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Technology gap assessment for a future large-aperture ultraviolet-optical-infrared space telescope

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Abstract. The Advanced Technology Large Aperture Space Telescope (ATLAST) team identified five key technology areas to enable candidate architectures for a future large-aperture ultraviolet/optical/infrared (LUVOIR) space observatory envisioned by the NASA Astrophysics 30-year roadmap, "Enduring Quests, Daring Visions." The science goals of ATLAST address a broad range of astrophysical questions from early galaxy and star formation to the processes that contributed to the formation of life on Earth, combining general astrophysics with direct-imaging and spectroscopy of habitable exoplanets. The key technology areas are internal coronagraphs, starshades (or external occulters), ultra-stable large-aperture telescope systems, detectors, and mirror coatings. For each technology area, we define best estimates of required capabilities, current state-of-the-art performance, and current technology readiness level (TRL), thus identifying the current technology gap. We also report on current, planned, or recommended efforts to develop each technology to TRL 5. [DOI: 10.1117/1.JATIS.2.4.041209]

Keywords: space telescopes; technology development; coronagraph; starshade; lightweight mirrors; ultra-stable systems.

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1 Introduction

The 2010 National Research Council (NRC) Decadal Survey, "New Worlds, New Horizons in Astronomy and Astrophysics,"[1] recommended as its highest-priority medium-scale activity, a "New Worlds Technology Development Program" to "lay the technical and scientific foundations for a future space imaging and spectroscopy mission" (page 20). The Decadal Survey further recommended the definition of a future UV-optical space telescope as a small-scale activity for the 2010 to 2020 decade. In 2013, the NASA Astrophysics 30-year roadmap, "Enduring Quests, Daring Visions,"[2] identified a large UV–optical–infrared surveyor (hereafter, referred to as LUVOIR) as a strategic mission in the "Formative Era" (roughly the 2020s through the 2030s). The science objectives for LUVOIR include a broad array of general astrophysics priorities, including the origins of stars, planets, and galaxies, as well as the detection and characterization of habitable exoplanets. In 2015, the Association of Universities for Research in Astronomy (AURA) report "From Cosmic Birth to Living Earths"[3] provided a detailed science case and notional architecture for a 12-m segmented-aperture space telescope, dubbed the high-definition space telescope (HDST). In 2016, the NASA Astrophysics Division announced the establishment of four "Large Mission Concept Studies" to prepare for the National Academies of Science (NAS) 2020 Decadal Survey.[4] To prepare for the survey, a UV/optical/infrared (UVOIR) surveyor is one of the four missions to be studied to produce a final report that details a compelling science case, a design reference mission with a straw-man payload, technology and cost assessments, and a high-level schedule for the major mission phases.

Beginning in spring 2013, we assembled a team led by NASA Goddard Space Flight Center and including NASA's Marshall Space Flight Center, NASA Jet Propulsion Laboratory, and the Space Telescope Science Institute, to study the Advanced Technology Large Aperture Space Telescope (ATLAST).[5] ATLAST is a reference concept for LUVOIR and very similar in capability to the HDST. In addition to outlining the science goals and performing a preliminary engineering analysis, our team produced an assessment that identifies the technology gaps (the difference between estimated technology needs and the current state of the art) associated with achieving the ATLAST science mission, and priority activities to begin closing those gaps. This paper presents the ATLAST technology gap assessment and serves as a reference point from which the upcoming LUVOIR mission concept study will build. It is expected that these gaps will be included in the NASA Astrophysics program office annual technology report process, which is used to prioritize technologies for funding in the annual Strategic Astrophysics Technology and Astrophysics Research and Analysis (APRA) programs.

The ATLAST technology gap assessment highlights five technology areas to enable its science mission. These technology areas include internal coronagraphs, starshades, ultra-stable large-aperture telescope systems, detectors, and mirror coatings. In Secs. 3–7 of this paper, we provide an overview of each

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technology area and define the technology gap for specific technology components. We also summarize current and future technology development activities necessary to close the technology gaps. First, in Sec. 2, we provide the context for the ATLAST technology gap assessment.

2 Context for Technology Gap Assessment

2.1 *Science Case*

The science goals of ATLAST draw heavily from the documents referenced in Sec. 1 and are based on the scientific heritage of the Hubble Space Telescope. The investigation of the origins of cosmic structures from galaxies to stars to planets, and how matter flows from galaxy to galaxy and star to star are primary science objectives. Equal in importance is the ambitious aim of detecting and spectrally characterizing dozens of habitable exoplanets and searching for biosignatures in their atmospheres. In the process of executing this search for life, ATLAST would characterize hundreds of planetary systems, enabling comparative planetology. We refer the reader to AURA's "From Cosmic Birth to Living Earths" report for a detailed discussion of the science that can be achieved by an ATLAST-like mission.[3]

2.2 *Notional Mission and Instrument Parameters*

To help guide the engineering analysis and technology development plan, the ATLAST team studied several reference architectures, including an 8-m monolithic primary mirror,[6] a 9.2-m segmented aperture primary mirror,[7] and 13-m-class apertures[8] that would be enabled by NASA's space launch system (SLS), currently under development. These reference architectures were guided by a set of top-level, science-driven telescope requirements, as summarized in Table 1.

A large primary mirror aperture enables high resolution and sensitivity for astrophysical observations, as well as enabling small inner-working angles (IWAs) for exoplanet observations. Recent yield studies also show that the exo-Earth yield is most sensitive to telescope aperture, varying as approximately the aperture diameter to the 1.97 power.[9] The observatory operating temperature is driven by several constraints. A "warm" (i.e., noncryogenic) telescope reduces system complexity, cost, and schedule associated with mirror fabrication, integration, and testing on the ground. Conversely, the background emission of a warm telescope limits how far into the infrared sensitive observations can be performed, reducing the mission science yield. We expect the LUVOIR Science and Technology Definition Team (STDT) will undertake a trade study of the mission science yield as a function of observatory temperature during the pre-Decadal Survey studies.

While the two science goals of general astrophysics and exoplanet characterization are equal in importance, high-contrast imaging with an internal coronagraph for exoplanet characterization drives the wavefront stability requirements. Current internal coronagraphs require thermal and dynamic wavefront stability on the order of tens of picometers RMS per wavefront control step.[10,11] Two approaches can be taken to achieve picometer-level stability. First, in the scenario of a slow wavefront control system, the optomechanical system must be made to be extraordinarily stable such that the wavefront error does not change over the long periods of time (e.g., tens of minutes) between updates to the wavefront control system [e.g., a deformable mirror (DM)]. Conversely, if the wavefront control system

Table 1 Science requirements flow-down to the ATLAST telescope.

