Potential large missions enabled by NASA's Space Launch System

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ABSTRACT

Large space telescope missions have always been limited by their launch vehicle's mass and volume capacities. The Hubble Space Telescope (HST) was specifically designed to fit inside the Space Shuttle and the James Webb Space Telescope (JWST) is specifically designed to fit inside an Ariane 5. Astrophysicists desire even larger space telescopes. NASA's "Enduring Quests Daring Visions" report calls for an 8- to 16-m Large UV-Optical-IR (LUVOIR) Surveyor mission to enable ultra-high-contrast spectroscopy and coronagraphy. AURA's "From Cosmic Birth to Living Earth" report calls for a 12-m class High-Definition Space Telescope to pursue transformational scientific discoveries. NASA's "Planning for the 2020 Decadal Survey" calls for a Habitable Exoplanet Imaging (HabEx) and a LUVOIR as well as Far-IR and an X-Ray Surveyor missions. Packaging larger space telescopes into existing launch vehicles is a significant engineering complexity challenge that drives cost and risk. NASA's planned Space Launch System (SLS), with its 8 or 10-m diameter fairings and ability to deliver 35 to 45-mt of payload to Sun-Earth-Lagrange-2, mitigates this challenge by fundamentally changing the design paradigm for large space telescopes. This paper reviews the mass and volume capacities of the planned SLS, discusses potential implications of these capacities for designing large space telescope missions, and gives three specific mission concept implementation examples: a 4-m monolithic off-axis telescope, an 8-m monolithic on-axis telescope and a 12-m segmented on-axis telescope.

Keywords: space telescopes, astrophysics, astronomy, ATLAST, LUVOIR, HabEx.

1. INTRODUCTION

The astrophysics science community desires larger more capable space telescopes to answer some of humanity's most compelling questions. The 2010 *New Worlds, New Horizons* Decadal Report[1] recommended as its highest priority medium-scale activity a New Worlds Technology Development (NWTD) Program to "lay the technical and scientific foundations for a future space imaging and spectroscopy mission". NASA's *Enduring Quests Daring Visions*[2] called for an 8- to 16-meter Large UV-Optical-IR (LUVOIR) Surveyor mission to "enable ultra-high-contrast spectroscopic studies to directly measure oxygen, water vapor and other molecules in the atmospheres of exoEarths"; and, "decode the galaxy assembly histories through detailed archeology of their present structure." And, AURA's *From Cosmic Birth to Living Earths*[3] details the potential revolutionary science that could be accomplished with a 12-m class space telescope: from "directly finding habitable planets showing signs of life" to "producing transformational scientific advances in every area of astronomy and astrophysics from black hole physics to galaxy formation, from star and planet formation to the solar system." The proposed High-Definition Space Telescope (HDST) concept would achieve unprecedented angular and spectral resolution from the UV to Near-IR. The baseline concept is a 12-m serviceable observatory, diffraction limited at 500 nm, operating at Sun-Earth-Lagrange-2 (SE-L2) with a versatile instrument package to optimize its scientific yield. In response, NASA's "Planning for the 2020 Decadal Survey"[4] calls for consideration of a Habitable Exoplanet Imaging Mission (HabEx) and a Large UV/Optical/IR Surveyor (LUVOIR) as well as Far-IR and X-Ray Surveyor missions. A detailed discussion of the long term desire for larger space telescope missions can be found in Thronson et al[5].

There are many potential mission concepts to provide larger more capable space telescopes to the astrophysics science community[5-9] including three proposed by the 2008 ATLAST study[10] and another three proposed by the 2015 ATLAST study[11]. Unfortunately, packaging larger space telescopes into existing launch vehicles is a complex engineering challenge that drives cost and risk. Any telescope mission placed in space on a single launch has been fundamentally constrained by that launch vehicle's mass and volume capacities. This was true for Hubble, Chandra and the James Webb Space Telescope (JWST) and will be true for any potential LUVOIR or HabEx. The Hubble Space Telescope (HST) and Chandra X-ray telescope were specifically designed to match the Space Shuttle's payload volume and mass capacities, Table 1. (Note: Hubble was actually sized based on maximum abort landing mass.) And the James Webb Space Telescope (JWST) is designed to match the capacities of an Ariane 5, Table 2.

Table 1. Space Shuttle Launch Capabilities vs Science Missions Requirements		
	Payload Mass	Payload Volume
Space Shuttle Capabilities	25,061 kg (max at 185 km) 16,000 kg (max at 590 km)	4.6 m x 18.3 m
Hubble Space Telescope	11,110 kg (at 590 km)	4.3 m x 13.2 m
Chandra X-Ray Telescope (and Inertial Upper Stage)	22,800 kg (at 185 km)	4.3 m x 17.4 m

Table 2. Ariane 5 Launch Capabilities vs JWST Science Missions Requirements		
	Payload Mass	Payload Volume
Ariane 5	6600 kg (at SE L2)	4.5 m x 15.5 m
James Webb Space Telescope	6530 kg (at SE L2)	4.47 m x 10.66 m

This paper asserts that the mass and volume capacities of NASA's planned Space Launch System (SLS) mitigates engineering complexity by enabling simpler, more robust mission architectures with enhanced performance and reduced cost and risk, than can be accomplished on a launch vehicle with less volume and mass capacity. This paper reviews the SLS's planned mass and volume capacities, discusses the implications of these capacities for designing large space telescope missions, and gives three specific mission concept implementation examples: a 4-meter monolithic off-axis telescope, an 8-meter monolithic on-axis telescope and a 12-meter segmented on-axis telescope.

2. POTENTIAL SPACE LAUNCH SYSTEM CAPABILITIES AND CAPACITIES

As described in the SLS Mission Planner Guide[12], the SLS program is conducting a phased development effort frequently referred to as Block-1, 1B, and 2 (Figure 1). It should be noted that these configuration descriptors apply only to the launch vehicle and not to the fairing. Block-1 uses shuttle derived liquid engines and solid rocket boosters. It also uses an interim, commercially derived, upper stage propulsion system that can only be used with a 5-meter fairing and limits the payload mass to 70+ mt to LEO. Block-1 is available no earlier than 2018. The Block-1B replaces the interim upper stage with a new Exploration Upper Stage (EUS). The EUS is designed for an 8.4 meter fairing and enables 105+ mt to LEO. Block-1B is available no earlier than 2021. Block-2 replaces the Block-1's solid rocket boosters with new advanced boosters that enable payload mass of 130+ mt to LEO. These more powerful boosters also allow for longer 8.4m and 10m diameter payload fairings. Block-2 is available no earlier than 2028.

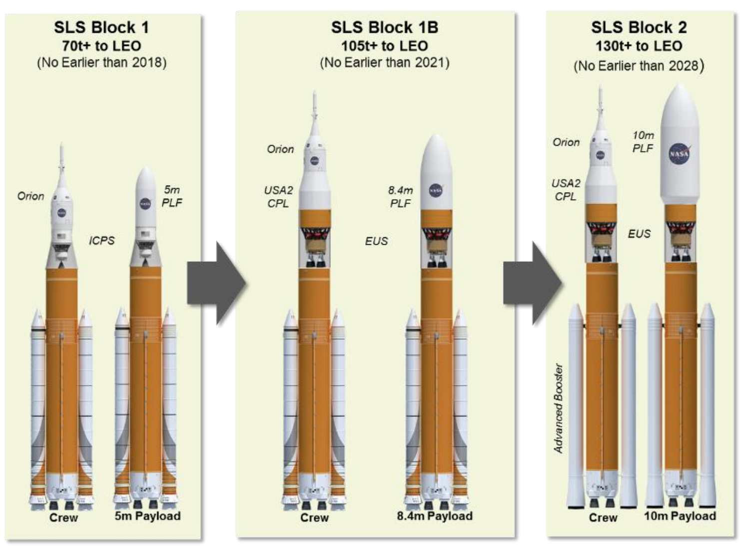


Figure 1: SLS Block Development Plan

Figure 2 shows the planned payload fairing options. The 5-m fairing is a commercial fairing and is planned for Block-1. The 8.4-m 'short' and long fairings are for Block-1B and Block-2. They are available no earlier than 2022. The only difference between a short and long fairing is the addition of a cylindrical 'barrel' section. The 10-m fairings is exclusively available for Block-2 and available no earlier than 2028. All SLS versions will be compatible with the Orion crewed human spacecraft (not shown). For Block-1B and Block-2, the conical Universal Stage Adapter (USA) that connects the EUS to the Orion is hollow and can accommodate a 7.5 to 4.5-m diameter (conical) by 8.4-m tall 'co-manifested' payload. For the Block-1B, the projected mass goal of this payload is 10 mt; and, for the Block-2 the projected mass goal is 20-mt.

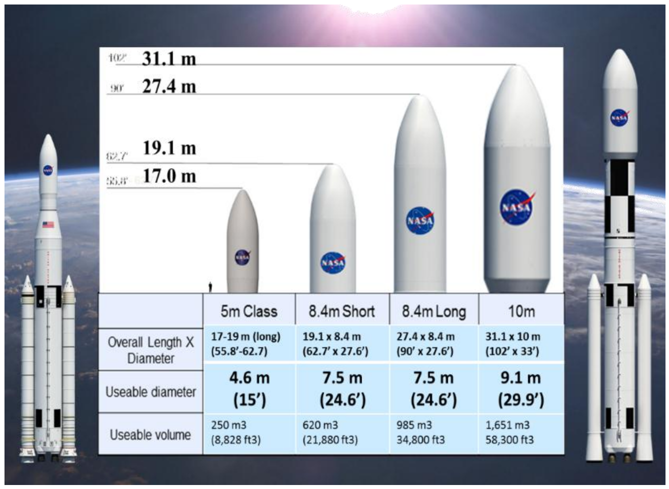


Figure 2: SLS Payload Fairing Volume Options

Figure 3 summarizes the SLS's projected mass capacity. Block-1 is projected to have the ability to launch a 25 mt payload into a Sun-Earth Lagrange point (SE-L2) transfer orbit (with a C3 = -0.7 km^2/s^2). Block-1B, with its 8.4-m 'short' fairing (7.5-m by 16.5-m dynamic envelope), will be able to launch 35 to 40 mt to SE-L2. Block-2, with its 8.4-m 'long' fairing (7.5-m by 24.8-m dynamic envelope), will be able to launch ~50 mt to SE-L2. Finally, Block-2, with its 10-m fairing (9.1-m by 24.8-m dynamic envelope), will be able to launch ~ 45 mt to SE-L2.

