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LESSONS LEARNED

Large mission implementation lessons from history

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ABSTRACT. Pathways to Discovery in Astronomy and Astrophysics for the 2020s has recommended a Great Observatory Maturation Program (GOMaP) to invest in co-maturation of mission concepts and technologies to inform an analysis of alternatives study for an ∼6 m off-axis inscribed telescope. The purpose of this telescope is to sample atmospheric spectra of around 25 potentially habitable exoplanets using ultraviolet, visible, and near-infrared wavelengths; it is planned to launch in the early 2040s with a total cost of less than $11B, including 5 years of operation. A historical review of past missions yields basic programmatic lessons learned to be considered as the community prepares to implement the Decadal Vision. First, technology development is critical for enabling missions. The robustness, breadth, and duration of concept/technology co-maturation is important for mission success. Second, NASA has never "exactly" implemented a Decadal mission as it was recommended. Third, all missions have the same basic technology challenges of mass constraints: mechanical and thermal stability to design, building a space telescope that achieves the required on-orbit performance, and verifying and validating that performance by test and model correlation. Finally, Decadal missions require sustained community support.

Keywords: space telescopes; astrophysics; technology development

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1 Introduction

Per the Pathways to Discovery in Astronomy and Astrophysics for the 2020s Decadal Report,[1] the question "Are we alone?" continues to excite the human imagination and drives the "Paths to Habitable Worlds" science area. "How did the solar system form? Are systems like our own common or rare? Are planets like Earth common or rare? And, ultimately, do any of those Earth-like planets harbor life?"

But before authorizing the start of a new mission, the Decadal Report recommended creating a Great Observatories Mission and Technology Maturation Program to invest in co-maturation of mission concepts and technologies for large missions. And, "inspired by the vision of searching for signatures of life on planets outside of the solar system, and by the transformative capability such a telescope would have for a wide range of astrophysics, the survey recommended that the first mission to enter this program is a large (∼6 m aperture) infrared/optical/ultraviolet (IR/O/UV) space telescope." To search for signatures of life, the goal is to sample around 25 atmospheric spectra of potentially habitable exoplanets (assuming eta_earth = 0.24) using UV, visible, and near-infrared wavelengths (Fig. 1). This telescope is planned to be launched in the early 2040s with a lifecycle cost of $11B (including 5 years of operation).

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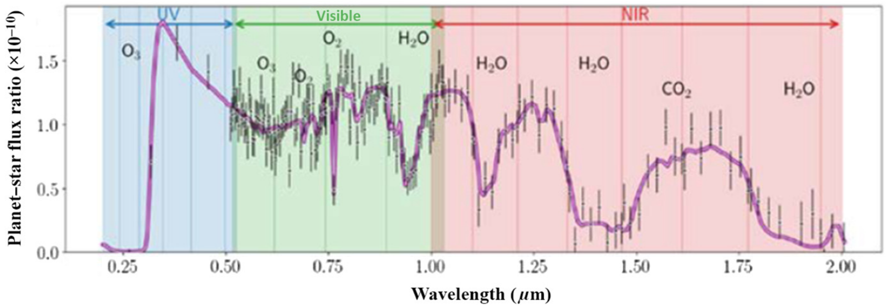

Fig. 1 Copy of Figure 7.5 from Pathways to Discovery Decadal Report pre-publication draft showing the spectrum over which the Decadal recommended that exoEarth atmospheres be sampled.

The Decadal Study Panel on Exoplanets, Astrobiology, and the Solar System suggested in their report detailed science goals (see Decadal Report Appendix E, Table E.1, pg E-17). Specifically, the large-aperture mission should be able to image and perform spectroscopy from 0.3 to 1.8 μm and achieve host-star contrast reduction of $\sim$1e $-$ 10 at an inner working angle of <60 mas and an outer working angle of >1 arc- sec. Its imaging spatial resolution should be approximately less than 0.01 mas, and its spectral resolution should be $R \sim 150$. The desire is to detect and characterize dozens of potential Earth analogs in the habitable zone of Sun-like stars and hundreds of planetary systems.

Finally, the Panel on Electromagnetic Observations from Space 1, in their report, provided suggestions regarding GOMaP's technology maturation goals. First, the panel suggested that a study be undertaken to enable an informed choice between monolithic and segmented primary mirror architectures. The panel explicitly stated that they were neither suggesting a preferred primary mirror configuration (monolithic or segmented) nor that one configuration was more feasible than another. Second, the panel suggested a Grand Technology Roadmap to mature technologies to technology readiness level 6 (TRL-6) before Phase-A to enable two critical capabilies required for detecting exoearths: 1e$-$10 starlight suppression and an ultra-stable telescope. For the starlight suppression capability, the panel suggested continued funding of high-contrast coronagraph instruments and suggested that an in-space demo of a sub-scale starshade would be helpful for retiring operational risk and validating the predicted performance. For the ultra-stable telescope capability, the panel suggested five specific technologies that needed development: ultra-stable structural composites, low-creep adhesives, coefficient of thermal expansion (CTE) measuring techniques, milli-K thermal sensing, and correlation between finite element models and measured surface-figure-error/wavefront-error.

So, how does history inform these recommendations and suggestions? First, every NASA astrophysics space mission has been enabled by technology advances. Second, every mission has undergone extensive co-maturation of both concept and technology. Third, NASA missions seldom (if ever) launch exactly as they are "recommended" by their Decadal. Most are descoped for cost.

This paper (first presented at SPIE Astronomical Telescopes and Instruments 2022, Montreal)[2] summarizes the history of Decadal recommendations and reviews the co-maturation of concept and technology from 1957 to the present that resulted in Hubble and Webb. Specific technology areas that enabled both missions include the evolution of telescope architectures, mirror design, material development, and improvements in optical fabrication and testing technology. Its content comes from official NASA historical documents, archival documents collected by the author, and the author's personal experience.

2 Summary of Decadal Recommendations

The standard narrative is that there is a one-to-one correlation between Decadal Reports and NASA "flagship" missions (Fig. 2). Although this narrative is correct at its core, the history is more complicated. None of these missions were implemented exactly as their respective Decadal Reports recommended, and some Decadal recommended missions were cancelled during concept/technology development.

For example, although it had been under study since 1962, the 1970 Decadal Report ranked a high-resolution UV/O Large Space Telescope (LST) as its #9 recommendation.[3]

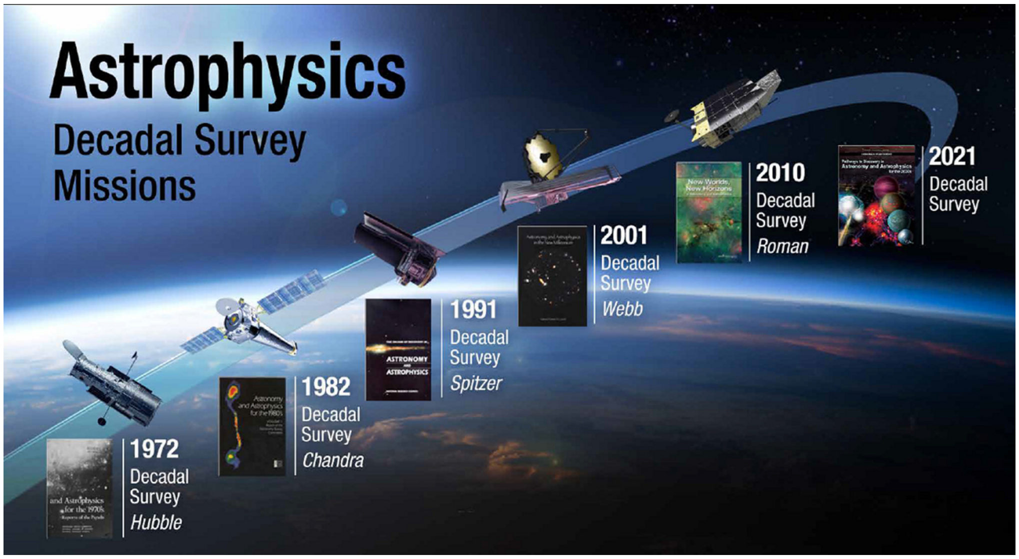

Fig. 2 Decadal survey missions.

The recommended specification for this telescope was 3 m in diameter with a spectral range from 0.1 to 5 μm. What eventually flew as Hubble was a 2.4 m telescope operating from 0.1 to 2.5 μm. As part of the UV/O science program, the 1970 report recommended that NASA consider launching a 1.5 m telescope to demonstrate technologies and provide continuity between OAO-C (orbiting astronomical observatory #3 commonly known as Copernicus) and LST—this telescope never flew. For completeness, the 1970 Decadal made a total of 11 primary recommendations for both ground astronomy and space astrophysics: (1) a very large radio array, (2) upgrade ground telescopes with electronic detectors and build the Multiple Mirror Telescope, (3) design an IR aircraft stratospheric observatory, (4) x-ray/gamma-ray balloon and space telescopes, (5) a 65 m millimeter-wave antenna, (6) balloon missions, (7) Orbiting Solar Observatories, (8) theoretical investigations, (9) High-resolution UV/O LST, (10) Large Radio Telescope, and (11) a system to measure geographic position and motion.

