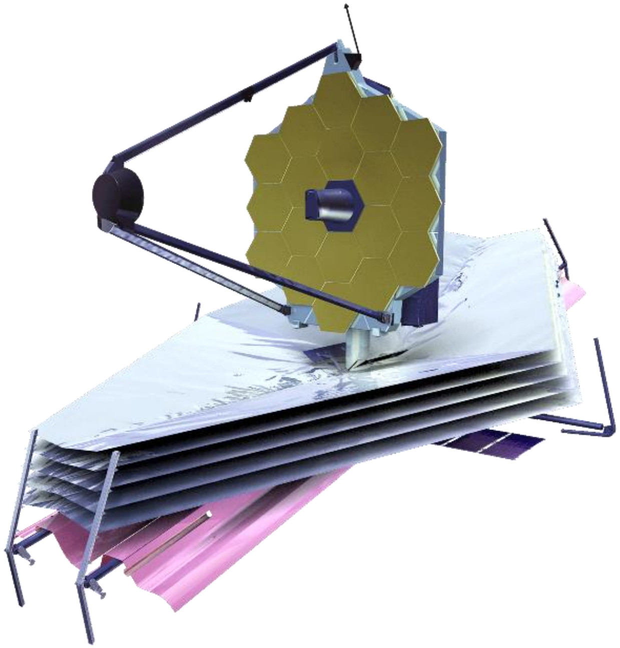
How History can inform an Analysis of Alternatives Study



H. Philip Stahl, Ph.D.
NASA

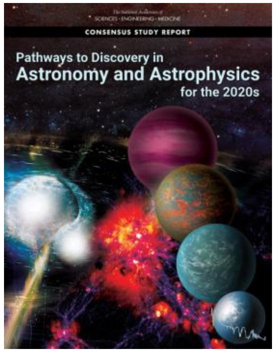
Overview

How might History inform likely implementation of Decadal 2020 Recommendations & Suggestions

How do the 2020 Decadal Recommendations & Suggestions compare with History?

- Maturation of Mission Concepts
- Technology Development

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

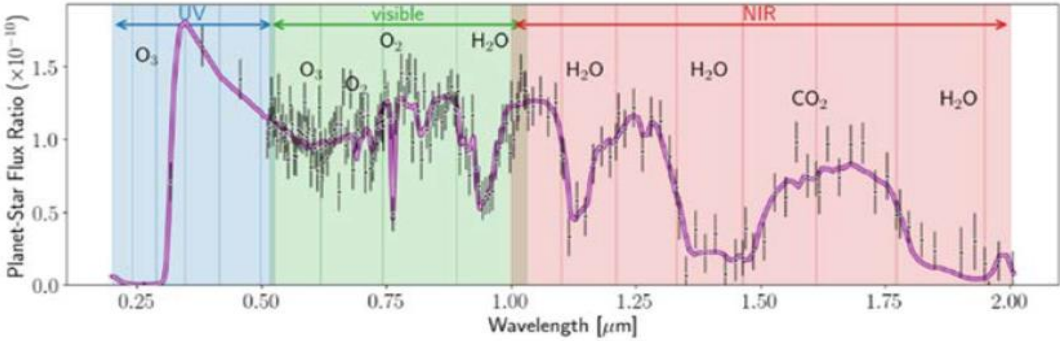


Decadal 2020 recommended GOMaP to invest in co-maturation of mission concepts and technologies for:

- ~6 m off-axis inscribed IR/O/UV telescope

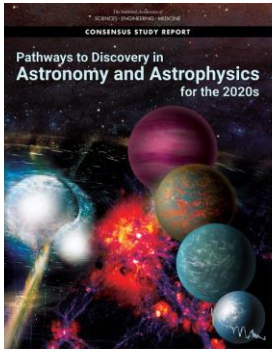
EOS-1 Panel explicitly stated that they were not suggesting a preferred mirror configuration (monolithic vs segmented), nor that one configuration was more feasible than another.

- to sample atmospheric spectra of ~25 potentially habitable exoplanets using UV, visible and Nir-IR wavelengths (REF Fig. 7.5)



- and be launched in early 2040s with cost <$11B (including 5 yrs operation).

Pathways to Discovery in Astronomy and Astrophysics for the 2020s



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

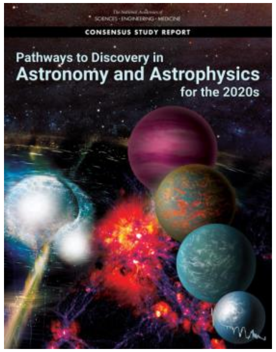
CONSENSUS STUDY REPORT

Pathways to Discovery in
Astronomy and Astrophysics
for the 2020s

Exoplanets, Astrobiology and Solar System Panel suggested that the Large-Aperture Space-Based Telescope needed to have these ‘bounding’ Capabilities (REF Table E.1):

- UV to NIR Imaging Spectroscopy (0.3 to 1.8 micrometers)
- Contrast ~ 1e-10
- IWA < ~ 60 mas
- OWA > 1 arc-sec
- Spatial resolution < ~ 0.01 mas
- R ~150 for dozens of potential Earth analog planets

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

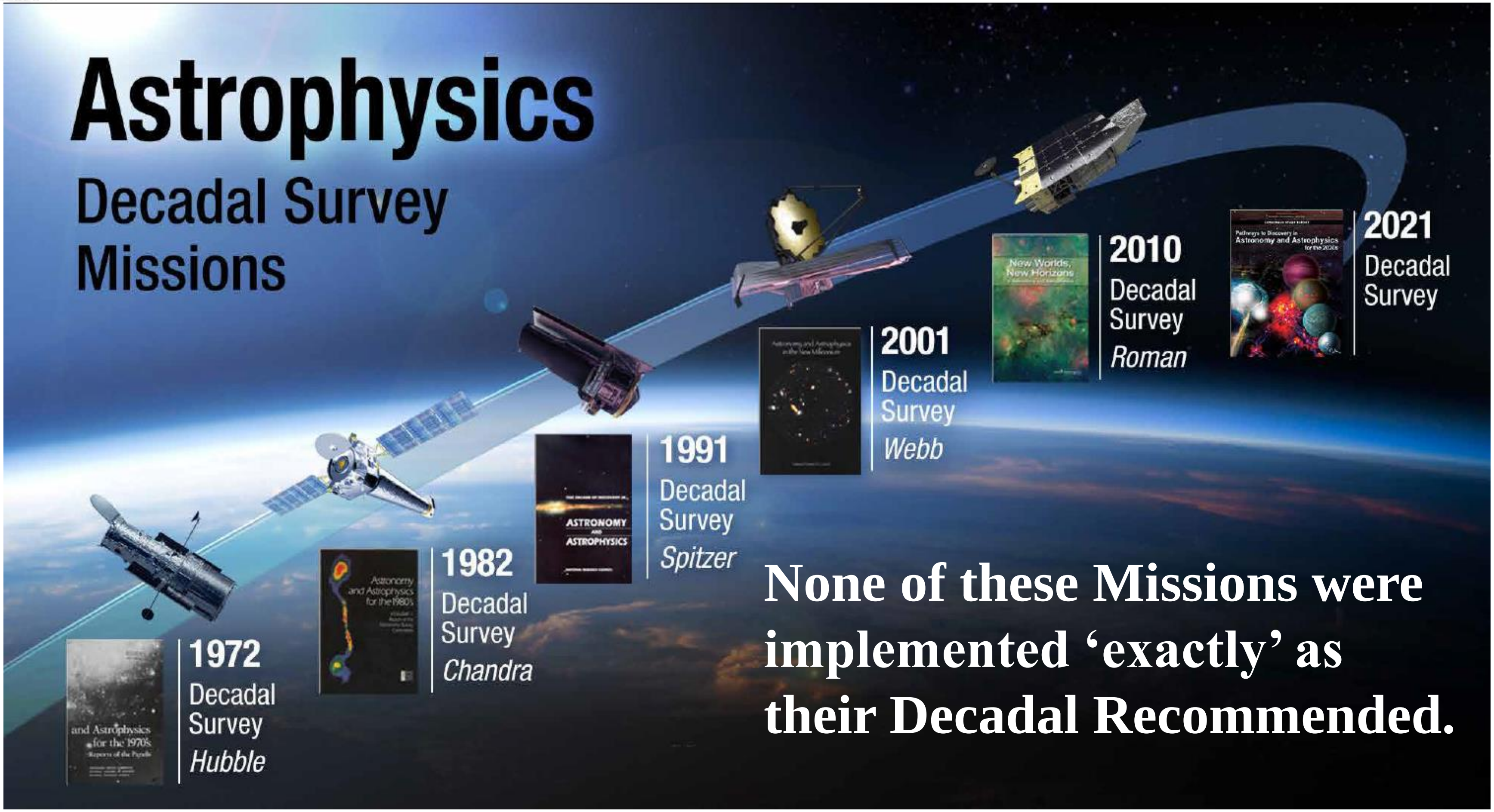


Electromagnetic Observation from Space (EOS-1) Panel suggested:

- Conduct a Study to make an informed choice between monolithic and segmented primary mirror architectures.
- Invest in a Grand Technology Roadmap to mature technology for detecting exoEarths to TRL-6 before Phase-A
    - 10-10 Starlight Suppression
        - In-space demo of sub-scale star shade to retire operational risk & validate performance
        - High-Contrast Coronagraph Instrument
    - Ultra-Stable Telescope
        - Ultra-Stable Structural Composites
        - Low-Creep Adhesives
        - CTE measuring Techniques
        - Milli-K Thermal Sensing and Control
        - FEM/Test Surface Figure Error/Wavefront Error Model Correlation

How might History inform likely implementation of Decadal 2020 Recommendations & Suggestions?

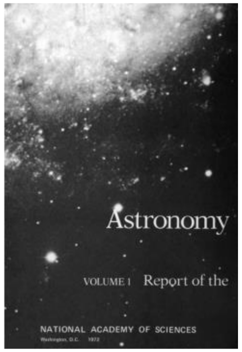
Decadal Studies and Flagship Missions.



None of these Missions were implemented 'exactly' as their Decadal Recommended.

- Each of these missions underwent extensive co-maturation of both concept and technology.
- All had to solve the same basic technology challenges.

Astronomy and Astrophysics for the 1970's (1972)



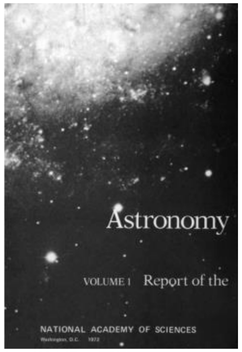
Astronomy

VOLUME I Report of the

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1972

1. Very Large Radio Array
2. Upgrade Ground Telescopes with Electronic Detectors and build the **Multiple Mirror Telescope**.
3. Design an Infrared aircraft stratospheric observatory
4. X-Ray/Gamma-Ray balloon & space telescopes
5. 65m millimeter-wave antenna
6. Balloon Missions
7. Orbiting Solar Observatories
8. Theoretical Investigations
9. **High-Resolution UV/Optical Large Space Telescope**
10. Large Radio Telescope
11. System to measure geographic position and motion

Astronomy and Astrophysics for the 1970's



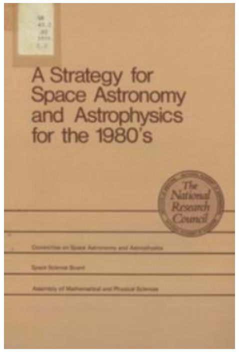
#9 Priority: Large Space Telescope

- Recommended a UVOIR space telescope
  - Spectroscopy brings some of the most far-reaching additions to our knowledge. But this knowledge is lacking UV & near-IR regions.
  - As a continuation of the OAO program beyond OAO-C.
- Specifications:

		Hubble (1990)
Diameter	**3-meter (120 inch)**	**2.4-meter**
Performance	**"Diffraction Limited"**	
Spectral Range	**0.1 to 5 micrometers**	**0.1 to 2.5 µm**
Pointing	"accurate"	

- Consider launching a 1.5m (60 inch) telescope to:
  - Demonstrate Technologies, i.e. reduce risk
  - Provide continuity between OAO-C and LST.

Strategy for Space Astronomy and Astrophysics for the 1980's (1979)

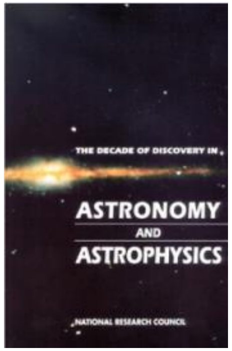


A Strategy for
Space Astronomy
and Astrophysics
for the 1980's

The National Research Council

1. **2.4-m Space Telescope**
   - **Congress Funded in 1977**
   - **New Start in 1978**
   - **NOTE: at time of New Start, Hubble had 15 years of Mission Concept & Technology Development (with enabling inventions).**
2. Solar Polar Mission
3. Gamma-Ray Observatory
4. **X-Ray Telescope** **Chandra (1999)**
   - **1 to 2-meter class** **1.2-m**
   - **Free-flying** **Yes**
   - **Maintainable/Retrievable** **No**
5. Cosmic-Ray Observatory
6. Planning for a space-based 10-m baseline 1-m aperture optical telescope interferometer to achieve high-spatial resolution.

Decade of Discovery in Astronomy and Astrophysics (1991)



THE DECADE OF DISCOVERY IN
ASTRONOMY
AND
ASTROPHYSICS
NATIONAL RESEARCH COUNCIL

Existing Programs

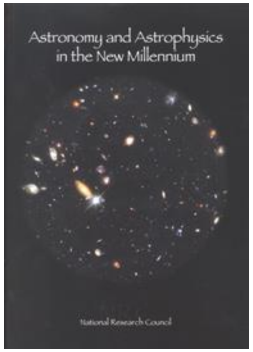
- Hubble WF/PC with Corrective Optics Servicing
- Gamma-Ray Observatory
- AXAF
  - Reaffirm 1982 Field Committee decision to make AXAF highest-priority large program of the 1980s.

New Programs

1. Space Infrared Telescope Facility		**Spitzer (2003)**
• **Aperture**	**0.9-m**	**0.85-m**
• **Spectral Range**	**3 to 200 µm**	**3.6 to 160 µm**

2. FUSE
3. SOFIA

Astronomy and Astrophysics in the New Millennium (2001)



Complete 1991 Decadal recommended missions:

- SIRTF
- ALMA
- SOFIA

Complete 1997 Task Group on Space Astronomy recommended:

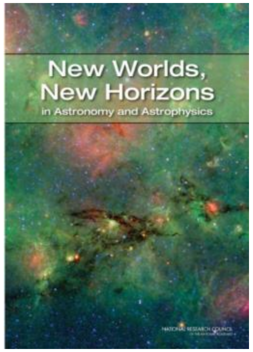
- SIM **Cancelled**
- MAP
- PLANCK

When Webb was recommended, it had only 5 yrs of funded development.

New Programs

1. **Next Generation Space Telescope** **Webb (2021)**
   - **Aperture** **8-m** **6.2-m (5.2-m inscribed)**
   - **Spectral Range** **0.6 to 27 μm** **0.6 to 28 μm**
2. Constellation-X (Con-X) **Cancelled**
3. Terrestrial Planet Finder (TPF) **Cancelled**
4. Single Aperture Far-IR (SAFIR) **Cancelled**

New Worlds, New Horizons in Astronomy and Astrophysics (2010)



Complete Webb

Recommended Large Programs:

1. **WFIRST**
    - **Diameter 1.5-m**
2. Explorer Program
3. LISA
4. IXO

Roman (202?)

2.4-m

How might History inform likely implementation of Decadal 2020 Recommendations & Suggestions?

Most Decadal Missions are not implemented 'exactly' as there were Recommended.

All Missions undergo extensive Concept Maturation

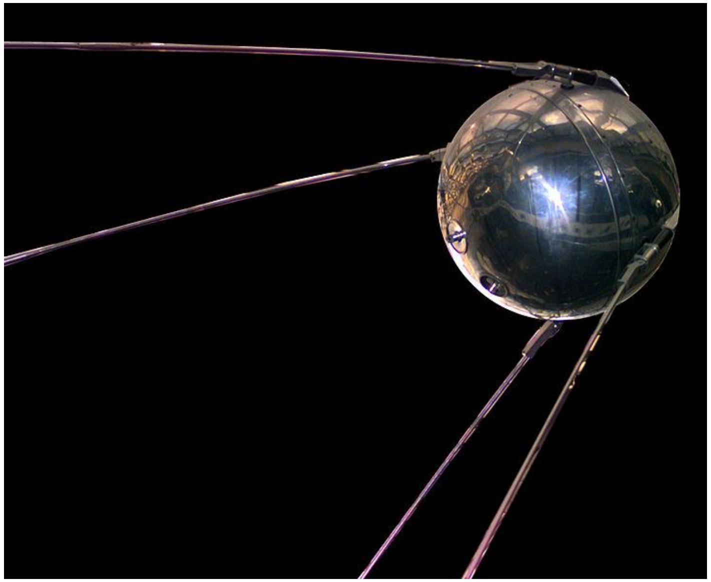
and

All Missions require Sustained Support from Industry and the Scientific Community

Hubble Mission Concept Maturation Process

Hubble started with Sputnik

On 4 Oct. 1957 the world changed – Sputnik was placed in orbit around the Earth – and the Space Race was begun.



NASA formally opened for business on 1 Oct. 1958.

The Berkner Telegram

On July 4, 1958, Dr. 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 & fly in 2 years.

Proposals were due in 1 week. He got 200 responses leading to:

- Explore & Monitor Program, first launch 1961
- Orbiting Solar Observatory (OSO) Program, 1962
- Orbiting Geophysical Observatory (OGO) Program, 1964
- Orbiting Astronomical Observatory (OAO) Program, 1966

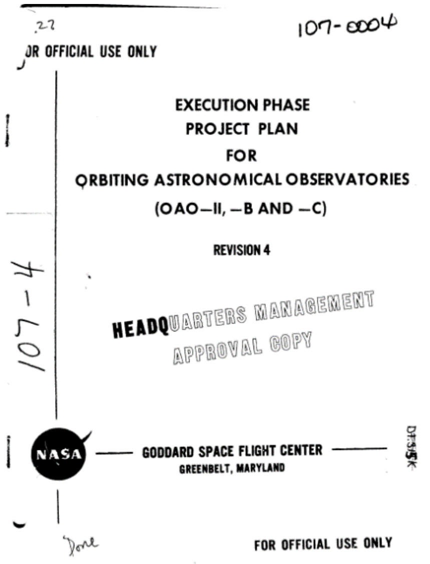
Kick-off meeting was in 1959
Ames defined Requirements
GSFC was lead center
Grumman was Prime.

