

The path to a UV/optical/IR flagship: ATLAST and its predecessors

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Abstract. The recently completed study for the Advanced Technology Large-Aperture Telescope (ATLAST) was the culmination of three years of work that built upon earlier engineering designs, science objectives, and sustained recommendations for technology investments. Since the mid-1980s, multiple teams of astronomers, technologists, and engineers have developed concepts for a large-aperture UV/optical/IR space observatory to follow the Hubble Space Telescope (HST). Especially over the past decade, technology advances and exciting scientific results has led to growing support for development in the 2020s of a large UVOIR space observatory. Here we summarize the history of major mission designs, scientific goals, key technology recommendations, community workshops and conferences, and recommendations to NASA for a major UV/optical/IR observatory to follow HST. We conclude with a capsule summary of the ATLAST reference design developed over the past three years.

Keywords: space telescope, optical systems, exoplanets, ATLAST, LUVOIR, HDST

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1 Early Concepts for a Large UVOIR Space Observatory

*1.1 Concepts Before the 2000 NRC Decadal Survey**

Years before the Hubble Space Telescope (HST) was even launched and became a celebrated space observatory, the scientific and engineering communities were already discussing a much larger-aperture follow-on mission that would cover the ultraviolet, optical, and infrared (UVOIR) wavelength regime and be able to continue breakthrough science when HST was no longer available. To a remarkable degree, many of the basic design requirements and some priority scientific objectives of those flagship concepts of three decades ago are reflected in the more

* Smith and McCray (Reference 1) describe this time period in depth, although including several topics beyond the scope of this paper.

advanced recent concepts described in this journal and were advocated as the natural eventual successor to HST.

Probably the earliest substantive identification of a large UVOIR space observatory specifically intended to follow HST was the National Research Council Space Science Board (SSB) report, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 – 2015* (begun in 1984 and published in 1988; see summary by Field in Reference 2). Volume II of this report observed, “A large-aperture space telescope for the [UVOIR] regions has immense scientific potential. The need for such a telescope will be very high after 10 to 20 years of use of HST . . . Even now we see that some of the most fundamental of all astronomical questions will require the power of a filled-aperture telescope of 8- to 16-m diameter designed to cover a wavelength range of 912 Å to 30 μm, with ambient cooling to 100 K to maximize infrared performance.” The 1986 Report on the National Commission on Space, *Pioneering the Space Frontier* (aka, The Paine Report) recommended a broadly similar mission as it drew heavily on the nearly simultaneous SSB report and personnel, including operation at ~ 100 K.

Not long after the SSB and Paine Reports, in his overview of the influential 1989 Space Telescope Science Institute community workshop report, *The Next Generation Space Telescope*,³ Illingworth urged the participants to recognize the limited lifetime of the major astrophysics missions, such as HST, and “look beyond, to the missions that will succeed the Great Observatories.” Illingworth summarized the basic parameters of the notional mission concept embraced at the workshop: again, a 10 – 16 meter-class telescope operating from ~0.1 μm to “beyond 10 μm” thanks to passive cooling to 100 K. [As Smith and McCray point out (p. 49 (Ref. 1)), “This widely quoted apparent limit to a low temperature achievable via passive (aka, radiative) cooling alone became for some years a major hindrance . . . in achieving sensitive observations at

long wavelengths.” Wide recognition that radiatively cooled optical system temperatures far colder than 100 K were possible emerged as a significant factor in the mid-1990s in emphasizing infrared observations, rather than UV/optical wavelengths, for the first major post-HST observatory (see below)].

Illingworth summarized a selection of some of the most exciting science that the large post-HST observatory would be capable of, including important structures in cosmologically distant galaxies observable throughout the Universe with scale sizes of 100 – 1000 pc. [Notional details of the large UVOIR space observatory are listed on Table 1 of the workshop report.] Furthermore, Illingworth pointed out the exciting prospect of such a mission being able to detect Earth-like planets orbiting stars within 10 pc of the Sun. In the same proceedings, Angel⁴ observed that the search for Earth-like planets “was in large measure the original rationale for such a large telescope” in the SSB report published in 1988. His article, which emphasized the daunting engineering challenges to such a mission, included discussion of the required performance of an observatory able to search for biomarkers in hypothetical Earth-like planets and discussed those biomarkers considered at the time to be most revealing.

Interestingly, NASA first explicitly considered direct imaging of extrasolar planets with a large-aperture telescope as part of the Project Orion design study (Black 1980). Both ground- and space-based imaging were evaluated, with the final report optimistic that a 2.4 m space telescope would enable the detection of large Jovian planets around stars within 10 pc. Coronagraphic imaging of the beta Pictoris circumstellar disk by Smith & Terrile (1984) provided impetus to the first mission study work, leading to a proposal for the modest-aperture, ultra-smooth Circumstellar Imaging Telescope (CIT) by the Jet Propulsion Laboratory (Terrile 1988, 1989).

The difficulty of manufacturing large optics at the time to the required smoothness limited aperture sizes and, consequently, the size of exoplanets that could be studied.

In 1991, two years after the STScI meeting, JPL hosted a workshop, “Technologies for Large Filled-Aperture Telescopes in Space,” which emphasized developments necessary to enable the 8 – 16 m UVOIR telescope operating from 0.12 μm to $\sim 10 \mu\text{m}$ described in Illingworth’s workshop executive summary.⁵ To demonstrate the impressive capabilities of such an observatory, page 6 in Reference 4 compares simulated visual-wavelength images of distant galaxies as observed by the 10 m Keck telescope, HST, and a hypothetical future 16 m space observatory.

