Wide-Field Infrared Survey Telescope (WFIRST) – Optical Telescope Assembly (OTA) Status

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ABSTRACT

The WFIRST Mission is the next large astrophysical observatory for NASA after the James Webb Space Telescope and is the top priority mission from the 2010 National Academy of Sciences' decadal survey. The WFIRST OTA includes the inherited primary and secondary mirrors with precision metering structures that are to be integrated to new mirror assemblies to provide optical feeds to the two WFIRST science instruments. We present here: (1) the results for the review of the inherited hardware for WFIRST through a thorough technical pedigree process, (2) the status of the effort to establish the capability of the telescope to perform at a cooler operational temperature of 265K, and (3) the status of the work in requirement development for OTA to incorporate the inherited hardware, and (4) the path forward.

Keywords: WFIRST, telescopes

1. INTRODUCTION

The NASA led, Wide-Field Infrared Survey Telescope (WFIRST) project is the next great observatory with the objective to address the basic science questions at the forefront of astrophysics:

- What is dark matter and energy?
- On a cosmic scale, what is the fate of the universe?
- Is our solar system special?
- Are the planets around nearby stars like those of our own solar system?
- How do galaxies form and evolve?

The WFIRST Project successfully passed the Mission level System Requirements Review in Feb, 2018 and is now in the early stages of Phase B. Unless otherwise stated, the content of this paper is based on Phase A models, analysis, and activities. Additionally, the project held an independent review in later half of 2017, and the WFIRST Independent External Technical/Management/Cost Review (WIETR) board report can be found here.[1] The Observatory is shown in Figure 1 and Figure 2 (a).

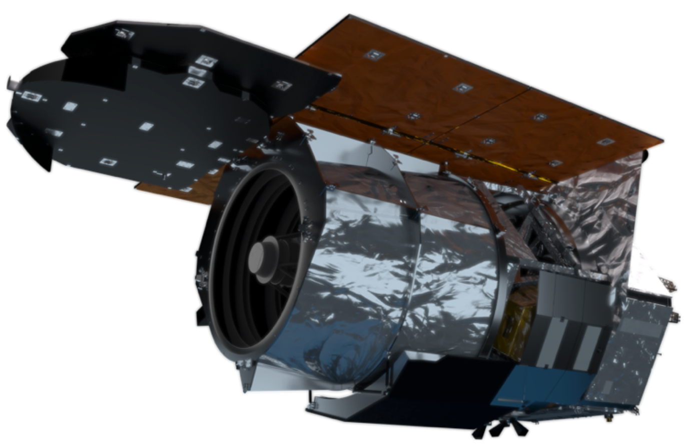
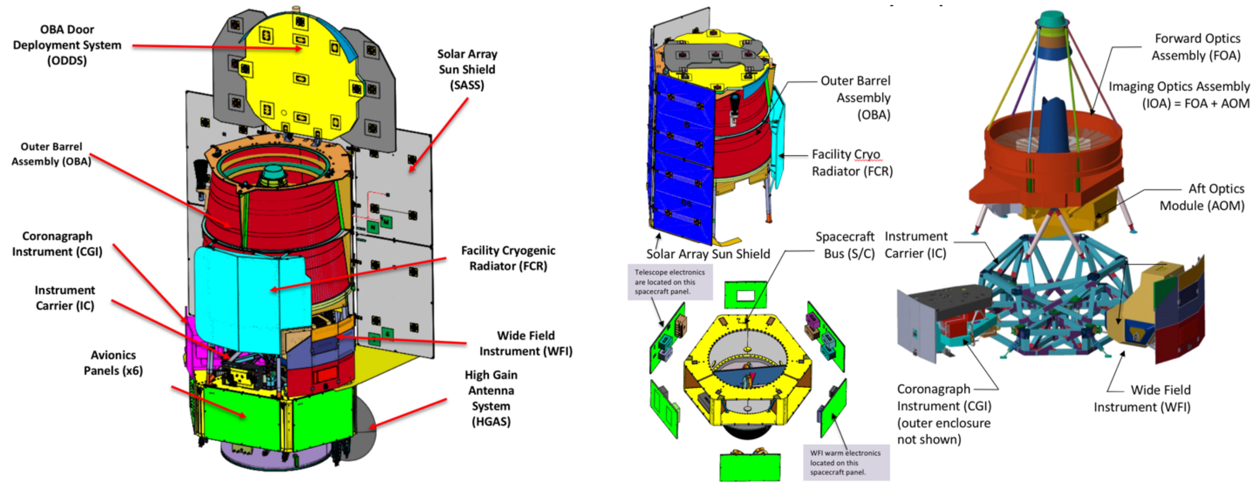


