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# Path to a UV/optical/IR flagship: review of ATLAST and its predecessors

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**Abstract.** Our recently completed study for the Advanced Technology Large-Aperture Space Telescope (ATLAST) was the culmination of three years of initially internally funded work that built upon earlier engineering designs, science objectives, and technology priorities. Beginning in the mid-1980s, multiple teams of astronomers, technologists, and engineers developed concepts for a large-aperture UV/optical/IR space observatory intended to follow the Hubble Space Telescope (HST). Here, we summarize since the first significant conferences on major post-HST ultraviolet, optical, and infrared (UVOIR) observatories the history of designs, scientific goals, key technology recommendations, and community workshops. Although the sophistication of science goals and the engineering designs both advanced over the past three decades, we note the remarkable constancy of major characteristics of large post-HST UVOIR concepts. As it has been a priority goal for NASA and science communities for a half-century, and has driven much of the technology priorities for major space observatories, we include the long history of concepts for searching for Earth-like worlds. We conclude with a capsule summary of our ATLAST reference designs developed by four partnering institutions over the past three years, which was initiated in 2013 to prepare for the 2020 National Academies' Decadal Survey.

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## 1 Early Concepts for a Large Ultraviolet, Optical, and Infrared Space Observatory to Follow the Hubble Space Telescope

### 1.1 Concepts Before the 2000 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, which were advocated as the natural eventual successors to HST, are reflected in the more advanced recent concepts described in this special section of the *Journal of Astronomical Telescopes, Instruments, and Systems* (JATIS) (Smith and McCray<sup>1</sup> described this time period in depth, although included several topics beyond the scope of this paper.).

Probably the earliest substantive identification of a large UVOIR space observatory specifically intended to follow HST was the National Research Council (NRC) 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<sup>2</sup>). Volume II of this report presciently 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 IR performance.” The 1986 Report of the National Commission on Space, “Pioneering the Space Frontier”<sup>3</sup> (aka, the Paine report) recommended a broadly similar mission as it drew heavily on the nearly simultaneous SSB report and personnel, notably telescope operation at ~100 K.

Not long after the SSB and Paine reports, in his overview of the influential 1989 Space Telescope Science Institute (STScI) community workshop report, “The Next Generation Space Telescope,”<sup>4</sup> Illingworth urged the participants to recognize the limited lifetime of 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- to 16-m class telescope operating from ~0.1 μm to “beyond 10 μm” due to passive cooling to 100 K. (As Smith and McCray<sup>1</sup> point out on page 49, “This widely quoted apparent

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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. This recognition contributed to an emphasis on IR observations, rather than UV/optical wavelengths, for the first major post-HST observatory as discussed later in this section.)

In the proceedings of the STScI workshop, Illingworth summarized a selection of some of the most exciting science that a large post-HST observatory would be capable of, including revealing important structures in cosmologically distant galaxies observable throughout the Universe with scale sizes of 100 to 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, Angel<sup>5</sup> 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.

With respect to the search for life, interestingly NASA apparently first explicitly considered direct imaging of extrasolar planets with a large-aperture telescope as part of the Project

Orion design study<sup>6</sup> in the late 1970s. Both ground- and space-based imaging were evaluated in this study, 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 and Terrile<sup>7</sup> in the mid-1980s provided impetus to the first mission study work leading to a proposal for the modest-aperture, ultrasmooth Circumstellar Imaging Telescope by the Jet Propulsion Laboratory.<sup>8,9</sup> A major technical challenge at the time, however, was manufacturing large optics to the required smoothness, which motivated years of subsequent NASA technology investments.

Momentum in the scientific and technical communities was building. In 1991, two years after the NGST meeting at STScI, JPL hosted a workshop, “Technologies for Large Filled-Aperture Telescopes in Space,” which summarized developments necessary to enable the 8- to 16-m UVOIR telescope operating from 0.12 to  $\sim 10 \mu\text{m}$  described in Illingworth’s<sup>10</sup> workshop executive summary. To demonstrate the impressive capabilities of such an observatory, page 6 in the workshop report 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. (See also the cover of Refs. 4 and 5.)

