Predictive Thermal Control (PTC)
Technology to enable Thermally Stable Telescopes

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Summary

The Predictive Thermal Control (PTC) technology development project is a multiyear effort initiated in Fiscal Year (FY) 2017, to mature the Technology Readiness Level (TRL) of critical technologies required to enable ultra-thermally-stable telescopes for exoplanet science. A key PTC partner is Harris Corporation (Rochester NY).

PTC has three defined objectives:

1. Validate thermal optical performance models.
2. Derive thermal system stability specifications.
3. Demonstrate Predictive Thermal Control.

And five quantifiable milestones.

- ✓ Milestone #1: Completed in FY17/18. A high-fidelity STOP model was created by merging X-Ray computed tomography data of the 1.5-m ULE© mirror and coefficient of thermal expansion (CTE) boule data provided by Harris Corp.
- ✓ Milestone #2: Completed in FY17/18 and Updated in FY18/19. Thermal control specification was revised using a new HabEx telescope WFE stability specification error budget.
- ✓ Milestone #3: Will be completed in FY19/20. Significant progress was accomplished in FY18/19:
    - 1.5-m multi-zone thermal enclosure (Figure 1) was fabricated by Harris Corp and delivered to MSFC for integration with control electronics and software.
    - STOP analysis predicts that the ULE© mirror's thermally induced figure error will be small. Thus, PTC procured a 1.2-m aluminum pathfinder test mirror. The Al mirror is expected to have a 2X larger signature than the ULE© mirror. Also, PTC plans to cryo-test this mirror for a potential Origins Space Telescope mission.
- ✓ Milestone #4 Completed in FY18/19. The high-fidelity STOP model mirror was validated by test. The 1.5-m ULE® mirror's response to soak temperature changes and imposed temperature gradient was measured and correlated with the high-fidelity model.
- ✓ Milestone #5: Completed in FY18/19. PTC and the HabEx mission study defined a baseline primary mirror assembly that optimizes predicted thermo-optical performance as a function of mirror design, material selection, material properties (i.e., CTE) mass, etc.

MSFC continues mentoring the next generation of scientists and engineers as interns, co-ops and volunteers. In this cycle, PTC involved three NASA Pathways Interns (Meghan Carrico, Adam Cedrone and Tim Little). Additionally, PTC results were published in SPIE proceedings and presented at Mirror Technology Days in the Government Workshop **[1-4]**. PTC results were also cited in the ULTRA SMTP Phase-1 Final Report **[5]**.

Figure 1: *Thermal enclosure for 1.5-m mirror with 37 thermal control zones.*

Background

"*Are we alone in the universe?*" is probably the most compelling science question of our generation.

Per the 2010 New Worlds, New Horizons Decadal Report **[6]**: "One of the fastest growing and most exciting fields in astrophysics is the study of planets beyond our solar system. The ultimate goal is to image rocky planets that lie in the habitable zone of nearby stars."

Directly imaging and characterizing habitable planets requires a large-aperture telescope with extreme wavefront stability. For an internal coronagraph, this requires correcting wavefront errors (WFEs) and keeping that correction stable to a few picometers root mean square (rms) for the duration of the science observation. This places severe specification constraints on the performance of the observatory, telescope, and primary mirror. Thermal stability is key to obtaining the required WFE stability.

Thermal wavefront error occurs because of coefficient of thermal expansion (CTE); slewing the telescope relative to the sun causes its structure or mirrors to change temperature. Thermal heat load changes cause the structure holding the mirrors to expand/contract and the mirrors themselves to change shape. Fortunately, thermal drift tends to be slow, i.e., many minutes to hours. State-of-the-art (SOA) for ambient temperature space telescopes are 'cold-biased' with heaters. The telescope is insulated from solar load such that, for all orientations relative to the sun, it is always at a 'cold' temperature (for example, 250K). The telescope is then warmed to an ambient temperature via heater panels on the forward straylight baffle tube as well as behind and beside the mirror. Current TRL-9 thermal control capability is defined by the Harris Corp SpaceviewTM telescopes. Their thermal control system's sensors have a noise of ~50-mK and controls the 1.1-m telescope to a temperature of 100 to 200-mK. **[7]**

PTC plans to advance the SOTA in thermal control by demonstrating a control logic called Model Predictive Control (MPC) **[8, 9]**. MPC places a physics-based model into the control loop to determine control variables (heater power levels) based on state variables (temperature measurements). MPC determines heater power levels using a completely different logic than proportional control. Proportional control adjusts heater power in proportion to the difference between measured and desired temperatures at one location. MPC uses multiple control zones and takes into account the interdependency between all control zones' temperatures and heater power. Preliminary analysis indicates that (assuming that thermal performance is linear) it is possible to achieve pm wavefront stability by either controlling the shroud to a small temperature (10 mK) or by rapidly correcting the temperature. Given that mirrors and telescope have a thermal response time, the best way to achieve pm-level stability is to sense and correct for changes in the thermal environment faster than the telescope can respond. Additional stability can be achieved by increasing the system's thermal mass.