It is notable that before even a year had passed after launch of HST, multiple assessments and community workshops of a follow-on UVOIR flagship converged on basic observatory parameters, technology investment priorities, and science objectives – including observations of nearby Earth-like worlds – generally similar to the concepts discussed in this issue (Refs. 2, 3, 4, 5). Of course, to a large degree this is simply due to the fact that major scientific objectives evolve slowly and the observational requirements to achieve those objectives are set by the basic laws of physics and optics. However, these early 1990s workshops represented a high-water mark in proposing large UVOIR observatories on the lunar surface or in high-Earth orbit: in 1990, Farquhar and Dunham (Ref. 6) wrote briefly on the value of the Sun-Earth libration points for space observatories and in 1995 NASA’s very successful Solar and Heliophysics Observatory (SOHO) began operating at the Sun-Earth L1 point.

The mid-1990s also marked a pause for some years in the candidacy of a large UV/optical-optimized observatory for selection as a high-priority major post-HST mission for NASA. In late 1993, the Association of Universities for Research in Astronomy (AURA) empaneled an eighteen-person committee, chaired by Alan Dressler, to assess compelling science objectives for the

coming decades. In 1996, the committee issued its influential report, *HST and Beyond: Exploration and the Search for Origins: A Vision for Ultraviolet-Optical-Infrared Space Astronomy*⁷ (aka, The Dressler Report). That report identified two high-priority science objectives intended to motivate selection of the mission concepts to achieve them, which were again very similar to the goals of the workshops noted above: (1) visiting a time when galaxies were young (i.e., formation and early evolution of galaxies) and (2) the search for Earth-like worlds. To achieve these goals, the Dressler Committee made three recommendations, two of which were in a substantially new direction from previous community recommendations and would ultimately lead to selection by the 2000 NRC Decadal Survey⁸ of the Next Generation Space Telescope (NGST): (1) extend the lifetime⁷ of HST, (2) build a large filled-aperture infrared-optimized space observatory, and (3) develop and demonstrate space interferometry. [With respect to the third recommendation, although beyond the scope of this paper, space astrometry became a priority of NASA's thinking about exoplanet observations with the establishment of a Space Interferometry Science Working group in 1991, which led to the development of the Space Interferometry Mission (Allen, Peterson, and Shao 1997). At about the time of the release of the Dressler Committee report in mid-1996, a major workshop in Toledo, Spain was held on the subject of IR interferometry from space and the search for life-bearing planets (Ref. XX).]

With HST's flawed optics corrected in 1993, and two new instruments (STIS and NICMOS) installed during a servicing mission in 1997, numerous individuals continued to remind the astronomical community that HST would eventually reach its end-of-life and no mission proposed to extend its science programs at UV/optical wavelengths was in the offing. Given the long gestation period for building a flagship-class mission (over ~20 years), with the IR-optimized Next Generation Space Telescope (NGST) recommended by the Dressler Report as the next large

mission to follow HST, planning for a large UV-optical-near-IR flagship continued as a candidate to follow NGST.

In 1998, a workshop was held at the University of Colorado to discuss the future of UV-optical astronomy from space.⁹ The consensus was that the next step after HST at UVOIR wavelengths should be a 4 - 6 meter-class instrument to complement NGST. In response, NASA's UV-Optical Working Group (UVOWG) was commissioned to study the scientific rationale for new missions in the ultraviolet-optical bandpass. This group produced a report¹⁰ in 1999 that likewise recommended (1) a 4-meter aperture telescope that emphasized wide-field imaging and UV spectroscopy and (2) investigation into the feasibility of an 8 m telescope with deployable optics similar to NGST. The 4 m concept, dubbed the Space Ultraviolet Observatory (SUVO), was subsequently proposed to the 2000 Decadal Survey. Technology development was identified as a priority by a Survey panel, although not recommended by the full committee. The search for Earth-like worlds was a high priority for the Survey for which the infrared-optimized Terrestrial Planet Finder (TPF) was the recommended mission to achieve this NASA goal.

1.2 Preparing for the 2010 Decadal Survey

1.2.1 Terrestrial Planet Finder Concepts: Interferometry or Coronagraphy?

Although the technologies for extraordinarily smooth large mirrors remained out of reach at the time of the 2000 Decadal Survey, so that spatial interferometry seemed favored for studying Earth-sized worlds, interest in direct imaging was sustained for example by the first exoplanet detections by the radial velocity technique. Imaging of terrestrial exoplanets remained a priority, even as some attention shifted to mid-infrared wavelengths where the targets present a contrast relative to the central star that is three orders of magnitude easier to obtain than in the optical: 10^{-7} versus 10^{-10} . Starlight suppression would be done by interferometric nulling between separate telescopes mounted on a large boom or flying in formation (Angel and Woolf 1997). This concept became

known as the Terrestrial Planet Finder (TPF) and was the subject of detailed study by a NASA Science Working Group (SWG; Beichman, Woolf, and Lindensmith 1999).

The endorsement of the Decadal Survey of technology development for TPF led NASA to fund four university-industry teams to examine a range of architecture options, and to commission a TPF SWG report on the spectral signatures that could be used to diagnose habitability and the presence of life (Des Marais et al. 2001). A key outcome of the architecture studies (Beichman et al. 2002) was the revival of interest in a coronagraphic alternative for TPF working at visual wavelengths. This was made possible by the development of deformable mirror technology for adaptive optics: wavefronts could now be corrected to the required smoothness without the need to manufacture large optics with ultra-smooth surface quality. At this point, the TPF SWG went forward on two parallel paths studying both the infrared interferometer (TPF-I) and optical coronagraph (TPF-C) versions of the concept.