Parameter		Requirement	Stretch goal[a]	Traceability
Primary mirror aperture		≥8.0 m	>12.0 meters	Resolution, Sensitivity, Exoplanet Yield
Telescope temperature		273 to 293 K	—	Thermal stability, integration and test, contamination, IR sensitivity
Wavelength coverage	UV	100 to 300 nm	90 to 300 nm	—
	Visible	300 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 dust emission-limited between 400 nm and 1.8 μm	Zodiacal dust emission-limited between 200 nm and 2.5 μm	Exoplanet imaging and spectroscopy SNR
Wavefront error stability		~10 pm RMS uncorrected system WFE per wavefront control step	—	Starlight suppression via internal coronagraph
Pointing	Spacecraft	≤1 milliarcsec	—	—
	Coronagraph	<0.4 milliarcsec	—	—

[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-IR; MIR, mid-IR; SNR, signal-to-noise ratio; RMS, root-mean-square; WFE, wavefront error.

can operate quickly (i.e., a few hertz), then the system stability can be relaxed, as the control system will be able to keep up with dynamic and thermal drifts.

The broad array of science objectives identified by the ATLAST team requires a diverse suite of instruments. Table 2 outlines a notional instrument suite, subject to additional engineering analysis of the available payload mass and volume, as well as further definition of the mission science goals.

Table 2 Science requirements flow-down to a notional candidate instrument suite.

Science instrument	Parameter	Requirement[a]
UV multiobject spectrograph	Wavelength range	100 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	41 milliarcsec at 0.55 μm
	Outer-working angle	>170 milliarcsec at 0.55 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)

[a]Instrument wavelength coverage is matched to the requirements identified in Table 1 and would be extended to the stretch goals where achievable.

A dual focal-plane system would optimize instrument performance. The UV instrument and the starlight-suppressing exoplanet instrument suite would split the narrow on-axis field-of-view available at the intermediate focus produced by the primary and secondary mirrors (often referred to as the Cassegrain focus). Throughput is maximized for these sensitive instruments since the incoming light suffers reflection losses only at two surfaces. The other instruments would share a well-corrected, off-axis, wide-field-of-view focal plane produced by the addition of a tertiary mirror to the optical train, creating a three-mirror anastigmat system.

2.3 *Assumptions*

The ATLAST team operated under several assumptions when drafting this technology development plan. The first assumption pertains to timing: we assumed that an ATLAST/HDST/ LUVOIR-like mission will be a candidate for consideration by the National Academies' 2020 Decadal Survey, and, if selected, would be the NASA strategic mission to follow the wide-field infrared survey telescope (WFIRST). In this scenario, all required technologies would need to be at a technology readiness level (TRL)[12] of 6 in time for the preliminary design review (PDR) by about 2025.

The second assumption is one of flexibility with respect to mission architecture. We recognize the need to explore multiple reference architectures to help validate concepts at this early stage of a large-scale study. Our technology assessment identifies key gaps and investments that are broadly applicable to a wide range of observatory designs.

For example, we include the development of mirror technologies that are relevant to both segmented systems and large monoliths. A monolithic primary mirror may prove preferable if compatible launch vehicles are available (i.e., the SLS Block II configuration with an 8- or 10-m fairing) and coronagraphy with segmented apertures proves too difficult. Similarly, we also include both internal coronagraph and external occulter (starshade) starlight suppression systems as technologies to be developed. A coronagraph provides the greatest exoplanet characterization yield within a specific mission lifetime, yet it has limitations with respect to IWA in the infrared.[13] Internal coronagraphs also impose extremely challenging wavefront stability requirements on the telescope. A starshade with ATLAST would still perform groundbreaking exoplanet science (albeit at reduced exo-Earth yields[13]) in the event that the necessary contrast, throughput, bandpass, and wavefront error stability cannot be achieved with a coronagraph and a segmented aperture system. Furthermore, a follow-on starshade for the ATLAST mission could be used for extended characterization of candidate exo-Earths in the near-infrared.

While the ATLAST team assumed a five-year primary science mission, it is a certainty that any future flagship mission will be serviceable. The technologies identified here are necessary to achieve the initial 5-year science mission, with the exception of comments pertaining to a possible starshade rendezvous for follow-on exoplanet characterization. We do not comment on the infrastructure or technologies needed to perform servicing, either robotic or manned, of the ATLAST observatory, as that is beyond the scope of enabling the initial 5-year science mission, and therefore beyond the scope of this paper.

Finally, the extraordinary performance requirements involved in high-contrast imaging necessitate that a systems-level approach to technology development be adopted. No single technology area can be developed and evaluated independent of the others.

The impact of each technology must be assessed throughout the entire system, supported by detailed integrated modeling to determine the most feasible designs. Developing and validating such detailed models require time and the appropriate analysis tools. However, technology development must start immediately if sufficient progress is to be made in time for the 2020 Decadal Survey. We identify what we believe to be the most likely performance goals for each technology, but where uncertainty in the needed performance is large, we err on the side of being conservative. We expect that as technology development continues to progress, and as models continue to improve our understanding of inter-relationships among technologies, some of these performance goals will evolve and mature.

3 Internal Coronagraph

3.1 *Technology Overview*

The key to executing the science of detecting and characterizing habitable exoplanets is the ability to suppress the light originating from the host star, which is on the order of 10-billion times brighter than an orbiting exo-Earth. A starlight suppression system must be designed to perform such high-contrast imaging. To achieve statistical confidence in the occurrence rate of habitable worlds further requires the ability to survey hundreds of planetary systems during the mission lifetime.[9] Internal coronagraphs are included within the observatory instrument suite, and are capable of simultaneously providing high-contrast imaging and the necessary observational agility. Table 3 summarizes the technology needs and current state of the art for the internal coronagraph technologies.

3.2 *Broadband, High-Contrast Coronagraph for Obscured and Segmented Apertures*

While state-of-the-art internal coronagraphs are capable of high-yield science and are baselined on numerous ground- and space-based observatories, at present they do not yet simultaneously achieve the contrast, IWA, bandwidth, and throughput required to image and characterize habitable exo-Earths. Furthermore, a

Table 3 Internal Coronagraph technology components gap list.

