Predictive Thermal Control (PTC) Technology to enable Thermally Stable Telescopes: Year 3 Status

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PTC driven by NASA Technology Needs

Cosmic Origins Program Annual Technology Report (PATR): “Thermally Stable Telescope” is Priority 2 critical, highly desirable for a strategic mission.

“**Wavefront stability is the most important technical capability that enables 10^{-10} contrast exoplanet science** with an internal coronagraph. State of art for internal coronagraphy requires that the telescope must provide a wavefront that is stable at levels less than 10 pm for 10 minutes (stability period ranges from a few minutes to 10s of minutes depending on the brightness of the star being observed and the wavefront-sensing technology being used).”



Predictive Thermal Control (PTC)

- PTC's goal is to develop active thermal control technology that keeps 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.

Approach/Methodology

To accomplish our objectives, we:

- Use science-driven systems engineering.
- Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

Integrate science & systems engineering to:

- derive engineering specifications from science measurement needs and implementation constraints (i.e. launch vehicles);
- identify technical challenges in meeting these specifications;
- iterate between science and engineering to mitigate challenges; and
- prioritize the challenges.

Systematically mature TRL of prioritized challenges using

- design tools to construct analytical models and
- prototypes/test beds to validate models in relevant environments.

Objectives

PTC 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.

COMPLETE

2. **Derive thermal stability specifications** from wavefront stability requirement.

COMPLETE

3. **Demonstrate** use of PTC to achieve thermal stability.

IN-PROCESS

Milestones

PTC 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.

Milestone Status

PTC has completed all except Milestone #3:

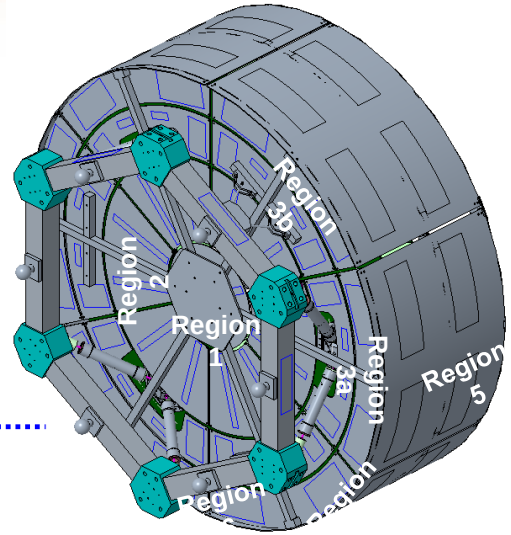
- ✓ #1: Created high-fidelity 'as-built' FEM of 1.5-m AMTD-2 ULE® mirror including CTE distribution.
- ✓ #2: Derived thermal control specification for HabEx.
- ✓ #3: Harris Corp built and delivered a 25-zone actively controlled thermal enclosure for a 1.5m ULE® AMTD-2 mirror.
- #3: Integrating control hardware and software to implement PTC with XRCF thermal environment and Harris thermal enclosure.
  - #3: FY20/21 test 1.2-m aluminum and 1.5-m ULE® mirrors.
- ✓ #4: Modified XRCF to enable lateral and axial thermal gradient testing of mirror systems.
- ✓ #5: Design primary mirror for HabEx baseline telescope.

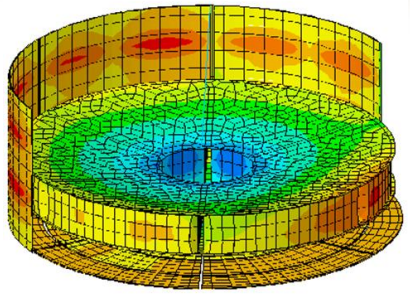
Milestone #3 Status

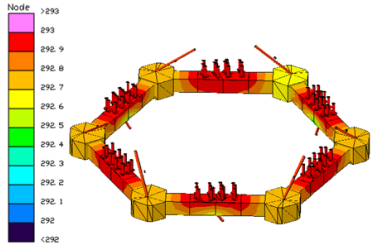
Design and build predictive Thermal Control System for 1.5m ULE® mirror with components that sense temperature changes at ~1mK level and actively control mirror's thermal environment at ~20mK level.

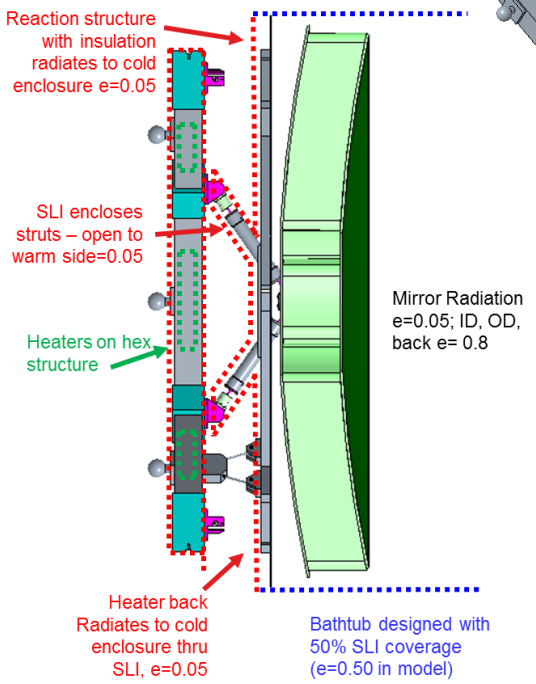
- **DONE: Designed PTC system and procured components.**
- **DONE: Harris Corp delivered Zonal Thermal Enclosure.**
- **IN-PROCESS: Integrate MSFC and Harris components of PTC system.**
- **IN PROCESS: Diamond Turning 1.2-m Al Test Mirror**
- **FY20/21: Test 1.2-m Al & 1.5-m ULE© mirrors.**

