

Wide Field Infrared Survey Telescope (WFIRST) Observatory Overview

ABSTRACT

NASA's Wide Field Infrared Survey Telescope (WFIRST) is being designed to deliver unprecedented capability in dark energy and exoplanet science, and to host a technology demonstration coronagraph for exoplanet imaging and spectroscopy. The observatory design has matured since 2013^[1]; we present a comprehensive description of the observatory configuration as refined during the WFIRST Phase-A study. The observatory is based on an existing, repurposed 2.4m space telescope coupled with a 288 megapixel near-infrared (0.6 to 2 microns) HgCdTe focal plane array with multiple imaging and spectrographic modes. Together they deliver a 0.28 square degree field of view, which is approximately 100 times larger than the Hubble Space Telescope, and a sensitivity that enables rapid science surveys. In addition, the coronagraph technology demonstration will prove the feasibility of new techniques for exoplanet discovery, imaging, and spectral analysis. A composite truss structure meters both instruments to the telescope assembly, and the instruments and the spacecraft are flight serviceable. We present configuration changes since 2013 that improved interfaces, improved testability, and reduced technical risk. We provide an overview of our Integrated Modeling results, performed at an unprecedented level for a phase-A study, to illustrate performance margins with respect to static wavefront error, jitter, and thermal drift.

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INTRODUCTION

The Wide Field Infra-Red Survey Telescope (WFIRST) Mission Study has been previously described at the mission level in detail¹. The purpose of this paper is to refresh this previously published overview with details of configuration changes adopted during the recently completed WFIRST Phase-A study.

WFIRST relies on the reuse of an existing 2.4M aperture Forward Optics Assembly (FOA) donated to NASA by another agency in 2013. The FOA consists of the first two mirrors of a three-mirror Anastigmat² optical form along with their supporting structure. With only minor modifications to this existing FOA hardware, WFIRST will enable wide area multi-band NIR surveys via imaging and spectroscopy to explore the expansion history of the universe, investigate the growth of large scale structures within the universe, and perform a microlensing survey to discover and catalog extra-solar planets within our galaxy. In addition, WFIRST will accommodate a technology demonstration of a starlight suppression coronagraph enabling direct imaging and spectroscopy of exoplanets and debris disks. Scheduled for launch in 2025, WFIRST will fly in a Sun-Earth L2 orbit with a mission life of 5 years.

Recent program milestones include:

- WFIRST Science Investigation Teams (SITs) selected December 2015
- Completed KDP-A in February 2016
- Completed Wide Field Opto-Mechanical Assembly (WOMA) Phase-A studies in May 2017
- TRL-6 on WFI H4RG detectors achieved December 2016
- Coronagraph testbed achieved dynamic contrast of 10⁻⁸ in Jan 2017

This paper will present an overview of the WFIRST Phase-A configuration, summarize three key innovations resulting from our Phase-A study, and document integrated modeling results performed in support of these changes. The three configuration modifications include:

1. The implementation of an Instrument Carrier structure to meter the WFI and Coronagraph independently of the donated FOA structure.
2. The relocation of the tertiary mirror from the WFI to the Optical Telescope Assembly (OTA).
3. The change from active to passive cooling for the ~100K WFI focal plane assembly.

As will be seen, the combined efforts of the WFIRST team in Phase-A on these key trades have resulted in significant risk reduction for the WFIRST program.

WFIRST OBSERVATORY OVERVIEW

The WFIRST Observatory consists of an Integrated Payload Assembly (IPA; see Figure One) and a Spacecraft (S/C). As will be discussed below, the IPA consists of components of the Optical Telescope Assembly (OTA), an Instrument Carrier (IC), components of the Wide Field Instrument (WFI) and the Coronagraph Instrument (CGI). A Hardware Breakdown Structure for the WFIRST is shown in Figure Two.