Technology component	Parameter	Required	State-of-the-art	Estimated current TRL
Broadband, high-contrast coronagraph (includes WFSC)	Raw contrast	1×10^{-10} (detect) 5×10^{-10} (characterize)	1.9×10^{-9} (Ref. 14)	3
	IWA	$3.6\lambda/D$ (detect) $2.0\lambda/D$ (characterize)	$3\lambda/D$ (Ref. 14)	
	OWA	$\sim64\lambda/D$	$24\lambda/D$ (Ref. 15)	
	Bandpass	10% to 20% (instantaneous) 400 nm to 1.8 μm (total)	20% (Ref. 14)	
		200 nm to 2.5 μm (goal)		
	Aperture	Obscured, segmented	Unobscured (Ref. 14)	
	WFSC	Fast WFSC at low stellar photon rates to generate initial dark hole	Multihour WFSC to generate initial dark hole, using bright laboratory sources	
		Low-order terms sensed and corrected to maintain 1×10^{-10} contrast	Tip/tilt errors sensed and corrected at subhertz frequencies (Ref. 16)	
DMs	Actuator Count	128×128 (continuous) >3000 (segmented)	64×64 (continuous) <200 (segmented)	3
	Environmental	Robust, radiation hard	Testing underway	
	Electronics	>16 bits	~16 bits	
		High-speed, high-throughput cabling and ASICs	Dense, single-point failure cables and electronics	
Autonomous onboard processing	Bandwidth	Closed-loop > a few Hz	Human-in-the-loop once every 14 days (JWST)	3
	Electronics	Radiation hard, >100 GFLOPS/W	SpaceCube 2.0 (Ref. 17)	
Starlight suppression image processing	PSF calibration	>10× improvement in contrast	3× demonstrated (Ref. 18)	3

WFSC, wavefront sensing and control; IWA, inner working angle; OWA, outer working angle; λ, wavelength; D, aperture diameter; ASIC, application-specific integrated circuit; GFLOPs, giga-floating-point-operations; PSF, point spread function.

>8 m diameter aperture capable of fitting in current and planned launch vehicles will almost surely be obscured, and very likely segmented.[7] Recent technology investments for the WFIRST mission have demonstrated that current coronagraphs can be made to work in the presence of additional diffraction due to aperture obscurations, although usually at the cost of throughput and Strehl ratio of the planet point-spread function (PSF).[19] Newer, less-mature coronagraph designs show promise in meeting the demanding contrast, IWA, and bandwidth requirements while also maintaining high throughput and high planet-PSF Strehl ratio with an obscured or segmented aperture.[20–22]

We adopt the same assumptions as Stark et al.,[9] and envision that the instrument would operate in two modes: detection and characterization. In detection mode, the coronagraph would operate in the visible band (~550 nm) and require higher contrast (1×10^{-10}) but would operate at a slightly relaxed IWA of $3.6\lambda/D$ (41 mas, for a 10-m aperture). The detection mode would be sufficient to detect a rocky world in the habitable zone and potentially identify it as a target of interest by at least identifying broad H_2O features in the spectrum. Once a target of interest has been identified, the instrument would switch to characterization mode, in which key spectral features in the NIR are of interest. In order to operate at longer wavelengths yet still keep the planet within the high-contrast region of the focal plane between the IWA and OWA, a smaller IWA of $2\lambda/D$ (41 mas for a 10-m aperture at 1 μm) is required. However, the contrast ratio can be slightly relaxed to 5×10^{-10} with a planet identified and located in the focal plane. This dual-mode operation alleviates the need to have the instrument simultaneously work at both the highest possible contrast and at the smallest IWA.

Similarly, we do not expect that the coronagraph will simultaneously work over the entire band between 400 nm and 1.8 μm (or the stretch goal of 200 nm to 2.5 μm). Instead, the instrument should be capable of working at a 10% to 20% instantaneous bandwidth. Complete characterization over the entire band would require either serial observations over each instantaneous bandpass, or parallel observations with several coronagraphic instruments, each tuned to a specific bandpass.

3.3 *Wavefront Sensing and Control*

In order to obtain a high-contrast image, the coronagraph must null speckles in the focal plane by controlling the amplitude and phase of the aberrated field produced by the optical system. A wavefront sensing and control system not only performs this task to create the initial focal plane "dark hole," where a planet might be observed, but also maintains the wavefront as the observatory experiences thermal and dynamic drifts during an observation with active control.

Several techniques have been developed to use the focal plane information to perform speckle nulling. However, these techniques have been demonstrated only in controlled lab environments with bright, artificial sources. On orbit, the stellar photon rate is substantially lower. The time required to acquire enough signal to generate a wavefront correction can require the speckle nulling task to last many hours. Laboratory demonstration of dark-hole generation with realistic stellar photon rates and in the presence of observatory instabilities is required.

Once the dark hole has been formed, dynamic and thermally induced drifts in the telescope's wavefront must be sensed and corrected to maintain a wavefront error stability of ~10 pm RMS per control step, i.e., at whatever update rate, the active wavefront sensing and control system is operating, the wavefront drift between control updates must be less than 10 pm RMS. For WFIRST, a low-order wavefront sensing (LOWFS) system has been developed and demonstrated to sense and correct tip, tilt, and focus.[16] Further development will be required for ATLAST to include additional low-order wavefront terms, including coma, astigmatism, and spherical aberration, as well as maintain a higher level of correction of these terms to achieve the 10 pm RMS stability requirement. It is also worth noting that metrology systems discussed in Sec. 5.6 would also contribute to the overall wavefront sensing architecture.

3.4 *Deformable Mirrors*

The wavefront sensing system uses DMs to perform wavefront correction. There are several varieties of DMs, ranging from larger-format mirrors that use voice coil, piezoelectric, or lead-magnesium-niobate electrostrictive actuators, to smaller microelectromechanical systems format mirrors. DMs can have either a continuous facesheet surface, where individual actuators push or pull on the surface to deform it, or they can have a segmented surface, where each individual segment can be controlled in piston, tip, and tilt degrees of freedom. In many coronagraphs, two DMs are required to correct speckles over a symmetric region of the focal plane. Actuated hybrid primary mirror segments, discussed in Sec. 5.6, can also serve as a DM system to correct coronagraph wavefronts.

Investments in DM technology have improved actuator performance, actuator yield, and actuator count for all varieties of DMs.[23] However, additional improvements are necessary for ATLAST-type performance requirements. The outer-working angles (OWAs) in the high-contrast region of the focal plane are largely determined by the number of DM actuators via a Nyquist relationship, e.g., a 64×64 actuator device can achieve an OWA of $\sim 32\lambda/D$, Thus, higher actuator count devices will be necessary to access larger OWAs. Better cable harnessing with reliable connections will be essential, and environmental testing is necessary to ensure DMs are robust enough to survive launch, and the radiation environment of the Sun-Earth L2 orbit. Finally, fast, high-precision, stable (i.e., low noise) electronics will enable finer control of wavefront errors while providing wavefront stability between control steps.

3.5 *Autonomous Onboard Processing*

The speckle nulling and low-order wavefront sensing and control algorithms will need to run autonomously onboard the spacecraft. The computational complexity itself is not a challenge: the algorithms are routinely demonstrated to run autonomously in lab settings. Modern day desktop computers equipped with consumer-level graphics processing units (GPUs) provide enough computational horsepower to control coronagraph systems at 10s or even 100s of Hz. However, these platforms consume hundreds of watts of power and are not traceable to a flight architecture. Development is needed to port coronagraphic control algorithms to flight-qualified, radiation-hardened, low-power computer architectures, including field-programmable gate arrays and application-specific integrated circuits (ASICs).

