Predictive Thermal Control (PTC)

Technology to enable

Thermally Stable Telescopes:

Year 4 Status

H. Philip Stahl, Thomas Brooks
NASA Marshall Space Flight Center

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 with a multi-zone active thermal control system:
  - Sensors measure temperature distribution on optic
  - Control algorithm estimates temperatures at unmeasured locations and determines heating needed to produce the desired temperature profile.
  - Sensors on outer barrel and attitude knowledge of the telescope relative to the sun can be used to determine the telescope's external thermal load changes and modify 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.

Objective Status

PTC has successfully completed its three Objectives

#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.

COMPLETED PREVIOUSLY

#2 Derive thermal stability specifications from wavefront stability requirement.

COMPLETED PREVIOUSLY

#3 Demonstrate zonal active thermal control system for achieving thermal stability.

COMPLETE THIS YEAR

Milestone Status

PTC completed all five defined Milestones:

- ✓ #1: Created a high-fidelity 'as-built' FEM of 1.5-m AMTD-2 ULE® mirror including CTE distribution.
- ✓ #2: Derived thermal control specification for HabEx.
- ✓ #3: **Designed, built and demonstrated Multi-Zone Active Thermal control System for 1.5m ULE® mirror.**
- ✓ #4: Modified the XRCF to enable lateral and axial thermal gradient testing of mirror systems.
- ✓ #5: Design primary mirror for HabEx baseline telescope.

Technical Success Metrics

- PTC's key performance success metric was to achieve 10 mK thermal stability of the 1.5-m ULE© AMTD-2 mirror in the XRCF thermal environment.
- For the 1.5-m ULE© mirror, PTC demonstrated:
  - **Ability to correct thermal gradients to an accuracy of 2K.**
  - **Ability to maintain that correction with a stability of 2mK.**
- PTC assesses that it has matured active thermal control via zonal heater system to at least **TRL-5.**
  - Technology demonstrated on a 1.5-m mirror assembly in a relevant thermal/vacuum environment.
- Additionally, PTC demonstrated ability to impose low-order surface deformations via active thermal control.

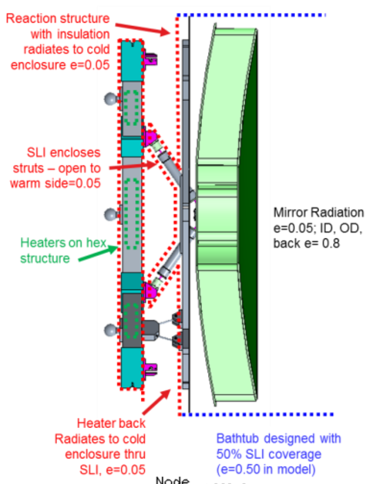
Milestone #3

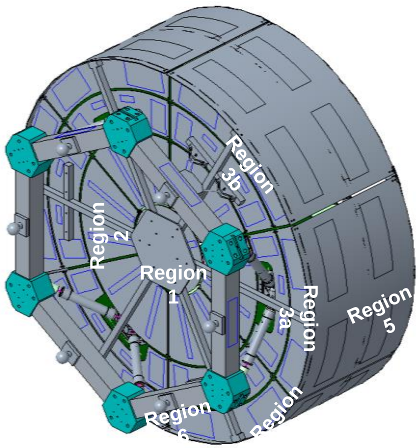
Design & Build Multi-Zonal Active Thermal Control System for 1.5m ULE® mirror with components that sense temperature changes at ~1mK level and actively control mirror's thermal environment at ~20mK level.

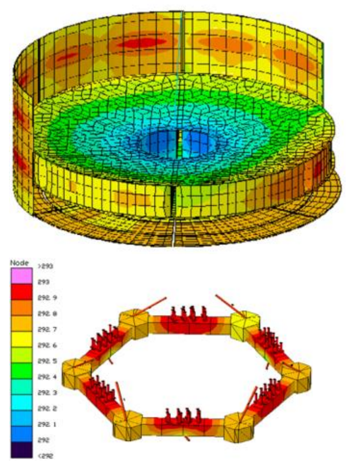
- 2019: Designed PTC system and procured components.
- 2019: Harris Corp delivered 25 Zone Thermal Enclosure.
- **2020: Integrated MSFC/Harris PTC system components**
- **2020: Tested 1.5-m ULE® mirror.**

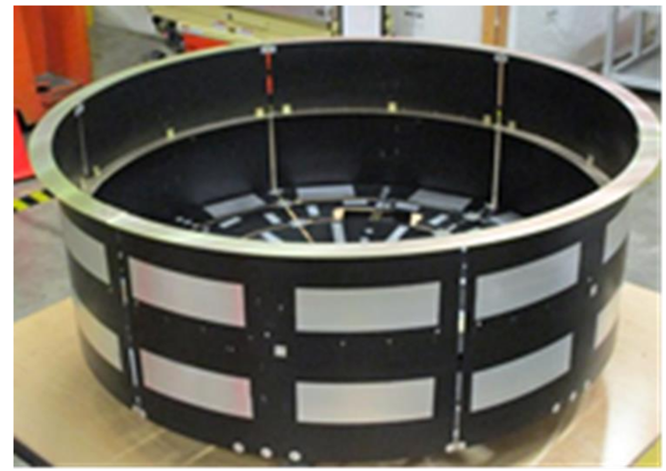
Active Thermal Control

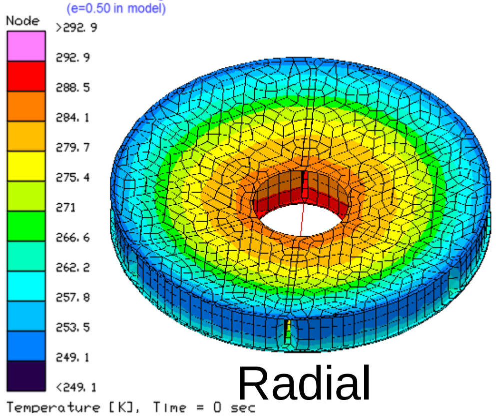
Zonal heaters design to ‘compensate’ for environmental induced gradients by producing radial, axial & diametric gradients mirror.