We assess the current TRL of such a system to be TRL-3. PTC will advance TRL by testing two different mirrors – a 1.2-m aluminum pathfinder mirror (Figure 2) and the AMTD-2 1.5-m Ultra Low Expansion (ULE®) mirror (Figure 3) – integrated with a 1.5-m 37-zone active thermal control system built by Harris Corp (Figure 1) inside a space thermal environment simulator at the NASA MSFC XRCF (Figure 4).

Figure 2: *1.2-m Al Test Mirror*

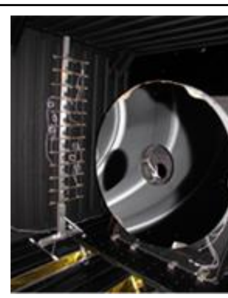


Figure 3: *1.5-m AMTD-2 ULE® Mirror*

Figure 4: *Solar Lamp Array inside MSFC XRCF He Cryo-shroud.*

Objectives and Milestone:

PTC has defined three objectives to mature by at least 0.5 TRL step the technology needed for an exoplanet science thermally stable telescope by developing “thermal design techniques validated by traceable characterization testing of components”:

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

To achieve our objectives, we have defined a detailed technical plan with five quantifiable milestones:

Milestone #1: Develop a high-fidelity model of the 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.

- ✓ Milestone #1 was completed in the FY17/18 annual report. A high-fidelity STOP model was created by merging X-Ray computed tomography data of the 1.5-m ULE® mirror and coefficient of thermal expansion (CTE) boule data provided by Harris Corp.

Milestone #2: Derive specifications for thermal control system as a function of wavefront stability.

- ✓ Milestone #2 was completed in the FY17/18 annual report. A thermal control specification was derived using a WFE stability specifications provided by the HabEx engineering team and thermal test data of the Schott 1.2-m Zerodur® mirror.

- ✓ Milestone #2 was updated in FY18/19, analysis was repeated using a new HabEx stability error budget.

Milestone #3: Design and build a predictive Thermal Control System for a 1.5m ULE® mirror that senses temperature changes and actively controls the mirror’s thermal environment.

- ✓ Milestone #3 accomplished significant progress during FY18/19. The multi-zone thermal enclosure for the AMTD-2 1.5-m ULE© mirror was fabricated by Harris Corp and delivered to MSFC.

- ✓ In FY19 MSFC will integrate this thermal system with the PTC control electronics and software.

- ✓ Milestone #3 initiated a new sub-task during FY18/19. STOP analysis predicts that the ULE© mirror’s thermally induced surface figure error will be small. Therefore, PTC is procuring 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.

- ✓ Additionally, PTC obtained internal MSFC IRAD funds to cryo-test the aluminum mirror in support of a potential Origins Space Telescope (OST) mission.

Milestone #4: Validate high-fidelity model by testing the 1.5-m ULE® AMTD-2 mirror in a relevant thermal vacuum environment at the MSFC X-ray and Cryogenic Facility (XRCF) test facility.

- ✓ Milestone #4 was completed in FY18/19. The high-fidelity STOP model mirror was validated by test. The 1.5-m ULE® mirror’s response to soak temperature changes and imposed temperature gradient was measured and correlated with the high-fidelity model.

Milestone #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.

- ✓ While Milestone #5 was not scheduled for completion until the end of PTC, the PTC program in conjunction with the HabEx study performed trade studies in FY18/19 that defined a baseline primary mirror design that optimizes predicted thermo-optical performance as a function of mirror design, material selection, material properties (i.e., CTE) mass, etc.

Progress and Accomplishment:

Objective #1: Validated High-Fidelity Structural-Thermal-Optical-Performance (STOP) Model

Need: Designing a telescope to have an ultra-stable wavefront requires using a validated high-fidelity STOP model to predict thermal optical performance of mirrors and structure based on their mechanical designs and material properties, i.e., CTE distribution, thermal conductivity, thermal mass, etc.

Milestone #1: Develop a high-fidelity STOP model of the1.5m ULE® AMTD-2 mirror, including 3D CTE distribution and reflective coating, that predicts its optical performance response to steady-state and dynamic thermal gradients.

Accomplishment: Completed in FY17/18. A high-fidelity STOP model of the AMTD-2 1.5-m ULE® mirror was created in NASTRAN that accurately models its 'as-built' mechanical dimensions and 3D CTE distribution. **[10]** The 'as-built' mechanical dimensions were quantified using 3D X-ray computed tomography to measure the internal structure of the mirror. To add a 3D mapping of CTE distribution, Harris Corporation provided MSFC with Corning CTE data maps for each of the 18 core elements and the location of each element in the core.

Milestone #4: Validate high-fidelity STOP model by testing the 1.5-m ULE® AMTD-2 mirror in a relevant thermal vacuum environment at the MSFC X-ray and Cryogenic Facility (XRCF) test facility.

Accomplishment: Started in FY17/18. Completed in FY18/19. Milestone #1's high-fidelity model was validated by correlating predictions with the measured response of the AMTD-2 1.5-m ULE® mirror to a 231K static thermal soak test and an 87.7K thermal gradient test. Both tests occurred in FY18 as part of the final AMTD-2 testing.