Orbiting Astronomical Observatory (OAO)

From 1966 to 1972 NASA launched 4 OAO satellites

All had UV Science Experiments

OAO-I	April 1966: Failed due to corona arching.
OAO-II	Dec 1968 (on Atlas Centaur) to Jan 1973
OAO-B	Nov 1970: Failed, Atlas Centaur didn't achieve orbit
OAO-C	Aug 1972 to Feb 1981



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107-0004

OR OFFICIAL USE ONLY

EXECUTION PHASE
PROJECT PLAN
FOR
ORBITING ASTRONOMICAL OBSERVATORIES
(OAO—II, —B AND —C)

REVISION 4

107-4

HEADQUARTERS MANAGEMENT
APPROVAL COPY

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

Done

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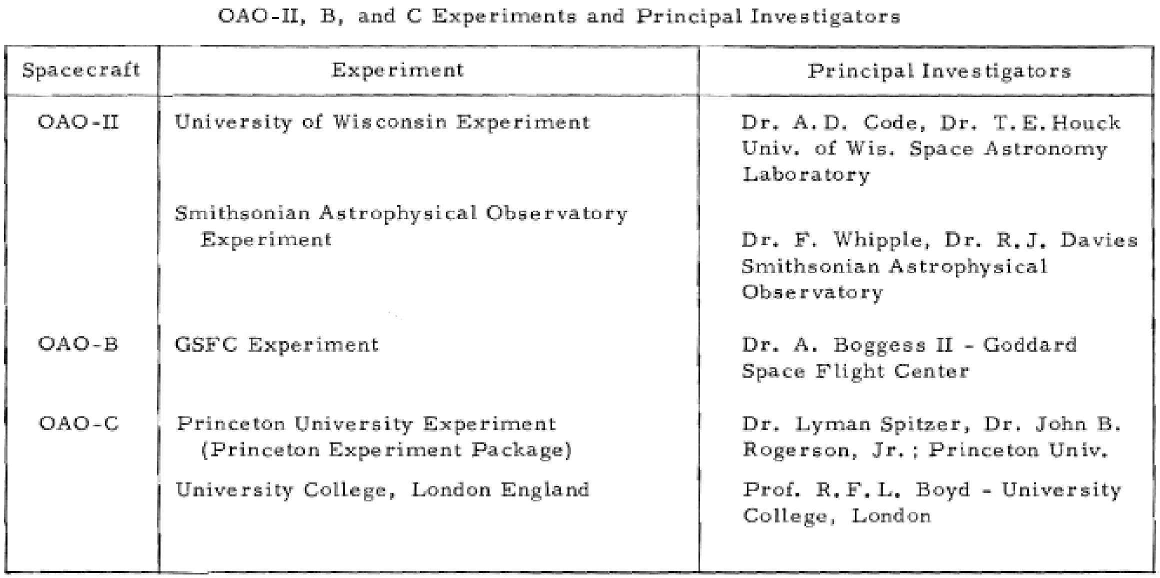


OAO-II, B, and C Experiments and Principal Investigators

Spacecraft	Experiment	Principal Investigators
OAO-II	University of Wisconsin Experiment	Dr. A. D. Code, Dr. T. E. Houck Univ. of Wis. Space Astronomy Laboratory
	Smithsonian Astrophysical Observatory Experiment	Dr. F. Whipple, Dr. R. J. Davies Smithsonian Astrophysical Observatory
OAO-B	GSFC Experiment	Dr. A. Boggess II - Goddard Space Flight Center
OAO-C	Princeton University Experiment (Princeton Experiment Package)	Dr. Lyman Spitzer, Dr. John B. Rogerson, Jr.; Princeton Univ.
	University College, London England	Prof. R. F. L. Boyd - University College, London

OAO-C (Copernicus)

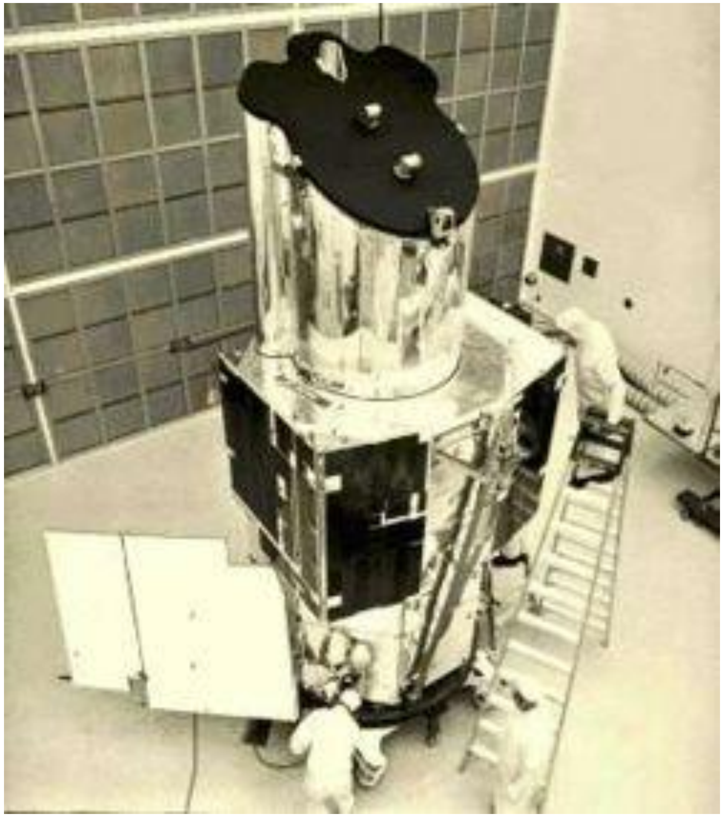
OAO-C had two Science Experiments

Princeton Experiment Package was a UV Spectrometer

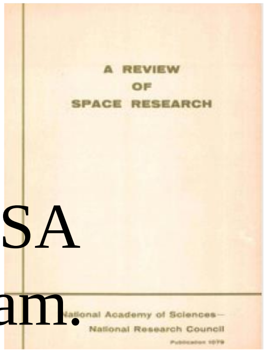
- 81 cm Cassegrain telescope
- Built by Perkin-Elmer for Princeton
- Fine Guider achieved 0.1 arc-sec pointing

London Experiment X-Ray Package

- 3 small x-ray telescopes
  - 5.5 cm2 for 3 to 9 Angstroms
  - 12 cm2 for 6 to 18 Angstroms
  - 23 cm2 for > 44 Angstroms
- Deep parabolic grazing incidence mirrors
- ‘first’ piggy-back experiment
- ‘first’ x-ray telescopes in space?



A Review of Space Research (1962)



A REVIEW
OF
SPACE RESEARCH

ational Academy of Sciences—
National Research Council
Publication 1079

In 1962, before OAO attempted its first launch in 1966, NASA asked the National Academy for advice on its science program.

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-meter telescope. The entire astronomy committee jumped on the idea."

Recommendations:

- Schedule launches so that during the next 10 years at least one OAO is operational at any given time.
- Organize a small study group for summer of 1963 to explore and prepare a report delineating technical problems and science objectives of a larger more versatile space telescope.

The Report of the Summer Study conducted under the auspices of the Space Science Board of the National Academy of Sciences", Publication 1079, NAS, 1962

Orbiting Research Laboratory

Oct 63 to June 64: Astronomy Panel of Space Science Steering Committee finalized requirements for Large Space Telescope by

- 120-inch (3.0 meter) Diameter
- Diffraction-Limited
- In Low Earth Orbit

June/July 1965 Space Science Board of the National Academy of Sciences held a meeting at Woods Hole that defined Science Goals.

- Aden Meinel of Kitt Peak was major proponent at 1962 & 64 meetings

25 Aug 65:

- President Johnson authorized DoD to create the Manned Orbiting Laboratory (MOL)
- NASA created what would become Apollo Application Program (AAP)

"Exploring the Unknown: Selected Documents in the History of the US Civil Space Program", Document III-13, Vol.V, Ed John M. Logsdon, NASA SP-2001-4407, 2001.

Apollo Application Program

Apollo Application Program developed science missions which required human flight capabilities.

- For example, Skylab and a solar telescope that few on Skylab

Large Telescope Experiment Program (LTEP) was a manned Astrophysics Telescope.

- Boeing did the initial study, but I don’t have their reports.

Disclaimer: much of the rest of this section was extracted from historical documents ‘handed-down’ to the author by Jim Bilbro upon his retirement from NASA.

Including reports from:

- Perkin-Elmer (Danbury, CT)
- Itek (Lexington, MA)
- Lockheed (Palo Alto, CA)

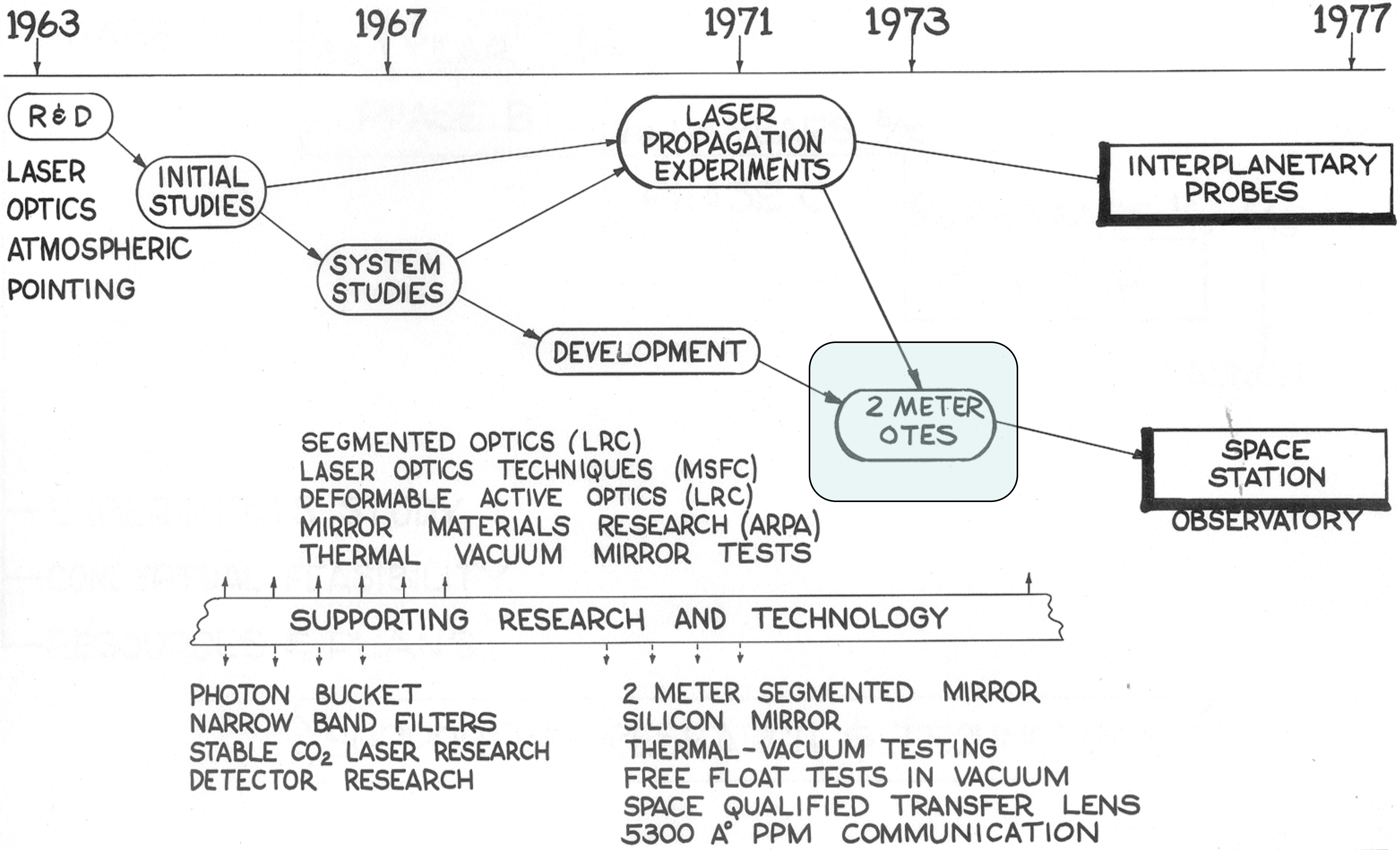
- WHERE IS THE U.S. GOING IN SPACE ?
- WHAT PROSPECTIVE NATIONAL GOALS REQUIRE NEW SPACE OPTICS ?
- SPACE ASTRONOMY
  - RESOLUTION
  - ULTRAVIOLET SPECTROSCOPY
  - INFRARED SPECTROSCOPY
- PLANETARY PROBES
  - LASER COMMUNICATION

SPACE ASTRONOMY NEEDS

- LARGE-APERTURE DIFFRACTION-LIMITED OPTICS
  - 2 METER
  - 3 METER
  - 10 METER
- FINE POINTING SYSTEMS (< 1/100 SEC.)
  - ALL WAVELENGTH TRANSFER LENS
  - PRECISE TORQUER GIMBALS
  - FREE FLOAT TELESCOPES
- SPACE MAINTAINABILITY
  - ALIGNMENT AND TUNE-UP
  - MODULAR SERVICING
  - SCIENTIFIC EXPERIMENTS FLEXIBILITY

Perkin-Elmer 1967

NASA SPACE OPTICS TECHNOLOGY PLAN



1963
1967
1971
1973
1977

R & D

LASER
OPTICS
ATMOSPHERIC
POINTING

INITIAL STUDIES

SYSTEM STUDIES

DEVELOPMENT

LASER PROPAGATION EXPERIMENTS

INTERPLANETARY PROBES

2 METER OTES

SPACE STATION OBSERVATORY

SEGMENTED OPTICS (LRC)
LASER OPTICS TECHNIQUES (MSFC)
DEFORMABLE ACTIVE OPTICS (LRC)
MIRROR MATERIALS RESEARCH (ARPA)
THERMAL VACUUM MIRROR TESTS

SUPPORTING RESEARCH AND TECHNOLOGY

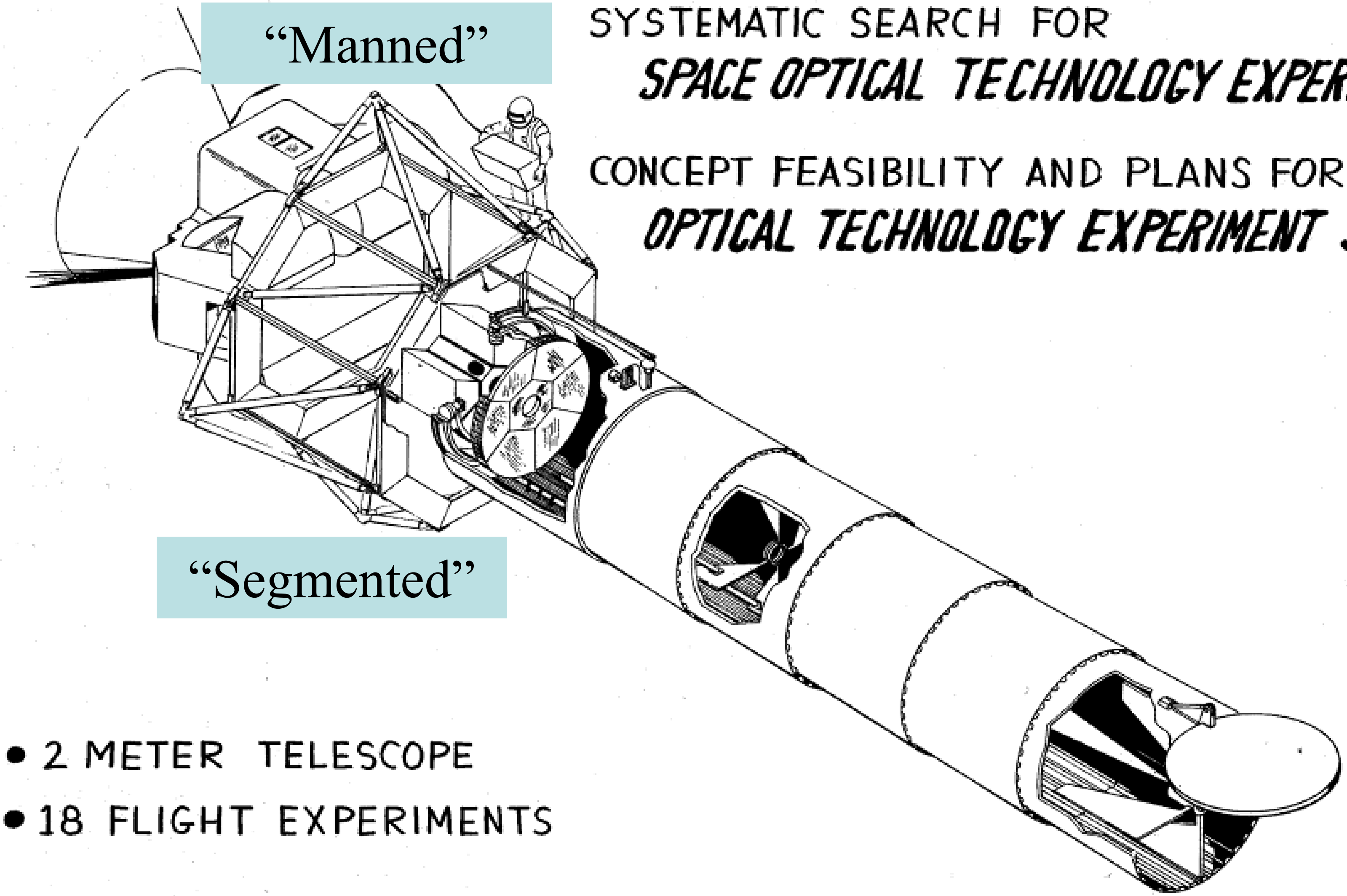
PHOTON BUCKET
NARROW BAND FILTERS
STABLE CO_2 LASER RESEARCH
DETECTOR RESEARCH

2 METER SEGMENTED MIRROR
SILICON MIRROR
THERMAL-VACUUM TESTING
FREE FLOAT TESTS IN VACUUM
SPACE QUALIFIED TRANSFER LENS
5300 Å PPM COMMUNICATION

PERKIN-ELMER

SYSTEMATIC SEARCH FOR
SPACE OPTICAL TECHNOLOGY EXPERIMENTS

CONCEPT FEASIBILITY AND PLANS FOR
OPTICAL TECHNOLOGY EXPERIMENT SYSTEM



"Manned"

"Segmented"

- 2 METER TELESCOPE
- 18 FLIGHT EXPERIMENTS

PERKIN-ELMER

Optical Technology Experiment System (OTES), PE, 1967
Large Telescope Experiment Program (LTEP), PE 1969

2-METER OTES JUSTIFICATION

PROVIDE NASA WITH DATA FOR NATIONAL SPACE OBSERVATORY

- ORBITAL ALTITUDE DECISION DATA
  - DAYLIGHT ASTRONOMY
  - POINTING DISTURBANCES
  - THERMAL BALANCE
- MANNED SPACE ASTRONOMY TECHNIQUES
  - ERECTION
  - ALIGNMENT
  - MODIFICATION
  - MAINTENANCE
- PRIMARY MIRROR EVALUATION
  - ACTIVE OPTICS
    - SEGMENTED TESTS
    - DEFORMABLE TESTS
    - THERMAL TESTS
  - MATERIALS
    - QUARTZ
    - SILICON
    - CERVIT
    - BERYLIUM
- POINTING DEVELOPMENT
  - TRANSFER LENS
  - FREE FLOAT
  - FLEXURE GIMBALS
  - CLUSTER — AUTONOMOUS MODES

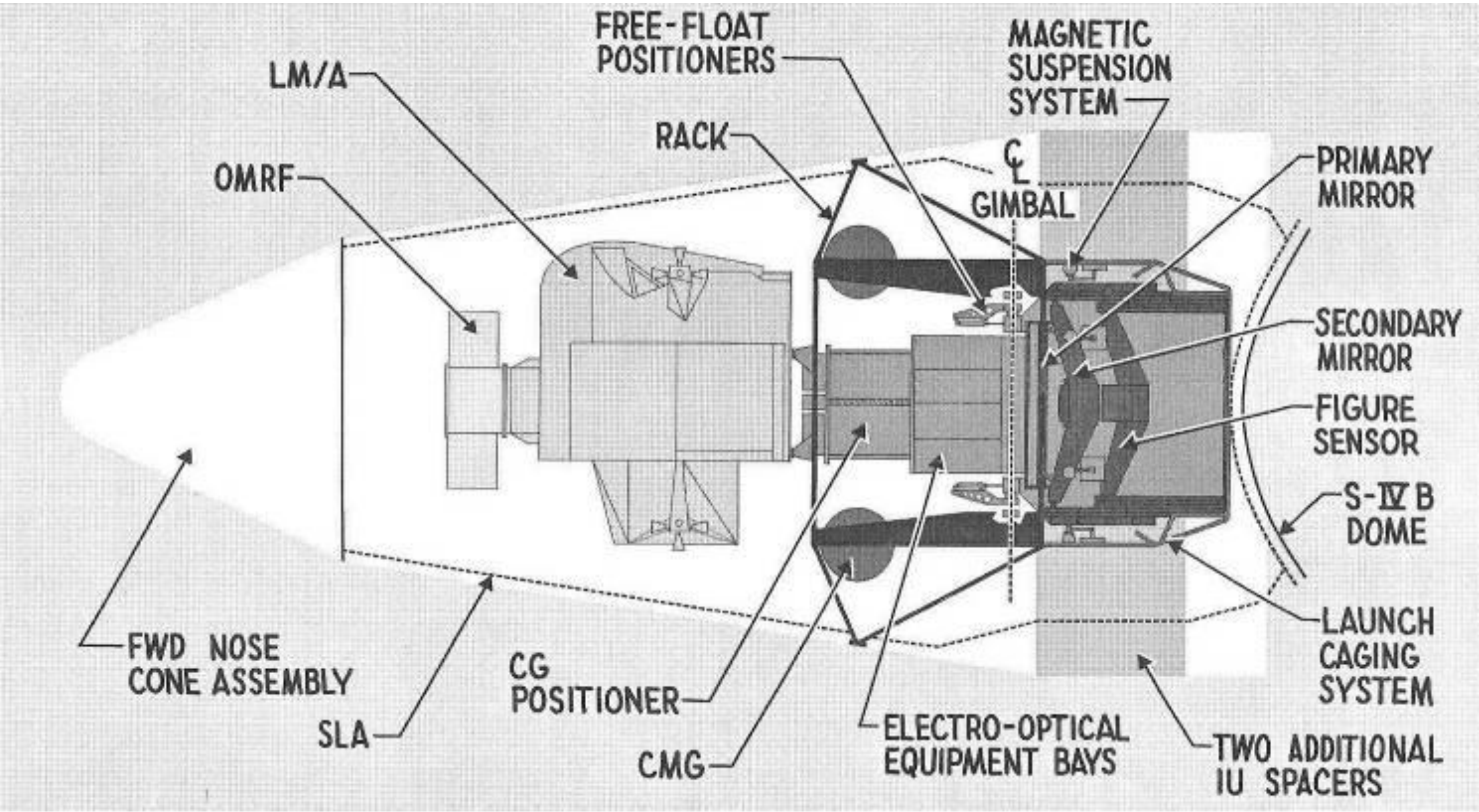
LARGE TELESCOPE EXPERIMENT PROGRAM (LTEP)

