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Future large-aperture UVOIR space observatory: reference designs

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Abstract. Our joint NASA GSFC/JPL/MSFC and STScI study team has used community-developed science goals to derive mission needs, design parameters, notional instruments, and candidate mission architectures for a future large-aperture, noncryogenic UVOIR space observatory. We describe the feasibility assessment of system dynamic stability that supports coronagraphy. The observatory is in a Sun–Earth L2 orbit, which provides a stable thermal environment and excellent field of regard. Reference designs include a 36-segment 9.2-m aperture telescope that stows within a 5-m diameter launch vehicle fairing. This paper presents results from the latest cycle of integrated modeling through January 2016. The latest findings support the feasibility of secondary mirror support struts with a thickness on the order of an inch. Thin struts were found not to have a significant negative effect on wavefront error stability. Struts with a width as small as 1 in. may benefit some coronagraph designs by allowing more optical throughput. [DOI: 10.1117/1.JATIS.2.4.041214]

Keywords: advanced technology large-aperture space telescope; large UVOIR surveyor; high-definition space telescope; design concept; exoplanets; space telescope.

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1 Introduction

In the two decades since the discovery was reported of the first planet around a Sun-like star, 51 Pegasi, the study of exoplanets has progressed rapidly. The 2010 NRC Astronomy and Astrophysics Decadal Survey elevated the search for exo-Earths to a major science goal and technology investment for a mission to search for exo-Earths as its highest priority "medium activity" for the subsequent decade. NASA's Kepler mission, launched in 2009, demonstrated that the Milky Way is teeming with planets, very likely—although not yet certainly—with millions of planets similar to the Earth.

As of this writing, there are now almost 2000 confirmed exoplanets and roughly another 3000 candidate exoplanets waiting additional data. Among these are some 300 objects lying within the so-called "habitable zone" around the central star. That is, perhaps around 10% or more of the stars in the sky have a planet roughly similar to the Earth at a location neither too hot nor too cold for life to arise.

In parallel with the growing recognition that Earth-like worlds may be abundant has been increasingly detailed study of a future space observatory capable of both distinguishing an exoplanet from its central star and suppressing the intense starlight that would otherwise overwhelm the faint planetary light. We will describe here conceptual design work intended to enable such a facility.

In addition to the capability to analyze the spectra of exoplanets and search for indicators of a biologically active world, the broader astronomical community has identified other major scientific goals in the UV/optical/IR (UVOIR) wavelength regimes. NASA's 30-year vision for astrophysics, "Enduring Quests, Daring Visions," last year highlighted a large UV/Optical/IR (LUVOIR) observatory as a priority mission for the 2020s. More recently, the Association of Universities for Research in Astronomy (AURA), which operates the Space Telescope Science Institute, established a study team that recommended to the scientific community a similar concept, the high-definition space telescope (HDST) in its 2015 report, "From Cosmic Birth to Living Earths."[1] The LUVOIR and HDST concepts are broadly similar to the design work described here, a mission study that we refer to as the advanced technology large-aperture telescope (ATLAST), which is also described elsewhere in this special issue by Thronson et al.[2] Therefore, for simplicity of reference, we use here the single acronym "ATLAST," although it is intended as generally applicable to the science objectives referenced by LUVOIR and HDST.

The ATLAST concept was originally developed late last decade and was submitted to the 2010 Decadal Survey by a consortium of GSFC, MSFC, JPL, and STScI. The proposal summarized three alternative observatory design concepts, including telescopes based on an 8-m monolithic primary mirror, 9.2-m segmented deployed primary mirror, and a 16-m primary mirror. That proposal was well received by the 2010 Decadal Survey: the Decadal Survey identified technology investment for a mission to search for exo-Earths as its highest-priority "medium activity" for the decade.

In early 2013, in response to the recommendation in the 2010 decadal survey and in preparation for the 2020 survey, we initiated an internally funded design study for a concept that builds upon the ATLAST studies of the previous decade. In our paper, we present brief descriptions and references for observatory design concepts with an 8-m monolith primary mirror and a 12.7-m deployed segmented primary mirror. We also address

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aspects of mechanical stability for the conceptual design of an observatory with a 9.2-m deployable segmented primary mirror that is readily scalable to larger or smaller apertures as may be dictated by available budget and launch vehicles (see also Ref. 2).

2 Observatory Parameters Traceable to Science Objectives

The design parameters for the ATLAST mission are summarized in Tables 1 and 2. These parameters are responsive to a broad program of interest to the science community as reflected in NASA's 30-year vision for astrophysics, "Enduring Quests, Daring Visions." The parameters are also consistent with the science goals that appear in the AURA report for HDST.[1] The ATLAST design reference missions in this report are primarily driven by two key elements of these tables. The first element that corresponds to the aperture size of 8 m or greater is shown in Table 1. The second driving element is the need for exceptional wavefront error (WFE) stability, also shown in Table 1, along with the related contrast stability for the starlight suppression system shown in Table 2. Section 8 of this paper examines the ways the conceptual design addresses aspects of aperture size and WFE stability.