The high-fidelity model predicted the AMTD-2 mirror's response to 231-K static thermal soak test by combining mount and CTE effects. The model predicted 24.7-nm rms of the 28.8 nm rms measured cryo-deformation for a residual uncertainty of 13.4-nm rms (Figure 5). **[2, 11]**

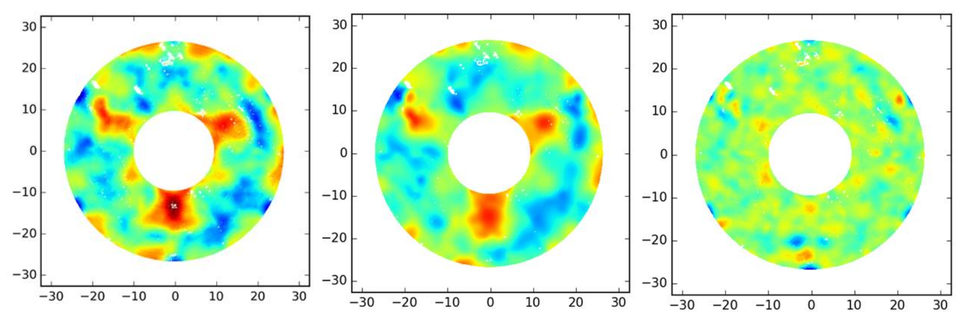
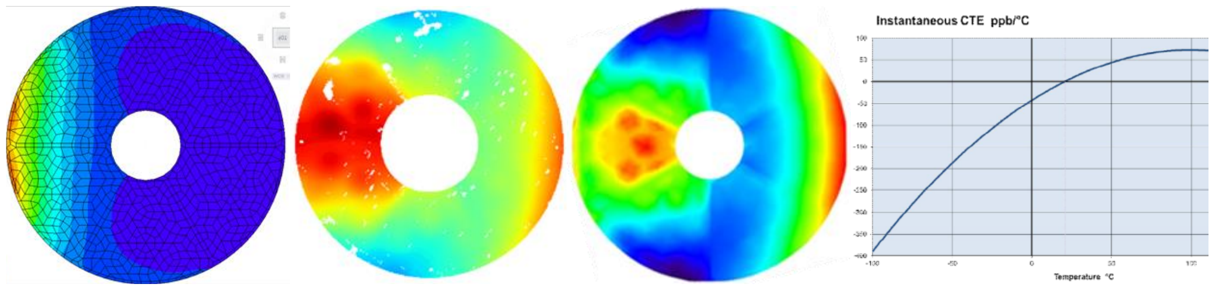


Figure 5. Left: *Thermal soak of the mirror and mount going from 293 to 231 K resulted in a measured cryo-deformation of 28.8-nm rms.* Center: *High-fidelity AMTD-2 model predicts 24.7-nm rms of deformation from mount effects and CTE inhomogeneity.* Right: *Difference between measured deformation and predicted deformation is 13.4-nm rms.*

To further validate the high-fidelity model, the 1.5-m ULE® AMTD-2 mirror's response to a lateral thermal gradient was tested in the XRCF. PTC modified MSFC's XRCF facility to introduce thermal gradients into mirror systems using solar lamps (Figure 4). This test was a bare-mirror-only test, i.e. mirror only with no thermal control system (Figure 1) – which will be done via Milestone #3. The results of this test were published in FY18/19. **[1]** The solar lamps introduced a thermal gradient of 87.7 K into the mirror causing a 78.7-nm rms surface deformation (Figure 6). The high-fidelity model was able to match this deformation by increasing the average CTE of the mirror substrate in the model to 81 ppb/K. As show in Figure 6d, Corning published data shows that ULE® bulk CTE changes from ~0 ppb/K at 20 C to approximately 70 to 80 ppb/K at 100C. **[12]**



(a) *(b)* *(c)* *(d)*

Figure 6. *(a) Temperature distribution (ΔT = 87.7K PV) calculated by Thermal Desktop from thermocouple data on mirror back for heat lamps outputting 406W. (b) Measured surface figure error (RMS = 78.5nm). (c) To match measured SFE caused by temperature distribution, model had to increase average substrate CTE to 81ppb/K. [1] (d) Per Corning, ULE® bulk CTE increases from ~0 ppb/K at 20C to ~70 to 80 ppb/K at 100C.* ***[12]***

Objective #2: Derive Traceable Specifications for an Active Thermal Control System

Need: Designing a telescope to have an ultra-stable wavefront via active thermal control requires a validated STOP model to define the thermal control system's performance specifications, such as: sensing resolution (1 or 10 mK), control accuracy (10 or 50 mK), control period (1 or 5 min), number and distribution of sense and control zones. **[13]**

Milestone #2: Derive specifications for thermal control system as a function of wavefront stability.