WEDNESDAY
20 AUG 1969

P-E/L[illegible]C

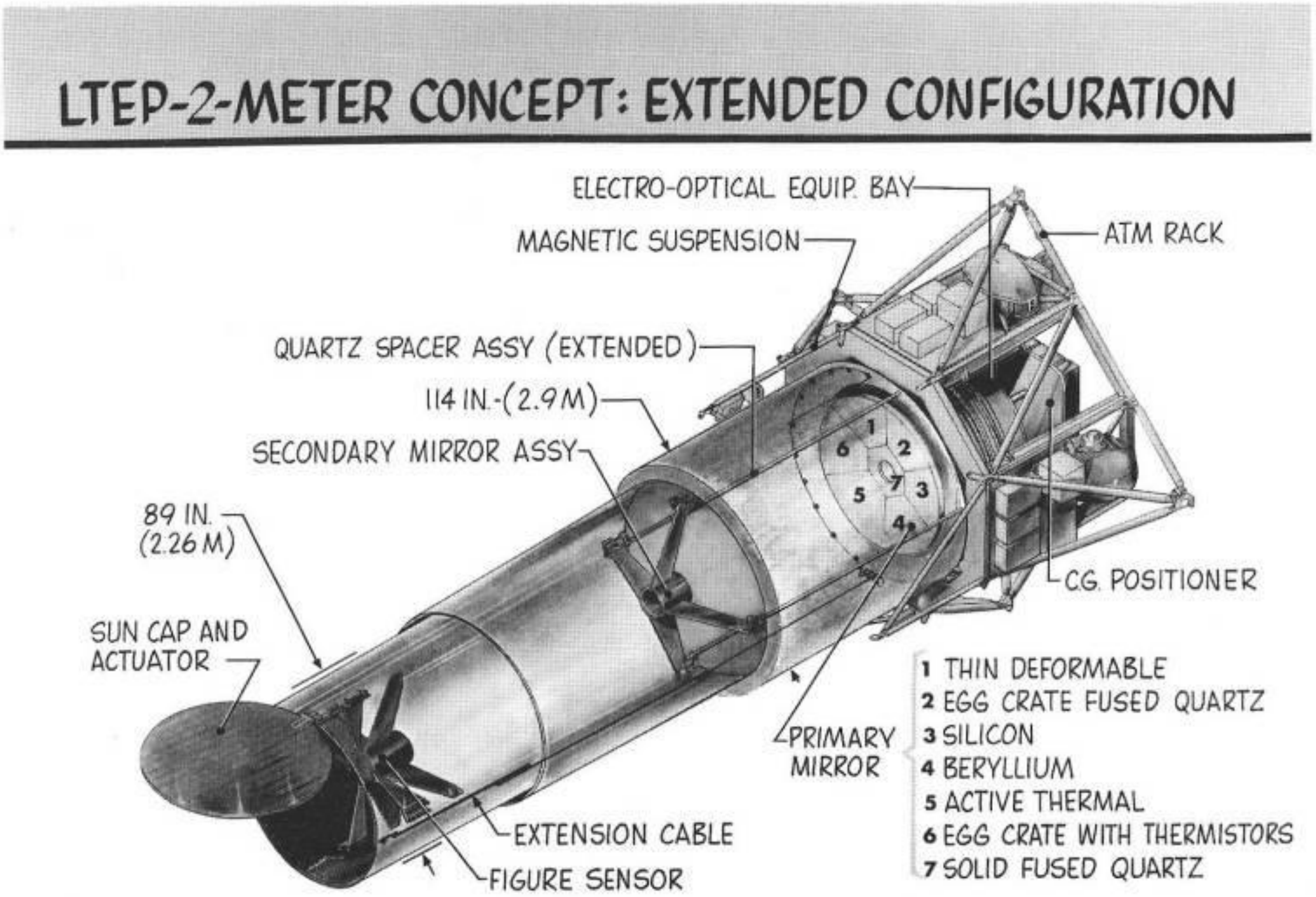
"Large Telescope Experiment Program (LTEP)", Perkin-Elmer, Aug 1969

Initial Launch Configuration for Saturn IB



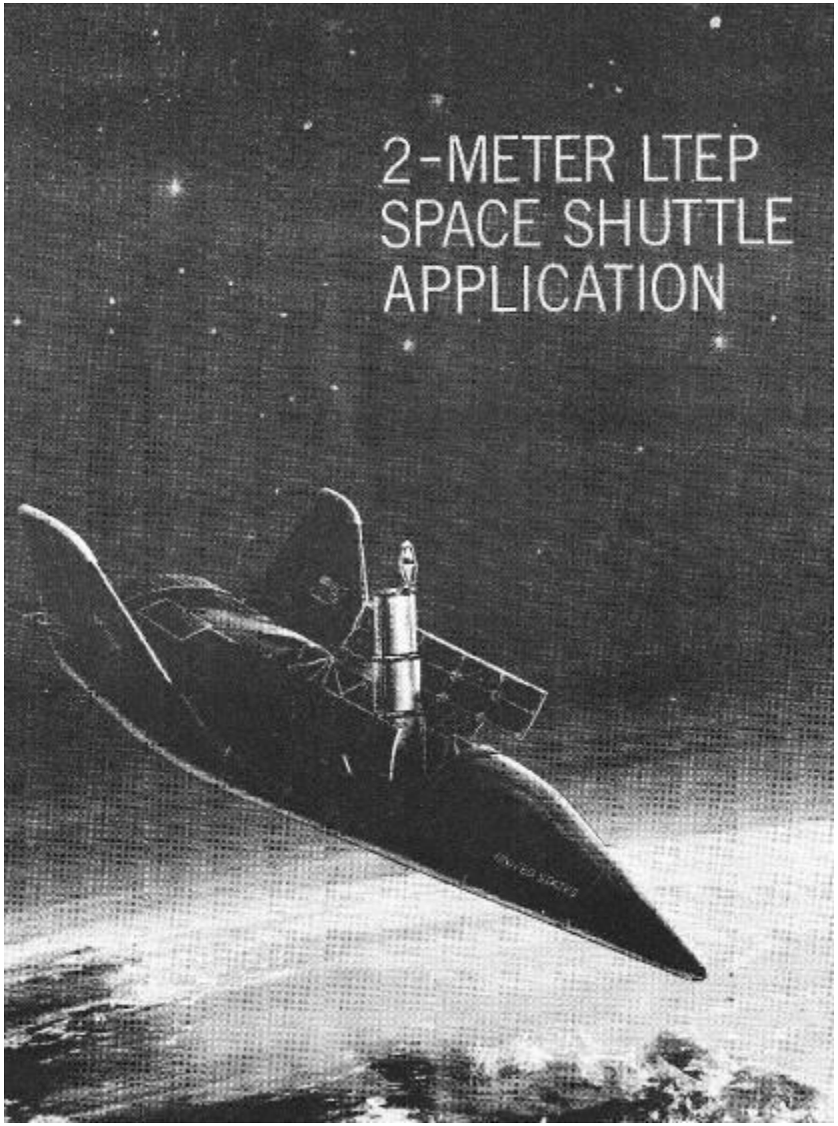
"Large Telescope Experiment Program (LTEP)",
Lockheed Missiles and Space Company, Jan 1970

“Large Telescope Experiment Program (LTEP)”, Perkin-Elmer, Aug 1969



LTEP-2-METER CONCEPT: EXTENDED CONFIGURATION

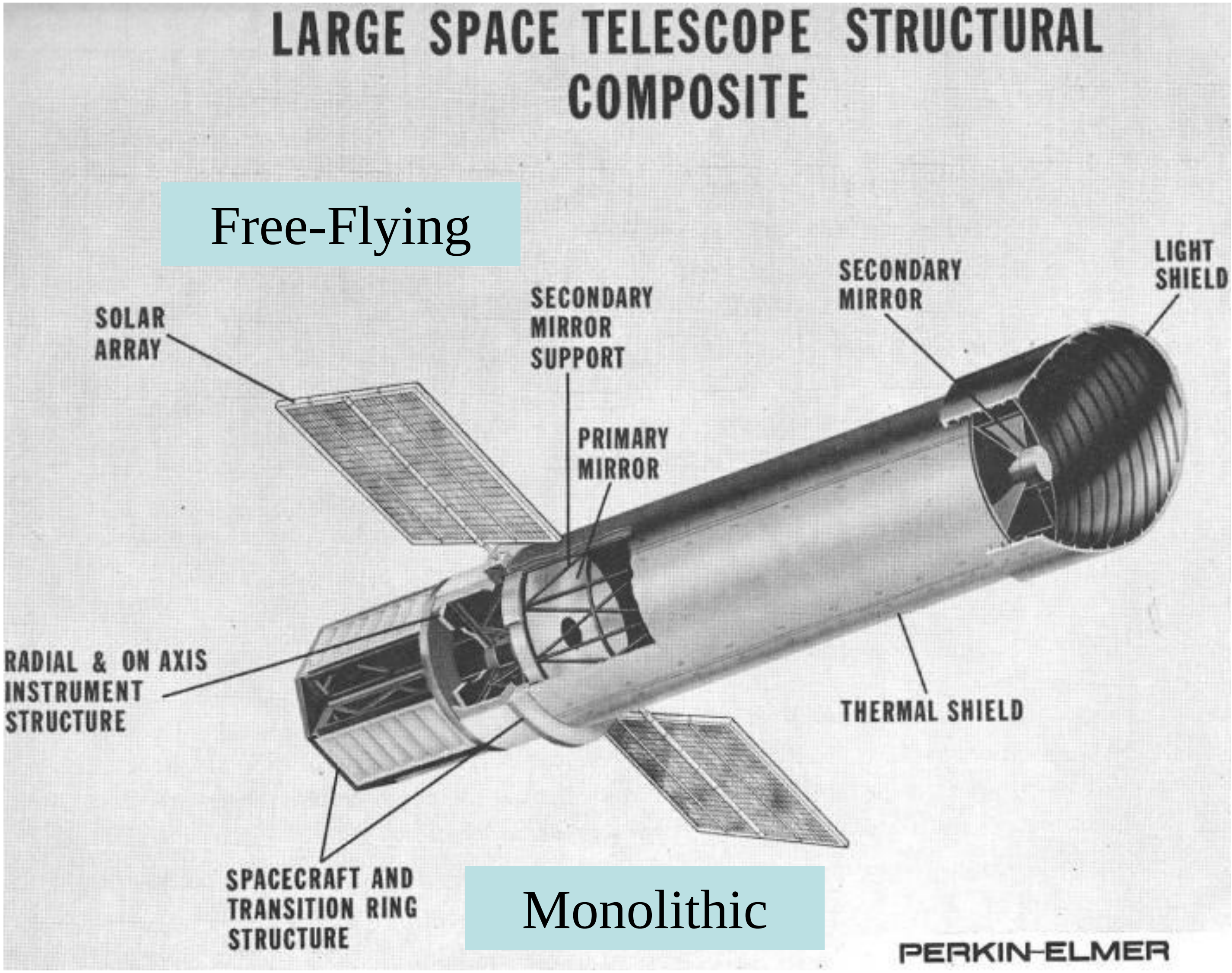
1 THIN DEFORMABLE
2 EGG CRATE FUSED QUARTZ
3 SILICON
4 BERYLLIUM
5 ACTIVE THERMAL
6 EGG CRATE WITH THERMISTORS
7 SOLID FUSED QUARTZ



2-METER LTEP
SPACE SHUTTLE
APPLICATION

“Large Telescope Experiment Program (LTEP) Executive Summary”,
Alan Wissinger, April 1970

"3-meter Configuration Study Final Briefing", Perkin-Elmer, May 1971



Free-Flying

Monolithic

Space Shuttle

Jan 1972: President Nixon authorized Space Shuttle development.

May 1973: Space Shuttle Payload Planning Group

- 3.0-m Diameter Diffraction-Limited UV/O/NIR Telescope
- Deployed and Periodic Serviced by Shuttle
- AND a 1.5-m 20K Infrared Telescope
- AND a Large Microwave Telescope

"Exploring the Unknown: Selected Documents in the History of the US Civil Space Program", Document III-19, Vol.V, Ed John M. Logsdon, NASA SP-2001-4407, 2001.

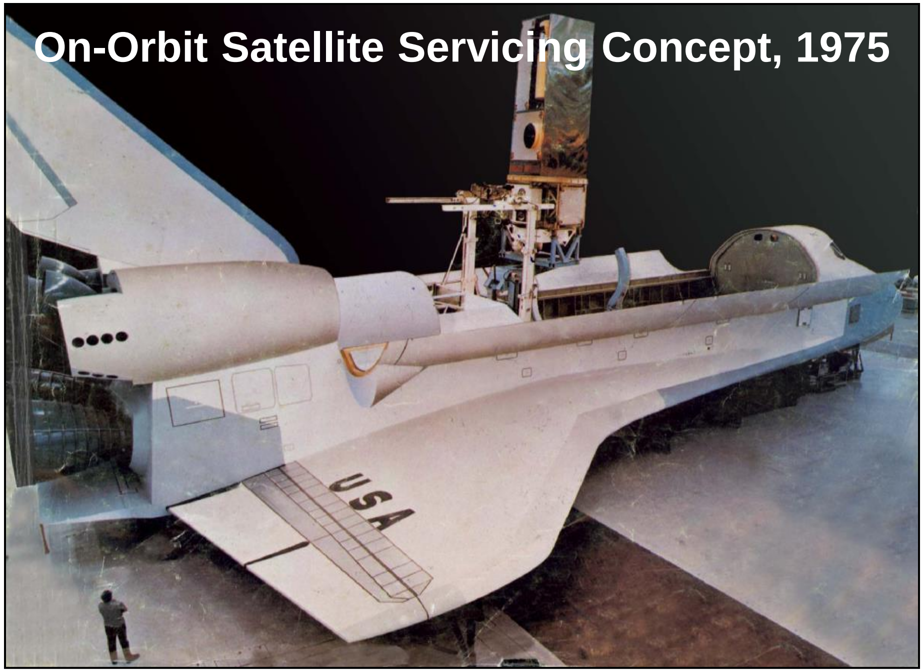
LST Shuttle Concept

Shuttle

- Payload Bay designed to deploy, retrieve and service spacecraft
- Robotic Arm for capturing and repairing satellites.

Mission Spacecraft

- Spacecraft designed to be approached, retrieved, and repaired
- Generic Shuttle-based carriers to berth and service on-orbit


On-Orbit Satellite Servicing Concept, 1975

Hubble Non-Technical

Cost (some things never change)

"Exploring the Unknown: Selected Documents in the History of the US Civil Space Program", Chapter 3, Vol.V, Ed John M. Logsdon, NASA SP-2001-4407, 2001.

•"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

•"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**"

•After Phase C/D contracts were awarded "contractors increased their cost estimates substantially. Yet, Marshall was not allowed to budget additional funds." **Program was saved via a 1983 replan.**

"Exploring the Unknown: Selected Documents in the History of the US Civil Space Program", Chapter 3, Vol.V, Ed John M. Logsdon, NASA SP-2001-4407, 2001.

Mirror Diameter

Initial 3.0-m diameter for LST was defined by Langley Research Center (LaRC) – who was responsible for the Apollo Program – based on largest mirror that would fit in a **5-m Apollo Fairing**.

For 1978 new start MSFC was directed to find ways to cut cost.

Three options were investigated: 1.8-m, 2.4-m and 3.0-m.

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
- A 2.4-m telescope could still do the science.

Note:

- Hubble descope of 3 to 2.4-m reduced collecting area from 7 to 4.5 m2 (63%).
- Webb’s descope from 8 to 6.2-m reduced area from 50 to 25 m2 (50%).

“Exploring the Unknown: Selected Documents in the History of the US Civil Space Program”, Chapter 3, Vol.V, Ed John M. Logsdon, NASA SP-2001-4407, 2001.

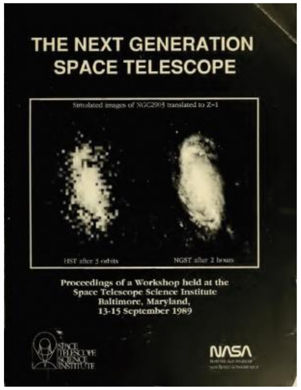
Hubble Deployment April 25 1990

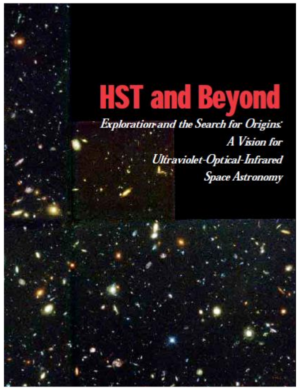
Webb Mission Concept Maturation Process

Webb Space Telescope

The start of Webb is typically traced back to:

- 1989 Next Generation Space Telescope workshop at STScI
- 1996 HST & Beyond report
- 16 Apr 1996 Optical Systems Concepts and Technology for Next Generation Space Telescope Workshop at MSFC





- 1996 Industry Day

Next Generation Space Telescope Study

In 1996 (based on the 1989 Next Generation Space Telescope workshop and the 1996 HST & Beyond report) NASA initiated a feasibility study.

Science Drivers

Near Infrared	1-5 microns (.6-30 extended)
Diffraction Limited	2 microns
Temperature range	30-60 Kelvin
Diameter	At least 4 meters ("HST and Beyond" report)

Programmatic Drivers

25 % the cost of Hubble	Cost cap - $500 million
25 % the weight of Hubble	Weight cap ~3,000 kg

Baselines for OTA study

Atlas IIAS launch vehicle	**Low cost launch vehicle**
L2 orbit	Passively cool to 30-60 K
1000 kg OTA allocation	Launch vehicle driven

Telescope Architecture defined in 2003 with Prime selection; with 7 yrs of concept and technology maturation.

Study Results ….

Science requires a 6 to 8-meter space telescope, diffraction limited at 2 micrometers and operating at below 50K.

Segmented Primary Mirror

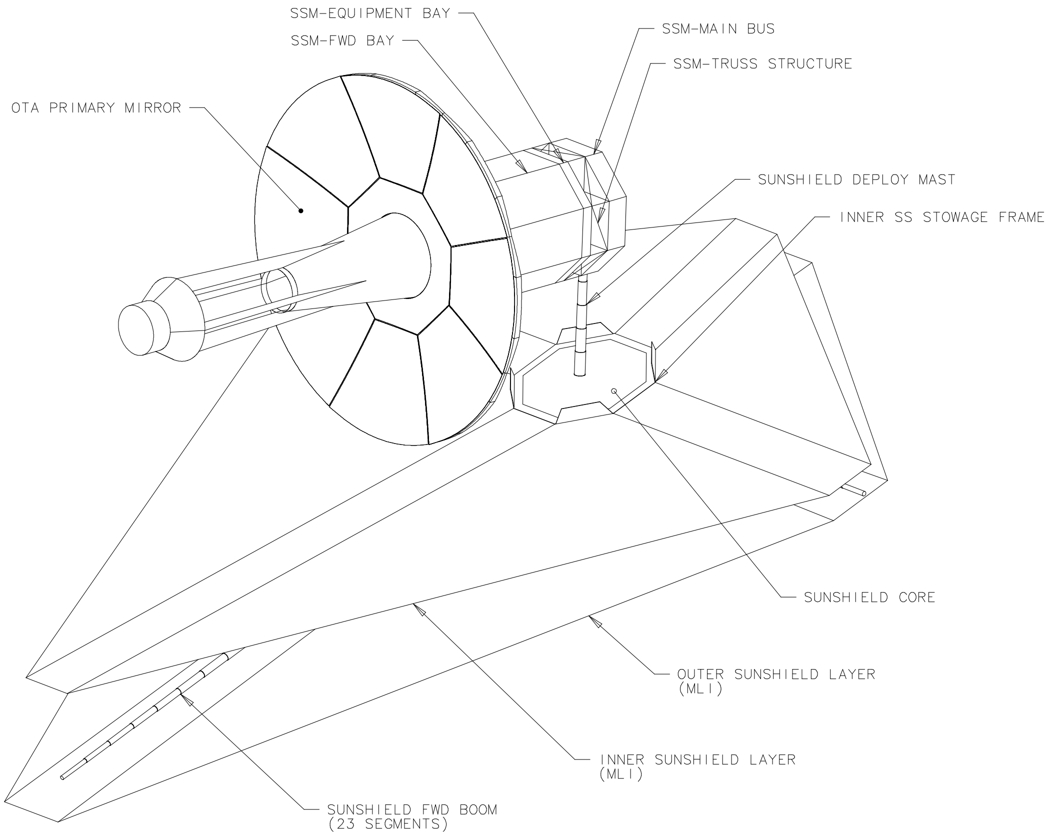
The only way to put an 8-meter telescope into a 4.5-meter fairing is to segment the primary mirror.