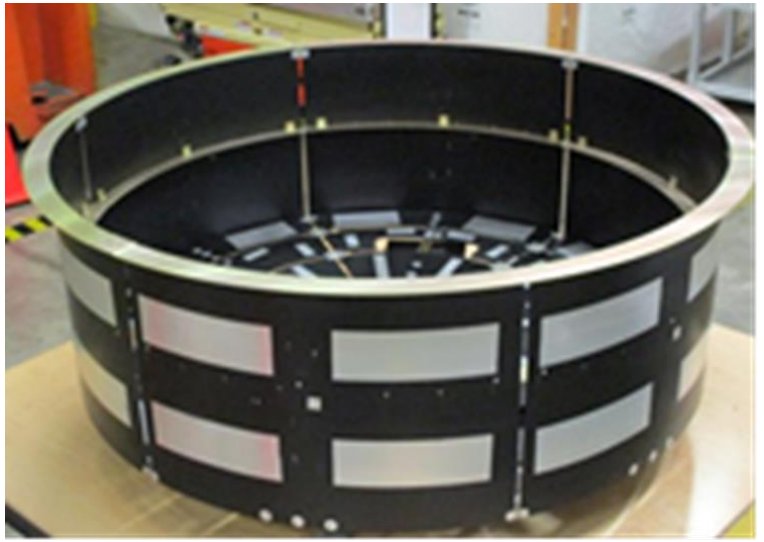
Multi-Zone Thermal Enclosure for 1.5m AMTD ULE® mirror





