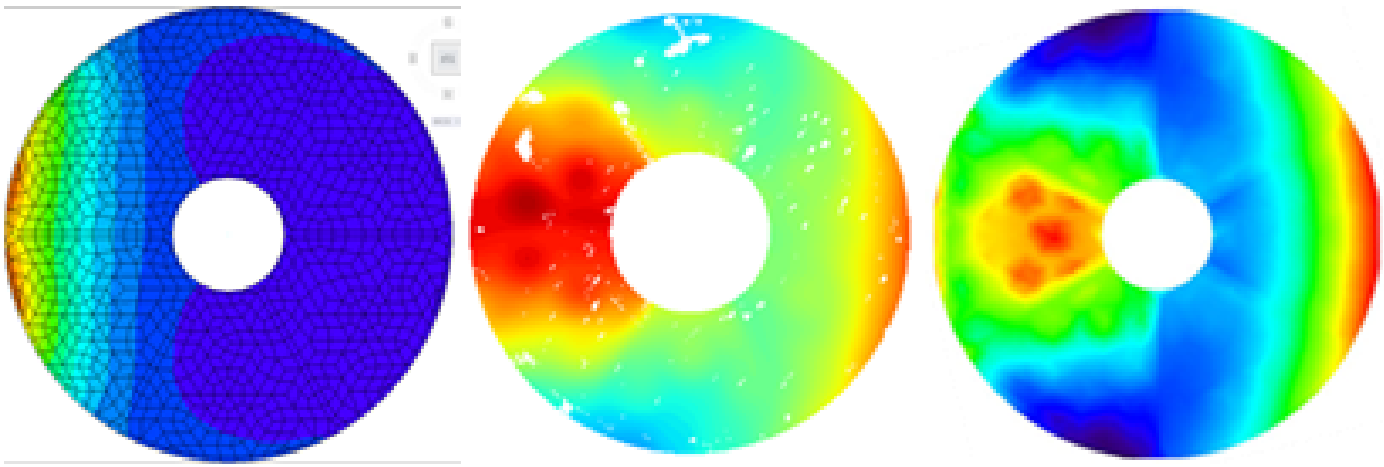
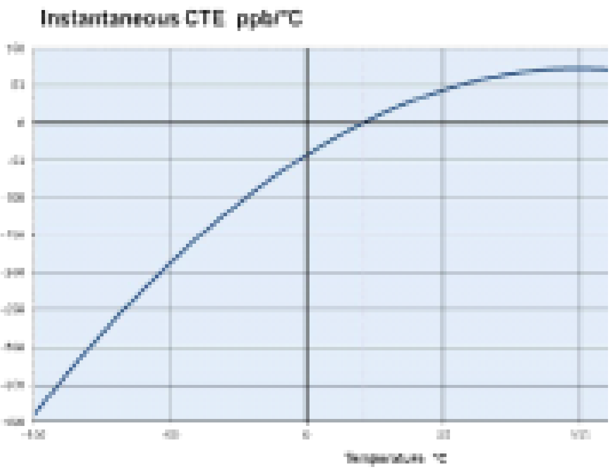
# Thermal Gradient Test

| Calculated Temperature Gradient $\Delta T = 87.7K$ | Measured Deformation 78.5 nm rms | Correlated Deformation requires 81 ppb/K CTE |
|---|---|---|






Instantaneous bulk CTE of ULE® changes by ~ 80 ppb/K from 20C to 100C.

# Objective #2

Derive thermal stability specifications from wavefront stability requirement.

Milestones #2 and #5 support Objective #2 (Derive Specifications)

# 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

allocation  tolerance

$$\epsilon_i = \left(\frac{\partial \epsilon}{\partial x_i}\right) \cdot \delta x_i$$

sensitivity

| 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

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# 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 |