Tables 1 and 2 are provided here mainly for providing context of the overall mission goals. It is beyond the scope of this paper and the resources of our preliminary conceptual design effort to attempt to address all of these parameters. For instance, we recognize that the goals for the short end of the UV wavelength range will need to be consistent with the needs for supporting coronagraphy as a distinct area of future study. This will require substantial technology development, conceptual design, and science and engineering trade studies that were beyond the available resources during the time of the study described here.

3 Launch Vehicle Considerations

The ATLAST concept is intended to achieve in the late 2020s or early 2030s scientific breakthroughs with the largest telescope aperture ever deployed in space. At some future time, it is reasonable to expect that even larger telescopes will be assembled in space. For our ATLAST concept, the most straightforward and cost-effective architecture is to put a large aperture in space with a single launch.

The ATLAST observatory will be in a Sun–Earth L2 orbit, which provides an excellent field of regard. The nature of the L2 orbit also allows it to be designed for very few or no solar eclipses, which provides near constant exposure to the sun and deep space. Having this stable radiative heat source and heat sink available nearly constantly in L2 orbit provides opportunities for thermal stability that orbits with routine eclipse periods do not. The mass to orbit and fairing diameter represent driving launch vehicle interfaces for the observatory at the conceptual design level, constraining the size of the telescope aperture.

Of paramount concern, in addition to enabling a broad program of breakthrough science, is controlling mission cost and risk. The launch vehicle industry in the mid-2020s will not be the same as it is today. In order to control launch vehicle

Table 1 ATLAST telescope parameters.

Parameter		Requirement	Stretch goal[a]	Traceability
Primary mirror aperture		≥8.0 m	>12.0 m	Resolution, sensitivity, exoplanet yield
Telescope temperature		273 K to 293 K	—	Thermal stability, integration and test, contamination, IR sensitivity
Wavelength coverage	UV	100 nm to 300 nm	90 nm to 300 nm	—
	Visible	300 nm to 950 nm	—	—
	NIR	950 nm to 1.8 μm	950 nm to 2.5 μm	—
	MIR	Sensitivity to 8.0 μm[b]	—	Transit spectroscopy
Image quality	UV	<0.20 arcsec at 150 nm	—	—
	Vis/NIR/MIR	Diffraction-limited at 500 nm	—	—
Stray light		Zodiacal light-limited between 400 nm and 1.8 μm	Zodiacal light-limited between 200 nm and 2.5 μm	Exoplanet imaging and spectroscopy SNR
WFE stability		∼10 pm RMS uncorrected system WFE per wavefront control step	—	Starlight suppression via internal coronagraph
Pointing	Spacecraft	≤1 mas	—	—
	Coronagraph	<0.4 mas	—	—

[a]Stretch goals are identified where mission-enhancing capabilities could be realized.
[b]No requirements are to be levied on the telescope beyond those that would enable the NIR capabilities. IR, infrared; UV, ultraviolet; NIR, near infrared; MIR, midinfrared; SNR, signal-to-noise ratio; RMS, root-mean-square; WFE, wavefront error.

Table 2 Notional ATLAST instrument candidates.

Science Instrument	Parameter	Requirement
UV multiobject spectrograph	Wavelength range	100 nm to 300 nm
	Field-of-view	1 to 2 arcmin
	Spectral resolution	$R = 20{,}000$ to 300,000 (selectable)
Visible-NIR imager	Wavelength range	300 nm to 1.8 μm
	Field-of-view	4 to 8 arcmin
	Image resolution	Nyquist sampled at 500 nm
Visible-NIR spectrograph	Wavelength range	300 nm to 1.8 μm
	Field-of-view	4 to 8 arcmin
	Spectral resolution	$R = 100$ to 10,000 (selectable)
MIR imager/ spectrograph	Wavelength range	1.8 μm to 8 μm
	Field-of-view	3 to 4 arcmin
	Image resolution	Nyquist sampled at 3 μm
	Spectral Resolution	$R = 5$ to 500 (selectable)
Starlight suppression system	Wavelength range	400 nm to 1.8 μm
	Raw contrast	1×10^{-10}
	Contrast stability	1×10^{-11} over science observation
	Inner-working angle	34 milli-arcsec at 1 μm
	Outer-working angle	>0.5 arcsec at 1 μm
Multiband exoplanet imager	Field-of-view	~0.5 arcsec
	Resolution	Nyquist sampled at 500 nm
Exoplanet spectrograph	Field-of-view	~0.5 arcsec
	Resolution	$R = 70$ to 500 (selectable)

risk and its associated costs, ATLAST incorporates flexibility and robustness by being adaptable to a variety of different launch vehicles and fairing sizes.