For advocates of future major space observatories, it is worth noting that less than a year had passed after launch of HST, multiple engineering 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,

**Table 1** ATLAST observatory requirements derived from science goals.

Parameter		Requirement	Stretch goal	Traceability
Primary mirror aperture		$\geq 8.0$ m	$> 12.0$ m	Resolution, sensitivity, exoplanet yield
Telescope temperature		273 to 293 K	—	Thermal stability, integration & test, contamination, IR sensitivity
Wavelength coverage	UV	100 to 300 nm	90 to 300 nm	—
	Visible	300 to 950 nm	—	—
	NIR	950 nm to $1.8 \mu\text{m}$	950 nm to $2.5 \mu\text{m}$	—
	MIR	Sensitivity to $8.0 \mu\text{m}$	—	Transit spectroscopy
Image quality	UV	$< 0.20$ arcsec at 150 nm	—	—
	Vis/NIR/MIR	Diffraction-limited at 500 nm	—	—
Stray light		Zodiacal light-limited between 400 nm to $1.8 \mu\text{m}$	Zodiacal light-limited between 200 nm to $2.5 \mu\text{m}$	Exoplanet imaging & spectroscopy SNR
Wavefront error stability		$\sim 10$ pm RMS uncorrected system wave front error per wavefront control step	—	Starlight suppression via internal coronagraph
Pointing	Spacecraft	$\leq 1$ milli-arcsec	—	—
	coronagraph	$< 0.4$ milli-arcsec	—	—

Note: 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.

broadly similar to the concepts discussed elsewhere in this special issue of JATIS. 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. Note, however, these early 1990s workshops represented a high-water mark in proposing large UVOIR observatories on the lunar surface or in high-Earth orbit: Farquhar and Dunham<sup>11</sup> wrote briefly on the value of the Sun-Earth libration points for space observatories. In 1995, NASA's very successful Solar and Heliophysics Observatory began operating at the Sun-Earth L1 point and HST had by then amply demonstrated sustained precision operation of an observatory in free space.

The mid-1990s also began an extended hiatus in the candidacy of a large UV/optical-optimized observatory for selection as the high-priority major post-HST mission for NASA. In late 1993, the Association of Universities for Research in Astronomy (AURA) empaneled an 18-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 UV-Optical-IR Space Astronomy"<sup>12,13</sup> (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 previously: (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 different direction from previous community recommendations and would ultimately lead to selection by the 2000 NRC Decadal Survey<sup>14</sup> of the Next Generation Space Telescope (NGST): (1) extend the lifetime of HST, (2) build a large filled-aperture IR-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<sup>15</sup>. To underscore European interest, 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.<sup>16</sup>

With HST's flawed optics corrected in 1993, and two new instruments 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 under consideration. Given the long gestation period for building a flagship-class mission (over ~20 years) and with the IR-optimized NGST recommended by the Dressler Report very different from the UVOIR version of NGST recommended by the STScI conference<sup>4</sup> in 1989 as the next large mission to follow HST, advocacy resumed for a large UV-optical-near-IR flagship. Such a mission would now be 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.<sup>17</sup> The meeting consensus was that the next step after HST at UVOIR

wavelengths should be a 4- to 6 m-class instrument to complement NGST, an aperture notably more conservative than that generally advocated a decade earlier. In response to this workshop, NASA's UV-optical working group (UVOWG) was commissioned to study the scientific rationale for new missions in the UV-optical bandpass. This group produced a report<sup>18</sup> that also recommended (1) a 4-m 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, 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 IR-optimized Terrestrial Planet Finder (TPF; see Sec. 1.2) was the recommended mission to eventually achieve this NASA goal, although the 2000 Decadal Survey's highest-priority major recommendation was NGST.