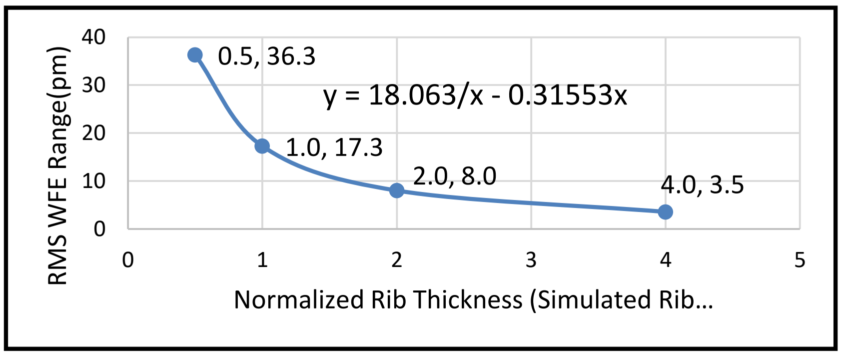
# Milestone #5 Status

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**

# 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.




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

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

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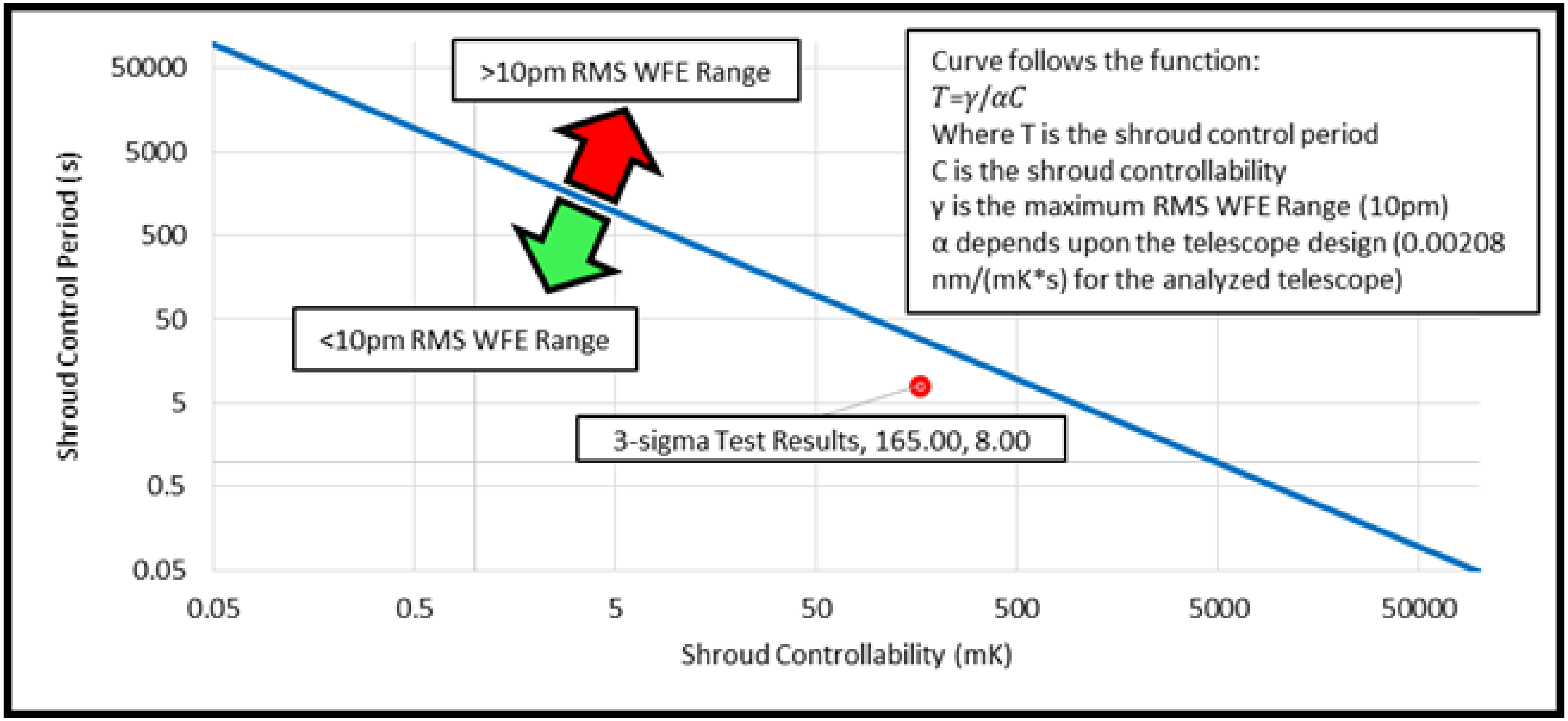
# Thermal Stability

- Key to achieving Stability is control period and sensitivity.
- The less sensitive or ‘noisy’ the control system the faster the required control period.
- Control faster than the mirror can respond to the noise.