3.6 *Starlight Suppression Image Processing*

While starlight suppression systems are expected to provide raw contrasts on the order of 10^{-10}, additional gains in contrast will provide margin against scenarios in which the raw contrast achieved by the coronagraph is insufficient to detect or characterize an exoplanet. Image postprocessing techniques, such as PSF calibration and subtraction, have been shown to deliver large gains in contrast for systems with higher raw contrast of 10^{-5} or so.[18,24] For the direct imaging and characterization of exo-Earths, it is believed that gains of 10× or more will be needed for coronagraphs with raw contrast of 10^{-9} to 10^{-10}.

3.7 *Current and Future Development Activities*

Internal coronagraphs are currently receiving substantial investment as part of the WFIRST study,[25] which should be leveraged as much as possible for ATLAST. The development of wavefront sensing algorithms and low-order wavefront sensing, robust DMs, onboard processing, and PSF calibration and subtraction can be directly applied to ATLAST's needs. However, significant additional investment is still required to bridge the gap between WFIRST's performance requirements, and those of ATLAST.

Notably, coronagraphs are needed that achieve an order-of-magnitude higher contrast, and they must do so while maintaining higher throughput in the presence of aperture obscurations and segmentation than is currently achieved with the WFIRST coronagraphic instruments. This is perhaps the single highest-priority technology investment needed for ATLAST. Fortunately, there are several promising options. Phase-induced amplitude apodization complex-mask coronagraphs (PIAA-CMC),[21] apodized pupil Lyot coronagraphs (APLC),[20] and visible nulling coronagraphs[22] theoretically work with obscured and segmented apertures at high-throughput, and other designs are beginning to show promise as well. In 2016, the Exoplanet Exploration Program Office initiated the Segmented Coronagraph Design and Analysis study, which will model the performance of existing and to-be-developed coronagraph designs with a range of aperture architectures, including various obscured and segmented configurations.[26] Coronagraph designs that perform well in these simulation studies should be demonstrated in traceable testbeds in the next 3 to 5 years to verify their performance.

In addition to the WFIRST development, NASA's Strategic Astrophysics Technology (SAT) program funds a portfolio of technologies relevant to this technology area, including coronagraph instrument designs, wavefront sensing and control, DM development, coronagraph modeling, and detector development.[27] A number of small-business innovative research (SBIR) program grants have also been made to develop DMs.

In addition to continuing to leverage the WFIRST development, our ATLAST team recommends continued investment in the development of individual coronagraph architectures through the rest of this decade. By about 2020, three or four candidate coronagraph architectures should be selected for targeted, high-priority development, culminating in a TRL 5 demonstration and downselect to two instrument designs in 2023. By mission PDR around 2025, the two instruments should be demonstrated at TRL 6 and prioritized as primary and backup flight instruments.

4 Starshade

4.1 *Technology Overview*

A starshade, or external occulter, is a second starlight suppression technique. Instead of suppressing the diffracted starlight with an instrument inside the telescope, a starshade blocks all of the starlight from entering the telescope to begin with. The starshade is a separate spacecraft, flying in formation with the observatory at separation distances of tens or hundreds of thousands of kilometers. The starshade size, separation distance, and petal-shaped edge are specially designed to cast a dark shadow at the telescope's entrance aperture, allowing the exoplanet's light to be observed directly.

Although analysis indicates that an internal coronagraph provides the highest exo-Earth yield for an ATLAST-like mission,[13] the coronagraph possesses some inherent limitations that a starshade does not. First, despite the promise of the PIAA-CMC, APLC, and PONC concepts, it is still possible that no single instrument will achieve the required contrast, IWA, bandwidth, and throughput performance with an obscured or segmented aperture. On the other hand, it is possible that they can deliver the performance, but at the cost of unachievable wavefront stability of the telescope. In this scenario, a starshade may be the preferable starlight suppression technique.

An additional limitation for an internal coronagraph is the scaling of the IWA with λ. Assuming a 10-m aperture, a planet that is detected at $3.6\lambda/D$ at 550 nm moves to $\sim 2\lambda/D$ in the focal plane when observed at 1 μm. As the desired characterization wavelength shifts longer, where many of the interesting spectral biomarkers exist,[28] the coronagraph must achieve the more challenging task of working at higher-contrast closer to the stellar-PSF core. A starshade can be specifically designed to operate in the near-IR at small IWAs for follow-up spectral characterization and biomarker confirmation.

We therefore include starshade development in the technology plan as both risk mitigation in the event that an internal coronagraph proves prohibitively difficult, or as a mission enhancement to provide greater depth of exoplanet characterization in a potential ATLAST rendezvous. Table 4 summarizes the technology needs and current state of the art for the starshade technology area.

4.2 *Starshade Construction and Deployment*

To date, many of the investigations into starshade construction and deployment have been for starshade designs optimized for smaller aperture telescopes <4 m in diameter. The Exo-S Probe Study STDT, for example, considered starshade designs for a 1.1-m telescope and for the 2.4-m WFIRST telescope.[32] The central truss design, petal design, and deployment techniques would need to be re-evaluated, and likely redesigned for a telescope with an aperture greater than 8 meters.

4.3 *Optical Edges*

To reduce reflected glint, the optical edges must achieve razor sharpness, with an edge radius of curvature ≤1 μm.[31] The edges must also maintain a precision shape when deployed, and remain optically dark, with low reflectivity. Machined graphite and chemically etched metal edges are both close to meeting the necessary performance, with the former lacking a small enough edge radius and the latter lacking the deployed shape tolerance.

4.4 *Formation Flight*

A starshade works by essentially casting a shadow on the trailing telescope. In order to maintain the necessary image-plane contrast for exoplanet observations, the telescope must remain in that shadow, requiring high-precision formation-flight

Table 4 Starshade technology components gap list.