## 1.2 Preparing for the 2010 Decadal Survey

### 1.2.1 Terrestrial planet finder concepts: interferometry or coronagraphy?

The technologies for extraordinarily smooth large mirrors remained out of reach at the time of the 2000 Decadal Survey. Thus, spatial interferometry seemed favored for studying Earth-sized worlds and interest in direct imaging was sustained, e.g., by the first exoplanet detection by the radial velocity technique of a planet orbiting a Sun-like star.<sup>19</sup> Some attention shifted to mid-IR wavelengths where targets present a contrast relative to the central star that is three orders of magnitude easier to obtain than at optical wavelengths:  $10^{-7}$  versus  $10^{-10}$ . Starlight suppression would be done by interferometric nulling between separate telescopes mounted on a large boom or flying in formation.<sup>20</sup> This concept became known as the Terrestrial Planet Finder (TPF) and was the subject of detailed study by a NASA Science Working Group<sup>21</sup> (SWG). This concept was also one of the original candidate future missions adopted by the Origins Program, created in the late 1990s within NASA Headquarters Office of Space Science to lead the agency in the search for life-bearing planets: i.e., the cosmic origins of life.

The endorsement of the 2000 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.<sup>22</sup> A key outcome of the architecture studies was the revival of interest in a coronagraphic alternative for TPF working at visual wavelengths.<sup>23</sup> 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 ultrasurface quality. At this point, the TPF SWG went forward on two parallel paths studying both the IR interferometer (TPF-I) and optical coronagraph (TPF-C) versions of the concept.

Laboratory experiments achieving  $10^{-9}$  contrast<sup>24</sup> gave confidence that the UV/optical-optimized 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 coordinated JPL and NASA Goddard mission study beginning in 2004.

Unfortunately, changing budget priorities within NASA led to the termination of the TPF-C design study and technology investment. A final report<sup>25</sup> was produced. 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 Sec. 1.2.2.

### 1.2.2 *Large-aperture ultraviolet, optical, and infrared concepts: preparing for the 2010 Decadal Survey*

With the emphasis of the 2000 Decadal Survey on the IR-optimized NGST, the UVOIR community's attention turned to preparing for the 2010 Survey.

A series 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, consequently, essential technology development by NASA: "Hubble's Science Legacy: Future Optical-Ultraviolet Astronomy from Space"<sup>26</sup> in April 2002; "Innovative Designs for the Next Large Aperture UV/Optical Telescope"<sup>27</sup> in April 2003; "Future Optical/UV Astronomy from Space: Science and Mission Concepts"<sup>28</sup> in May 2003; and "The Science Potential of a 10- to 30-m UV/Optical Space Telescope"<sup>29</sup> in February 2004. In addition to these formal conferences, NASA headquarters organized during this period a pair of so-called "Loya Jirga" workshops<sup>30</sup> in Boulder, Colorado, intended specifically to bring together a modest number of experts in observatory engineering design, technologies, and operations to develop over a few days credible large-aperture telescope designs as input to NASA's Advanced Planning and Integration Office (APIO), discussed later.

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 2003, with the subsequent hiatus in servicing missions to HST, and the priority in the 2000 Decadal Survey allocated IR observations with NGST, all contributed to a sense of urgency to define compelling mission concepts and science goals in UVOIR space astronomy.

In 2004, NASA Headquarters Science Mission Directorate solicited so-called "Vision Missions" in space science. NASA chose the 10 m-class UV-optical Modern Universe Space Telescope (MUST) for study,<sup>31</sup> along with 10 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 proposed Ares V rocket, which was a priority of the newly announced vision for space exploration<sup>32</sup> (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.