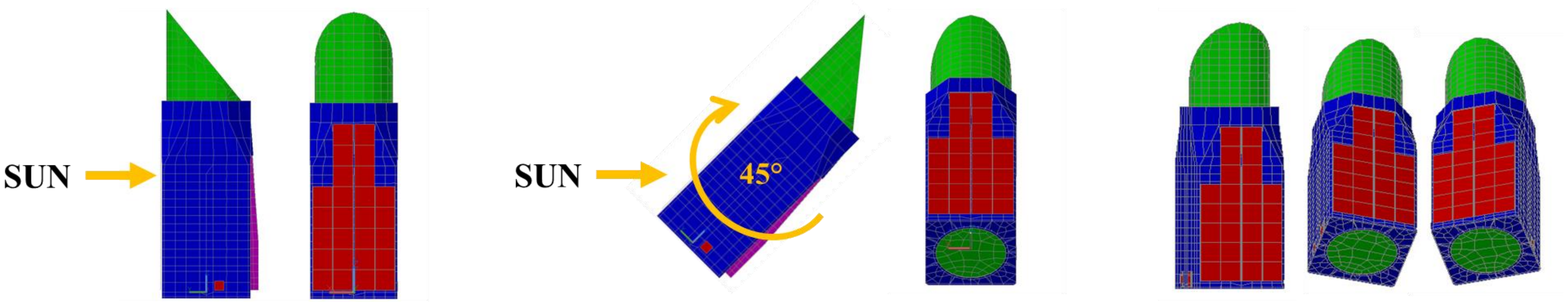


# STOP Model

PTC/HabEx Study Team

- Designed 4-m Zerodur mirror for HabEx baseline telescope.
- Created high-fidelity model to perform STOP analysis
  - Thermal Desktop model has 20K elements and calculates telescope’s structure and mirror temperature distribution at 10K node.
  - Temperature distribution is mapped into NASTRAN FEM and deflections calculated using each nodes CTE.
  - Rigid body motions and surface deformations calculated from NASTRAN deflections using SigFit.

for various Design Reference Missions (DRM):




**“ReferenceStar” View from the sun** **“After 45° pitch” View from the sun** **“+/- 15° roll” View from the sun**

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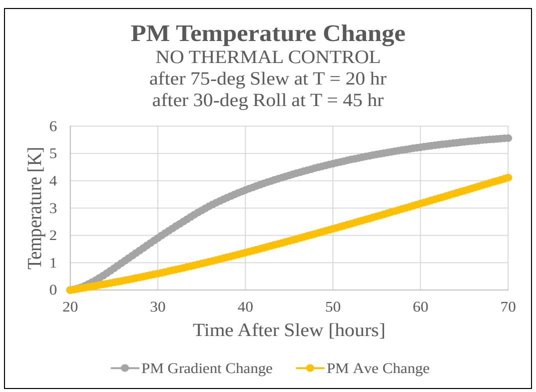
# Predicted Thermal Performance

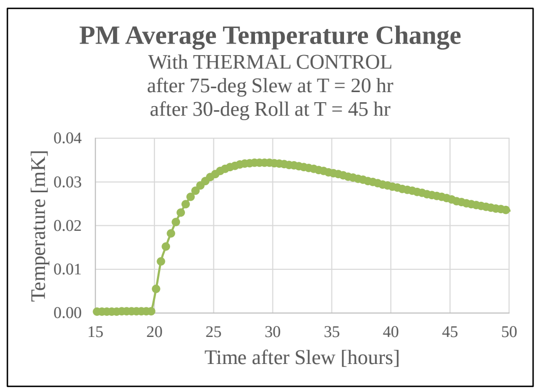
For a DRM consisting a 75 degree pitch of the telescope after it has spent 20 hours pointing at a reference star to dig the dark hole followed by a 30 degree roll (from +15 deg to -15 deg) at 45 hours.