A 2.4 m Space Telescope was the #1 priority of the 1980 Decadal Report[4]—although it was noted that Congress had already approved funds for the project in 1977 and NASA authorized its new start in 1978. The other recommended large space missions were: #2 Solar Polar Mission, #3 Gamma-Ray Observatory, #4 X-Ray Telescope, #5 Cosmic-Ray Observatory, and #6 a 10 m baseline 1 m aperture optical telescope interferometer. The 1980 Decadal recommended that the x-ray telescope should have an aperture of 1 to 2 m and be maintainable/retrievable. Launched in 1999, Chandra had an aperture of 1.2 m and was not serviceable.

The 1990 Decadal Report expressed support for the Hubble Corrective Optics Servicing mission and completion of the Gamma-Ray Observatory (Compton).[5] In addition, it reaffirmed the 1992 Field Committee decision to make advanced X-ray astrophysics facility now known as Chandra (AXAF) the highest-priority large program of the 1980s. The 1990 Decadal then recommended three new space missions: Space Infrared Telescope (SIRTF), Far Ultraviolet Spectroscopic Explorer, and Stratospheric Observatory for Infrared Astronomy (SOFIA). The 1990 Decadal recommended that SIRTF have a 0.9 m aperture and operate from 3 to 200 μm. When Spitzer launched in 2003, it had a 0.85 m aperture and operated from 3.6 to 160 μm.

The 2000 Decadal Report recommended completing three 1990 Decadal recommended missions: SIRTF, Atacama Large Millimeter Array (ALMA), and SOFIA.[6] It also endorsed completing three missions recommended by the 1997 Task Group on Space Astronomy: space interferometer mission (SIM), microwave anisotropy probe (MAP), and PLANCK. SIM would be explicitly terminated in the 2010 Decadal. SOFIA flew until ended by the 2020 Decadal. The 2000 Decadal then recommended four new, large programs: Next Generation Space Telescope (NGST), Constellation-X, Terrestrial Planet Finder, and Single Aperture Far-IR. Of these, only NGST was built—but not to the recommended 8 m diameter (50 m^2 collecting area). When the Webb telescope was launched in 2021, its effective collecting area was only 25 m^2 (6.2 m point to point, 5.6 m effective diameter, and 5.2 m inscribed aperture). Finally, the 2010 Decadal[7] recommended a 1.5 m wide field infrared space telescope (WFIRST) mission, which became the Roman mission when a 2.4 m telescope was transferred to NASA.

3 Mission Concept Maturation

The reason NASA has never flown a mission exactly as recommended by a Decadal Report is because all of those missions underwent a concept maturation process that resulted in descopes for technological and programmatic reasons—mostly to fit inside a cost box. This is a historical trend that continues to the present. Since 2005, the average cost growth [from Preliminary Design Review (PDR) to Launch] for 79 Optical Instruments has been 74% (with a standard error of 41%).[8] This section reviews two case studies: Hubble and Webb.

3.1 Hubble Mission Concept Maturation

As summarized in Exploring the Universe,[9] the scientific foundation for the Hubble Space Telescope was laid by Spitzer's 1946 paper and Whipple's 1952 paper. Technology development started with a UV solar spectrum provided by the October 1946 sub-orbital launch of a V-2 rocket from White Sands and the first launch of the Stratoscope I balloon mission in September 1957. But the space astronomy age truly started with the launch of Sputnik on October 4, 1957. The United States responded by launching Explorer I on January 31, 1958 and founded NASA on October 1, 1958. In advance of NASA's founding, on July 4, 1958, Lloyd Berkner, Chair of the Space Science Board of the National Academy of Sciences, sent telegrams requesting suggestions for scientific experiments that may be performed by a satellite with a 50 kg capacity that would fly in 2 years. Proposals of a few paragraphs describing the experiment's scientific value, estimated total cost, and months to complete were due in 1 week (see Ref. 9, Document 1 to 14). Berkner received 200 responses and in December 1958 thirty experiments were recommended for initial study, including the "Feasibility Study of the Development of an Astronomical Telescope in a Satellite Orbit"—which would become Orbiting Astronomical Observatory (OAO).[9]

By 1962, NASA's space science program of record included the following:[10]

1. Explore & Monitor Program, first launched in 1961
2. Orbiting Solar Observatory Program, first launched in 1962
3. Orbiting Geophysical Observatory Program, first launched in 1964
4. OAO Program, first launched in 1966.

In the summer of 1962, NASA asked the National Academy for advice on its science program.[10] Though OAO had not yet attempted its first launch, the recommendations were (1) to schedule launches so that during the next 10 years at least 1 OAO is operational at any given time and (2) organize a small study group for the summer of 1963 to explore and prepare a report delineating technical problems and science objectives of a larger more versatile space telescope. According to Vera Rubin's "The Gestation of the Hubble" recollections, "One astronomer had studied the characteristics of the Saturn rocket and determined that it could carry a 3 m telescope. The entire astronomy committee jumped on the idea."[11]

From October 1963 to June 1964, the Astronomy Panel of Space Science Steering Committee studied requirements for an LST and determined that it should have a 120 inch (3.0 m) diameter and be diffraction limited. The science requirements were defined in the summer of 1965 at Woods Hole meeting held by the Space Science Board of the National Academy of Sciences. Aden Meinel of Kitt Peak was a major proponent of the space telescope at both the 1962 and 1964 meetings (see Ref. 9, Document III-13). As a result, NASA froze technology development for OAO-C in 1963 and started a concept/technology maturation process (Fig. 3), which resulted in a 1978 new start for what would later become Hubble.

On August 25, 1965, President Johnson authorized the Department of Defense (DoD) to create the Manned Orbiting Laboratory. At the same time, NASA created what would become the Apollo Application Program's LST study.[9] Specific desired capabilities were a "maintainable" "diffraction-limited" telescope with an aperture of 3 to 10 m and pointing stability of <10 mas. In addition, the process was tasked with developing technology for IR science and planetary probe laser communication. As shown in Figs. 4 and 5, the initial concept was a

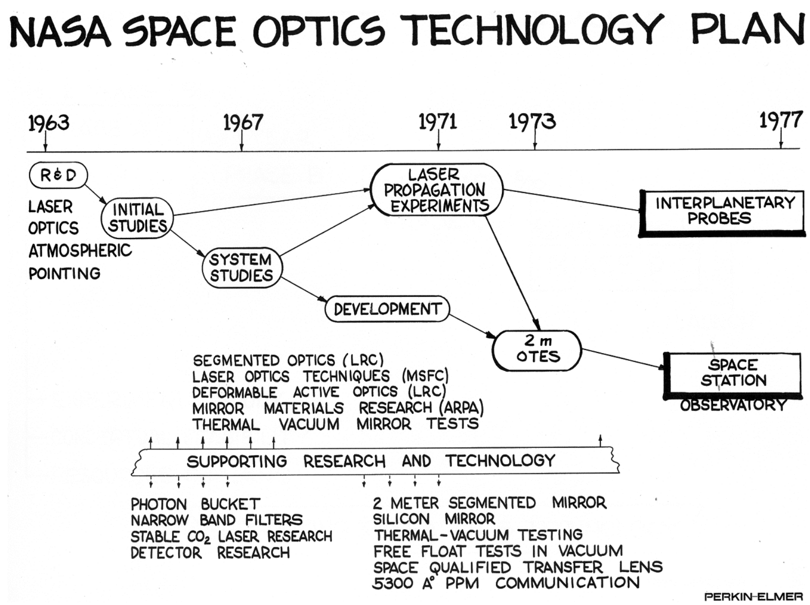

Fig. 3 NASA Space Optics Technology Plan Perkin-Elmer 1967.