Figure 1: An artist rendition of the early phase B design of the WFIRST Observatory

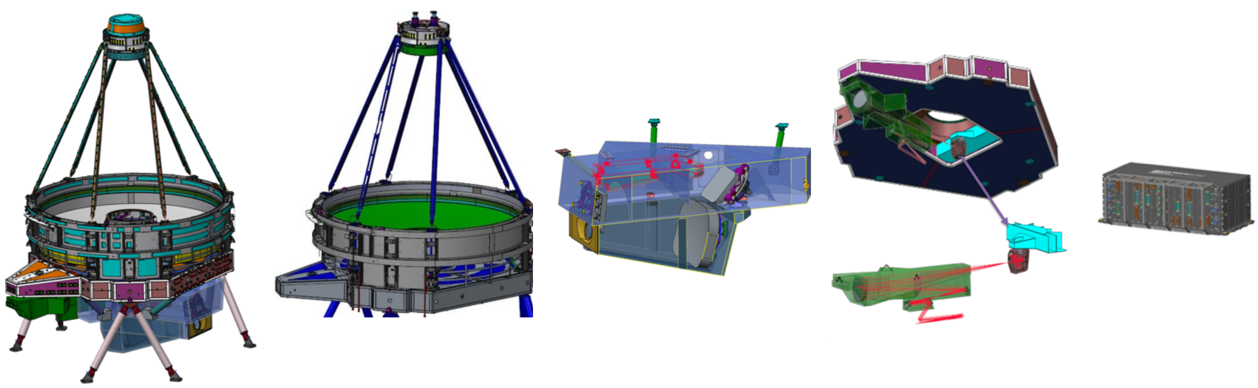
The WFIRST Payload consists of the Optical Telescope Assembly (OTA), two instruments - the Wide-Field Instrument (WFI) and the Coronagraph Instrument (CGI), and the unifying metering structure, the Instrument Carrier (IC), as shown in Figure 2 (c).



(a) (b) (c)

Figure 2: The Phase A design of Observatory in the (a) operational configuration, (b) spacecraft expanded view, and (c) payload expanded view.

The WFIRST OTA is a multi-mirror diffraction-limited imaging space telescope with a 2.4-meter diameter primary mirror with a three-mirror anastigmat (TMA) design to feed the WFI and a four-mirror design to provide a collimated light beam to the CGI. The OTA includes the complete integration of the flight hardware consisting of the Primary Mirror Assembly (PMA), a Secondary Mirror Assembly (SMA) and 6 SMA support tubes – which combines with the PMA to form the Forward Optical Assembly (FOA) - a tertiary mirror and structure in the Aft-Optics Module (AOM) for the Widefield Instrument (WFI), the Tertiary Collimator Assembly (TCA) for the Coronagraph Instrument (CGI), and the Telescope Control Electronics (TCE), which resides on the spacecraft. The Imaging Optical Assembly (IOA) is the opto-mechanical and thermal-electrical hardware, i.e. PMA, SMA, AOM, TCA, heaters, wires, etc. The OTA is the combination of the IOA and the TCE. The key pieces of hardware are shown in Figure 3.



IOA: Imaging Optical Assembly | Inherited Hardware FOA: Forward Optical Assembly | AOM: Aft-Optics Module | TCA: Tertiary Collimator Assembly | TCE: Telescope Control Electronics

Figure 3: The Phase A design of key pieces of the OTA hardware

WFIRST inherited two mirrors and supporting structure, specifically the PMA (Figure 4), SMA (Figure 5), and the secondary mirror support tubes (SMSTs) (not shown). The inherited hardware enables the WFIRST mission to achieve an additional 3x in collecting area and 2x resolution relative to the 1.3-1.5m telescope aperture designs around the 2010 Decadal time frame, and accommodates a second instrument, i.e. the exoplanet imaging coronagraph.

