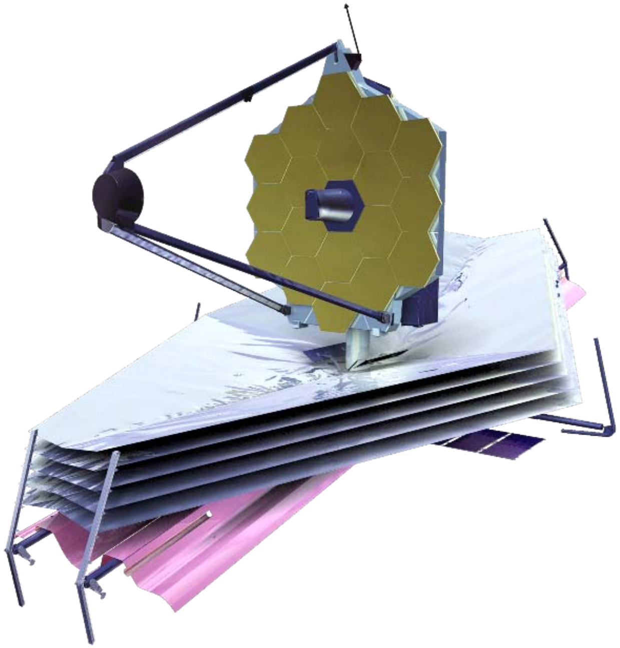
50 years of Mirror Technology Investment at NASA:

from Hubble to JWST and Beyond



H. Philip Stahl, Ph.D.
NASA

- 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

Presidential Vision

"… both optical and radio astronomy … new fields of interest have been uncovered – notably in the high energy x-ray and gamma-ray regions. Astronomy is advancing rapidly at present, partly with the aid of observations from space, and a deeper understanding of the nature and structure of the Universe is emerging … <u>Astronomy has a far greater potential for advancement by the space program than any other branch of physics</u>".

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

Presidential Vision

"… both optical and radio astronomy … new fields of interest have been uncovered – notably in the high energy x-ray and gamma-ray regions. Astronomy is advancing rapidly at present, partly with the aid of observations from space, and a deeper understanding of the nature and structure of the Universe is emerging … Astronomy has a far greater potential for advancement by the space program than any other branch of physics".

Space Task Group report to the President, September 1969

"A Long-Range Program in Space Astronomy", position paper of the Astronomy Missions Board, Doyle, Robert O., Ed., Scientific and Technical Information Division Office of Technology Utilization, NASA, July 1969.

1965 Technology Needs

The most difficult technical questions:

– Diffraction-Limited Performance of Large Apertures
– Guidance to Fraction of an Arc-Second
– Isolation from Vehicle Disturbances

Key technical issue in space astronomy is how to launch 100 inch (and larger) giant aperture telescope and maintain its performance to diffraction limits.

Stratoscope II mirror designed for 'soft' balloon flight and not suitable for the more violent rocket launch operations.

Stratoscope II operates in the presence of gravity.

"Determination of Optical Technology Experiments for a Satellite", Wischnia, Hemstreet and Atwood, Perkin-Elmer, July 1965.

Stratoscope I & II – 1957 to 1971

Stratoscope I (initial flight 1957)

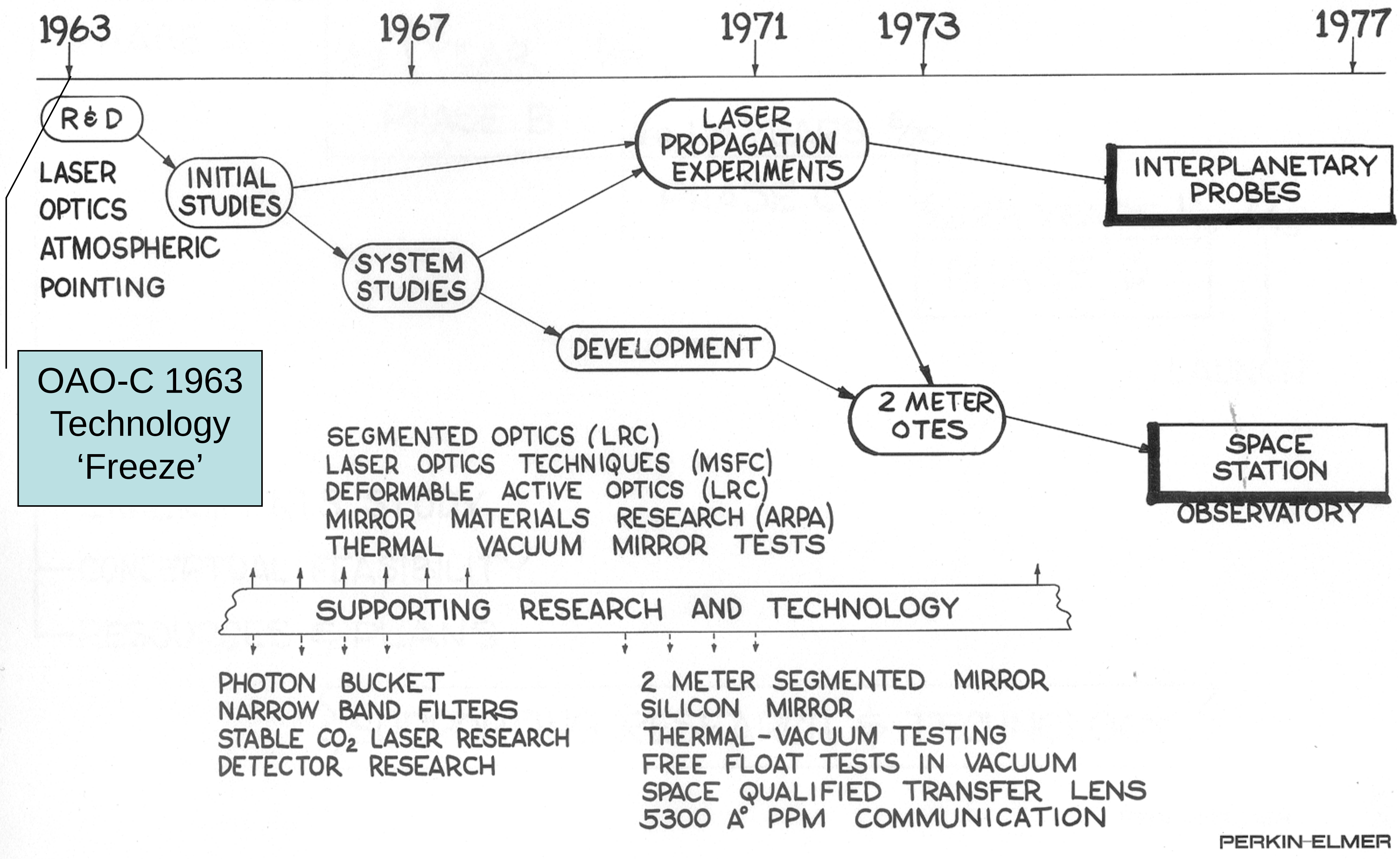
- Conceived by Martin Schwarzchild
- Build by Perkin-Elmer
- 30 cm (12 inch) primary mirror
- Film recording

Stratoscope II

- Conceived by Martin Schwarzchild
- Build by Perkin-Elmer
- 90 cm (36 inch) primary mirror
- Payload 3,800 kg
- 25 km altitude
- Film & Electronic

MSFC Launch September 9, 1971

NASA SPACE OPTICS TECHNOLOGY PLAN



Orbiting Astronomical Observatory (OAO) Satellites

NASA launched 4 OAO satellites from 1966 to 1972.

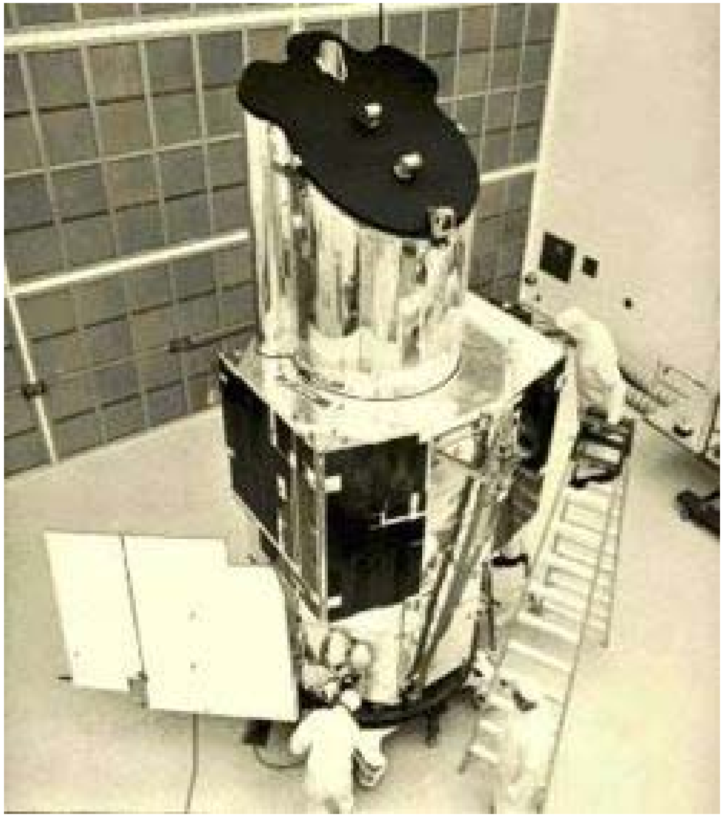
- OAO-1 and OAO-B failed.

OAO-2 (Dec 1968 to Jan 1973)

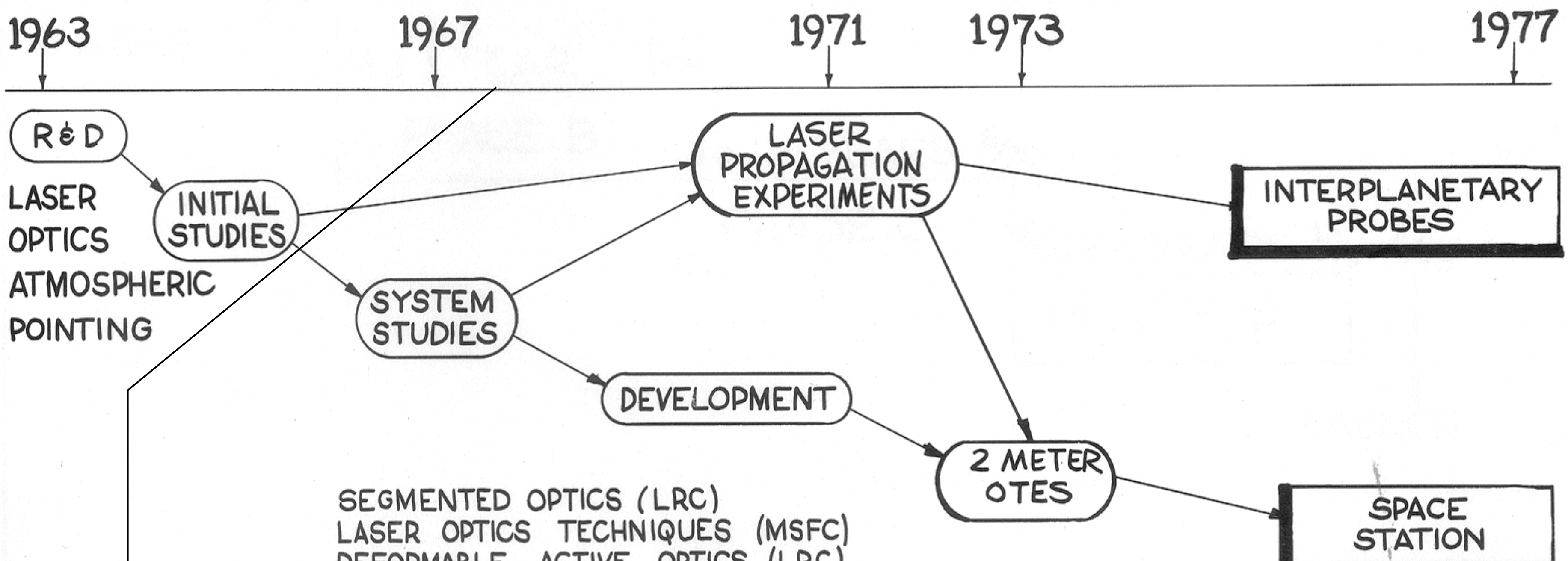
- UV telescopes.