It is clear that a mission with the ambitious goals of ATLAST will need a suitably capable launch vehicle. Figure 1 depicts representative values of lift capabilities for a variety of launch vehicles to Sun–Earth L2 orbit. Figure 2 depicts outer and inner diameter dimensions of the associated payload fairings. These launch vehicles range in maturity from existing vehicles with proven flight records to vehicles that are undergoing development.

A few of the larger vehicles most relevant for ATLAST are discussed below. By designing the mission to be compatible with a variety of launch vehicles, ATLAST will manage risks and costs with a flexible suite of alternatives. The Delta IV

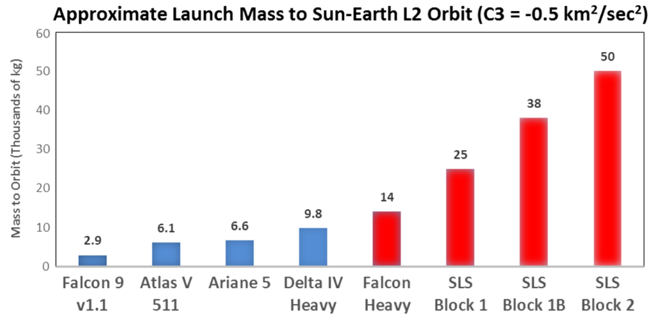

Fig. 1 Launch mass to Sun–Earth L2 orbit for a variety of current and future launch vehicles.[3–8] Existing vehicles are in blue, ones in development are in red. These are representative values subject to refinement of designs in development and evolutions of existing vehicles. C3 is characteristic energy, a measure of the excess energy per unit mass over that required to just barely escape the Earth's gravity.

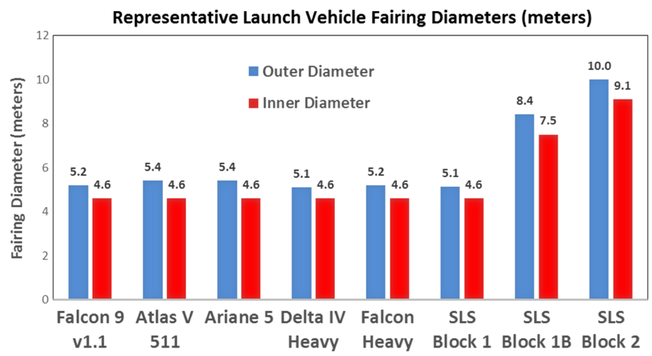

Fig. 2 Launch vehicle fairing diameters for a variety of current and future launch vehicles.[3–8] The outer diameter values are shown in blue and the inner diameter values are shown in red. Outer diameters correspond to the exterior physical extent of the fairing. The accuracy of inner diameters depends on the maturity of the vehicle. For flight-proven vehicles like the Atlas V, Ariane 5, and Delta IV Heavy, the inner diameter is the published static envelope for these vehicles with these fairings. The diameter shown for the Falcon 9 is the published dynamic envelope. The inner diameter shown for the Falcon Heavy corresponds to the static envelope. The fairings for the SLS are in conceptual design and the inner diameter is a less specific conceptual design dimension. These fairing diameters are representative values subject to refinement of designs in development and evolutions of existing vehicles.

Heavy is an existing heavy lift launch vehicle with a proven track record. Five-m launch vehicle fairings are a standard in the industry, which the Delta IV Heavy possesses. Our ATLAST concept demonstrates readiness for implementation in the 2020s by having a design option for an existing launch vehicle: compatibility with the proven Delta IV Heavy achieves this purpose. United Launch Alliance (ULA) has stated that it will continue to manufacture the Delta IV Heavy for as long as the Air Force wants it. ULA has also stated that it intends to build a heavy lift launch vehicle as the successor to the Delta IV Heavy to compete with the Falcon Heavy. The Falcon Heavy is in development by SpaceX and offers a lift capability in excess of the Delta IV Heavy and will also have a 5-m fairing. The Falcon Heavy is expected to be relatively economical, with launch costs currently projected to be on the order of \$100 M. The Space Launch System (SLS) is currently in development and will have unsurpassed mass-to-orbit capabilities, even in excess of the Falcon Heavy. Options are under study for 5-, 8.4-, and

10-m fairings. The ATLAST and SLS teams have conducted regular engineer-to-engineer working group meetings to develop conceptual designs for interfaces between the observatory and the SLS launch vehicle. Concepts have been studied that allow ATLAST to be compatible with any of the SLS launch vehicle fairings. The SLS can provide unsurpassed mass margin and the potential for unrivaled fairing volume for ATLAST, which can provide substantial risk mitigation, flexibility, and robustness to the development of the observatory.

4 Starlight Suppression Techniques

Priority ATLAST science goals include both exoplanet studies and general ultraviolet, optical and near-IR astronomy. The identification of biomarkers in exoplanet atmospheres may be the most compelling and potentially revolutionary achievements toward understanding the fundamental question of "Are we alone?" The exoplanet science goals for the mission include unique driving requirements, so early emphasis has been on accommodating these aspects of the mission. Thus, a key architectural feature of ATLAST is the starlight suppression system. Conceptually, this could be achieved with a free-flying star shade or with a coronagraph that is internal to the observatory. Each of these approaches has its own strengths and challenges.