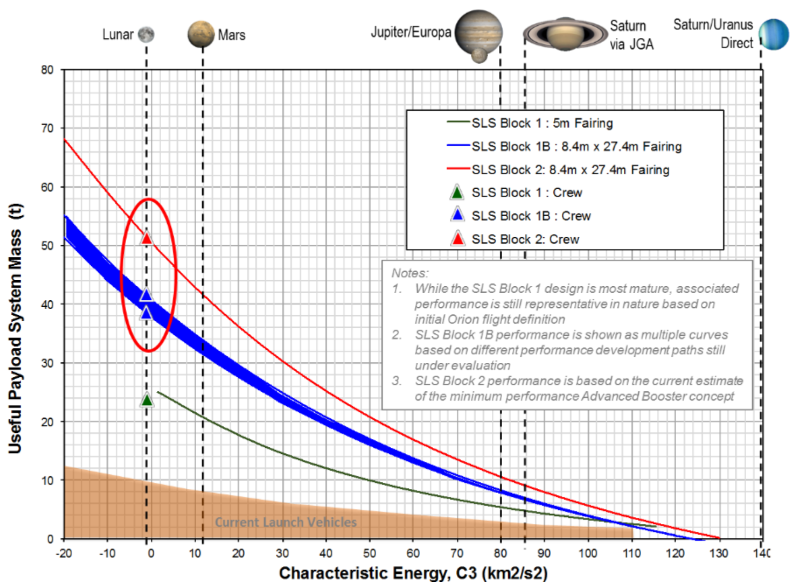


Figure 3: Planned SLS Mass to Orbit Capacities

Additionally, the SLS Mission Planner Guide[12] contains extensive details regarding payload interfaces and the SLS's launch environment, including: thermal, vibration, shock and acoustic.

3. MISSION IMPLICATIONS OF SLS CAPACITIES: DESIGN FOR AFFORADABILITY

3.1 Design for Affordability

There are many different potential architectures for a large space telescope. But all potential architectures are constrained by launch vehicle mass and volume capacities, and by the authorized budget. It is the fundamental premise of NASA's Marshall Space Flight Center (MSFC) that complexity drives cost. MSFC believes that an important way to reduce complexity and lower mission cost is to use a launch vehicle with a large payload mass and volume capacity. Having a large volume capacity can be important in simplifying packaging inside the fairing, i.e. minimizing deployments. Having a large mass capacity allows for design approaches and margins which might make ground handling and launch survival easier. Having more mass to orbit and volume can also provide options for designing a stiff and stable telescope.

MSFC's commitment to simplicity is based on the work of David Bearden[13-14]. He has shown that there is a direct correlation between mission payload complexity and total mission cost; between complexity and cost, and schedule growth; and that the greatest predictor of mission success is technology maturity. The reason for these relationships is because the only way to achieve increasingly demanding performance requirements in a mass and volume constrained launch vehicle is to design increasingly complex mission payload architectures. JWST is actually a case study example of Bearden's methodology. Consider how JWST's cost was driven by the complexity of a deployment architecture needed to package a 6.5 meter telescope inside a 4.5 meter fairing and the light-weighting need to fit within a 6500 kg mass capacity. The JWST Independent Comprehensive Review Panel found that JWST is "one of the most complex science missions carried out to date and therefore falls at the high end of the range, greater than 90%, on the complexity index. JWST is consistent with being "in family" for a Life Cycle Cost around $6 billion–$7 billion"[15] (Figure 4). It should be noted that originally, JWST was even more complex. The initial primary mirror design called for 36 segments in 3 rings. But, based on complexity arguments (with its associated cost and risk) it was decided to change to a 2-ring 18-segment design. The cost versus complexity relationship is also evident in the NASA Advanced Mission Cost Model[16] (Figure 5). While many assert that this model says that mass is the dominant mission cost driver, a closer look at the model indicates that cost grows more with increasing Difficulty Level (DL) than with increasing mass. Mass is only the dominant effect in the model if difficulty is constant. Cost can be reduced more by decreasing difficulty than by reducing mass. It is interesting to observe where HST and JWST fall on the NASA model. According to the model, at ~6500kg JWST is nearly half HST's 11,110kg mass. Thus, if JWST and HST were equally difficult, then JWST should be 70% the cost of HST. But, JWST's ~$6.5B Phase A-D total mission cost is over 2X the ~$3B cost of HST.

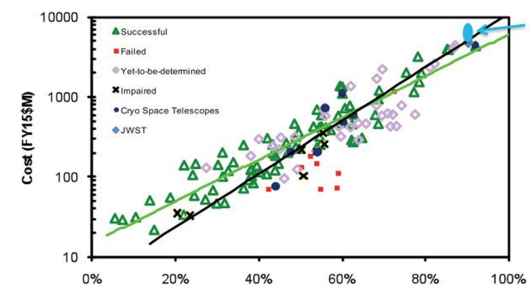


Figure 4: JWST on the Aerospace Complexity Index[15]

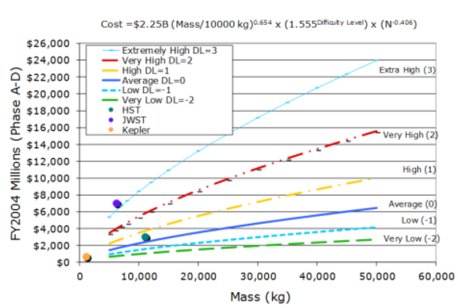


Figure 5: NASA Advanced Mission Cost Model[16]

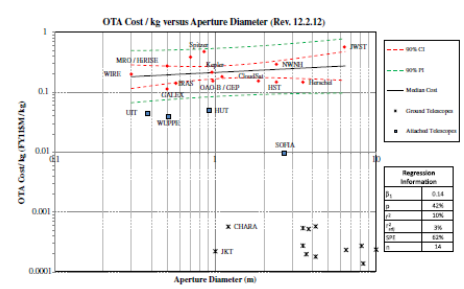


Figure 6: OTAs built to different design-margin mass budgets have different cost densities (cost per kilogram).

Given the available mass and volume capacity of the SLS, some subsystems may be able to use simpler, more mature (and more massive) technologies or higher design rule margins to eliminate complexity, lower risk and lower cost. According to the Air Force, the biggest drivers for reducing cost are reuse of heritage components and having a high mass margin.[17] Another Air Force study found that inserting new technology into a program versus using heritage technology can double total system cost, while reusing existing design and technology can reduce cost at least 50%.[18] Technology reuse saves money on sub-system acquisition as well as engineering labor and management overhead. Because of program overhead, a savings of $500M in component cost might reduce total program cost by $1B to $2B.[19] Evidence of cost saving associated with high mass margin is shown in Figure 6. On average, free-flying telescopes have the lowest design margins and highest cost per unit mass. The Shuttle attached telescopes and SOFIA are designed to entirely different margin rules and have lower costs. And, ground telescopes have the most robust design margins and lowest cost density.[19] For completeness, the biggest drivers for increasing cost are tight thermal stability requirements, design complexity, inadequate requirement definition and number of unique oversight organizations. This last point is reinforced by the fact that for all Air Force space projects, program management and systems engineering is the single largest cost element.[17]

4. SLS MASS ENABLED DESIGN RULES

In developing a new mission concept, the most important question is: 'Is there a concept that fits within the mass and volume capacities of the launch vehicle?' For example, the JWST design was driven by the capacity limits of the Ariane 5. While, as demonstrated on JWST, volume constraints can be overcome by clever (complex) engineering, it is much more difficult to overcome the mass constraint. Having a larger mass capacity launch vehicle provides designers with more options. This Section describes one approach for how launch vehicle mass capacity can be flowed down from the payload to the observatory and finally to the primary mirror assembly.

4.1 Payload Mass

Per Section 2, the SLS Block-1B is expected to have an up-mass to SE-L2 of 35 to 40 mt; Block-2 is expected to have an up-mass of ~50 mt for the 8.4-m fairing and ~45 mt for the 10-m fairing. Unfortunately, mission designers are not allowed to utilize the total expected mass capacity. NASA MSFC routinely uses a 30% margin; and, for the HabEx study, the Exoplanet Exploration Program Office required a 43% mass margin. Table 3 summarizes the total mass available to mission developers based on launch vehicle and design margin. As a point of reference, JWST's design mass constraint was 6500 kg and HST's mass was 11,000 kg.

Table 3: Available Payload Mass after Margin

SLS	Block-1B min	Block-1B max	Block-2 (10m)	Block-2 (8.4m)
Projected Mass to SE-L2	35,000 kg	40,000 kg	45,000 kg	50,000 kg
Max Payload with 30% Margin	26,900 kg	30,800 kg	34,600 kg	38,500 kg
Max Payload with 43% Margin	24,500 kg	28,000 kg	31,500 kg	35,000 kg

4.2 Observatory and Spacecraft Mass

The next step is to flow payload mass into an allocation for the observatory and spacecraft - where observatory is defined to include the telescope assembly and science instruments; and, the spacecraft is defined to include propulsion, avionics, power, and propellant. Historically, because of launch vehicle mass capacity, mission concept designers must minimize mission mass and thus the mass of every subsystem. But, in our study, we explored a different question. How might we allocate the maximum mass allowed by the SLS? And how might that mass impact performance?