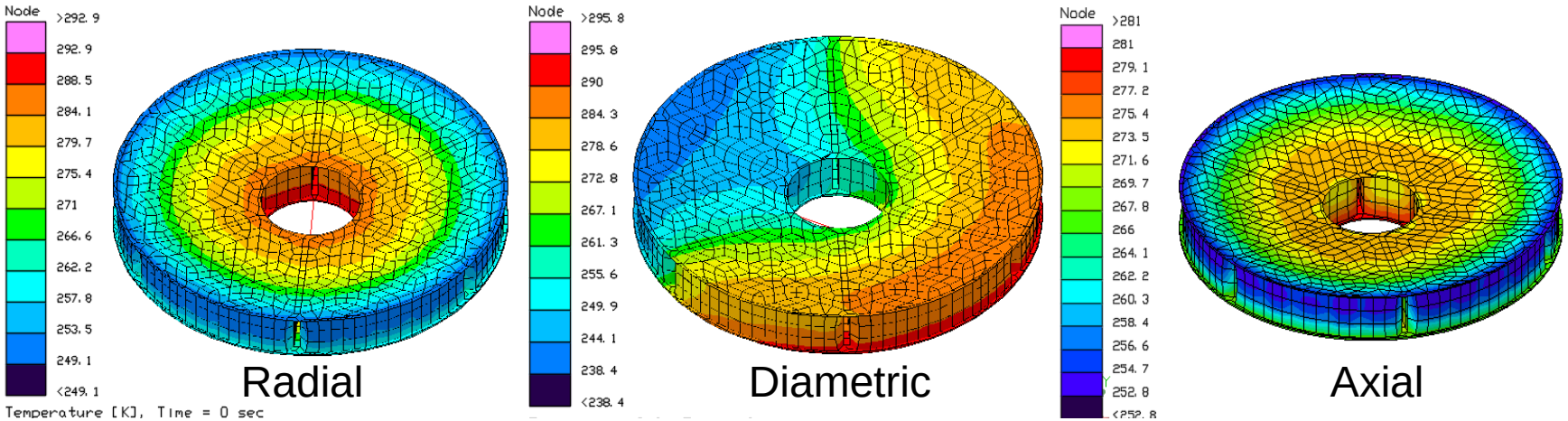






Active Thermal Control

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



Thermal Control System

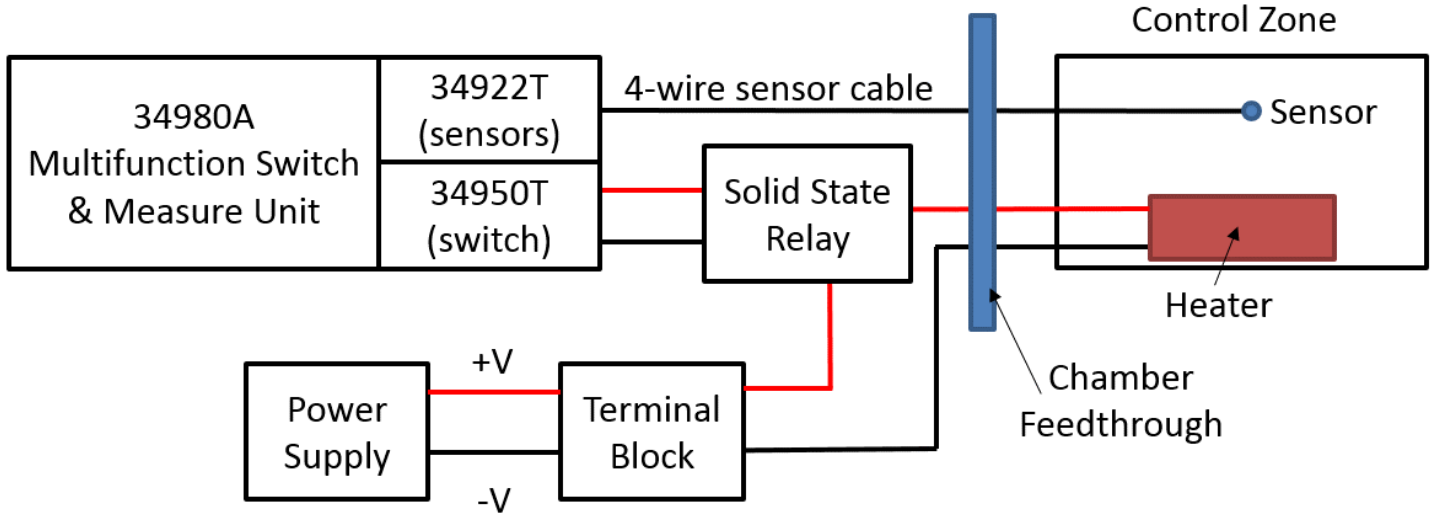
- Thermal control system hardware includes:
  - 34980A Multifunction Switch & Measure Unit
  - 34950T Digital I/O Modules
  - 34922T Sensor Modules
  - Keithley Power Supplies
  - PT102 Sensors
  - Solid State Relays



- System being installed in XRCF.

Control System

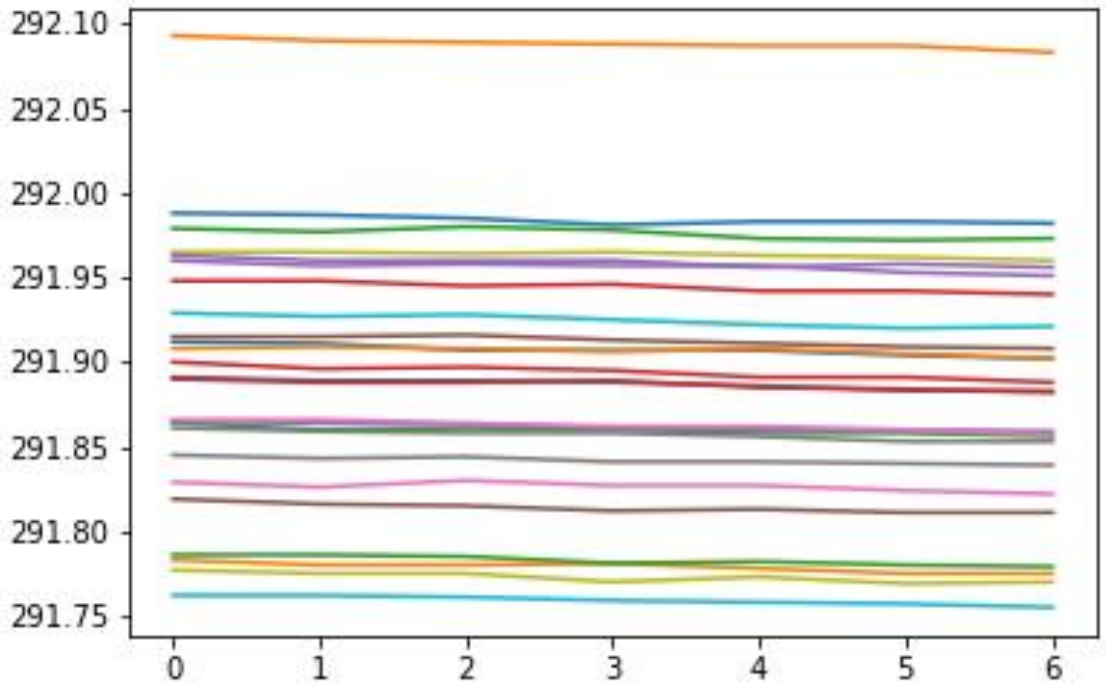
- Concept of Operations
  - 34980A connects to a laptop that runs LabVIEW.
  - Sensor measures temperature measurements and digital I/O modules switch solid state relays on/off to provide a pulse width modulated power to heater zones at an average power determined by algorithm.



