Predictive Thermal Control

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

Tech Days 2016

Predictive Thermal Control

Predictive Thermal Control (PTC) is a new 3 to 4 year Strategic Astrophysics Technology (SAT) grant.

The goal of PTC is to mature by at least 0.5 TRL step the technology needed for an exoplanet science thermally stable telescope. State-of-the-art (SOA) for ambient temperature space telescopes that are ‘cold-biased’ with heaters.

PTC driven by NASA Technology Need

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)."

PATR: to advance beyond TRL-3, "Significant technology development is needed to produce 'stable' isothermal or thermally 'insensitive' telescopes:

- Thermal design techniques validated by testing of components;
- Passive thermal isolation;
- Active thermal sense at the < 0.1mK level; and
- Active Thermal Control at the < 10 mK level.

State of Art: Passive

No previous telescope has ever required <10 pm per 10 min. stability.

- When JWST slews from its coldest to its warmest pointing, its temperature is predicted to change by 0.22K and its WFE is predicted to change by 31 nm rms. While not designed to do exoplanet science, it would take JWST over 14 days to ‘passively’ achieve <10 pm per 10 min. stability.

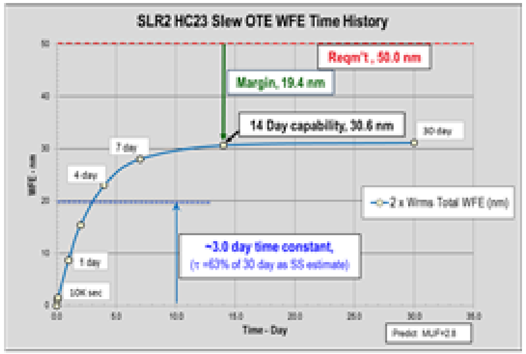


Fig 5: JWST thermal slew[23]

- HST is a cold-biased telescope heated to an uncontrolled ambient temperature. HST’s telescope temperature changes by nearly 20C per orbit. This change causes the structure between the primary and secondary mirrors to change (typically ±3 µm) resulting in WFE changes of 10–25 nm every 90 min (1–3 nm per 10 min.)

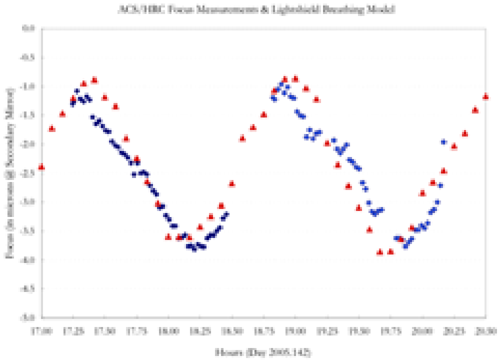


Fig 6: HST Orbit Focus[25]

Assuming linear performance, HST could be used for exoplanet science if its thermal variation were controlled to <20mK.

State of Art: Active Control

PTC partner Harris Corporation uses a ‘bang/bang’ thermal control system on its commercial NextView telescope. The NextView thermal control system telescope’s dead-band is ±300mK. The actual telescope temperature varies over a wider range (~±1K).

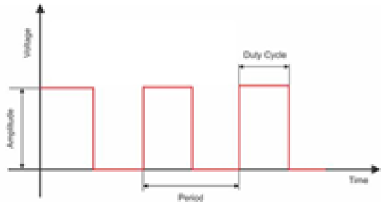


Fig. 8: Bang/Bang Control Cycle

Based on a detailed integrated model prepared for ACCESS Study (with NextView telescope), Krist predicted that after a12 hour settling time from a 30 degree rotation, the wavefront would have 151 pm rms of defocus and 19 pm rms of coma and astigmatism.

Thermal control has been improved with the introduction of proportional heater control. PTC partner Harris performed a study in support of the Eclipse program that predicted that proportional control could keep a 1.8-m telescope stable in the 200mK to 70mK range.

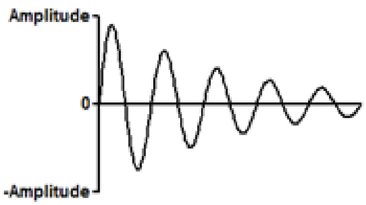


Fig. 9: Proportional Control

Predictive Thermal Control

PTC advances the SOA in thermal control by demonstrating a control logic called Model Predictive Control (MPC).

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.