Technology component	Parameter	Required	State-of-the-art	Estimated current TRL
Starshade construction and deployment	—	Petal and central truss design consistent with an 80-m class starshade.	Demonstrated prototype petal for 40-m class starshade, excluding blankets and optical edges (Ref. 29)	3
		Demonstrate manufacturing and deployment tolerances	Demonstrated deployment with 12-m Astromesh antenna and four petals (Ref. 30)	
Optical edges	Edge radius Specular Reflectivity	$\leq 1\ \mu$m (Ref. 31) $\leq 10\%$ (Ref. 31)	$\geq 10\ \mu$m (Ref. 32) —	3
	Stowed radius	≤ 1.5 m (Ref. 32)	—	
Formation flight	Lateral sensing accuracy	≤ 20 cm	—	3
	Peak-to-peak control	<1 m	—	
	Centroid estimation	$\leq 1/40$th of a pixel at stellar flux rates	$\leq 1/100$th of a pixel with bright lab sources	
Contrast performance demonstration and model validation	—	1×10^{-10} broadband contrast at Fresnel numbers ≤ 50.	3.3×10^{-11} contrast excluding petal edges, narrowband, at Fresnel number of ~ 500	3
		Testbed performance correlated with model predictions.	Model correlation is good in regions excluding petal edges (Ref. 33)	
Starshade propulsion and refueling	—	Refueling and propulsion to enable >500 slews during 3 years of a 5-year mission	5-year mission assuming solar electric propulsion (Ref. 34) robotic refueling appears feasible for extended mission lifetimes but requires study	3

sensing and control.[35] The guidance, navigation, and control of maintaining the telescope position relative to the starshade is believed to be tractable; however, sensing the position of the starshade at separation distances of hundreds of thousands of kilometers is challenging and requires demonstration. To maintain alignment between star, starshade, and telescope, a guidance camera can compare the centroid of two signals: an out-of-band beacon on the starshade and the out-of-band starlight that leaks around the edges of the starshade. To maintain adequate alignment, the guidance camera must be able to compute centroids to within 1/40th of a pixel at low stellar flux rates.

4.5 *Contrast Performance Demonstration and Validation*

One of the biggest challenges to demonstrating starshade performance is that a full-sized, end-to-end optical test of a starshade can never be performed on Earth due to the size of the necessary structures, gravity sag, and the separation distances required between source, starshade, and telescope. Instead, the theoretical models that are used to predict starshade performance must be verified and validated. Subscale laboratory demonstrations that preserve the Fresnel number of a flight starshade-telescope configuration must be performed.

Initial demonstrations[36] indicate model-predicted contrasts at Fresnel numbers that are factors of $\sim 10\times$ too large. Additional efforts are underway to improve laboratory and field demonstrations to more closely match flight-like configurations.[37]

4.6 *Starshade Propulsion and Refueling*

The greatest limitation to starshades is the reduced exo-Earth yields due to the finite number of slews that can be executed in the mission lifetime, either due to fuel consumption, or to propulsion capabilities.[13] Launching multiple starshades is one possible solution. Additional starshades could even be adapted in response to the planets that are discovered by an initial starshade launch. Alternatively, the ability to continuously refuel a starshade provides an extendable mission lifetime, and therefore, more slews, with a single starshade. New propulsion technologies may also provide faster slews for more observations with a fixed amount of fuel. Both of these developments would provide mission-enhancing capabilities to an ATLAST-starshade concept.

4.7 *Current and Future Development Activities*

Starshade technology development activities have mostly been funded out of NASA's SAT program, focusing on model validation, formation flight, and optical materials for edges and blankets.[27] NASA's SBIR program has also promoted industry involvement in deployable structures and actuators. Engaging industry partners on a larger scale will be critical to developing deployment strategies and truss designs for larger starshades that work with telescopes that are greater than 8 m in diameter.

Propulsion and refueling technologies should be investigated to help improve exo-Earth yields. Robotic refueling has been extensively studied and demonstrated in low-Earth orbit.[38] A study of the appropriate trade space is required, addressing such questions as: "Which services are required?" (refueling, repair, replacement, and so on); "Where should servicing be performed?" (low-earth orbit, cis-lunar space, SEL2, and so on); "How much fuel is needed, and how often?"; and "What infrastructure exists, and what will be required?".

These activities should be pursued through the rest of this decade, culminating in the design, fabrication, and demonstration of an 80-m-class starshade truss with a few petals in the early 2020s. A probe-scale (or smaller) mission demonstrating the deployment, operation, and formation flight of a smaller-scale starshade would also pave the way for larger starshade missions in the future.[32]

5 Ultra-Stable Large Aperture Telescope Systems

5.1 *Technology Overview*

The extraordinary wavefront stability requirements levied on an observatory by an internal coronagraph necessitate that the entire observatory be developed as a system, including mirrors, structures, disturbance isolation and damping, metrology, actuators, and thermal control systems.

Assuming the high-contrast exoplanet science is performed with an internal coronagraph, the top-level requirement for wavefront stability is currently understood to be tens of picometers RMS per wavefront control step.[10,11] This is based on the current set of coronagraphs being developed for the WFIRST mission. It is also generally accepted that the control frequency of the wavefront sensing and control system is on the order of tens of minutes, although it depends specifically on the coronagraph architecture, observing strategy, wavefront sensing system, and brightness of the host star. As these are still trades yet to be performed, we desire to make the telescope as stable as possible to accommodate the possibility of a slow wavefront control system coupled with a demanding coronagraphic instrument.

Table 5 summarizes the technology needs and current state of the art for the ultra-stable large aperture telescope system technologies.

5.2 *Mirrors*

Mirror technologies for operation at near-room temperature in space are actually not far from where they need to be in terms of areal density, cost, and production. The biggest challenges involve incorporating the mirrors into the larger system and maintaining thermal and dynamic stability. In the case of mirror segments, demonstrating the necessary thermal control at the segment level, as well as maintaining segment-to-segment stability is needed. In the case of a monolithic architecture, it is necessary to demonstrate that stiff, lightweight mirror fabrication techniques are scaleable to an 8-m-class primary mirror.

Our ATLAST team recommends a mirror development program similar to the Advanced Mirror System Demonstration.[52] Multiple mirror materials (ULE®, Zerodur®, SiC, composite, and so on) and mirror architectures (open versus closed back, monolith versus rigid-body segments versus high-authority actuated segments, and so on) should be evaluated and compared.

5.3 *Structure Materials*

Subscale demonstrations of backplane and mirror support structures should be used to advance the development of new composite materials with lower outgassing and new joint designs to reduce micro/nano-lurch properties. As an example, the backplane stability test article (BSTA) on JWST demonstrated that the lightweight cryogenic composite could meet its required stability. The work demonstrated mirror pad mount interface motion of 28.5 nm/K over a 25 K static gradient from 30–55 K.[53] By comparison, ATLAST will need about 3 pm/K but over a gradient of a few mK at room temperature, and a subscale test will be critical to that demonstration. The inherent stiffness of silicon carbide (SiC) makes it an attractive option for the support structure, although additional effort will be required to maintain thermal stability; SiC has a higher coefficient of thermal expansion (CTE) than glass, requiring finer thermal control, on the order of 0.1 mK instead of $\sim$1 mK for glass. Most importantly, testing a subscale structure, regardless of material, at the picometer level will validate linearity assumptions that are commonly used in integrated modeling. Once validated, integrated modeling can then be used to accurately predict the performance of full-scale systems.

A distributed, tiered-approach to thermal control needs to be studied and implemented. Elements of the thermal control system could include: (1) thermally stable mirrors with uniform CTE distributions; (2) new thermally stable composite material structures, or fast thermal control systems for a SiC structure; (3) observatory-level architecture trades between flat sunshields similar to JWST or stray-light barrels similar to HST; (4) new thermal sensing and control schemes to manage residual thermal instabilities. Components of this tiered-approach may require new technologies (e.g., new materials or sensing technologies) or may require only engineering development to achieve the necessary system performance.