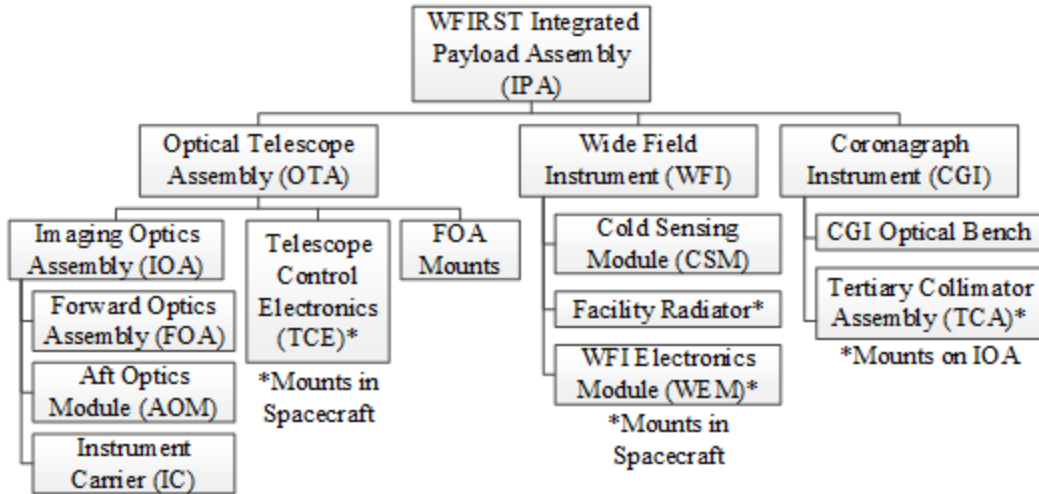


Figure One: WFIRST Hardware Breakdown Structure

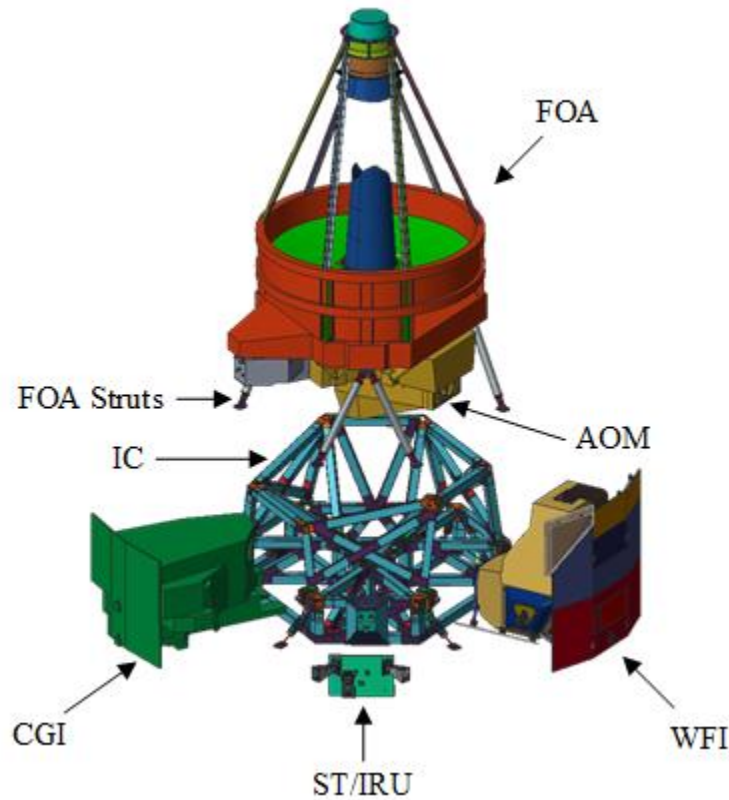


Figure Two: The WFIRST Integrated Payload Assembly (Expanded View)

The OTA consists of the donated Forward Optics Assembly (FOA) integrated with an Aft Optics Module (AOM) and supported by the Instrument Carrier (IC) via FOA mounts. The OTA is controlled by its Telescope Control Electronics (TCE) mounted within the WFIRST Spacecraft. Functionally, the first two optics of the OTA's three mirror anastigmat imaging system is in the common path for all WFIRST science modes. The existing FOA will undergo a minor optical prescription change for the WFIRST mission via optical re-polishing. The passively isolated FOA Mounts and the AOM are new hardware

specifically designed for WFIRST. As a result of one of the trades described in this paper, the Tertiary Mirror of the three mirror Anastigmat is now mounted in the AOM instead of the WFI. A functional block diagram of the WFIRST payload is illustrated in Figure Three.