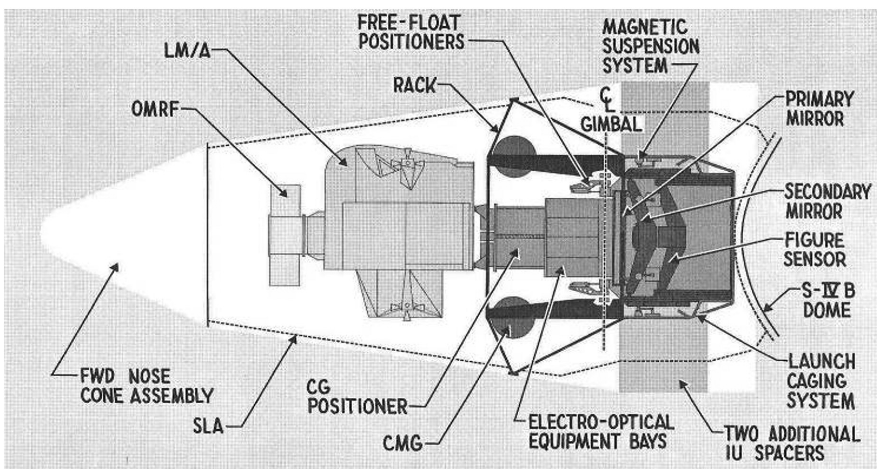

Fig. 4 Stowed launch configuration for Saturn 1B.[12]

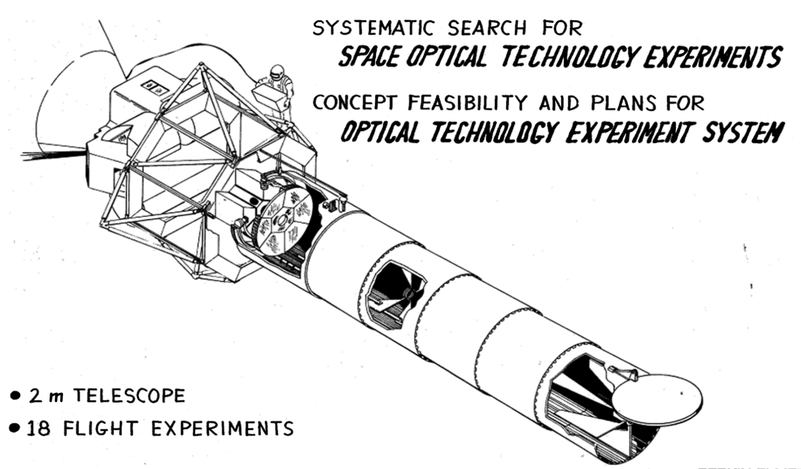

Fig. 5 Deployed on-orbit configuration.[13]

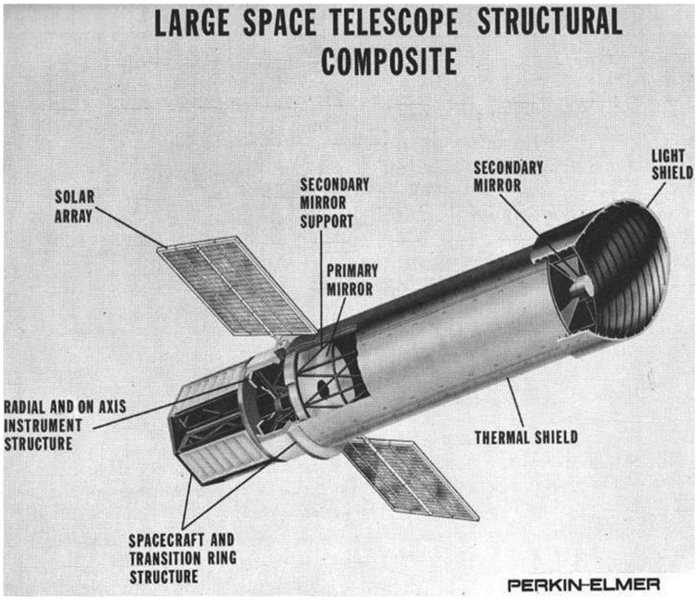

Fig. 6 Free-flying 3 m telescope.[14]

"manned" telescope (using a modified Lunar Command Module) with a deploying secondary tube to fit into the fairing of a Saturn 1B rocket. For reasons discussed in the technology maturation section, the primary mirror was segmented. But by 1971, technology advances allowed the primary mirror to become monolithic (Fig. 6).

3.2 Webb Mission Concept Maturation

Webb went through a similar process, typically traced to the 1989 NGST workshop held at the Space Telescope Institute, the 1996 "HST and Beyond" AURA report,[15,16] and a 1996 Industry Day Meeting (Fig. 7).

In 1996, NASA held an Optical Systems Concepts and Technology for NGST Workshop at NASA's Marshall Space Flight Center (MSFC) (Fig. 8) and initiated a feasibility study for an 8 m space telescope, diffraction limited at 2 μm and operating at below 50 K. It has been said that NGST required 10 miracles—one of which was the primary mirror. Because the only available launch vehicle fairing had an internal diameter of 4.5 m, the primary mirror had to be segmented. In addition, because of the launch vehicle's mass capacity, the primary mirror could not weigh more than 1000 kg for an areal density of $<20\ \mathrm{kg/m^2}$. In 1996, such mirror technology did not exist. Study contracts to develop mission concepts were awarded to Ball Aerospace (BATC) and TRW (they would combine their studies), and Lockheed (LMCO)/Raytheon. The TRW/BATC team developed a concept based on the Keck Telescope with a drop-leaf table folding mechanism (Fig. 9). The LMCO/Raytheon team concept employed a fold-forward/fold-aft architecture based on the Air Force's 4 m Large Active Mirror Project (LAMP) telescope (Fig. 10). After 7 years of funded concept and technology maturation, the TRW/BATC concept was selected in 2003.

Fig. 7 1996 industry day.

Fig. 8 Concepts and technology workshop.

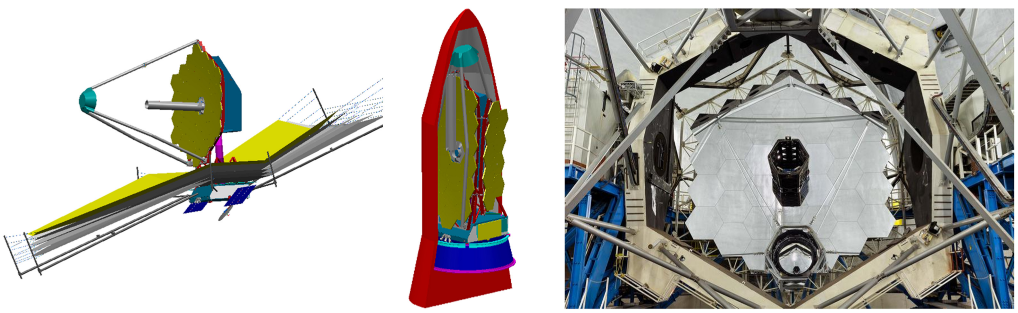

Fig. 9 TRW/BATC drop leaf table concept used hex segments similar to the Keck Telescope.

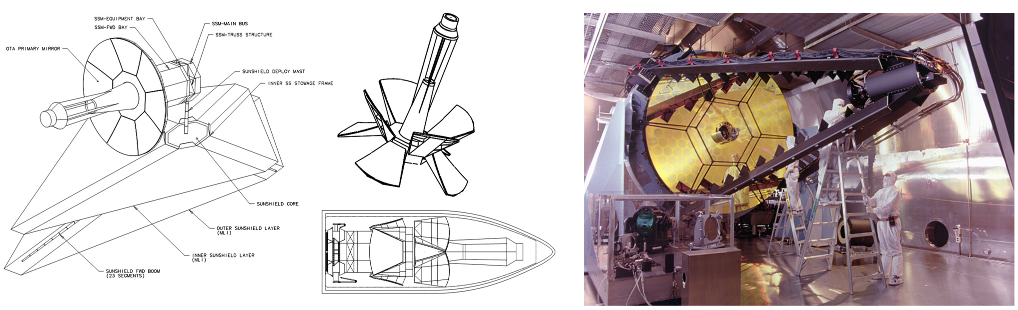

Fig. 10 LMCO/Raytheon fold-forward/fold-Aft concept was similar to the Air Force LAMP telescope.

4 Technology Development Enables Missions

The largest challenge for Hubble and Webb alike was how to make their respective primary mirrors with the required diameter, areal density, and diffraction limited performance. Per the 1970 "Large Telescope Experiment Program Executive Summary" report, the telescope specifications were 3 to 5 m aperture, diffraction limited at 100 nm and a total mass of 12,100 kg. The actual Hubble telescope was 2.4 m, diffraction limited at ~500 nm and ~2200 kg (total mission mass was ~11,000 kg). Figure 3 shows the 1963 technology development plan. Technologies to be investigated included segmented optics, deformable mirrors, different mirror materials, thermal vacuum testing, gravity off-loading tests, and detector technology. The following developed technologies have been consequential: phase-measuring interferometry (PMI), deformable mirrors, low-CTE glass materials, and gravity off-loading mounts.