Laboratory experiments achieving 10^{-9} contrast (Trauger et al. 2004) gave confidence that TPF-C was on a path to technical readiness. As a single large telescope operating at room temperature, TPF-C also appeared to be a more feasible mission than TPF-I, which would require five formation-flying spacecraft with large cryogenic optics. NASA therefore made the decision to prioritize TPF-C as the first mission for assessment and technology funding, supported by a substantial investment in a JPL/Goddard mission study during 2004-2006.

The TPF-C science and technology development team (STDT) identified fourteen science objectives to drive the design. The Flight Baseline 1 (FB1) design featured an elliptical 8 x 3.5 m primary mirror able to be launched within existing launch vehicle fairings. The telescope was off-axis and unobscured with instruments operating over 0.5 - 1.1 μm , including an imaging camera, integral field spectrograph, and wide field camera for general astrophysics. Multiple coronagraph

designs were studied as starlight suppression options. The entire observatory would operate at Earth-Sun L2 and over a five-year life, the equivalent of 30 stellar habitable zones would be searched. This was calculated to permit a 95% probability of detecting one habitable planet if the probability of an exoEarth around each target star was 0.1.

Unfortunately, budget pressures within NASA led to the termination of the TPF-C design study and technology investment. A final report was produced in 2006 (Levine, Shaklan, and Kasting 2006). As NASA's largest development effort to date towards the goal of imaging Earth-like exoplanets, the TPF-C study strongly influenced subsequent mission concepts, including the concepts described in the next section

1.2.2 Large-Aperture UVOIR Concepts and ATLAST

With the emphasis of the 2000 Decadal Survey on the infrared-optimized Next Generation Space Telescope (NGST), the UVOIR community's attention turned to preparing for the 2010 Survey.

A string of workshops were held in the early 2000s to consider further concepts for a UV-optical space telescope compelling enough to win endorsement by the NRC and development by NASA: "Hubble's Science Legacy: Future Optical-Ultraviolet Astronomy from Space" at the University of Chicago in April 2002; "Innovative Designs for the Next Large Aperture UV/Optical Telescope" at the Space Telescope Science Institute (STScI) in April 2003; "Future Optical/UV Astronomy from Space: Science and Mission Concepts" as a topical session at the American Astronomical Society (AAS) meeting in May 2003; and "The Science Potential of a 10 – 30 m UV/Optical Space Telescope" at STScI in February 2004.

Events were rapidly changing during this time on both the scientific and programmatic fronts. The discovery of dark energy and exoplanets in the late 1990s significantly influenced thinking about the goals of future telescopes. The failure of the Columbia Space shuttle in 1993, with the

subsequent hiatus in servicing missions to HST, provided a sense of urgency to define the next missions in UVOIR space astronomy.

In 2004, NASA Headquarters Science Mission Directorate solicited so-called “Vision Missions” in space science. NASA chose the 10 meter-class UV-optical Modern Universe Space Telescope (MUST) for study (Refs. 11, 12), along with ten other missions spanning a large range of science objectives. The MUST concept called for a robotic servicing module to construct the telescope on orbit after launch by NASA’s newly proposed Ares V rocket, which was a priority of the newly announced *Vision for Space Exploration*¹³ (VSE). Although the VSE specifically called for NASA to “conduct advanced telescope searches for Earth-like planets and habitable environments around other stars, the MUST telescope, as envisioned at the time, did not explicitly include the study of exoplanets.

In parallel with the science workshops and the “Vision Missions” solicitation, shortly after the VSE was announced, NASA initiated an extensive program to develop long-term roadmaps for high-priority science goals, explicitly including the astronomical search for Earth-like planets, and an assessment of required technology investments necessary to achieve this goal. The exo-Earth science roadmap was completed in 2005 (Ref. 14).

To enable the search for life-bearing planets, among other goals, the NASA Administrator established the Advanced Planning and Integration Office (APIO) in spring 2004 with the goal of developing an agency-wide strategy for investing in new technologies that generally would take advantage of capabilities expected to be developed as part of the VSE. Although much of this activity was terminated a year later with the arrival of a new NASA Administrator, several technology roadmaps were reviewed by the NRC, recommended to NASA for implementation, published in 2006, and included a strategy to enable future flagship observatories. The strategy for

space observatories consisted of (1) broad science goals and a summary of anticipated discoveries and achievements, specifically including the search for Earth-like worlds and study of the early universe; (2) high-level milestones, options and decision points; (3) suggested implementation approaches and missions sets, with options and possible pathways; (4) key dependencies on and relations to other roadmaps; and (5) identification of required capabilities, facilities and infrastructure (Ref. 15).

In summer 2007, NASA issued a call for proposals for “Astrophysics Strategic Mission Concept Studies” (ASCMS), seeking to identify concepts for scientifically ambitious space astronomy missions and to help identify technology developments such missions might require. The Advanced Technology Large-Aperture Space Telescope (ATLAST) was one of the concepts selected by NASA for study. The objective of the study was to develop a technology development program for the 2010 – 2019 timeframe that would enable a large UVOIR space telescope to be considered by the 2010 Decadal Survey for flight in the 2020s. ATLAST improved on TPF-C (Sec. 1.2.1) by elevating general astrophysics to an equal footing with exoplanet science in the mission requirements. ATLAST adopted many of the exoplanet science requirements, starlight suppression options, and technology plans developed by the TPF-C STDT. The legacy of TPF-C therefore lived on in the ATLAST mission concept.