Systems engineering analysis indicates that to achieve the most challenging science measurement goal of detecting and characterizing the atmosphere of an exoEarth-like planet in the Habitable Zone requires a telescope with ultra-stable wavefront error on the order of 10 picometers per 10 minutes[21]. While not designed to meet the requirements of a UV/Optical/IR Surveyor (UVOIR) exoplanet science mission, JWST is an example of what is possible. The predicted response of JWST is <13 nm rms for temporal frequencies up to 70 Hz[22]. The JWST structure has an ~40 nm rms 'wing flap' mode at ~20 Hz and the individual Primary Mirror Segment Assemblies have a ~20 nm rms 'rocking' mode at ~40 Hz. To meet the exoplanet stability requirement, these amplitudes need to be reduced by 1000×. JWST engineers estimate that JWST could achieve this level of performance by a combination of methods: an ambient telescope will have 10× more damping, the structure can be made stiffer, and active vibration isolation can be added. JWST has ~90 dB of isolation and to achieve UVOIR performance requires ~140 dB of isolation.

One approach to achieve such a demanding level of isolation is the Lockheed Martin (LM) Disturbance Free Payload (DFP) technology[23]. The DFP approach achieves a high level of payload vibration isolation with a non-contact electro-magnetic interface that effectively "floats" the payload separate from the spacecraft. At the request of NASA MSFC, the LM Advanced Technology Center studied the sensitivity of DFP isolation performance to: (a) payload mass fraction (that is, the fraction of total system mass that is associated with the payload); and (b) the total system mass (that is, the sum of payload and spacecraft mass). The vibration isolation performance metric is expressed as a payload-to-spacecraft transmissibility, which is defined as the ratio of Payload angular motion to the Spacecraft angular motion, due to a common disturbance force and/or torque located on the Spacecraft. The transmissibility is dependent on disturbance frequency, and its maximum value for all frequencies greater than 10 Hz is plotted in Figure 7 versus payload mass fraction, for three different total observatory masses (6, 20 and 30 metric tons). The sensitivity analysis was performed by holding all system parameters (such as payload-to-spacecraft cable stiffness, electromagnetic actuator residual coupling) constant and scaling both Spacecraft and Payload mass and inertia linearly[24]. From Figure 7, two observations can be made. First, for a given total system mass, the transmissibility improves (i.e., the ratio of payload to spacecraft angular motion decreases) as the Payload mass fraction increases. Second, as the total system mass increases, the transmissibility improves, as indicated by the family of curves shifting to more negative dB as shown in Figure 7. It is noted that while isolation performance improves with increasing system mass and increasing payload mass fraction, other system design and launch vehicle considerations will largely dictate these quantities. It should also be noted that payload mass fraction does not affect the payload pointing accuracy or pointing stability. The payload points itself relative to inertial space by commanding the non-contact interface actuators and using its own knowledge of pointing error directly sensed on the payload (by means of a fine guidance camera, or a suite of inertial attitude sensors). The spacecraft controls its attitude via reaction wheels to ensure the non-contact of the DFP interface.

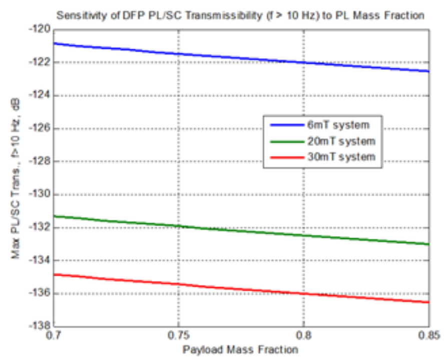


Figure 7: Role of Mass and Mass Distribution in performance of Lockheed Disturbance Free Payload isolators.[24]

4.3 Primary Mirror Mass and Areal Density

For any potential large space telescope, the primary mirror assembly will be the single most important design element and its mass will be central to the design. Based on Section 4.2, to maximize vibration isolation via a DFP interface, we choose to allocate 80% of the payload mass to the observatory. And, we choose to allocate ~50% of the observatory (40% of total mission) mass to the primary mirror assembly. While this may seem simplistic, it is a matter of engineering necessity. There is a limit to how light-weighted, or low-stiffness, mirror can actually be fabricated. And, there is great benefit to having as stiff a mirror as possible. Mirror stiffness minimizes G-release uncertainty and on-orbit dynamic motion. Thus, larger aperture telescopes will require a larger portion of the total mission mass. For reference, HST's 2.4-m PMA was about 17% of total mission mass and JWST's 6.5-m PMA is about 28%. As shown in Table 4, these simple mass assumptions can provide first order system design insight as to the maximum areal density allowed for each size telescope.

Table 4: Flowdown from allowable Payload Mass to Primary Mirror Areal Density

SLS	Block-1B	Block-2 min	Block-2 max
Max Payload Mass with 43% Margin	24,500 kg	31,500 kg	38,500 kg
Spacecraft Allocation (20% of Payload)	5,000 kg	6,250 kg	7,500 kg
Observatory Allocation (80% of Payload)	20,00 kg	25,000 kg	30,000 kg
Science Instruments (10% of Observatory)	2,000 kg	2,500 kg	3,000 kg
Telescope (PMA, SMA, and Structure) (90%)	18,000 kg	22,500 kg	27,000 kg
SMA and Structure	8,000 kg	10,000 kg	12,000 kg
Primary Mirror Assembly Allocation	10,00 kg	12,500 kg	15,000 kg
Primary Mirror Assembly Areal Mass	[kg/m^2]	[kg/m^2]	[kg/m^2]
4 meter diameter (12.5 m^2)	800	1000	1200
8 meter diameter (50 m^2)	200	250	300
12 meter diameter (100 m^2)	100	125	150
16 meter diameter (200 m^2)	50	62.5	75

To help assess feasibility of these areal density limits relative to the state of art, Hubble's primary mirror assembly (primary mirror and structure) weighed ~1860 kg for an areal density of 460 kg/m^2; and its primary mirror weighed ~740 kg for an areal density of 180 kg/m^2. The JWST Primary Mirror with Back Plane Support Structure has an areal density of ~70 kg/m^2; and its primary mirror segment assemblies have an areal density of ~30 kg/m^2. Additionally, an Arizona 8.4-meter 'cast' mirror substrate has an areal density of ~300 kg/m^2 and the Thirty Meter Mirror Telescope mirror segments have an areal density of ~150 kg/m^2. Finally, the Advanced Mirror Technology Development program has demonstrated a sub-scale mirror that is 'traceable' to a 4-meter diameter x 40 cm thick monolithic mirror with an areal density of 60 kg/m^2 (without support structure)[25]. It is reasonable to extrapolate from these examples that a primary mirror assembly with an areal density of >100 kg/m^2 is within the state of the art. Further, as part of the three design concept discussed below, we have determined that mirrors of this areal density can be manufactured and tested to UVOIR specifications; and, that support systems can be designed to keep their maximum stress during launch well below accepted limits. And, the higher its areal density, the lower its fabrication cost and risk.

5. THREE EXAMPLE SLS ENABLED MISSIONS CONCEPTS

Since 2007, the NASA MSFC Optics Office and Advanced Concepts Office (ACO) has developed multiple large telescope mission concepts using a heavy lift launch vehicle. This Section summarizes three separate concepts in the order of their development: ATLAST-8, ATLAST-12 and HabEx-4. Each concept has two goals: 1) provide mission performance capabilities that meet science requirements[6, 26-27] (summarized in Table 5) to enable the potential LUVOIR or HabEx mission as defined by NASA's *Enduring Quests Daring Visions*[2] report or enable the HDST mission as defined in AURA's *Cosmic Birth to Living Earth*[3] report; and, 2) fully utilize the mass and volume capacities of the SLS for placing a mission into a Sun-Earth Lagrange 2 halo orbit. Each concept was developed and documented in a standard ACO report. The following information illustrates each concept and touch on some of the more interesting engineering features. Complete cost estimates were generated for each concept but are considered NASA proprietary.

Table 5 Science requirements flow-down to the ATLAST telescope.[27]

Parameter		**Requirement**	**Stretch Goal**[†]	**Traceability**
Primary Mirror Aperture		≥ 8.0 meters	> 12.0 meters	Resolution, Sensitivity, Exoplanet Yield
Telescope Temperature		273 K – 293 K	-	Thermal Stability, Integration & Test, Contamination, IR Sensitivity
Wavelength Coverage	UV	100 nm – 300 nm	90 nm – 300 nm	-
	Visible	300 nm – 950 nm	-	-
	NIR	950 nm – 1.8 μm	950 nm – 2.5 μm	-
	MIR	Sensitivity to 8.0 μm[‡]	-	Transit Spectroscopy
Image Quality	UV	< 0.20 arcsec at 150 nm	-	-
	Vis/NIR/MIR	Diffraction-limited at 500 nm	-	-
Stray Light		Zodi-limited between 400 nm – 1.8 μm	Zodi-limited between 200 nm – 2.5 μm	Exoplanet Imaging & Spectroscopy SNR
Wavefront Error Stability		~ 10 pm RMS uncorrected system WFE per wavefront control step	-	Starlight Suppression via Internal Coronagraph
Pointing	Spacecraft	≤ 1 milli-arcsec	-	-
	Coronagraph	< 0.4 milli-arcsec	-	-

[†]Stretch goals are identified where mission enhancing capabilities could be realized. [‡]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