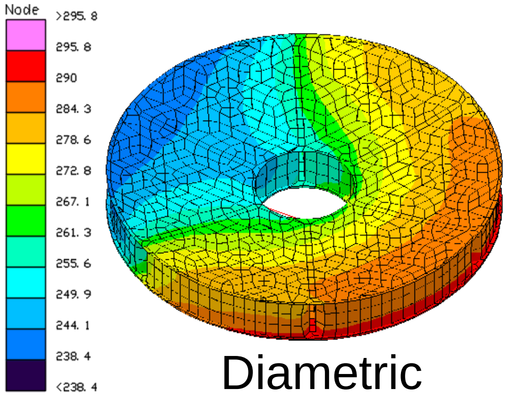




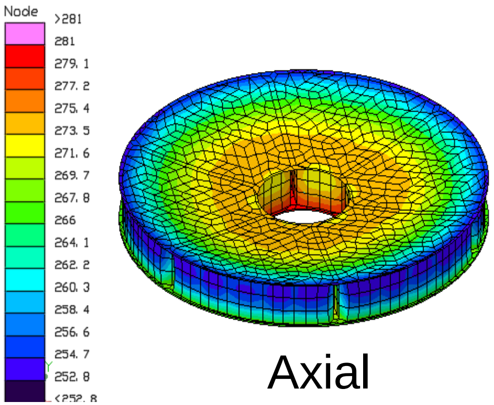




Radial



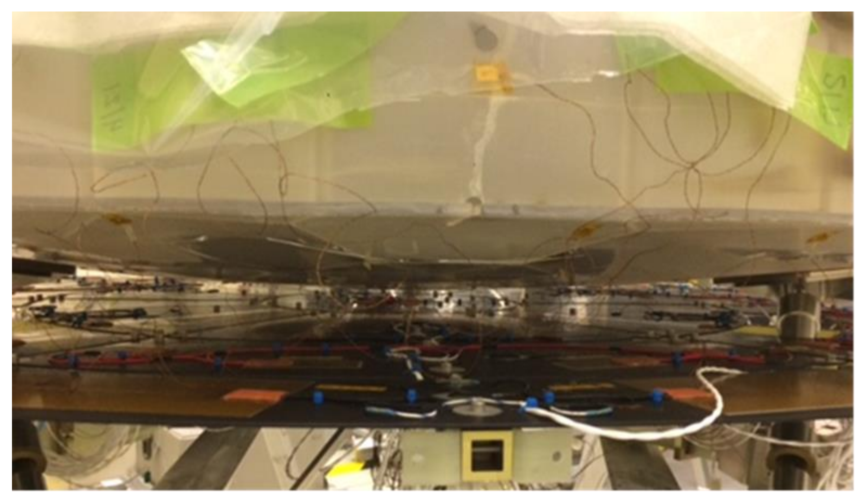
Diametric



Axial

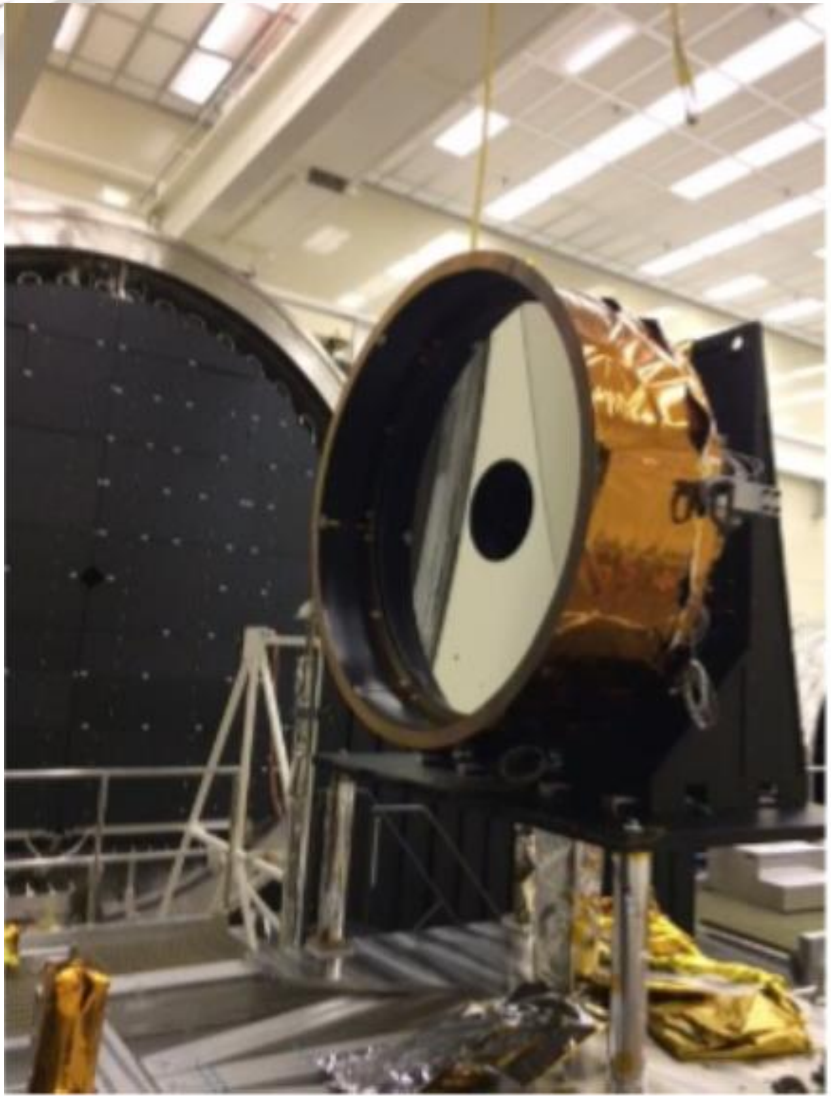
Thermal Control Harware

- Thermal control system hardware includes:
  - 34980A Multifunction Switch & Measure Unit
  - 34950T Digital I/O Modules
  - 34922T Sensor Modules
  - Keithley Power Supplies
  - PT100 Sensors
  - Solid State Relays



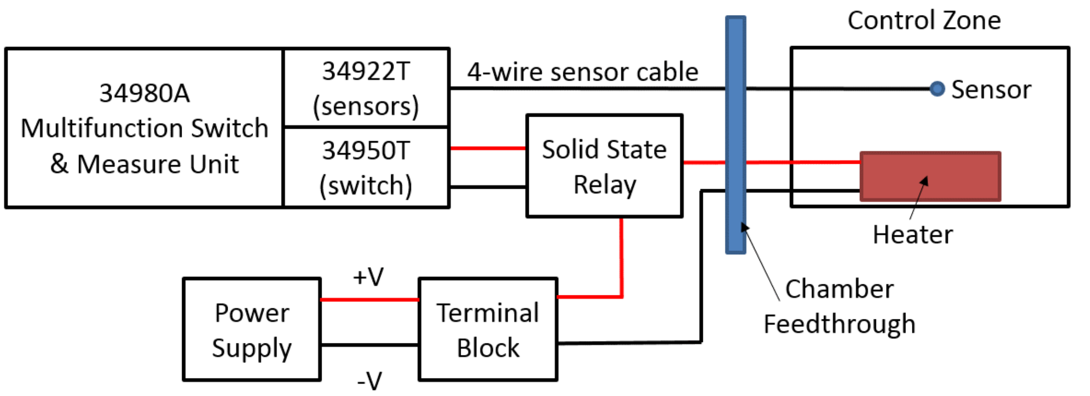
- Installed Thermal Diodes
- Heater behind mirror

Integrated Mirror Assembly



Control System

- Concept of Operations
  - 34980A connects to a laptop running Python.
  - 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.