The ATLAST study consisted of three UVOIR telescope concepts: an 8 m monolithic mirror telescope¹⁶ and two segmented telescopes, one with a 9.2 m primary¹⁷ (that could fit into an existing Evolved Expendable Launch Vehicle (EELV)) and one with a 16.8 m primary. The 8 m and 16 m designs required a heavy lift launcher akin to the Constellation Program’s heavy-lift Ares V vehicle.

All three concepts had similar scientific goals, with the direct detection and study of exoplanets as a goal on par with a variety of compelling astrophysical investigations. These priorities were notionally similar to the science priorities posited for the large UVOIR concepts over the preceding two decades, although developed in much greater depth, in addition to taking advantage of the widely recognized success of HST and the growing numbers of discovered exoplanets. The ATLAST team considered an aperture about 8 m to be the minimum size needed to characterize the atmospheres of a significant number of terrestrial mass planets in the habitable zones of their host stars, as well as providing the required spatial resolution and collecting area for other science goals.¹⁸ The monolith concept took advantage of the planned Ares V mass and volume capacities, while adapting high-mass ground-based mirror and support-structure technologies. The segmented designs relied on heritage from the James Webb Space Telescope (JWST, renamed from NGST earlier in the decade). The ATLAST telescopes were designed to be operated at near room temperature, which greatly decreased the cost of the optics and testing compared to the cryogenic JWST.[†] That said, however, ATLAST-type missions will require much higher optical stability than JWST, which is likely to be a significant factor in cost.

NASA's commitment to a large heavy-lift launch vehicle as part of the Constellation Program encouraged additional community meetings to assess the scientific benefit of such a capability as a new Decadal Survey approached. NASA Ames Research Center hosted a pair of workshops in early 2008 specifically to assess the scientific community's interest in using Ares V (Refs. 19, 20). Not long after, the NRC produced a study, *Launching Science*,²¹ of the science opportunities enabled by NASA's Constellation program and especially taking advantage of the Ares V heavy-

[†] Similarities between the UVOIR concepts of the decade of the 2000s and those of the 1980s were generally limited to the very large apertures and the highest-priority science goals. The earlier designs favored, for example, radiative cooling to ~ 100 K and possible operation on the lunar surface. Neither feature survived the 1990s.

lift vehicle. The report identified observations of Earth-like planets as a compelling goal for large-aperture missions for which Ares V appeared to be appropriate. In addition to the eleven Vision mission concepts already solicited by NASA HQ SMD, the NRC sought community input. This resulted in two of the ATLAST concepts being considered for Ares V science payloads: an 8 m monolithic mirror telescope and a 16 m segmented mirror telescope. Both telescopes took advantage of the large lift capacity and larger diameter fairing of the Ares V rocket, and both telescopes were recommended in the *Launching Science* report to NASA for further study.

With more than two decades of increasingly sophisticated engineering designs, community science input, and NRC reviews behind it, the ATLAST ASMCS report was submitted for consideration by the 2010 Decadal Survey. Responding to the scientific importance of study of exoplanets and the search for life, the Survey's report, *New Worlds, New Horizons*,^{xx2} identified as its highest priority "medium" activity, investment in technologies to "[Prepare] for a planet-imaging mission beyond 2020" with mission-specific funding of ~\$200 M over the decade of the 2010s.

In addition to assessment of very large-aperture space observatories, the astronomy community demonstrated characteristic opportunism earlier this current decade when NASA was offered a second-hand National Reconnaissance Office (NRO) telescope with the same aperture as HST (2.4 m) and capable of operating over visual and near-infrared wavelengths. For some years, NASA and the Department of Energy (DoE) together had been assessing a concept called the Joint Dark Energy Mission (JDEM) intended to investigate in depth the mystifying dark energy. As it turned out, the donated NRO telescope could be modified to accomplish JDEM goals along with extra capabilities, including the search for extra-solar planets. This new incarnation has been dubbed the Wide-Field Infrared Survey Telescope (WFIRST) and has an expected launch date in the mid-

2020s. Relevant to the development of capabilities to enable a future larger-aperture UVOIR observatory, WFIRST is proposed to include a high-performance coronagraph to allow direct imaging of exoplanets.

1.3 The NASA Astrophysics Roadmap: Vision for the Next Three Decades

In spring 2013, the Astrophysics Subcommittee of the NASA Advisory Council's Science Subcommittee chartered a community-wide task group to develop a vision for NASA's Astrophysics Division that would span the subsequent three decades. This vision built upon the products of the 2010 Decadal Survey and included science objectives likely to remain priorities at until the middle of the century; thus the name of its final report, released in late 2013: *Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades*²². The roadmap also identified key technology investments necessary to enable the missions recommended to NASA Headquarters' Astrophysics Division.

The scientific objectives, mission concepts to achieve them, and technologies required to enable them were divided into three time periods, each about a decade long, beginning with the near-term missions already under development (e.g., JWST and WFIRST). Following this period was the Formative Era, which identified for NASA science priorities now familiar from conferences and workshops referenced in the earlier sections in this paper, with a special emphasis on the search for and characterization of exoplanets – and perhaps even Earth-like worlds – in the solar neighborhood, as well as the birth and evolution of galaxies, stars, and planets. To achieve these goals, the report recommended, as had others before it, a large UV/optical/near-IR mission dubbed the LUVOIR Surveyor, which was described in the final report as having an aperture of 8 – 16 m with wavelength coverage from “near-IR to near-UV,” the specific wavelengths to depend upon technology development.