5.1 Origin of ATLAST

The path to an 'ATLAST' launched via a heavy lift rocket started when this paper's lead author attended the November 28-30, 2006, "Astrophysics enabled by the return to the Moon" workshop at Space Telescope Science Institute. Because of his role leading the effort to develop mirrors to enable JWST[28-29] he knew firsthand the limitations associated with reducing mirror areal density to meet a required primary mirror mass allocation. And, because of his role as a co-author of the NASA 2005 'Advanced Telescopes and Observatory' Capability Roadmap[30-31] he knew that reducing mass had been identified as a critical technology required to enable the agencies highest priority future astrophysics missions. As Dr. Harley Thronson presented a briefing on the Constellation project and capabilities of the planned Ares V, it was instantly obvious that this was a disruptive technology which solved many problems facing potential future astrophysics missions. With a phone call to Dr. Matt Mountain, Director of the Space Telescope Science Institute, ATLAST was initiated.[32] Dr. Mountain assigned Dr. Marc Postman to develop the science case; and, it was Dr. Postman who coined the ATLAST acronym. The first STScI/MSFC concept was a 6-meter monolithic Ares-V launched telescope[7,33]. In 2008, NASA awarded the Space Telescope Science Institute and its NASA Center Partners (GSFC, JPL and MSFC) an Astrophysics Mission Concept Study called Advanced Technology Large-Aperture Space Telescope (ATLAST). The ATLAST final report[10] documents three potential mission concepts: ATLAST-8m (MSFC) [34-40], ATLAST-9.2m (GSFC)[41-42], and ATLAST-16m (Northrop). The MSFC ATLAST-8 Team included members from GSFC, Ball Aerospace Technology Corporation, and Northrop Grumman. Since 2014, NASA GSFC refined their ATLAST-9 concept and developed a new ATLAST-11 concept[11]. In 2015, NASA MFSC performed new studies for a 12.7-meter on-axis segmented telescope (ATLAST-12), a 4-meter off-axis telescope (HabEx-4) and refreshed the ATLAST-8 concept.

5.2 ATLAST-8: 8-meter on-axis monolithic aperture concept for LUVOIR

ATLAST-8 (Figure 8) is an 8-meter monolithic aperture UVOIR space observatory in a cold-biased heated Kepler style scarfed straylight tube with a dual foci optical design. It is designed for a 30 year operational life at SE-L2 enabled by servicing. While which instruments go at each focus will be determined by the science community, the baseline plan is a coronagraph and UV spectrometer at the narrow FOV Cassegrain focus, and an imager and multi-object spectrograph at the wide FOV foci. The revised ATLAST-8 concept retains much from the 2009 Mission Concept Study which performed detailed studies on: optical design; structural design/analysis including primary mirror support structure, sun shade and secondary mirror support structure; thermal analysis; spacecraft conceptual design including structure, propulsion, GN&C, avionics, thermal and power systems; mass and power budgets; and system cost[10]. In 2015, MSFC updated the study for differences between the Ares V and SLS. Finally, ATLAST-12 and HabEx-4 share many of ATLAST-8's elements, including the optical design, the heated scarfed straylight baffle, the momentum management subsystem and the spacecraft design.

Figure 8: ATLAST-8 with scarfed Kepler style light baffle and deployable solar panels for momentum control.

5.2.1 Optical Design and Science Instrument Accommodation

The Optical Telescope Assembly (OTA) has a dual-field design with three foci: a 1 arc-minute Cassegrain focus and two 8 x 23 arc-minute Three-Mirror Anastigmatic (TMA) foci (Figure 9) [36-37]. All three are diffraction limited at 500 nm. The main telescope is a two-mirror system which forms the narrow-field-of-view (NFOV) Cassegrain image (Figure 10). The Cassegrain focus provides a high quality NFOV focus for exo-planet characterization science and a high-throughput two-bounce path for UV spectroscopy science. The wide field of view (WFOV) imager, multi-object spectrograph and IFU spectrograph are divided between the two TMA foci. Separating the two WFOV instruments allows flexibility in packaging as well as future servicing.

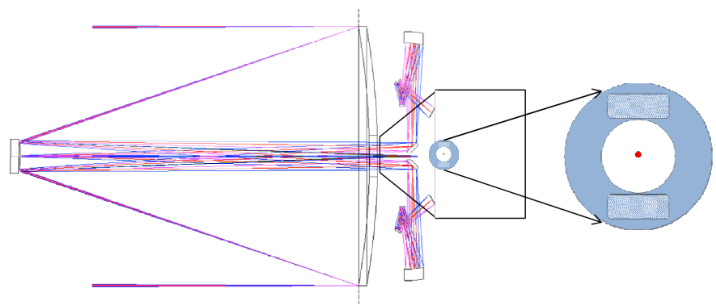


Figure 9: Optical Layout of 8-m OTA showing 2 TMA foci and Cass focus (at red dot)

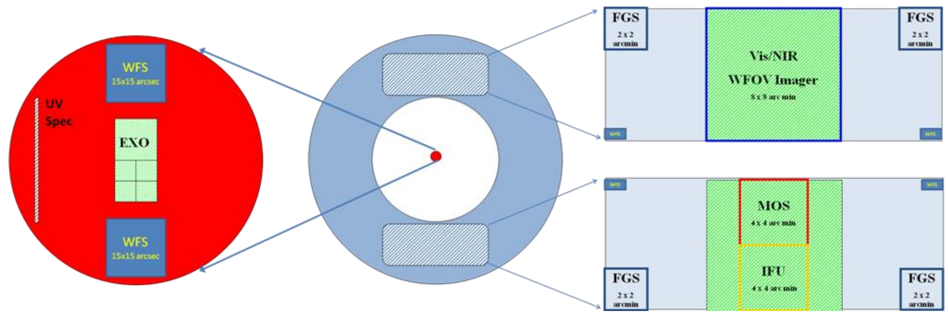


Figure 10: Cassegrain and TMA Foci Instrument Allocations.

Additionally, each focus has wavefront sensors and each TMA focus has two Fine Guidance Sensors (FGS). The FGS system has four modules, two in each WFOV TMA focus (one active and one backup). ATLAST-8m controls pointing using guide stars in two FGS modules separated on the sky by 0.5 degree. This separation provides roll control about the boresight at a lower bandwidth and with much better stability than the 0.2 mas rms requirement.

All three foci are directly accessible to a 4.0 m diameter by 4.5 m deep instrument bay centered on-axis behind the primary mirror. The spacecraft envelope surrounds the instrument bay, which is isolated from both the primary mirror support structure and the instrument bay. The Instrument Command and Data Handling unit (IC&DH) provides centralized OTA electronics for control of telescope mechanisms and heaters, wavefront sensing (WFS) processors, and science instruments. Each instrument module is a self-contained On-orbit Replaceable Unit using HST-style mounting rails accessible from the back of the instrument bay to facilitate servicing missions. The instrument bay provides all required mechanical, electrical, data and thermal interface connections for the science modules using standard HST-style 'blind-mate' connectors.

The primary and secondary mirrors' optical coatings are identical to what was used by HST: aluminum with MgF2 overcoat to provide good spectral transmission from 110 nm to 2400 nm. These coatings are important to the UV science instruments at the Cassegrain focus. Two pick-off fold mirrors, on either side of the Cassegrain focus, direct off-axis portions of the Cassegrain image plane to two tertiary-mirror aft-optics assemblies, which form two WFOV 8 x 22 arc-min TMA images. The TMA provides a 13 milli-arc-second plate scale. The aft optics are coated with Kepler protected silver for enhanced visible/near-IR spectral transmission.

5.2.2 Structure

Structure is critical to ATLAST-8's ability to provide the wavefront stability required for exoplanet science. Taking advantage of the SLS's mass and volume capacity, a very deep, very stiff, and massive structure was designed. The design philosophies are simplicity, modularity, and redundancy. To mitigate assembly risk, the structure is designed using a bolt-together truss structure of repeated components. Each component is fabricated with a conservative design margin and tested individually. The structure is designed to safely launch an 8-meter primary mirror (PM) and maintain the on-orbit optical alignment necessary to achieve a 500 nm diffraction limited telescope. Using fault-tolerant design principles, the PM support structure provides a 10X margin of safety during launch by distributing the forces between 66 axial and lateral support points to keep the primary mirror max stress loads at least an order of magnitude below its design limit. For more information, the reader is referred to Arnold et. al. (2009)[38].

The ATLAST-8 structure contains several major elements (Figure 11): primary mirror support structure, metering truss, instrument bay, secondary mirror spiders, aft optics structure and payload adapter fixture (PAF)[38]. The back structure supports the primary mirror during launch. The forward structure, which is attached to the back structure as are the spacecraft and the science instruments, supports the secondary mirror assembly and straylight baffle. A key design element is that all observatory mass (telescope, instruments and spacecraft) is carried via a separate skeletal load-path through the back support structure to an interface ring which attaches via the PAF to the launch vehicle. This allows the use of a completely conventional spacecraft; i.e. it does not need extra mass because it does not provide the interface between the observatory and the launch vehicle. During launch, the spacecraft is attached to the rear of the telescope structure, and does not support the observatory nor transfer launch loads to the launch vehicle. Structural elements were sized for 5g axial and 2g lateral sustained loads, with a yield and ultimate factors of safety of 1.25 and 1.4, respectively.