In 1996, the NGST project identified mirror technology as a critical enabling need. Achieving the desired science objectives required a never before demonstrated space telescope capability, an 8 m primary mirror (providing 50 m^2 of collecting aperture) that was diffraction limited at 2 μm and operated at temperatures below 50 K. Furthermore, because of launch vehicle limitations, two very significant architectural constraints were placed upon the telescope: segmentation and areal density. Each of these directly resulted in specific technology capability requirements. First, because the launch vehicle fairing payload dynamic envelope diameter was 4.5 m, the only way to launch an 8 m class mirror was to segment it, fold it, and deploy it on orbit. Second, because of launch vehicle mass limits, the primary mirror allocation was only 1000 kg—resulting in a maximum areal density of 20 $\mathrm{kg/m^2}$. Programmatically, a cost goal of \$500M was levied on the optical telescope assembly (OTA) (yielding an areal cost of \$10 $\mathrm{M/m^2}$), and a production goal of 1 m^2 per month. And, the mission had to launch by 2007—for the 500th year anniversary of the invention of the telescope—this goal was later restated to by the end of the decade before the replan.

An assessment of the pre-1996 state of the art for primary mirrors (as demonstrated by existing space, ground, and laboratory test bed telescopes) indicated that the necessary mirror technology was at a TRL of 3 (Table 1).

The largest space telescope was Hubble. Its 2.4 m glass primary mirror has an areal density of 180 $\mathrm{kg/m^2}$ and operates at 300 K. Its primary mirror assembly has an areal density of 240 $\mathrm{kg/m^2}$, and its OTA has an areal density of 420 $\mathrm{kg/m^2}$. Ground telescopes such as Keck demonstrated 10 m class semi-actively controlled segmented mirrors but were exceedingly massive (2000 $\mathrm{kg/m^2}$) and thermally unsuitable. Test beds such as the Itek Large Optical Telescope and the Kodak Advanced Optical System Demonstrator demonstrated proof of concept for 4 m class pseudo-space-qualifiable actively controlled segmented telescopes in a laboratory environment, whereas the US Air Force LAMP demonstrated a 4 m class actively controlled segmented primary mirror operating in a vacuum environment (although at 300 K). But again, these test beds were two to six times too massive and only operated at ambient temperatures. The largest cryogenic mirror under development was the 0.85 m diameter Infrared Telescope Technology Testbed Beryllium (Be) primary mirror, which would eventually fly in the Spitzer Space Telescope in 2003. In addition, the cost per square meter of primary mirrors for both Hubble and Spitzer was approximately \$10 $\mathrm{M/m^2}$ (FY10). Finally, the production rate for Hubble had been ~1 $\mathrm{m^2/year}$ of polished glass, whereas Spitzer's was ~1 m^2 in 4 months.

Given this technology assessment, NASA and its DoD partners initiated a systematic mirror technology development program to invent mirror systems that could meet the NGST requirements; reduce the cost, schedule, mass, and risk of such mirror systems; and demonstrate a TRL of 6. Approximately \$40M was invested in mirror technology development from 1998 to 2004 via a series of related contracts: Sub-scale Beryllium Mirror Demonstrator, NGST Mirror System

Table 1 1996 Webb optical system requirements compared with predecessor telescopes.

Parameter	JWST	Hubble	Spitzer	Keck	LAMP	Units
Aperture	8	2.4	0.85	10	4	m
Segmented	Yes	No	No	36	7	Segments
Areal density	20	180	28	2000	140	$\mathrm{kg/m^2}$
Diffraction limit	2	0.5	6.5	10	1.4	μm
Operating temp	<50	300	5	300	300	K
Environment	L2	LEO	Drift	Ground	Vacuum	Environment
Substrate	TBD	ULE glass	I-70 Be	Zerodur	Zerodur	Material
Architecture	TBD	Passive	Passive	Hexapod	Adaptive	Control
First light	TBD	1993	2003	1992	1996	First light

Demonstrator, Advanced Mirror System Demonstrator (AMSD), and several small development contracts.[17] Although \$40M may seem like a small number, it was 30% of the expected primary mirror cost. And, one potential lesson learned is that, to be successful, the next mission may also need to invest 30% of its expected cost in technology development.

The mirror technology development program was explicitly designed to be broad, follow a sequential or spiral development path, and employ phased down-select competition. Specific technology areas investigated included: substrate material (glass, beryllium, silicon carbide, nickel, etc.; mechanical, thermal and optical material properties; the ability to manufacture large enough substrates; etc.); mirror design (open back, closed back, arched, thin face sheet; launch loads; etc.); architecture (passive, active, rigid, semi-rigid, etc.); the fabrication process (substrate fabrication, grind and polish, coating); metrology (vibration insensitivity, cryogenic characterization, etc.); and performance (cryogenic, thermal, mechanical, launch loads, etc.). Full and sub-scale mirror systems and their constituent components (i.e., flexures, coatings, and actuators) were fabricated and cryogenically tested. Significant investments were made in facilities, equipment, procedures, and expertise. Also, to improve the ability of models to accurately predict on-orbit performance, an extensive program was conducted to characterize cryogenic properties (i.e., CTE and CTE uniformity, dynamic dampening, stiffness, and tensile strength) of various mirror and structure materials as well as their susceptibility to micrometeoroid impacts.

The NGST mirror technology development effort's eventual success can be attributed to four technical advances: Brush Wellman's development of O-30 grade Beryllium (funded by the Air Force) with its greatly improved CTE uniformity (compared with I-70 Be used on Spitzer); improvements to computer-controlled polishing at Tinsley; the NASA funded development of the 4D PhaseCAM and Leica Absolute Distance Meter (ADM); and the AMSD program.

A critical element of the AMSD program was competition. Competition between ideas and vendors resulted in a remarkably rapid TRL advance for modern large-aperture lightweight cryogenic space mirrors. AMSD followed a phased down-select approach. Phase 1 awarded contracts to five different vendors to study and develop designs for a total of eight different mirror architectures. The best three of these designs were then funded for fabrication in Phase 2. Once the prime contractor architecture was selected, the designs were narrowed to two.

In 2007, the Non-Advocate Review (NAR) panel assessed that Webb's mirror technology had achieved TRL-6 by the combination of the mirror technology development effort and testing of flight mirrors.

5 Technology Challenges

All space telescopes have the same basic challenges and require the same enabling technology advances.

5.1 Mass

Since the beginning, science missions have been constrained by launch vehicles. As detailed in the 1962 Space Science Report,[10] the available payload mass to 480 km ranged from 68 kg for a Scout to 3800 kg for a Centaur (see Fig. 11 and Table 2).

In 1960, the state of the art for a primary mirror was defined by the 0.9 m 180 kg Stratoscope II mirror (Fig. 12). Obviously, this mirror was too massive for the existing launch vehicles. For OAO-B, the solution was a 0.95 m 57 kg (80 $\mathrm{kg/m^2}$ areal density) Be S200B mirror with an electroless nickel overcoat (Fig. 13).[18] By 1963, lightweight egg-crate mirrors had been developed. The OAO-C (Copernicus) Princeton Experiment mirror was an 80 cm 47 kg (94 $\mathrm{kg/m^2}$ areal density) fused-silica mirror (Fig. 14).[18]

After President Nixon authorized development of the Space Shuttle in 1972, the Hubble and Chandra telescopes' mass and sizes were designed to match the Space Shuttle's payload volume and mass capacities (Table 3).[9] In the same way, the Webb telescope's mass and architecture were designed to match the Ariane 5 capabilities (Table 4).

In 1996, the NGST program desired an 8 m diameter (i.e., 50 $\mathrm{m^2}$ collecting area) telescope, which—because of launch vehicle mass capacity—required a primary mirror areal density of $\sim$20 $\mathrm{kg/m^2}$. The primary objective of AMSD was to develop mirror technology with this areal

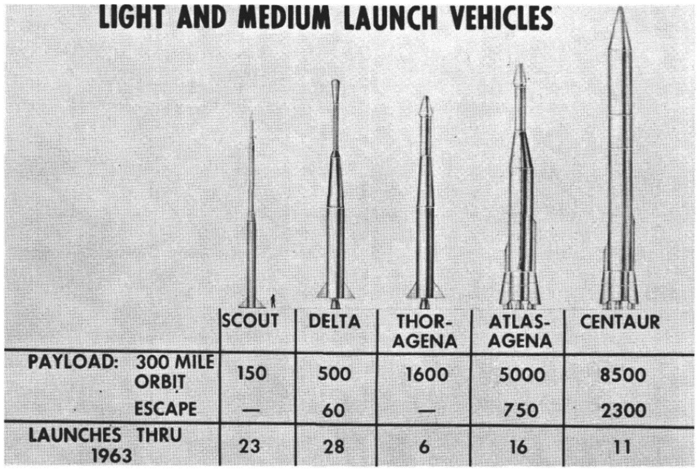

Fig. 11 1962 available rockets.

Table 2 1962 mass to orbit.