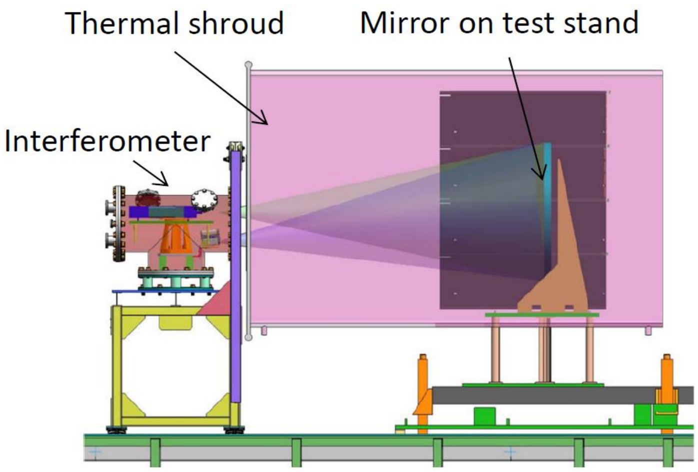
- Conventional PID Control Algorithm

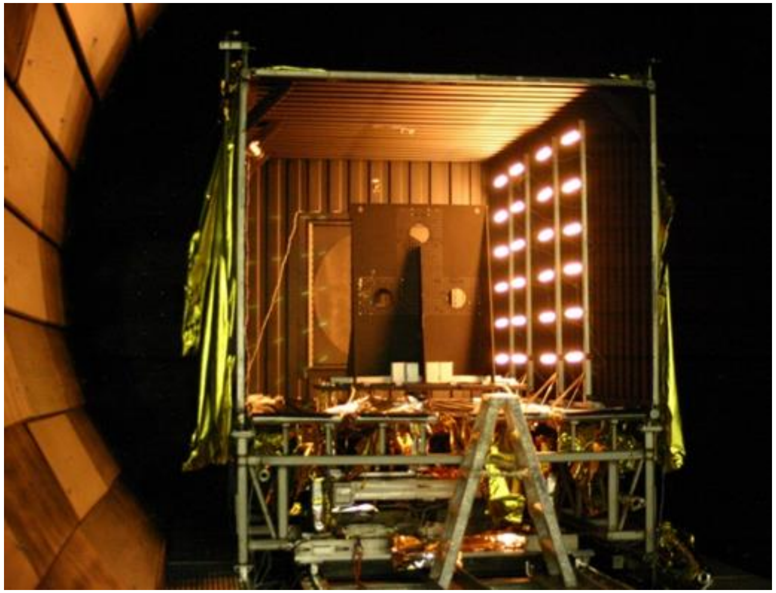
Multi-Zonal Active Thermal Control Demonstration

XRCF PTC Test Configuration

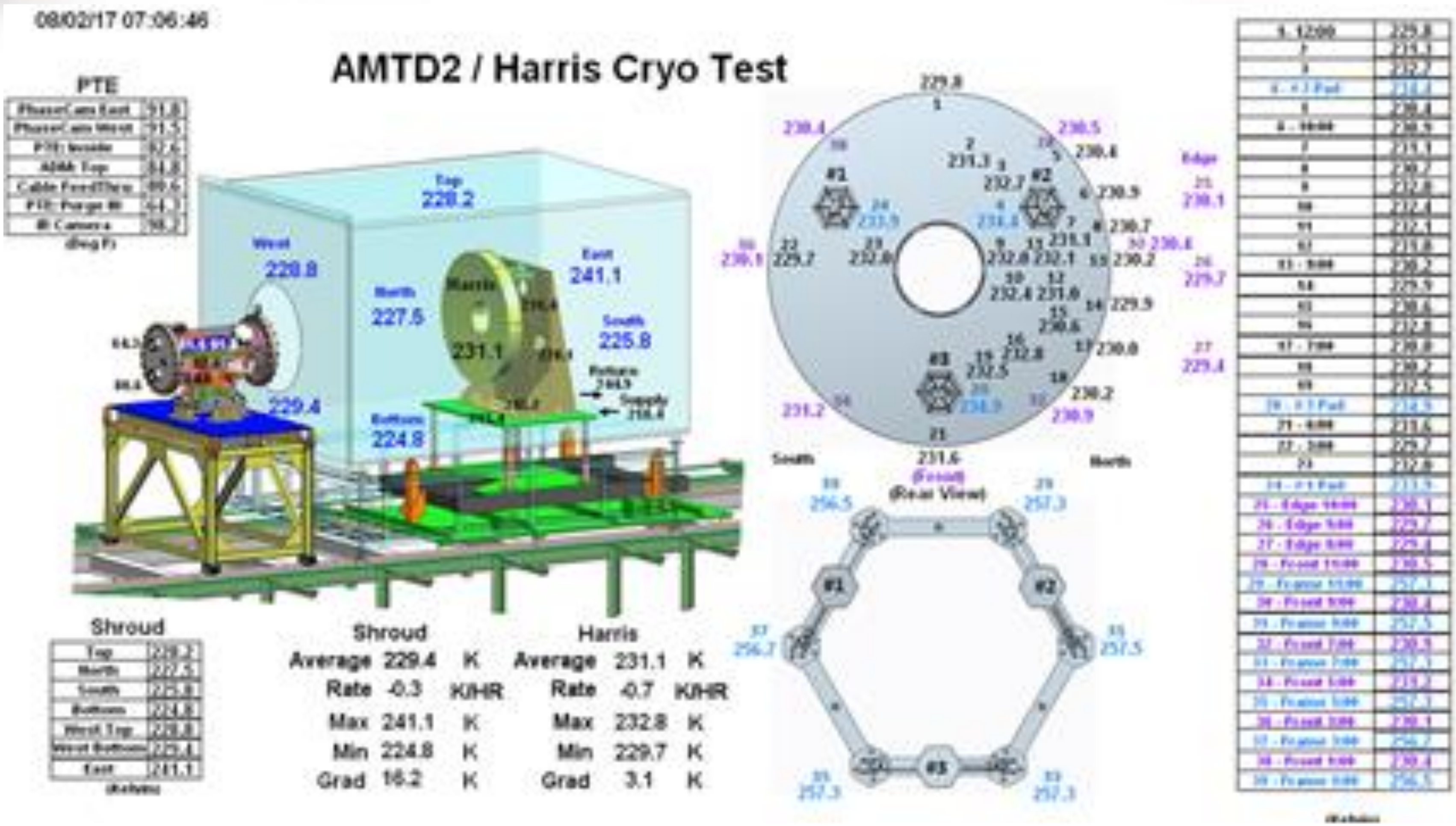
PTC test configuration in XRCF:

- Interferometer in Pressure Tight Chamber (PTC)
- A Thermal Shroud surround Mirror Assembly and provides a 230K thermal sink for the test.
- Solar Lamps impose Lateral Gradient