The roadmap technologies are consistent with the more detailed description presented in the issue by Bolcar *et alia*: precision deployment and wavefront control, mirror coatings, detector systems, and – very critically – high-performance starlight suppression.

1.4 AURA's High-Definition Space Telescope

In early 2013, the Association for Research in Astronomy (AURA) chartered a team of seventeen scientists and technologists to study again how the challenging dual goals of cosmic origins science, especially of extremely distant objects and processes, and the search for life-bearing planets, could be combined into a single mission. Released in mid-2015, the report, *From Cosmic Birth to Living Earths*,²⁴ described the science cases and technology drivers for a space telescope concept, dubbed the High-Definition Space Telescope (HDST). While the basic HDST concept was broadly similar to earlier UVOIR observatory concepts and science goals and the ATLAST designs of last decade, its science drivers and design concepts had progressed significantly and are described in depth.

Significant scientific advances over the performance of HST at these wavelengths require developing the capability to deploy an aperture much larger than can currently be accommodated within the inner diameter of existing launch vehicles, as earlier concepts had found (e.g., Refs. 3, 5). Success with JWST continues to build confidence that precision deployment of very large segmented optical systems is a successful engineering solution. To give an indication of the advancements in imaging capabilities, Figure 1 compares the relative sizes of the primary mirror for HST, JWST, and HDST. In the particular concept shown in the figure, the HDST primary is made up of 36 1.7-meter segments, although segments of different sizes could be adopted.

The AURA study developed a notional instrument suite that permitted realistic estimates of observatory performance consistent with being both a powerful general-purpose flagship, as well

as capable of detecting biomarkers in the candidate Earth-like worlds. HDST was proposed to have 25 times the pixel density per area of HST at the same optical wavelengths, four times better resolution at near-IR wavelengths than JWST, and up to 100 times the point-source UV spectroscopic sensitivity. Furthermore, HDST was proposed to have multi-object UV spectroscopy for up to 100 sources in a ~ 3 arcmin field of view, as well as extremely stable wavefronts to provide precise point-spread functions over long observational timelines.

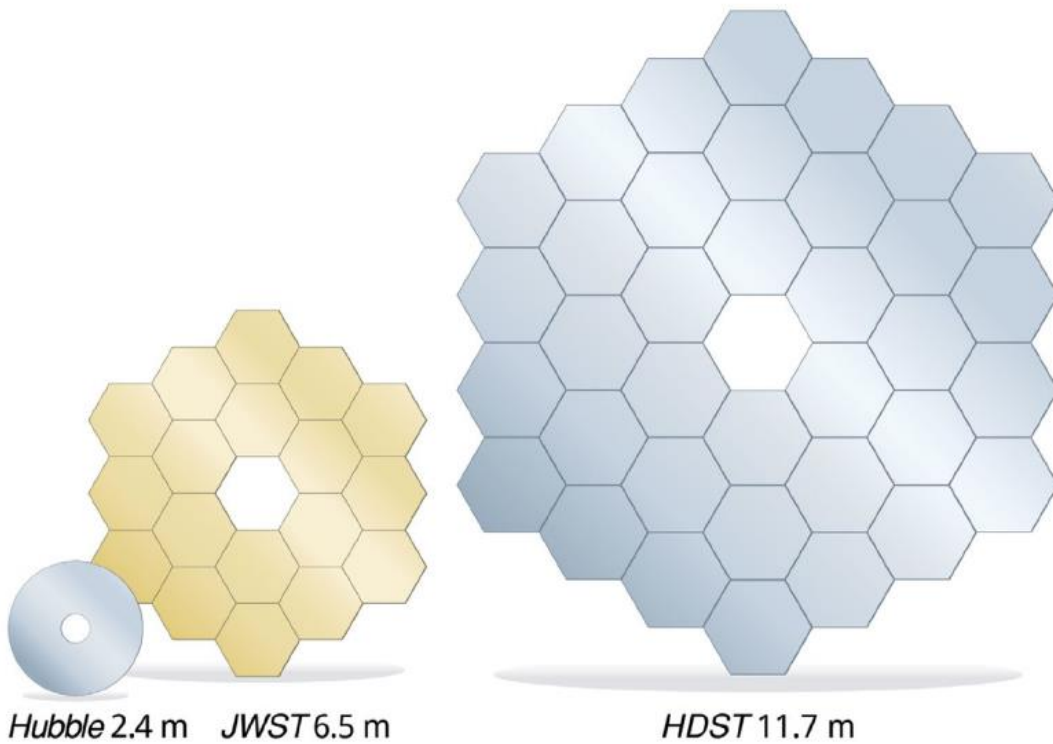


Fig. 1. Relative sizes of the primary mirrors for HST, JWST, and HDST (from Ref. 24)

For galaxies out to cosmological distances, a mission such as HDST would have the capability to reveal features on a scale size of 100 pc or smaller (Fig. 2), which will reveal structures and processes critically important to major leaps in our understanding of the cosmos.

Images from HST have thrilled both scientists and the general public for a quarter century and a mission such as HDST will do no less. Figure 3 compares synthetic images of a galaxy at high redshift as would be observed by HST, JWST, and a mission such as HDST. The breathtaking capability of such a mission would continue public and professional support for flagship observatories exploiting the limits of optical design and instrument sensitivity.