5.4 *Dynamic Stability (Disturbance Isolation)*

Dynamic stability of the system can be improved by either making the structures and mirror more massive, or by isolating the optical system from the disturbance sources. The advancement of industry-developed noncontact isolation technology,[54] which has the potential of meeting the stringent dynamic stability requirements, should also be prioritized. Demonstrating the required isolation with this type of system at TRL 6, including power and data transmission across the bus-payload interface, will retire a key risk. It is also important to investigate other potential isolation and pointing techniques (i.e., reaction wheel isolation systems, microthrusters, and so on) that may be combined to meet the dynamic stability requirements in order to increase margin and reduce overall system cost and risk.

5.5 *Metrology and Actuators*

Similar to the thermal control system, a tiered approach to metrology and wavefront control is needed. Components, such as image-based wavefront sensing, laser metrology, or capacitive edge sensors, should be studied in combination to detect dynamic disturbances over various temporal and spatial

Table 5 Ultra-stable large aperture telescopes technology components gap list.

Technology component	Parameter	Required	State-of-the-art	Estimated current TRL
Mirrors	Surface figure	<7 nm RMS: 5 nm < 4 cpa	<7 nm RMS (Ref. 39)	4
		5 nm 4 to 60 cpa		
		1.5 nm 60 cpa to 100 μm/cyc		
		<1 nm > 100 μm/cycle		
	Areal density	<36 kg/m^2 (DIVH)	~12 kg/m^2 (SiC w/nanolaminates) (Ref. 40)	
		<500 kg/m^2 (SLS)	~9.8 kg/m^2 (MMSD) (Ref. 41)	
			20 kg/m^2 (JWST) (Ref. 42)	
	Areal cost	<2 M/m^2	< 3 M/m^2 (JWST) (Ref. 43)	
	Areal production rate	30 to 50 m^2/year	~6 m^2/year (JWST) (Ref. 43)	
			~100 to 300 m^2/year planned by TMT but not yet demonstrated (Ref. 44)	
Structure materials	Moisture expansion Lurch	<1 ppt/day <10 pm/WFC step	<50 ppb/day (Ref. 45) Micro-lurch at joints (Ref. 46)	3
	Thermal stability	~10 nm/K	~100 nm/K (Ref. 47)	
Disturbance isolation system	End-to-end attenuation	140 dB at frequencies >20 Hz	80 dB at frequencies >40 Hz (JWST passive isolator only; Ref. 48)	4
Metrology and actuators	WFE estimation accuracy	5 pm RMS in compact form	<1 pm RMS in noncompact forms (Ref. 49) <1 nm RMS in compact forms (Ref. 50)	3
	Control accuracy	~1 pm	~7.7 nm (Ref. 51)	

RMS, root-mean-square; cpa, cycles per aperture; DIVH, delta IV-heavy; SLS, space launch system; SiC, silicon carbide; MMSD, multiple mirror system demonstration; TMT, thirty meter telescope; WFC, wavefront control.

frequencies. Metrology of the optical train using laser distance measuring gauges arrayed in an optical truss configuration could provide high-bandwidth measurements of the optical state even when there is no guide star for wavefront sensing, such as during telescope slews. Maintaining optical alignment during a slew would help reduce the overhead associated with coronagraph observations by providing a stable, known optical state at the beginning of the speckle nulling routine, rather than starting from "scratch" after every telescope slew. Extension of the metrology technology developed for the SIM and TPF projects[55] offers the potential for picometer accuracy estimation of the wavefront errors due to misalignments, at bandwidths over 100 Hz, in a compact and lightweight form. Primary and secondary mirror control via segment-level rigid-body actuators or embedded high-authority actuators[40] may be paired with DMs in the instrument payload to provide the picometer-level control needed for high-contrast imaging.

5.6 *Current and Future Development Activities*

The ultra-stable large aperture telescope technology area is equal in priority to the development of an internal coronagraph and requires a systems level approach to providing a picometer-level stable wavefront. Yet, it is receiving very little attention and funding. The Advanced Mirror Technology Development program has been funded through NASA's SAT program to investigate mirror technologies and has focused primarily on fabrication techniques relevant to large monolithic systems.[56] A recent SAT award also focuses on developing high-speed speckle interferometry to investigate dynamics of ultra-stable structures. In addition to these efforts, a significant investment in developing the telescope as a system is critical.

Technology development of mirrors, structures, thermal architectures, disturbance isolation systems, and metrology systems should continue through the rest of this decade. All of these components should be brought together in the early 2020s in a subscale testbed to demonstrate the required wavefront stability, as well as validate integrated modeling techniques at the picometer level. A systems-level demonstration at TRL 5 by 2023 would allow a TRL 6 demonstration by mission PDR around 2025.

6 Detectors

6.1 *Technology Overview*

The habitable exoplanet detection and characterization component of ATLAST is enabled by improvements in extremely low-noise detectors in the visible-NIR band (VISIR; 400 nm to 1.8 μm). Single-photon detectors would be preferred if the cooling challenges could be solved without introducing unacceptable vibration and wavefront disturbance. While promising VISIR technologies exist, additional improvements for radiation hardness and further reductions in noise and dark count rate are required to maximize mission science yield.[9]

For the visible, radiation hardening electron-multiplying charge-coupled devices (EMCCDs) would be a wise first step. Space radiation tolerance was not a design consideration for the current generation parts. The radiation tolerance of EMCCDs can almost certainly be improved by applying known CCD radiation hardening techniques.[57] The interested reader is referred to Canavan et al.[58] and references therein for more information on the radiation tolerance of EMCCDs and what can be done to improve it for LUVOIR.

The exoplanet characterization science goal is enhanced by further developments of extremely low-noise, single-photon detectors in the UV (200 to 400 nm). These are needed to detect a strong ozone bandhead at 260 to 350 nm that is a potential biosignature.[28]

The general astrophysics component of ATLAST can be enhanced by improvements in large-format, high-sensitivity, radiation-hard UV detectors. To take advantage of the resolution afforded by a large-aperture system, higher-pixel-count detectors are needed to cover desired fields-of-view. Furthermore, current UV detector technologies are limited in sensitivity at all wavelengths, but especially <150 nm, where critical science goals exist. Some applications also benefit from "visible blind" detectors with little or no sensitivity for wavelengths longer than 300 nm.

In all cases, it is extremely desirable to avoid the need for cryogenic operation that requires a cryocooler in order to minimize cost, complexity, mass, and vibration that may impact wavefront stability for high-contrast exoplanet science. Only cooling technologies that can fit within a realistic vibration budget without being the dominant component in the error budget should be considered.