OAO-3 or OAO-C (Copernicus) (Aug 1972 to Feb 1981)

- 80 cm UV telescope
- Built by Perkin-Elmer for Princeton



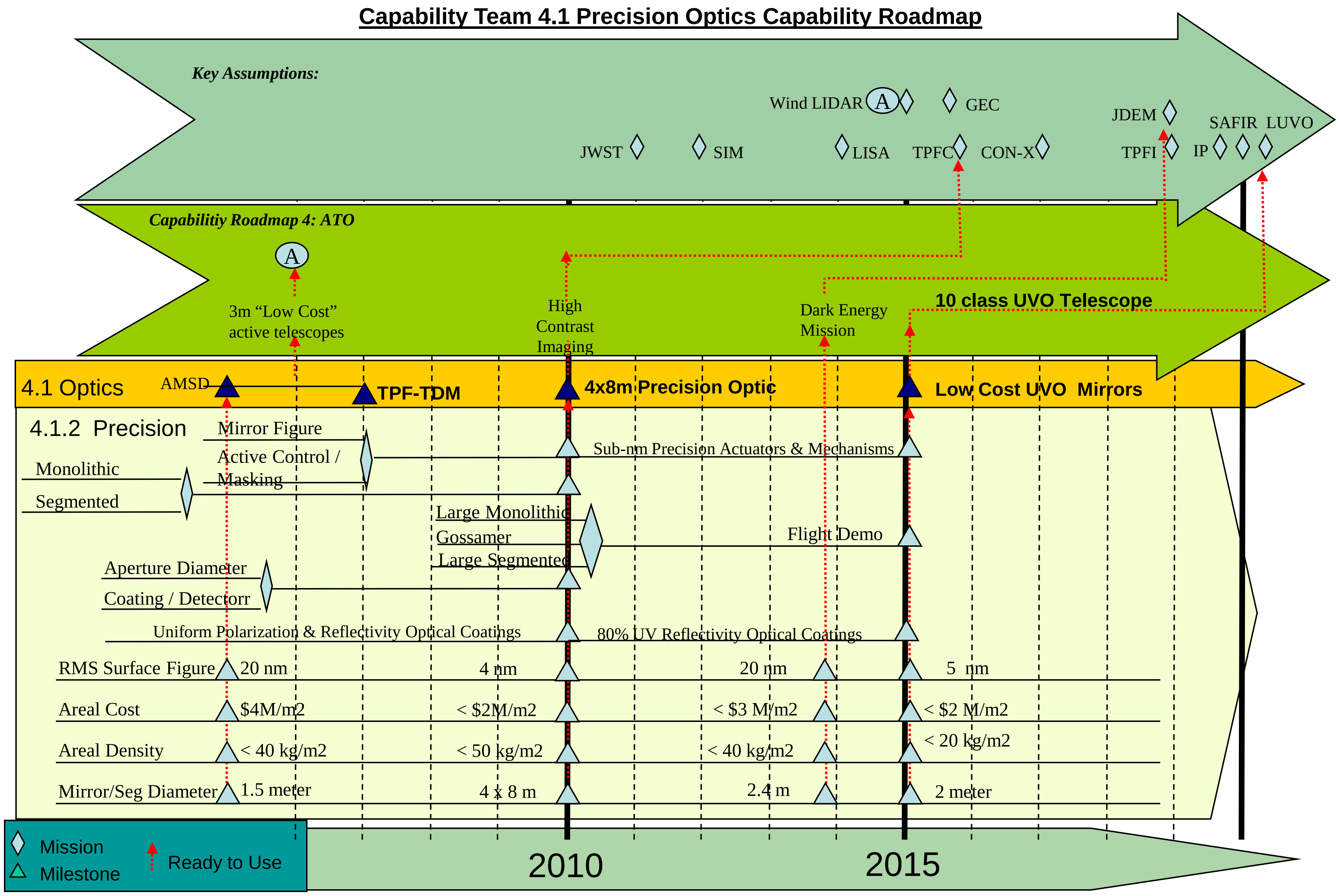
NASA SPACE OPTICS TECHNOLOGY PLAN



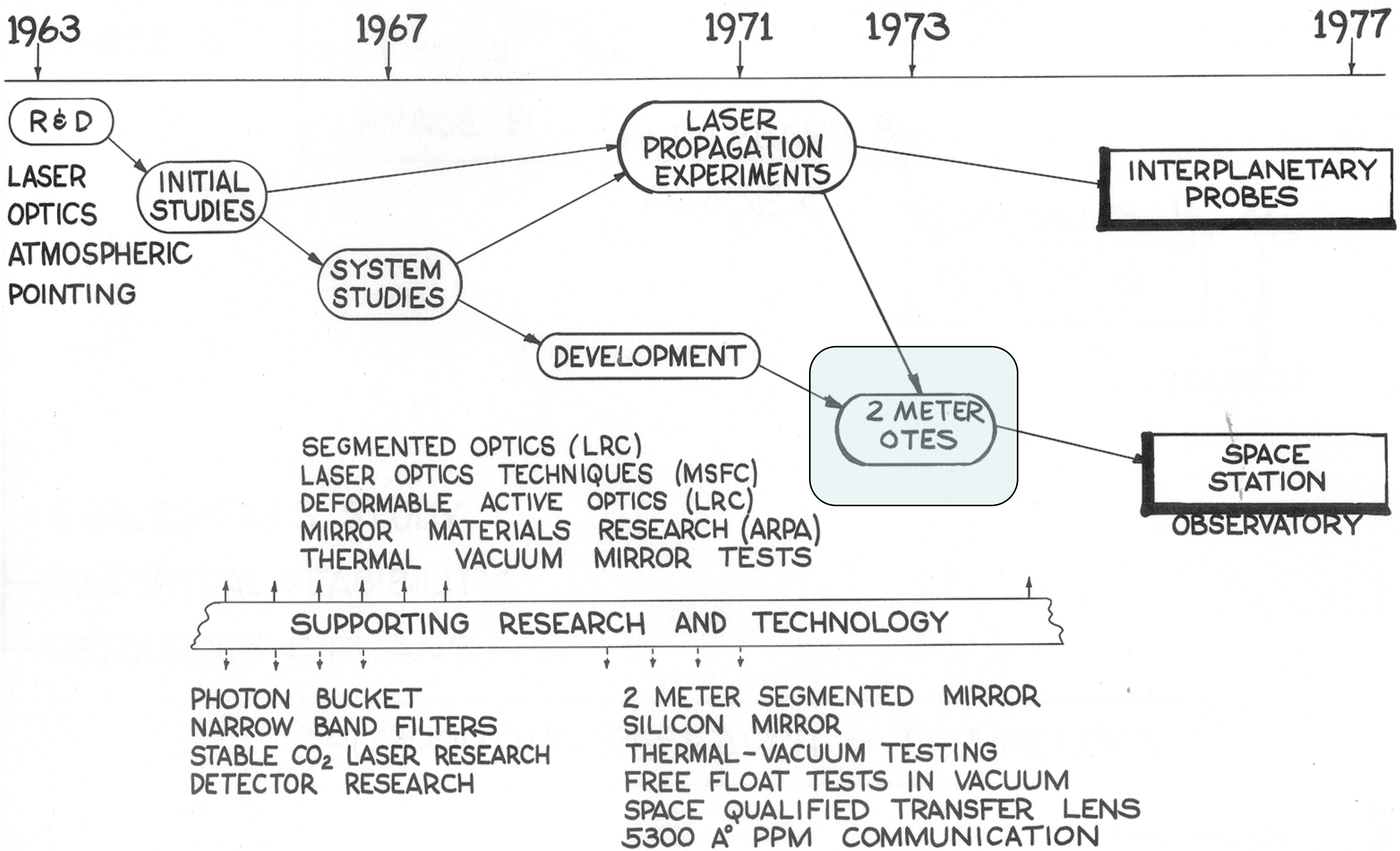
"Active Optical Systems for Space Stations", Hugh Robertson, PE, Jan 1968.
"Advanced Optical Figure Sensor Techniques", Robert Crane, PE, Jan 1968
"Advanced Actuator Project", Hugh Robertson, PE, Jan 1968.
"Thermal Vacuum Figure Measurement of Diffraction Limited Mirrors", J. Bartas, PE, Aug 1968
"Silicon 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

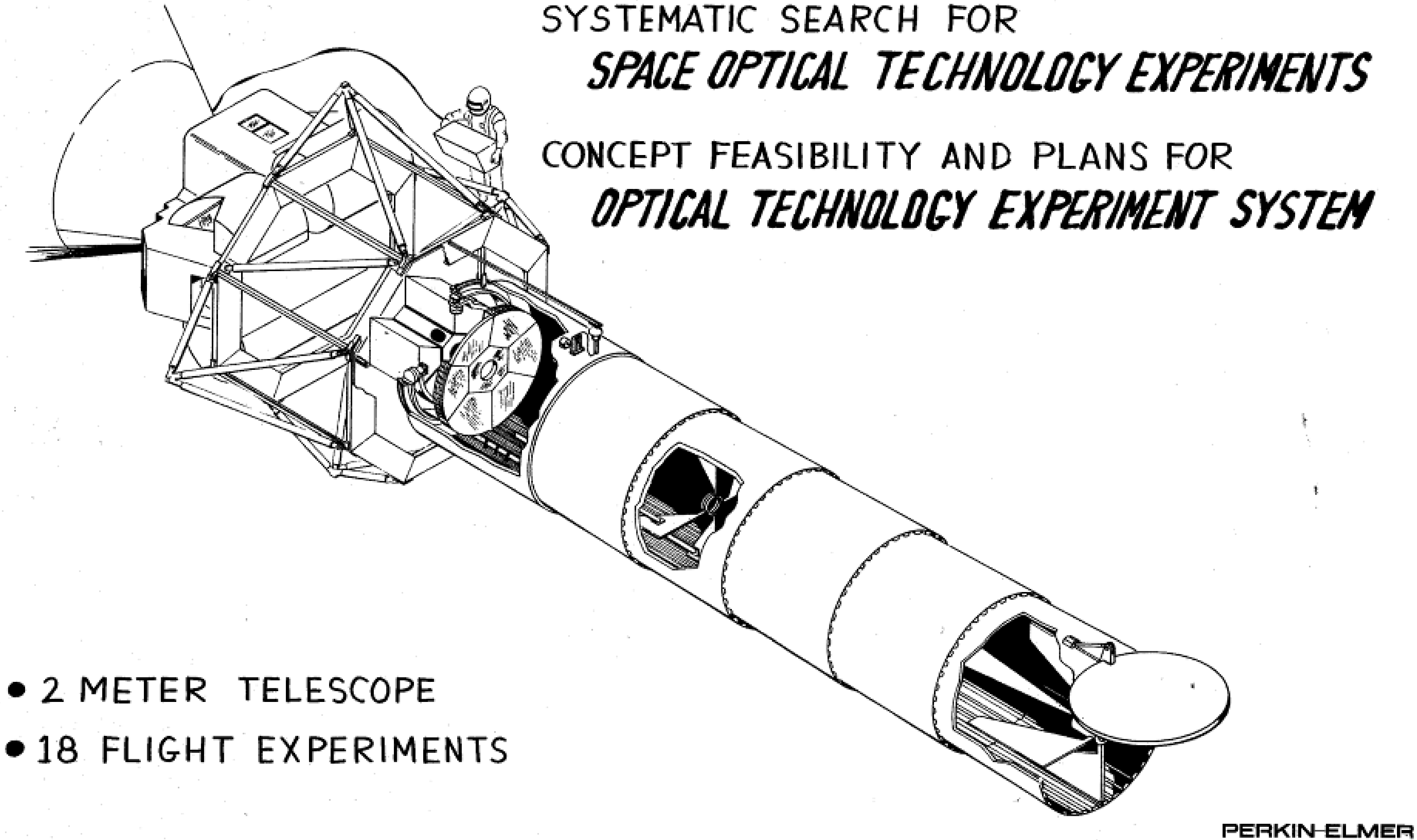
ATO CRM Optics Roadmap (NRC 2005)



NASA SPACE OPTICS TECHNOLOGY PLAN



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)”, Perkin-Elmer, Aug 1969

Large Telescope Experiment Program (LTEP)

Funded by the NASA Apollo Application Office

NASA is seriously search out meaningful goals for after the most successful Saturn-Apollo missions to the lunar surface.