- Control Algorithms
  - Conventional PID Algorithm
  - Algorithm based upon the thermal characteristics of the system.

Functional Check

Control System able to read temperatures of 25 RTDs (same as the number of control zones) into Python



Thermal Control System Emulator

A code pipeline has been created that enables simulation and test of custom thermal control algorithms:

- Calculated Thermal Distribution
- Calculates heater powers
- Applies heater powers to thermal model.
- Repeat

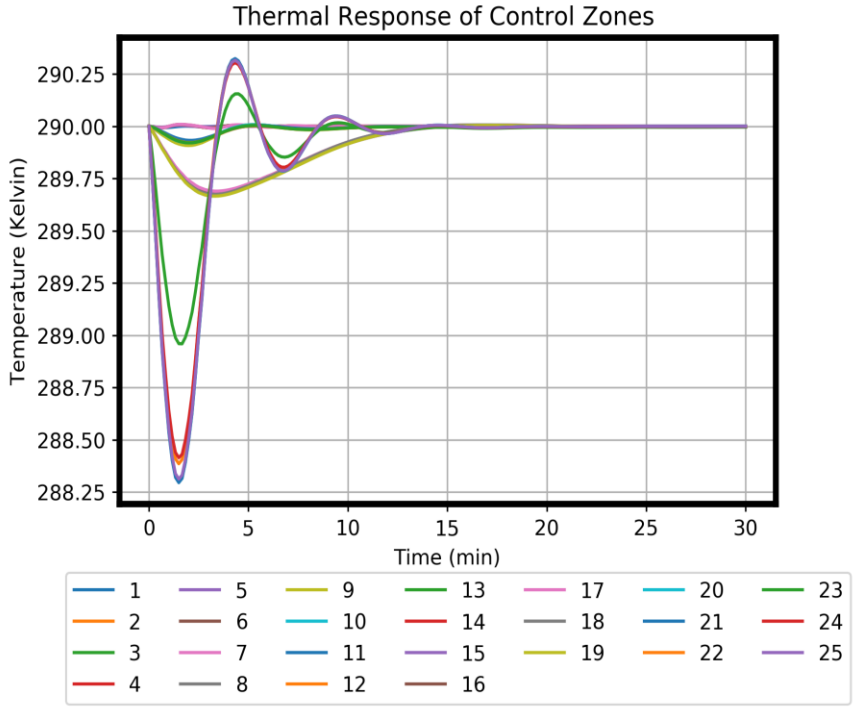
This enables quick, analytical comparisons between different control approaches.

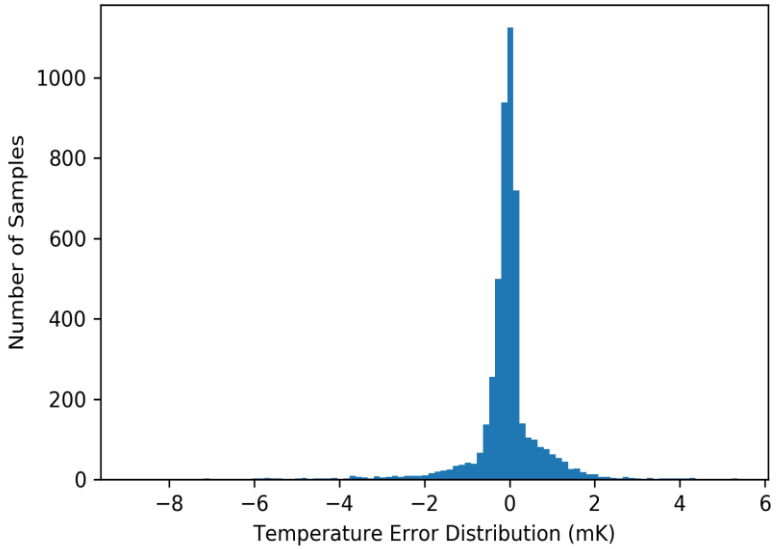
Additionally, MSFC Technical Investment Program is developing an Artificial Intelligence (AI) Thermal Control System.

Artificial Intelligent Control System

Machine learning algorithm wrapped around pipeline can optimizes PID control to converge to steady-state stabilities ranging from 0.1 to 3.7-mK for enclosure's 25 zones.

Neural network is able to predict future temperatures accurately with a 0.9-mK 1-sigma error distribution which is promising for AI Thermal Control.