Table 6 summarizes the technology needs and current state of the art for the detector technology area. Additional information on detector technologies for biosignature characterization can be found in Canavan et al.[58]

6.2 *Low Noise Visible-Near-Infrared Detectors*

We do not expect that a single detector technology will necessarily span the VISIR band. Rather, these two bandpasses (visible and near-IR) are lumped together as they are both critical to enabling the desired exoplanet science for biomarker detection.

In the visible regime, EMCCD technologies are the most promising and are currently being developed as part of the WFIRST coronagraph technology development plan, specifically undergoing full characterization and radiation testing. Even if EMCCDs are deemed acceptable for WFIRST, the detectors that are being radiation tested now may not be sufficiently radiation hardened for LUVOIR. In other contexts, the n-channel design and thick oxide layers that are employed in current generation EMCCDs are known to cause radiation tolerance problems.[57] Fortunately, phasing in known radiation hardening techniques could be accomplished in 2 to 3 years with appropriate investment.[57]

In the near-infrared, it is likely that the overall performance of HgCdTe photodiode array systems can be incrementally improved beyond what will be achieved for WFIRST. We believe that some improvement is possible in both sensor chip array performance and the readout electronics. The result would not be a single-photon detector system, but it would increase mission science yield.[9]

For all wavelength bands, superconducting technologies such as microwave kinetic inductance detectors (MKIDs) and transition edge sensor (TES) arrays function as single-photon detectors with built-in energy resolution. To our knowledge, they are the only VISIR array detector technologies that have functioned as single-photon detectors at relevant flux levels. The built-in energy resolution offers the possibility of building a nondispersive imaging spectrograph that would require ~100× fewer pixels than a conventional spectrograph. For both MKID and TES arrays, improvements in energy resolution and photon absorption efficiency would be required.[58]

The biggest disadvantage is the need for cryogenic operation for MKID and TES detectors. Ultra-low-vibration cryocooler technology development would be necessary to enable the use of these detectors while simultaneously achieving the picometer-level stability required to perform high-contrast imaging. In this context, "ultra-low" means that the cryocooler can be accommodated within a realistic vibration budget without being the most significant contributor to the error budget.

6.3 *Ultraviolet Single-Photon Detectors*

Extending the bandpass of exoplanet characterization into the UV will be necessary to observe the O_3 spectral band at 255 nm. Development of these detector technologies represents an enhancement to the science mission but is not necessary to meet fundamental science goals. The main challenge to overcome in this regime is to simultaneously enable single-photon detections while improving the overall sensitivity of the detectors to at least 50%. One approach to meeting these goals might be to apply δ-doping or bandwidth-specific antireflective coatings to detector technologies that also meet science requirements for noise and radiation hardness.[59]

6.4 *Large-Format High-Sensitivity Ultraviolet Detectors*

For general astrophysics observations in the UV, sensitivity and array size are the driving requirements. Improving the quantum efficiency to greater than 70% and array sizes to greater than 2000×2000 pixels is needed. For many applications, it is also necessary (or desirable) to have the UV detectors be "visible blind"—that is have sufficiently suppressed response at wavelengths greater than 300 nm.

6.5 *Current and Future Development Activities*

A number of detector technology development efforts are currently funded by NASA's SAT, Astrophysics Research and Analysis (APRA), and SBIR programs; other technologies [such as scientific complementary metal–oxide–semiconductor (sCMOS)] are under active commercial development. For future efforts, close collaboration between government, academic, and industry partners will promote detector advancements. A near-term priority should be to radiation-harden

Table 6 Detector technology components gap list.

Technology component	Parameter	Required	State-of-the-art	Estimated current TRL
Vis-NIR low noise detectors for enabling exoplanet science	Operational bandwidth	400 nm to 1.8 μm (2.5 μm goal)	EMCCD technology is promising, but could be improved by radiation hardening, and has a hard cutoff at 1.1 μm; HgCdTe APDs are candidates for NIR but need better dark count rates (Refs. 57 and 58) Superconducting MKID and TES meet requirements, but need cryogenic temperatures. Smaller formats ($\sim 100 \times 100$ pixels) are acceptable for energy resolving MKID and TES (Ref. 58)	3 to 5
	Read noise	$\ll 1$ e$^-$		
	Dark current	<0.001 e$^-$/pix/s		
	Spurious count rate	Small compared to dark current		
	Quantum efficiency	>80% over entire band		
	Format	>2 k $\times$ 2 k pixels		
	Other	Radiation hard, minimum 5-year lifetime at SEL2, noncryogenic operation preferable		
UV low noise detectors for enhanced EXOPLANET science	Operational Bandwidth	200 to 400 nm	GaN-based EBCMOS and MCP detectors meet required noise specifications, but require better quantum efficiency to >50% and improvements in lifetime Superconducting MKID and TES detectors also apply here (Ref. 58)	2 to 4
	Read noise	$\ll 1$ e$^-$		
	Dark current	<0.001 e$^-$/pix/s		
	Spurious count rate	Small compared to dark current		
	Quantum efficiency	>50% over the entire band		
	Format	>2 k $\times$ 2 k pixels		
	Other	Radiation hard, minimum 5-year lifetime at SEL2, noncryogenic operation preferable		
Large-format high-sensitivity UV detectors for general astrophysics	Operational bandwidth	90 to 300 nm	Same as above δ-doped EMCCD also a candidate here but requires improved radiation hardness and reduction in clock-induced charge. Current δ-doped EMCCDs are not visible blind (Ref. 59)	4
	Read noise	<5 e$^-$		
	Quantum efficiency	>70%		
	Format	>2 k $\times$ 2 k pixels		
	Other	Radiation hard, minimum 5-year lifetime at SEL2, noncryogenic operation preferable, visible blind		

EMCCD, electron multiplying charge coupled device; SEL2, sun–earth Lagrange 2; APD, avalanche photodiode; MKID, microwave kinetic inductance detector; TES, transition edge sensor; EBCMOS, electron bombarded complementary metal-oxide semiconductor; MCP, micro-channel plate.

EMCCD technologies to withstand a nominal mission in a halo orbit at the Sun-Earth L2 point. Additional development of HgCdTe APD, MKID, TES, sCMOS, and other technologies can be pursued via parallel paths, perhaps by several competing teams, with modest funding. Downselecting candidate technologies around 2020 will help focus resources toward mission-specific milestones in time for a TRL 6 demonstration by mission PDR around 2025.

In the event that superconducting detector technologies such as MKIDs and TESs are selected, investment in ultra-low vibration cooling solutions will be critical to enabling the exoplanet science component of ATLAST.