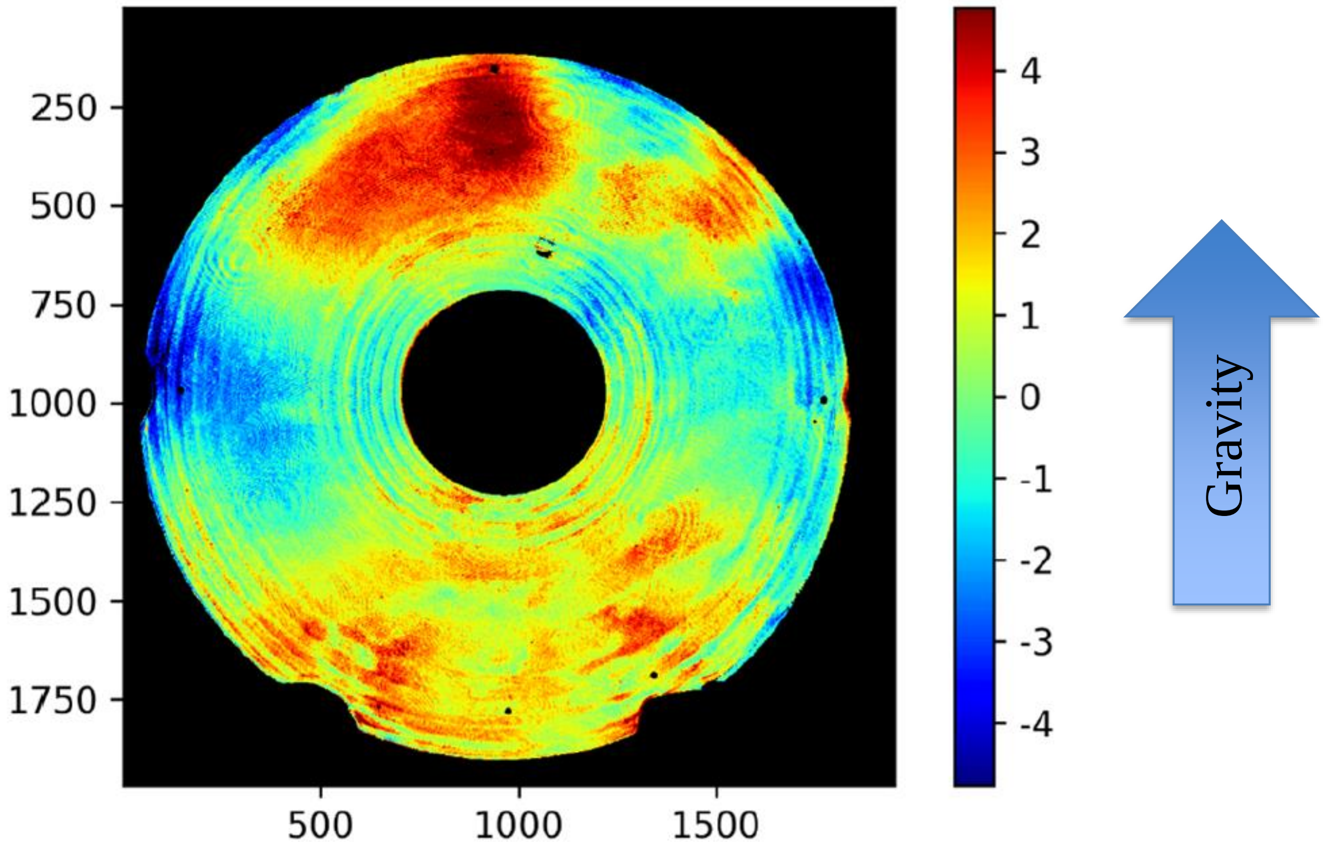


XRCF Tests are Fully Instrumented



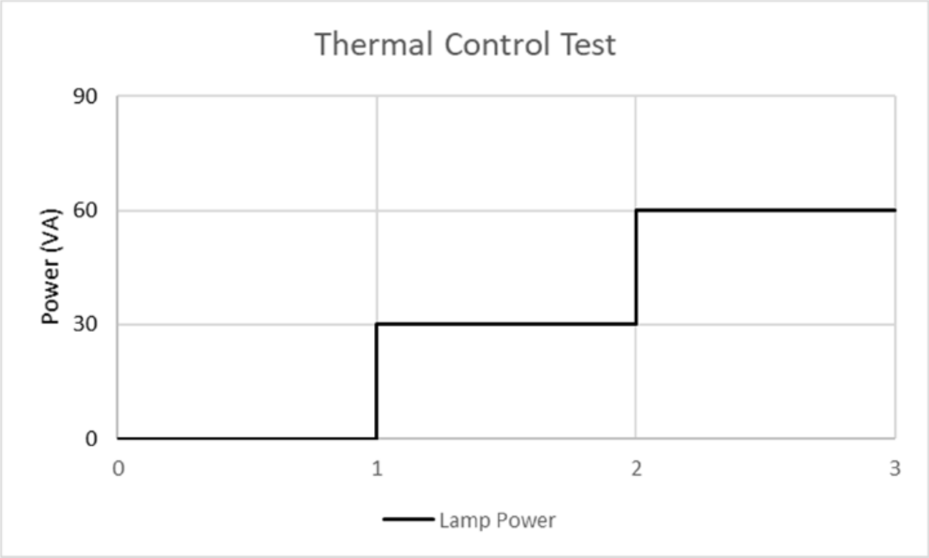
Measurement Repeatability

Measurement Repeatability (determined by differencing back-to-back 128 average measurements) is 1.6 nm rms.



Passive Thermal Test

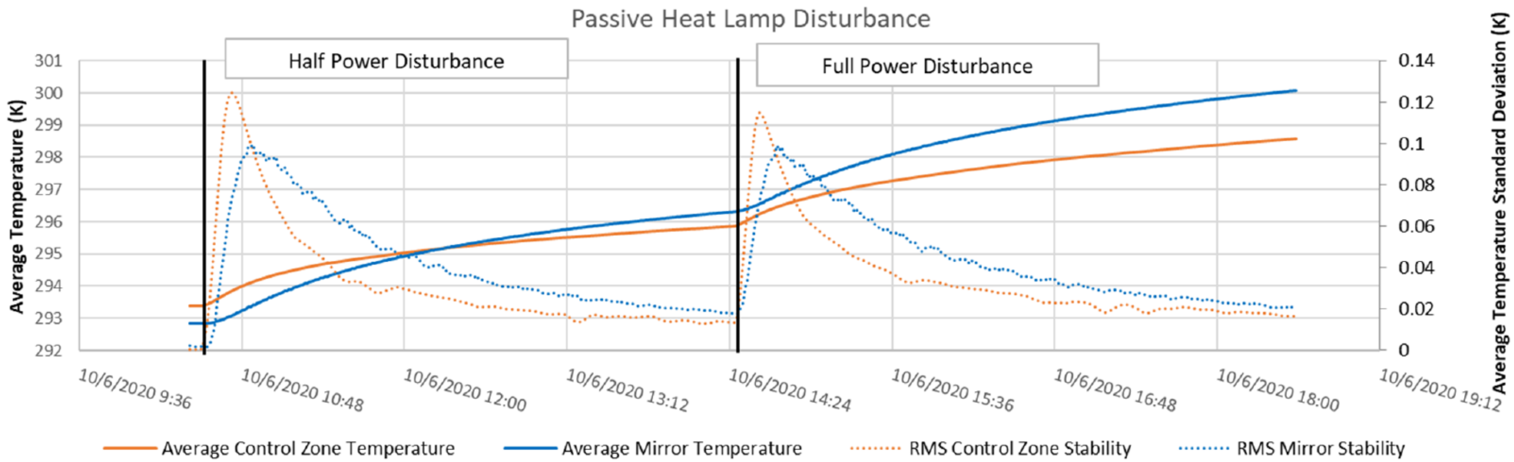
- 12 solar lamps turned on to half power (30VA each) and maintained until thermal stability achieved.
- Lamps then turned on to full power (60 VA each) and maintained until thermal stability achieved.