Without active thermal control, average bulk temperature changes ~4K

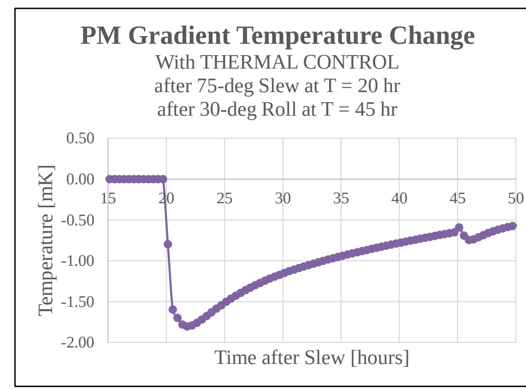
Active zonal control keeps PM average bulk temperature change to <~0.035-mK and axial gradient change to < ~1.75-mK.




Passive PM average and axial gradient temperature change from 75 deg pitch.




Actively controlled PM average bulk temperature change from 75 deg pitch.




Actively controlled PM axial temperature gradient from 75 deg pitch

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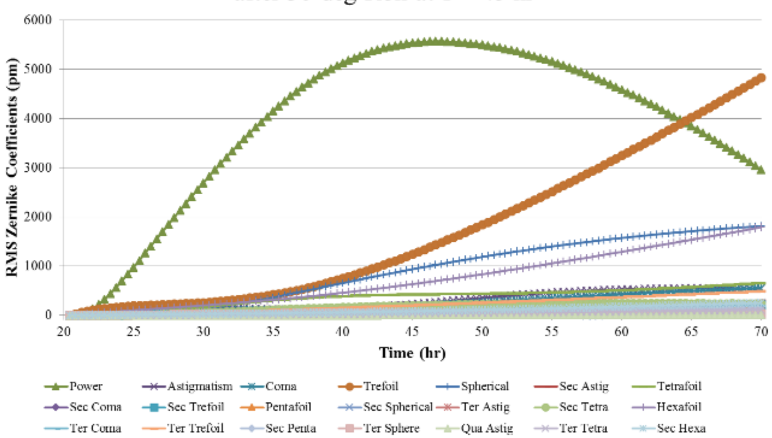
# Predicted Thermal Performance

Without active thermal control, PM experiences several nanometers of wavefront error (power, astigmatism, trefoil, etc.)

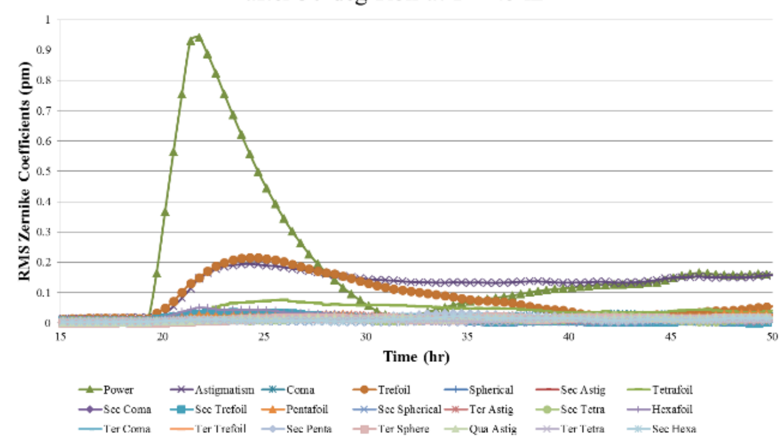
Active zonal control keeps PM wavefront error less than 1 pm rms for all Zernike polynomials.

Active Thermal Control with a thermally stable Primary Mirror design enables HabEx baseline telescope design to meet its error budget.

**PM RMS Wavefront Error vs Time**
NO THERMAL CONTROL
after 75-deg Slew at T = 20 hr
after 30-deg Roll at T = 45 hr




**PM RMS Wavefront Error vs Time**
With THERMAL CONTROL
after 75-deg Slew at T = 20 hr
after 30-deg Roll at T = 45 hr

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# Objective #3

Demonstrate use of PTC to achieve thermal stability.