To enable the search for life-bearing planets, among other priority goals, NASA Administrator Sean O'Keefe established the<sup>33</sup> APIO in spring 2004. The APIO was the most ambitious

activity of its kind in many years, involving hundreds of scientists and technologists to develop an agency-wide strategy to guide human space flight and science in investing in new capabilities well into the future. The final reports were intended to be reviewed in depth by the NRC and would take advantage of capabilities expected to be developed as part of the VSE. Although most of the APIO activities were terminated a year later upon the arrival of a new NASA Administrator, several technology roadmaps mainly to achieve science goals were permitted to be concluded, reviewed by the NRC, and recommended to NASA for implementation. Twelve roadmaps were published in 2006 and included a strategy to enable future flagship observatories.<sup>34</sup> This strategy 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.

### 1.2.3 *First iteration of the advanced technology large-aperture space telescope concept*

In summer 2007, NASA issued a call for proposals for "Astrophysics Strategic Mission Concept Studies" (ASMCS), seeking to identify concepts for scientifically ambitious space astronomy missions and to help identify technology developments such missions might require in time for the looming Decadal Survey. The ATLAST was one of the concepts selected by NASA for study. The objective of the study was to develop a technology investment plan for the 2010 to 2019 timeframe that would enable a large UVOIR space telescope to be considered by the Survey to begin development 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 study teams. 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 telescope<sup>35</sup> and two segmented telescopes, one with a 9.2-m primary<sup>36</sup> that could fit into an existing Evolved Expendable Launch Vehicle, and one with a 16.8-m primary.<sup>37</sup> The 8- 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 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.<sup>38</sup> 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 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 (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  $\sim 100$  K and possible operation on the lunar surface. Neither feature survived the 1990s.). 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 community meetings specifically to assess the scientific benefit of such a capability as another Decadal Survey approached. NASA Ames Research Center hosted a pair of workshops<sup>39</sup> in early 2008 specifically to assess the scientific community's interest in using Ares V. Not long after, the NRC produced a study, "Launching Science,"<sup>40</sup> of the science opportunities enabled by NASA's constellation program and especially taking advantage of the Ares V heavy-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 11 "Vision" mission concepts (see above) already solicited by NASA HQ SMD, for its study the NRC sought broader 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 NRC "Launching Science" report to NASA for further study.

With more than two decades of increasingly sophisticated engineering designs, community science input, international and industrial interest, 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,"<sup>41</sup> identified as its highest priority "medium" activity, investment in technologies to "(Prepare) for a planet-imaging mission beyond 2020" with mission-specific funding of  $\sim \$200$  M over the decade of the 2010s.

The 2010 Decadal Survey recommended as its highest priority "major" activity that NASA develop a mission later named the Wide-Field IR Space Telescope (WFIRST) in order to study dark energy, take a census of exoplanets using the microlensing technique, and to perform deep-sky surveys. The proposed telescope had an aperture of 1.5 m and was adopted from the Joint Dark Energy Mission concept, a combined NASA and Department of Energy initiative. However, shortly after the Decadal Survey report was published, NASA announced that they had received a donated 2.4-m aperture wide-field optical telescope assembly (OTA) and capable of operating over visible and near-IR wavelengths. This OTA, with some modifications, was promptly adopted as the baseline for WFIRST. The larger aperture permitted a much-improved science program, including direct imaging of exoplanets via coronagraphy, and a General

Observer program. The technology development for a high-contrast coronagraph for WFIRST is also intended to benefit a subsequent larger-aperture space telescope. WFIRST recently entered into Phase-A development, and has an expected launch date in the mid-2020s.

### 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 long-range 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 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."<sup>42</sup> The roadmap also identified key technology investments necessary to enable the missions recommended to NASA Headquarters' Astrophysics Division.