Accomplishment: During FY17/18, PTC completed Milestone #2 using WFE stability specifications provided by the HabEx engineering team and thermal test data of the Schott 1.2-m Zerodur® mirror **[14]** and published the result. **[15]**

However, in FY18/19, the PTC and HabEx engineering teams revisited the WFE stability error budget and performed a more detailed, higher-fidelity analysis. An active thermal control enclosure was designed that achieves a HabEx engineering study team provided wavefront stability error budget for the baseline HabEx 4-m Zerodur® primary mirror design when exposed to a representative design reference mission. The specification was developed by deriving an error budget based on the vector vortex coronagraph's contrast leakage sensitivity to wavefront error decomposed into Zernike polynomials **[3]** and the measured thermal wavefront error performance of the Schott 1.2-m Zerodur® mirror characterized by the AMTD-2 project. **[14]** The resulting specification is for an active thermal control system with 86-control zones on the primary mirror and its hexapods, thermal sensors with 50-mK measurement uncertainty, and proportional controller systems (PID) operating with 30 second periods.

Milestone #5: Use validated model to perform trade studies to determine how thermo-optical performance can be optimized as a function of mirror design, material selection, material properties (i.e., CTE) mass, etc.

Accomplishment: While Milestone #5 was not scheduled for completion until the end of PTC, PTC in conjunction with the HabEx study performed trade studies in FY18/19 that defined a baseline primary mirror design that optimizes predicted structural-thermo-optical performance. **[15, 16]** Given the feedback loop between the primary mirror design and the thermal enclosure specifications, Milestone #5 and Milestone #2 had to be completed together.

Baseline HabEx Primary Mirror Active Control System

Deriving a specification for a potential HabEx primary mirror active control system required three steps. First was defining an error budget. Second was defining the baseline primary mirror's thermal sensitivity. And third was created an integrated telescope thermal model which could be exercised for a given design reference mission (DRM).

A Zernike polynomial based wavefront stability error budget was derived from the total maximum allowed vector vortex coronagraph leakage to detect an exoEarth. **[3]** The process starts by calculating the amount of raw contrast leakage that a coronagraph can have and still detect an exoplanet relative to its host star, at a defined signal to noise ratio. For the case illustrated in Figure 7, this is 40 parts-per-trillion. Next the contrast leakage sensitivity of the coronagraph is calculated for each Zernike polynomial. Finally, the allowed contrast leakage is allocated between Zernike polynomials and converted into WFE. For example, the vector vortex charge 4 coronagraph is insensitive to tilt and power, therefore, more WFE can be allocated to these terms. But, all higher order terms must be very stable. As shown in Figure 8, the error budget can be further sub-allocated between thermal, inertial and LOS WFE.

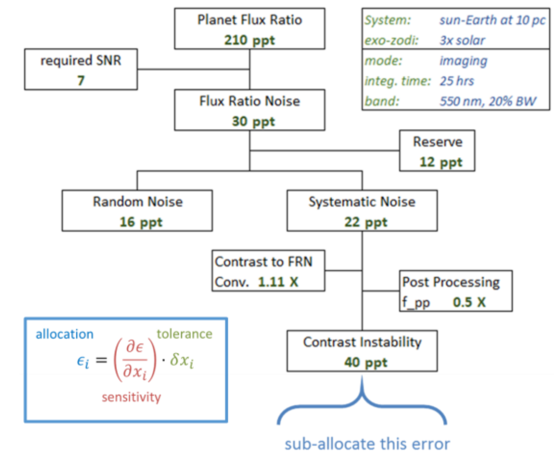


Figure 7: *Wavefront Stability Error Budget Development Method* **[3]**

			Allocation	100%	30%	30%	30%	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	892	892	892	515
1	1	1	Tilt	1192.8	653.32	653.32	653.32	377.19
2	2	0	Power (Defocus)	1108.6	607.19	607.19	607.19	350.56
3	2	2	Pri Astigmatism	3.8	2.09	2.09	2.09	1.21
4	3	1	Pri Coma	3.3	1.81	1.81	1.81	1.05
5	3	3	Pri Trefoil	3.3	1.81	1.81	1.81	1.05
6	4	0	Pri Spherical	3.1	1.69	1.69	1.69	0.97
7	4	2	Sec Astigmatism	3.1	1.69	1.69	1.69	0.97
8	4	4	Pri Tetrafoil	3.0	1.62	1.62	1.62	0.94
9	5	1	Sec Coma	2.7	1.48	1.48	1.48	0.85
10	5	3	Sec Trefoil	2.7	1.48	1.48	1.48	0.85
11	5	5	Pri Pentafoil	2.7	1.48	1.48	1.48	0.85
12	6	0	Sec Spherical	2.7	1.48	1.48	1.48	0.85
13	6	2	Ter Astigmatism	2.1	1.13	1.13	1.13	0.65
14	6	4	Sec Tetrafoil	2.5	1.37	1.37	1.37	0.79
15	6	6	Pri Hexafoil	2.5	1.37	1.37	1.37	0.79
16	7	1	Ter Coma	1.4	0.77	0.77	0.77	0.45
17	7	3	Ter Trefoil	1.6	0.90	0.90	0.90	0.52
18	7	5	Sec Pentafoil	1.6	0.87	0.87	0.87	0.50
19	7	7	Pri Septafoil	1.8	0.98	0.98	0.98	0.56
20	8	0	Ter Spherical	0.7	0.37	0.37	0.37	0.22
21	8	2	Qua Astigmatism	1.0	0.55	0.55	0.55	0.32
22	8	4	Ter Tetrafoil	1.2	0.67	0.67	0.67	0.38
23	8	6	Sec Hexafoil	1.4	0.79	0.79	0.79	0.45
24	8	8	Pri Octafoil	1.4	0.75	0.75	0.75	0.43
25	9	1	Qua Coma	0.9	0.50	0.50	0.50	0.29
26	10	0	Qua Spherical	1.1	0.63	0.63	0.63	0.36
27	12	0	Qin Spherical	2.0	1.07	1.07	1.07	0.62