No Control Heat Lamp Test

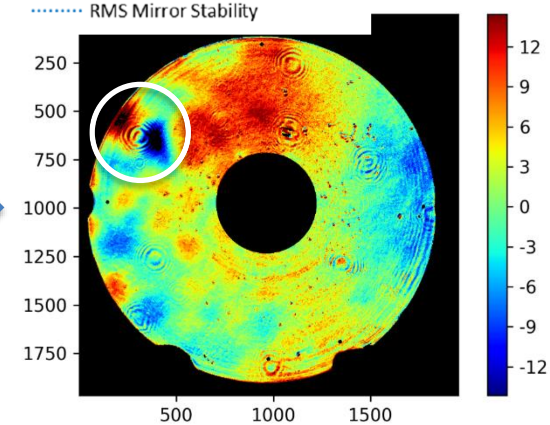
Mirror System Response

- Max Thermal Instability ~ 0.1K
- Average Temperature Increase ~ 3 to 4K
- Thermal Time Constant ~ 1 hr.



Produced surface figure change of 5 nm rms

Thermal Load

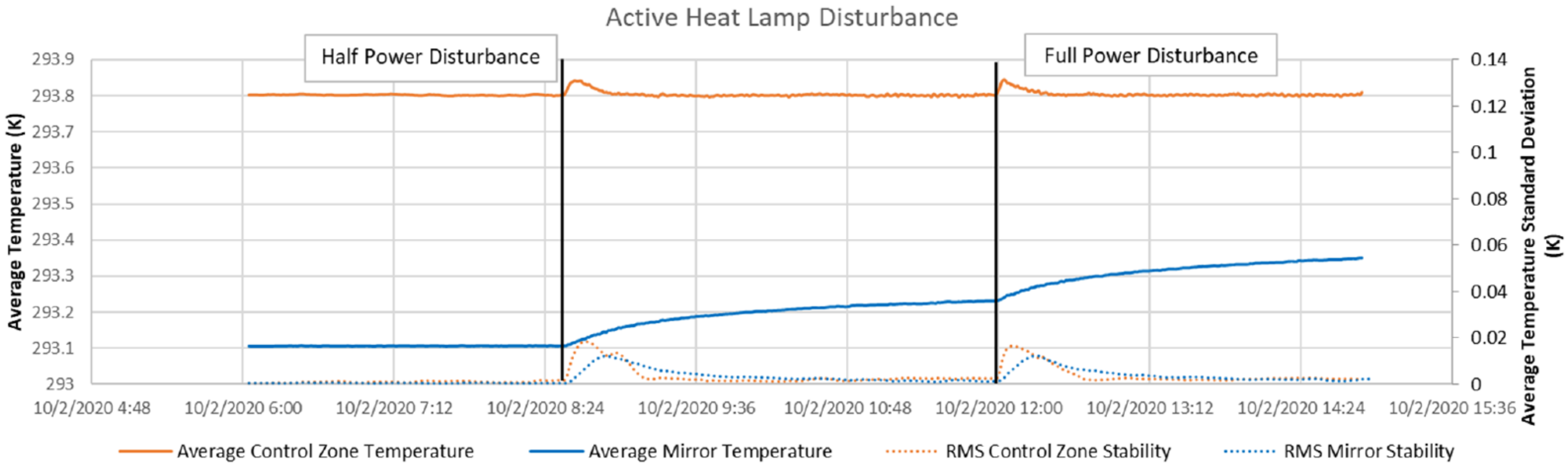


- Effect of bond pad temp change in top left

Active Control Thermal Test

PTC Active Thermal Control:

- 12-mK thermal instability Corrected to 2-mK in 20 minutes.
- Control Zones maintained Average Temperature
- Mirror Average Temperature drifted < 0.25K



Extrapolating to HabEx

- Full power equal to changing HabEx baffle from 240K to 400K.
- 50 mK baffle change would produce < 0.03-mK drift