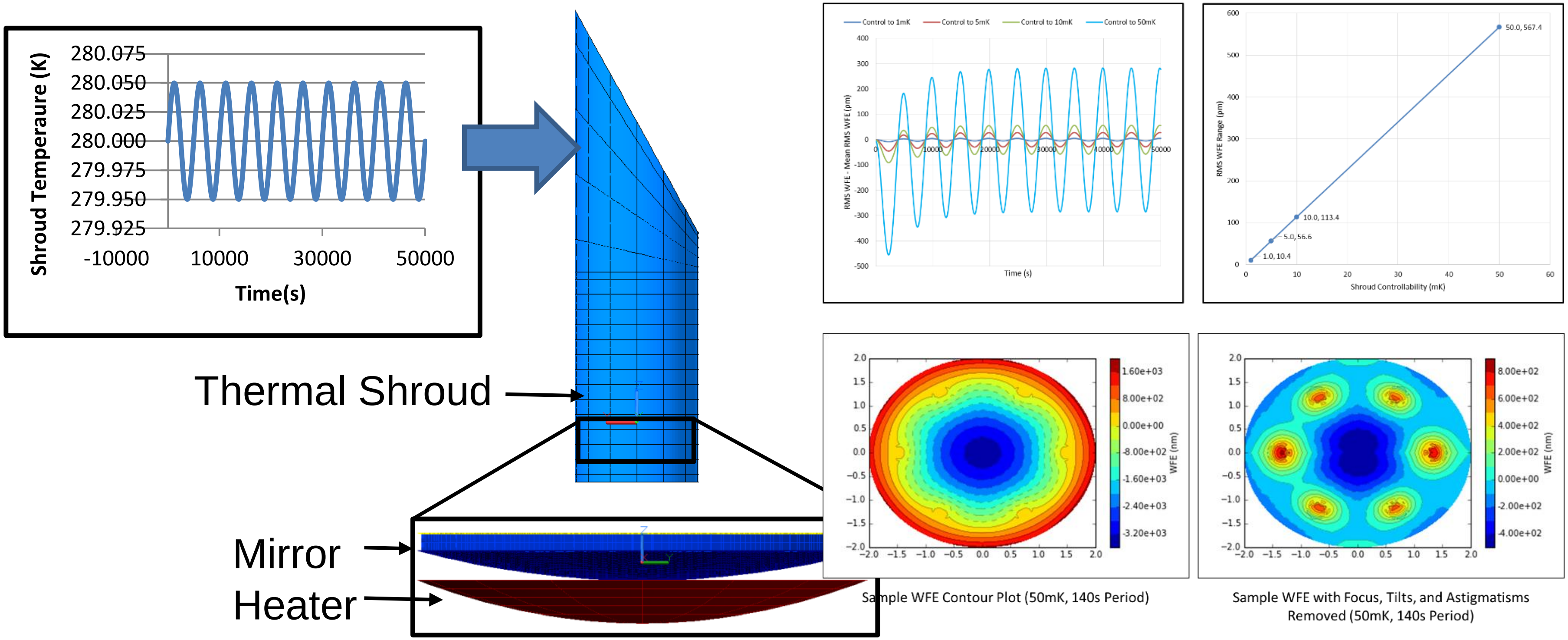
Proportional control adjusts heater power proportion to difference between measured & desired temperatures at one location.

MPC uses a system of equations based on the governing physics to back solve for the desired temperature distribution.

MPC takes into account the interdependency between all control zone’s temperatures and all control zone’s heater power.

Thermal Stability

- Primary mirror responds to dynamic external thermal load
- Required stability (10 pm per 10 min) can be achieved by controlling the telescope thermal environment.