Orbit	Scout	Delta	Thor	Atlas	Centaur	
480 km	68	227	727	2273	3800	Kg
Escape	—	27	—	341	1045	Kg

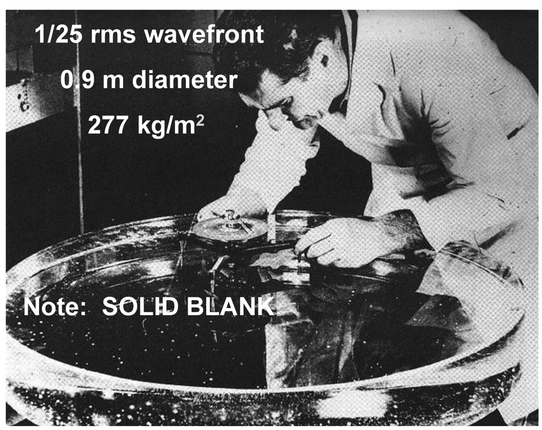

Fig. 12 Stratoscope II mirror.

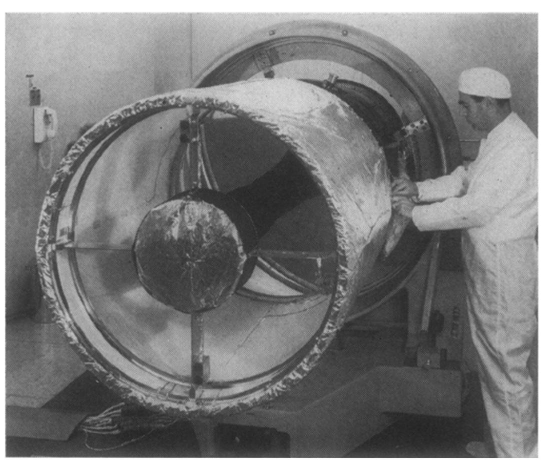

Fig. 13 OAO-B mirror.

Fig. 14 OAO-C mirror.

Table 3 Space Shuttle launch capabilities versus science mission requirements.

	Payload mass	Payload volume
Space Shuttle capabilities	25,061 kg (max at 185 km)	4.6 m × 18.3 m
	16,000 kg (max at 590 km)	
Hubble Space Telescope	11,110 kg (at 590 km)	4.3 m × 13.2 m
Chandra x-ray telescope (and inertial upper stage)	22,800 kg (at 185 km)	4.3 m × 17.4 m

Table 4 Ariane 5 launch capabilities versus Webb science mission requirements.

	Payload mass	Payload volume
Ariane 5	6600 kg (at SE L2)	4.5 m × 15.5 m
James Webb Space Telescope	6530 kg (at SE L2)	4.47 m × 10.66 m

density—both glass and beryllium mirrors were successfully demonstrated. However, Webb did not fly the AMSD technology as demonstrated. Subsequent Pre-Phase-A design studies determined that more mass was required to survive launch. The final Webb primary mirror segments assemblies had an areal density of $\sim 30\ \mathrm{kg/m^2}$, the primary mirror assembly (including backplane) areal density was $70\ \mathrm{kg/m^2}$, and the OTA areal density was $\sim 100\ \mathrm{kg/m^2}$. By comparison, Hubble's primary mirror had an areal density of $180\ \mathrm{kg/m^2}$, its primary mirror assembly was $460\ \mathrm{kg/m^2}$, and its telescope was $590\ \mathrm{kg/m^2}$.

It is interesting to observe that Hubble's ULE® primary mirror areal density of $180\ \mathrm{kg/m^2}$ was larger than the OAO-C fused silica primary mirror's $94\ \mathrm{kg/m^2}$. This is likely because Hubble needed a more massive, i.e., stiffer, telescope to achieve its $0.5\ \mu\mathrm{m}$ diffraction limited performance versus OAO-C's $2.4\ \mu\mathrm{m}$ limit. Similarly, Webb's O-30 Be primary mirror assembly areal density of $70\ \mathrm{kg/m^2}$ (diffraction limit of $2\ \mu\mathrm{m}$) is larger than the Spitzer I70 Be mirror's $28\ \mathrm{kg/m^2}$ areal density ($6.5\ \mu\mathrm{m}$ diffraction limit). One implication might be that there were engineering constraints that placed a lower limit on the primary mirror areal density to achieve a given diffraction limited performance and survive launch. For future missions, if larger aperture telescopes are desired, then launch vehicles with more mass capacity may be required. Potential solutions are the new super heavy lift rockets such as NASA's Space Launch System (SLS) and Space-X's Starship.

5.2 Aperture Diameter and Diffraction Limited Performance

One of Hubble's and Webb's largest challenges was how to achieve the desired science aperture with the desired diffraction limited performance within the allowable budget. For the LST, the desire was a 3 m telescope diffraction limited at 100 nm. What was actually achieved was a 2.4 m telescope diffraction limited at 500 nm. It is informative to note that the desired 3 m aperture was driven by a Langley Research Center analysis that concluded that this was the largest size telescope that could fit inside the 5 m Saturn fairing. However, the descope to 2.4 m was driven by cost.[7] For NGST, the desire was an 8 m (50 m^2) telescope with 2 μm performance. What was achieved was a 6.2 m (25 m^2) telescope with 1 μm performance. As with Hubble, Webb's architecture was driven by its launch vehicle. The only way to get an 8 m telescope into a 5 m fairing was if it was deployed, and it turns out that the only way to meet the mass and cost budgets was to make the telescope smaller.

A detailed discussion of political and programmatic constraints on the Space Telescope program is documented in Ref. 9. Below are important excerpts to note:

1. "In early 1973, politically astute NASA managers realized that the cost of the LST would limit their ability to sell it to either the Administration or Congress. Hence, Marshall was given a cost target well below its estimate of the cost of the telescope concept then under examination. Various cuts were made in the plans to reduce the cost; these reductions often had to be reinstated later in the program. The flight of the precursor 1.5 m telescope to test the many complicated systems on LST was dropped at this time."
2. "In 1974, Congress appeared unenthusiastic about the LST. The House cut all funds for the project." LST was saved in 1973 and again in 1976 only because the "astronomical community launched a major lobbying effort."
3. Before the 1978 new start, MSFC was directed to cut cost. Three descopes were investigated: 1.8, 2.4, and 3.0 m. Finally, 2.4 m was selected because: "facilities existed for the manufacture of a precision 2.4 m mirror"; a 2.4 m telescope more easily fit inside the Space Shuttle; and a 2.4 m telescope could still do the science.
4. After Phase C/D contracts were awarded, "contractors increased their cost estimates substantially. Yet, Marshall was not allowed to budget additional funds." The program was saved via a 1983 replan.

As someone who worked on Webb starting in 1999, this all seems very familiar. In January 2000, Bernie Seery, NGST study manager, assigned this author to lead an independent cost estimate (ICE) study with Mark Kahan and Marc Daigle of Optical Research Associates and Gary Golnik of Schafer Corp. (a study that directly led to the author's parametric ground and space telescope cost model[19]) and to be the NGST mirror technology development lead. In these roles, the author was a first-person witness to the NGST architecture change from 8 m (50 m^2 collecting area) to 6 m (25 m^2 collecting area). Using a bottom-up methodology, the ICE team reported its findings in an unpublished Dec 6, 2000, memo. The likely NGST optical telescope element (OTE) cost could range from \$218M to \$944M (clearly more than the \$500M goal but consistent with the actual \$1.25B for the 6 m OTE). Reducing the aperture to 6 m might save at least 26% (the current Stahl parametric cost model predicts that a 6 m OTE costs 40% less than an 8 m) and that the earliest the OTE could complete integration and test—if started in 2003—was the second half of 2010 (clearly later than the 2007 launch goal). In addition, by early 2002, it was clear that the AMSD architecture mirrors could not survive launch, they needed to be stiffer, and they needed more mass. These and other factors made the 6 m descope unavoidable. This author was not a first-person witness to the later replan that saved the program.

5.2.1 *Substrate material*

In 1963, state of the art for space mirrors was defined by the 80 cm OAO-C Princeton Experiment fused silica mirror (Fig. 15).[20,21] Unfortunately, this mirror technology could not meet the LST's size or performance specifications. Likely because of its lightweight low-stiffness substrate, the mirror was only polished to a surface figure error of 55 nm rms, and because fused silica has a relatively high CTE of ~500 ppb/K, the mirror was thermally unstable. To overcome these limitations, the LST program investigated a range of technologies, including silicon, beryllium, and fused quartz mirrors; segmented aperture mirrors (Fig. 16); deformable mirrors (Fig. 17), and active thermal controlled mirrors.[22] Eventually, low-CTE glasses (Cervit, ULE® and Zerodur®) were developed, which enabled the manufacture of a passive monolithic 2.4 m mirror.

Fig. 15 OAO-C Princeton mirror in thermal/deformation test.