Figure 4: The inherited PMA

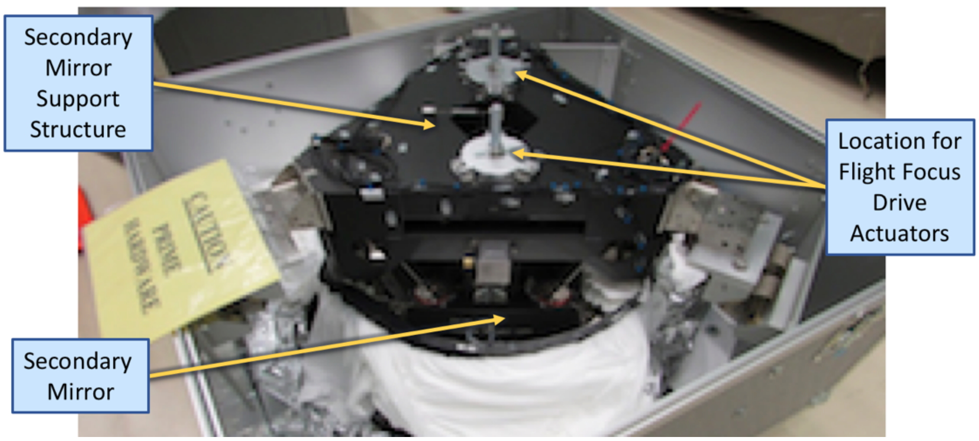


Figure 5: The inherited SMA

2. PEDIGREE AND INHERITED HARDWARE

The WFIRST project produced the first proof-of-concept design with the inherited hardware in 2012, and matured the concept further with a detailed study in 2013.[2] Since then, the project has made multiple iterations with the design team to develop a mature Phase A design. In parallel, the team performed an extensive pedigree assessment of the inherited hardware. The pedigree assessment included the following: (1) thorough evaluation of historical records, including build books, drawings, parts lists, non-conformance reports (NCR), failures, etc. (2) additional testing of the hardware for chemical analysis, coupon testing, corrosion, strength and load testing, thermal testing, etc., (3) subject-matter expert assessment and evaluation, and (4) documentation and organization of the findings in compliance with NASA and WFIRST standards. The reuse of heritage hardware of this magnitude for flight missions has limited history at GSFC, and poses issues and potential problems not usually addressed in GSFC processes. The governing document, Goddard Procedural Requirement (GPR) 8730.5[3], provided guidance. Additionally, due to the very complex nature of this heritage hardware, a more robust and comprehensive approach was used for the evaluation. The WFIRST team completed and passed an independent review of the project's assessment of the pedigree in May, 2016 – all actions are closed.