A free-flying star shade tends to impose less stringent requirements on the stability of the telescope, but it could take on the order of weeks to reposition from one target to another due to its significant distance from the telescope observatory. This, in turn, would reduce observing efficiency and exoplanet yield. On the other hand, for example, a star shade may be the suppression system of choice for detailed study of an exoplanet that has been previously identified for study by other means.

An internal coronagraph repoints with the telescope within which it is installed. For this reason, it may be more applicable for exoplanet surveys and achieving a larger exoplanet yield. Coronagraphs tend to place more stringent requirements on telescope stability in ways that free-flying star shades do not. Both star shades and coronagraphs are currently the subject of technology development programs and their design and performance characteristics are becoming more mature. Exoplanet yield tends to be a dominant science consideration for improving the statistics to estimate the frequency and characteristics of potentially life-bearing exoplanets. For that reason, early emphasis of our ATLAST mission concepts discussed below adopted a coronagraph.

5 Engineering Design Reference Missions

Our ATLAST study has been motivated since its beginning in early 2013 by enabling breakthrough, revolutionary science. Paired with that vision is emphasis on cost control and cost effectiveness as paramount priorities. A key to formulating the most cost-effective ATLAST mission possible is the derivation and validation of detailed, verifiable requirements. Detailed requirements, decomposed and flowed down to the lowest level of assembly drive the mission implementation, and the implementation drives costs. Implementing the system and verifying the implementation against the requirements also drives the schedule and the critical path. The critical path will have a dominant effect on the mission cost.

The purpose of our ATLAST Engineering Design Reference Missions (EDRMs) is to provide a basis for deriving a validated set of mission requirements from the science objectives and top-level science requirements. The EDRMs allow the engineering design trade space to be explored in depth and the determination in detail of where the most demanding requirements are and where there are opportunities for margin against requirements. The EDRMs provide access to a rich trade space where implementations and requirements can be analyzed and evaluated against each other to formulate the most effective, well-balanced, and lowest-risk designs. With greater resources than were available to the ATLAST study we report on here, multiple EDRMs would be developed simultaneously in parallel and in depth to make the most progress promptly in assessing the science objectives against the requirements, implementation space, and costs. Since mission formulation must be done within the limitations of available resources, there are practical limits to how many in-depth EDRMs can be developed in parallel. The EDRMs developed by our ATLAST study, which concluded in late 2015, were submitted to the Large UVOIR Surveyor study now underway and supported by NASA HQ.

Two of the key words in EDRM are "reference" and "design." The EDRMs are not the final mission design. The EDRMs are conceptual designs used for deriving and validating requirements. Settling on "the design" in pre-phase A would be a recipe for misunderstood requirements and cost growth as the true requirements get discovered along the project critical path. Validated mission requirements are critical for allowing implementers to propose the most cost-effective methods possible for delivering results against the mission requirements. Validated mission requirements enable robust trade studies to be performed that will help determine the most cost-effective mission implementation. With validated requirements in hand, opportunities will be created for implementers in industry, academia, and government organizations to create and bring forward their best ideas to support the most cost-effective mission implementation.

6 ATLAST Conceptual Design Studies

Building on earlier design work described in this issue by Thronson et al.[2] and with the goal of a feasible concept for the next Decadal Survey, multiple EDRMs have been generated for ATLAST. These multiple EDRMs support the pursuit of the most cost-effective ATLAST concept by ensuring that the merits of more than one approach have been considered. These include observatories based on an 8-m monolithic primary mirror, a monolithic mirror surrounded by deployable mirror petals, and a segmented deployable mirror. Each of these is a different approach to achieving the necessary aperture and system stability for the ATLAST mission. Each of them needs more conceptual design work to quantify its feasibility, performance, and cost effectiveness.

The 8-m monolith EDRM was generated late last decade and submitted to the NRC 2010 Decadal Survey along with two design concepts using segmented deployable mirrors. These concepts were evaluated by the 2010 Decadal Survey, which led to the highest-priority "medium" activity recommendation that NASA invest substantially in key technologies to enable a future observatory capable of studying Earth-like planets for consideration by the 2020 Decadal Survey. In response to this recommendation, our team developed the technology plan described by Bolcar et al.[9] The 8-m monolith concept (Fig. 3) is described in Ref. 10 and offers the advantage of not having segment gaps in the primary mirror. Although deployable primary mirrors enable aperture sizes greater than the diameter of the launch vehicle fairing, they necessitate gaps between segments in the deployed mirror. A monolith without gaps provides advantages with regard to some current coronagraph designs

Fig. 3 ATLAST design concept utilizing an 8-m monolithic primary mirror.

in development. An 8-m monolithic mirror, however, would uniquely require the SLS Block II launch vehicle with a 10-m fairing. This vehicle is slated for development, but there would be no alternative means of launching the mission if this particular variant of the SLS launch vehicle does not materialize, creating a clear mission risk. Since new discoveries in astrophysics tend to be photon limited, it is reasonable to expect that future space telescope missions will need larger apertures than ATLAST, and monolithic primary mirrors do not appear readily evolvable to larger diameters. Thus, the 8-m monolith EDRM provides a conceptual design for the largest diameter monolithic primary mirror for space application.