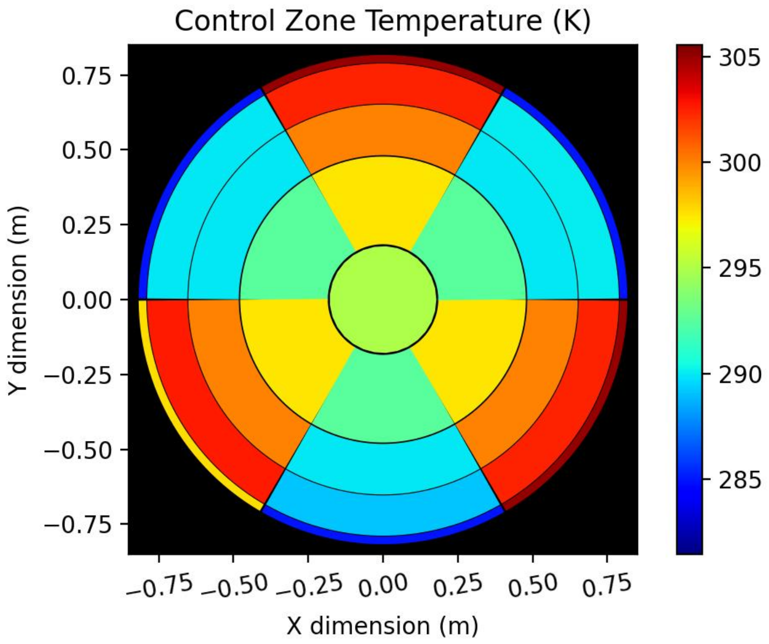
Active Figure Control

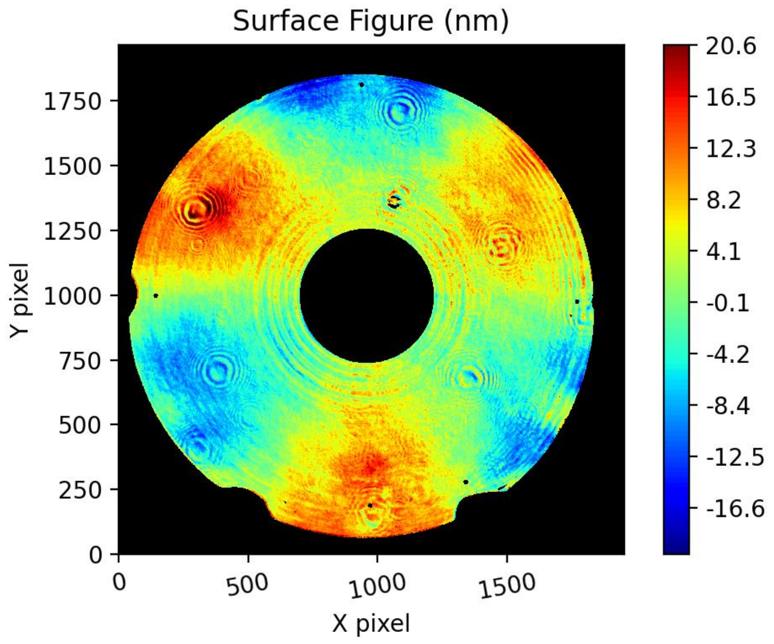
In addition to being able to sense and correct for thermal environment induced gradients, it is also possible to use zonal thermal control to adjust the mirror's shape – similar to mechanical actuators.

Demonstrated capability by introducing aberrations by modulating the Heater Zone temperature by +/- 20K.

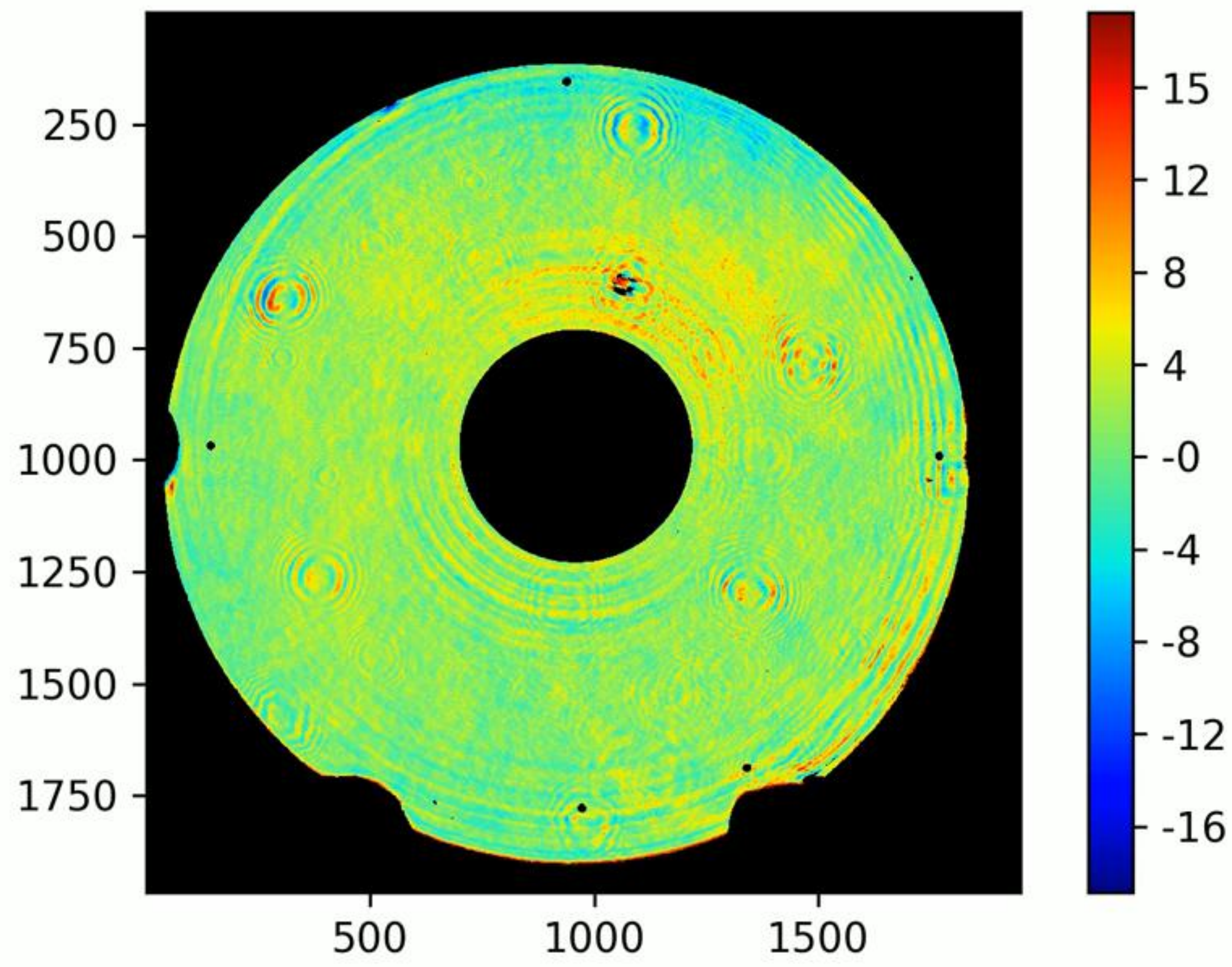
Trefoil Test

- Left image shows measured Heater Zone temperatures.
- Right image shows measured surface figure.
- Total Trefoil stroke length was 30nm PV (12.5nm RMS)