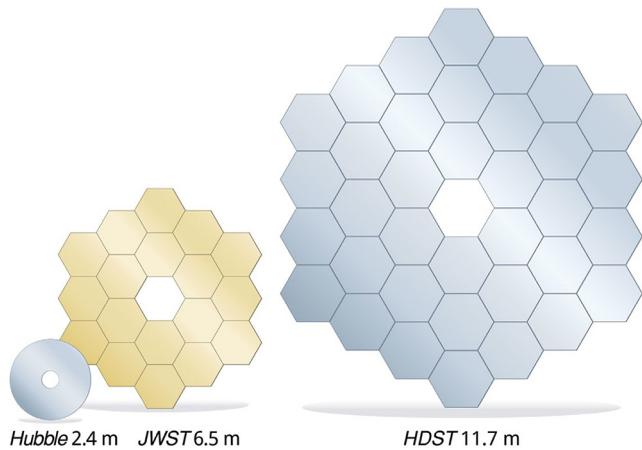
The scientific objectives, mission concepts to achieve them, and technologies required to enable them were divided into three time periods, each about a decade long, beginning with the near-term missions already under development (e.g., JWST and WFIRST). Following this period was the Formative Era, which identified for NASA science priorities now familiar from multiple conferences and workshops referenced previously, 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 many others before it, a large UV/optical/near-IR mission now dubbed the LUVOIR Surveyor, which was described in the final report as having an aperture of 8 to 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 developed by Bolcar et al.<sup>43</sup> for the ATLAST concept described in Sec. 2: precision deployment and wavefront control, mirror coatings, detector systems, and—very critically—high-performance starlight suppression.

### 1.4 *Association of Universities for Research in Astronomy's High-Definition Space Telescope*

In early 2013, the Association of Universities for Research in Astronomy (AURA) chartered a team of seventeen scientists and technologists to assess further 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,"<sup>44</sup> described in depth 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 the last decade, its science drivers and design concepts had progressed substantially.

Significant scientific advances over the performance of HST at these wavelengths require developing the capability to deploy



**Fig. 1** Relative sizes of the primary mirrors for HST, JWST, and HDST (Fig. 5-1 from Ref. 44).

an aperture much larger than can currently be accommodated within the inner diameter of existing launch vehicles, as earlier concepts described (e.g., Refs. 4 and 10). 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 required in deployed optics, Fig. 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-m segments, although segments of different sizes could be adopted.

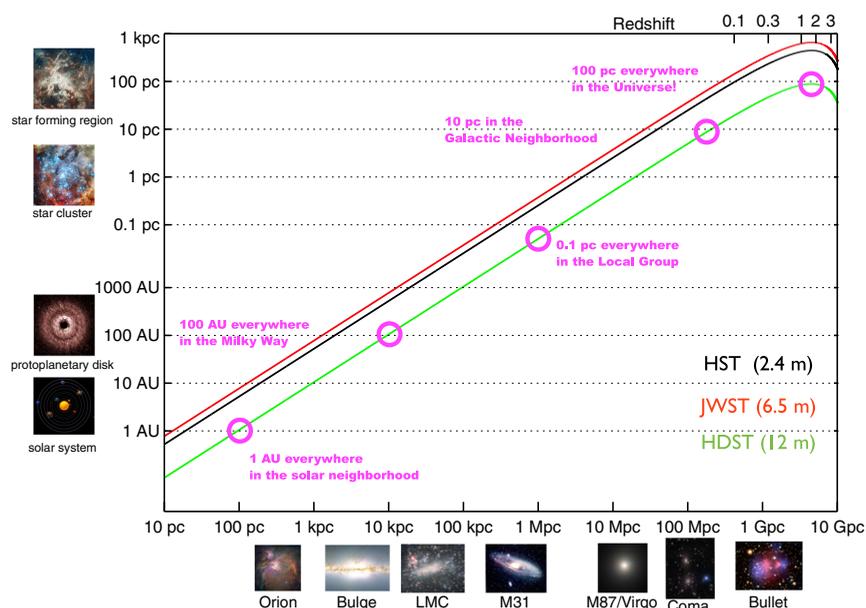
The AURA study developed a notional instrument suite that permitted realistic estimates of observatory performance consistent with being both a powerful general-purpose flagship, as well as capable of detecting biomarkers in the candidate Earth-like worlds. HDST was proposed to have 25 times the pixel density per area of HST at the same optical wavelengths,

than four times better resolution at near-IR wavelengths JWST, and up to 100 times the point-source UV spectroscopic sensitivity. Furthermore, HDST was proposed to have multiobject UV spectroscopy for up to 100 sources in an  $\sim 3$  arcmin field of view, as well as extremely stable wavefronts to provide precise point-spread functions over long observational timelines.