The new science and technologies of space labs and solar observatories are in the immediate future.

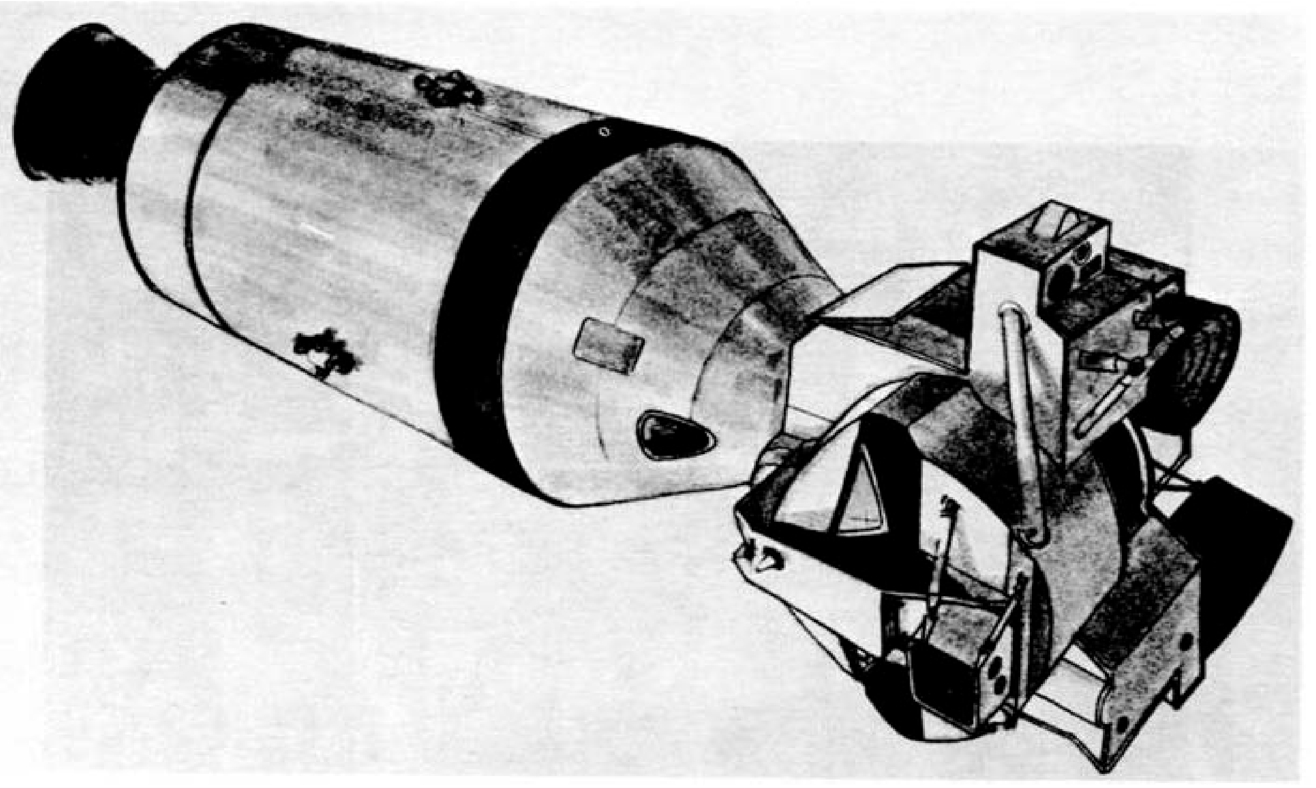
Data … are critical for settling major questions in cosmology:

is the Universe is infinite or not.”

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

Apollo Application Program (AAP)

Lunar module adapted for astronaut-tended solar and astrophysics observations.



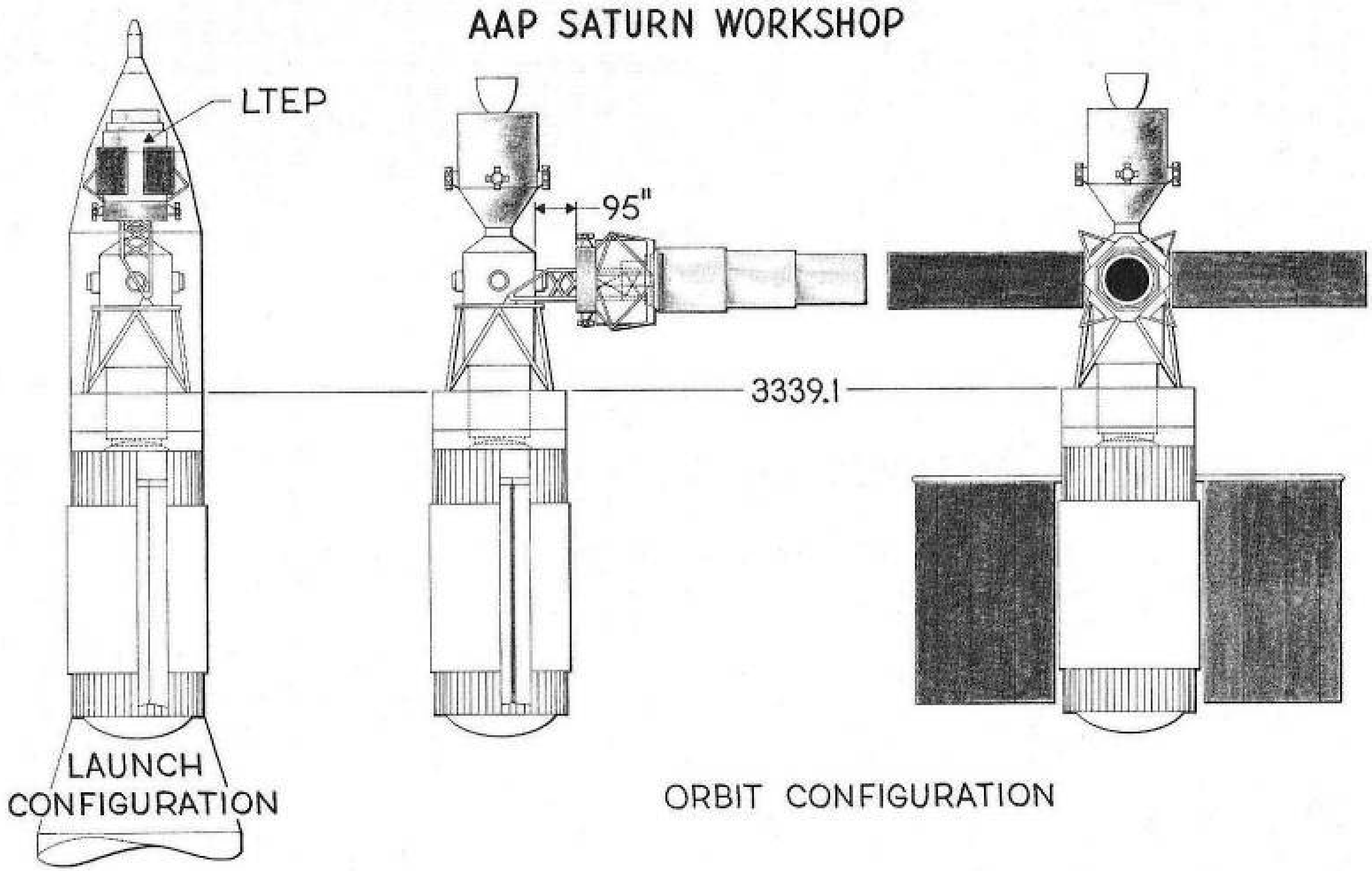
While this particular concept was never built, aspects of the design evolved into Skylab and the Apollo Telescope Mount.

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 limit of at least 3 meters (0.006 arc-seconds) at 100 nm.
- Interchangeable experiment packages
- Life time 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



“Large Telescope Experiment Program (LTEP)”, Final Technical Report,
Lockheed Missiles and Space Company, Jan 1970
“Large Telescope Experiment Program (LTEP)”, Executive Summary,
Alan Wissinger, April 1970

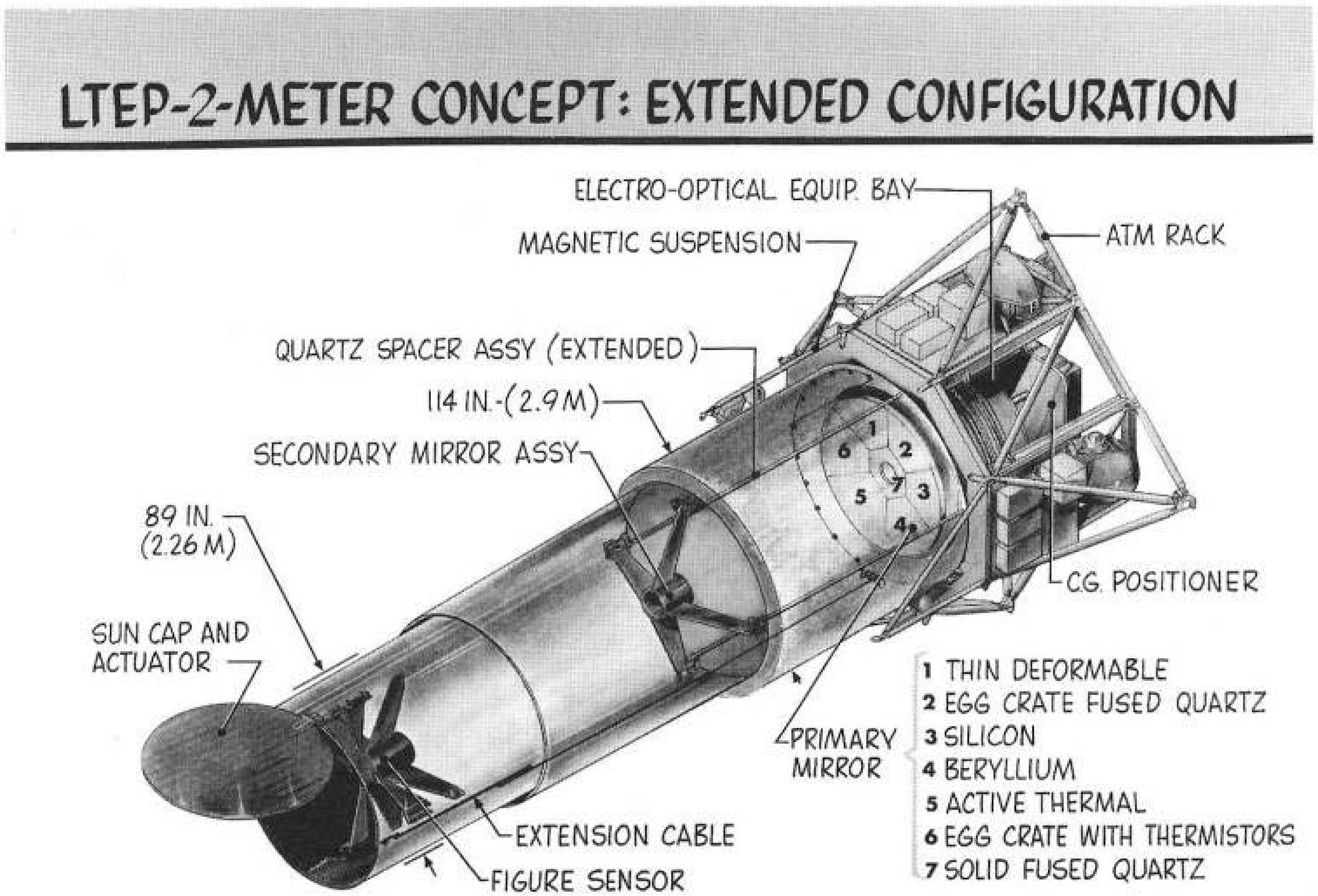
1969 Technology Needs

The optical technology required for the 120-inch space telescope has not been demonstrated in the following critical areas:

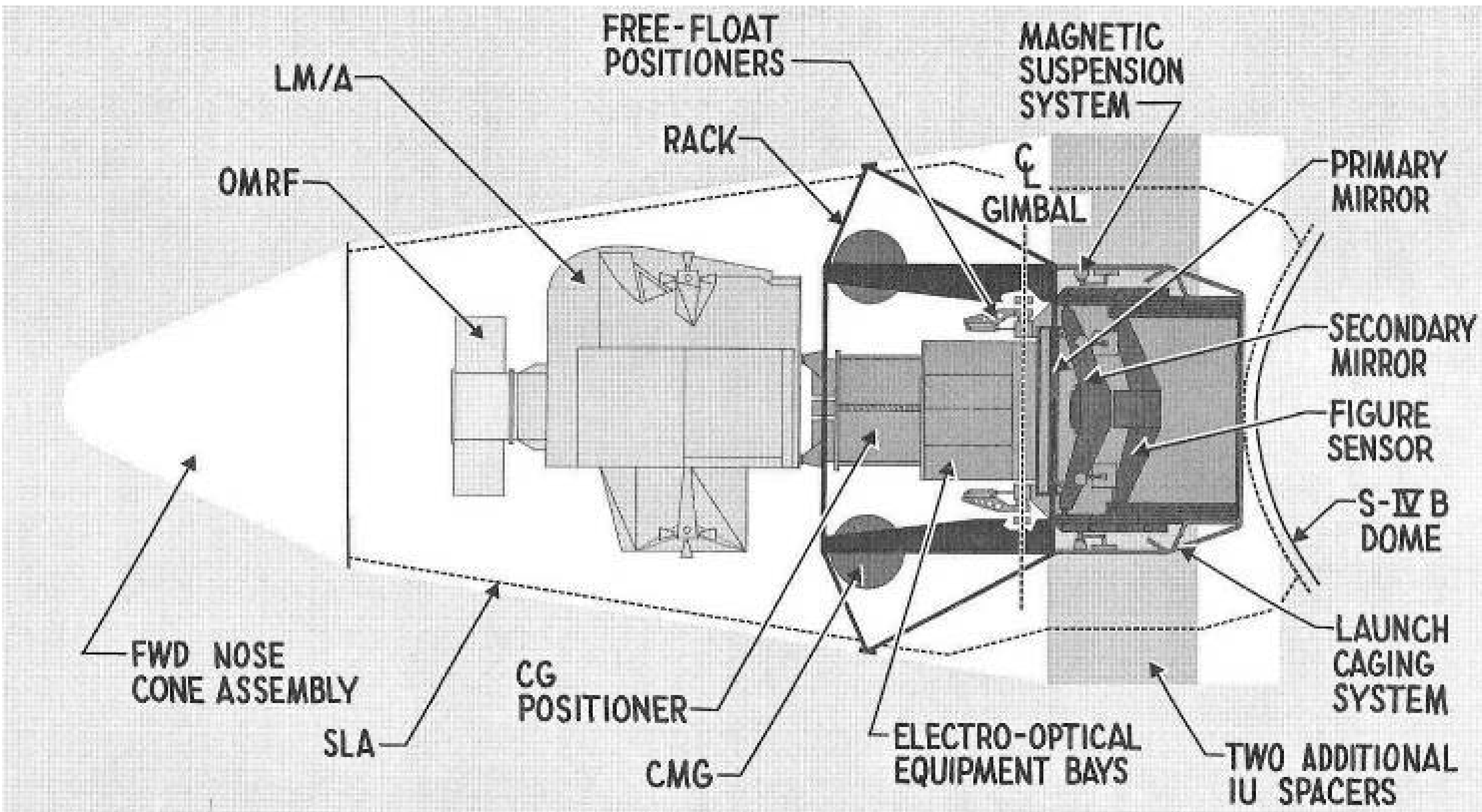
- Precision figuring of 120-inch mirrors to 1/50 wave rms
- Long-term substrate stability to 1/50 wave rms for 120-inch mirrors
- Long-life high-reflectivity ultraviolet mirror coatings
- Stellar pointing to 1/100 arc-second for a 120-inch space telescope
- Space maintenance of large astronomical telescopes by astronauts

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

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

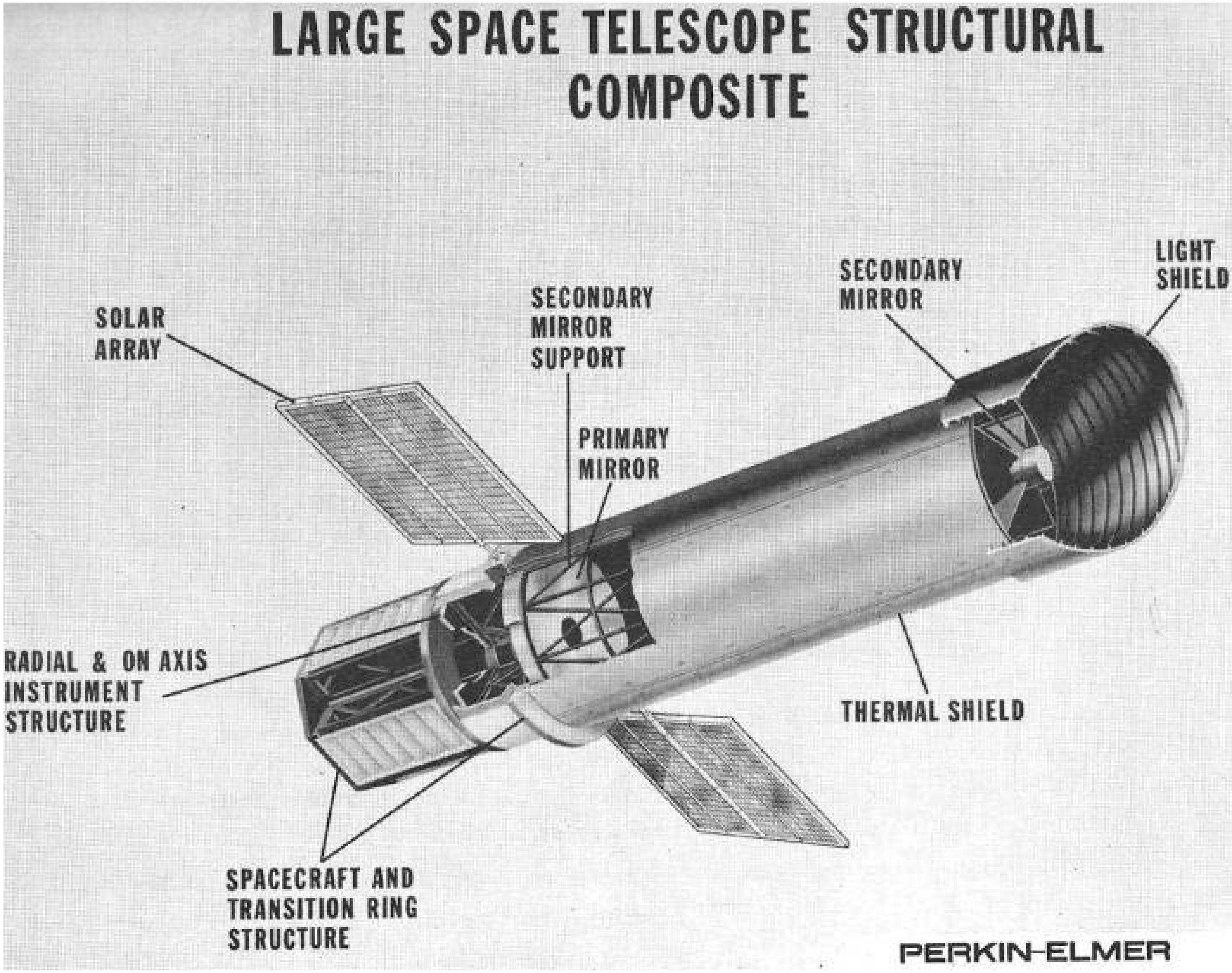


Initial Launch Configuration for Saturn IB



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

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



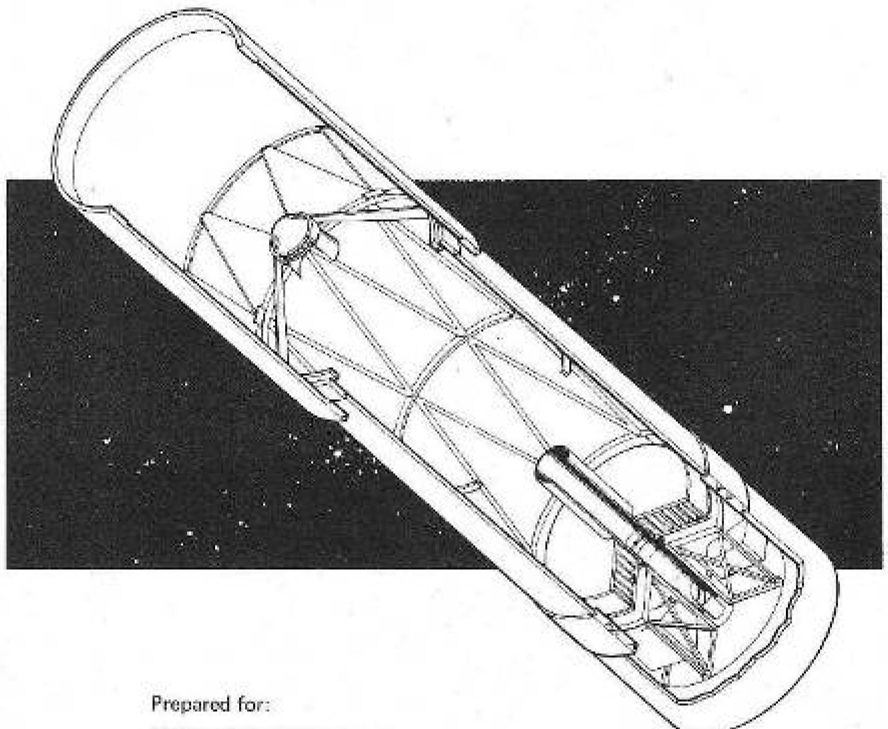
Itek 71-9463-2

FINAL REPORT

3 SEPTEMBER 1971

LARGE SPACE TELESCOPE

CONTINUATION OF A TECHNOLOGY STUDY



Prepared for:

NASA HEADQUARTERS
OFFICE OF SPACE SCIENCE AND APPLICATIONS
WASHINGTON, D.C. 20546

Under Contract No. NASw-2174

Itek **Optical Systems Division**
10 MAGUIRE ROAD, LEXINGTON, MASSACHUSETTS 02173

PPR-71-131

Hubble Deployment April 25 1990

Next Generation Space Telescope Study

In the summer of 1996, NASA initiated a mission study for a Next Generation Space Telescope

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

Study Results ….