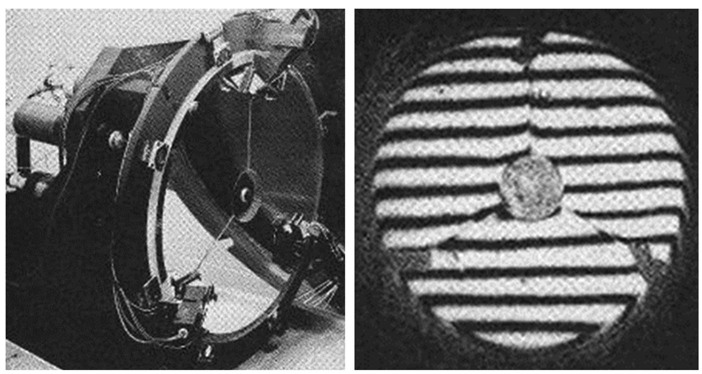

Fig. 16 OTES Experiment #1 segmented mirror and interferogram.

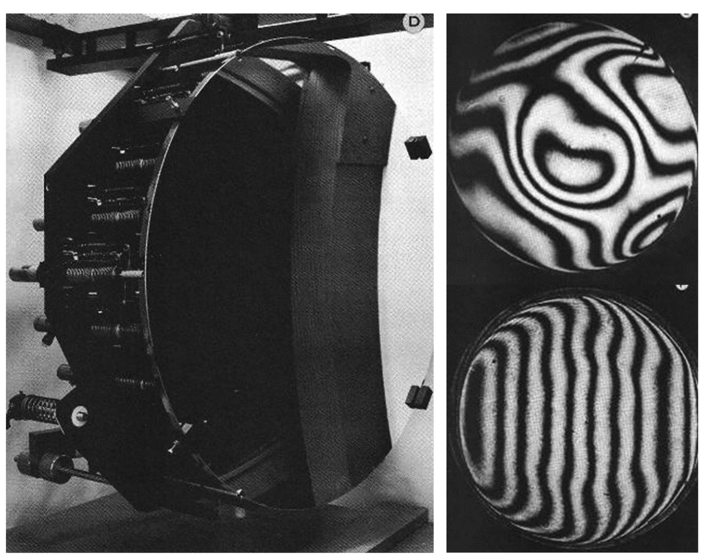

Fig. 17 76 cm thin facesheet deformable mirror.

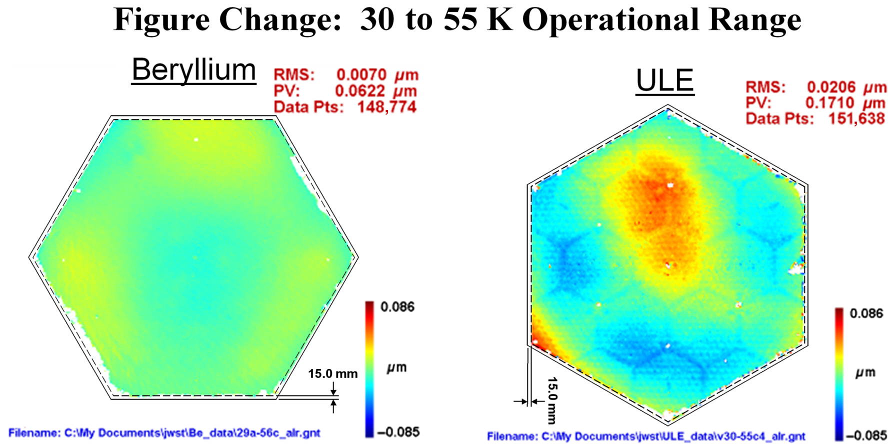

Fig. 18 Cryo-stability Be versus ULE.

In 1996, NGST had a similar problem. The state-of-the-art cryogenic mirror was the 85 cm Spitzer Telescope with diffraction limited performance of 5 μm. In 1994, the Spitzer program undertook a material trade study and selected I-70 grade Beryllium for its primary mirror.[23] But I-70 Be was not a good choice for the NGST primary mirror.[24] Because it was produced using a mechanical pulverization process, its powder had irregular grain shapes. This irregularity limited how densely the powder could be packed into a hot isostatic pressure (HIP) can, which limited the maximum size mirror that could be made. Also, the irregular grain shapes resulted in large CTE inhomogeneity.

The solution was O-30 Be developed by Brush Wellman for the Air Force in the late 1980s.[24] Because O-30 Be is a spherical powder material, it has a high packing density (thus allowing hot isostatic pressuring of larger billets), and its CTE distribution is very uniform (which results in smaller cryo-distortion and higher cryo-stability). Also, because O-30 Be has a lower oxide content than I-70 Be, it can achieve a smoother polished surface (i.e., less scatter). The ability to HIP a meter class billet was demonstrated in the late 1990s via the manufacture of the very large telescope (VLT) secondary mirror. By 1999, Brush-Wellman had full production capability sufficient for the NGST program.

In the summer of 2003, the NGST Mirror Recommendation Board convened the OTE Optics Review to select the NGST primary mirror material. Both ULE® and O-30 Be were found to be acceptable, but O-30 Be was rated as the highest performing, lowest technical risk solution. Its strengths included its stiffness to mass ratio, thermal conductivity, and CTE homogeneity. But most important was its cryogenic CTE stability. The Be mirror had only 7 nm rms of cryo-deformation (versus 20 nm rms for the ULE® mirror) over the thermal environment operating range (Fig. 18).[25]

5.2.2 *Fabrication process*

Primary mirror surface figure error is typically the single largest factor in a telescope's diffraction limited performance. In 1960, the 90 cm Stratoscope II balloon mission primary mirror was polished by hand to ~10 nm rms surface. But the 80 cm OAO-C Princeton Experiment primary mirror was only able to be polished to ~55 nm rms surface. The likely difference is that the Stratoscope II mirror was a solid blank and the OAO-C mirror was lightweight. Thus, it likely had quilting error over the pockets (facesheet bending from the polishing tool) and gravity back-out uncertainty.

To overcome these problems, the Hubble primary mirror was designed to be structurally stiff and was fabricated using small-tool computer-controlled grinding and polishing (Fig. 19). The Hubble primary mirror was polished to a surface figure error (ignoring the conic error) of better than 8 nm rms.[26] Small-tool computer-controlled technology was also used to manufacture both the Spitzer (Fig. 20) and Webb primary mirrors (which was fabricated with a composite surface figure error of <25 nm rms).[27]

Fig. 19 Hubble primary mirror fabrication 1979–1981 (courtesy Goodrich).

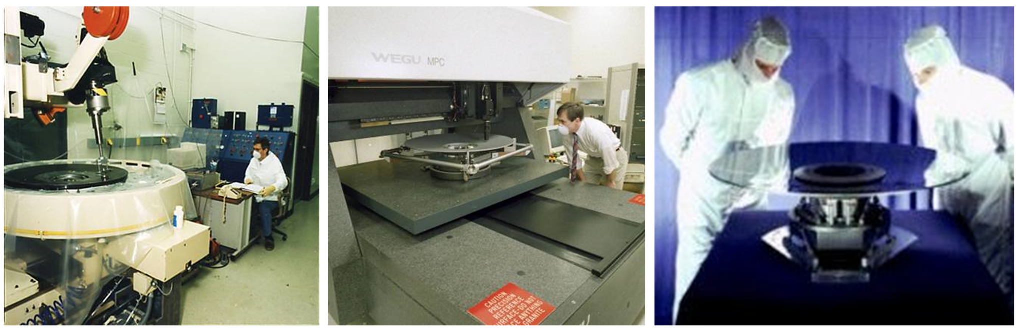

Fig. 20 Spitzer primary mirror fabrication 1996–1998 (courtesy Goodrich and Ref. 23).

5.2.3 *Optical testing*

The precision to which a mirror can be polished depends on the precision to which it can be measured—you cannot make what you cannot measure. Challenges that limit the ability to precisely measure mirrors include atmospheric turbulence, mechanical vibration, and gravity sag.