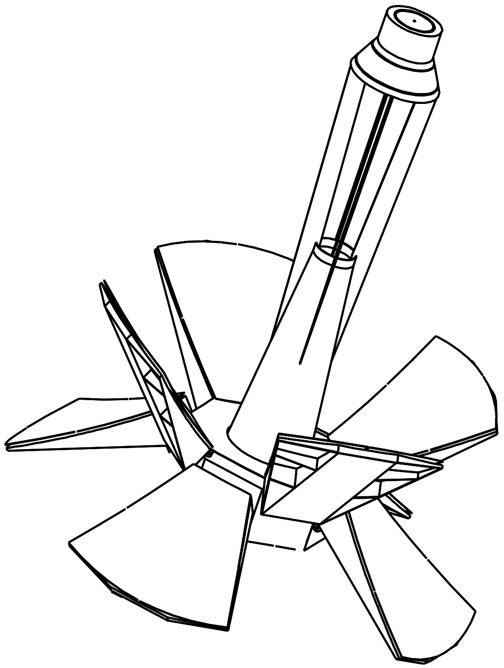
Mass Constraint

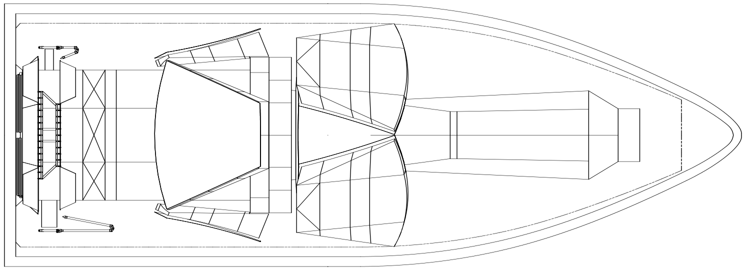
Because of severe launch vehicle mass constraint, the primary mirror cannot weight more than 1000 kg for an areal density of < 20 kg/m2

Such mirror technology did not exist

Reference design – Lockheed / Raytheon







LAMP Telescope - 1996

Optical Specifications

- 4-meter diameter
- 10-meter radius of curvature
- 7 segments
- 17 mm facesheet
- 140 kg/m2 areal density

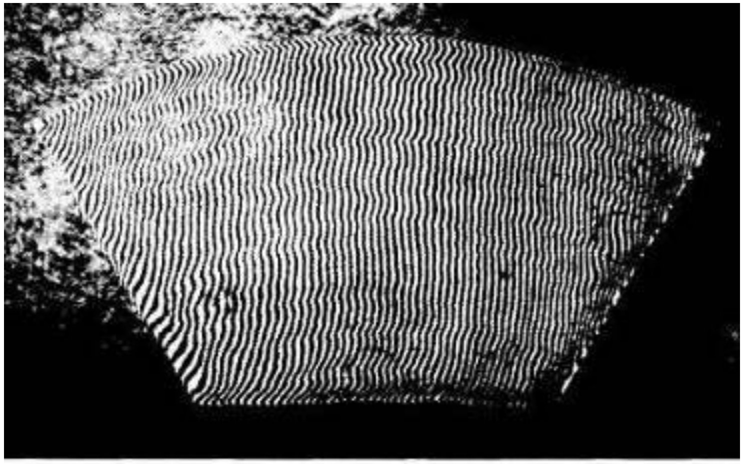
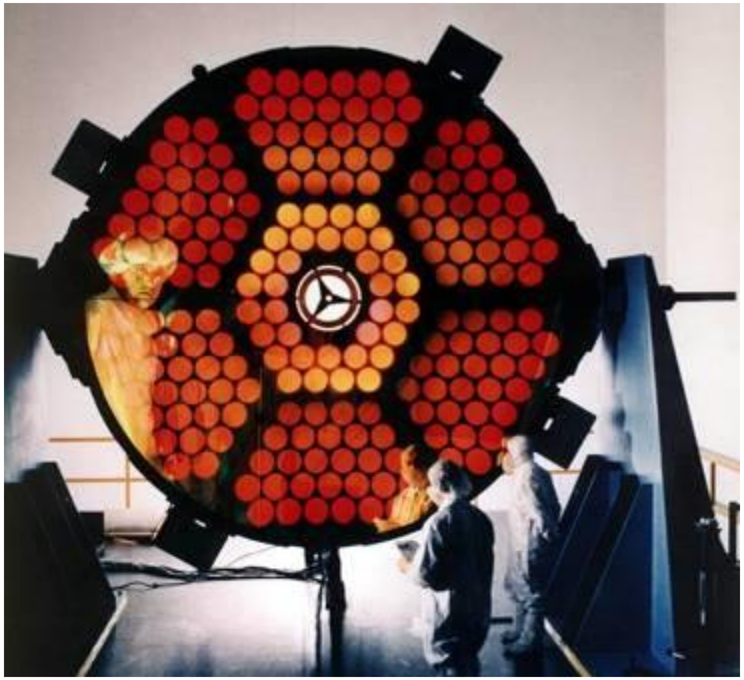
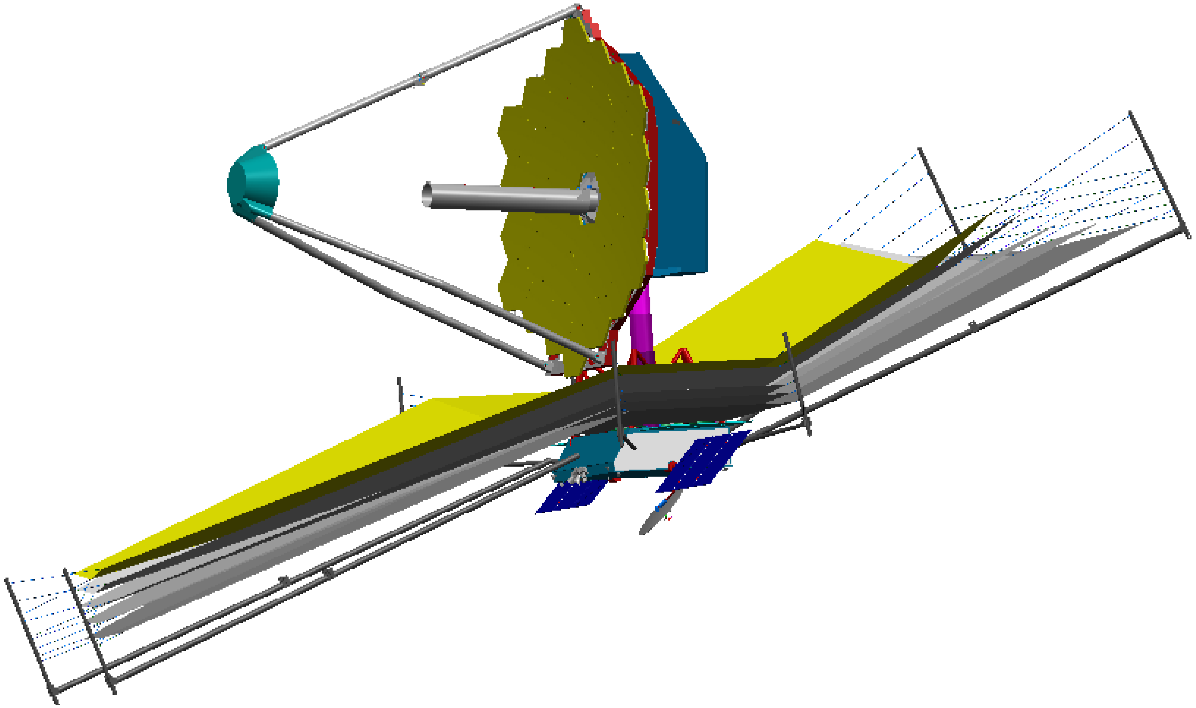
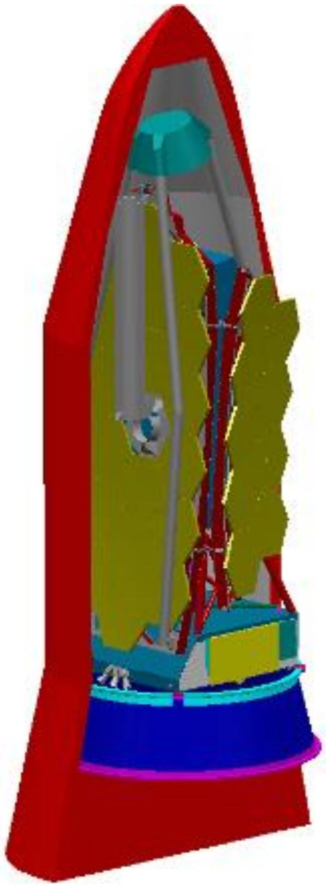


Fig. 12. Facesheet 3 final interferogram



Reference design – TRW/Ball





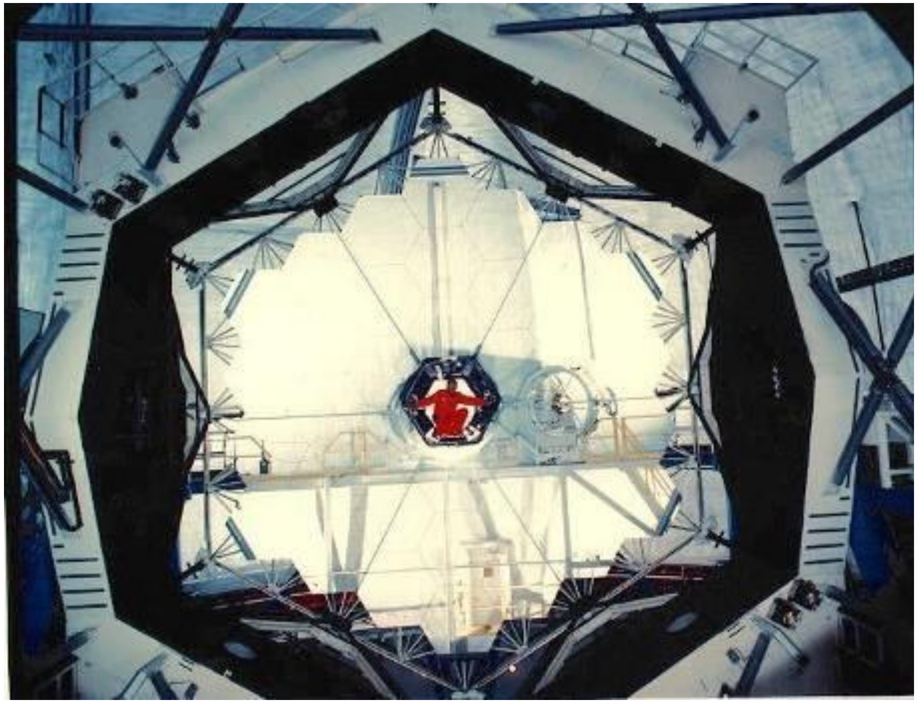
Keck Telescope - 1992

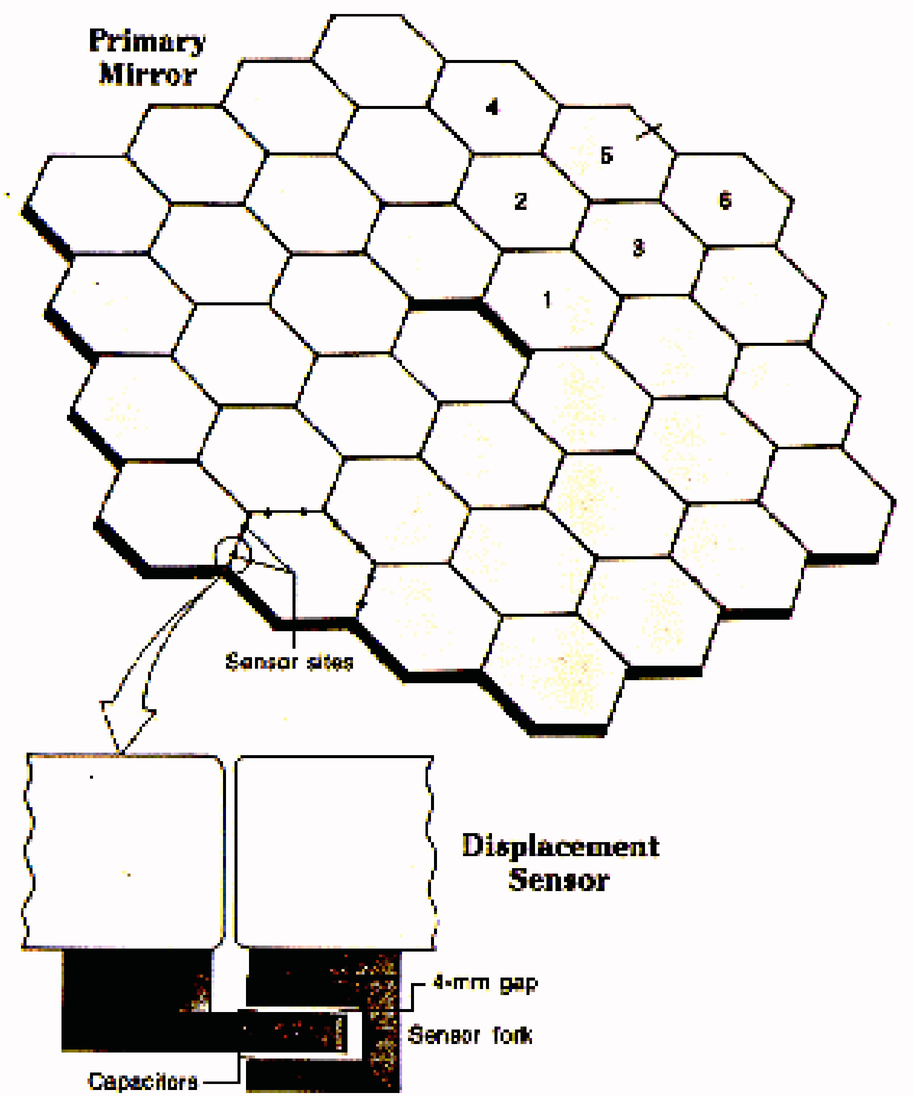
10 meter diameter

36 segments

Capacitance Edge Sensors

Diffraction Limited ~ 10 micrometers





Conclusions from Part 1

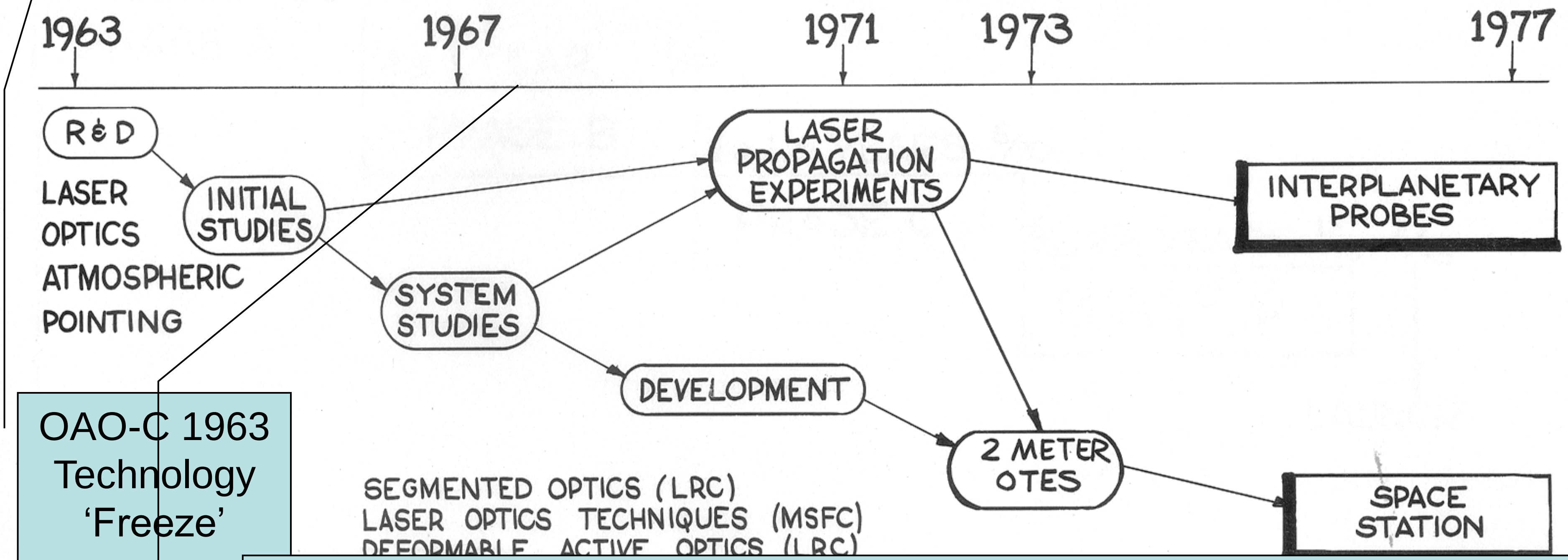
Most Decadal Missions are not implemented ‘exactly’ as they were Recommended.

All Missions undergo extensive Concept Maturation.

All Missions require sustained support from Industry and the Scientific Community.

Technology Development Enables Missions

NASA SPACE OPTICS TECHNOLOGY PLAN



OAO-C 1963
Technology
'Freeze'

Start of
Hubble

"Active Optical Systems for Space Stations", Hugh Robertson, PE, Jan 1968.
"Advanced Optical Figure Sensor Techniques", Robert Crane, PE, Jan 1968
"Advanced Actuator Project", Hugh Robertson, PE, Jan 1968.
"Thermal Vacuum Figure Measurement of Diffraction Limited Mirrors", J. Bartas, PE, Aug 1968
"Silicon Mirror Development for Space Telescopes", David Markle, PE, Aug 1968
"Fabry-Perot Filters for Solar and Stellar Astronomy", David Markle, PE, Aug 1968
"Study of Telescope Maintenance and Updating in Orbit", ITEK, May 1968

PERKIN-ELMER

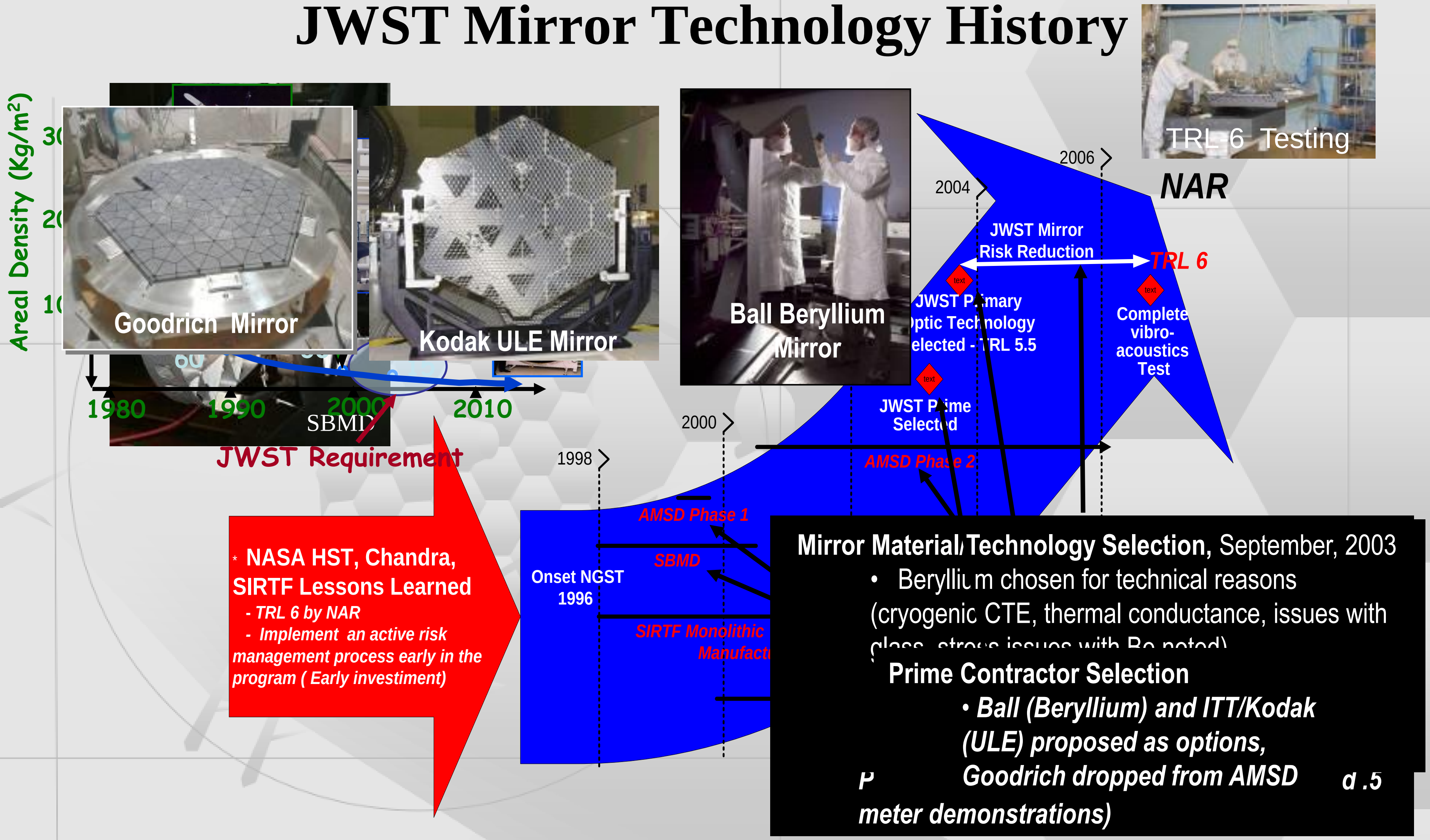
Technical Challenges of NGST

Assessment of pre-1996 state of art indicated that necessary mirror technology (as demonstrated by existing space, ground and laboratory test bed telescopes) was at TRL-3

1996 JWST Optical System Requirements State of Art

Parameter	JWST	Hubble	Spitzer	Keck	LAMP	Units
Aperture	8	2.4	0.85	10	4	meters
Segmented	Yes	No	No	36	7	Segments
Areal Density	20	180	28	2000	140	kg/m2
Diffraction Limit	2	0.5	6.5	10	1.4	micrometers
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

JWST Mirror Technology History



* **NASA HST, Chandra, SIRTF Lessons Learned**

- TRL 6 by NAR

- Implement an active risk management process early in the program (Early investiment)

Mirror Material Technology Selection, September, 2003

- Beryllium chosen for technical reasons (cryogenic CTE, thermal conductance, issues with glass, stress issues with Be noted)