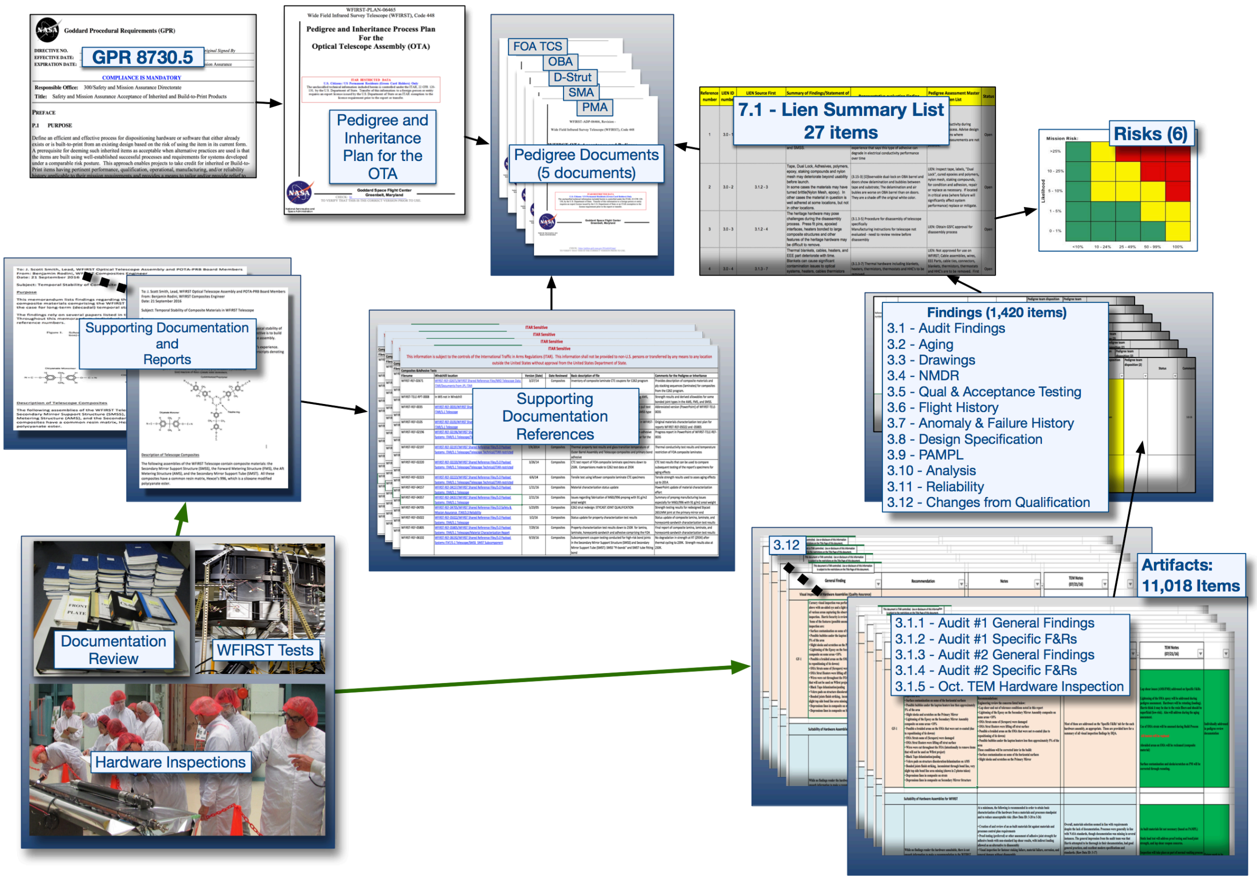


Figure 6: The Pedigree Assessment Flow

In following the GPR[3], the WFIRST team was able to bring flight hardware into the flow of the normal Goddard process; and did not preclude any elements of environmental test for acceptance, in particular to verify workmanship. In following the steps above, and outlined in Figure 6, the team was able to reduce the assessment from artifacts, to findings, then liens, and lastly, risks, using the following definitions:

- Artifacts: audit results, inspection results, drawings, parts and materials list, technical reports, documentation, etc.
- Findings: items that could affect the pedigree of the hardware and is pertinent to WFIRST, grouping similar Artifacts of the same item, remove "do not use" by item.
- Liens: grouping of similar findings of related groups, remove "do not use" by group, grouped by assembly
- Risks: Liens that are not retired by normal processes. Cross the threshold of GSFC's risk criteria (very low likelihood, very low consequence)

The summary of the Pedigree Assessment can be found in Table 1. The key take away is the project has performed an extensive review of the hardware and documentation and has reduced the extensive volume of artifacts to key risks that can be carried through and evaluated during the development and build of the WFIRST flight hardware.

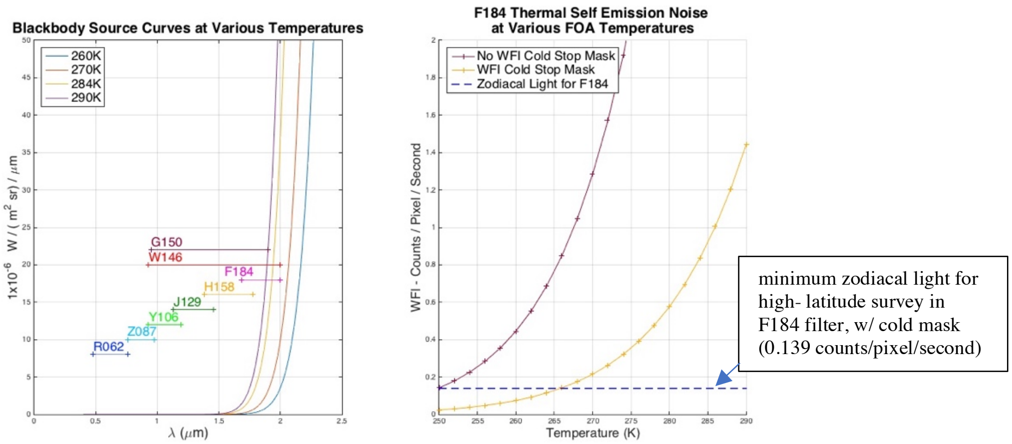
Table 1: Inherited Hardware Pedigree Assessment Summary