The 12.7-m EDRM is a monolithic central primary mirror surrounded by deployable mirror petals that extend the aperture to 12.7 m. This is based on an analysis determining the largest diameter telescope with a center core and a single ring of segments that packages inside the mass and volume of an SLS launch vehicle with a 10-m diameter fairing (Fig. 4), as described by Stahl and Hopkins.[11] This particular EDRM incorporates a coronagraph for exoplanet observations. As a conceptual design, the 12.7-m EDRM proposes to solve the need for providing the necessary optical system stability by leveraging depth in the axial dimension of the primary mirror structure.

Our segmented EDRM consists of a deployable primary mirror, as illustrated in Figs. 5 and 6. The aperture is scalable, meaning that its architecture is designed to support adding more rings of segmented mirrors to increase the aperture in response to the refinement of the science requirements. Our 9.2-m configuration has been validated to fit within a 5-m launch vehicle fairing, which is an industry standard. This EDRM provides ATLAST immediate substantiation to the 2020 Decadal Survey that it is compatible with the flight-proven Delta IV Heavy launch vehicle and SLS, which is currently in development. As discussed in the launch vehicle section, this is a benefit in controlling launch vehicle programmatic risks and associated costs. This EDRM will be described in more detail below.

7 Systems Considerations

The objectives associated with exoplanet science are challenging. The mission must provide simultaneous solutions for multiple science requirements that affect the end-to-end telescope-coronagraph system. These simultaneous solutions are part of the development of coronagraph design candidates. Key science parameters involved include inner working angle, throughput, band pass, contrast, survey integration time, aperture, and exoplanet yield. Yield is a key performance parameter for the survey of potentially life-bearing exoplanets. Aperture is perhaps the most easily recognized parameter associated with the system, but it must be taken into account with the simultaneous solution space for the other parameters. The scalability of our segmented EDRM is an essential element as it provides an opportunity to optimize aperture size in balance with multiple other key performance parameters, while not having to change the basic mission architecture. This ATLAST EDRM has demonstrated compatibility with an existing launch vehicle, and an opportunity to close on all the science parameters in an efficient manner

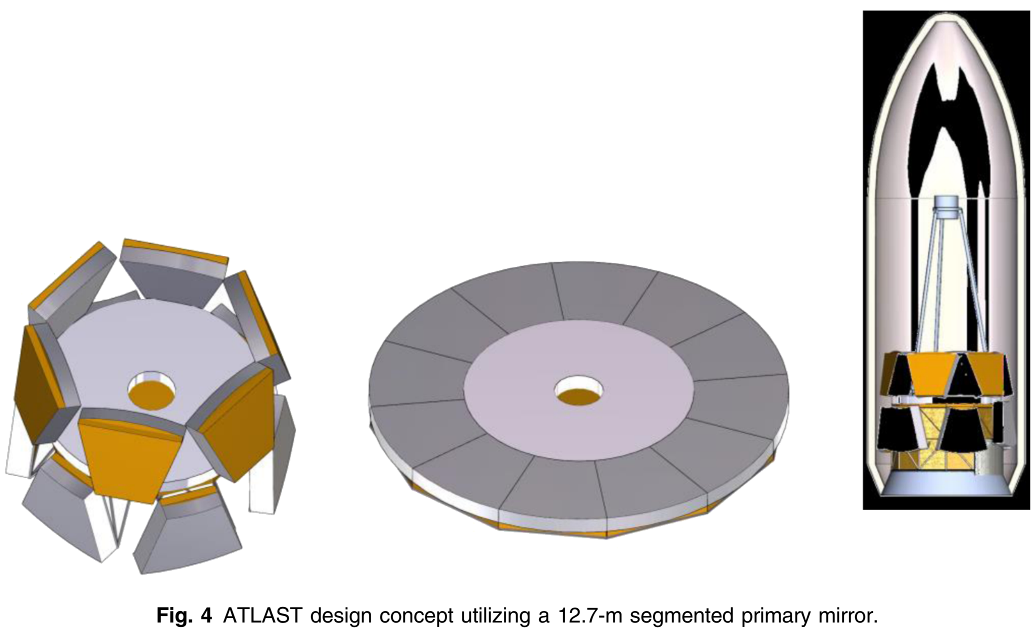

Fig. 4 ATLAST design concept utilizing a 12.7-m segmented primary mirror.