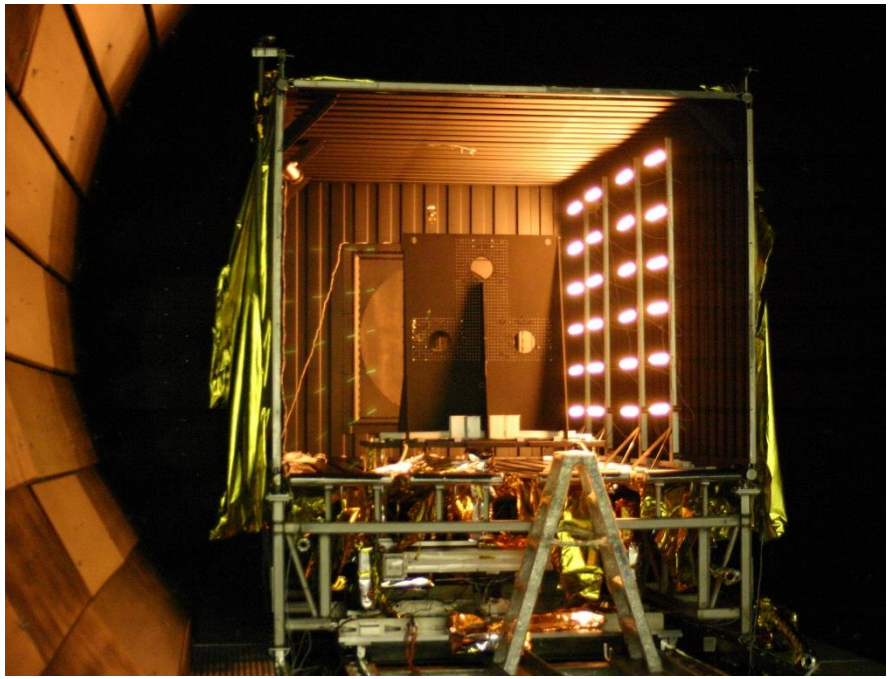
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PTC Demonstration Test Plan

XRCF PTC test configuration

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

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

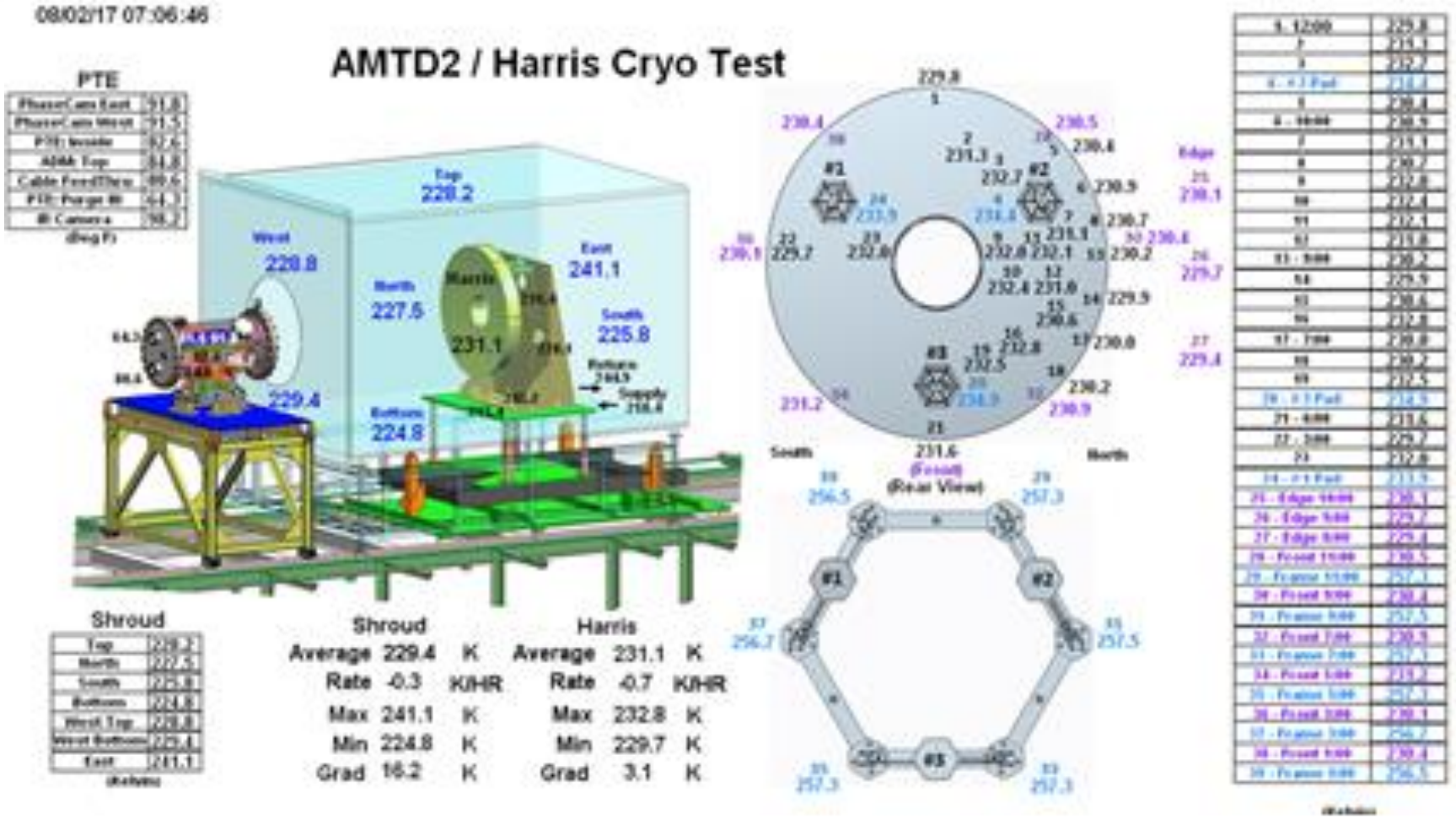


Solar lamp array consists of 24 lamps connected in a 3-phase delta configuration (8 per phase).