Section	Artifacts	Findings	CLOSED	Liens and Action Items	Risks
Audit Findings	181	40	28	12	3
Aging Assessment and Lifetime Analysis	1462	373	371	2	
Drawing and Assembly Prints	2734				
Deviations NCR's and waivers	5045	38	36	2	
Summary results of qualification, or acceptance testing					
Flight History					
Anomaly and Failure History	613	11	7	4	1
Design Specifications and Standards	2	2	0	2	2
Parts, Materials and Processes List, Material Usage Agreements, and NSPARs	793	768	766	2	
Analyses Performed					
Reliability Analyses	3	3	3		
Changes from Qualified Unit					
Disposition list	185	185	183	2	
Total	**11,018**	**1,420**	**1,394**	**26**	**6**

3. OPERATIONAL TEMPERATURE

The inherited hardware for the OTA was designed for a thermal environment near room temperature, 293K, with minimum survival to 284K. The WFIRST science wavelength cutoff can be extended with a colder operating temperature than the original design of the inherited hardware, resulting in better signal-to-noise for fainter red-shifted object and overall better science return. Operating at a colder temperature provides marginal gains in the overall observatory power consumption and improves the thermal interface to the rest of the observatory – independent of the telescope temperature, the WFI detectors operate at ~100K. Choosing a temperature outside of the original operating range causes programmatic impacts, namely rework or possibly replacement of some of the Telescope structures, and re-figuring of the Primary Mirror to have the proper shape at its operating temperature. The WFIRST project has spent significant time and resources to assess and quantify the impact of various operational temperatures – which includes the feasibility of the various temperature options. The current baseline and model predictions are ~260K Primary Mirror, 269K Secondary Mirror, and 216K Tertiary Mirror. The Telescope temperature capability study assessed hardware integrity, science performance, and additional resources (programmatic and spacecraft power) that would be required for cool operation – and is summarized below.

WFIRST is a near-infrared mission, with the objective of detecting light to 2.0 µm in the Wide-Field Instrument (WFI).[4][5] Near-infrared light is blocked by the Earth's atmosphere, and thus, an astronomical telescope, above the atmosphere, can measure fainter objects that are further red-shifted. These measurements enable the WFIRST Observatory to complement current and planned ground-based experiments. To take full advantage of the L2 orbit, the telescope and WFI must minimize the thermal-self-emission (TSE), and thus the operational temperature, in order to balance various noise sources in the signal-to-noise budget. Figure 7 (a) shows the black-body curves at various temperatures for the WFI filters, and the TSE noise for the F184 filter. The WFI baseline design includes a cold stop mask, which improves the signal-to-noise, yet there are additional gains required to balance TSE noise with Zodi noise. Figure 7 (b) shows the Zodi noise and TSE noise for the baseline design are equal at ~266K and the TSE is roughly 6x the Zodi at 284K, thus supporting a strong case for a colder telescope. There is negligible impact for WFI science below wavelengths of 1.5 µm and for the Coronagraph Instrument (CGI).



(a) (b)

Figure 7: Thermal Self Emission Noise at various Forward Optical Assembly (FOA) temperatures.

The inherited hardware was designed to operate at 293K. As such, deviations from this temperature can stress the system resulting in changes in performance. For example, some of the technical challenges include, (1) the composites, struts, and other opto-mechanical structures are optimized for a near zero coefficient of thermal expansion (CTE) for the original operational temperature, (2) the challenge in meeting wavefront error requirements for the primary and secondary mirrors increase as temperature decreases, and (3) the thermal management system and the Hybrid-Heater-Controllers (HHC) are hard-wired to turn-on at a specific temperature that cannot be changed without replacing the HHCs.