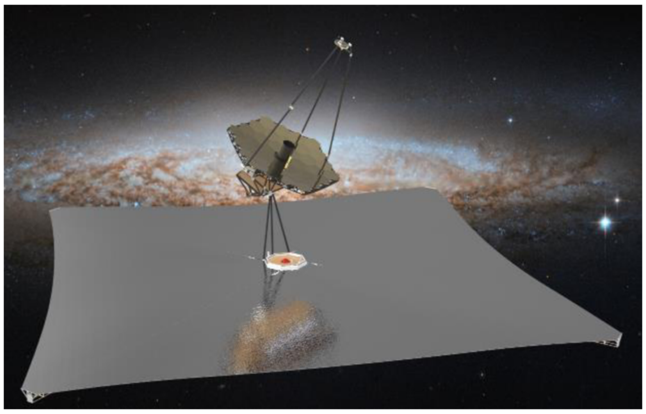

Fig. 5 ATLAST scalable segmented design concept utilizing a 9.2-m segmented primary mirror.

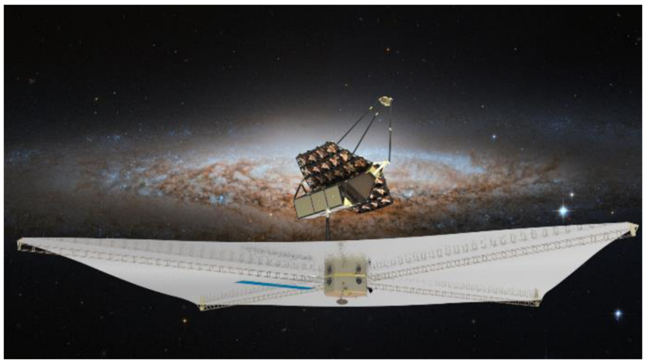

Fig. 6 ATLAST scalable segmented design concept utilizing a 9.2-m segmented primary mirror–view from spacecraft side of observatory.

with limited early resources while identifying opportunities for design margin against requirements. Our approach enables a cost-effective and well-balanced mission design process in this early stage, where there are naturally many uncertainties and system requirements yet to be quantified. Once a balanced system that closes on the mission requirements has been validated, available margin can be evaluated for maximizing aperture in the most cost-effective manner possible. A scalable architecture is unique in this respect.

An onboard coronagraph will place stringent WFE stability requirements on the end-to-end optical system. This, in turn, will drive requirements for mechanical dynamics and jitter stability, as well as thermal stability. Preliminary studies were carried out to analyze the extent to which jitter can be suppressed and managed, as well as the effect of thermal control and stability on WFE of the primary mirror. As the candidate coronagraph designs mature, their individual stability requirements will become better understood. There is at least one coronagraph design under consideration that may offer an easing of stability requirements of the telescope system. These coronagraph developments are being monitored as progress is being made. In the meantime, efforts are underway on observatory conceptual designs that seek to maximize the amount of system stability that can practically be achieved.

8 Mechanical Design and Dynamic Stability

Our ATLAST segmented EDRM set out to validate that a large deployed telescope aperture can readily be stowed inside a 5-m diameter launch vehicle fairing. Five-meter diameter fairings are an industry standard and are the most routinely available large fairing. During our ATLAST assessment, computer-aided design mechanical engineering studies validated the feasibility of stowing and deploying a 9.2-m diameter primary mirror aperture from a 5-m fairing. This version of our scalable segmented EDRM will be referred to here as the 9.2-m EDRM. The concept as developed through the end of 2015 when our study ended appears in Figs. 7 and 8. The deployment architecture leverages the primary mirror deployment work accomplished under JWST.

Fig. 7 ATLAST 9.2-m primary mirror in a 5-m fairing.

Fig. 8 ATLAST 9.2-m primary mirror in a 5-m fairing–one quarter rotated view.

While JWST uses two deployable wings (one on each side of the primary mirror aperture), our 9.2-m EDRM uses three deployable wings on each side of a central strip of mirror segments.

Initial mechanical design work has been carried out on the observatory, with particular emphasis on the structure of the primary mirror backplane. Figure 9 shows the current (end of 2015) backplane design concept. Preliminary structural analysis indicates a first mode of 7.5 Hz, which meets its initial design target for stiffness. Figure 10 illustrates the shape of the first mode at an exaggerated scale to make it visible.

Based on the results of preliminary dynamics analyses, our conceptual design for the 9.2-m EDRM primary mirror backplane underwent an iterative process of development and refinement.