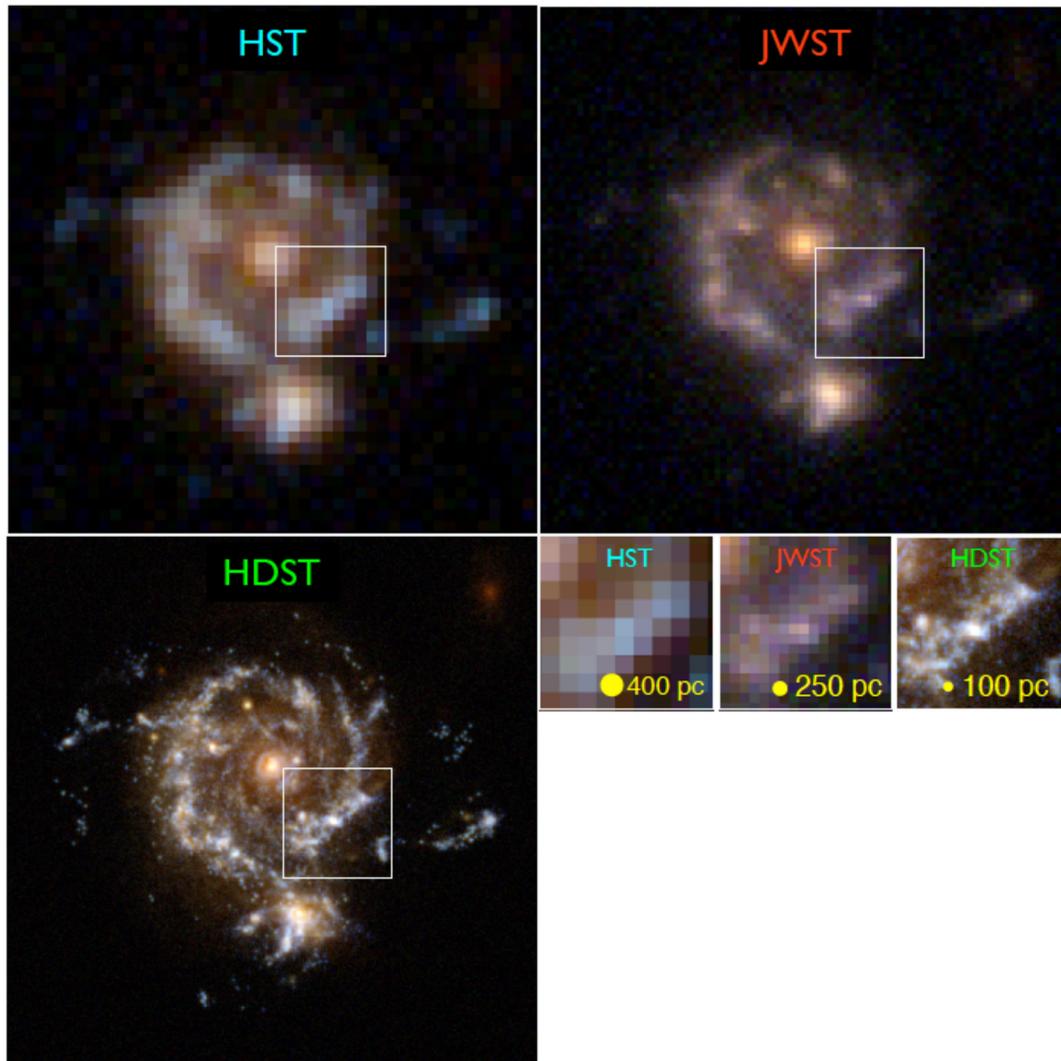
For galaxies out to cosmological distances, a mission such as HDST would have the capability to reveal features on a scale size of 100 pc or smaller (Fig. 2), which will reveal structures and processes critically important to major leaps in our understanding of the cosmos.