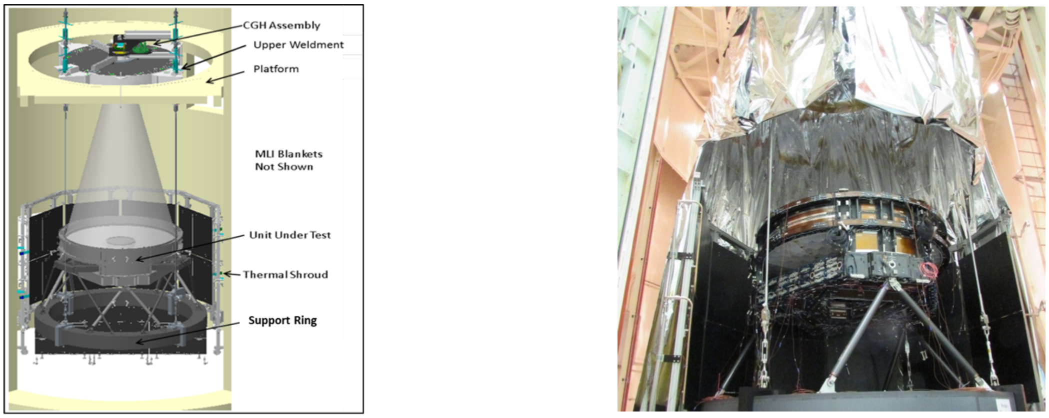
The Telescope temperature capability study assessed integrity, performance, and additional resources that would be required for cool operation. Integrity refers to the ability of the Telescope to withstand static and dynamic structural loads as well as the ability to handle thermo-elastic stresses, which is discussed elsewhere in these proceedings.[6] Performance refers to various parameters by which the telescope is assessed. Resources refers to additional costs, power, etc. associated with reworking the telescope design for an operating temperature below 293K, impacts to the telescope integration and test schedule, and the amount of mission resources needed such as electrical power to heat the telescope.

The planned engineering activities in the evaluation of the operational temperature telescope included the following, with most topics discussed elsewhere[6]:

- Material characterization
- Thermal cycling and static load testing of 1/3 development model of Aft Metering Structure and Forward Metering Structure
- Subcomponent testing of the secondary mirror support structure fittings
- Static load testing of the SMST's after thermal cycling
- Analysis of the optical performance of the Telescope with temperature dependent material properties
- Analysis using bond joint models with measured material properties to assess structural margins
- Random vibe testing of the secondary mirror assembly after thermal cycling
- Analysis of actuator components at temperature for potential rework
- Final analysis of the optical performance of the Telescope with temperature dependent material properties
- Cool optical test of flight Primary Mirror

The project followed a methodical flow which prioritized work to ensure a prudent use of project resources.