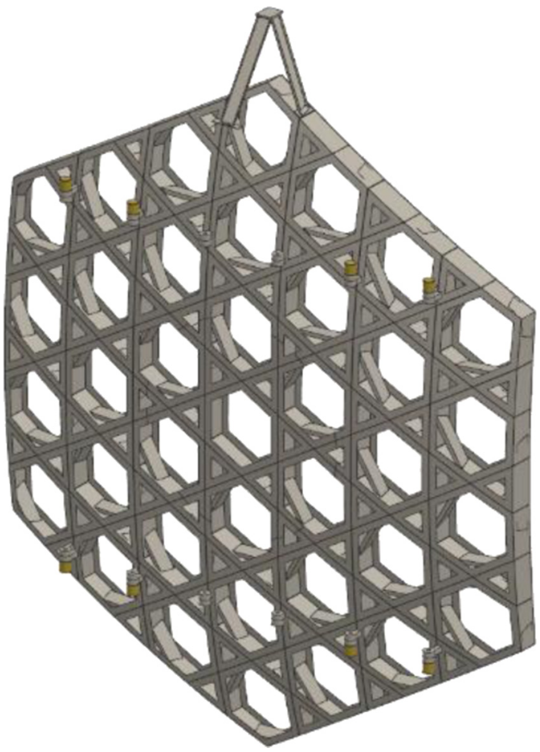

Fig. 9 Backplane design concept.

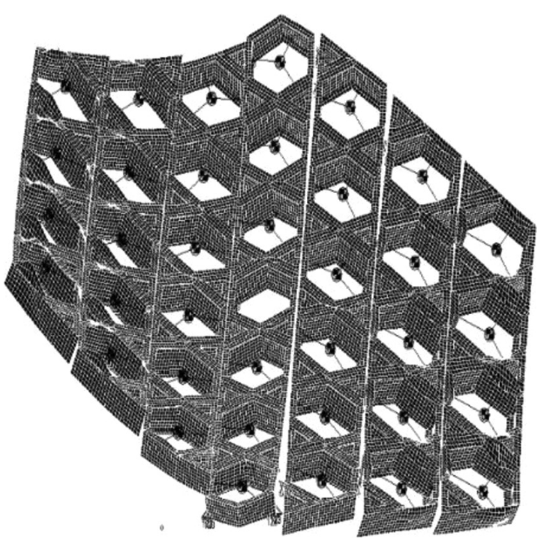

Fig. 10 7.5-Hz first primary mirror mode.

This allowed us to quickly evaluate backplane configurations with respect to the 5-m diameter class fairings. Figure 11 shows the 2015 concept iteration stowed inside the fairing. Primary mirror wing hinge locations, individual cell dimensions (see Fig. 9), and a number of other gross dimensional parameters were evaluated for packaging options.

Important driving parameters for the mission are shown in Tables 1 and 2 of Sec. 2 of this paper. From the perspective of observatory mechanical design and stability, the entry in Table 1, "Telescope Parameters," regarding WFE stability is an important driver. An objective of the ATLAST 9.2-m EDRM is to begin to quantify what level of WFE stability might be feasible with a deployable aperture this large in the presence of reaction wheel disturbances. Similarly, the entry in Table 2, Instrument Parameters, indicates the need for the starlight suppression system to provide on the order of 1×10^{-11} contrast stability over a science observation. The telescope WFE stability plays an important role in enabling this capability for starlight suppression. A key component of WFE at the output of the telescope is jitter from the reaction wheels that induces instability in the WFE. For this reason, integrated modeling (IM) has been carried out on the observatory conceptual design in order to create preliminary assessments of jitter-induced WFE in the deployed, observing configuration of the telescope.

As of January 2016, when our ATLAST study activity was brought to conclusion, three IM design cycles have been completed to evaluate the dynamic stability of the concept and provide feedback for improving the design concept. The IM cycles focused primarily on the stability of the primary and secondary mirrors and associated structures, which are the main drivers for stability. The disturbance source is represented by a disturbance model of a commercial reaction wheel that includes static and dynamic imbalances. The performance of a representative and realizable noncontact dynamic disturbance isolation system was modeled and included in the analysis.

Originally, we represented the ATLAST primary mirror backplane as a simple shell with masses and frequency response characteristics assigned in a scaled fashion based on analysis of JWST. The initial IM cycle was run to establish and validate the analysis operations associated with using the mechanical design models, data files, and formats. The initial cycle culminated in calculations of WFE versus reaction wheel speed. The results

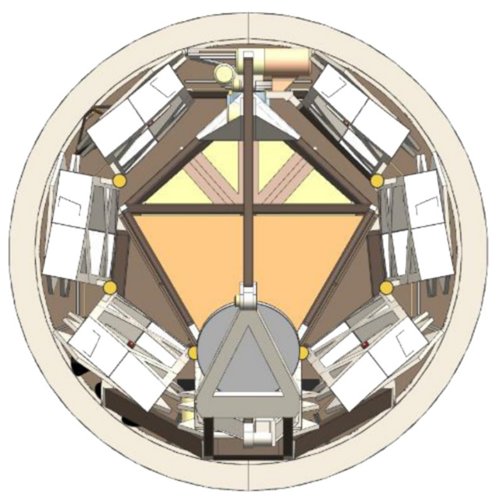

Fig. 11 Iterated concept of ATLAST stowed in 5-m fairing viewed from above.

validated the modeling process and yielded encouraging results. The initial results were consistent with the feasibility of a primary mirror being stiff enough to support operation with a coronagraph. Most of the primary mirror responses fell below the 10 pm level over a large range of wheel speeds.