Prime Contractor Selection

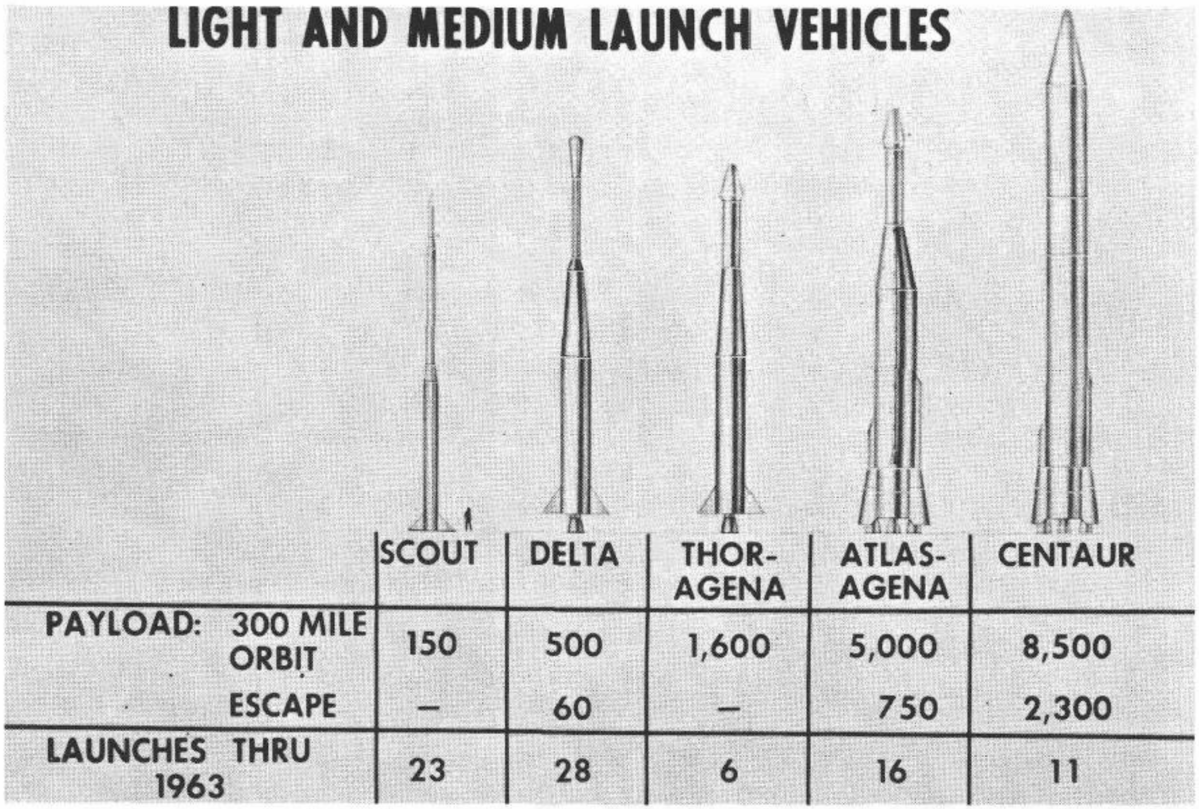
- ***Ball (Beryllium) and ITT/Kodak (ULE) proposed as options, Goodrich dropped from AMSD***

P d .5 meter demonstrations)

Based on lessons learned, JWST invested early in mirror technology to address lower areal densities and cryogenic operations

Technical Challenge: Mass

1962 Available Launch Vehicles



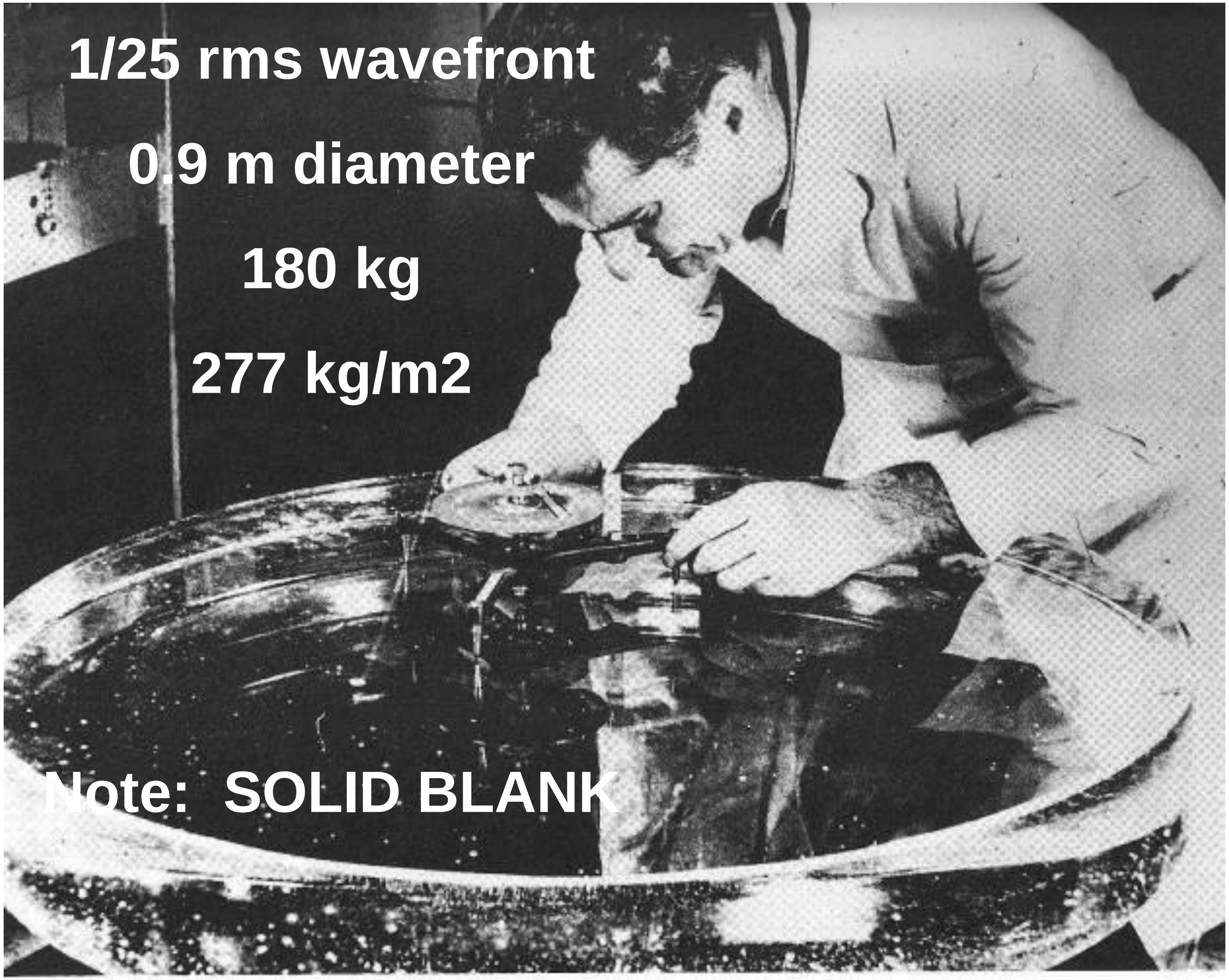
LIGHT AND MEDIUM LAUNCH VEHICLES

	SCOUT	DELTA	THOR-AGENA	ATLAS-AGENA	CENTAUR
PAYLOAD: 300 MILE ORBIT	150	500	1,600	5,000	8,500
ESCAPE	—	60	—	750	2,300
LAUNCHES THRU 1963	23	28	6	16	11

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

Stratoscope II – Primary Mirror



1/25 rms wavefront

0.9 m diameter

180 kg

277 kg/m2

Note: SOLID BLANK

36-Inch Diameter Stratoscope II Mirror
Solid Fused Silica Blank 7940 - Weight 400 Pounds

OAO-B Primary Mirror

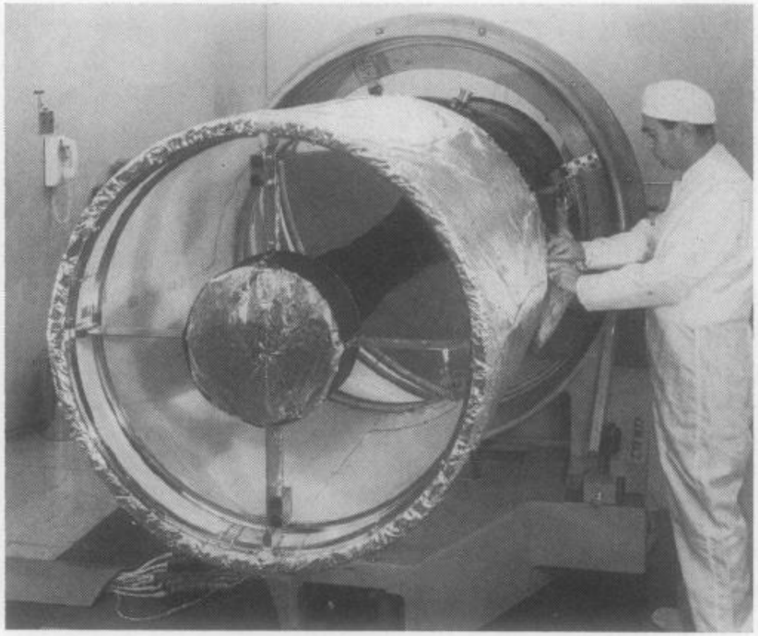


Fig. 1. View of the 38-inch GEP space telescope.

Beryllium (S200B) 95-cm thin meniscus (25:1) substrate with electroless nickel overcoat was fabricated.

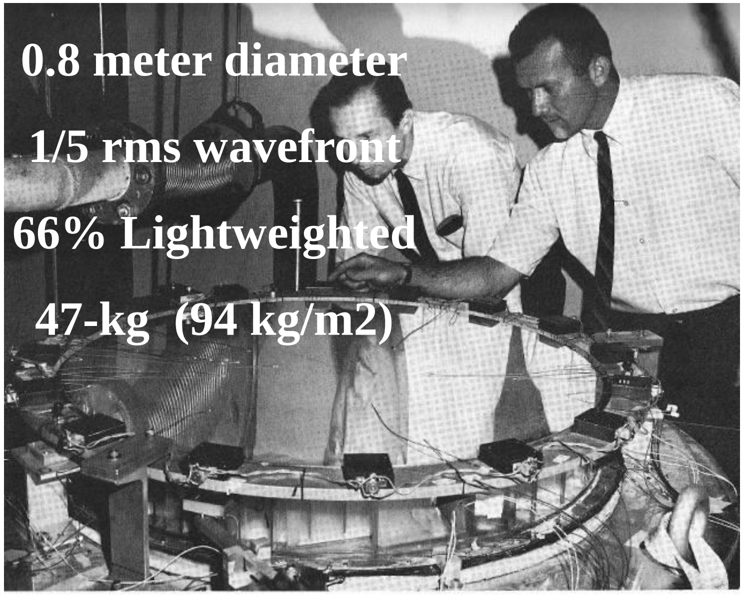
Mass was 57-kg (125-lb) and its areal density was 80-kg/m2.

Stiffness minimized gravity sag

“The Goddard Experiment Package – an Automated Space Telescope”, Mentz and Jackson,, Kollsman Instrument Corp, IEEE Transactions of Aerospace and Electronic Systems, Vol. 5, No. 2, pp. 253, March 1969

OAO-C Primary Mirror

Fig. 4 Primary mirror before coating.



0.8 meter diameter

1/5 rms wavefront

66% Lightweighted

47-kg (94 kg/m2)

32 Inch Diameter OAO-C Princeton University Eggcrate Mirror
(Thermal/Deformation Test Instrumentation)

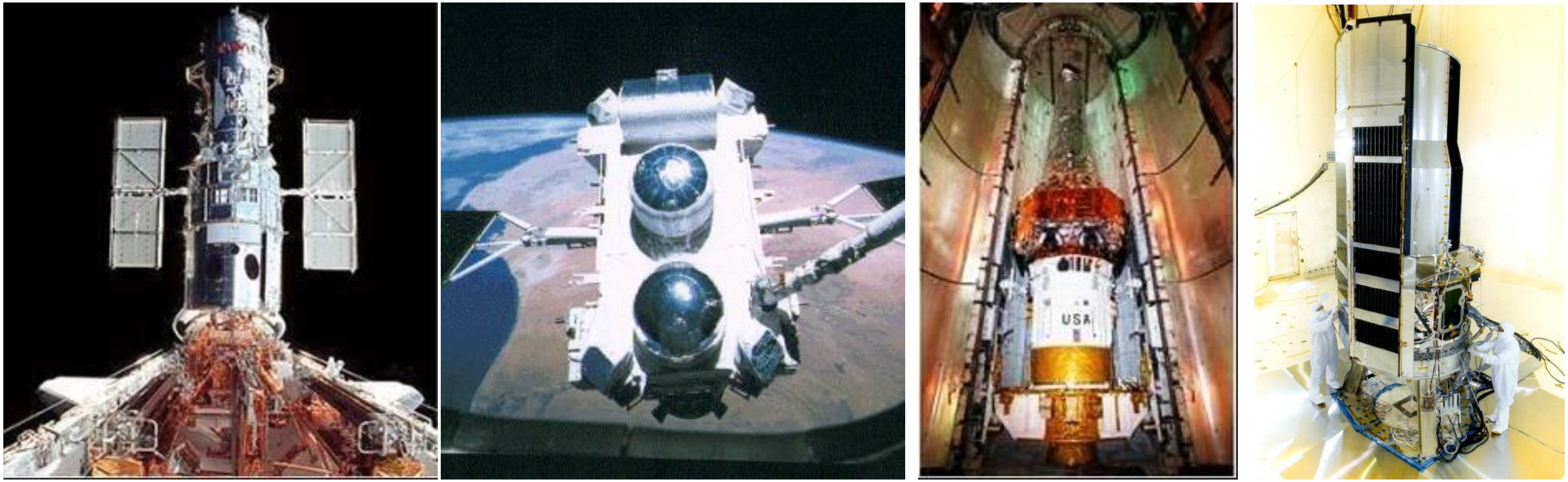
NASA developed lightweight Egg-Crate Fused Silica Mirror Substrates with total mass of 47-kg (areal density 94-kg/m2).

“Princeton Experiment Package for OAO-C”, Norm Gundersen, Sylvania Electric Products Inc., J Spacecraft, Vol. 5, No. 4, pp. 383, April 1968.

Great Observatories designed for Shuttle

Hubble, Compton and Chandra were specifically designed to match Space Shuttle’s payload volume and mass capacities.

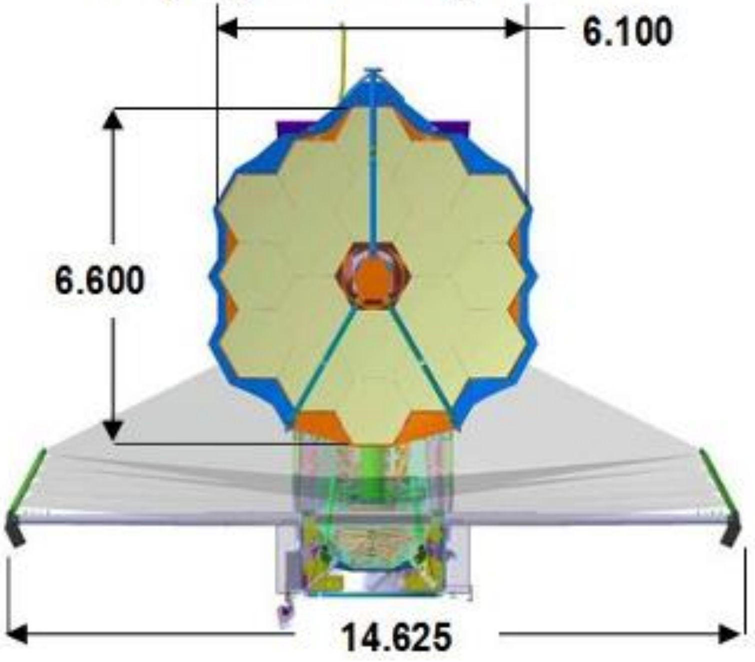
	Launch	Payload Mass	Payload Volume
Space Shuttle Capabilities		25,061 kg (max at 185 km) 16,000 kg (max at 590 km)	4.6 m x 18.3 m
Hubble Space Telescope	1990	11,110 kg (at 590 km)	4.3 m x 13.2 m
Compton Gamma Ray Observatory	1991	17,000 kg (at 450 km)	
Chandra X-Ray Telescope (and Inertial Upper Stage)	2000	22,800 kg (at 185 km)	4.3 m x 17.4 m
Spitizer was originally Shuttle IR Telescope Facility (SIRTF)			



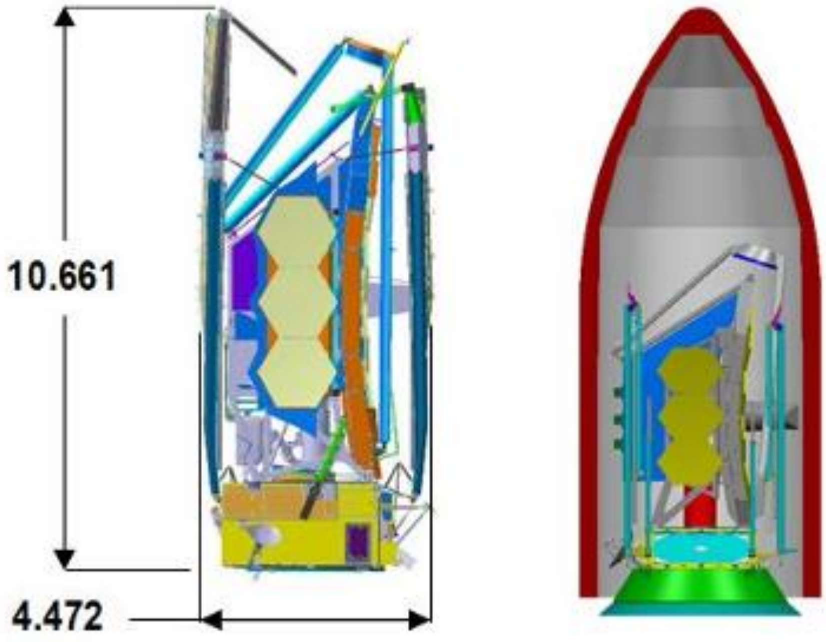
Webb Mass Constrained by Launch Vehicle

	Payload Mass	Payload Volume
Ariane 5	6600 kg (at SE L2)	4.5 m x 15.5 m
James Webb Space Telescope	6530 kg (at SE L2)	4.47 m x 10.66 m

Deployed Configuration



Stowed Configuration

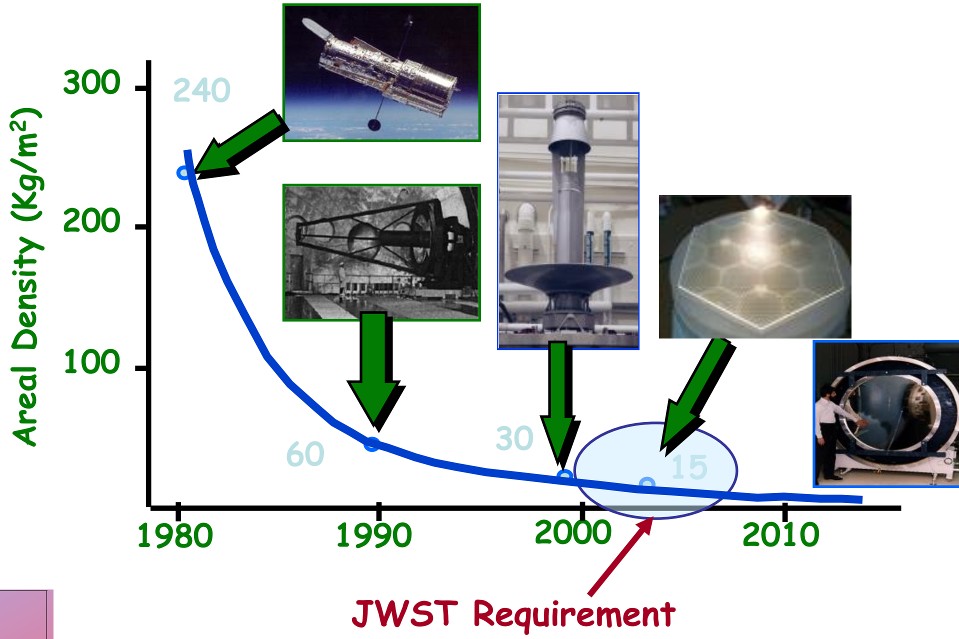


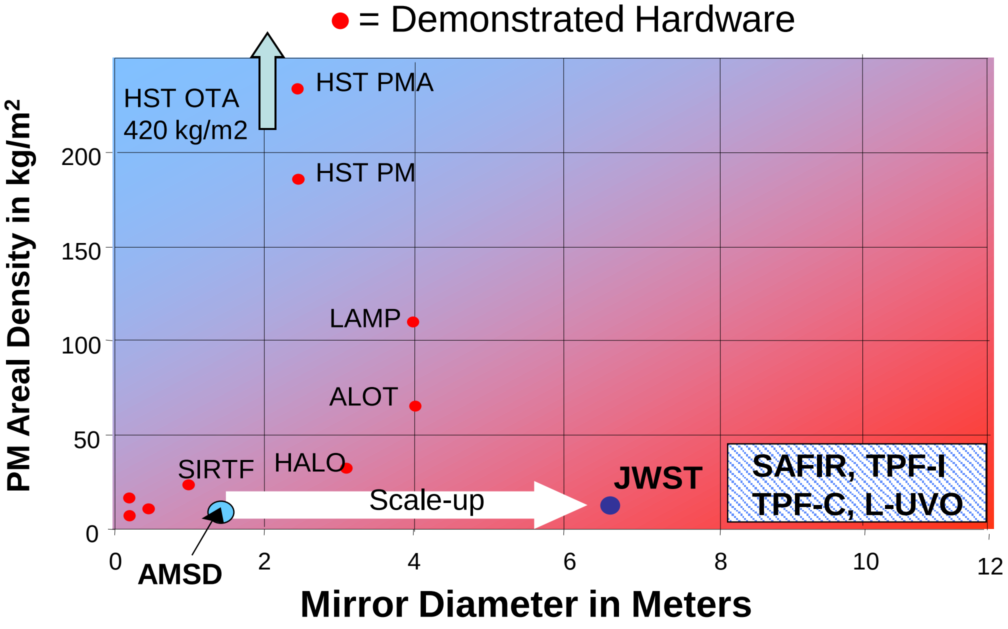
In 1999, driving requirement for NGST were Areal Density, Cost & Schedule

Challenges for Space Telescopes:

Areal Density to enable up-mass for larger telescopes.

Cost & Schedule Reduction.