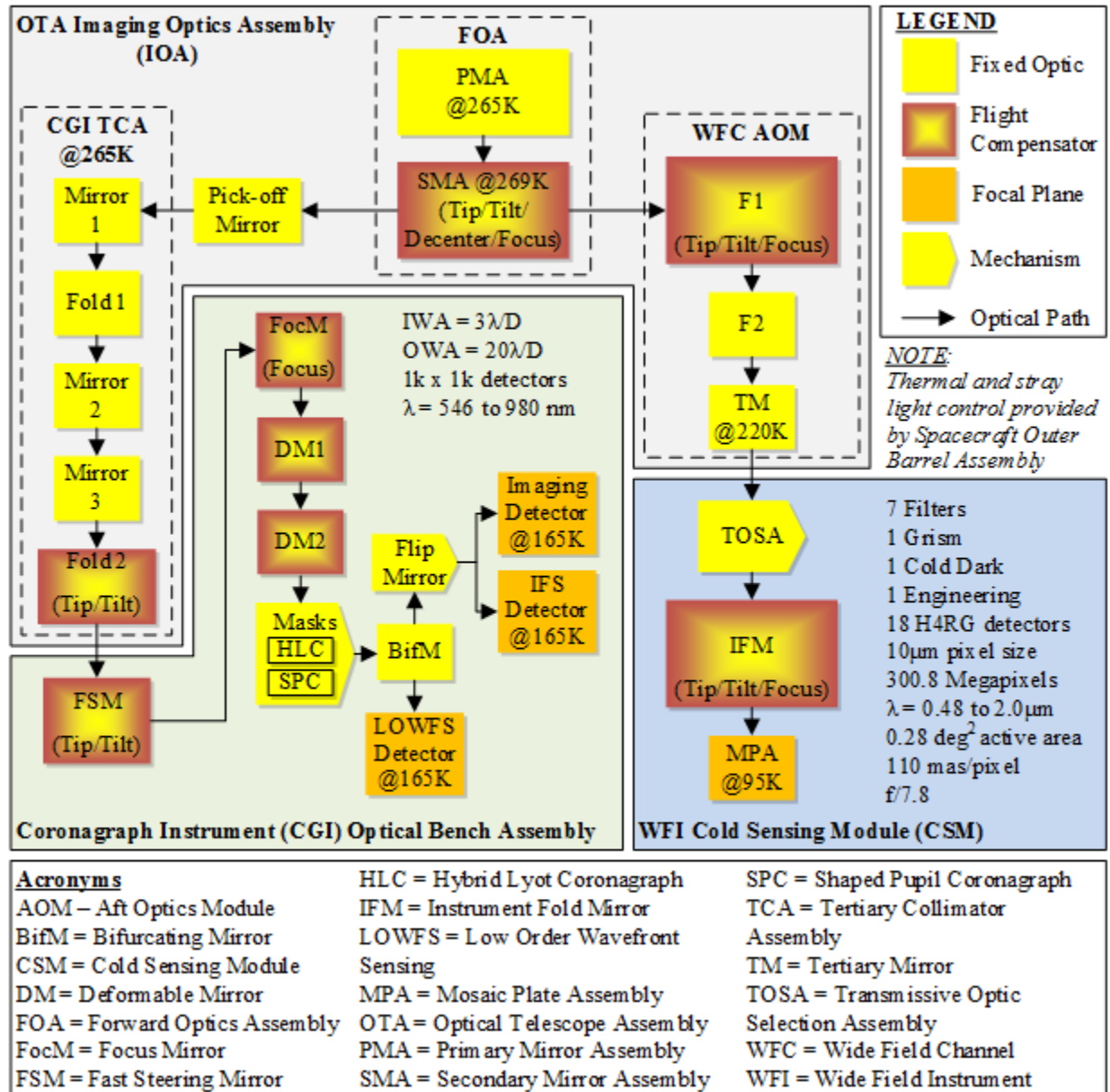


Figure Three: WFIRST Payload Functional Block Diagram

As shown in the block diagram, numerous on-orbit optical compensators are available to ensure the WFIRST Payload meets on-orbit alignment, optical quality, and long term optical stability requirements. The FOA secondary mirror provides a five degree-of-freedom rigid body adjustment capability. In the WFI channel the IFM provides alignment and focus adjustment, enabling on-orbit focus diversity phase retrieval during Observatory commissioning and as required thereafter.