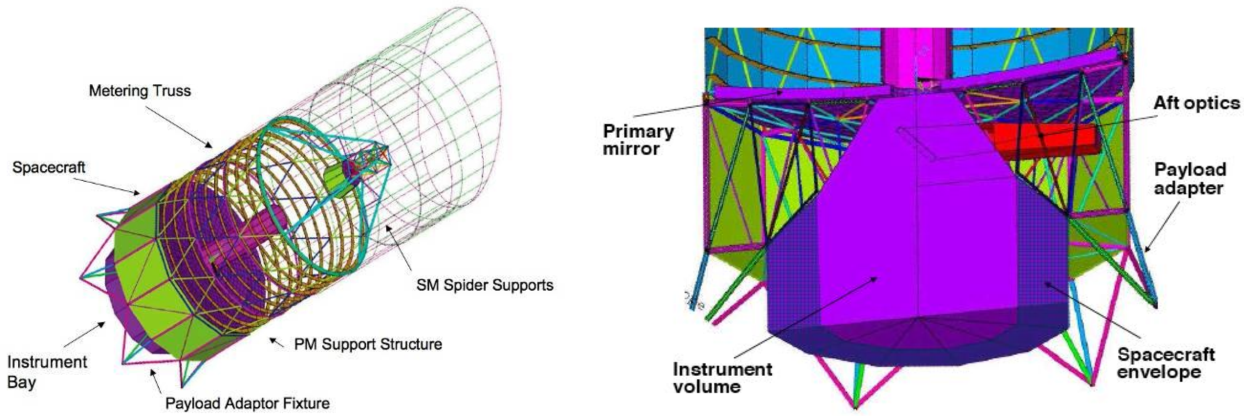


Figure 11: ATLAST-8 Observatory Structural Layout

5.2.3 Spacecraft and Momentum Management

The spacecraft provides all pointing, power, communication, data handling, station keeping, momentum unloading, and thermal control for the ATLAST-8m telescope and its science instruments, and provides the propulsive maneuvers for midcourse corrections[40]. Key requirements include enabling the observatory to slew 60 degrees in 90 minutes (required) or 40 minutes (desired); ensuring a coarse pointing stability of 1.6 mas; enabling the observatory to roll about the telescope's line of sight by ± 30 degrees in 30 to 60 minutes, and provide a minimum of 4500 minutes continuous observing time before momentum unloading is required.

ATLAST-8 uses employs HST style body pointing. The reason is UV science. To maximize UV throughput, telescope pointing places the science object of interest directly onto the UV spectrograph entrance slit. Star Trackers command the OTA boresight pointed to within a few arc-sec of the desired target using the RWA/CMG. The active vibration isolation (AVI) system then engages using FGS feedback to minimize the apparent motion of the guide star centroid for the duration of that science exposure. During a science observation, sensors continuously monitor the travel of the AVI actuators. This information is used by the ACS software to command the reaction wheels, changing the orientation of the spacecraft so as to maintain the AVI actuators at or near their center of travel. The reaction wheels provide 698 N-m-s of momentum storage capability for a minimum of 4500 minutes continuous observation time. ATLAST-8 uses two solar panels on 10 m deployable booms to balance solar radiation pressure exerted on its sunshade tube. As the observatory slews relative to the sun, the solar panel booms extend to keep the center of pressure as close as possible to the center of mass as seen in Figure 12. Additionally, the booms have gimbal joints that articulate during observatory roll and pitch maneuvers to keep the solar panels perpendicular to the sun. Analysis shows that, with a few 10 meter booms extended from the spacecraft midpoint, only 35 N-m-s momentum is required for 6.25 days of continuous high-precision pointing observation. And, by making slight adjustments in boom length, indefinite observation times can theoretically be achieved.

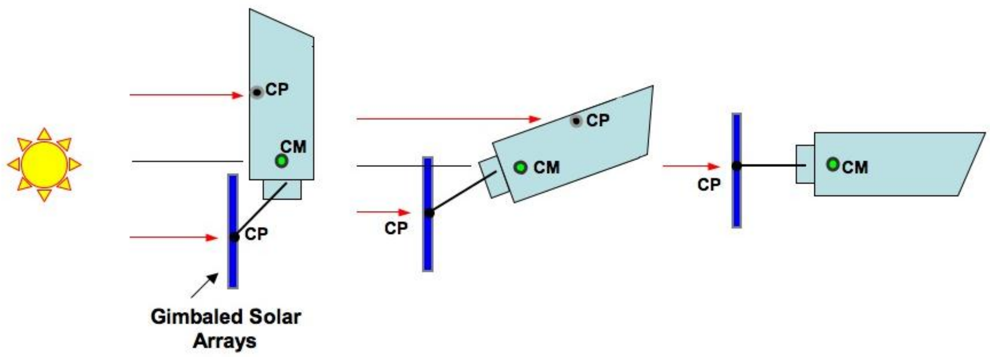
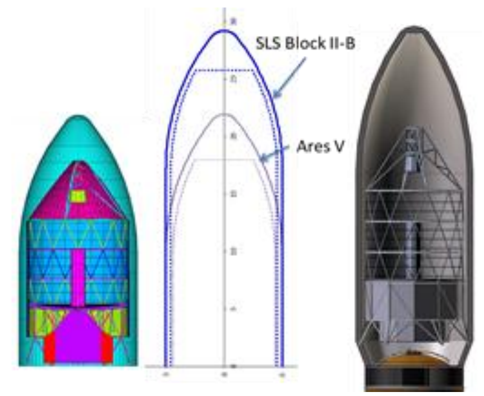


Figure 12: Solar Torque / Momentum Build-Up Mitigation Scheme for ATLAST-8m

5.2.4 SLS Accommodation

The 2009 ATLAST-8 mission concept was specifically designed to accommodate the mass and volume capacities of the Ares V [43-44]. Because of the Ares V 10-m fairing's total height, the PAF was integrated into the structure such that the payload could be placed as low in the payload volume as possible. But because this did not provide enough vertical capacity, a partial truss structure with four spider legs designed to fit inside the tapered section was also used, see Figure 13. Finally, the forward scarf was deployed on-orbit. Because of the mass capacity, a massive, thin-meniscus, solid monolithic primary mirror[33-34] was base-lined. Now, with the SLS 10-meter 'long' fairing being 6-meters longer than the Ares V, ATLAST-8 could be packaged above the PAF, and the secondary support structure could be made longer for greater stability. But, because the SLS has less mass capacity, it is necessary to change the primary mirror from a 20 mt solid to 8.5 mt (170 kg/m^2 areal density) lightweight. Fortunately as discussed in Section 4.3, this areal density is within the existing state of the art. The Advanced Mirror Technology Development program has designed an 8-meter class mirror using its demonstrated deep core technology[25, 45-46].



(a) (b) (c)

Figure 13: (a) ATLAST-8 Concept in Ares V; (b) SLS 10-m fairing is longer than Ares V 10-m fairing; (c) ATLAST-8 in SLS Block IIB.

5.3 ATLAST-12: 12.7-meter off-axis segmented aperture concept for LUVOIR

ATLAST-12 is a 12.7-meter segmented aperture UVOIR space observatory with a dual foci optical design. It is designed for a 30 year operational life at SE-L2 enabled by servicing. The most significant differences between ATLAST-8 and ATLAST-12 are the primary mirror, forward baffle tube, and sizing of the momentum management system to accommodate a larger solar radiation pressure load on the forward baffle tube.

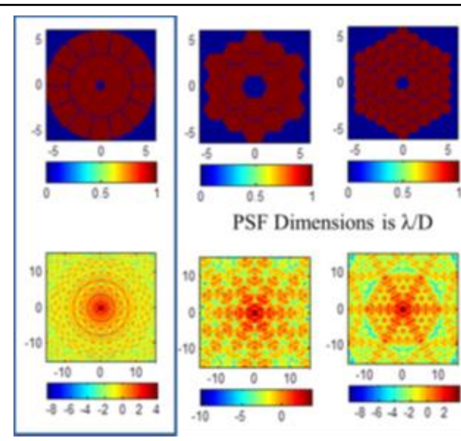


Figure 14: Different segmented aperture symmetries produce different PSF patterns which have compatibility benefits for specific coronagraphs.

5.3.1 Segmented Primary Mirror Assembly

The enabling element of ATLAST-12 is the primary mirror assembly. A goal of ATLAST-12 was to determine the largest primary mirror that could be packaged inside the SLS Block IIB fairing using a center core surrounded by a single ring of petal segments architecture. This architecture was selected for five reasons: 1) It provides a potentially more coronagraph-friendly point spread function (PSF) than a hexagonal segmented aperture (Figure 14)[47]. 2) The wavefront stability requirement is potentially more relaxed for an architecture with a central large segment surrounded by a single ring of small petals, than for a hexagonal segmentation architecture with multiple rings of equal size segments[48]. 3) Unless there is an existing manufacturing facility to mass produce hexagonal segments (i.e. for TMT), it is potentially more cost effective to manufacture multiple copies of a single petal than 3 or more different hexagonal prescription. 4) Having the large central core provides a simple descope path. And 5) other members of the ATLAST team were investigating hexagonal segmentation[11]. Additionally, the ATLAST-12 design was constrained to segments which could be fabricated from commercially available 2.4 m or 4 m mirror blanks. Because segment radial height depends on blank diameter and segment aspect ratio, the maximum diameter primary mirror that can be fabricated using this architecture depends on the number of segments which are placed around the center core and the size of the central core (Table 6). For ATLAST-12 a 12.7 m diameter primary mirror architecture composed of an 8-m center core surrounded by twelve 2.35 m tall by 3.3 m arc length segments was selected (Figure 15). To fit inside the 9.1 m dynamic envelope of the SLS Block IIB fairing, a fold-forward/fold-aft deployment was selected.

Table 6: Potential Primary Mirror Diameter using Petal Architecture

Center Core Diameter	6 m	8 m
12 Segments from 4-m Blanks	12 m	13 m
18 Segments from 4-m Blanks	13 m	14.5 m
24 Segments from 2.4-m Blanks	10 m	12 m

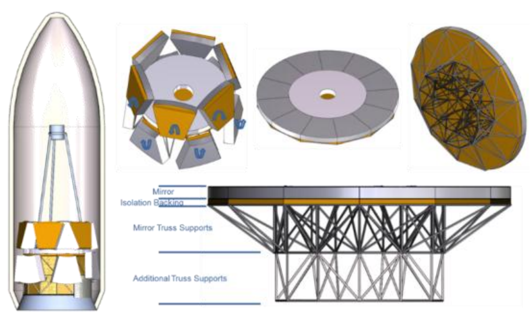


Figure 15: 12.7-m 12-fold-forward/ fold-aft petal segments around an 8-m central core on a 20 Hz structure.