Primary Mirror	Time &	Cost
HST (2.4 m)	$\approx 1\ \mathrm{m}^2/\mathrm{yr}$	$\approx \$10\mathrm{M/m}^2$
Spitzer (0.9 m)	$\approx 0.3\ \mathrm{m}^2/\mathrm{yr}$	$\approx \$10\mathrm{M/m}^2$
AMSD (1.2 m)	$\approx 0.7\ \mathrm{m}^2/\mathrm{yr}$	$\approx \$4\mathrm{M/m}^2$
JWST (8 m)	$> 6\ \mathrm{m}^2/\mathrm{yr}$	$< \$3\mathrm{M/m}^2$

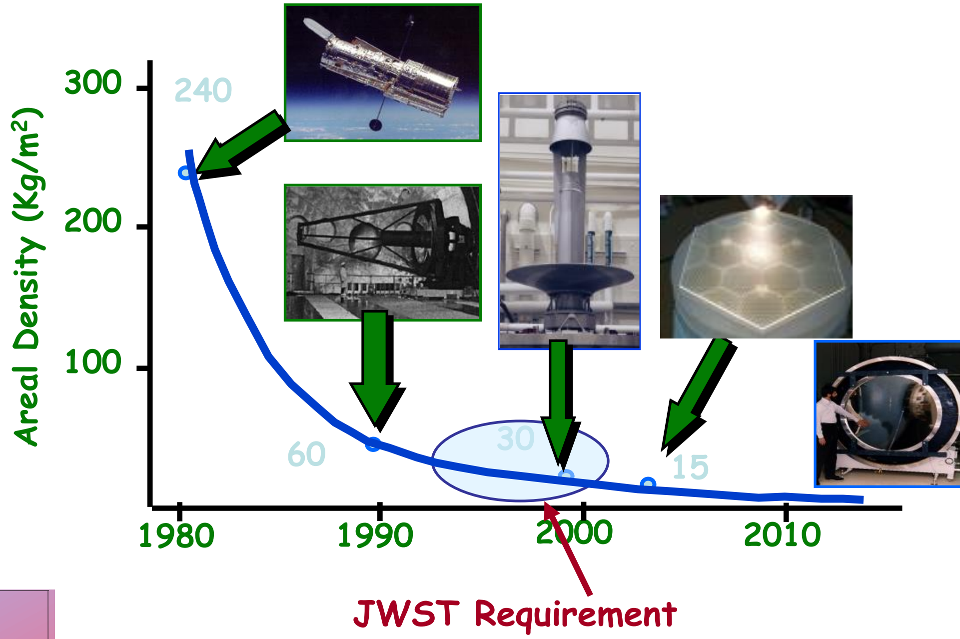
Note: Areal Cost in FY00 $

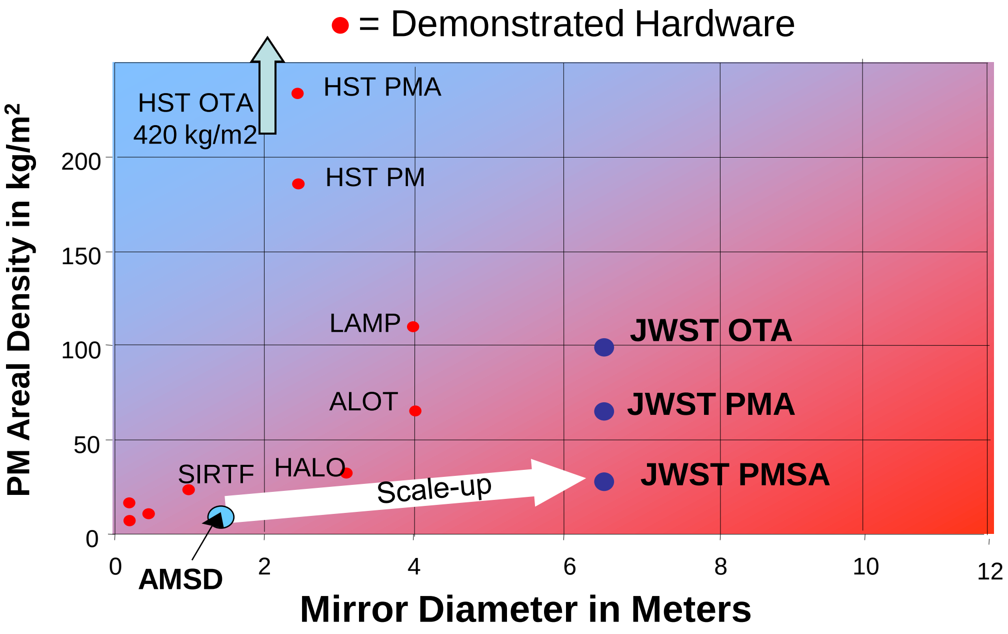
Mirror Technology Lessons Learned 2010

Lessons Learned

Mirror Stiffness (mass) is required to survive launch loads.

Cost & Schedule Improvements are holding but need another 10X reduction for even larger telescopes





Primary Mirror	Time &	Cost
HST (2.4 m)	≈ 1 m²/yr	≈ $12M/m²
Spitzer (0.9 m)	≈ 0.3 m²/yr	≈ $12M/m²
AMSD (1.2 m)	≈ 0.7 m²/yr	≈ $5M/m²
JWST (6.5 m)	≈ 5 m²/yr	≈ $6M/m²

Note: Areal Cost in FY10 $

Technical Challenge: Aperture and Diffraction Limited Performance

National Astronomical Space Observatory (NASO)

Initial Specifications:

- Operated at permanent space station
- Aperture of 3 to 5 meters
- Spectral Range from 80 nm to 1 micrometer
- Diffraction limited at 100 nm (0.006 arc-seconds)
- Interchangeable experiment packages
- Lifetime of 10 years
- Field Coverage = 30 arc min
- Pointing Accuracy of 6 milli-arc second
- Thermal control - -80C +/- 5 C
- Mass (telescope only) = 5500 lb

“Large Telescope Experiment Program (LTEP) Executive Summary”, Alan Wissinger, April 1970

Primary Mirror Material drives Aperture

1963 State of Art: OAO-C Primary Mirror

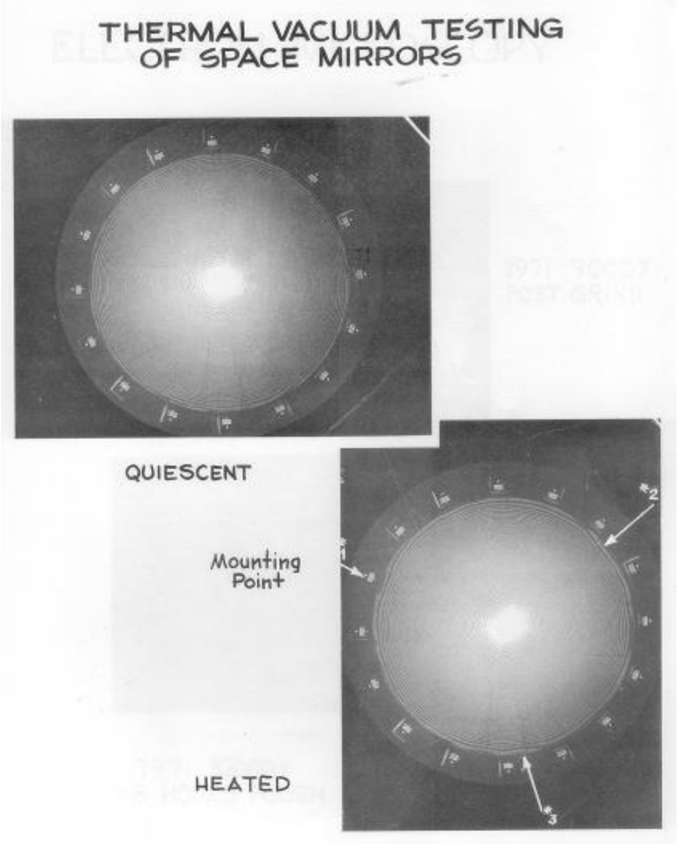
OAO-C Fused Silica Mirror could not achieve LST Spec:

- Aperture = 80-cm
- Not Thermally Stable: CTE = 500 ppb/K

THERMAL VACUUM TESTING OF SPACE MIRRORS

OTES EXPERIMENT 12

INSTRUMENTED OAO MIRROR



THERMAL VACUUM TESTING OF SPACE MIRRORS

QUIESCENT

Mounting Point

HEATED

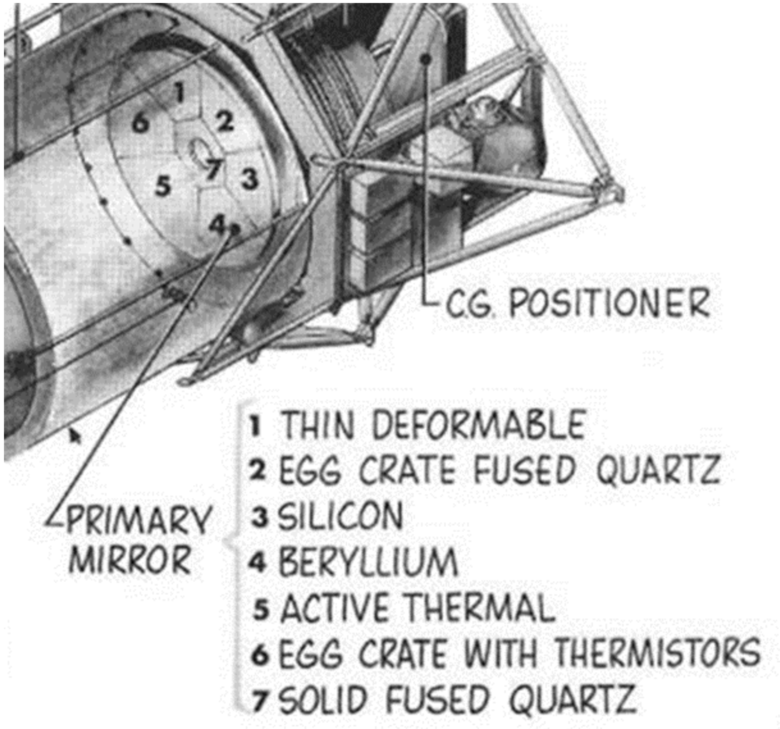
Primary Mirror Technology Development

To over come the challenge of achieving a large-aperture thermally-stable mirror, the LST Program investigated multiple Materials:

- Silicon
- Beryllium
- Fused Silica

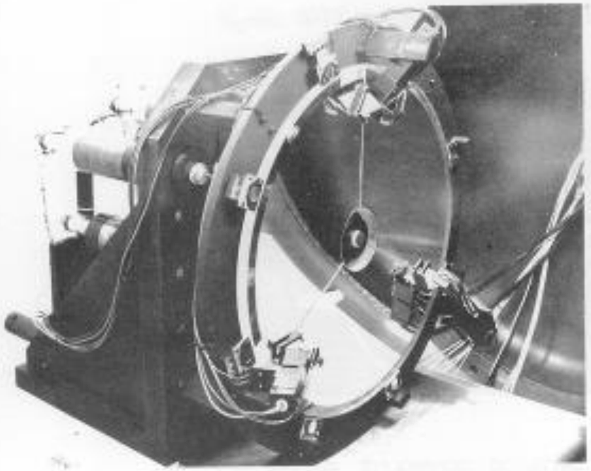
And Architectures:

- Segmented Mirror
- Deformable Mirror
- Active Thermal Control

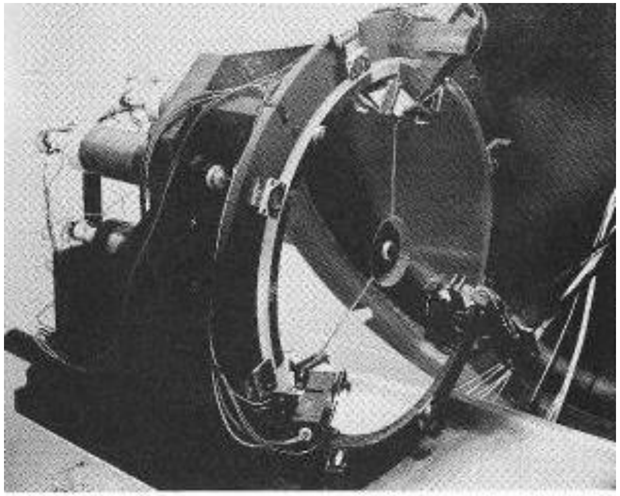


Solution to inability to make a 3-m to 5-m Mirror was Segmentation

SEGMENTED ACTIVE OPTICS



REFER TO
OTES
EXPERIMENT
NO. 1



Segmented Mirror

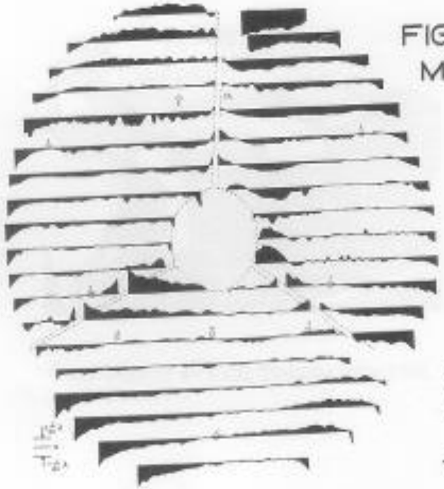


FIGURE ERROR
MEASUREMENT

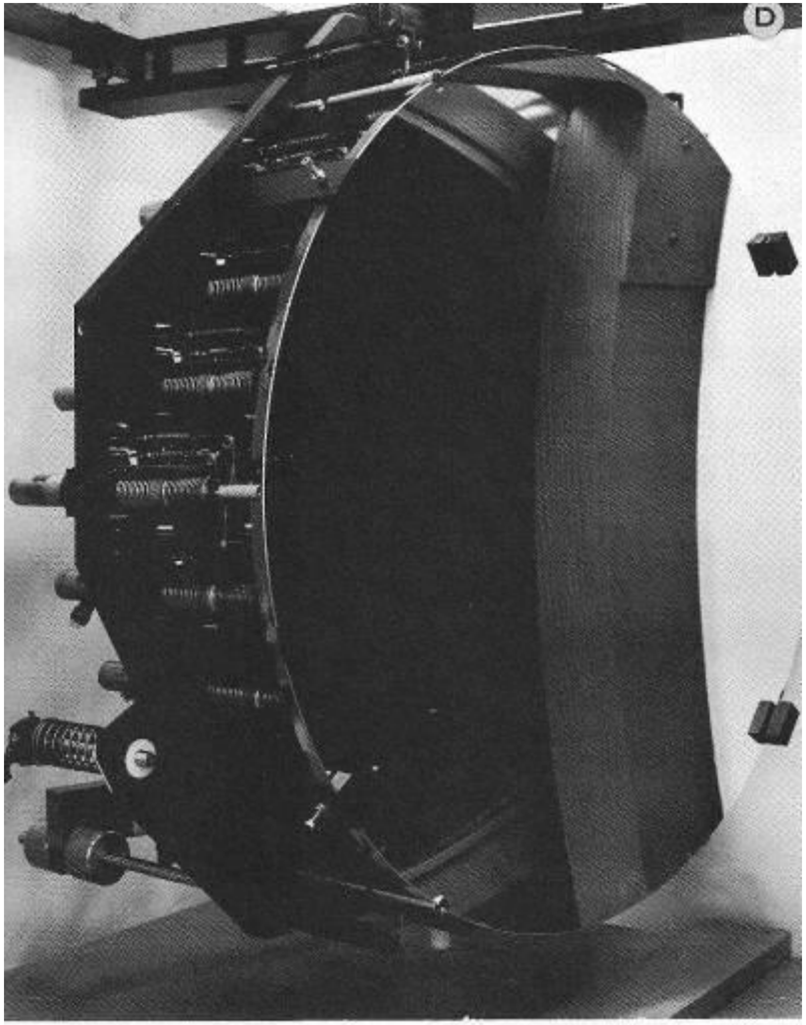
Raster Scan of
Figure Error for Composite
Active Optics Mirror with
Automatic Alignment in
Operation

Figure Error ≈ $\frac{1}{40}\lambda$ rms.

Interferogram of Active Segmented Mirror

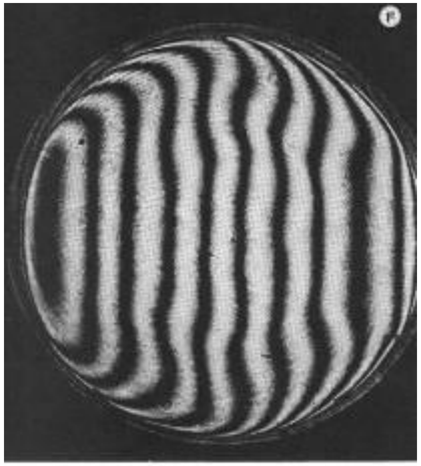
Active Segmented Optics

Solution to Thermal Instability Active Mirror



30 Inch Diameter Thin Deformable Mirror

Thin Deformable Mirror – Before Active
Optics System Activated



Thin Deformable Mirror – During Active
Optics System Operation

Final Solution was …

Solution which enabled a passive monolithic space telescope was

- Development of ‘zero’ CTE materials:
  - Cervit,
  - ULE,
  - Zerodur

- That could be manufactured at 2.4-m scale.

1996 Cryogenic Mirror State of Art

In 1996, Spitzer Telescope represented the state-of-art.

- 85-cm diameter
- 5 micrometer diffraction limit
- I-70 Beryllium

Because I-70 was a mechanically pulverized power with irregular grain shapes, it had limitations:

- CTE was not uniform
- Packing density limited size of billet that could be hipped.

NGST Mirror Technology Development

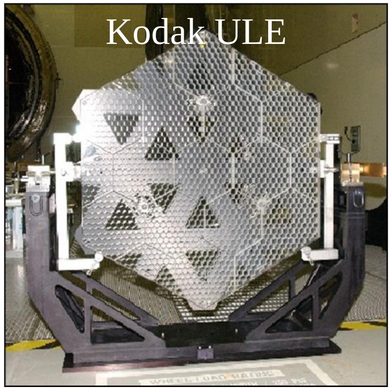
As was done for LST Program, to overcome Size and CTE challenges of I-70 Be, the NGST Mirror Technology Development Program investigated:

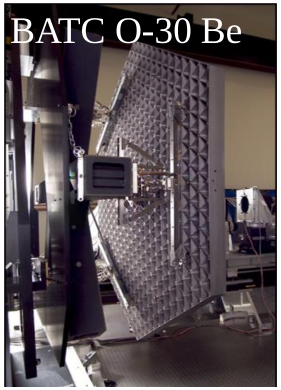
- Mirror Materials
  - O-30 Beryllium, BATC (SBMD, AMSD)
  - ULE®, Kodak (AMSD)
  - Fused Silica, Goodrich (AMSD)
  - Borosilicate, University of Arizona (NMSD)
  - Zerodur/Graphite Composite Hybrid, COI (NMSD)
  - Silicon Carbide, Goodrich (AMSD)


COI Hybrid Mirror


Arizona High Authority Mirror

- CTE Compensation Architectures
  - Cryo-Null Figuring (AMSD)
  - Active Control
    - 16 force actuators, Kodak (AMSD)
    - 37 axial actuators, Goodrich (AMSD)
    - 166 axial actuators, University of Arizona (NMSD)


Kodak ULE


BATC O-30 Be

O-30 Beryllium was selected material for Webb Telescope

O-30 Beryllium enabled Webb

O-30 Be (developed by Brush-Wellman for Air Force in late 1980’s early 1990’s) has significant technical advantages over I-70 (per Tom Parsonage)

Because O-30 is a spherical powder material:

- It has very uniform CTE distribution which results in a much smaller cryo-distortion and high cryo-stability
- It has a much higher packing density, thereby providing better shape control during HIP’ing which allows for the manufacture of larger blanks than what could be produced for Spitzer with I-70.

Because O-30 has a lower oxide content:

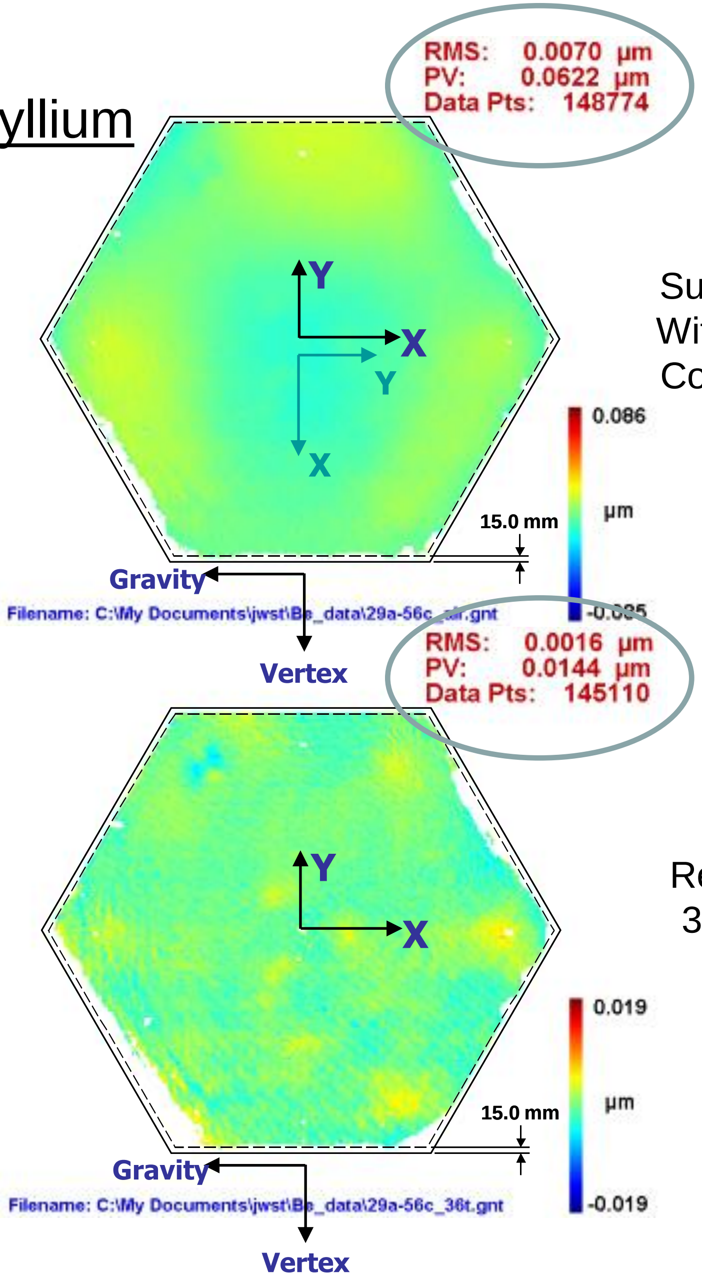
- It provides a surface quality unavailable to Spitzer, both in terms of RMS surface figure and in scatter.