7 Mirror Coatings

7.1 Technology Overview

A UVOIR telescope, such as ATLAST, will require protected aluminum coatings very similar to those employed on HST, which are arguably already TRL 9. However, some mission-enhancing gains in coating performance can be realized via better coating deposition processes. Furthermore, some new study is required to fully understand the impact of instrument-induced polarization effects on coronagraph performance.[60,61]

Our ATLAST team recommended four areas of improvement: higher reflectivity (specifically in the Far-UV), better coating uniformity of all the layers in the mirror coating across the entire UVOIR bandpass, lower induced polarization phase, and amplitude differences between orthogonal polarizations and cross polarization leakage (specifically over the exoplanet science band between 400 nm and 1.8 μm), and better durability.

Table 7 summarizes the technology needs and current state of the art for the mirror coating technology area.

7.2 Reflectivity, Uniformity, Durability

It is unlikely that much will change in the fundamental technology of coatings. By far, the best coating for a broad UVOIR bandpass is aluminum protected by a thin dielectric layer (typically, MgF_2, LiF, or AlF_3). Instead, investments should be focused on improving deposition processes for these materials. New techniques in atomic layer deposition (ALD) and ion-beam assisted physical vapor deposition (IBAPVD) can improve material packing densities, resulting in higher reflectivity and better uniformity.[66–68] Importantly, scaleable processes that can be applied to meter-class segments and 8-m-class monoliths should be developed.

7.3 Induced Polarization Aberration

The effect of coating polarization on high-contrast imaging with a coronagraph is an issue that needs to be addressed regardless of what coating is used. All metallic coatings induce a polarization change on the light that is reflected, an effect that is dependent on the angle-of-incidence, and is usually increased by the dielectric overcoat. The net effect is polarization-induced aberration, whereby each polarization state of the incident light "sees" a different wavefront error upon propagation through the system. Additionally, cross-polarization leakage introduces additional aberrations in each polarization state. These polarization aberrations present a challenge to high-contrast imaging with a coronagraph, since only a single-polarization state can be sensed and controlled at a time, requiring serial observations in each polarization state, or dual coronagraph instruments operating in parallel. This is also an area in which technology development for WFIRST can be leveraged.[60,61] Even though the WFIRST coatings are protected silver, polarization aberration is still induced in the collected light. A thorough understanding of how ATLAST's protected aluminum coatings affect polarization aberration, and the impact of that aberration on achieving 10^{-10} contrast needs to be quantified and understood. If the effects are significant, a mitigation plan is needed to implement polarization control/correction in the coronagraph.

7.4 Current and Future Development Activities

Similar to the other technology areas, mirror and component coatings are being developed under a number of efforts funded by NASA's SAT, APRA, and SBIR programs. In the near term, deposition processes and coating technologies to improve reflectivity, uniformity, polarization aberration, and durability can be pursued on small-scale samples, although techniques that are scaleable to large mirrors should be given preference. The most promising processes and coating formulas should be demonstrated on a large-scale, flight-traceable mirror system by 2023, potentially being incorporated into the subscale stability testbed that is recommended in Sec. 5.6.

The impact of mirror curvature and coating properties on the polarization wavefront error, and how this affects the high-contrast image produced by a coronagraph requires special attention[60,61,65] and will impact architecture decisions for the ATLAST optical design. The WFIRST program has addressed one potential solution to this problem, which is to observe and control the wavefront for only a single polarization at a time (effectively losing 50% of the incoming planet light). Additional methods should be investigated, including dual-channel coronagraphs, simultaneous control of both polarization states, telescope architecture trades to reduce the angles of

Table 7 Mirror coatings technology components gap list.

Technology component	Parameter	Required	State-of-the-art	Estimated current TRL
Reflectivity	90 to 120 nm	70%	<50% (Ref. 62)	2
	120 to 300 nm	>90%	80% (Ref. 62)	3
	>300 nm	>90%	>90% (Ref. 62)	5
Reflectivity uniformity over the full aperture	90 to 120 nm	<1% (Ref. 63)	TBD (Ref. 64)	2
	120 to 250 nm	<1% (Ref. 63)	>2% (Ref. 64)	2
	>250 nm	<1% (Ref. 63)	1 to 2% (Ref. 64)	3
Induced polarization aberration	≥90 nm	<1%	Not yet assessed; requires additional study (Ref. 65)	2
Durability	—	Stable performance over mission lifetime (10 years minimum)	Stable performance, but with limited starting reflectivity below 200 nm	4

incidence on relevant optical surfaces, and how improvements in coating formulas or deposition techniques may be used to reduce the impact on polarization. General astrophysics observations are unlikely to be impacted by polarization aberrations or cross talk, unless one is interested in observing the state of polarization of galactic sources.

8 Conclusion

In response to the high-priority recommendation to NASA in the 2010 NRC Decadal Survey, we developed a technology gap assessment for the ATLAST mission concept that is broadly applicable to a range of observatory options. Five key technology areas that enable the ATLAST mission were developed in detail: internal coronagraphs, starshades, ultra-stable large aperture telescopes, detectors, and mirror coatings. For each technology area, we presented a technology gap list and a high-level plan for developing each technology component in time for a notional mission start date in the mid-2020s.

Internal coronagraphs that leverage the recent development for the WFIRST mission will be critical to detecting and characterizing habitable exo-Earths. Specifically, they will be required to achieve 10^{-10} contrast at IWA of $\sim 2\lambda/D$ over the visible to NIR band, while maintaining high throughput and operating with obscured and segmented apertures.

A starshade is a possible alternative to an internal coronagraph, or more likely, an enhancement to a mission already equipped with a coronagraph. Starshades that are compatible with telescope apertures greater than 8 m in diameter are needed. Methods of improving starshade slew rates, or increasing the number of slews possible in a mission lifetime, should also be investigated in order to improve exo-Earth yields.

To enable high-contrast imaging with an internal coronagraph requires extraordinary wavefront stability, on the order of 10 pm RMS per wavefront control step. To achieve this level of stability, the telescope, and indeed the entire observatory, must be designed and assessed as a system, incorporating all aspects of the mirrors, structure, thermal control system, dynamic control system, metrology, and actuation.

Detector sensitivity is critical to achieving both the exoplanet and general astrophysics science missions. Ultra-low noise detectors that cover the visible to NIR bandpass are necessary to achieve sufficiently low-noise for exoplanet detection and characterization. General astrophysics observations will benefit from improved sensitivity and larger format detectors in the UV.

Improved mirror coatings are needed to leverage the large collecting area of an aperture >8 m in diameter. Deposition techniques that improve reflectivity, uniformity, and coating durability that are also scaleable to larger mirrors are needed. The polarization aberration due to mirror coatings and its impact on high-contrast imaging with a coronagraph also need exploration.

While we present each of these technology areas separately, it is important to recognize the inter-related nature of the entire system. The performance capabilities of each of these technologies will impact the performance requirements of each of the others. Ultimately, a systems-level approach to studying and developing these technologies will be necessary.

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