Figure 8: *Allocation of WFE Stability between LOS, Inertial and Thermal Sources.*

Next, an integrated observatory thermal model was created in Thermal Desktop using a geometry created in Pro-Engineer CAD. The Thermal Desktop model has 20K elements and calculates telescope's structure and mirror temperature distribution at 10K nodes. The temperature distribution for each node is mapped onto the NASTRAN FEM and the deflections created by each node's coefficient of expansion (CTE) is calculated using NASTRAN Solution 101. Rigid body motions (RBM) and mirror surface deformations are calculated from the NASTRAN deflections using SigFit. The primary and secondary mirror's mesh grids were sized to enable SigFit to fit thermally induced surface figure error (SFE) to higher order Zernike polynomials.

The model assumes multi-layer insulation (MLI) to control heat loss and to isolate thermal disturbances (i.e. the Sun). Radiators pull heat from the science instruments and spacecraft electronics. Between the MLI and radiators, the payload is passively cold-biased and active thermal control is required to maintain the primary mirror at an operating temperature of ~270K. Without heaters, the model predicts a primary mirror temperature of 206K. The model assumes TRL-9 capabilities for the primary mirror thermal enclosure: sensors with 50-mK measurement uncertainty; and proportional controller systems (PID) operating with 30 second periods. The model has 86 control zones on the primary mirror and its hexapods. The model predicts that the primary mirror front surface will have ~200 mK 'trefoil' thermal gradient (Figure 9). The source of this gradient is thermal conduction into the hexapod struts. And, the model predicts that the mirror will have ~3 K front to back gradient.

The primary and secondary mirror coefficient of thermal expansion (CTE) are modeled as consisting of a uniform 'bulk' CTE and a CTE homogeneity distribution. The uniform CTE value determines the mirror's low-order shape response to bulk temperature changes, and/or gradient temperature changes (i.e. axial, radial or lateral). Such temperature changes can produce low-order errors such as power and astigmatism. The homogeneity distribution determines the mirror's mid-spatial response. The model calculates mirror shape changes from two effects: (1) response of mirror with uniform CTE to changes in temperature at each of the 10K nodes; and (2) response of a mirror with a CTE inhomogeneity distribution to a uniform bulk temperature change. One method to estimate CTE inhomogeneity is to measure the thermal deformation of the mirror and assume that CTE is linear with temperature. As part of the Advanced Mirror Technology Development (AMTD) project, a 1.2-m ELZM was measured to have an ~11 nm rms deformation over a 62K thermal range (from 292K to 230K). Figure 10 shows the measured error and its decomposition into Zernike polynomials. **[14]** The model assumes this measured thermal signature for its CTE inhomogeneity distribution.

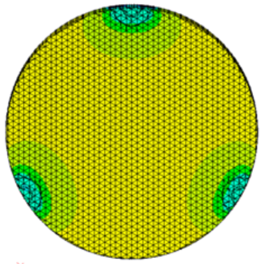
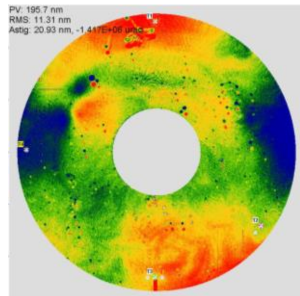


Figure 9: Predicted 200 mK trefoil thermal distribution of primary mirror front surface.



	Measured Delta-SFE 292-230K		
	Zernike Coefficient [nm] RMS Surface		
	RMS-Zern	X-Zern	Y-Zern
	[nm rms]	[nm rms]	[nm rms]
Aberration			
TOTAL RMS	26.016	nm rms	
Tilt	0.095	0.055	0.077
Power (Defocus)	0.416	0.416	
Pri Astigmatism	20.940	-19.960	-6.330
Pri Coma	2.541	-2.539	0.109
Pri Trefoil	6.089	-3.970	-4.617
Pri Spherical	0.599	0.599	
Sec Astigmatism	2.283	-2.046	-1.012
Pri Tetrafoil	5.471	-3.683	4.046
Sec Coma	2.591	-1.050	2.369
Sec Trefoil	4.811	0.912	-4.724
Pri Pentafoil	1.838	1.713	-0.666
Sec Spherical	1.067	1.067	
Ter Astigmatism	3.465	3.341	-0.918
Sec Tetrafoil	1.089	-0.647	0.876
Pri Hexafoil	4.772	-4.569	-1.376
Ter Coma	3.073	0.786	-2.971
Ter Trefoil	6.863	-1.165	6.763
Sec Pentafoil	1.953	-0.487	1.891
Ter Spherical	0.729	-0.729	
Qua Astigmatism	0.171	-0.091	-0.144
Ter Tetrafoil	1.999	1.262	-1.550
Qua Coma	3.659	3.220	-1.738
Qua Spherical	1.883	-1.883	
Qin Spherical	2.635	2.635	