Ability to HIP meter class blanks demonstrated in late 1990’s for VLT Secondary

Full production capability in sufficient quantities for JWST on-line in 1999/2000.

Figure Change: *30-55K Operational Range*

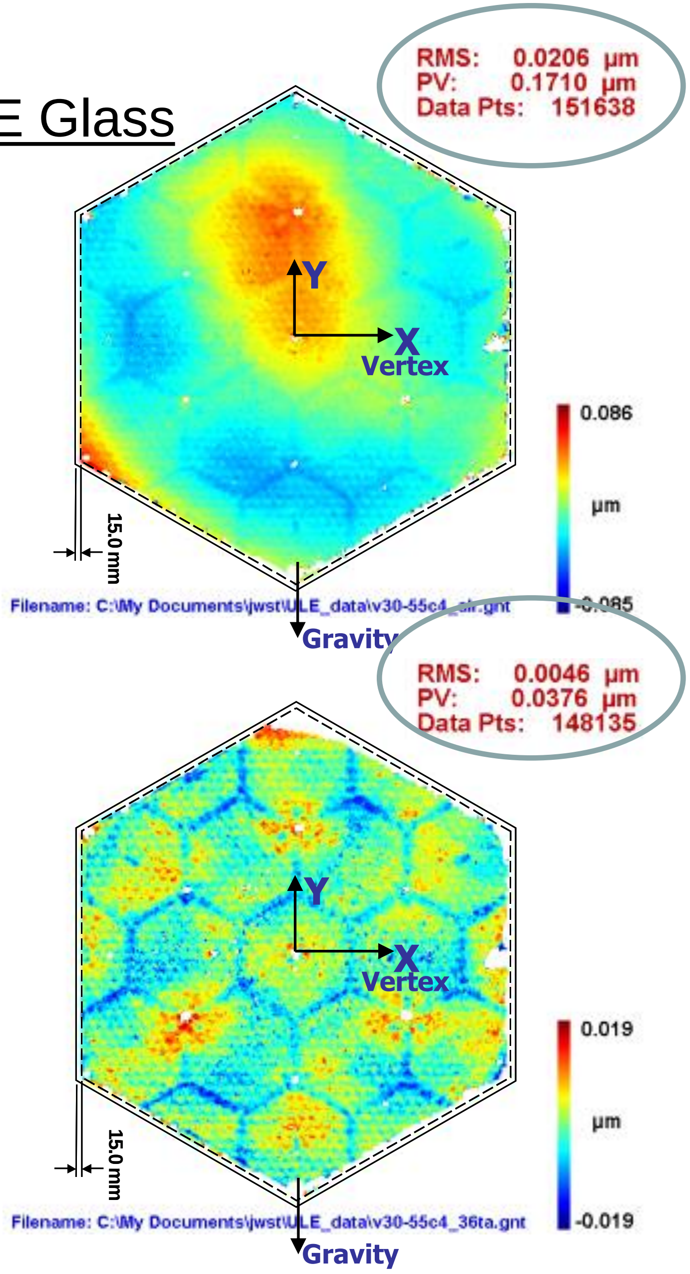
Beryllium



Surface Figure
With Alignment
Compensation

Residual with
36 Zernikes
Removed

ULE Glass

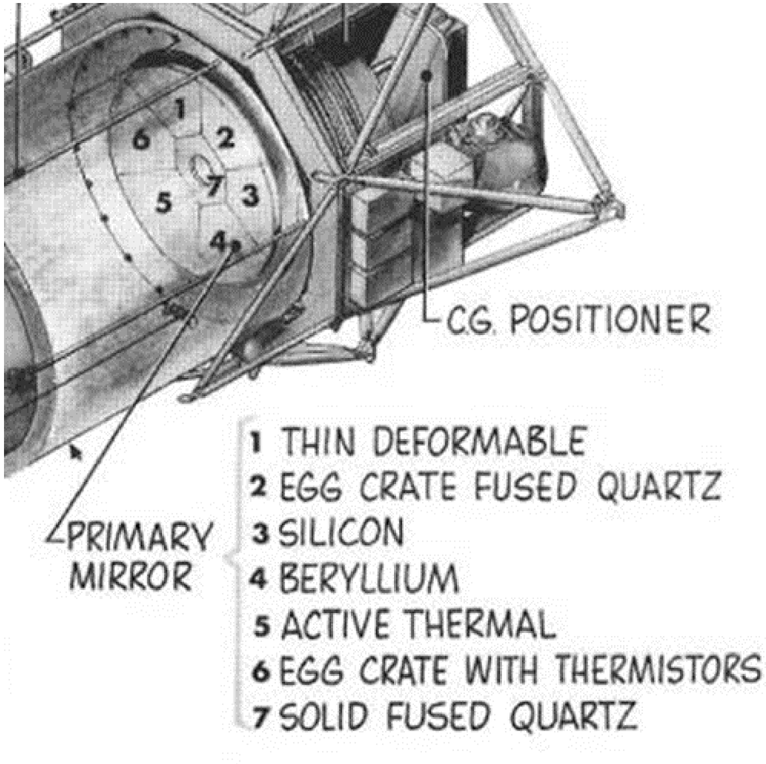


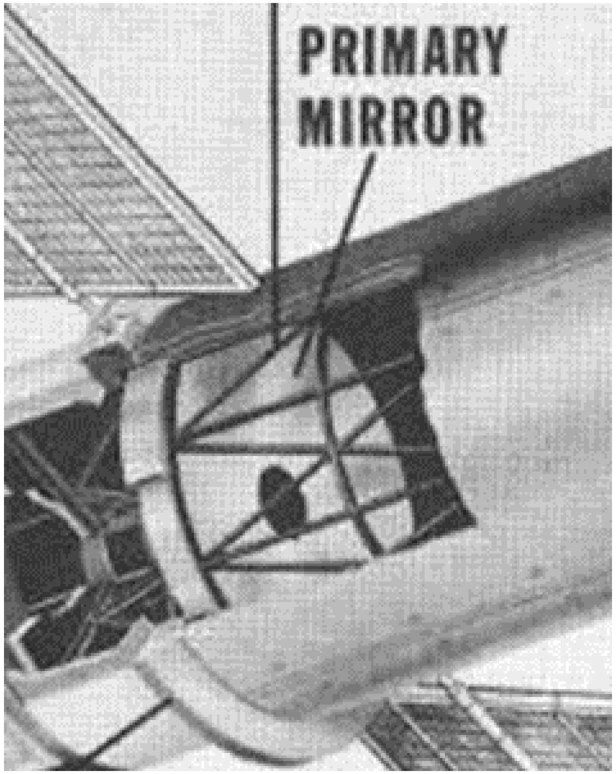
Aperture Diameter

Monolithic vs Segmented

Designers have always traded between segmented and monolithic

Hubble studied multiple segmented options before solving its material and size problem to enable a monolith.





Monolithic vs Segmented

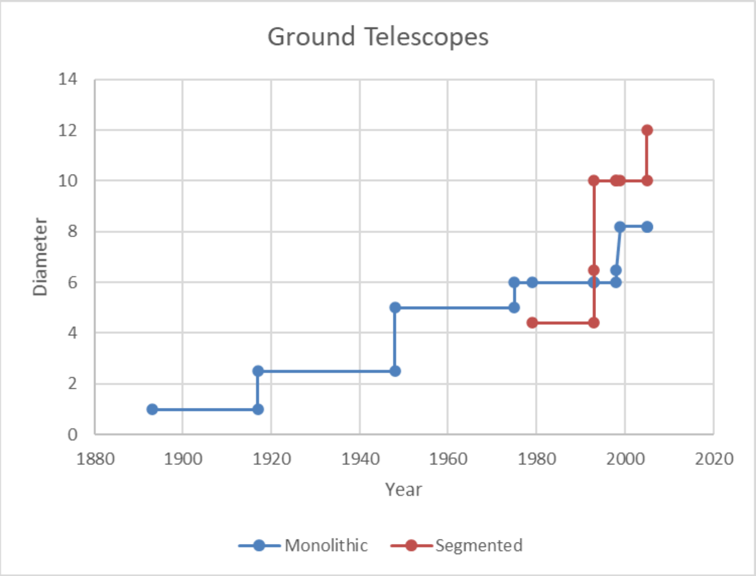
Ground telescopes used monolithic until there was not a way to make a monolithic bigger than 5 or 6m (Hale Telescope).

Solution was segmented primary mirror such as MMT and Keck.

Then Roger Angel showed how to make an 8-m monolithic, and soon both Corning and Schott were also making 8-m mirrors.

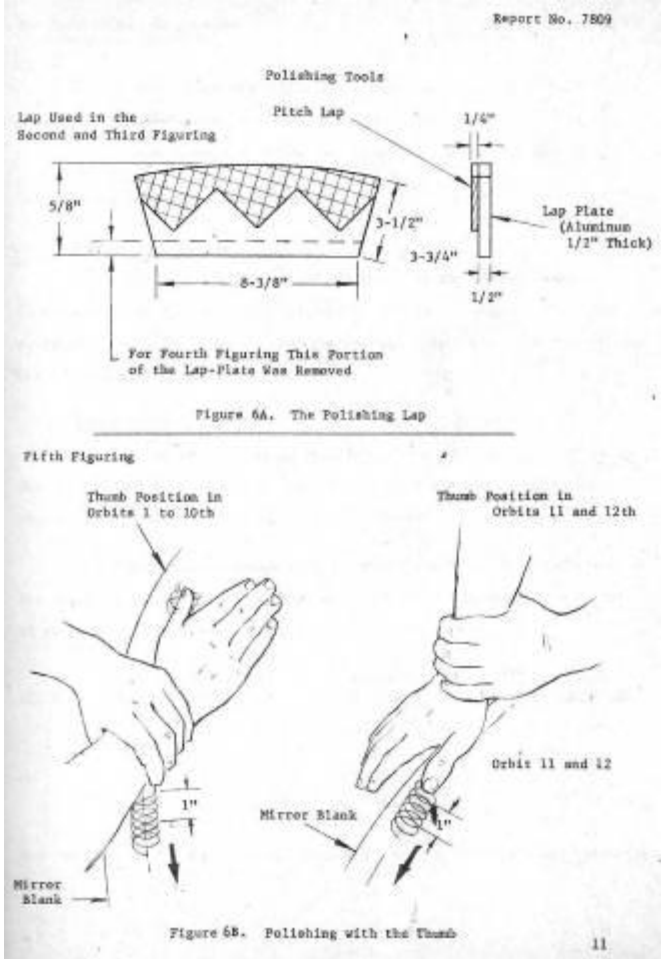
But > 8m requires segments.

Assertion: History indicates that Segmented is only used when Monolithic is not possible.



Technical Challenge: Fabrication Process

Stratoscope II SFE = ~ 10 nm rms



Report No. 7809

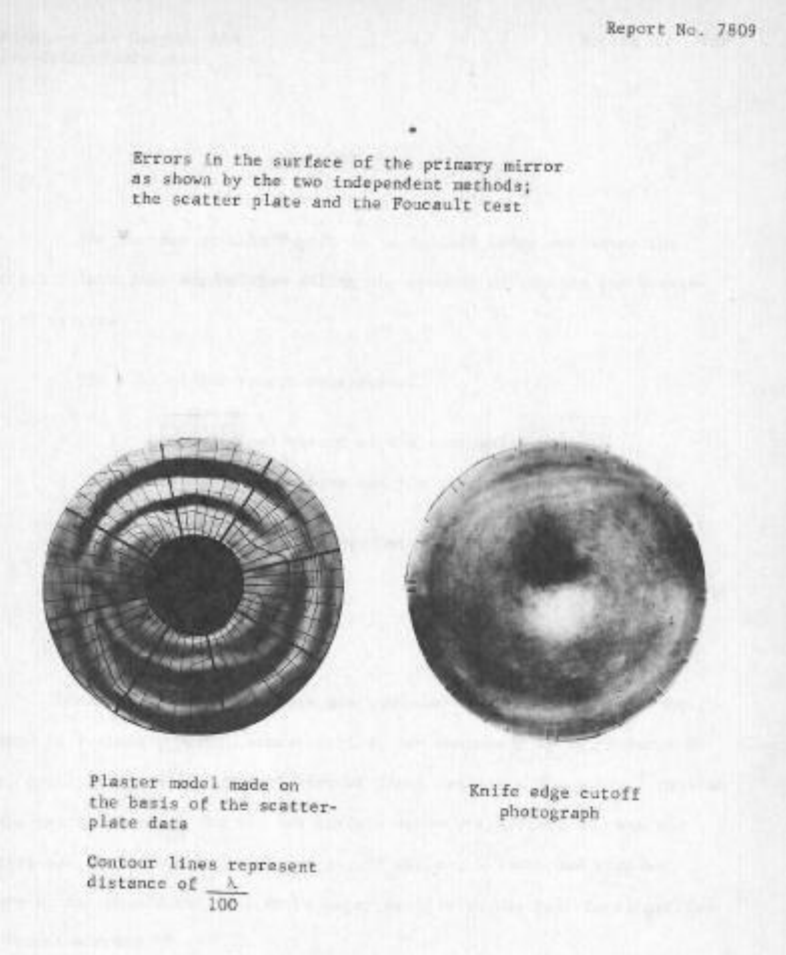
Polishing Tools

Figure 6A. The Polishing Lap

Fifth Figuring

Figure 6B. Polishing with the Thumb

11



Report No. 7809

Errors in the surface of the primary mirror as shown by the two independent methods; the scatter plate and the Foucault test

Plaster model made on the basis of the scatter-plate data

Knife edge cutoff photograph

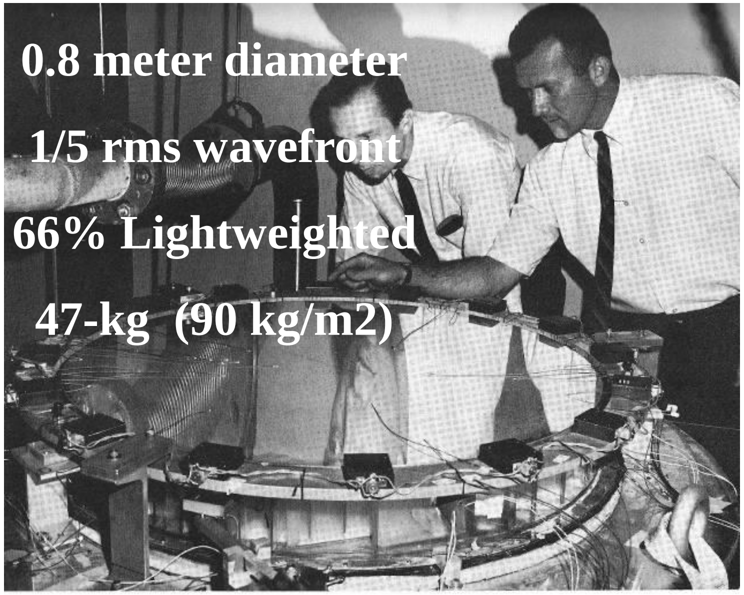
Contour lines represent distance of $\frac{\lambda}{100}$

Classical Fabrication Techniques - Shaped Laps and Hand Figuring

“Test of the Primary and Secondary Mirrors for Stratoscope II”, Damant, Perkin-Elmer, Oct 1964.

OAO-C Primary Mirror SFE = ~ 55 nm rms

Fig. 4 Primary mirror before coating.



0.8 meter diameter

1/5 rms wavefront

66% Lightweighted

47-kg (90 kg/m2)

32 Inch Diameter OAO-C Princeton University Eggcrate Mirror
(Thermal/Deformation Test Instrumentation)

OAO-C Primary Mirror Surface Figure Error = ~ 55 nm rms.

- No where close to UV quality needed for LST
- Probably because of its light-weighted low-stiffness substrate

"Princeton Experiment Package for OAO-C", Norm Gundersen, Sylvania Electric Products Inc., J Spacecraft, Vol. 5, No. 4, pp. 383, April 1968.

Hubble Primary Mirror Fabrication 1979-81

Start of Small Tool Computer Controlled Polishing

Spitzer Mirror Fabrication

PM used Large and Small Tool Computer Controlled Polishing

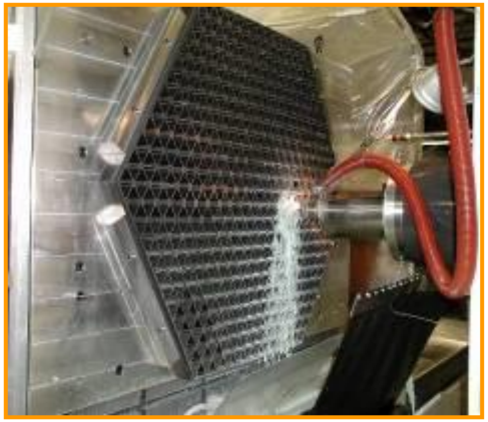
SM used Full Aperture Shaped Laps and Zonal Laps

JWST Mirror Manufacturing Process

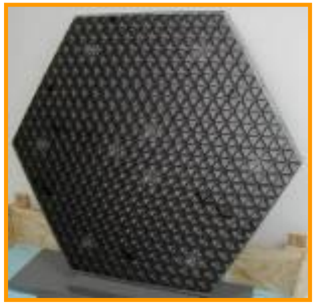
Blank Fabrication


HIP Vessel being loading into chamber

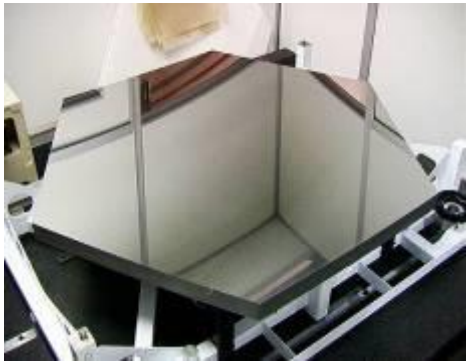
Machining


Machining of Web Structure


Machining of Optical Surface


Completed Mirror Blank

Polishing



Mirror System Integration

Optical Testing

you cannot make what you cannot measure

Optical Testing

The quality to which one can make a telescope depends largely on the precision to which the primary mirror can be tested.

Key challenges include:

- Atmospheric Turbulence
- Mechanical Vibrations
- G-Release Error

Stratoscope II and OAO-C

Once solution to atmospheric turbulence & mechanical vibration is to use a Common Path Interferometer

Scatterplate Interferometer

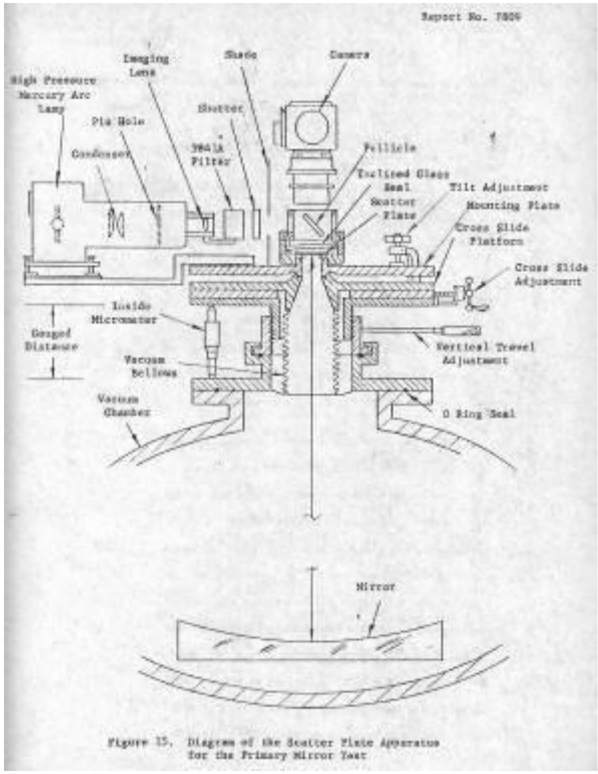


Figure 15. Diagram of the Scatter Plate Apparatus for the Primary Mirror Test

Fringe Scanning Digitizer

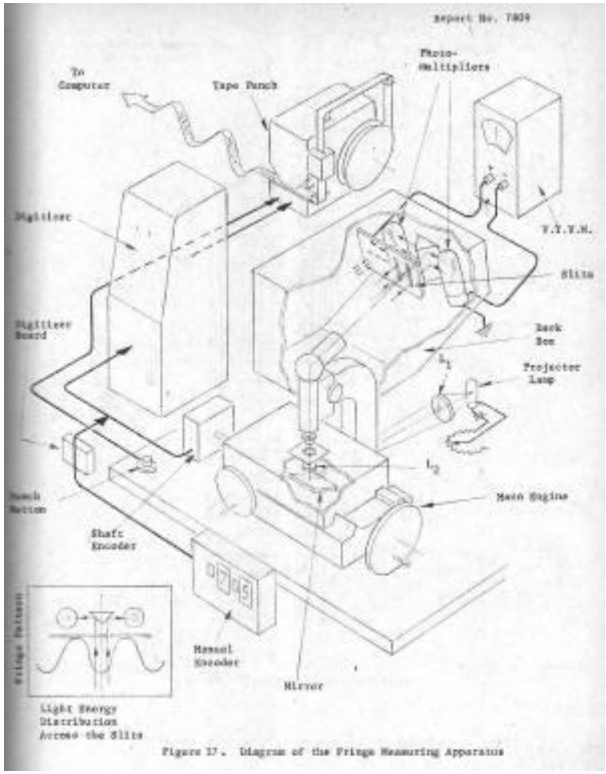


Figure 17. Diagram of the Fringe Measuring Apparatus

Testing support from J.M. Burch, A. Offner, J.C. Buccini and J. Houston

“Test of the Primary and Secondary Mirrors for Stratoscope II”, Damant, Perkin-Elmer, Oct 1964.