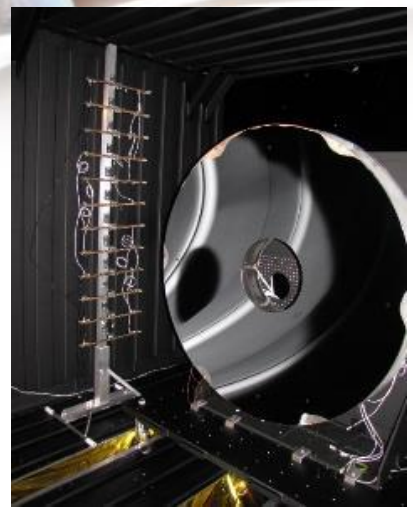
Stands designed and fabricated to provide a variety of coverage areas (i.e. 6x4, 3x8 and 2x12 etc.)

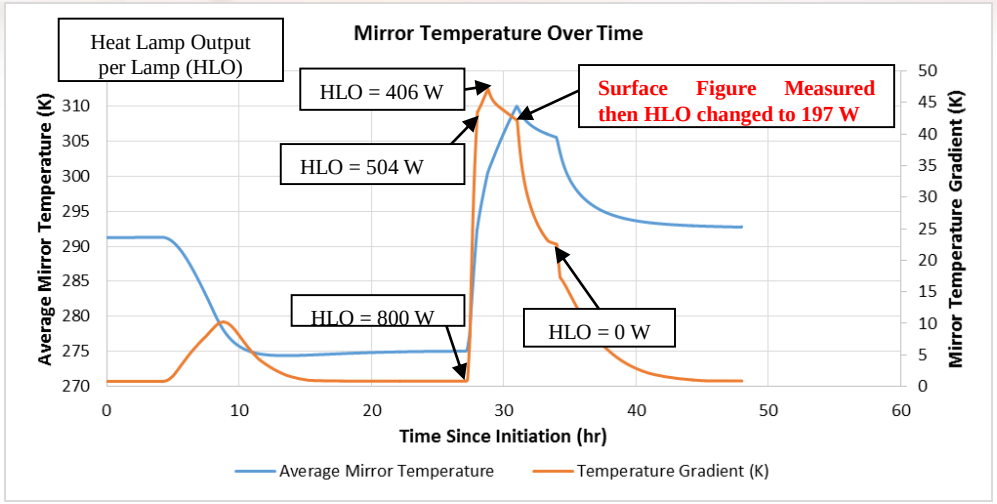
Controllable from 0 to 100% power.

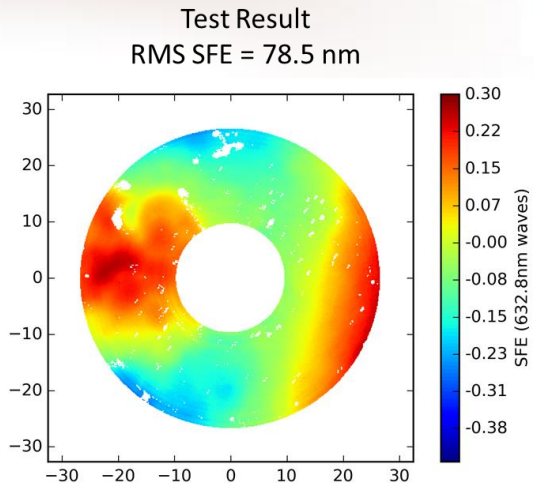
XRCF Tests are Fully Instrumented



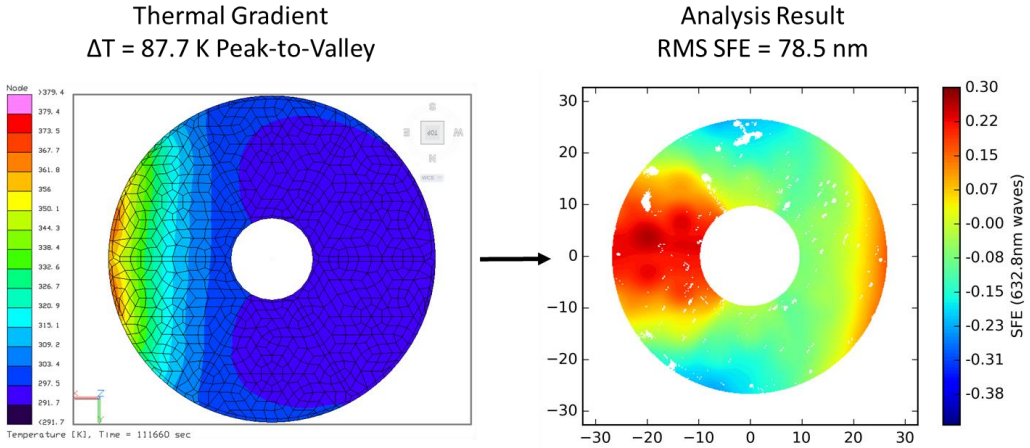
Thermal Gradient Test – Imposed by Solar Lamps