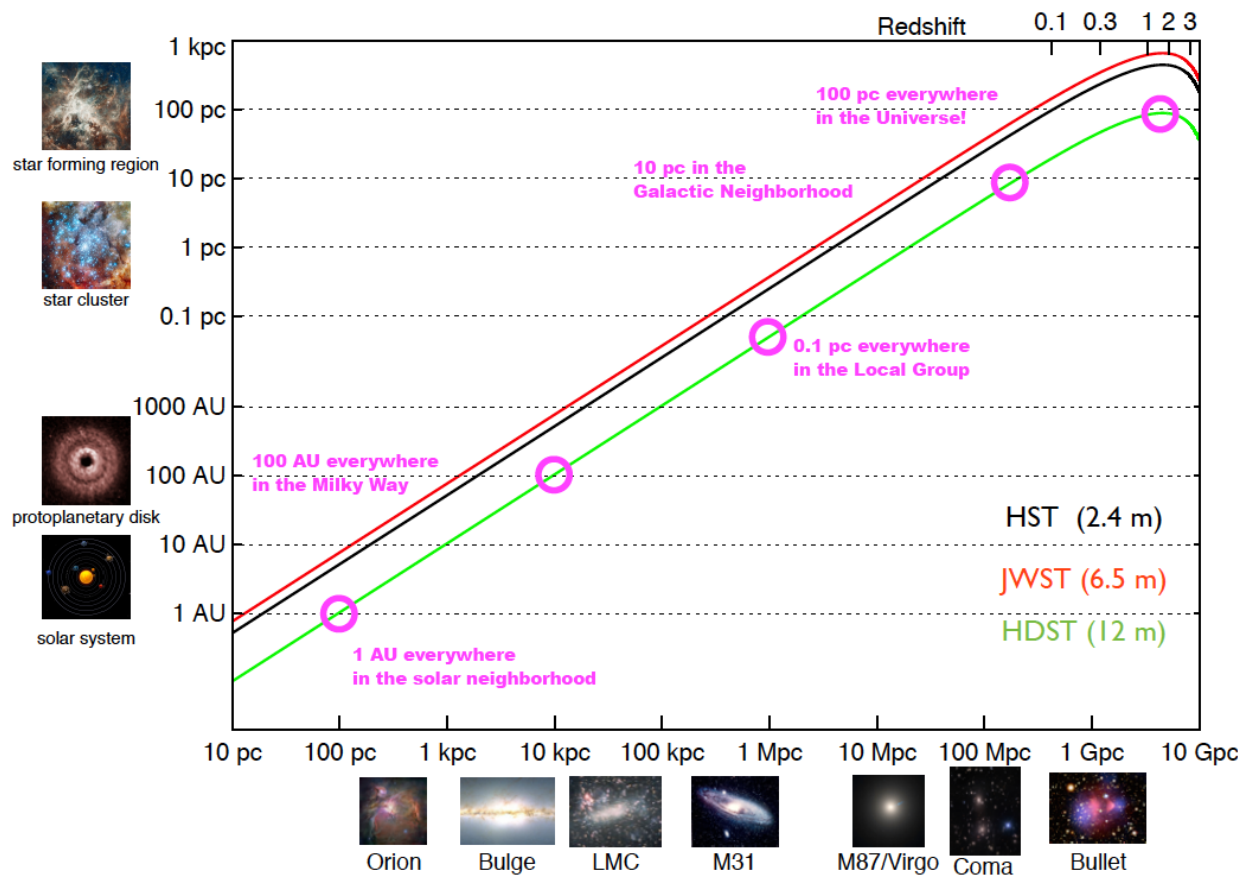


Fig. 2. An observatory with an aperture the size proposed for HDST will permit observations on a scale smaller than 100 pc throughout the universe (from Ref. 24).