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.

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 Sec. 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.



**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 (Fig. 4-1 from Ref. 44).



**Fig. 3** Comparison of synthetic images taken of an extremely distant ( $z = 2$ ) galaxy as would be revealed by three flagship observatories. Diffraction-limited angular resolution of each observatory is indicated in each of the three smaller insets (Fig. 4-5 in Ref. 44).

## 2 Advanced Technology Large-Aperture Space Telescope

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 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 considered by the 2020 Decadal Survey for development in the 2020s. Building upon the concept studied about a half-decade earlier for the previous Survey, our design retained the earlier acronym, the ATLAST. Unlike last decade’s ATLAST study, our more recent assessment was originally internally funded by the partnering institutions, augmented subsequently by the NASA Headquarters’ Astrophysics Division.

In short order, the GSFC design team invited its partners from the previous study: the NASA Jet Propulsion Laboratory, the Space Telescope Science Institute, and the NASA Marshall Space Flight Center. Within a few months, regular informal discussions began with the AURA HDST team

(Sec. 1.4). Our ATLAST study was concluded in late 2015 with study results passed on to the current Large UV/Optical/IR (LUVOIR) Surveyor assessment. Our ATLAST design reference mission is reported on in additional detail elsewhere by Bolcar et al.<sup>43</sup> and Rioux et al.<sup>45</sup> The remainder of this paper gives an overview of the design, including the strategy pursued in its development.

### 2.1 Scenario Planning for the Advanced Technology Large-Aperture Space Telescope

Our scenario planning activity for the study summarized here recognized, e.g., uncertainties in major science goals for this wavelength range in the 2020s, characteristics of plausible future launch vehicles at that time, as well as capabilities for astronauts and robotic systems at notional operations’ site for an ATLAST-type mission. Moreover, at the time we began our assessment, NASA HQ had yet to prepare plans for the 2020 Decadal Survey. Our final reference design was, therefore, intended to be flexible enough to be a successful candidate for

**Table 2** Notional ATLAST instrument candidates.

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

future development, regardless of the scientific, programmatic, and engineering environment of the 2020s. In addition, as mandated by Congress, the ATLAST designs that our team assessed were all intended to be serviceable, if not actually serviced, when eventually operational.

Basic science requirements were derived from the ATLAST design from last decade,<sup>37</sup> and updated by our team at the start of our current assessment in 2013. These requirements were consistent with those described in NASA’s 30-year roadmap<sup>42</sup> and AURA’s HDST concept<sup>44</sup> and determined reference design requirements, as summarized in Table 1 and notional candidate instruments summarized in Table 2. In our scenario planning, our team was unambiguous about the design being capable

of carrying out a broad range of astronomical investigations, including our team’s priority of the challenging search for and characterization of Earth-like worlds in the solar neighborhood. We concluded that an aperture of  $\sim 10 \text{ m}$  was a compellingly attractive advance in general scientific capabilities over HST. Moreover, it is larger than the minimum aperture ( $\sim 8 \text{ m}$ ) 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.<sup>46</sup>

## 2.2 A Deployable Concept for Advanced Technology Large-Aperture Space Telescope

By adopting a segmented design as one concept for ATLAST, we had a basic design that was adaptable to different launch vehicles by increasing or decreasing the size of the segments, their number, or the adopted deployment scheme.

Our engineering design reference mission (EDRM) consists of a deployable primary mirror. Consistent with our scenario planning, the aperture is scalable, meaning that its engineering design 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. With study resources at first limited largely to internal funds, we were constrained to assess in depth only a single segmented design, a 9.2-m configuration. This aperture was validated to fit within a 5-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 shown in Fig. 4. The 9.2-m aperture is made up of 36 hexagonal segments and reflects the design heritage of JWST.