Figure 10: 1.2m Schott ELZM 62K thermal deformation decomposed into Zernikes [14]

The model was used to predict thermal performance for a potential science design reference mission (DRM). The DRM starts by pointing the telescope pointing at a reference star to dig the dark hole in the coronagraph. The analysis assumes that the telescope reaches a steady state thermal condition at this sun orientation. Next, the telescope is pointed at the science star. To make the analysis 'worst-case' it is assumed that when the telescope is pointing at the reference star, the sun is perpendicular to the sun-shade/solar-panels with a +θ degree roll. And, when it points to the science star, it pitches away from the sun (Figure 11). Figure 12 shows the DRM motions as viewed from the sun.

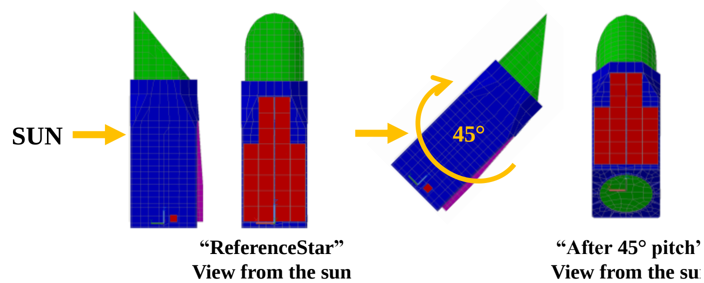


Figure 11: Nominal observing scenario slews for thermal analysis

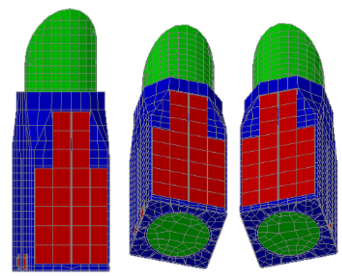


Figure 12: Telescope motions as viewed from the Sun

Figures 13 to 15 show how well the modeled active zonal thermal enclosure controls the temperature of the primary mirror 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. Figure 13 shows the predicted change in average bulk temperature and axial gradient temperature of the primary mirror if there were no active control. Please note that the axial gradient changes faster than the average temperature, this will have WFE impact. Figures 14 and 15 show the predicted average and gradient temperature changes for the primary mirror under active thermal control. The zonal control system keeps the PM average bulk temperature change to less than ~ 0.035-mK and the axial gradient change to less than ~ 1.75-mK.

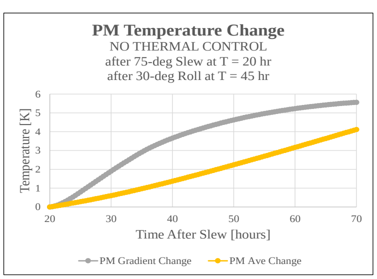


Figure 13: Passive PM average and axial gradient temperature change from 75 deg pitch.

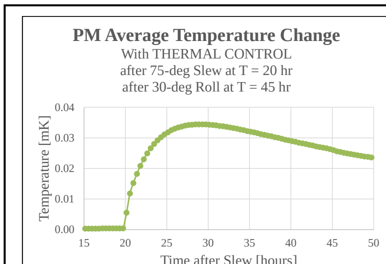


Figure 14: Actively controlled PM average bulk temperature change from 75 deg pitch.

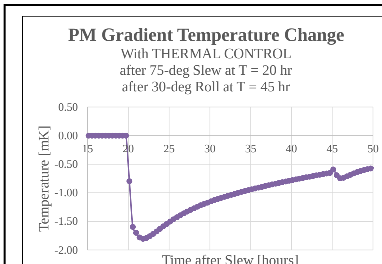


Figure 15: Actively controlled PM axial temperature gradient change from 75 deg pitch.

To calculate primary mirror wavefront stability, Thermal Desktop calculated its temperature distribution as a function of time and NASTRAN calculated the surface deformations produced by that distribution. The temporal WFE was then decomposed into Zernike polynomials by SigFit. Figure 16 shows the change in primary mirror WFE produced by the 75 degree thermal slew DRM with no active thermal control. Figure 17 shows the change in the primary mirror WFE caused by the 75-deg slew DRM with active zonal thermal control. Because the control system is able to keep the average and axial gradient temperatures very small, the Thermal WFE remains less than 1 picometer rms. As shown in Figure 18, the predicted primary mirror thermal WFE stability has significant performance margin relative to the error budget tolerance. The most important errors are astigmatism and coma.