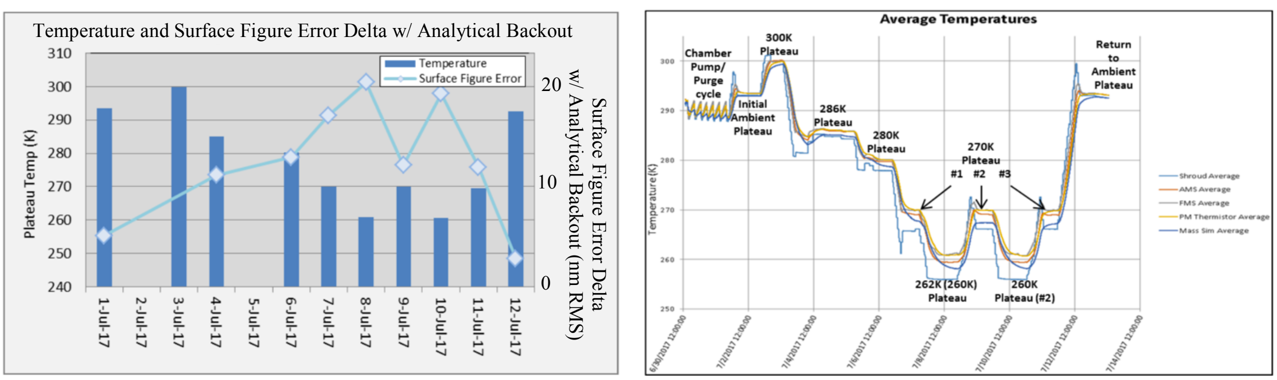
One of the more significant tasks in the planned activities is the Cool Test of the flight PMA. The Cool test of the flight primary mirror was one of the last activities due to programmatic resources and possible risks to the flight hardware. During the test, the PMA was predominantly unchanged with the primary mirror figured with the heritage program prescription and heritage PM struts. The test was conducted between 13 June and 7 August 2017, with the main objective to assess the performance impact of having the Primary Mirror (PM) operate at the nominated telescope operating temperature of 260K. The test configuration is shown in Figure 8. The test was conducted at Harris in building 101 Chamber IIIA under soft vacuum in the range of 1-10 Torr, interferograms were collected of the Primary Mirror across a temperature range of 260K to 300K with the test beginning and ending with optical data collection at ambient temperature and pressure. Shown in Figure 8(a) is the test configuration, and in Figure 8(b) is the flight PMA inside the chamber, prior to close-out at the start of the test.



(a) (b)

Figure 8: (a) Cool Test configuration and (b) PMA in Chamber IIIA prior to test

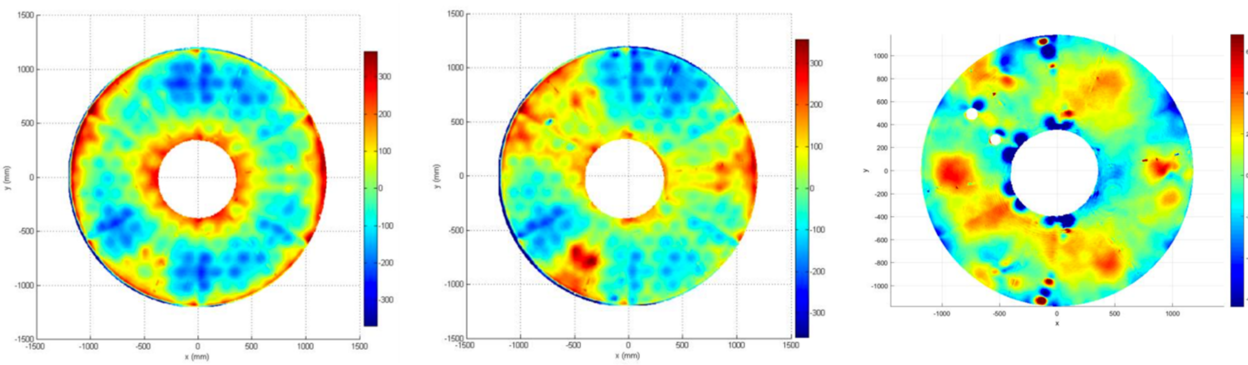
The Cool Test was conducted using an interferometer configured with a thermally stabilized hologram on the optical test assembly. The hologram was mounted near the center of curvature of the Primary Mirror (PM), and was used to back out the nominal prescription and gravity, as predicted using a Finite Element Model (FEM) of the PMA. The test temperature profile is shown in Figure 9. Coincident with the ongoing thermal data collection, interferogram images were captured at temperature plateaus and transitions in between each temperature plateau as illustrated in Figure 9 (b).



(a) (b)

Figure 9: (a) Cool Test Summary of Temperature and Surface Figure Error Deltas from 300K and
(b) Cool Test As-Run Average Temperature Profile

The key results are shown in Figure 10, which is the directly measured wavefront for (a) ambient at 293K, (b) the cool temperature surface map at 260K, and (c) the delta between the two measurements with analytical backouts. As stated, the test was performed with non-flight PM struts, which were optimized for a 293K operational temperature. This caused complications in directly measuring the changes in wavefront error for the PM, and the team performed a series of analysis steps to remove this non-flight signature from the delta. Furthermore, the delta map removes some of the anomalies in the data due to thermal hardware on the glass. The project is working a redesign of the struts and mounts to optimize performance for the WFIRST operational temperature. The delta surface map in Figure 10(c) is 22 nm RMS surface, which substantiates through test, the need for cool figuring the PM for the WFIRST prescription.