The structure under the mirror center has two functions: support the 8500 kg mirror during launch and provide ultra-stable on-orbit optical performance. Given that exoplanet science is a primary mission of this telescope, it is necessary for the telescope's on-orbit wavefront to be stable on the order of 10 picometers per 10 minutes[47-48]. Since the JWST structure has a 13 Hz first mode and because preliminary analysis indicates that it might be possible to achieve the required wavefront stability using an enhanced JWST structure and an active isolation system[22-24], the ATLAST-12 primary mirror structure was designed for a 20 Hz first mode. Achieving this goal required a 4036 kg 4-meter deep structure (Figure 16a). To survive launch (according to NASA Standard 5001A and anticipated SLS launch loads), the structure was designed to support 5g axial and 2g lateral loads with a 1.4 ultimate safety factor (Figure 16b). The structure is constrained at the bottom by the PAF which connects the payload to the SLS. Interestingly, the 4036 kg mass of the primary mirror structure is driven by the 20 Hz requirement and not launch survival.

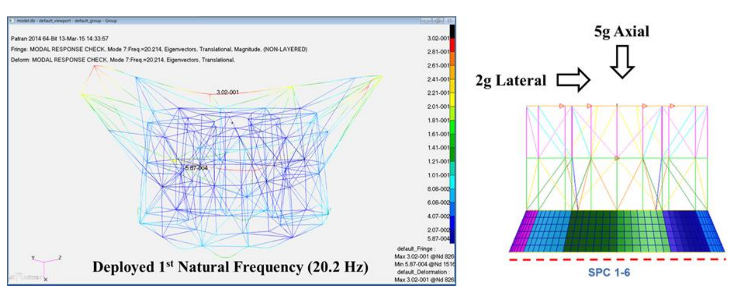


Figure 16: (a) Primary Mirror Support Structure was designed to provide a 20 Hz first mode for an 8500 kg mirror. To achieve this specification required a 4 meter deep and 4036 kg structure. (b) Designed 20 Hz structure survives 5g Axial and 2g Lateral launch loads.

5.3.2 Actively Thermal Controlled Forward Baffle

ATLAST-12 has a scarfed Kepler style forward baffle tube (Figure 17). For packaging reasons, the scarf is 60 degrees and deploys on orbit. The deployment system's mass and power were estimated using 40 ATK booms which have already successfully flown on NuSTAR. The tube has sufficient insulation for the telescope to passively reach 200K for infrared operation. For UV/Optical operation, zonal heaters in the baffle tube and around the primary mirror and secondary mirrors heat the optical surfaces to 280K to prevent ice or frost. The primary mirror assembly requires an R-θ heater system to compensate for sky view factor induced power and lateral solar load. Finally, active thermal sense and control keeps the telescope at a constant temperature regardless of where it points on the sky. As the observatory slews or rolls, sensors monitor the change in solar thermal load and adjust the zonal heaters to compensate.

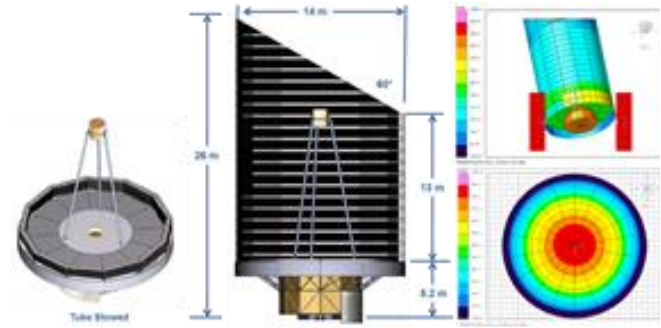


Figure 17: ATLAST-12 has a heated scarfed forward baffle tube for straylight control and thermally stable wavefront.

5.3.3 Spacecraft: Pointing Control and Momentum Management

Because of the size of ATLAST-12, the most important technical challenge for the spacecraft is pointing and momentum management. The science derived requirement is to point the observatory with a stability of < 1 mas for a period of up to 3000 minutes without interruption. Pointing stability enables exoplanet and UV science. Exoplanet science requires stability to minimize contrast leakage. UV science requires stable body pointing to maximize throughput by placing the science object directly onto the entrance slit of the UV spectrograph without the need of a fine steering mirror. Pointing duration is essential for both exoplanet and faint object science.

The spacecraft is designed to provide 1 arc-second pitch/yaw/roll accuracy and, with the active isolation system, 1.0 mas stability. Two sets of 6 reaction wheels, arranged in hexagonal pyramids, provide redundancy and pointing authority/control to 1 arcsec. Additionally, the reaction wheels are sized to slew the observatory 60 degrees in 180 minutes and roll the observatory around its line of sight +/- 30 degrees in 30 minutes. The active isolation system then engages using feedback to minimize the apparent motion of the guide star centroid for the duration of that science exposure. The AVI system eliminates jitter to achieve < 1 mas pointing stability. There are two potential approaches for the active vibration isolation system, Lockheed's DFP[23] and Northrop's active strut technologies. During a science observation, sensors continuously monitor the active isolation system and command the reaction wheels, changing the orientation of the spacecraft to keep the AVI actuators at or near their center of travel.

To achieve up to 3000 minutes of continuous observation the reaction wheels must be sized to provide the necessary momentum storage capability, with thrusters providing the means to unload momentum periodically. The problem is that ATLAST-12 is very large and solar pressure on the baffle tube during observation could quickly saturate the reaction wheels. To compensate, ATLAST-12 uses two solar panels, each with a solar pressure kite, on 10 m deployable booms to balance solar pressure exerted on the tube. As the observatory slews relative to the sun, the solar panel booms extend and rotate to keep the center of pressure as close as possible to the center of mass (Figures 9). The required area of the solar pressure kites depends on the length of the boom from the center of mass and the desired continuous observing time (Figure 18).

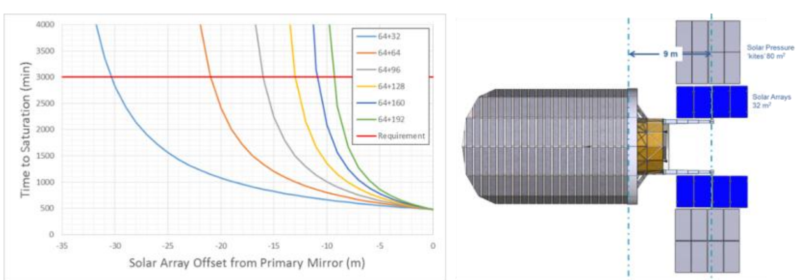


Figure 18: Maximum continuous observing time depends on size of the solar pressure kites and boom offset.

5.3.4 *Spacecraft Lifetime: Delta-V and Power*

ATLAST-12 is envisioned as a 30 year (or longer) lifetime observatory at SE-L2. A JWST orbit and transfer trajectory are assumed because it does not require a halo orbit insertion maneuver. Once at SE-L2 the spacecraft only has to begin station keeping. Lifetime can be achieved either by redundancy or servicing via modular on-orbit replaceable units. Because of the SLS's mass capacity, the observatory can carry sufficient propellant to either stay at SE-L2 for 30 years, or to bring itself back to EM-L2 for servicing and refueling. An average servicing interval of 5 years and a maximum servicing interval of 10 years is assumed (Table 7). Analysis indicates that only 7 m/s delta-v is needed per year for station keeping and 1.2 m/s for momentum unloading. Given the 6-month period of the halo orbit and the 45-degree keep-out angle between the telescope's line of sight and the sun, the telescope can see the entire sky in approximately six months. Finally, the total end of life power budget was estimated to 13kW.

Table 7: Delta-V (dV) Budget

	dV		
Manuever	**No Servicing, 30-year mission**	**5 Year Servicing (@EML1/L2)**	**Per Year at SEL2, no servicing**
Launch Correction	52.0 m/s	52.0 m/s	-
Mid-Course Correction	10.0 m/s	10.0 m/s	-
Station Keeping (SEL2)	208.8 m/s	34.8 m/s	7.0 m/s
Station Keeping (EML2, ~6 months)	-	52.8 m/s	-
Momentum Unloading	35.4 m/s	5.9 m/s	1.2 m/s
Transfer from SE L2	-	50.0 m/s	-
Transfer to SE L2	-	50.0 m/s	-
Margin	-6.2 m/s	44.5 m/s	
Margin (%)	-2%	15%	
Total	**300.0 m/s**	**300.0 m/s**	**8.14 m/s**

5.4 *HabEx-4: 4-meter off-axis monolithic aperture concept for HabEx*

HabEx-4 is a 4-meter monolithic aperture UVOIR space observatory. It is specifically designed for the SLS Block IB mass and volume capacities, and launch environment. Consistent with Table 3, its 'working' mass was constrained to 18 mt. And, as shown in Table 8, its 'design' mass is less than 11 mt (without margin). The structure is sized for a 3.5g axial and 1.5g lateral launch load. A ground rule given to the MSFC Advanced Concept Office for the HabEx-4 study was that every proposed system, subsystem or component of the spacecraft (including: propulsion; attitude control; power; avionics; communication; command and data handling; etc.) should be at TRL-9 except for the primary mirror assembly, actively heater controlled straylight baffle, and science instruments. HabEx-4 is designed for a 15 year operational life at SE-L2 with no servicing. Its propellant load is sized with a 25% reserve against this 15 year operational life requirement.