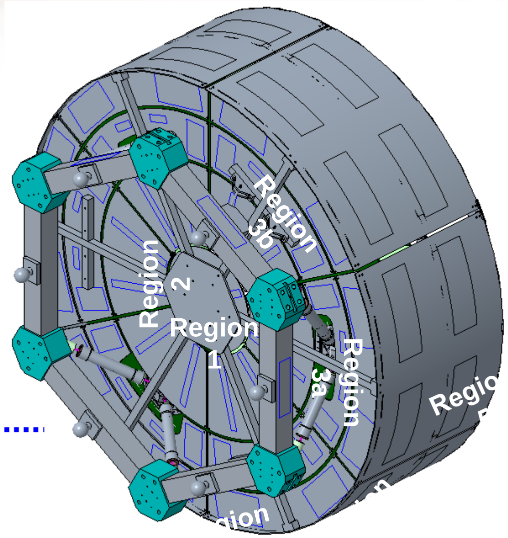
Milestone #3 supports Objective #3 (Demonstration)

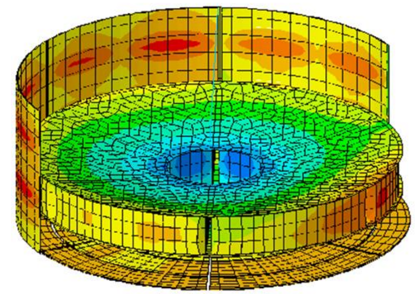
# Milestone #3 Status

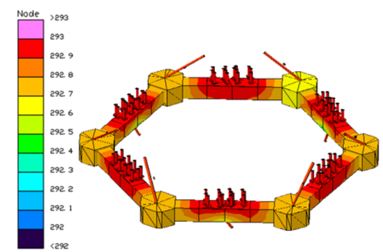
**Design and build predictive Thermal Control System** for 1.5m ULE® mirror with components that sense temperature changes at ~1mK level and actively control mirror's thermal environment at ~20mK level.

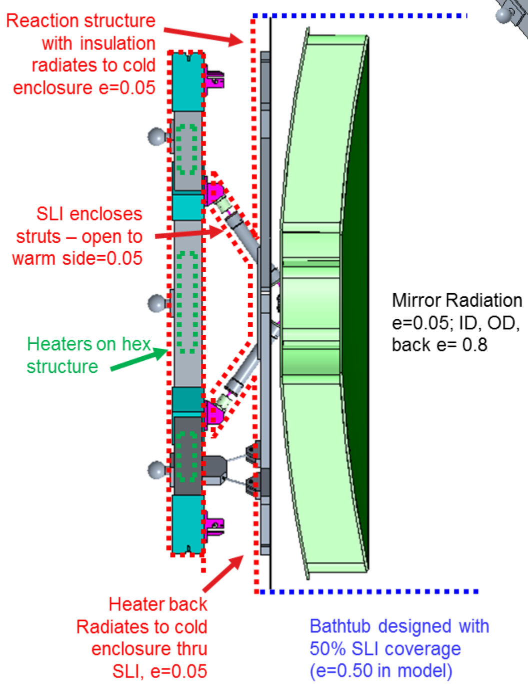
- **DONE: Designed PTC system and procured components.**
- **DONE: Harris Corp delivered Zonal Thermal Enclosure.**
- **IN-PROCESS: Integrate MSFC and Harris components of PTC system.**
- **IN PROCESS: Procuring a 1.2-m Aluminum Test Mirror**
- **IN PROCESS: Correlating 'preliminary' data with model**

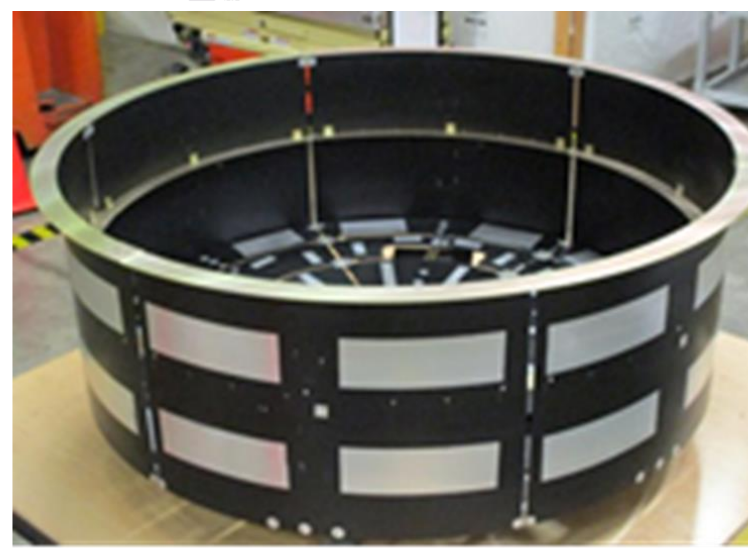
# Multi-Zone Thermal Enclosure for 1.5m AMTD ULE® mirror