(a) Measured surface map at 293K

(b) Measured surface map at 260K

(c) Delta surface map after analytical backouts

Figure 10: Measured surface maps and the Ambient to Cool surface map delta after analytical backouts

4. REQUIREMENT FLOW DOWN

The WFIRST planned science surveys program and system design offer groundbreaking and unprecedented survey capabilities to the Dark Energy, Exoplanets, and Astrophysics communities. In support of this, NASA has defined the science objectives, mission success, and the level 1 science and technical requirements. From this, the project defines the level 2 science and mission requirement documents. In further refinement and requirement flow-down, the team defines the level 3 requirements for the instruments, spacecraft, and the telescope. The complete set of OTA requirements are defined and will be presented at the OTA System Requirements Review in the summer of 2018.

The key OTA requirements are show in Table 2 and Table 3. The OTA design, as shown graphically in Figure 3, complies with these requirements. In some instances, given the state and capability of the existing hardware, some waivers, to be handled on a case-by-case basis will be needed. The baseline design to meet these requirements is Technology Readiness Levels (TRL)-6 or higher.

Table 2: Key OTA Requirements for Wide Field Science

OTA L3 Requirement	Evidence
<u>Existing Hardware</u> Use of the existing hardware	Pedigree assessment and review. Cool test of representative hardware approves use of existing FOA.
<u>Signal-to-Noise</u> OTA Subsystem Temperature Range Surface Roughness Coating Specification Stray Light Baffles	Cool test and history of comparable optical and baffle fabrication

Image Quality & Stability Total WFE Exposure Stability Wavefront Sensing Alignment	Budget are drafted for all error contributors comparable to similar telescopes, wavefront error, signal-to-noise, alignment, etc. Re-use hardware figured to original drawing tolerances. The PM and TM cool figured – i.e. tested at operating temperature between the final stages of surface figuring.
Prescription Payload Prescription	All OTA mirrors have been quoted and are manufacturable. PM and SM re-figuring is planned.
Common Alignment Simultaneous Instrument Operations AOM F1 Mirror Actuation TCA F2 Mirror Actuation IFC ROA F2 Mirror Actuation	All channels contain one independent actuated mirror. Actuator concepts similar to other missions.

Table 3: Key OTA Requirements for Coronagraph Technology

OTA L3 Requirement	**Evidence**
Exit Beam Position & Stability Radial Shear Tolerance Pupil Clocking Uncertainty Pupil Diameter Pupil Shear Stability Pupil Obstruction Design File Deliveries	Factory-to-orbit STOP analysis of OTA model with alignment plan and measurement uncertainty from similar systems show margin.
Image Quality Total WFE Measurement WFE Stability Weighted Rate of WFE Change PSD Limits of Surface Figure	Budget drafted for all error contributors comparable to similar telescopes. Includes design residual.

5. SUMMARY AND PATH FORWARD

The WFIRST project is now at the start of Phase B, and the OTA is on the path to PDR. The inherited hardware has been thoroughly vetted for use on WFIRST via the pedigree review process, a greater than 2 year effort, which was discussed in section 2. The OTA team has completed a significant effort of greater than 3 years to establish the capability of the telescope to perform at 260K, which was discussed in section 3. The key and driving OTA requirements are understood, and all technology TRL-6 or greater.

In the coming years, the OTA team will be maturing the design and further refining the requirements flowed to lower levels of assembly. The Payload team is nearly complete with the optical prescription re-optimization to close the aft optics packaging liens that were discovered in Phase A. The project will further refine error budgets and review these for OTA requirements flowdown. The project will continue to mature the concept of operations, which is key to develop the opto-mechanical and thermal stability control methodologies. Finally, the OTA team will be performing a multiorientation horizontal test of the existing PMA as a pathfinder to the horizontal test that will be run to verify gravity backouts and zero-G performance during the build of the flight WFIRST PMA.

ACKNOWLEDGEMENTS

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