5.4.1 *HabEx-4 Optical Design and SLS Packaging*

HabEx-4 is a 4-meter scale-up of the Exo-C 1.3-meter Mission Concept[49], with a few modifications. Exo-C has many important design features which were retained for HabEx-4, including: an off-axis primary mirror to provide the coronagraph with an unobscured aperture; and, science instruments on the side of the telescope to both isolate them mechanically from the spacecraft and provide better thermal isolation (Figure 19). For the primary mirror, HabEx-4 uses a 200 Hz first mode, 4-meter diameter, 400 mm thick, stacked-core ULE mirror designed by the Advanced Mirror Technology Demonstrator (AMDT) project. AMTD has already demonstrated the ability of this technology to produce a 400 mm thick mirror[25] and is currently demonstrating a 1/3rd scale model of a 4-meter mirror[45-46]. Because of the SLS's volume and mass capacity, it is possible for HabEx-4 to support multiple science instruments using the ATLAST dual foci optical design (Figure 20). To minimize polarization anisotropy, the Exo-C primary mirror focal length was F/2.5. Retaining this feature makes HabEx-4 significantly longer than the ATLAST concepts (which have an F/1.5 primary mirror), but the volume capacity of the SLS allows for both a longer telescope and a 45 degree scarfed straylight baffle without the need for any physical deployments (Figure 21). Making the scarf 60 degrees, i.e. same as ATLAST-8 and ATLAST-12, could make the total system length shorter by 1.6 meters.

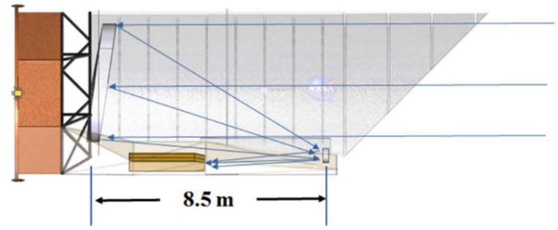


Figure 19: HabEx-4 is a 4-meter off-axis telescope based on the Exo-C mission concept study.

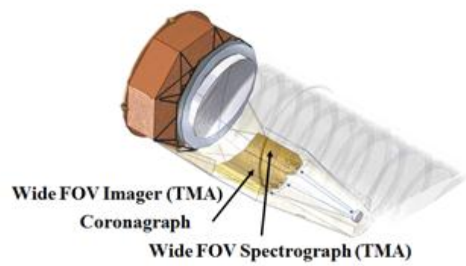


Figure 20: HabEx-4 has a dual foci optical design for multiple science instruments

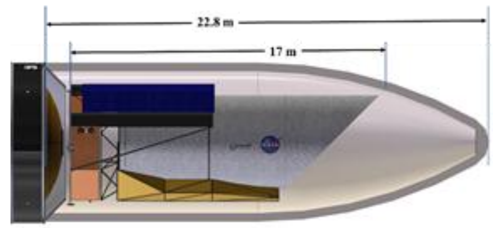


Figure 21: HabEx-4, even with an F/2.5 primary mirror and 45 degree scarfed baffle easily fits inside the SLS Block IB dynamic envelope.

5.4.2   HabEx-4 Actively Controlled Thermal Environment

Because wavefront stability is critical to exoplanet science, Exo-C paid particular attention to producing a stable thermal design. HabEx-4 replicates many of these features. The observatory is operated at fixed orientations relative to the sun, the solar panels provide thermal isolation, and the science instruments are placed opposite to the sun for more isolation. Additionally, to minimize mechanical disturbances, the solar panels are fixed to the spacecraft and isolated from the observatory. Going beyond Exo-C, HabEx-4 has a cold-biased actively-controlled thermal baffle (similar to ATLAST-8 and ATLAST-12). This keeps the HabEx-4 telescope in a constant thermal environment independent of where it points[50]. If the observatory slews or rolls relative to the sun, thermal sensors (or a calibrated look up table) measure the change in solar thermal load, with sub-mK sensitivity, and adjust the baffle tube heaters to compensate. Additionally, because the system is cold-biased, the telescope can be operated at temperatures ranging from 250K to 300K. Total power required for this capability is 1.5 kW.

5.4.3   HabEx-4 Momentum Management

Again, because wavefront stability is critical to exoplanet science, the solar panels are fixed to the spacecraft to minimize mechanical disturbances. Thus, HabEx-4 cannot use the ATLAST momentum balancing method to achieve the required 3000 minute minimum continuous observing time. Instead, it uses the more conventional brute force method. The reaction wheel system was designed to use reaction wheels with sufficient momentum storage capacity to provide at least 3000 minutes of continuous observing time – even after the loss of two reaction wheels (Figure 22).

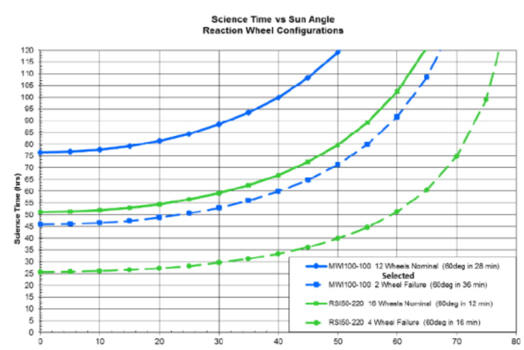


Figure 22: HabEx-4 reaction wheel configuration is designed and sized to provide at least 3000 minutes of continuous observing time, even with the loss of two reaction wheels.

5.5 Mass Budget

For each mission concept, Master Equipment Lists (MELs) were generated for every subsystem and component of the telescope, instruments and spacecraft. These MELs were used to estimate the mass of the payload and to size the power system. Table 8 shows the mass budget for the three concepts. It should be noted that the mass for ATLAST-8 and ATLAST-12 are identical. This is deliberate. The only difference between these two concepts is the size of the telescope. And, obviously then, the areal density of the primary mirror (Table 4). Everything else is identical. And to make these systems as stiff as possible, in order to make the design margins as high as possible, and to reduce cost and risk as much as possible, a 'design to mass' philosophy was followed. ATLAST-8 and ATLAST-12 were designing to be 33.3 mt (less than the 35 mt mid-range SLS Block-II with 43% mass margin shown in Table 3). HabEx-4 has a different mass budget because it is a smaller system. The primary mirror assembly mass is based on a design produced by the Advanced Mirror Technology Development project. It should be noted that the HabEx-4 payload mass is well below the 43% margin capacity of even the smallest SLS Block IB (Table 3). Finally, regarding propellant, the ATLAST propellant mass is sized to provide for 30 to 50 years of continuous operation; and, the HabEx-4 propellant mass is sized for a 15 year mission.

Table 8: Mass Budget for HabEx-4, ATLAST-8 and ATLAST-12

	HabEx-4 Mass [kg]	ATLAST-8 Mass [kg]	ATLAST-12 Mass [kg]
TOTAL PAYLOAD WET MASS	10,300	33,300	33,300
TOTAL PAYLOAD DRY MASS	9,300	28,800	28,800
Observatory	5,300	23,600	23,600
Telescope	4,600	21,800	21,800
Primary Mirror Assembly	1,600	12,750	12,750
Primary Mirror	1,000	8,500	8,500
Primary Mirror Support Sturcture	500	4,000	4,000
Mechanisms	100	250	250
Secondary Mirror Assembly	100	550	550
Optical Bench Structure	500	5,000	5,000
Auxillary Optic Assembly	200	1,500	1,500
Thermal & Straylight Control	2,200	2,000	2,000
Science Instruments	700	1,800	1,800
Spacecraft	3,000	4,200	4,200
Structure	1,000	1,500	1,500
Propulsion	200	400	400
Attitude Control System	500	500	500
Command and Data Handeling	300	300	300
Communications	300	300	300
Power	500	1,000	1,000
Thermal	200	200	200
Propellant	1,000	4,500	4,500
Payload Adapter Fixture	1,000	1,000	1,000

6. CONCLUSION

Space telescope missions have always been limited by their launch vehicle's mass and volume capacities. As discussed in Section 1.0, The Hubble Space Telescope was specifically designed to fit inside the Space Shuttle and the James Webb Space Telescope is specifically designed to fit inside an Ariane 5. But, astrophysicists desire even larger space telescopes. Unfortunately, packaging larger space telescopes into existing launch vehicles is a significant engineering challenge whose complexity, as discussed in Section 3, drives cost and risk. And, while it is impossible to eliminate all complexity, NASA's planned Space Launch System (SLS), with its 8.4 or 10-m diameter fairings and ability to deliver 35 to 45-mt of payload to Sun-Earth-Lagrange-2, mitigates this engineering complexity by allowing simpler design solutions. Cost and risk can be reduced by using the volume capacity to minimizing deployments and mechanisms. It can be reduced by using the mass and volume capacities to design stiffer systems with higher mass margins. It can be reduced by not being forced to select new immature technology to save mass. And, it can be reduced by using mass capacity to increase redundancy. In many space systems, much engineering effort is spent designing new low TRL systems with reduced mass that also meet the minimum margins. Designing to higher margins should save effort. Section 2 summarized the mass and volume capacities of various SLS options. And, Section 4 provided some high level design rules for creating a mass flow down budget from the launch vehicle to payload (with margin); and from the telescope to the primary mirror itself. It is important to note that the SLS enables telescopes up to about 16-meters to be fabricated using existing technology. Finally, Section 5 summarized three large aperture UVOIR space telescopes to be operated in orbit around the Sun-Earth Lagrange 2 point which are specifically designed to take advantage of the SLS mass and volume capacities: ATLAST-8 (an 8-meter on-axis monolithic aperture telescope), ATLAST-12 (a 12.7-meter on-axis segmented aperture telescope), and HabEx-4 (a 4-meter, off-axis monolithic aperture telescope).

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REFERENCES

1. Committee for a Decadal Survey of Astronomy and Astrophysics; National Research Council, New Worlds, New Horizons in Astronomy and Astrophysics, The National Academies Press, Washington, D.C. (2010).

2. Kouveliotou, Centrella, Peterson, et al, Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades, arXiv:1401.3741 (2014).

3. Dalcanton, Seager, et al, From Cosmic Birth to Living Earths: The Future of UVOIR Space Astronomy, Association of Universities for Research in Astronomy, www.hdstvision.org/report/ (2015).

4. Hertz, Paul, "Planning for the 2020 Decadal Survey: An Astrophysics Division White Paper", January 4, 2015, available at science.nasa.gov/astrophysics/documents/.