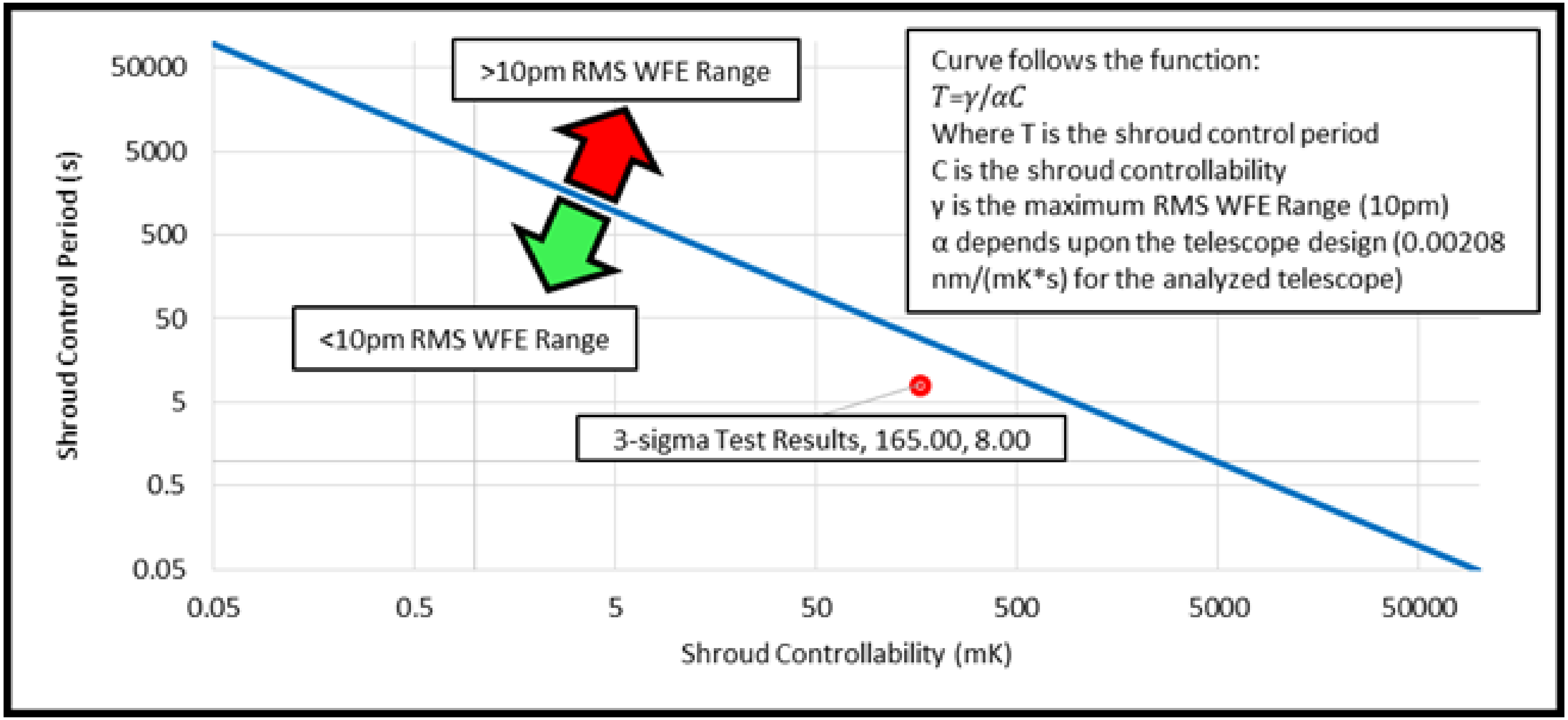
Sample WFE Contour Plot (50mK, 140s Period)

Sample WFE with Focus, Tilts, and Astigmatisms Removed (50mK, 140s Period)

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.



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)

Objectives

To mature Thermally Stable Telescope technology, PTC defines three objectives to develop “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. coefficient of thermal expansion (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.

Milestones

PTC has a detailed technical plan with 5 quantifiable milestones:

1. 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.
2. Derive specifications for thermal control system 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 the ~1mK level and actively controls the mirror's thermal environment at the ~20mK level.
4. Validate model by testing a flight traceable 1.5-m class ULE® mirror in a relevant thermal vacuum environment in the MSFC X-ray and Cryogenic Facility (XRCF) test facility.
5. 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.

PTC Test Configuration

PTC will be demonstrated by integrating the Harris 1.5m ULE® mirror with a heated forward baffle and a rear 'bath-tub' heater system. The forward baffle has axial and azimuthal control zones. The rear system has radial and azimuthal control zones.

PTC algorithm will be demonstrated inside the XRCF He environment with imposed 'solar' thermal loads.