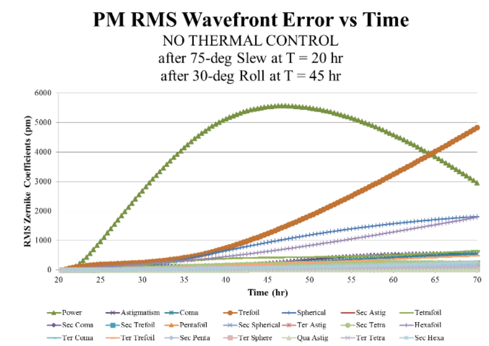


***Figure 16:** Changing PM Zernike WFE after 75-deg thermal slew with no thermal control*

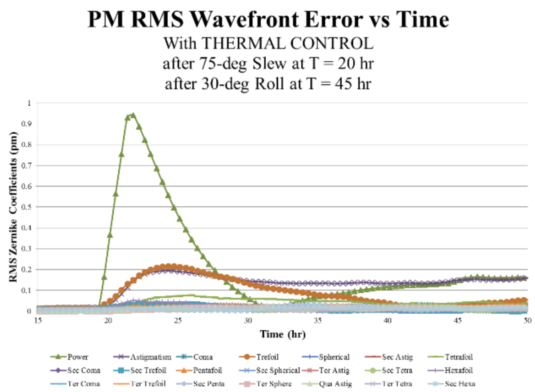


Figure 17: Changing PM Zernike WFE after 75-deg thermal slew with Active Zonal Thermal Control.

Order K	N	M	Aberration	Allocation Thermal [pm rms]	PM Allocation 50% [pm rms]	MARGIN	Zernikes Thermal WFE [pm rms]
			TOTAL RMS	814.22	575.74		1.990
1	1	1	Tilt	596.40	421.72	33469.48	0.013
2	2	0	Power (Defocus)	554.29	391.94	208.13	1.883
3	2	2	Pri Astigmatism	1.91	1.35	3.47	0.389
4	3	1	Pri Coma	1.65	1.17	15.90	0.074
5	3	3	Pri Trefoil	1.65	1.17	2.72	0.430
6	4	0	Pri Spherical	1.54	1.09	17.62	0.062
7	4	2	Sec Astigmatism	1.54	1.09	20.64	0.053
8	4	4	Pri Tetrafoil	1.48	1.05	6.86	0.153
9	5	1	Sec Coma	1.35	0.96	20.24	0.047
10	5	3	Sec Trefoil	1.35	0.96	14.05	0.068
11	5	5	Pri Pentafoil	1.35	0.96	14.17	0.067
12	6	0	Sec Spherical	1.35	0.95	37.30	0.026
13	6	2	Ter Astigmatism	1.03	0.73	13.99	0.052
14	6	4	Sec Tetrafoil	1.25	0.89	17.87	0.050
15	6	6	Pri Hexafoil	1.25	0.88	8.76	0.101
16	7	1	Ter Coma	0.70	0.50	10.09	0.049
17	7	3	Ter Trefoil	0.82	0.58	13.51	0.043
18	7	5	Sec Pentafoil	0.80	0.56	8.40	0.067
19	7	7	Pri Septafoil	0.89	0.63		0.000
20	8	0	Ter Spherical	0.34	0.24	5.81	0.042
21	8	2	Qua Astigmatism	0.50	0.36	8.78	0.041
22	8	4	Ter Tetrafoil	0.61	0.43	14.83	0.029
23	8	6	Sec Hexafoil	0.72	0.51	10.98	0.046
24	8	8	Pri Octafoil	0.68	0.48		0.000
25	9	1	Qua Coma	0.46	0.32		0.000
26	10	0	Qua Spherical	0.57	0.40		0.000
27	12	0	Qin Spherical	0.98	0.69		0.000

Figure 18: PM Thermal WFE meets its tolerance.

Objective #3: Demonstrate utility of Predictive Control thermal system for achieving thermal stability.

Need: Building a telescope that has an ultra-stable wavefront requires an active thermal control system that is beyond the current state of art (i.e., bang-band or proportional control). The goal of Objective #3 is to demonstrate the ability of a physics-based model in the control loop to control a mirror's shape by determining control variables (heater power levels) based upon state variables (temperature measurements).

Milestone #3: Design, build, and test a predictive thermal control system for the 1.5m ULE® AMTD-2 mirror.

Accomplishments: During FY18/19 PTC progressed technology for Milestone #3. PTCT Partner Harris Corp designed and built a thermal enclosure with 37 control zones for the 1.5-m ULE® AMTD-2 mirror. The enclosure has been delivered to MSFC (Figure 19) and is being integrated with the PTC control electronics and software.