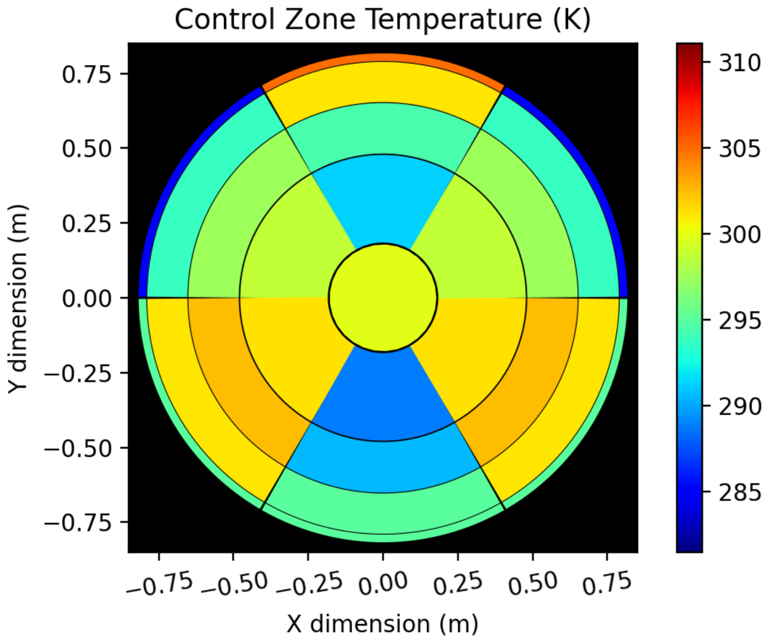


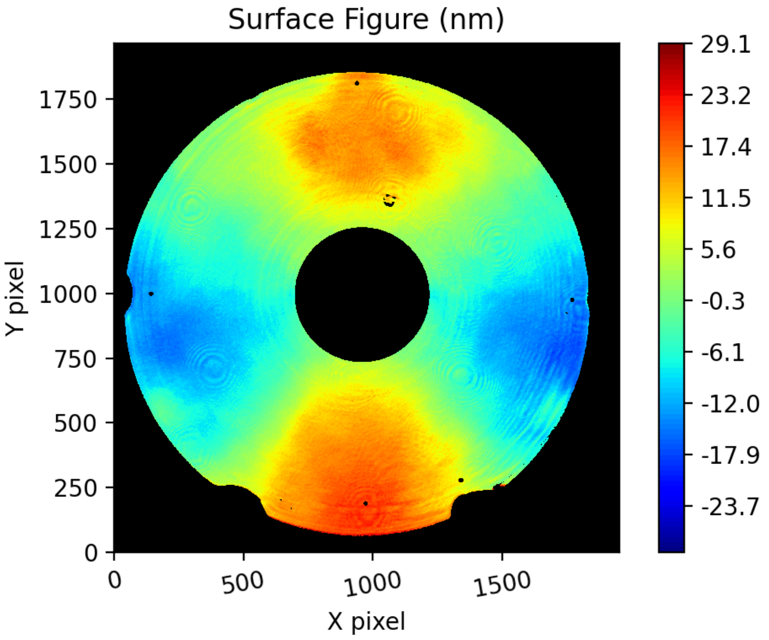
Trefoil Movie



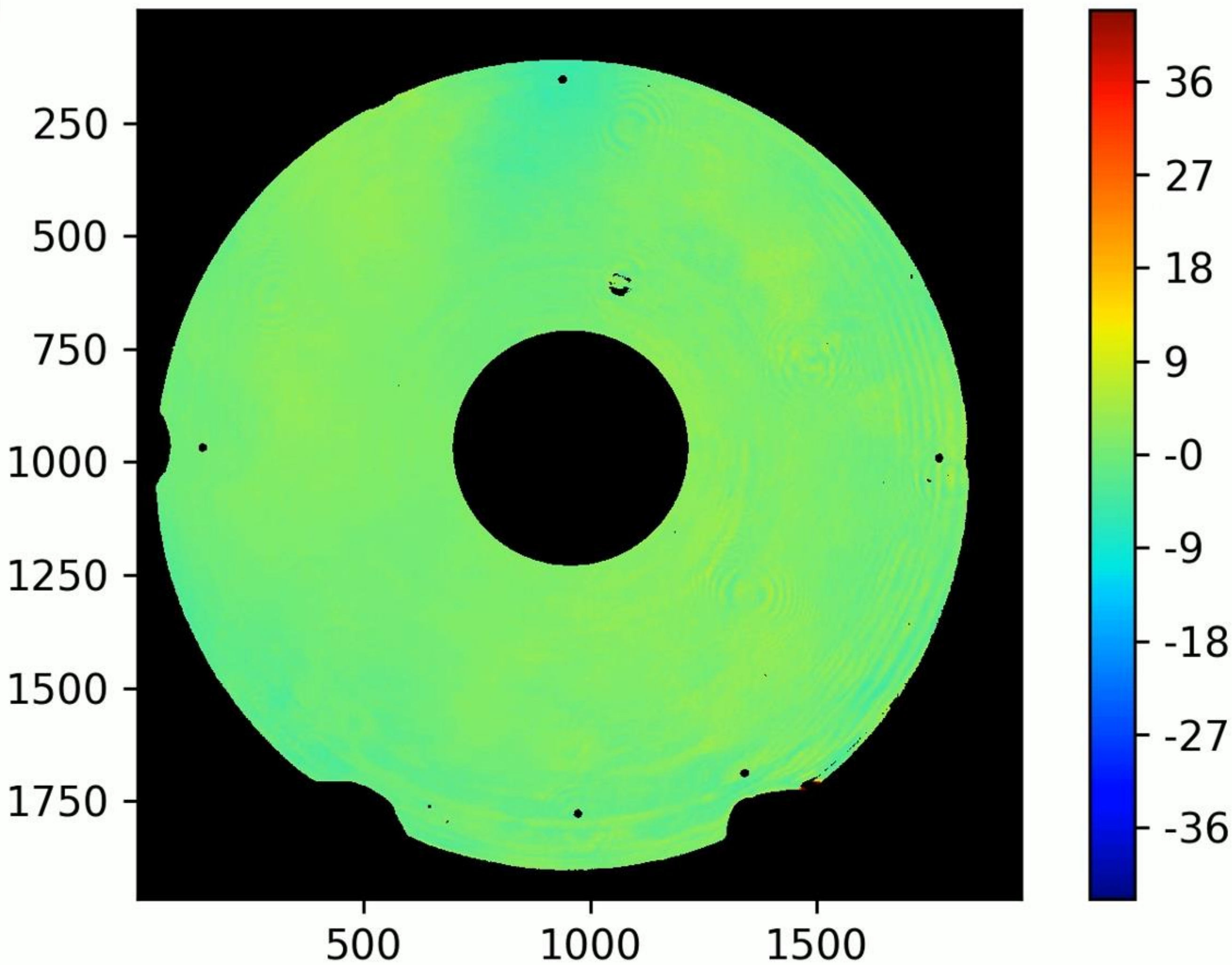
Astigmatism Test

Total Astigmatism stroke was about 65nm PV.