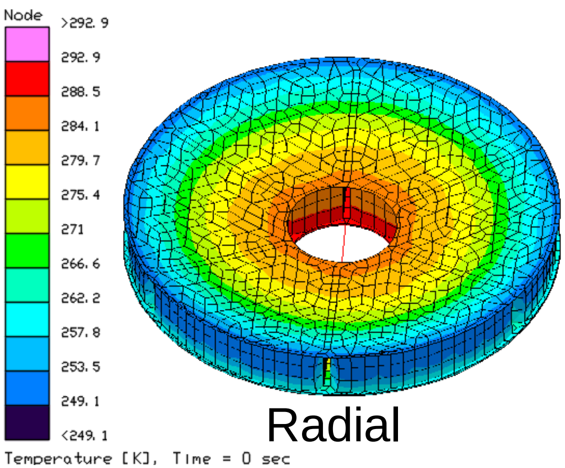


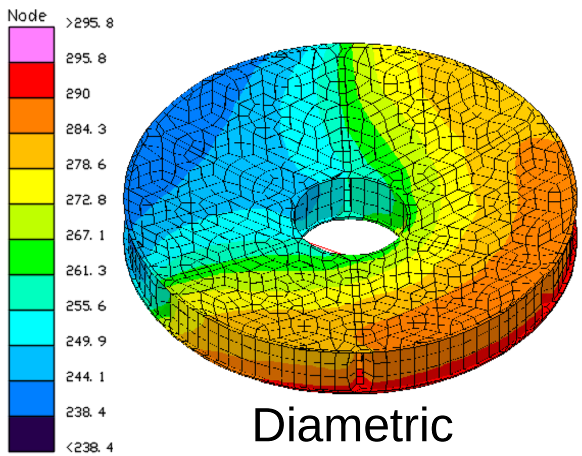



# Active Thermal Control

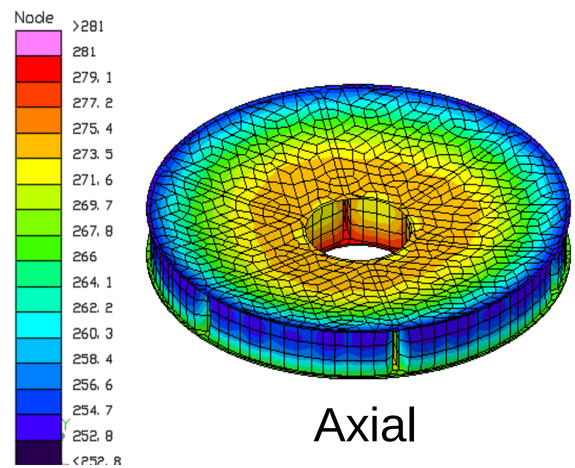
Thermal Enclosure zonal heaters are design to ‘compensate’ for environmental induced gradients by actively producing radial, axial and diametric thermal gradients in the mirror.