Atmospheric turbulence and mechanical vibration. Before the laser, mirrors were made via tests such as the Foucault knife edge test or the star test. The Stratoscope II primary mirror was tested by J. M. Burch, A. Offner, J. C. Buccini, and J. Houston using a scatterplate interferometer and fringe scanning digitizer (Fig. 21).[28] The advantage of a scatterplate is that it is

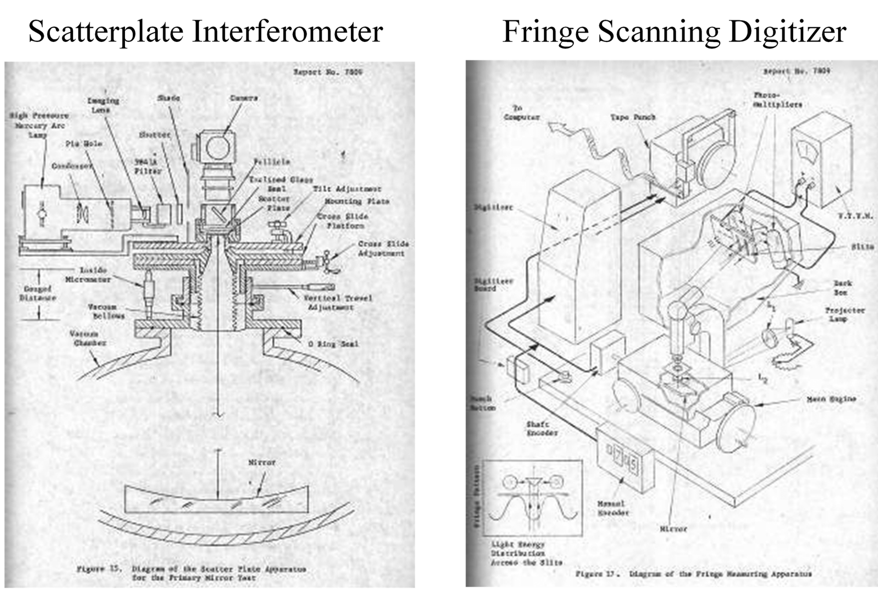

Fig. 21 Stratoscope II mirror test using scatterplate interferometer.

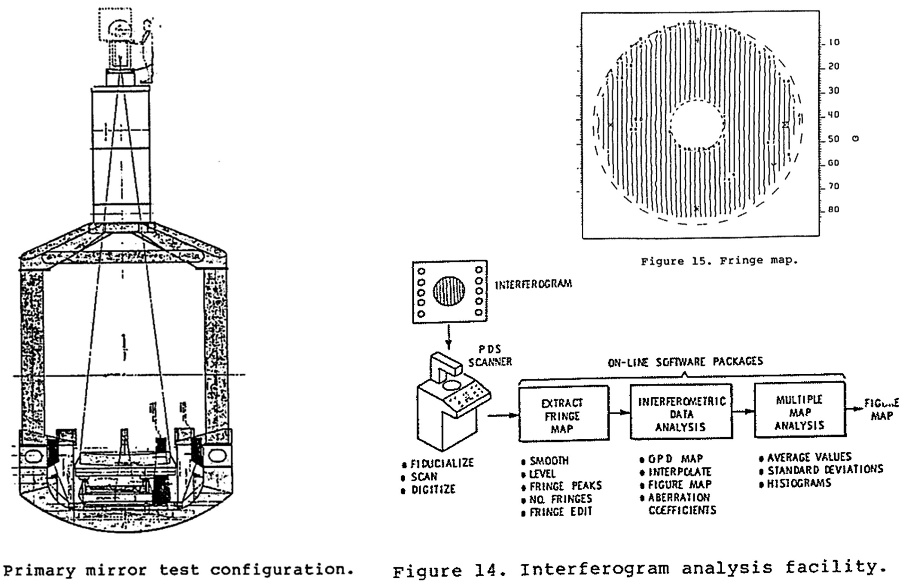

Fig. 22 Hubble primary mirror test configuration.

a common path test, which allowed it to be used with low coherence length sources (such as a mercury vapor lamp). Also, because it is common path, it is insensitive to rigid-body motion and some atmospheric turbulence. Atmospheric turbulence could be further reduced by taking short exposure photographs for digitization.

As a mirror's size and radius of curvature increases, so does atmospheric turbulence. To solve this problem, Perkin-Elmer tested the Hubble primary mirror in a vertical vacuum chamber (called the "ice-cream cone" chamber). To minimize mechanical vibration, short exposure photographs were recorded and digitized (Fig 22).[26] Another way to minimize the impact of mechanical vibration is to structurally connect the interferometer to the test setup. Although "low-tech," this author liked to use wood because of its dampening properties. The Spitzer secondary mirror was tested using this approach (Fig. 23).[29]

The LST technology program resulted in many important advances, but maybe none were as important as the invention of PMI.[30]

Similarly, the Webb Space Telescope was enabled by the invention and development of the 4D PhaseCAM and Leica ADM. In November 1999, NASA recruited this author to join the NGST mirror technology development effort to solve a specific problem—how to test the mirrors at their cryogenic operating temperature and avoid a "Hubble" problem. The challenge was that

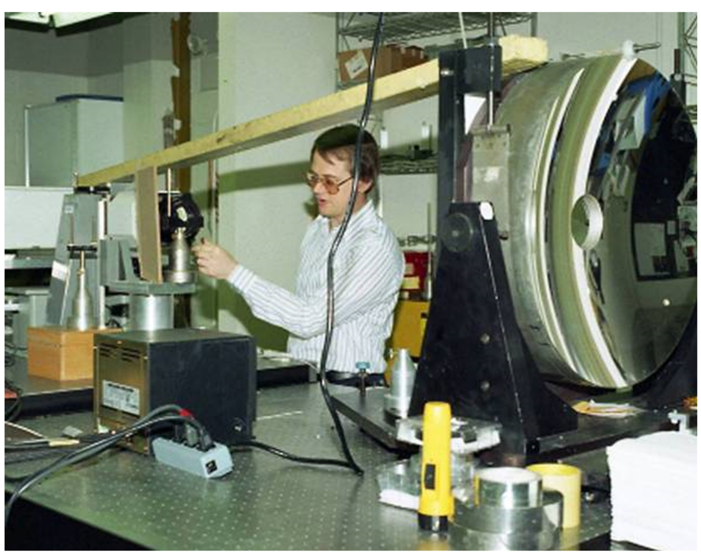

Fig. 23 Testing spitzer secondary mirror (courtesy Goodrich).

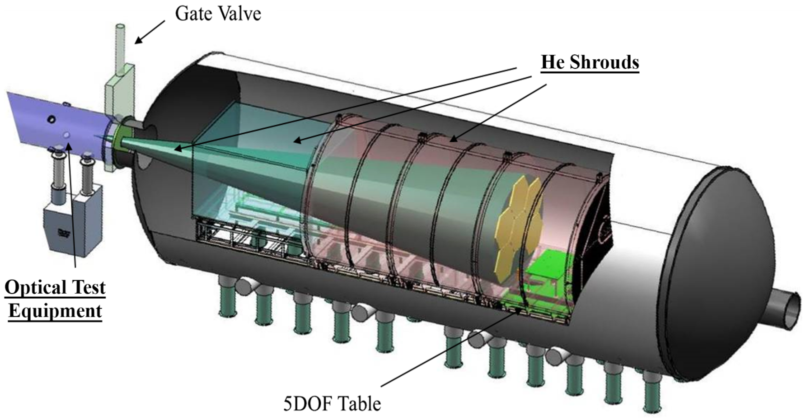

Fig. 24 Webb mirror testing in MSFC's X-ray and cryogenic facility (XRCF).

the mirrors were located inside a vacuum chamber (Fig. 24) where, because of building foundation bending, the interferometer and mirrors had relative piston motion of 4 μm—too much motion and too fast for a commercial phase-measuring interferometer. And, laser distance measuring interferometers could not be used to measure the radius of curvature.

The solution to the vibration problem was discovered by this author during a visit to MetroLaser on a different matter. On a table in a back lab, the author saw a breadboard setup of a "real-time" interferometer producing a phase-map of a flame plume. The first thing the author did at NASA was get Bernie Seery, Pre-Phase-A study manager, to fund a risk reduction experiment. The author defined the specifications and gave a $60K order to newly incorporated 4D Vision Technology. They delivered the first ever PhaseCAM in just 6 months and it worked great. Its resolution was 512×512, and its repeatability was 1.2 nm rms. Further, over a 20 m air path, its measurement uncertainty was 5 nm rms. We started using it immediately, and we could not have made Webb without the 4D PhaseCAMs (Fig. 25).

Regarding radius of curvature, the standard method is a distance measuring interferometer on a lens bench to measure the radius. But, this technique would not work for the NGST mirrors because it requires a displacement measurement from "cats-eye" to center of curvature. Leica had an interesting technology that was part of their laser tracking system, but its accuracy was only ± 5 mm and the NGST specification was ± 0.1 mm. So, MSFC funded a development effort that resulted in the Leica ADM. The ADM was used to measure and set the radius of curvature on all development and flight mirrors.

Gravity sag. G-release can be a significant error for UVO space primary mirrors. G-release error is the difference (or uncertainty) between the predicted zero-gravity shape of the mirror (during manufacture) and the actual on-orbit shape. The bigger and less stiff the mirror is, the bigger the potential error is.

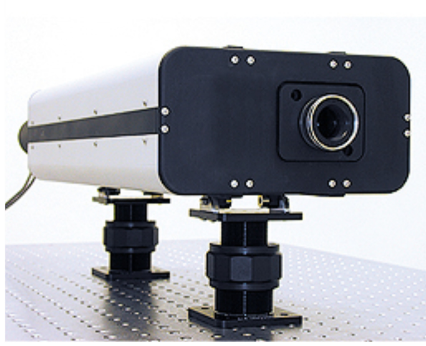

Fig. 25 4D PhaseCAM #1.