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

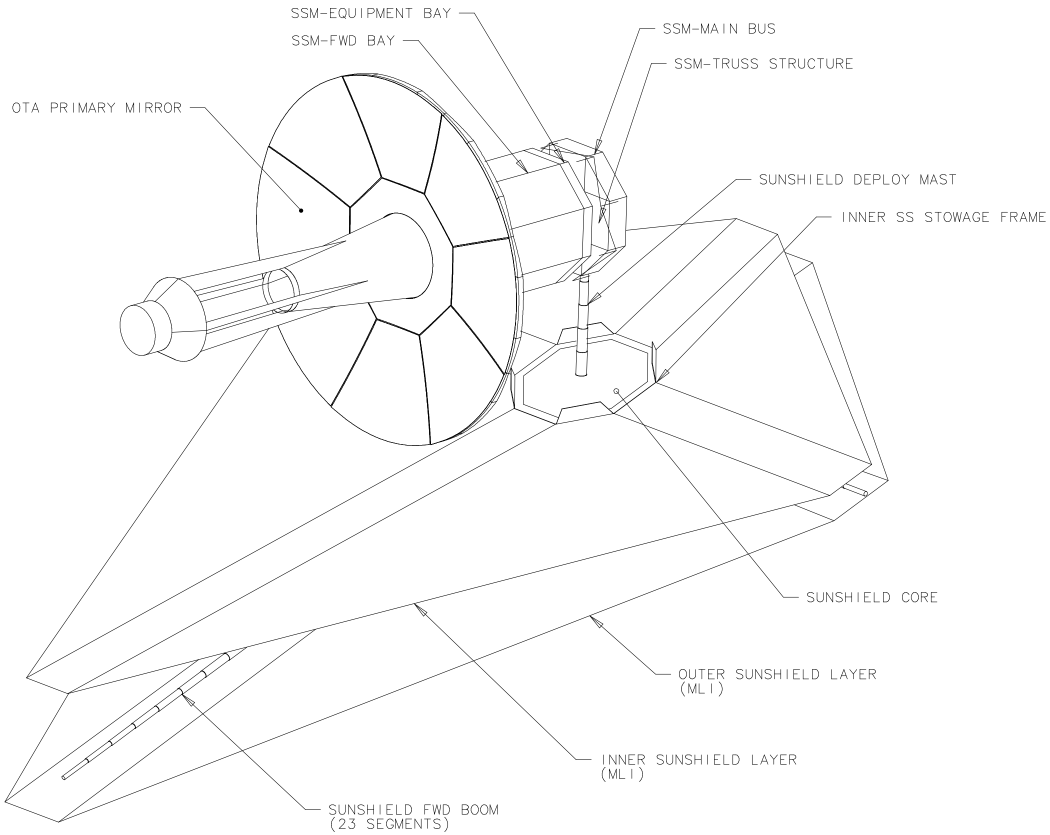
Segmented Primary Mirror

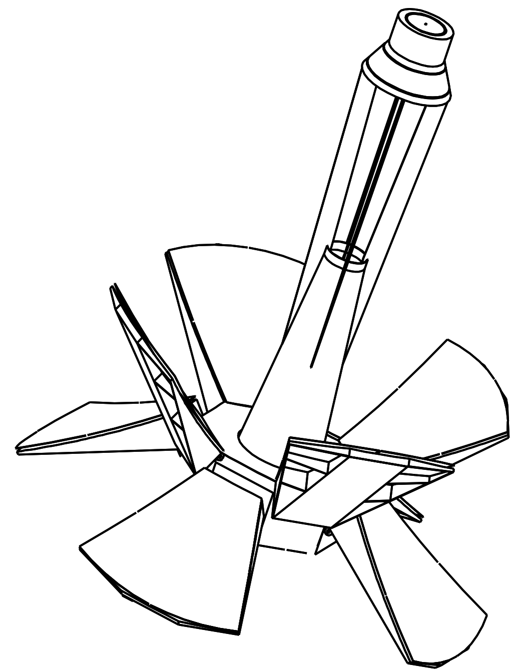
The only way to put an 8-meter telescope into a 4.5 meter fairing is to segment the primary mirror.

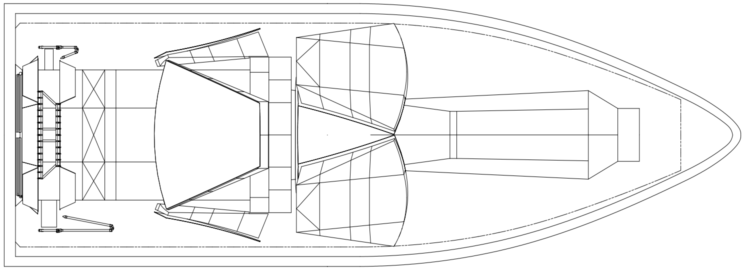
Mass Constraint

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

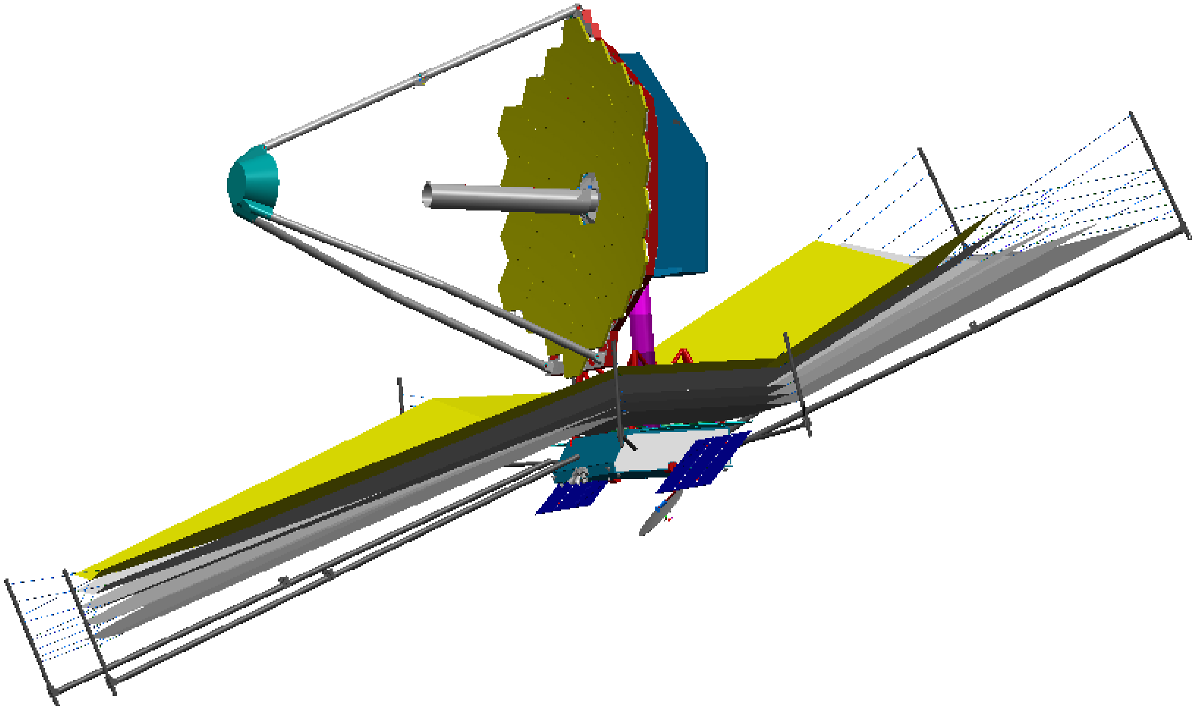
Reference design – Lockheed / Raytheon







Reference design – TRW/Ball



LAMP Telescope - 1996

Optical Specifications

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

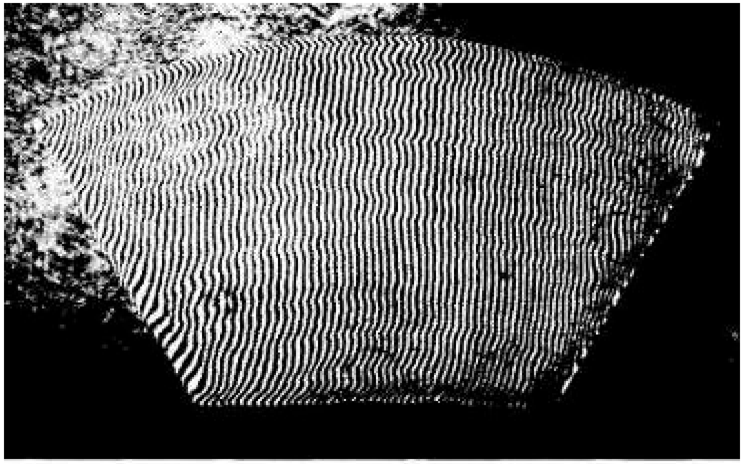
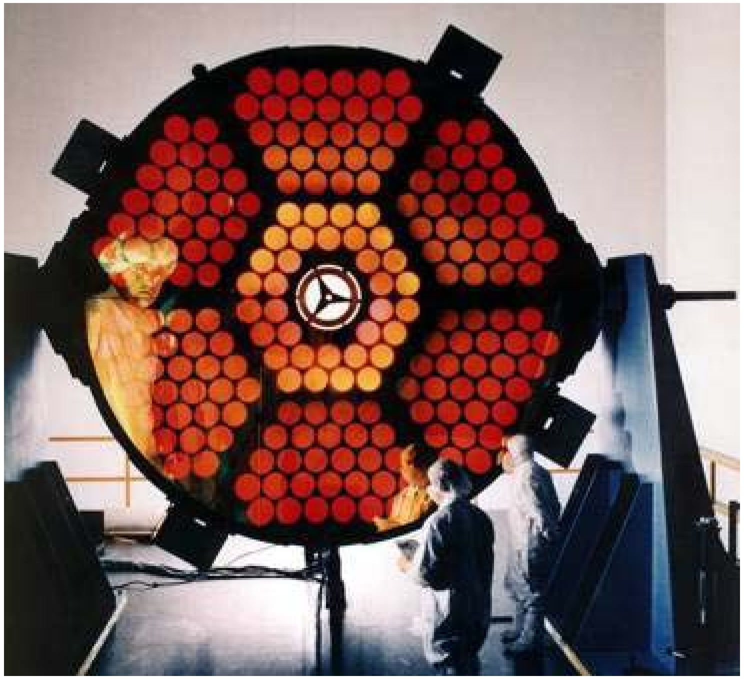


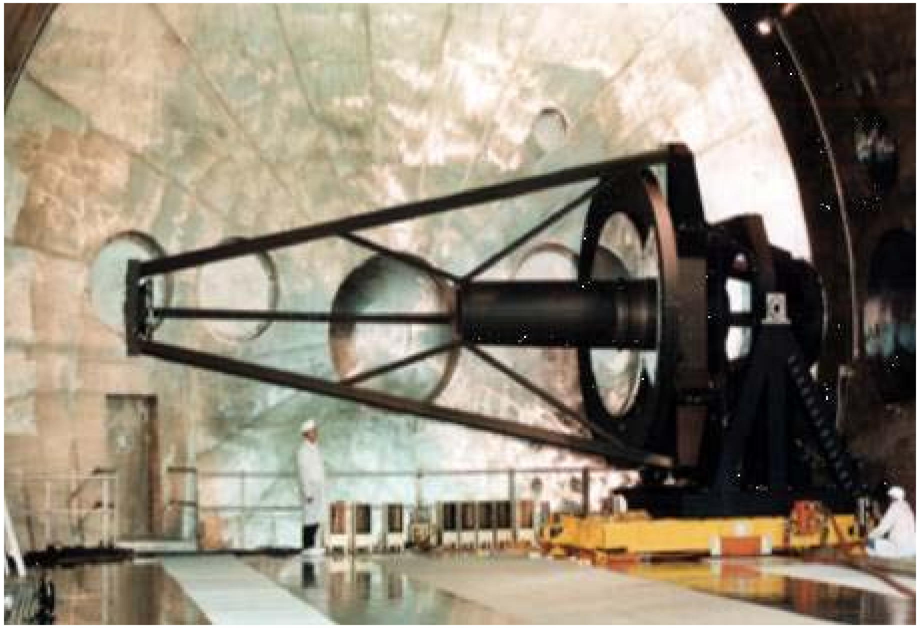
Fig. 12. Facesheet 3 final interferogram