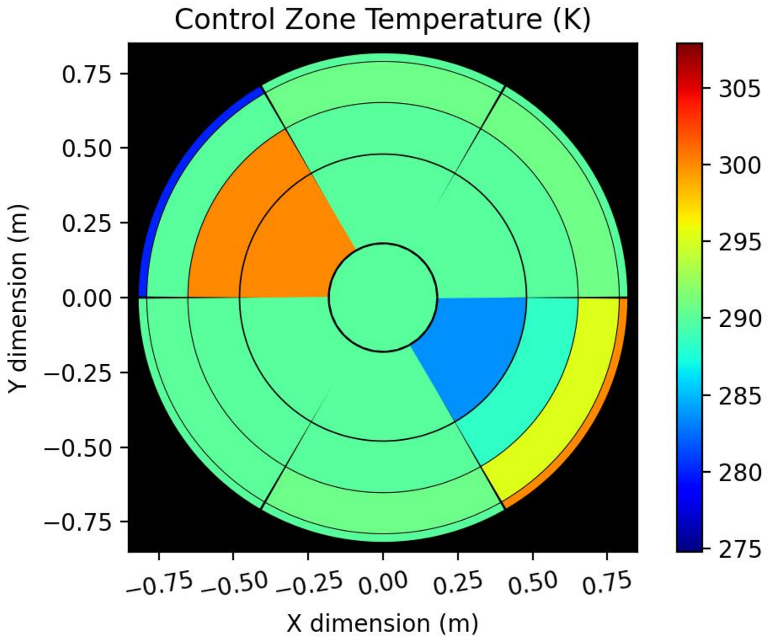


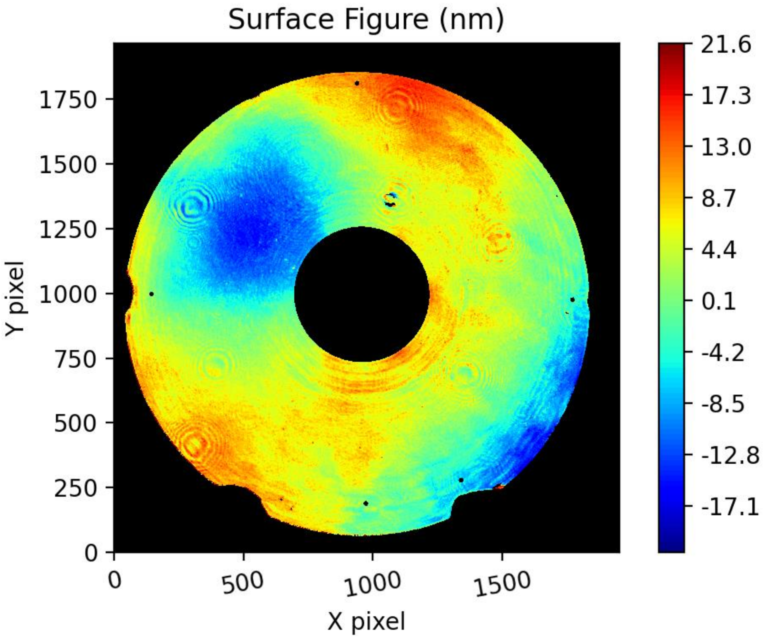
Astigmatism Movie



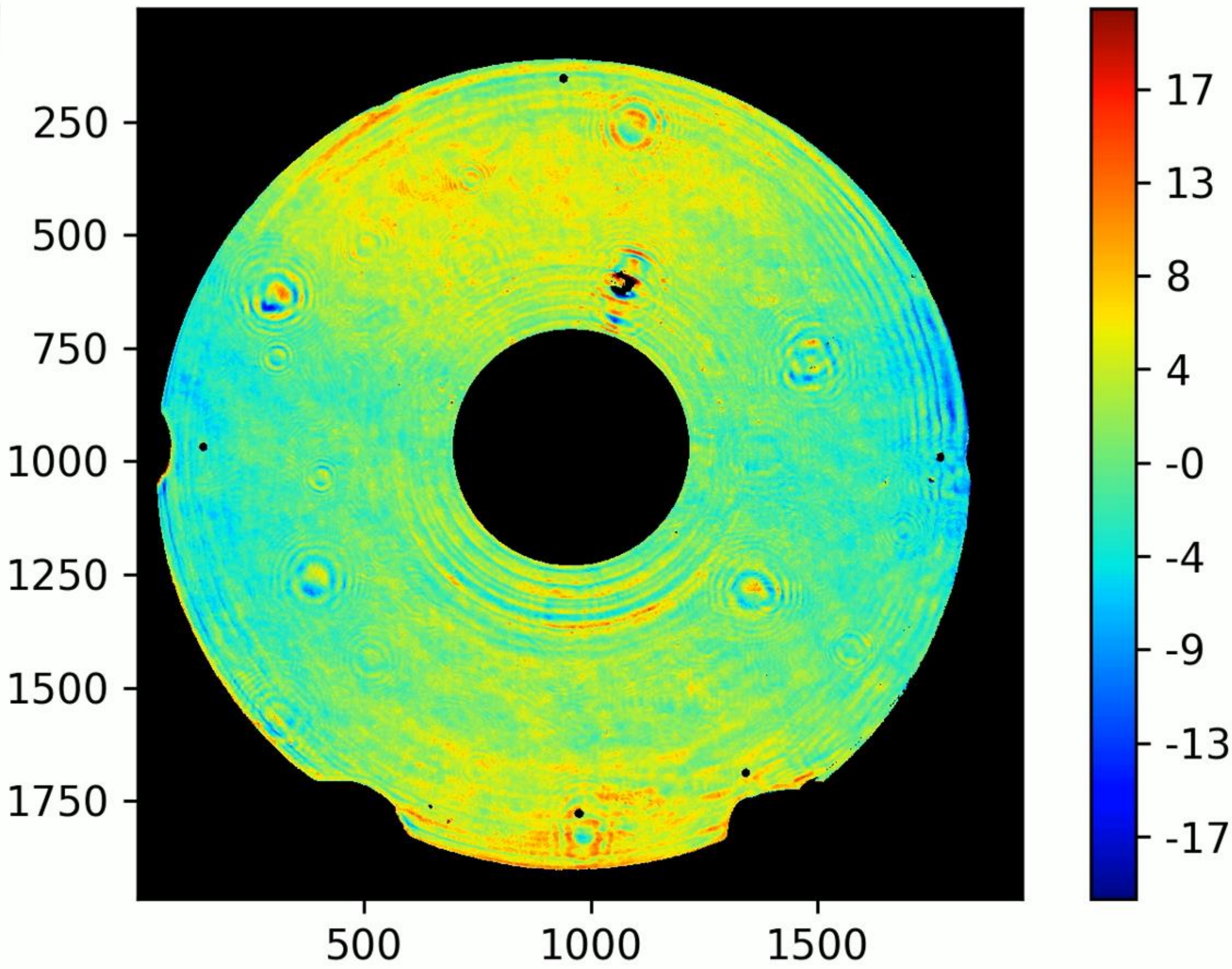
Coma Test

Total coma stroke length was about 17nm PV





Coma Movie



Active Figure Control

Thermal Control produces Correctabilty:

- Trefoil 0.75 nm/K PV
- Astigmatism 1.625 nm/K PV
- Coma 0.5 nm/K PV

Without observable mid-spatial frequency error.

Conclusion

- PTC used Science-Driven Systems Engineering methodology to mature technology for thermally stable telescopes.
- PTC successfully accomplished its objectives and milestones.
- PTC:
  - Advanced Multi-Zonal Active Thermal Control technology to TRL-5+.
  - Demonstrated (on flight traceable hardware in a relevant environment) ability to compensate for changes in the thermal environment to an accuracy of 2K with a stability of 2 mK
    - (meets the HabEx thermal performance specifications)
  - Demonstrated ability to introduce low-order surface shapes without introducing mid-spatial frequency error (could be useful for SFE correction).