5. Thronson, Harley, et. al., "The path to a UV/Optical/IR flagship: ATLAST and its predecessors", submitted to JATIS (15 Feb 2016)

6. Postman, et. al., "A large monolithic-aperture optical/UV serviceable space telescope deployed to L2 by an Ares-V cargo launch vehicle", Science Associated with Lunar Exploration Architecture, Tempe, AZ, 28 Feb 2007.

7. Hopkins, Randall and H. Philip Stahl, "A large monolithic telescope placed at the second Sun-Earth Lagrange point", AIAA Space 2007, AIAA-2007-6166, 2007

8. Polidan, Ronald S., James B. Breckinridge, Charles F. Lillie, Howard A. MacEwen, Martin R. Flannery, and Dean R. Dailey, "An evolvable space telescope for future astronomical missions", Proc. SPIE. 9143, 2014, DOI: 10.1117/12.2057161

9. Feinberg, Lee D., Jason Budinoff, Howard MacEwen, Gary Matthews and Marc Postman, "Modular assembled space telescope", Optical Engineering, Vol. 52(9), (2013).

10. ATLAST Astrophysics Mission Concept Study final report is available at: http://www.stsci.edu/institute/atlast.
11. Rioux, Norman, et. al., “A future large-aperture UVOIR space observatory: reference designs”, submitted to JATIS (15 Feb 2016).
12. NASA, SLS Mission Planner Guide, 2016.
13. Bearden, David A., “A Complexity-based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?”, Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel MD, 2-5 May 2000.
14. Freaner, Claude W., et. al., ”An assessment of the inherent optimism in early conceptual designs and its effect on cost and schedule growth”, SSCAG/SCAF/EACE 2009 Joint International Conference, ESTEC, Noordwijk, The Netherlands, 15-16 May 2008.
15. James Webb Space Telescope (JWST) Independent Comprehensive Review Panel (ICRP) FINAL REPORT, The Aerospace Corporation, 29 October 2010.
16. NASA Advanced Mission Cost Model is available at http://cost.jsc.nasa.gov/AMCM.html.
17. Fox, Bernard, Kevin Brancato, Brien Alkire, “Guidelines and Metrics for Assessing Space System Cost Estimates”, RAND Corporation, 2008.
18. Wong, Robert, “Chapter 20 Cost Modeling”, Space Mission Analysis and Design, Second Edition, ed. Larson and Wertz, Microcosm and Kluwer Academic Publishers, 1992
19. Stahl, H. Philip, “Survey of cost models for space telescopes”, Optical Engineering, 49(5) 053004 (May 2010).
20. Stahl, H. Philip, Todd Henrichs, Alexander Luedtke, Miranda West, “An Update to Single Variable Parametric Cost Models for Space Telescopes”, Optical Engineering, Vol.52, No.9, (3 June 2013); doi:10.1117/1.OE.52.9.091805
21. Stahl, Mark T., H. Philip Stahl, and Stuart B. Shaklan “Preliminary analysis of effect of random segment errors on coronagraph performance”, Proc. SPIE. 9605, Techniques and Instrumentation for Detection of Exoplanets VII, 96050P. (September 24, 2015) doi: 10.1117/12.2190160.
22. Private Communication: Mosier, Gary, “Isolation Requirement”, AMTD Report, 2014
23. Pedreiro, N., “Spacecraft Architecture for Disturbance-Free Payload”, J. Guidance, Control and Dynamics, v. 26, N. 5, 2003, pp. 794-804.
24. Private Communication: Larry Dewell, Nelson Pedreiro, Alison Nordt, “Disturbance Free Payload for Large Telescope Dynamic Stability”, Lockheed Martin Advanced Technology Center, 2 November 2015.
25. Stahl, H. Philip, “Overview and accomplishments of advanced mirror technology development phase 2 (AMTD-2) project”, Proc. SPIE. 9602, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VII, 960208. (September 22, 2015) doi: 10.1117/12.2186195.
26. Postman, Marc, et. al. ”Advanced Technology Large Aperture Space Telescope (ATLAST): Science drivers and technology developments.” Optical Engineering Vol.51, No.01, 2012, DOI:10.1117/1.OE.51.1.011007
27. Bolcar, Matthew, et. al., “A Technology Development Plan for a Future Large-Aperture Ultraviolet-Optical-Infrared Space Telescope”, submitted to JATIS (14 Feb 2016).
28. Stahl, H. Philip, “JWST mirror technology development results”, SPIE Proc.6671, 667102 (2007)
29. Stahl, H. Philip, “JWST primary mirror technology development lessons learned”, SPIE Proceedings 7796, 2010, DOI:10.1117/12.860264
30. Stahl, H. Philip, “Mirror Technology Roadmap for Optical/IR/FIR Space Telescopes”, SPIE Proc.6265, 626504 (2006)
31. Stahl, H. Philip, and Lee Feinberg, “Summary of NASA Advanced Telescope and Observatory Capability Roadmap”, IEEE Aerospace Conference, March 2007.

32. Billings, Lee, "Five Billion Years of Solitude: The Search for Life Among the Stars", Penguin Group, 3 October 2013.

33. Stahl, H. Philip, "Ares V an Enabling Capability for Future Space Science Missions", Science Associated with Lunar Exploration Architecture, Tempe, AZ Feb. 28, 2007

34. Stahl, H. Philip, Marc Postman, William R. Arnold, Sr., Randall C. Hopkins, Linda Hornsby, Gary E. Mosier, and Bert A. Pasquale, "ATLAST-8 Mission concept study for 8-meter Monolithic UV/Optical Space Telescope", SPIE Proceedings 7731, 2010, DOI:10.1117/12.856256

35. Stahl, H. Philip, Marc Postman, William R. Arnold Sr., Randall Hopkins, Linda Hornsby, Gary E. Mosier and Bert A. Pasquale, "Design for an 8 meter monolithic UV/OIR space telescope", SPIE Proceedings 7436, 2009.

36. Pasquale, Bert A., Philip Stahl, Lee Feinberg, Joseph Howard, Qian Gong, and David Aronstein, "Comparative Concepts for ATLAST Optical Designs", SPIE Proceedings 7731, 2010, DOI:10.1117/12.857170

37. Pasquale, Bert A., Philip Stahl, Lee Feinberg, Joseph Howard, Qian Gong, and David Aronstein, "Optical design process and comparison for ATLAST concepts" SPIE Proceedings 7652, 2010, DOI:10.1117/12.879040

38. Arnold, William R., and H. Philip Stahl, "Structural design considerations for an 8-m space telescope", SPIE Proceedings 7425, 2009.

39. Hornsby, Linda, Randall C. Hopkins, H. Philip Stahl, "Thermal analysis of the Advanced Technology Large Aperture Space Telescope (ATLAST) 8 meter primary mirror", SPIE Proceedings 7731, 2010, DOI:10.1117/12.857384

40. Hopkins, Randall C., Peter Capizzo, Sharon Fincher, Linda S. Hornsby, David Jones, Gary Mosier, H. Philip Stahl, Dan Thomas and Kevin S. Thompson, "Spacecraft conceptual design for the 8-meter Advanced Technology Large Aperture Space Telescope (ATLAST)", SPIE Proceedings 7731, 2010, DOI:10.1117/12.856474

41. Oegerle, William R., Lee D. Feinberg, Lloyd R. Purvess, T. Tupper Hyde, Harley A. Thronson, Jacqueline A. Townsend, Marc Postman, Matthew R. Bolcar, Jason G. Budinoff, Bruce H. Dean, Mark C. Clampin, Dennis C. Ebbets, Qian Gong, Theodore R. Gull, Joseph M. Howard, Andrew L. Jones, Richard G. Lyon, Bert A. Pasquale, Charles Perrygo, Jeffrey S. Smith, Patrick L. Thompson and Bruce E. Woodgate, "ATLAST-9.2m: a large-aperture deployable space telescope", Proc. SPIE 7731, 2010, DOI: 10.1117/12.857622

42. Feinberg, Lee D., Andrew Jones, Gary Mosier, Norman Rioux, Dave Redding and Mike Kienlen, "A cost-effective and serviceable ATLAST 9.2m telescope architecture", Proc. SPIE 9143, 2014, DOI:10.1117/12.2054915.

43. Stahl, H. Philip, "Ares V launch capability enables future space telescopes", SPIE Proc.6687, 66870L (2007)

44. Stahl, H. Philip, Phil Sumrall, and Randall Hopkins, "Ares V launch vehicle: an enabling capability for future space science missions", Acta Astronautica, Elsevier Ltd., 2009, doi:10.1016/j.actaastro.2008.12.017

45. Stahl, H. Philip, et. al., "Advanced mirror technology development (AMTD) project: 2.5 year status". Proc. SPIE. 9143, (August 02, 2014) doi: 10.1117/12.2054765

46. Matthews, Gary W., et. al. "The development of stacked core technology for the fabrication of deep lightweight UV-quality space mirrors", (August 28, 2014) doi: 10.1117/12.2055284

47. Stahl, H. Philip, et. al. "AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes", Proc. SPIE. 9143, (August 02, 2014) doi: 10.1117/12.2054766

48. Stahl, Mark T., Stuart B. Shaklan, H. Philip Stahl, "Preliminary analysis of effect of random segment errors on coronagraph performance", SPIE Proc.9505, (2015)

49. NASA, Exo-C: Imaging Nearby Worlds, CL#15-1197, March 2015 https://exep.jpl.nasa.gov/stdt/Exo-C_Final_Report_for_Unlimited_Release_150323.pdf

50. Brooks, Thomas, H. P. Stahl, William R. Arnold, "Advanced Mirror Technology Development (AMTD) thermal trade studies", Proc. SPIE. 9577, Optical Modeling and Performance Predictions VII, 957703. (September 23, 2015) doi: 10.1117/12.2188371