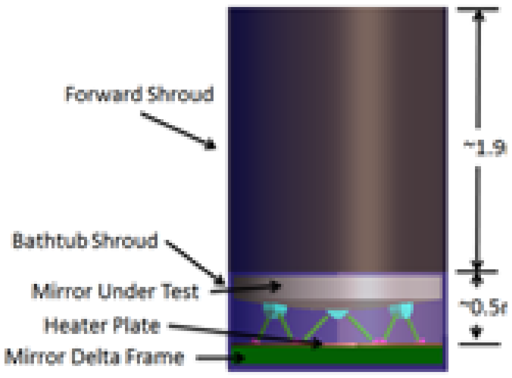
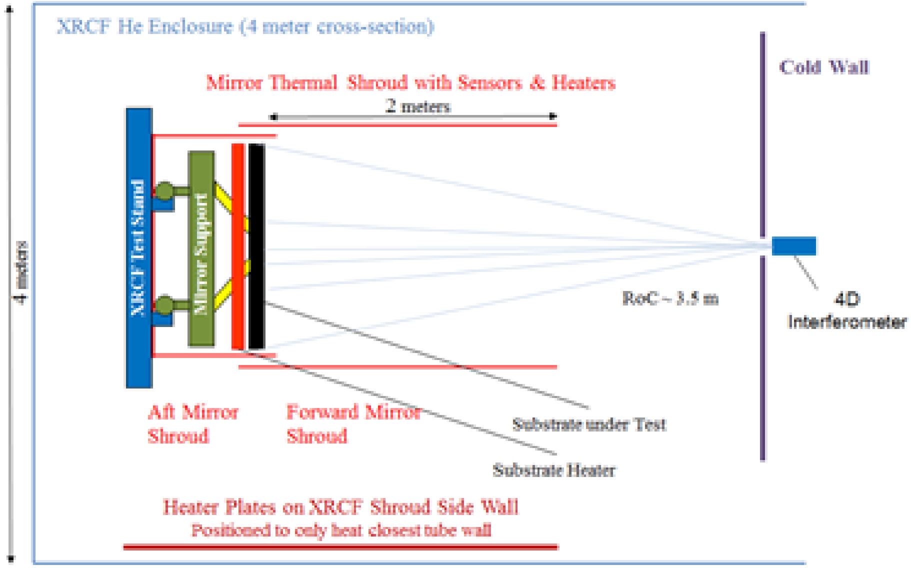


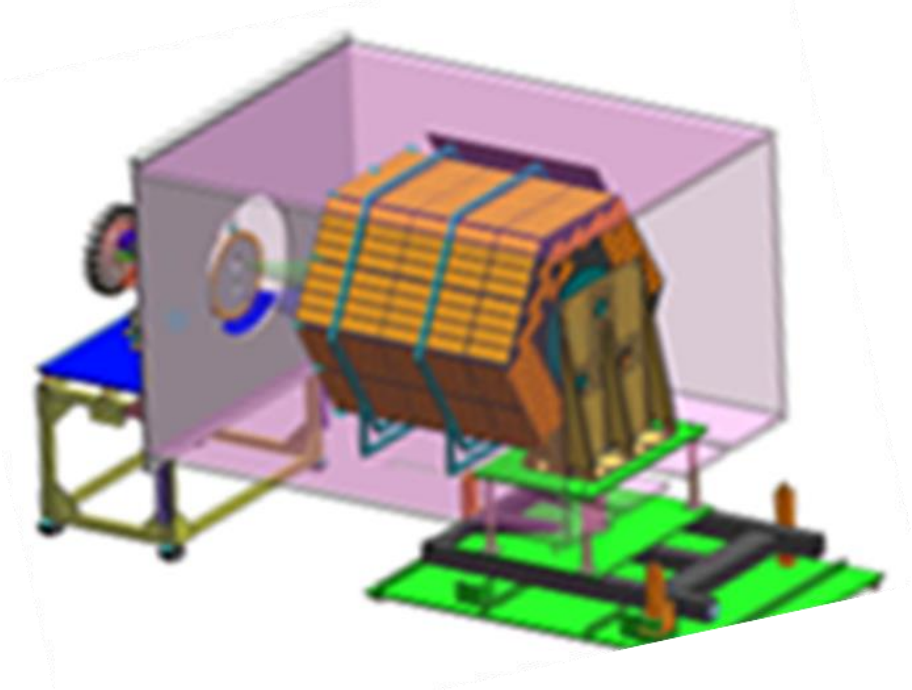
Fig. 14: Thermal System for AMTD-2

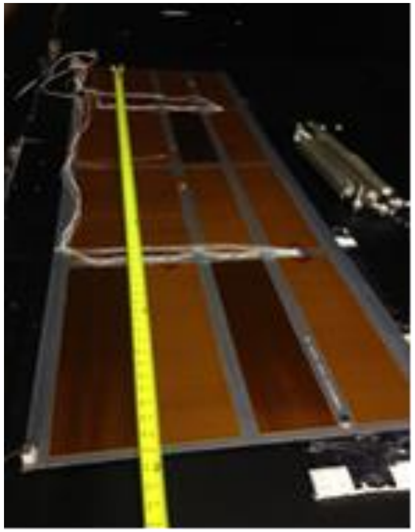


XRCF Capability

A key benefit of PTC is increased test capability at the XRCF.

To enable the ability to characterize a mirror's response to a dynamic thermal gradient, the XRCF will be upgraded to the ability to impose thermal gradients into mirror systems. We plan to use existing XRCF heater components.





Conclusion

PTC starts January 2017.