Radial



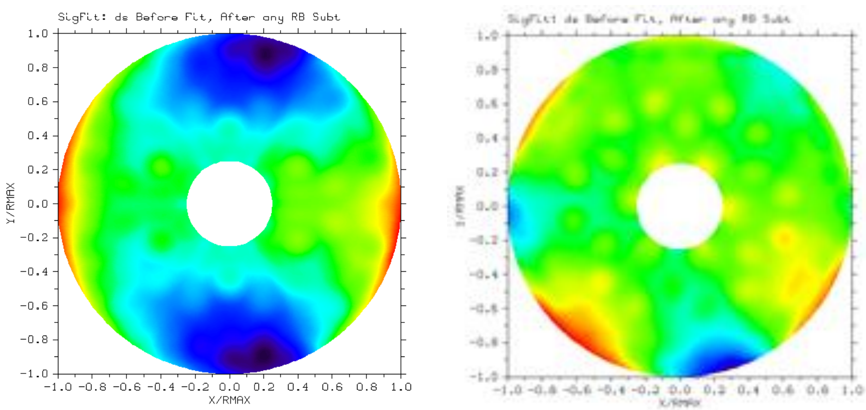

Diametric




Axial

# Predicted ULE® Performance & Al Mirror

STOP analysis predicts that when the 1.5-m ULE® mirror is integrated into the thermal enclosure, it will only experience a 7.5 nm rms figure change.




(left) Predicted SFE without thermal control.
(right) Predicted SFE with thermal control correction.

1.2-m Al Test Mirror

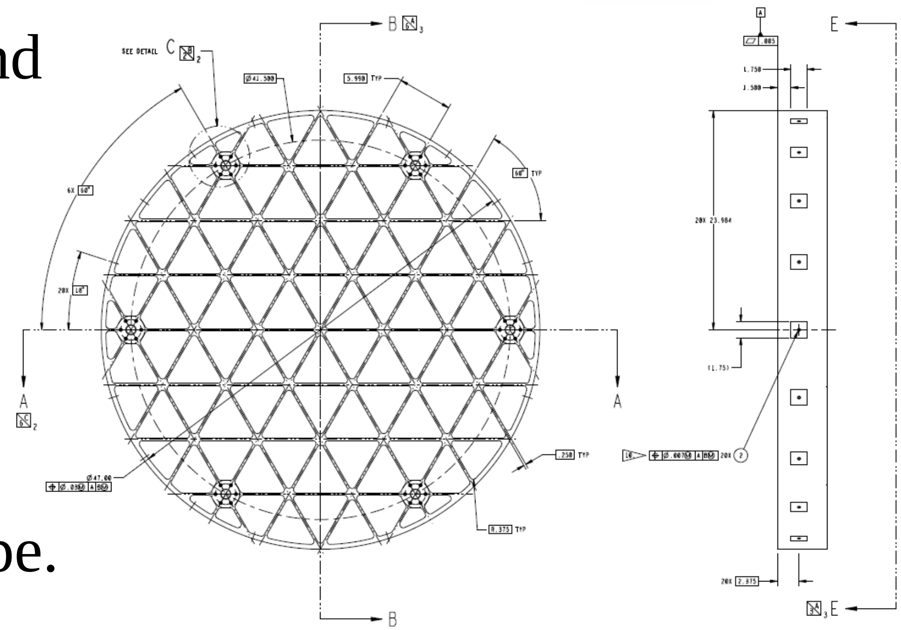
Thus, PTC procured a 1.2-m aluminum mirror to serve as a pathfinder test article. Since aluminum has a larger CTE than ULE®, it is expected to provide a 2X larger signature – which can be used to practice the PTC control algorithm.

# Aluminum Test Mirror

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.

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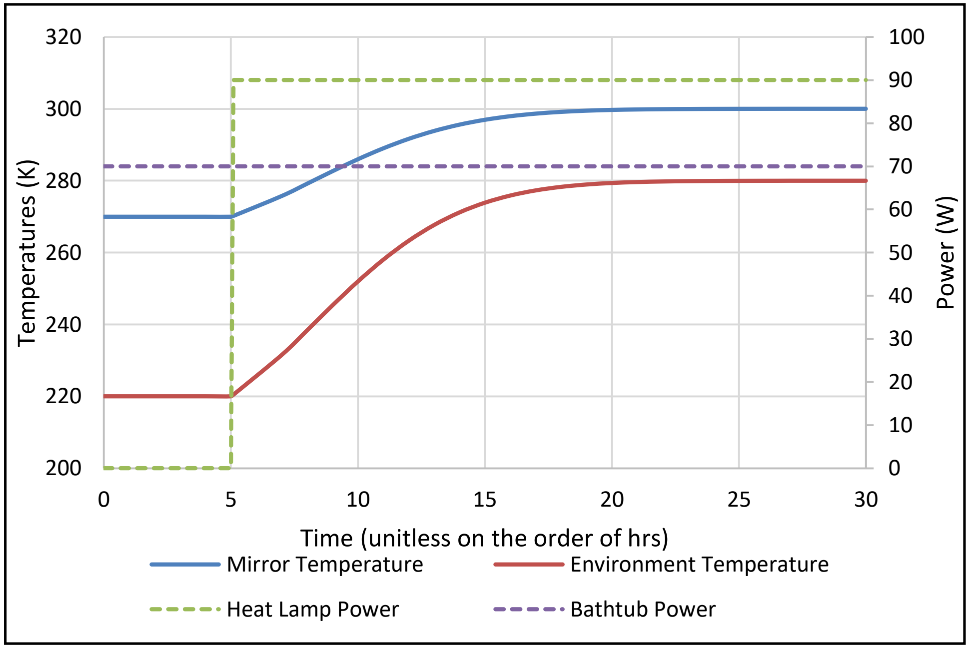
# Milestone #4 Future Work