## 2.3 A Monolith Concept for Advanced Technology Large-Aperture Space Telescope

In addition to the chord-fold 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.<sup>47</sup> 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, 8 m is the approximate upper limit for a monolithic aperture telescope. Consequently, as described also by Stahl and Hopkins,<sup>48</sup> the MSFC team also produced a 12-m concept consisting of a central monolith surrounded by a ring of identical petals. Both of these concepts, as well as segmented designs much larger than described in Sec. 2.2, would require the space launch systems (SLS) Block II launch vehicle with either its 8- or 10-m fairing. This vehicle is slated for eventual development and there is at present no alternative means of launching the largest ATLAST apertures. Depending on the SLS mass capacities, the 8-m monolith concept could use existing ground based mirror technology or the new “deep-core” mirror technology being developed via NASA’s advanced mirror technology development program.<sup>49</sup>

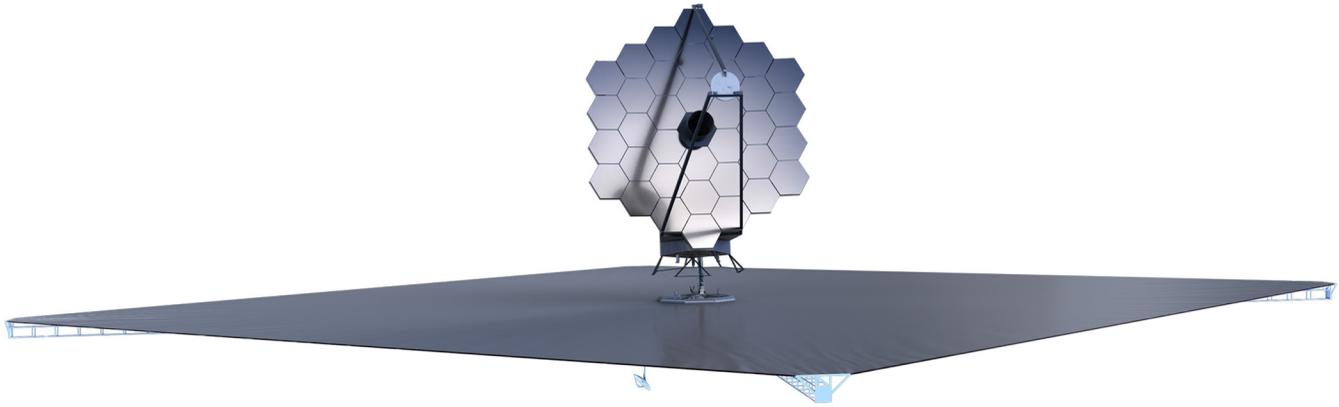


Fig. 4 Final visualization of the ATLAST segmented reference design from mid-2015.

### 3 Conclusion

Major science priorities – and the technologies required to achieve them—for a very large UVOIR space observatory can be traced to the late-1970s. Since the mid-1980s, multiple teams of astronomers, technologists, and engineers have developed increasingly detailed concepts for a large-aperture UVOIR space observatory to follow the HST. Especially over the past decade, technology advances in starlight suppression and precision optics, as well as exciting scientific results from HST and the Kepler mission, has led to growing support for development in the 2020s of a large UVOIR space observatory.

To a remarkable degree, the concepts advocated over the past few decades had broadly similar designs (e.g., an aperture in the range of 8- to 16-m, depending largely upon the design of the primary mirror and availability of launch vehicles; operation from  $\sim 100$  nm to  $\sim 2$   $\mu$ m), key required technology capabilities (e.g., very high-contrast starlight suppression, stringent wave-front 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 several NRC-reviewed technology assessments led to a number of formal recommendations to NASA 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 conclude with a capsule summary of ATLAST reference designs developed over the past three years by a joint funded NASA GSFC, MSFC, JPL, and STScI team, reference designs intended to be positioned for selection by the 2020 Decadal Survey as the highest-priority initiative for the 2020s.

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