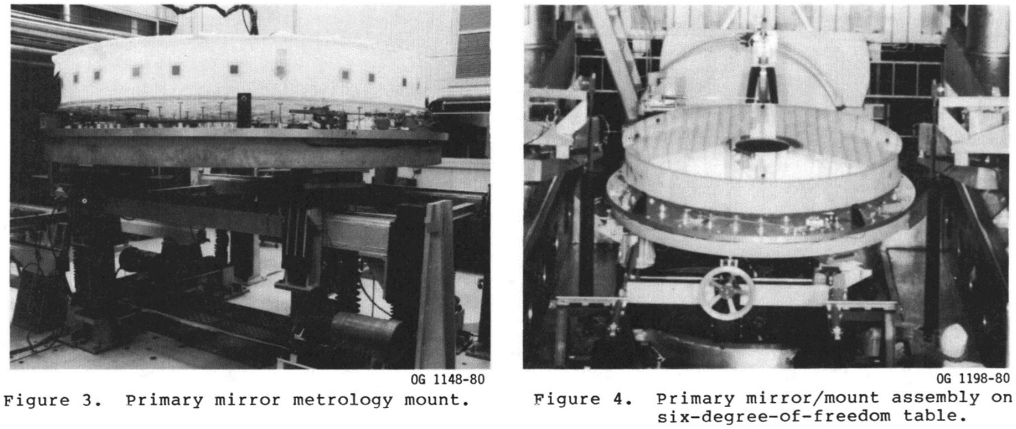

Fig. 26 Hubble primary mirror on its metrology mount.

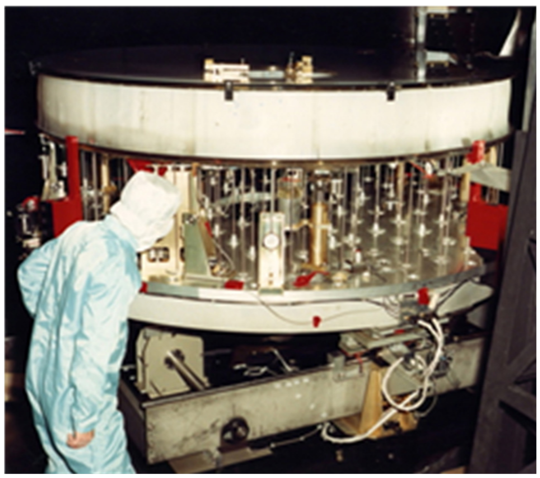

Fig. 27 2.4 m mirror on metrology mount.

The LST Program solved the G-release problem for the Hubble primary mirror by developing a 135 point metrology mount. The mount was able to compensate for the Hubble primary mirror's mounted 7.6 μm peak-to-valley self-weight deflection to an accuracy of 1.4 nm rms.[31–33] Figure 26 shows the Hubble primary mirror on its 135 point metrology mount. Figure 27 shows another 2.4 m mirror on a similar metrology mount.

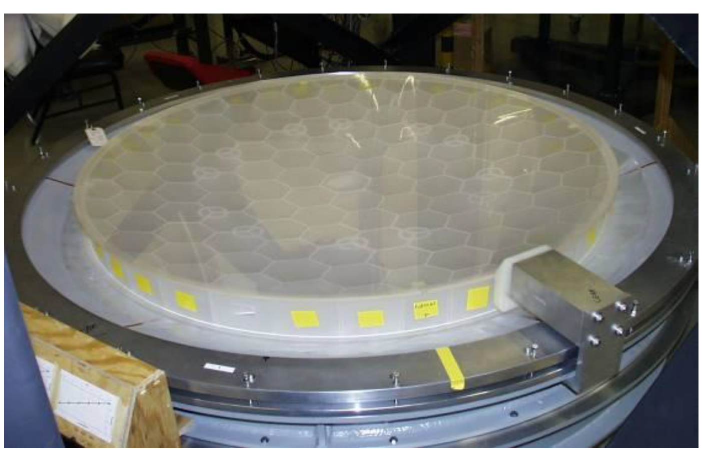

Fig. 28 Kepler primary mirror on air bladder.

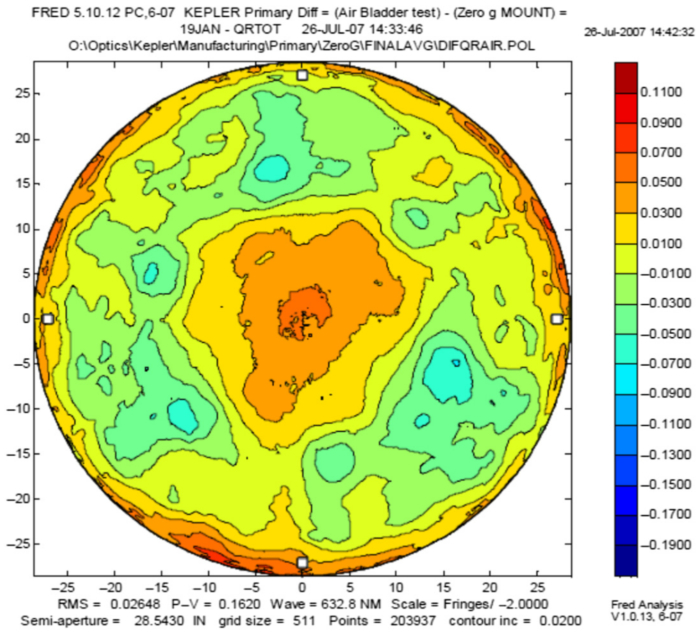

Fig. 29 Difference between air bladder test and 108 point zero-g mount is 16.4 nm rms.

The Kepler program characterized its 1.4 m primary mirror using an air bag (Fig. 28) and a 108 point metrology mount. The air bag was estimated to off-load gravity sag with an uncertainty of 5.6 nm rms. In addition, as shown in Fig. 29, the difference between the air bag test and multi-point mount test was 16.4 nm rms (mostly spherical aberration).[33]

NGST used the Evans and Kestner six-position horizontal rotation method published in 1996 to test the Webb primary mirror segments with an uncertainty of <10 nm rms.[26,34]

6 Conclusion

A casual review of the history of Decadal Studies and their implementation can provide some guidance for the recommended GOMaP and analysis of alternatives for a potential Habitable World Observatory. Every Decadal class NASA mission has been enabled by the co-maturation of concept and technology. And, NASA has never flown a mission exactly as was recommended by the Decadal Report. Each of these previous missions was descoped during their maturation process based on cost and feasibility. And given NASA's history (since 2005) of an average 74% cost growth from PDR to Launch for Optical Instruments,[8] it is probable that the Decadal's recommendations for the Habitable World Observatory will need to be descoped.

Most space telescopes face the same technical challenges: how to design and build a space telescope that achieves the required on-orbit performance—given the challenges of mass constraints and mechanical and thermal stability—and how to verify/validate that performance by test and model correlation. Technical advances in these areas are required to enable each new generation of mission capabilities. In addition, space telescopes require sustained support from both industry and the scientific community to overcome political challenges. Finally, launch vehicle capacity is potentially the single most important factor driving a mission architecture.

6.1 Postscript

Recently, this author read "How Big Things Get Done," by Flyvbjerg and Gardner.[35] Its findings are completely consistent with this paper. Based on a database of 16,000 projects, only about 48% finish on budget and only 8.5% finish on budget and schedule. And the more complicated the project is, the larger its likely overrun is. Also, overruns are not Gaussian, they are Laplacian with a long tail.

The problems are lack of planning, inaccurate cost and schedule estimates, and inexperience of the implementation team. To overcome these problems, the authors have four specific recommendations. First, before entering the implementation phase, the project should undergo seven or eight simulation and iteration cycles (which for NASA occurs when a mission passes key decision point "C" (KDP-C). The KDP-C process starts with a PDR/NAR to the project's Standing Review Board and ends with a Confirmation Review. Thus, Flyvbjerg and Gardner recommend eight design cycles before PDR.). Second, simulate physically at the smallest relevant scale and simulate digitally at the highest possible fidelity (which for a NASA mission involves building traceable physical test beds and integrated structural thermal optical performance (STOP) models and then validating the models by correlating their predictions with relevant environment testing. Such activities are typical during technology maturation and are consistent with a requirement that all technology be at TRL-6 before PDR.). Third, respectful skepticism is required to avoid the two primary reasons for inaccurate cost and schedule estimates: cognitive bias (i.e., optimism) and strategic misrepresentation (to gain project approval under false pretenses for political or financial gain). And fourth, success requires a team with relevant experience.

Code and Data Availability

Data sharing is not applicable to this paper as no new data were created or analyzed.

Acknowledgments

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