The flight serviceable WFI consists of a Cold Sensing Module (CSM), a Warm Electronics Module (WEM) mounted within the spacecraft (not shown), and a Facility Cryogenic Radiator (FCR) mounted to the Spacecraft's Outer Barrel Assembly (not shown). All optical functions of the WFI are contained within the CSM.

The Transmissive Optics Selection Assembly (TOSA) consists of 10 selectable modes; seven filters covering 0.48 to 2.00 microns, a grism for spectrographic studies, a cold dark for calibration, and an engineering filter used for ground AI&T.

The Coronagraph Instrument (CGI) consists of the flight serviceable Optical Bench Assembly (CGI-OBA) and the Tertiary Collimator Assembly (TCA). The TCA optically and mechanically interfaces with the FOA to provide a collimated (infinite conjugate) input to the CGI. The TCA mounts directly to the FOA, and is hence not flight serviceable.

INSTRUMENT CARRIER

Early in the pre-Phase A study it was quickly realized that the combined launch loads of the WFI and CGI would exceed the heritage design capability of the donated telescope. Various configurations of an Instrument Carrier (IC) to meter the WFIRST instruments off the spacecraft deck were subsequently traded. Our selected IC architecture (Figure Four) leverages GSFC recent experience with the James Webb Space Telescope Integrated Science Instrument Module (ISIM) structure. The IC accommodates the IOA, WFI, CGI, and the Spacecraft's Star Tracker/Inertial Reference Unit via flight serviceable mounting interfaces (Figure Two).

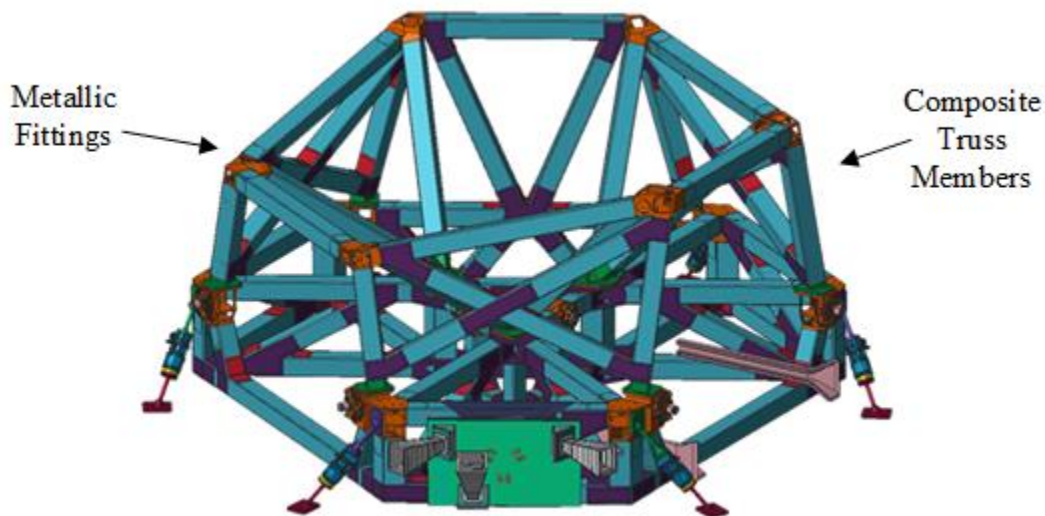


Figure Four: The WFIRST Instrument Carrier

The IC is kinematically mounted to the WFIRST Spacecraft and consists of a carbon fiber/cyanate ester composite (M55J/954-6) truss assembly to achieve high levels of structural strength and stability in a lightweight structure. This is the same material used for the JWST ISIM, with the same lay-up but with some of the composite tubes having a larger OD. Truss members are joined with a combination of titanium fittings and composite gussets and clips; again with design heritage in the JWST/ISIM; however WFIRST will use titanium fittings in lieu of invar to conserve mass. Analysis has shown that titanium works at expected IC temperatures throughout the WFIRST mission, and our analysis will be augmented

by test articles currently in fabrication. Dynamic isolation of the IC from the Spacecraft is achieved using Honeywell D-struts.

WFI OPTICAL INTERFACE

In the original WFIRST concept presented in 2013 (Ref. 1, Content, op. cit.) the third mirror of the three mirror anastigmat was mounted within the WFI assembly for the Wide Field Channel (AKA the WFC AOM TM in Figure Three). When the WFI was moved off of the OTA and into the IC, analysis revealed an increased sensitivity to observatory thermal and dynamic perturbations due to the metering of the WFC TM independently of the OTA. Trades (Ref. 2, Pasquale, op. cit.) supported the decision to reduce risk by moving the WFC TM out of the WFI and back to the OTA.