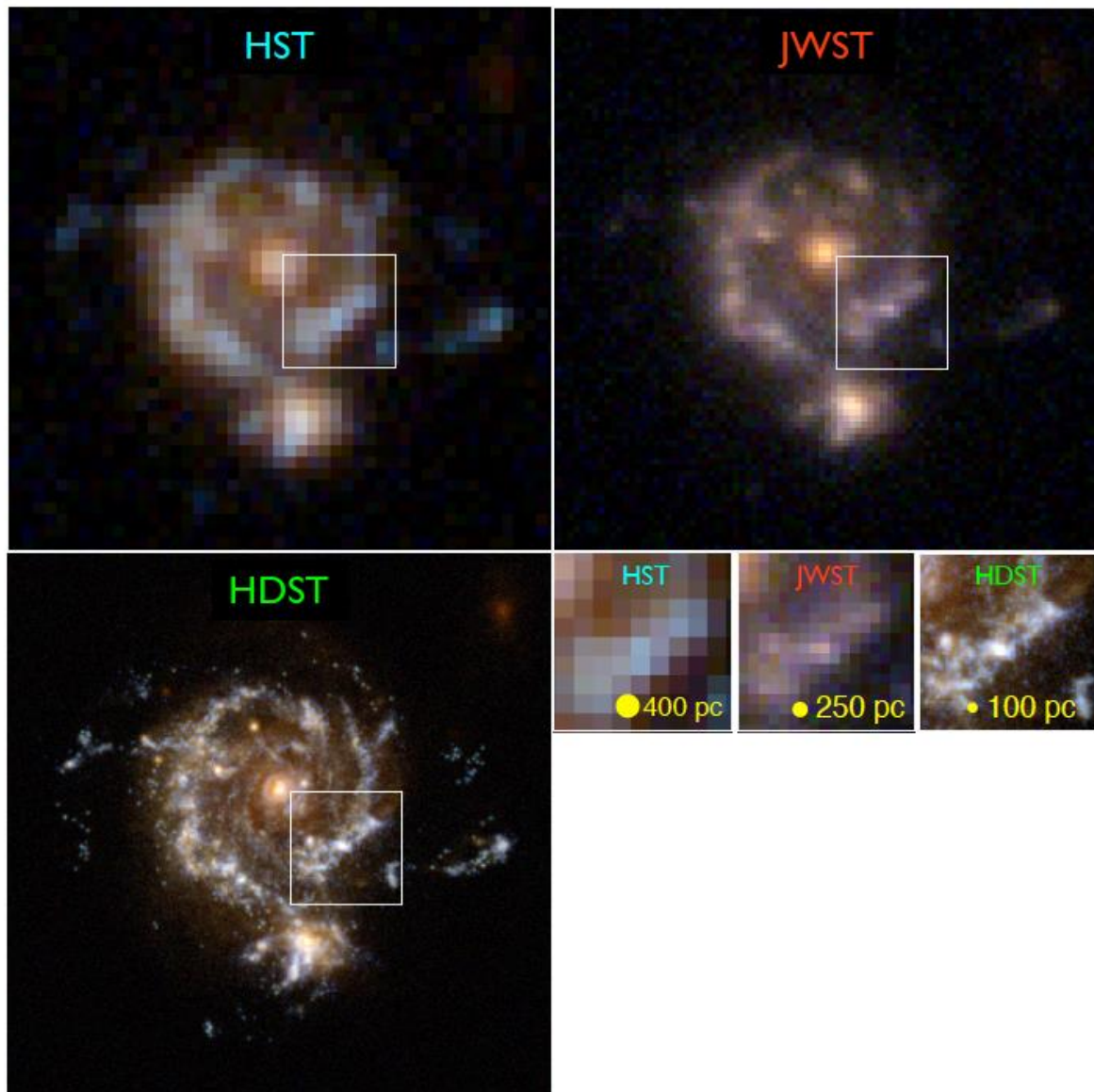


Fig. 3. Comparison of synthetic images taken of an extremely distant galaxy as would be revealed by three flagship observatories (Ref. 24).

Both the most challenging scientific goal proposed for HDST, as well as for what many believe is its most exciting, is the study of UVOIR “biomarkers” in the spectra of Earth-like worlds orbiting neighboring stars. This goal requires a very large aperture in space in order to be able to

(1) observe a sufficiently large number of stars to provide meaningful constraints on the occurrence of potentially habitable exoplanets and (2) acquire the spectra of those exoplanets, which are extremely faint, and (3) to resolve the angular separation between the exoplanet from its host star, as discussed in the work summarized in Section 1. Technologies to permit extremely stable wavefront control of a large aperture, as well as starlight suppression to about one part in 10 billion (10^{10}) via a coronagraph and/or starshade, were identified in the AURA report for HDST as priority investments to make the concept possible.

2. The Advanced Technology Large-Aperture Telescope in 2015

The 2010 Decadal Survey strongly recommended a technology development program to “[Prepare] for a planet-imaging mission beyond 2020.” In response, in spring 2013 NASA’s Goddard Space Flight Center (GSFC) initiated an internally funded assessment of a large-aperture UVOIR space observatory specifically intended to be sufficiently well-characterized to be recommended by the 2020 Decadal Survey for development in the 2020s. Building upon the concept studied about a half decade before, our design continued the earlier acronym, the Advanced Technology Large-Aperture Telescope (ATLAST). The GSFC design team was joined in short order by its partners from the previous study: the NASA Jet Propulsion Laboratory, the Space Telescope Science Institute, and the NASA Marshall Space Flight Center and informal discussions were carried on with the AURA HDST team (Sec. 1.4). Our ATLAST study was concluded in late 2015 at the beginning of the current Large UV/Optical/IR (LUVOIR) Surveyor assessment, which is led by GSFC. Our ATLAST design reference mission is reported on in greater detail elsewhere in this issue by Bolcar et al. (Ref. 24) and Rioux et al (Ref. 25). The remainder of this paper gives an overview of the design, including the strategy pursued in its development.

The science requirements derived for the ATLAST design from last decade¹⁸, updated by our team at the start of our current assessment, and consistent with AURA's HDST concept, determine reference design requirements, as summarized in Table 1 and a notional instrument suite summarized in Table 2. From the start, our team was unambiguous about the design being capable of carrying out a broad range of astronomical investigations, including the priority of the challenging search for and characterization of Earth-like worlds in the solar neighborhood. We concluded that an aperture of ~10 meters was a compellingly attractive advance in general scientific capabilities over HST. Moreover, it is larger than the minimum aperture (~8 m) that we judged would produce a sample size of candidate exo-Earths of sufficient size to permit us to confidently estimate statistically the yield of life-bearing planets in the solar neighborhood.^{xx3}

2.1 A Deployable Concept for ATLAST

Our segmented, deployable Engineering Design Reference Mission (EDROM) consists of a deployable primary mirror (Figs. 1 and 4). The aperture is scalable, meaning that its architecture supports adding more rings of segmented mirrors to increase the aperture in response to the refinement of the science requirements or availability of larger launch vehicles. The 9.2 m configuration that our team adopted to assess in depth was validated to fit within a five-meter launch vehicle fairing, an industry standard, which we chose as part of our strategy to build confidence that our design is feasible and costs are controllable. An image of the final ATLAST reference design for this concept from mid-2015 is presented in Fig. 4. The 9.2 m aperture is made up of 36 hexagonal segments, reflecting the design heritage of the James Webb Space Telescope (JWST).