**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.

- FUTURE: Test 1.2m Aluminum 'test mirror' and 1.5m ULE® AMTD mirror with rear PTC system.
- **FUTURE: Conduct test with 1.2m Aluminum mirror, and 1.5m ULE® mirror.**
- OPTIONAL: Test other mirrors in XRCF/PTC configuration.

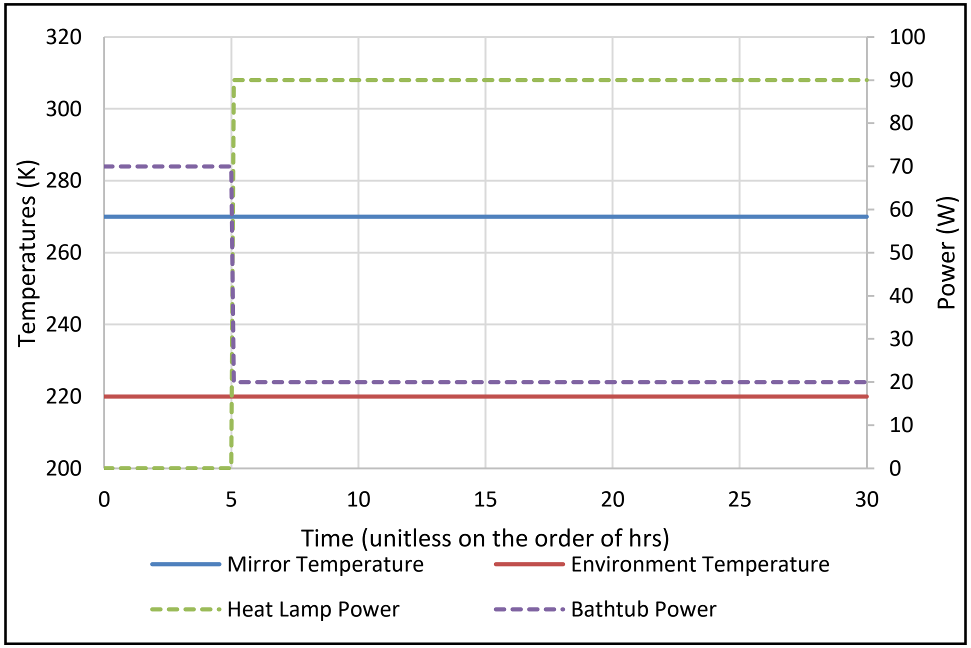
# Passive Thermal Test

- Initial Conditions:
  - Mirror starts at steady state of ~270K.
  - Environment starts at temperature ($T_E$) of ~ 220K.
- Passive Response to Thermal Load Change:
  - Increase heat lamp power ($Q_H$) at T=5
  - Keep thermal enclosure at power ($Q_B$)
  - Monitor mirror surface figure.



# Active Thermal Test

- Initial Conditions:
  - Mirror starts at steady state of ~270K.
  - Environment starts at temperature ($T_E$) of ~ 220K.
- Active Control of Thermal Load Change:
  - Increase heat lamp power ($Q_H$) at T=5
  - Reduce thermal enclosure power ($Q_B$) to compensate
  - Monitor mirror surface figure.



# 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.