Key outcomes of the move of the WFC TM from the WFI to the OTA included reduced OTA to WFI alignment tolerances, simplification of Payload AI&T by establishing a test point in the AI&T flow that allowed double pass interferometry of the entire image formation system (“test-as-you-fly”), and the elimination of costly support equipment intended to compensate for the absence of the TM during Payload AI&T. However, the most important outcome of the WFC TM move was not initially anticipated. The packaging of the OTA and WFI now allowed for the positioning of the WFI Mosaic Plate Assembly (AKA the WFI’s 95K focal plane) much farther outboard towards the anti-sun side of the Observatory. It was quickly realized that this could enable the largest risk reduction achieved for WFIRST since 2013, the elimination of the Observatory’s cryo-cooler in favor of passive cooling of the WFI cold electronics.

PASSIVE COOLING TRADE

The use of passive cryo-cooling to operate the WFC and IFC SCAs at ≤ 100 K was first seriously considered when the WFIRST mission orbit was changed from GEO to L2 in 2015. That change was based primarily on considerations related to SCA radiation tolerance, but it also afforded the mission with a more stable thermal environment. In particular, it offered the possibility of a true cold side of the observatory that would only be exposed to deep space.

Mechanical Cryo-cooling (MC) using a NICMOS-heritage Turbo-Brayton system was the baseline at the time, primarily due to the extremely low vibration of its non-reciprocating design, the ability of its heat transfer lines to provide cooling to focal planes located deep within the Payload, the tolerance of the high temperature (nearly room temperature) MC radiator to GEO thermal loading variations, and the relatively high technological maturity of the planned implementation.

With the move to L2, a trade was conducted to evaluate the MC concept against Passive Cryo-cooling Systems (PCS) employing either cryo heat pipes or traditional thermal straps. The recommendation at the time was to retain the MC concept, as the cryo heat pipes were a less mature technology, and the temperature gradient in the thermal straps given the inboard location of the SCAs was too large to allow an acceptable cryo radiator size. However, it was specifically noted in the trade closure that a PCS option could be reconsidered if the SCAs could be located closer to a PCS radiator, and the telescope outer barrel assembly could be made to support a large (~ 9 m²) PCS radiator, and/or the SCA operational temperature could be increased to ~ 120 K.

The optical redesign activity to relocate the WFC TM offered the possibility of developing and evaluating configurations that would also move the SCAs radially outboard, much closer to the potential location of a PCS radiator (dubbed the Facility Cryogenic Radiator, or FCR, which would remain as part of the

observatory if/when the WFI were changed out during servicing). When this SCA relocation proved practical, the mechanical vs. passive cryo-cooling trade was reopened and resulted in a change from MC to PCS SCA cooling. The primary advantages of the PCS concept were the unlimited life and zero intrinsic vibration, and the lower cost and complexity relative to MC.

It was realized that the PCS concept needed time to mature, so the MC and PCS options were carried in parallel for ~9 months in case unanticipated PCS issues were discovered. The new optical design was specifically chosen to be compatible with either a MC or PCS approach, enabling a change back to MC later in Phase A, should it be needed. Fortunately, the PCS design has remained robust, with parasitics margins fluctuating in the 110% to 130% range despite a lowering of the SCAs operational temperature from 100 K to 95 K (to improve SCA production yield), and a reduction in the size of the FCR from its original 9.5 m² to its current 7 m².

1. INTEGRATED MODELING RESULTS

Integrated Modeling (IM) is analysis that includes multiple disciplines and uses a flight observatory model to provide end-to-end perturbation to performance predictions. The WFIRST Project has developed the IM processes and capabilities in the last several years to validate requirements that cannot be verified by test on the ground. The tool is also used to support system-level trades by performing observatory performance evaluation for different proposed designs. During Phase A of the mission, the IM analyses focus on the thermal elastic effects due to ground-to-orbit and on-orbit temperature changes which distort structures and lead to optical alignment and surface figure errors, and the mechanical vibration effect that is generated from the spacecraft reaction wheels and propagated through the observatory structure which also degrades the optical performance.