The second IM cycle focused on the improved mechanical design models of the telescope. These incorporated a number of more detailed representations of structures, including a realizable telescope backplane structural design, a telescope pointing tower revised design to provide stiffer connection between spacecraft bus and science payload, and a representation of passive reaction wheel isolators. The conceptual design for the telescope backplane and secondary mirror support structure uses composite material to provide a high stiffness-to-weight ratio and a low coefficient of thermal expansion. The passive isolators are based on JWST design heritage and have an 8-Hz corner frequency and 5% damping. Results of the analysis included calculations of worst-case RMS WFE response stimulated by any of the four reaction wheels. The preliminary results reached by this second IM cycle showed RMS WFE generally below a picometer for reaction wheel speeds above 900 RPM. These are good results that were updated with more recent analysis in the third design analysis cycle described below.

In the meantime, discussions were carried out with coronagraph designers regarding the effect of the telescope secondary mirror support struts on the obscuration of light to the coronagraph. The cross-section of the secondary mirror support struts in the initial version of our 9.2-m scalable segmented EDRM was on the order of 10 cm × 10 cm. Consultation with coronagraph designers determined that for some candidate coronagraph designs, a strut thickness projected onto the primary mirror as thin as 2.5 cm might significantly reduce the effect of the secondary support struts on the performance of the coronagraph.[12]

The design of the secondary mirror support struts was revised to have a cross-section of 2.5 cm × 15 cm. Another IM cycle was run with this design feature included in the same mechanical model design from the previous IM run. This included the same analytical representations of the noncontact dynamic disturbance isolation system and passive reaction wheel isolators. Figure 12 illustrates these latest preliminary analytical results of WFE of the 9.2-m primary mirror as a function of reaction wheel speed. The result shown is for a worst-case one-wheel response. The analytical modeling shows primary mirror responses falling below 1 pm WFE at reaction wheel speeds over 1000 RPM.

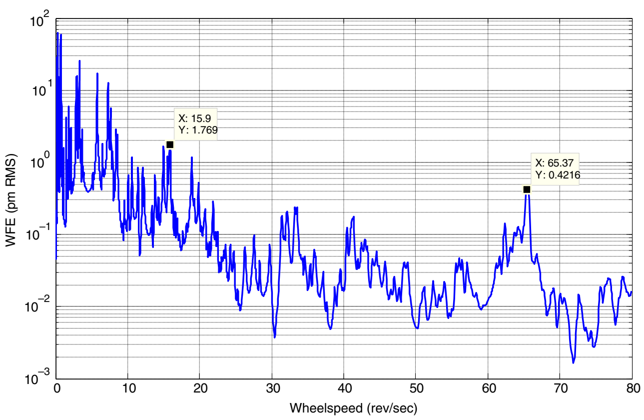

Fig. 12 Primary mirror WFE versus reaction wheel speed.

These initial results are consistent with the feasibility of the primary mirror being stiff enough to support operation with a coronagraph. The results also validate that designing a secondary mirror support system with struts as thin as 2.5 cm in the cross-section is worth pursuing, which might enable improvements in performance for some coronagraph designs.

These results are very encouraging, but they are only preliminary and more detailed modeling needs to be carried out with more mature models. Future improvements include adding the effects of the science payload gimbal, along with a model uncertainty factor. The design and modeling of the individual mirror segment structure will also benefit from more detailed development. Also, a key assumption thus far is that the structures will respond linearly at levels of disturbance relevant to picometer WFE control. This will be examined more closely in future analysis supported by inputs from test data. It may turn out that nonlinearity actually improves performance as energy is absorbed by the interfaces.

9 Thermal Stability

Preliminary thermal stability analysis has focused on the feasibility of achieving WFE consistent with picometer stability at the individual mirror segment level. Eisenhower et al.[13] carried out thermal analysis on a mirror segment that examines the ability to control WFE with a high-precision active heater control. Initial results are encouraging, and in the future, the intent is to extend the analysis to include the backplane.

10 Conclusion

Our paper presents the findings of the latest IM analysis cycle of the ATLAST 9.2-m telescope reference design to achieve priority science requirements. The motivation for this cycle was to examine the feasibility of secondary mirror support structure struts with a width dimension on the order of 2.5-cm thick. The results indicate that secondary mirror support struts as thin as 2.5 cm do not have a significant negative impact on the WFE stability. An appropriate caveat is that the telescope is still in a conceptual stage of design and this quantitative analysis is subject to further validation with more mature, higher fidelity models. Nevertheless, the current results validate that WFE stability on the order of tens of picometers is worth pursuing with more study, analysis, and maturation of the conceptual design. Struts with thickness on the order of 2.5 cm may benefit some types of coronagraph design by providing more optical throughput than struts with thicker cross-sections. These results represent progress in the feasibility of a telescope-coronagraph system for enabling the identification of biomarkers on exoplanets.

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