ALOT Telescope - 1994

Optical Specifications

- 4 meter diameter
- Center & one Outer Petal
- 70 kg/m2 areal density
- Active Figure and Piston Control
  - Eddy Current
  - Wavefront Sensor



Phased two segment performance of 35 nm rms surface

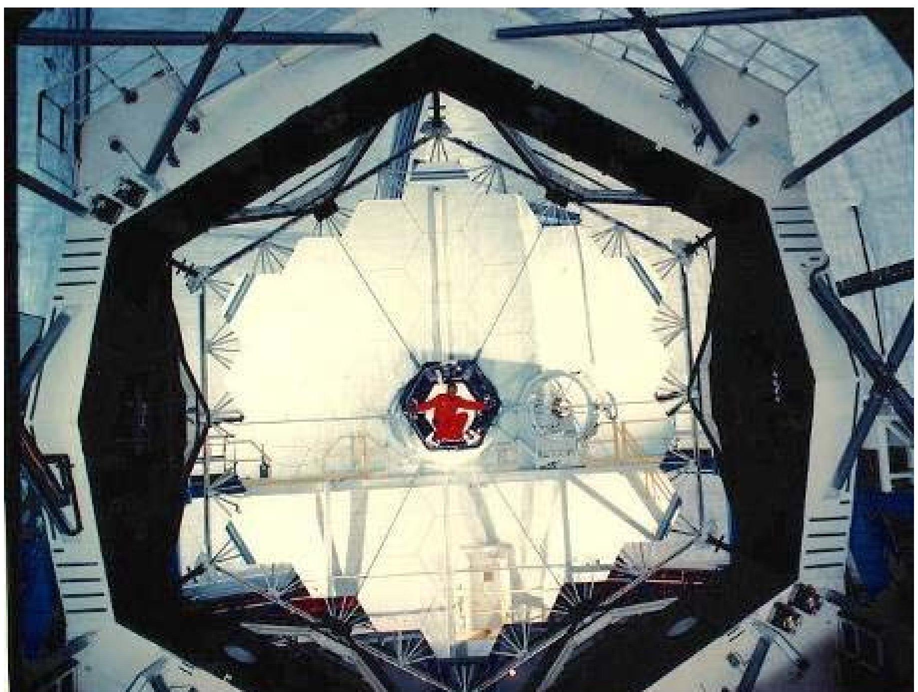
Keck Telescope - 1992

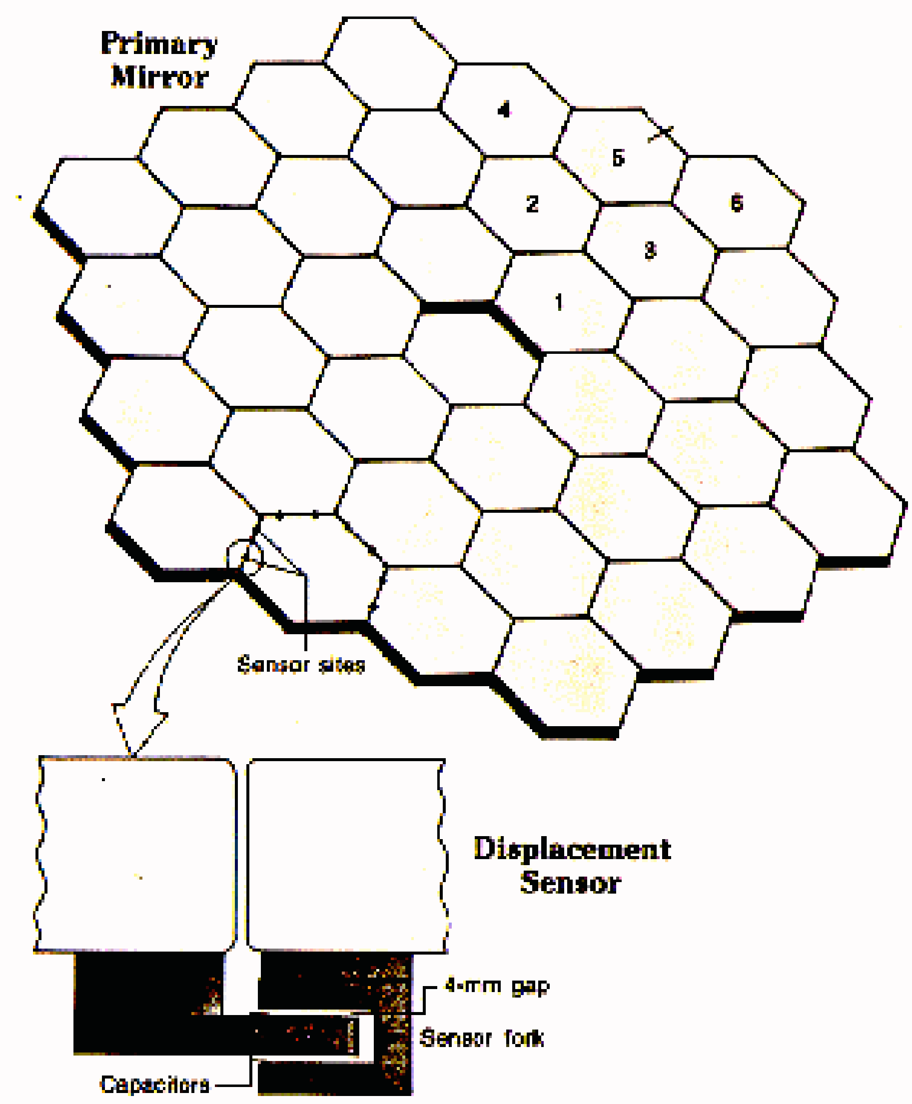
10 meter diameter

36 segments

Capacitance Edge Sensors

Diffraction Limited ~ 10 micrometers

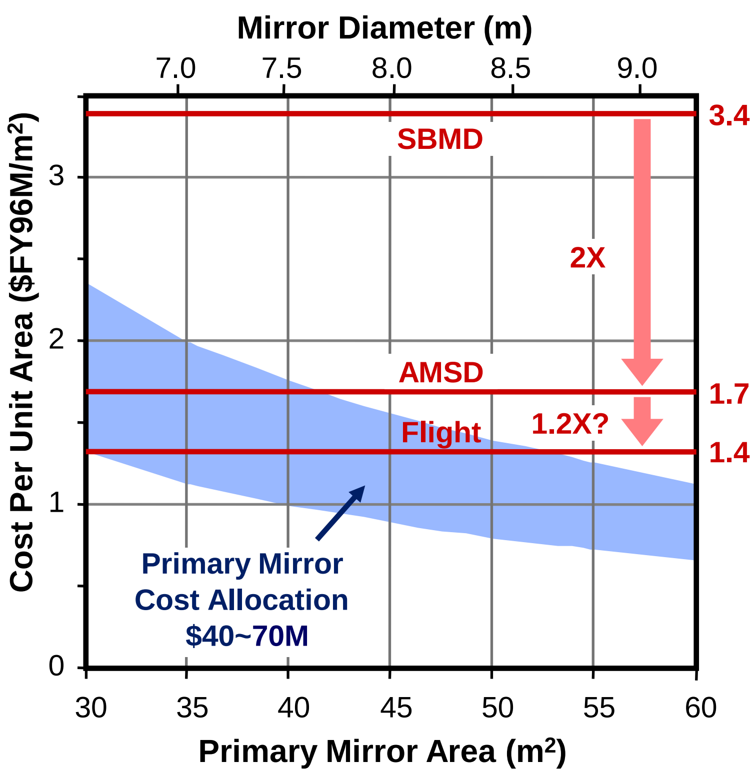


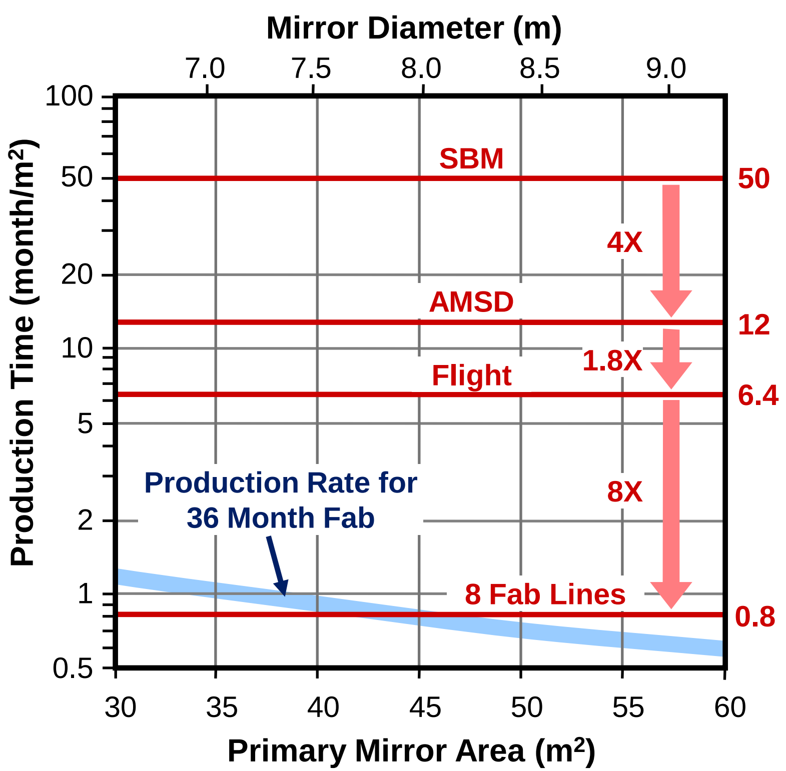


Programmatic Challenge of NGST

In 1996, the ability affordably make NGST did not exist.

Substantial reductions in ability to rapidly and cost effectively manufacture low areal density mirrors were required.