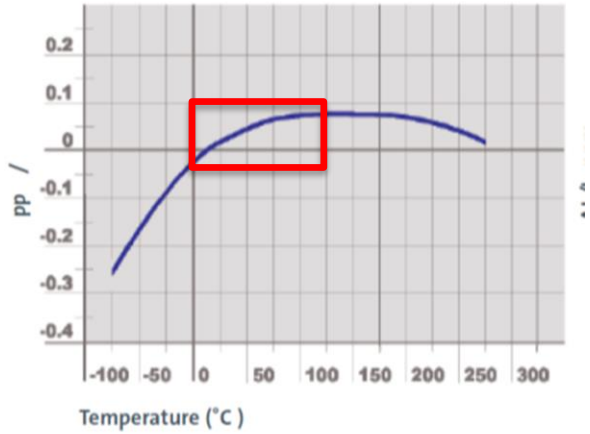




Combined analysis and temperature measurements to estimate temperature throughout mirror, predict performance and correlate with measured data.



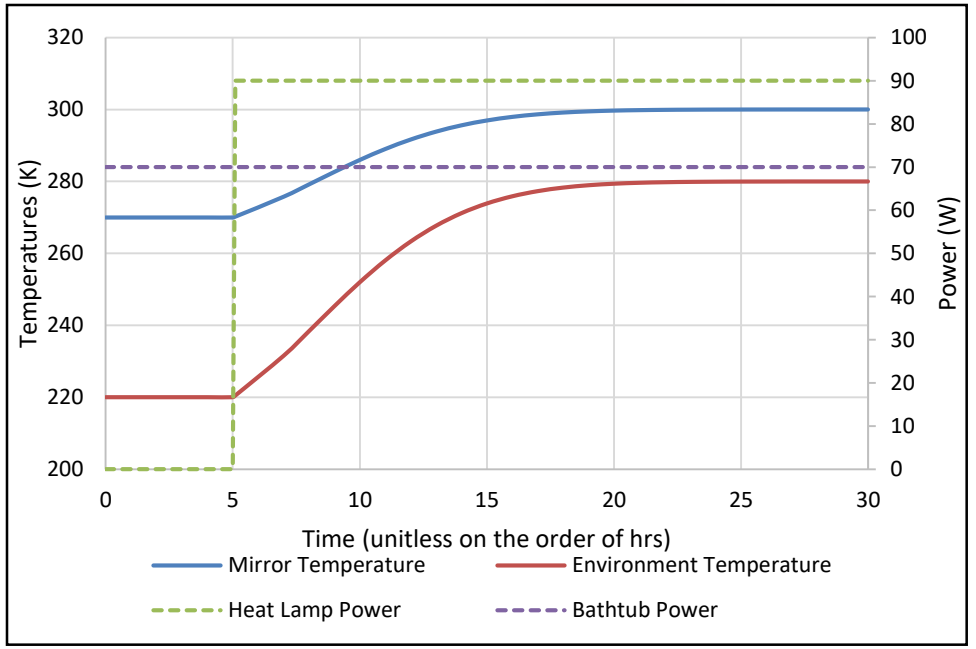
RMS SFE matched by uniformly scaling CTE to 81 ppb/K Consistent with Corning Published CTE specification for 100K Temp Range.



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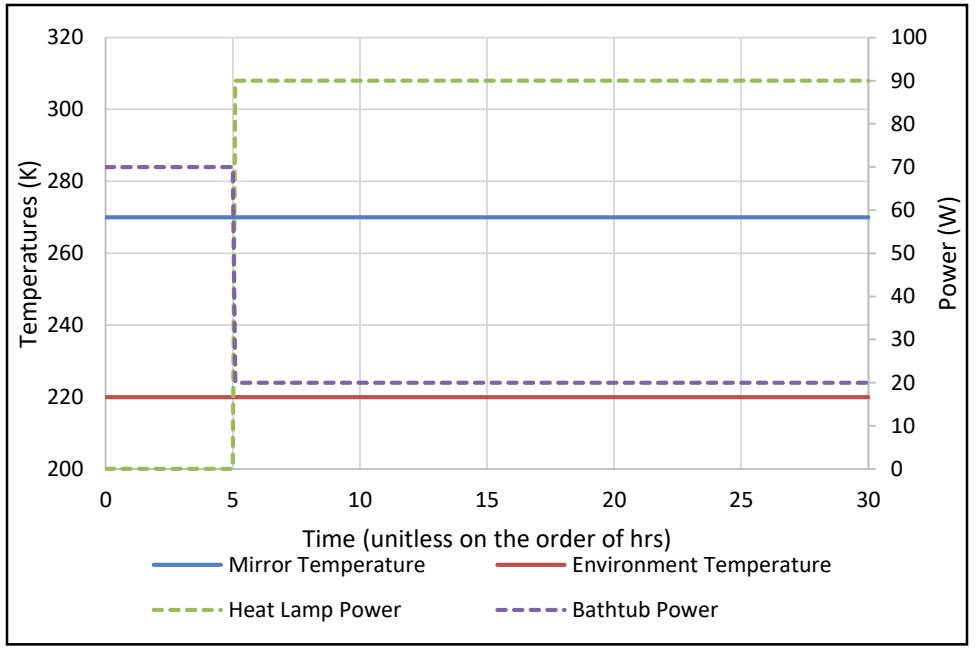
Passive Thermal Test