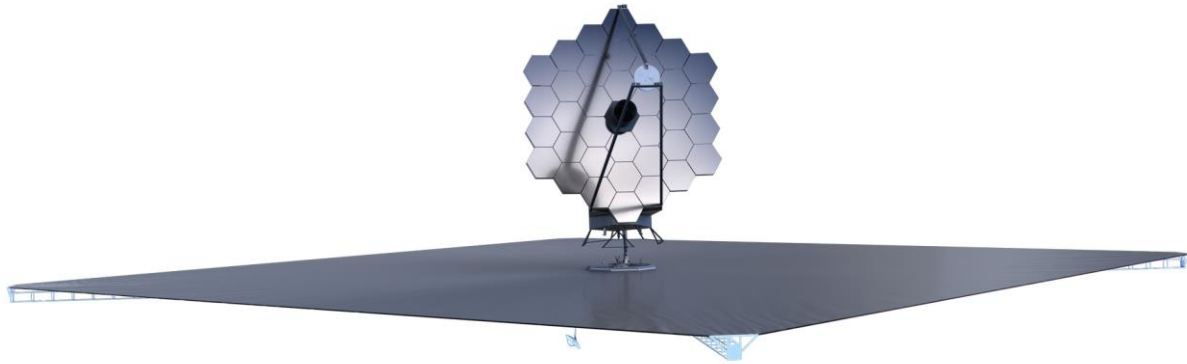


Fig. 4 Final visualization of the ATLAST segmented reference design.

Table 1 ATLAST Observatory Requirements Derived from Science Goals

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 wave front error 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 were levied on the observatory to achieve mid-IR goals beyond those that would enable the near-IR observations.

Table 2 ATLAST Instrument Suite

Science Instrument	Parameter	Requirement
UV Multi-Object Spectrograph	Wavelength Range	100 nm – 300 nm
	Field-of-View	1 – 2 arcmin
	Spectral Resolution	R = 20,000 – 300,000 (selectable)
Visible-NIR Imager	Wavelength Range	300 nm – 1.8 μ m
	Field-of-View	4 – 8 arcmin
	Image Resolution	Nyquist sampled at 500 nm
Visible-NIR Spectrograph	Wavelength Range	300 nm – 1.8 μ m
	Field-of-View	4 – 8 arcmin
	Spectral Resolution	R = 100 – 10,000 (selectable)
MIR Imager / Spectrograph	Wavelength Range	1.8 μ m – 8 μ m
	Field-of-View	3 – 4 arcmin
	Image Resolution	Nyquist sampled at 3 μ m
	Spectral Resolution	R = 5 – 500 (selectable)
Starlight Suppression System	Wavelength Range	400 nm – 1.8 μ m
	Raw Contrast	1×10^{-10}
	Contrast Stability	1×10^{-11} over science observation
	Inner-working angle	34 milli-arcsec @ 1 μ m
	Outer-working angle	> 0.5 arcsec @ 1 μ m
Multi-Band 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 – 500 (selectable)

2.2 A Monolith Concept for ATLAST

In addition to the deployable concept, our EDRMs included concepts using an 8 m monolith primary mirror and a monolith surrounded by deployable mirror petals.

The latest iteration of the 8 m monolith concept has been led by the ATLAST team at MSFC and is described by Stahl et al.²⁶. A major appeal for this design is the advantage of not having gaps due to segments in the primary mirror, which is characteristic of the deployable options for ATLAST. A monolith thus provides advantages with regard to some current coronagraph designs. However, an 8 m monolith observatory, as well as segmented designs much larger than described

in the previous subsection, would require the SLS Block II launch vehicle with a ten-meter fairing. This vehicle is slated for development, but there is at present no alternative means of launching the mission. The 8 m monolith concept relies on “deep-core” mirror technology newly developed via NASA’s Advanced Mirror Technology Development (ATMD) program.

3. Conclusion

Since the mid-1980s, multiple teams of astronomers, technologists, and engineers have developed concepts for a large-aperture UV/optical/IR space observatory to follow the Hubble Space Telescope (HST). Especially over the past decade, technology advances and exciting scientific results has led to growing support for development in the 2020s of a large UVOIR space observatory. To a remarkable degree, the concepts had broadly similar designs (e.g., an aperture in the range of 8 – 16 meters, depending largely upon the design of the primary mirror and availability of launch vehicle; operation from ~100 nm to ~2 μm), key required technology capabilities (e.g., very high-contrast starlight suppression, stringent wavefront error stability), and high-priority science objectives (e.g., search for and characterization of Earth-like worlds in the solar neighborhood, high angular-resolution imaging of extremely distant galaxies).

The consistency of the mission designs, increasing breadth of science objectives in this wavelength range, and NASA-supported technology assessments led to a series of formal recommendations for enabling technology funding that would permit development of a large UVOIR observatory. In this paper we summarized three decades of major mission designs, scientific goals, key technology recommendations, community workshops and conferences, and NRC recommendations. We concluded with a capsule summary of the ATLAST reference design developed over the past three years by a NASA GSFC, MSFC, JPL, and STScI team that was

intended to position such a mission for selection by the 2020 Decadal Survey as the highest-priority initiative for the 2020s.

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Caption List

Fig. 1. Relative sizes of the primary mirrors for HST, JWST, and HDST (from Ref. 24)

Fig. 2. An observatory with an aperture the size proposed for HDST will permit observations on a scale smaller than 100 pc throughout the universe (from Ref. 24).

Fig. 3. Comparison of synthetic images taken of an extremely distant galaxy as would be revealed by three flagship observatories (Ref. 24).

Fig. 4. Final visualization of the ATLAST segmented reference design

First Author.

Bio and image