Hubble Testing

Another solution is to eliminate the atmosphere.

Hubble optical testing (at Perkin-Elmer) was performed in a vertical vacuum chamber (called the ‘ice-cream cone’)

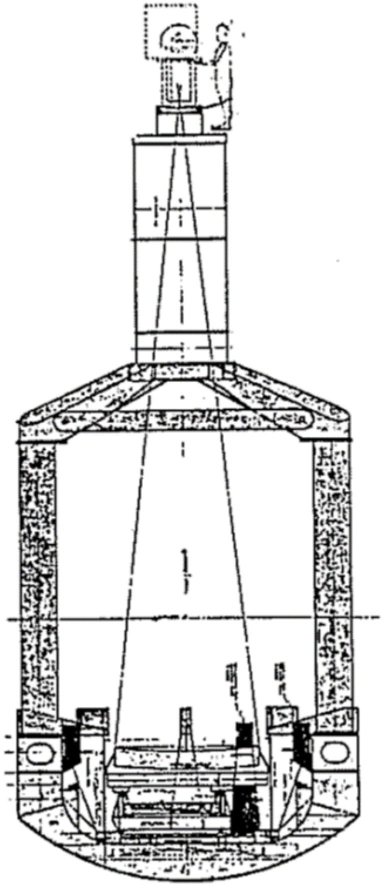


Figure 2. Primary mirror test configuration.

Montagnino, Lucian A., “Test and evaluation of the Hubble Space Telescope 2.4 meter primary mirror”, SPIE Vol. 571, pp. 182, 1985.

Hubble Testing

And, to eliminate mechanical vibration – use short exposure time.

Hubble optical testing (at both Perkin-Elmer and Kodak) was performed with custom interferometers taking dozens of film images which were digitized to produce a surface map.

- Camera Shutter Speed 'freezes' vibration/turbulence
- PE used custom micro-densitometer and Kodak manually digitized

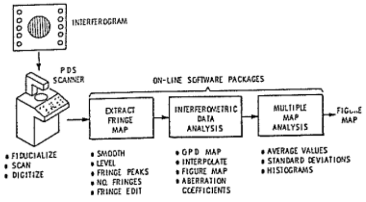


Figure 14. Interferogram analysis facility.

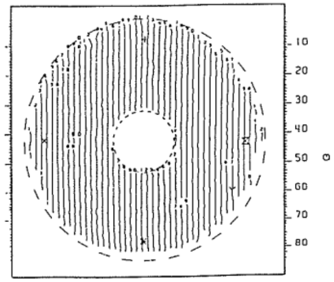
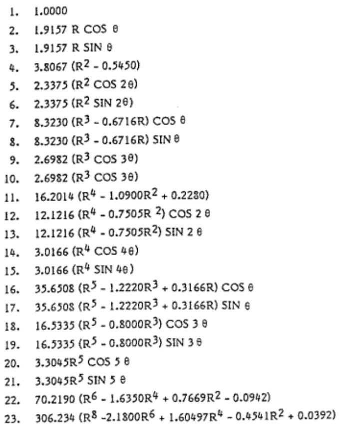


Figure 15. Fringe map.



1. 1.0000
2. $1.9157\ R\ \cos\theta$
3. $1.9157\ R\ \sin\theta$
4. $3.8067\ (R^2 - 0.5450)$
5. $2.3375\ (R^2 \cos 2\theta)$
6. $2.3375\ (R^2 \sin 2\theta)$
7. $8.3230\ (R^3 - 0.6716R) \cos\theta$
8. $8.3230\ (R^3 - 0.6716R) \sin\theta$
9. $2.6982\ (R^3 \cos 3\theta)$
10. $2.6982\ (R^3 \cos 3\theta)$
11. $16.2014\ (R^4 - 1.0900R^2 + 0.2280)$
12. $12.1216\ (R^4 - 0.7505R^2) \cos 2\theta$
13. $12.1216\ (R^4 - 0.7505R^2) \sin 2\theta$
14. $3.0166\ (R^4 \cos 4\theta)$
15. $3.0166\ (R^4 \sin 4\theta)$
16. $35.6508\ (R^5 - 1.2220R^3 + 0.3166R) \cos\theta$
17. $35.6508\ (R^5 - 1.2220R^3 + 0.3166R) \sin\theta$
18. $16.5335\ (R^5 - 0.8000R^3) \cos 3\theta$
19. $16.5335\ (R^5 - 0.8000R^3) \sin 3\theta$
20. $3.3045R^5 \cos 5\theta$
21. $3.3045R^5 \sin 5\theta$
22. $70.2190\ (R^6 - 1.6350R^4 + 0.7669R^2 - 0.0942)$
23. $306.234\ (R^8 - 2.1800R^6 + 1.60497R^4 - 0.4541R^2 + 0.0392)$

Figure 16. Annular Zernike polynomials for 0.3 obscuration.

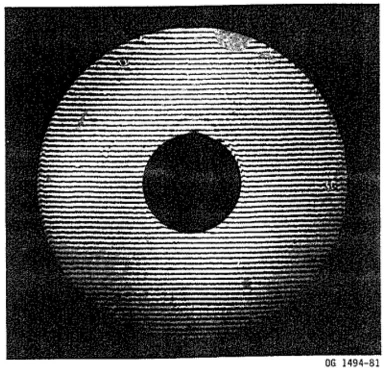


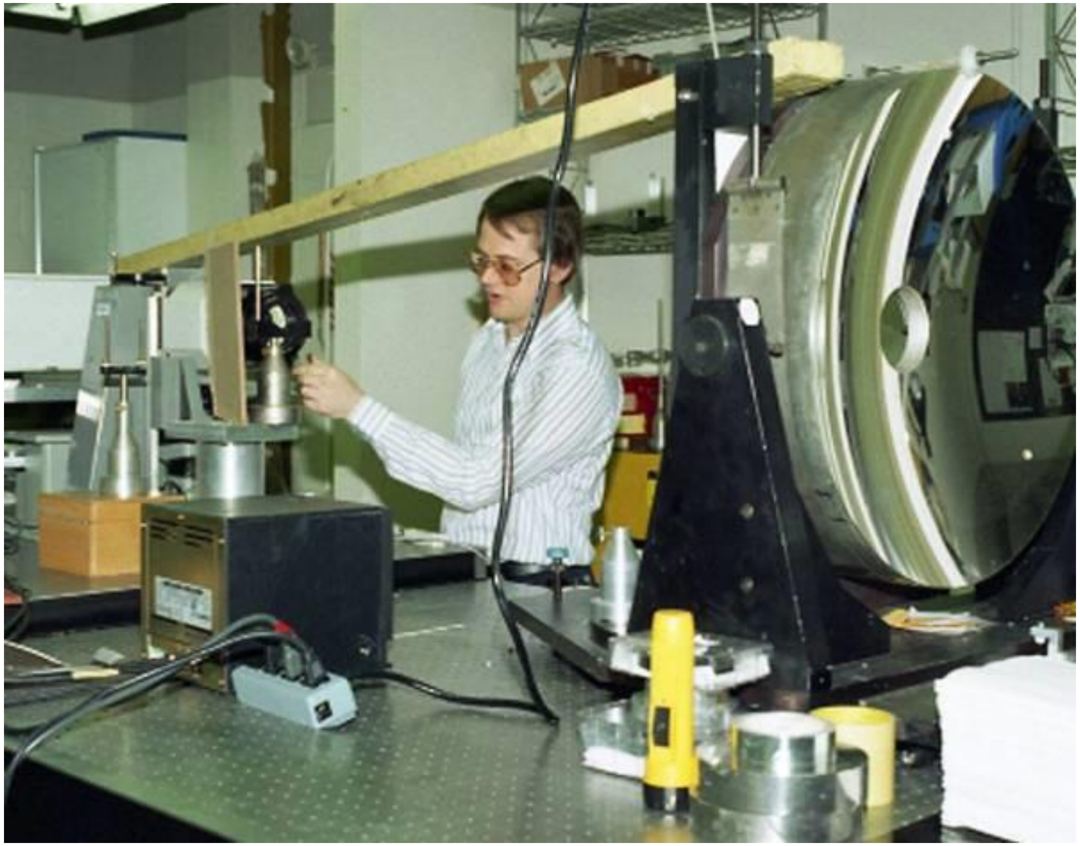
Figure 17. Interferogram of finished primary mirror masked to its clear aperture.

Hubble Primary Mirror was tested to better than 8 nm rms.

Montagnino, Lucian A., "Test and evaluation of the Hubble Space Telescope 2.4 meter primary mirror", SPIE Vol. 571, pp. 182, 1985.

Spitzer Secondary Mirror Testing

Another solution is to structurally connect interferometer & test.

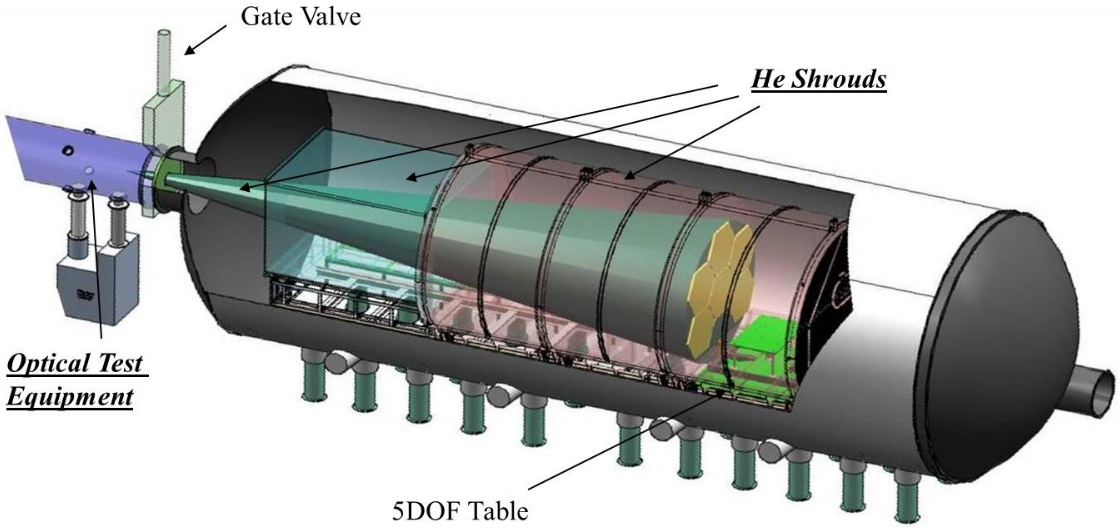


Spitzer (ITTT) Secondary Mirror Hindle Sphere Test using a Zygo GPI with Remote PMR Head (1997).

NGST

In 1999, the NGST program had a problem. How to test a 1.5-m class mirror with high-spatial resolution at 30K inside a vacuum chamber with an uncertainty of ~ 10 nm rms.

PROBLEM: because of ‘hot-dog’ bending mode of the ‘building’, Mirrors and interferometer had 4 micrometer of relative mechanical motion.



Cryo-Vacuum Chamber is 7 m dia x 23 m long

1999 Metrology State of Art

The state of the art was temporal shift phase-measuring interferometers, e.g. Zygo GPI and Wyko.

Spatial resolution was acceptable, but mechanical vibration made temporal phase-modulation impossible.

But this problem is nothing new ….. similar to Keck Testing

Keck Mirror Segment Testing

In 1987, Itek had a problem testing the Keck mirror segments.

To eliminate atmospheric turbulence over a 48-m air-path, tried using a real-time phase-shifting shearing (common-path) interferometer.

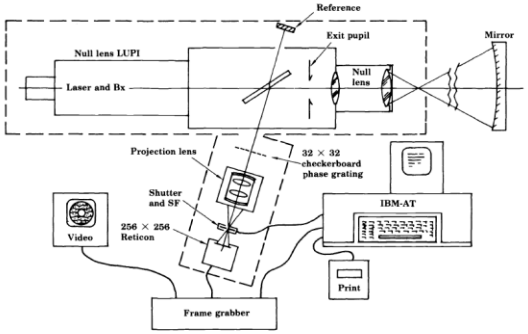


Figure 1. Real-time snapshot interferometer.

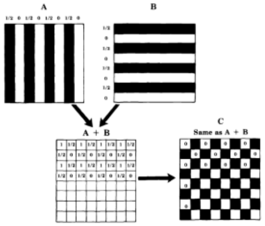


Figure 2. Half-wave checkerboard grating.

Solution was 340 Hz high-speed interferometer where reference & test beams co-propagated.

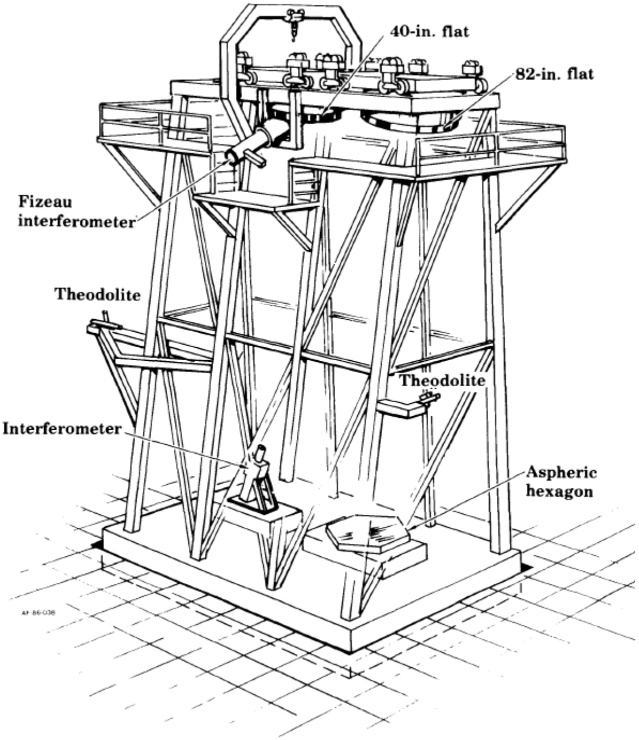


Figure 7. The autocollimation test facility

Evan Stryjewski, R J Zielinski, J T Smith, "Testing The Primary Mirror Of The W. M. Keck Observatory," Proc. SPIE 0680, Surface Characterization and Testing, (23 March 1987); doi: 10.1117/12.939592

Joseph L McLaughlin, Bruce A Horwitz, "Real-Time Snapshot Interferometer,“ Proc. SPIE 0680, Surface Characterization and Testing, (23 March 1987); doi: 10.1117/12.939589

H. Philip Stahl, “Testing Large optics: High-Speed Phase-Measuring Interferometry”, Photonics Spectra, Dec 1989.

PhaseCAM

As I prepared to leave Danbury for NASA, I was visiting Metrolaser where I saw a breadboard device taking phase-maps of a candle flame.

When I got to NASA, I defined the specifications for and ordered the first PhaseCAM interferometer.

They were enabling for Webb.

Tech Days 2001

G-Release Error

Because space mirrors are made in a 1-G, their gravity sag must be ‘backed-out’.

G-release error is error in this process.

Gravity off-loading is typically done via:

- Multipoint Mount
- Air Bag Support

Or Gravity Sag can be measured via a rotation test.

- Webb primary mirror segments were tested to an uncertainty of less than 10 nm rms using a 6-rotation tests

Gravity Off-Loading

Multi-point metrology mount technology was developed with NASA funding in the 1970s for the Large Space Telescope Program (Hubble).

Hubble primary mirror’s mounted 7.6 micrometer PV self-weight deflection was characterized to an accuracy of 1.4 nm rms using a 135-point metrology mount.

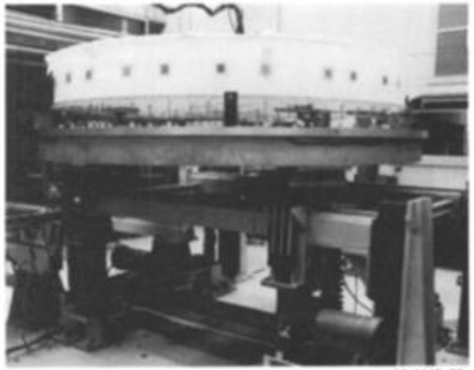


Figure 3. Primary mirror metrology mount.

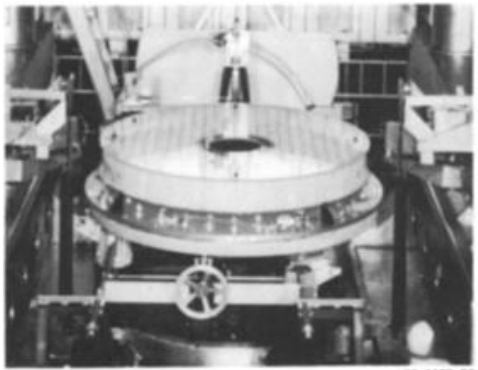
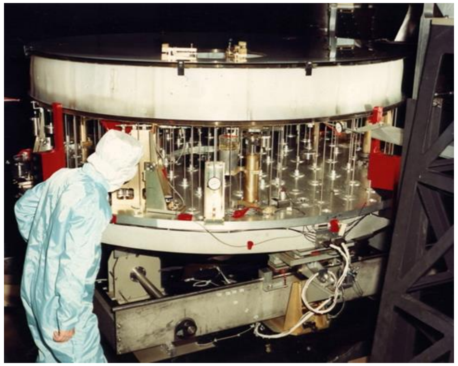


Figure 4. Primary mirror/mount assembly on six-degree-of-freedom table.



Montagnino, Lucian A., "Test And Evaluation Of The Hubble Space Telescope 2.4-meter Primary Mirror," Proc. SPIE 0571, Large Optics Technology, (21 February 1986)

Yoder, Paul and Danial Vukobratovich, Opto-Mechanical Systems Design, Fourth Edition, Two Volume Set, CRC, 2015 ISBN-10: 1439839778

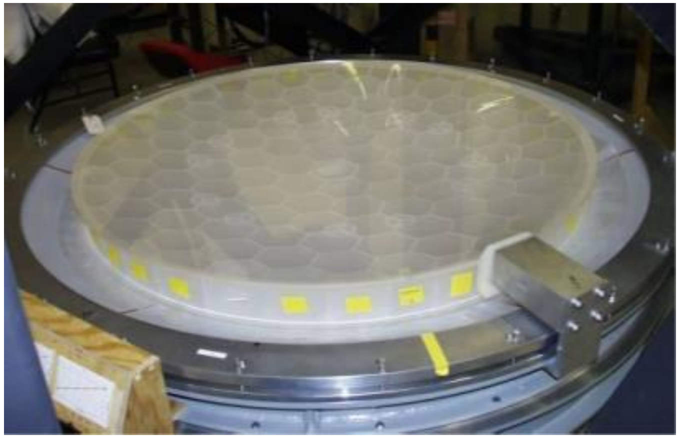
https://www.hexagonkh9.com/blog/2019/1/19/hexagon-looked-at-the-earth-the-hubble-looked-at-the-stars

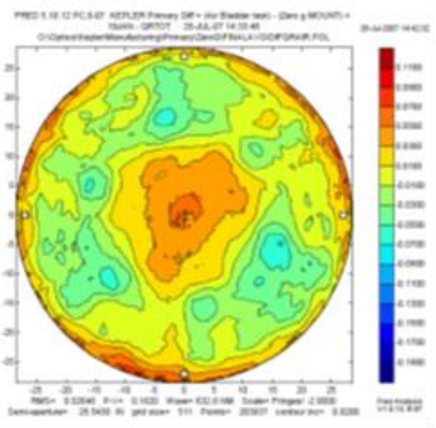
Kepler Primary Mirror

Kepler 1.4-m primary mirror was tested using both an air bag and a 108-point mount.

The air bag was estimated to off-load gravity sag with an uncertainty of 5.6 nm rms.

Difference between air bag test and multi-point mount test was 16.4 nm rms (mostly spherical aberration).





Zinn, John W., George W. Jones, "Kepler primary mirror assembly: FEA surface figure analyses and comparison to metrology," Proc. SPIE 6671, Optical Manufacturing and Testing VII, 667105 (14 September 2007)

Conclusions

History Can Inform GOMaP and AOA

- Most Decadal Missions are not implemented ‘exactly’ as they were Recommended.
- All Missions undergo extensive Concept Maturation.
- All Missions have the same basic Technology Challenges.
  - Design & Build a Space Telescope that achieves required Performance:
    - Mass Constraint
    - Mechanical & Thermal Stability
    - Manufacture and Test
    - Performance Modeling and Validation – Model Correlation
- Successful Missions require Robust Technology Development
- Successful Missions require Sustained Community Support

Any Question?