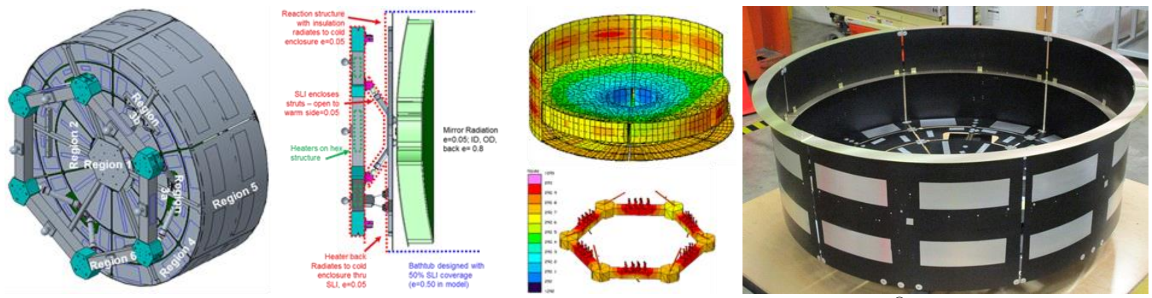


Figure 19: *Thermal Control System with 37 zone control for AMTD-2 1.5-m ULE© mirror (ITAR)*

PTC will be considered demonstrated if it can correct for externally imposed thermal gradients (i.e., radial, lateral, and axial gradients). Other goals include: self-tuning thermal parameters in the thermal model to improve the PTC's veracity, informing the design of enclosure hardware and thermal shrouds to enable controllability, and directly imposing measurable thermally-induced WFE into the mirror (Figure 20).

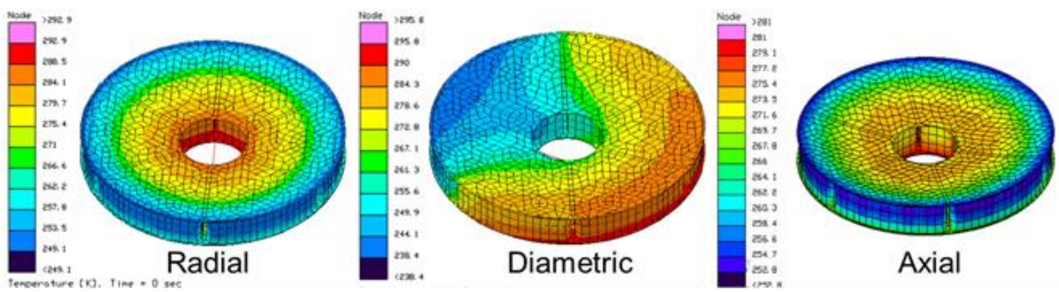


Figure 20: Thermal Control System can introduce Radial, Lateral and Axial thermal gradients.

Because when we perform the Milestone #3 tests, the thermal enclosure will prevent direct illumination of the mirror from the solar lamps, STOP analysis predicts that the 1.5-m ULE® mirror – when integrated with the enclosure – will experience only a 7.5 nm rms figure change without thermal control; and, with thermal control this change is reduced to 1.5 nm rms (Figure 21). For this reason PTC decided to procure a 1.2-m aluminum mirror to serve as a pathfinder test article (Figure 2). 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.

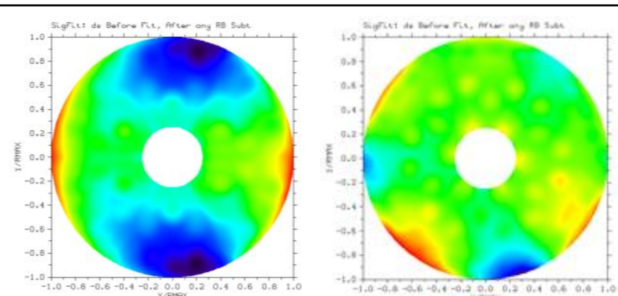


Figure 21: *(left) SFE without thermal control. (right) SFE with thermal control correction.*

Additionally, in support of a potential Origins Space Telescope (OST) mission, PTC obtained MSFC IRAD funds to test the aluminum mirror at 30K to characterize its cryo-deformation for a cryo-null polishing demonstration. And, to cycle this mirror to 30K three times to quantify any cryo-creep effects.

Path Forward

The primary remaining tasks in FY19/20 are to test the PTC algorithm with the pathfinder 1.2-m aluminum mirror in the thermal enclosure and repeat the test with the 1.5-m AMTD-2 ULE® mirror (Milestone #3) and correlate the test results with the high-fidelity model (Milestone #4).

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7. Havey, Keith, Harris Corporation, Private Communication, 13 March 2019.

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11. T.E. Brooks and R. Eng, “*1.5-m ULE® Cryo & Mechanical Test Results*,” Mirror Technology Days in the Government (2017)

12. Edwards, Mary J., *“Today’s ULE® Material of Choice for Premier Optics”*, Mirror Technology Days in the Government (2018)

13. Brooks, Thomas E, "Predictive thermal control applied to HabEx", Proc. SPIE 10398, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VIII, 1039814 (5 Sept 2017); doi: 10.1117/12.2274338; https://doi.org/10.1117/12.2274338

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16. Arnold, William R., H. Philip Stahl, "Design trade Study for a 4-meter off-axis primary mirror substrate and mount for the Habitable-zone Exoplanet Direct Imaging Mission", Proc. SPIE 10398, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VIII, 1039808 (5 September 2017); doi: 10.1117/12.2275193; http://dx.doi.org/10.1117/12.2275193

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