- 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

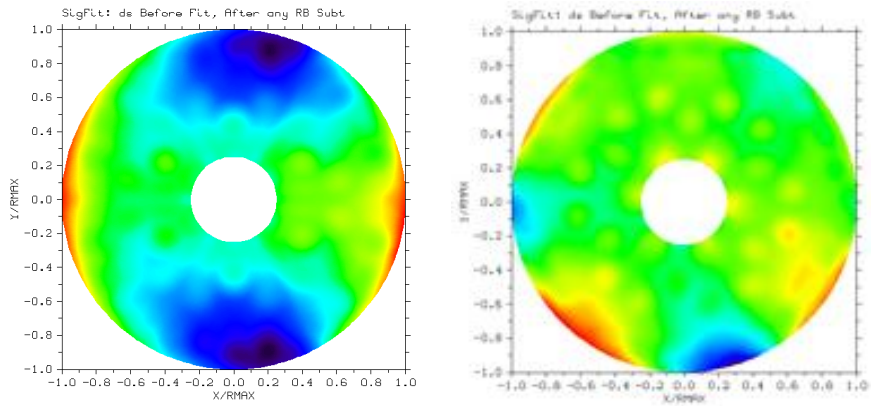
- Initial Conditions:
  - Mirror starts at steady state of ~270K.
  - Environment starts at temperature (T_E) of ~ 220K.
- Active Control of Thermal Load Change:
  - Increase heat lamp power (Q_H) at T=5
  - Reduce thermal enclosure power (Q_B) to compensate
  - Monitor mirror surface figure.



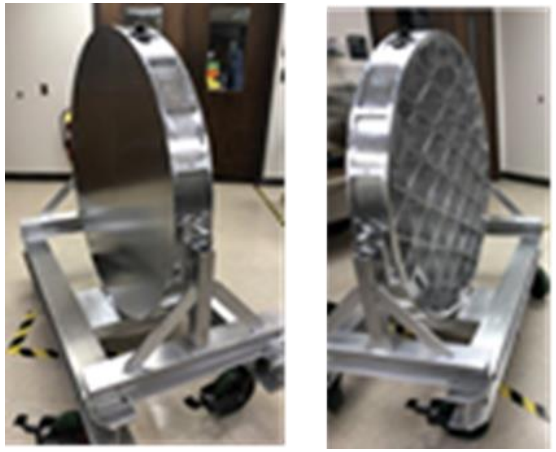
Aluminum Mirror

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.



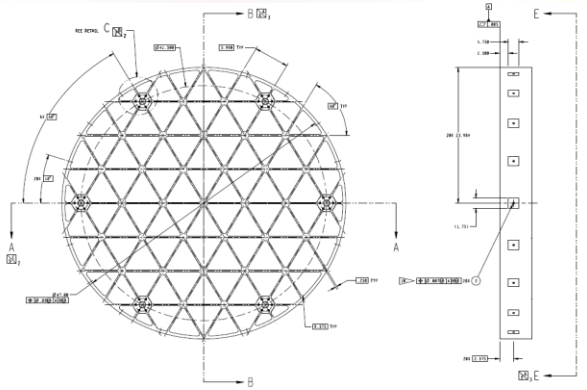
(left) Predicted SFE without thermal control.
(right) Predicted SFE with thermal control correction.



1.2m Aluminum 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.

Additionally, MSFC plans to cryot-test the mirror as a technology demonstrator for a potential Far-Infrared Mission such as Origins Space Telescope.

- Measured CTE Homogeneity by measuring cryo-deformation.
- Mirror is 5083 Cast Al (predicted to have better CTE homogeneity than 6160).
- Characterize Cryo-Hysteresis and Stress-Relief
- Cryo-Null Figure to demonstrate ability to achieve cryo-performance for Far-IR with aluminum mirror.

Conclusion

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

PTC 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 enable ultra-stability telescopes for exoplanet science and will be demonstrated on flight traceable hardware (1.5-m ULE® AMTD-2 mirror and 25-zone Thermal Enclosure).

PTC has successfully accomplished 4 of 5 milestones and will complete the last milestone in FY20/21.