For thermal distortion mitigations, WFIRST employs a thermal control system with proportional heaters on the optical telescope assembly. For reducing jitter disturbances, WFIRST implements a two-stage, passive vibration isolation system, where the first stage is co-located with the reaction wheels, and the second stage is between the spacecraft and payload interface. In order to maintain stable performance, WFIRST plans to avoid moving any mechanisms (e.g. spacecraft high gain antenna actuators and instrument filter wheel) during science exposures. All other errors due to long-term material changes or dry-out effects can be compensated by flight alignment actuators as necessary.

The key stability requirements for the WFIRST Wide Field Instrument and Coronagraph Instrument (CGI) are summarized in Table 1. The CGI has internal control systems that can correct for line-of-sight (LOS) and wavefront (WFE) drift, outside of the observatory stability mitigation capabilities. In Phase A, to simplify the modeling approach, the CGI control systems are modeled as simple high-pass rejection filters. Both CGI requirements and performance predictions include these closed-loop rejection filters where appropriate, as shown in Table 1.

As part of the IM process, all prediction results include appropriate model uncertainty factors (MUFs). The MUFs are determined from heritage data and relevant past experience at this stage of the program. More extensive analyses will be performed during Phase B of the mission to ensure that the MUFs chosen are sufficient for WFIRST. With the MUFs included, the IM current best estimates as shown in Table 1 demonstrate that all key stability requirements can be met with reasonable margin. To meet the CGI LOS and WFE jitter requirements, the observatory wheel speed range is limited to 5-19 rev/sec, from the nominal +/- 40 rev/sec. This wheel speed range is predicted to allow CGI to achieve its technology demonstration goals.

Table 1 WFIRST Key Stability Requirements

Wide Field Instrument (WFI)		
Title	Performance Requirement	Current Best Estimate
Wide Field Imaging Mode (WIM) Wavefront Error (WFE) Stability (< 180 sec)	1.0 nm RMS	0.7 nm RMS
WIM Long Term WFE Stability (> 24 hours)	26.5 nm RMS	7.2 nm RMS
WIM Line-of-Sight (LOS) Jitter	12 mas RMS	5.5 mas RMS
WIM WFE Jitter	0.9 nm RMS	0.7 nm RMS
Coronagraph Instrument (CGI)		
Title	Performance Requirement	Current Best Estimate
CGI WFE Drift (includes closed-loop filter)	Z4: 2.0 nm RMS RSS(Z5-Z11): 0.25 nm RMS	0.45 nm RMS 0.05 nm RMS
CGI LOS Jitter (includes closed-loop filter)	0.57 mas RMS	0.42 mas RMS (wheel speed: 5-19 rev/sec)
CGI WFE Jitter	0.25 nm RMS	0.07 nm RMS (wheel speed: 5-19 rev/sec)

SUMMARY

In summary, great progress has been made by the entire WFIRST team of scientists, engineers, and our empowering staff of managers to progress the design of the WFIRST observatory while reducing technical and programmatic risk, meet all science objectives, and satisfy our stakeholder commitments on mission cost and schedule. Since 2013 notable advances in observatory design, packaging, and performance has been achieved as reported herein, and the WFIRST Mission is now poised for an exciting and productive Phase B, leading to Mission PDR in late 2019.

ACKNOWLEDGEMENTS

A special thanks goes to Dr. Dave Content for his guidance and advice in the preparation of this paper, Dr. Art Whipple for his help in editing, Mr. Clif Jackson for his help in ensuring the thermal trades discussed herein were captured accurately, and Dr. Alice Liu for her tireless attention to detail in providing a comprehensive summary of the WFIRST integrated modeling results for publication herein.

REFERENCES

- [1] D. Content, K. Aaron, L. Alplanalp, K. Anderson, R. Capps, Z. Chang, J. Dooley, R. Egerman, R. Goullioud, D. Klein, J. Kruk, G. Kuan, M. Melton, J. Ruffa, M. Underhill, D. Van Buren, "Wide Field Infra-Red Survey Telescope (WFIRST) 2.4-meter Mission Study," Proc. SPIE 8860-14 (2013)
- [2] B. Pasquale, C. Marx, G. Gao, N. Armani, "Optical Design of the WFIRST Phase-A Wide Field Instrument," Proc. IODC ITh1B.2 (2017)