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**	**Classified**	**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**

The Spitzer Space Telescope

LOCKHEED MARTIN

- Multi-purpose observatory cooled passively and with liquid-helium for astronomical observations in the infrared
- Launch in August 2003 for a 5+ year cryo mission in solar orbit, followed by 5-year “warm” mission
- Three instruments use state-of-the-art infrared detector arrays, 3-180um
- Provides a >100 fold increase in infrared capabilities over all previous space missions
- Completes NASA’s Great Observatories
- An observatory for the community - 85% of observing time is allocated via annual Call for Proposal

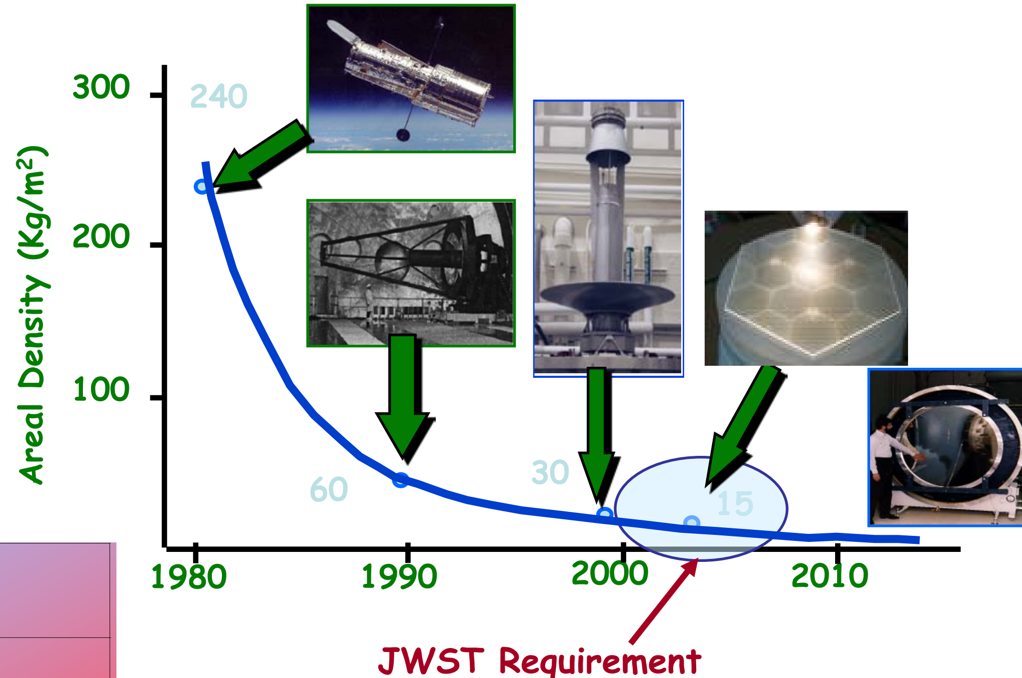
Assembled SIRTF Observatory at Lockheed-Martin, Sunnyvale.
<u>Key Characteristics:</u>
Aperture – 85 cm
Wavelength Range - 3-to-180um
Telescope Temperature – 5.5K
Mass – 870kg
Height – 4m

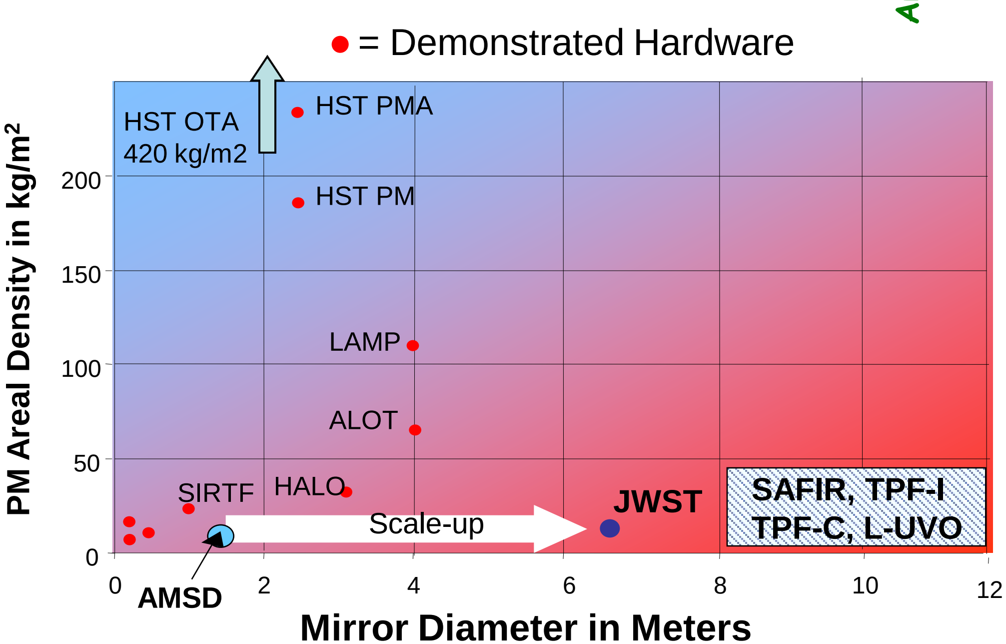
When I joined NASA is 1999, the over riding mantra for Space Telescopes was Areal Density, Cost & Schedule

Challenges for Space Telescopes:

Areal Density to enable up-mass for larger telescopes.

Cost & Schedule Reduction.





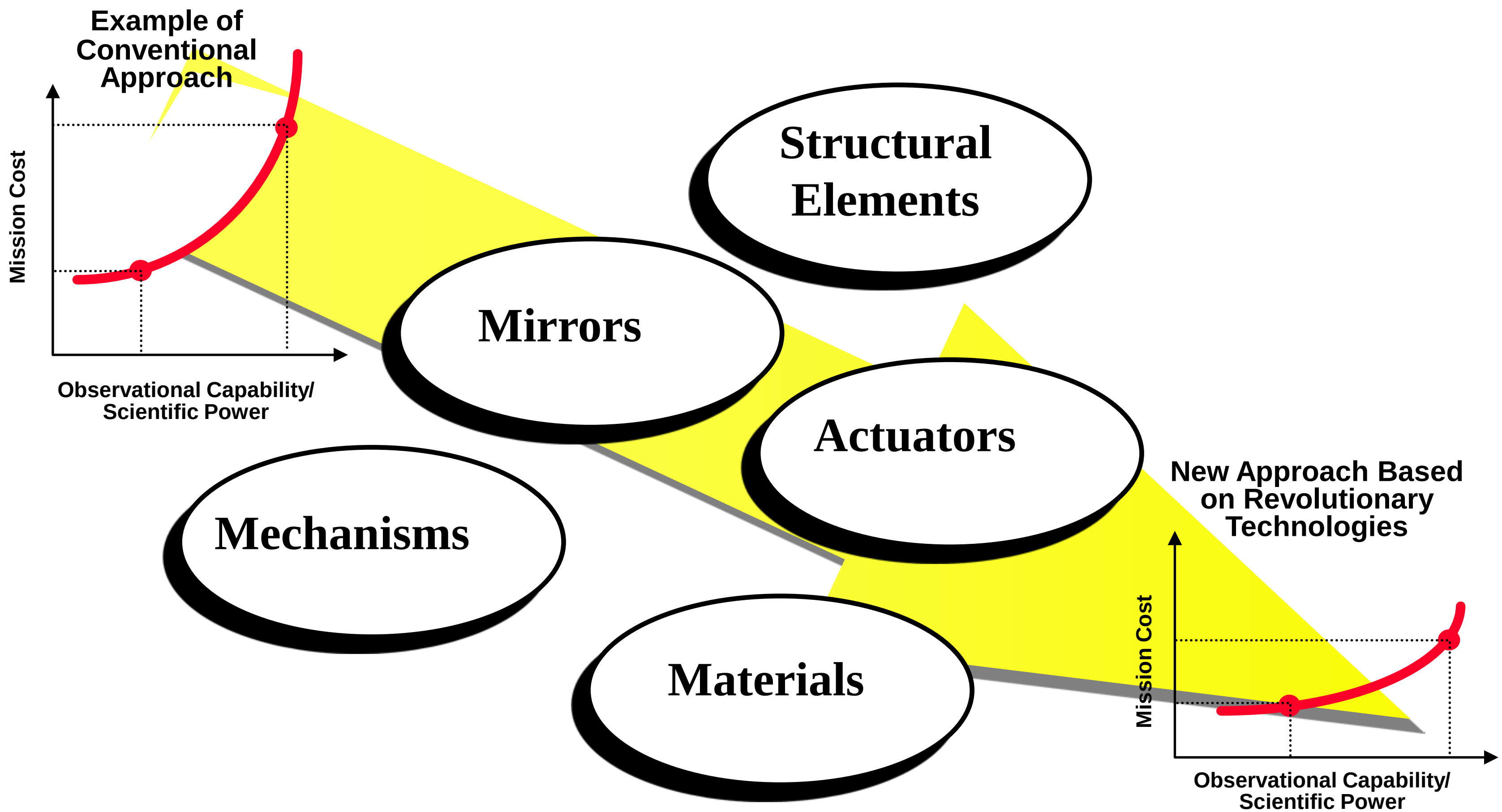
Primary Mirror	Time &	Cost
HST (2.4 m)	≈ 1 m²/yr	≈ \$10M/m²
Spitzer (0.9 m)	≈ 0.3 m²/yr	≈ \$10M/m²
AMSD (1.2 m)	≈ 0.7 m²/yr	≈ \$4M/m²
JWST (8 m)	> 6 m²/yr	< \$3M/m²

Note: Areal Cost in FY00 $

Although I've come to think that Stiffness and Areal Cost are more important

The Role of Technology

An aggressive $300M technology development program was initiated to change the cost paradigm for not only telescopes but also for detectors and instruments.



Mirror Technology Development

A systematic $40M+ development program was undertaken to build, test and operate in a relevant environment directly traceable prototypes or flight hardware:

- Sub-scale Beryllium Mirror Demonstrator (SBMD)
- NGST Mirror System Demonstrator (NMSD)
- Advanced Mirror System Demonstrator (AMSD)
- JWST Engineering Test Units (EDU)

Goal was to dramatically reduce cost, schedule, mass and risk for large-aperture space optical systems.

A critical element of the program was competition – competition between ideas and vendors resulted in:

- remarkably rapid TRL advance in the state of the art
- significant reductions in the manufacturing cost and schedule

It took 11 years to mature mirror technology from TRL 3 to 6.

Enabling Technology

It is my personal assessment that there was 4 key Technological Breakthroughs which have enabled JWST:

- O-30 Beryllium (funded by AFRL)
- Incremental Improvements in Deterministic Optical Polishing
- PhaseCAM Interferometers (funded by MSFC)
- Advanced Mirror System Demonstrator Project (AMSD)
  funded by NASA, Air Force and NRO

Substrate Material

O-30 Beryllium enabled JWST

Spitzer used I-70 Beryllium while JWST uses O-30 Beryllium.

O-30 Beryllium (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 power 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 that what could be produced for Spitzer with I-70.

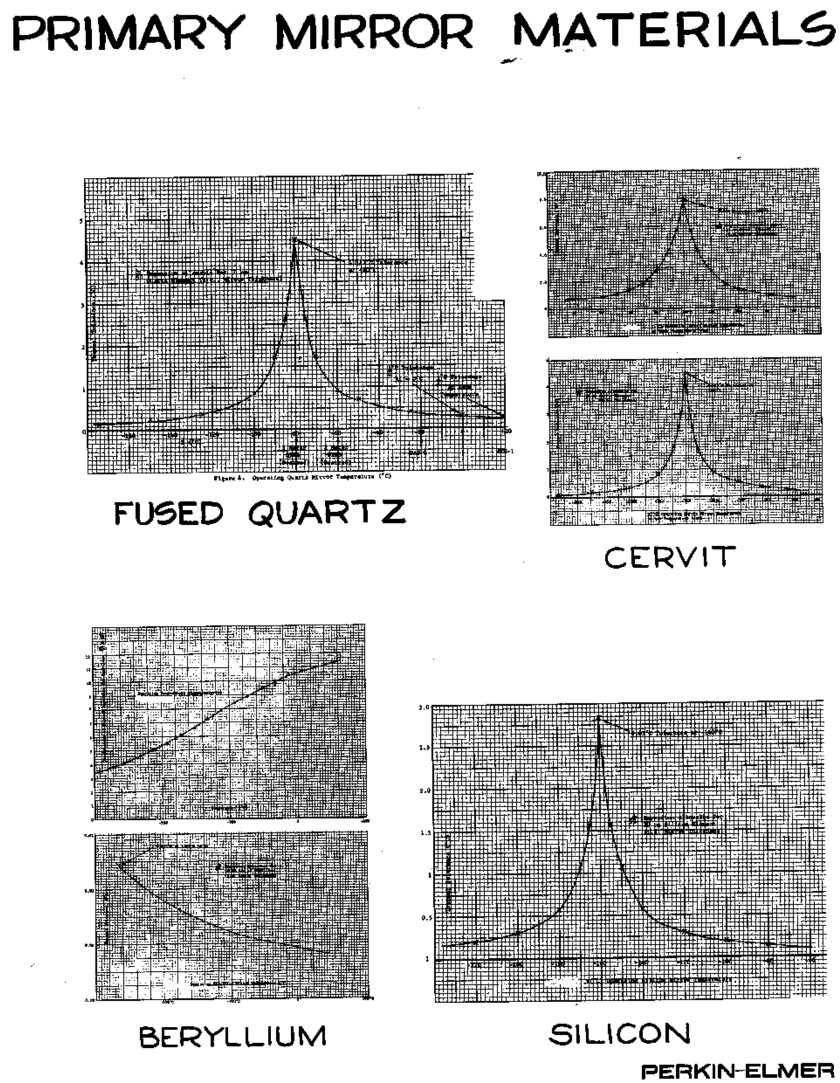
Because O-30 has a lower oxide content:

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

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

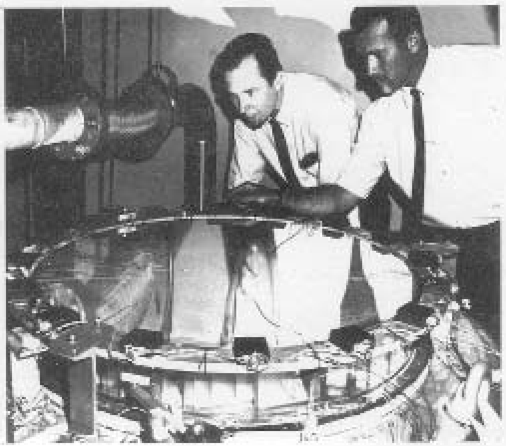
Full production capability in sufficient quantities for JWST on-line in 1999/2000.

1960 Material Property Studies

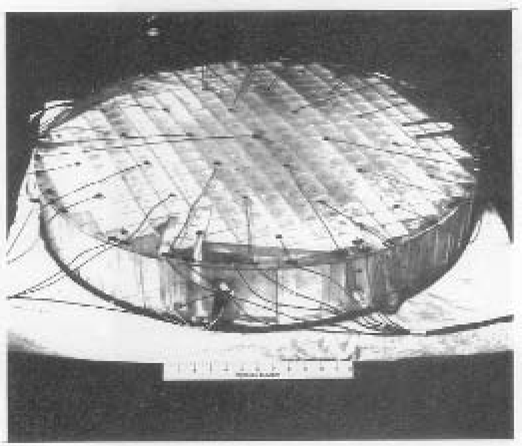


Thermal Stability was Significant Concern

THERMAL VACUUM TESTING
OF SPACE MIRRORS

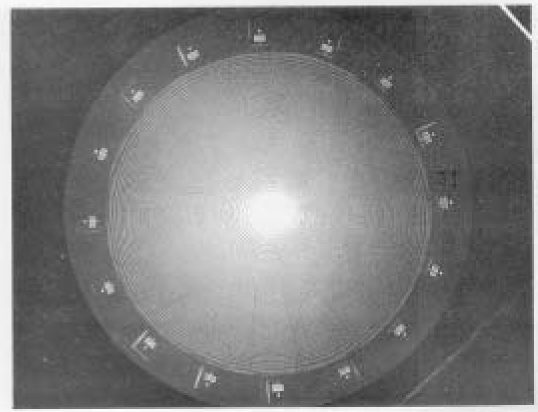


OTES
EXPERIMENT 12



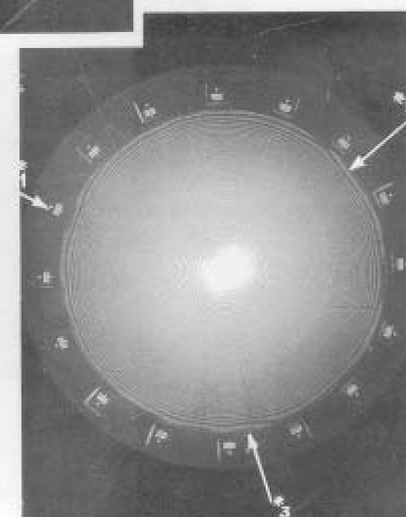
INSTRUMENTED
OAO MIRROR

THERMAL VACUUM TESTING
OF SPACE MIRRORS



QUIESCENT

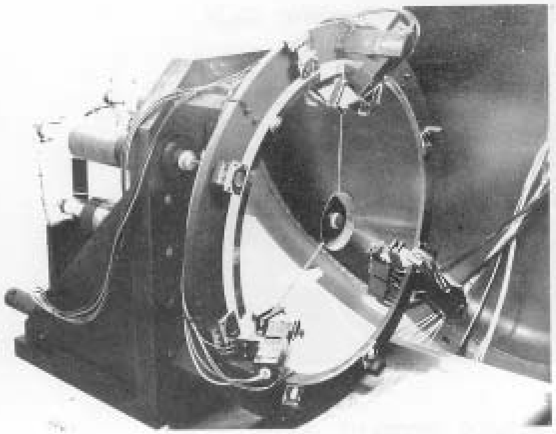
Mounting
Point



HEATED

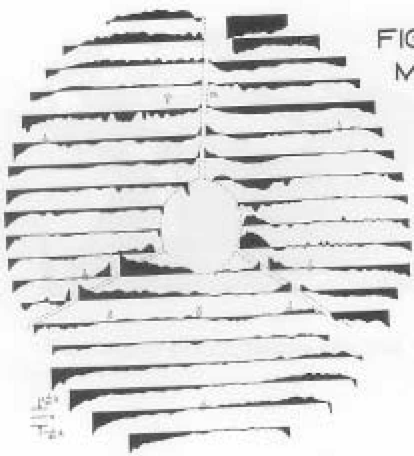
Solution to Thermal Instability was Segmented Mirror

SEGMENTED ACTIVE OPTICS

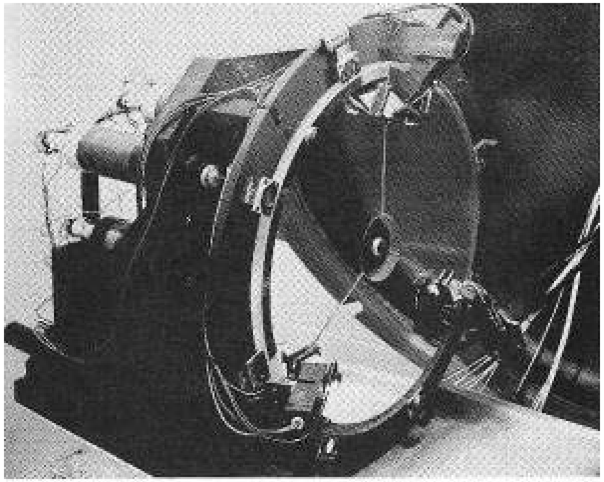


REFER TO OTES EXPERIMENT NO. 1

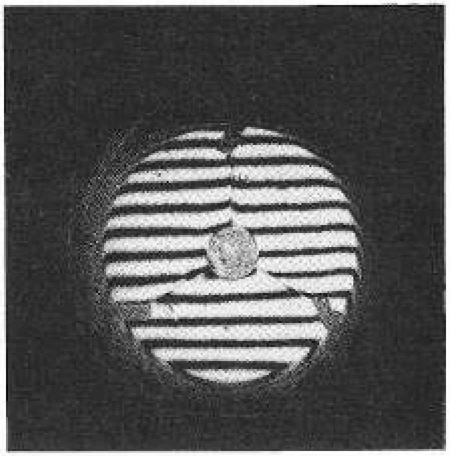
FIGURE ERROR MEASUREMENT



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



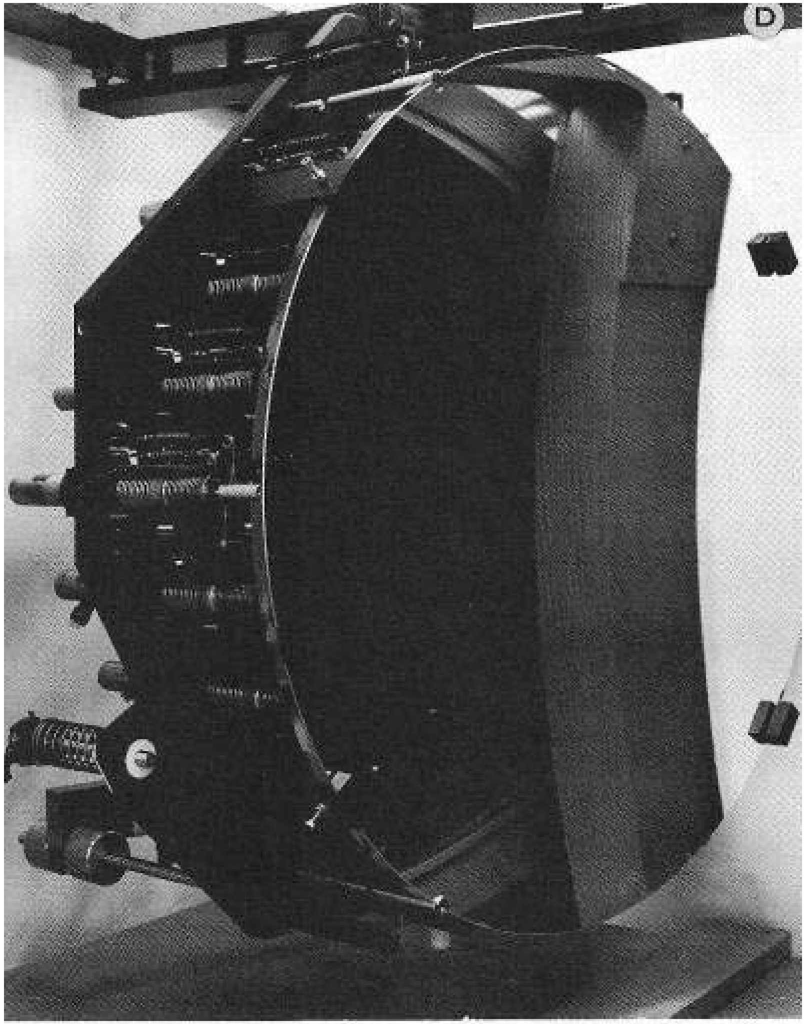
Segmented Mirror



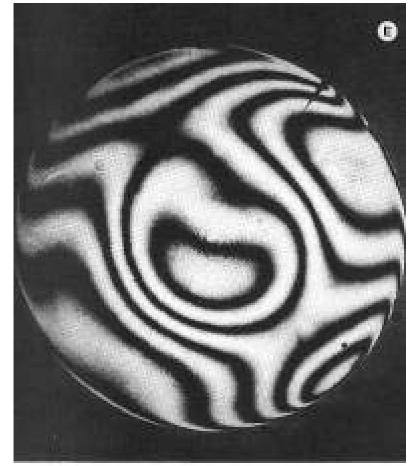
Interferogram of Active Segmented Mirror

Active Segmented Optics

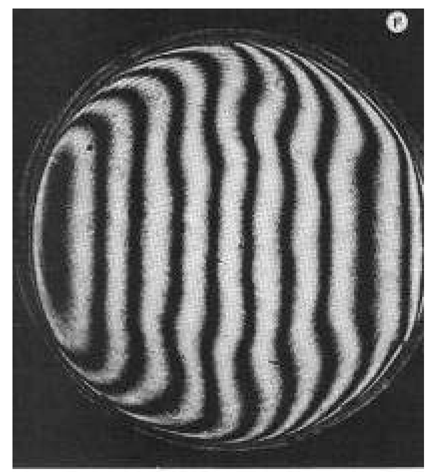
Other Solution to Thermal Problem was Active Mirror



30 Inch Diameter Thin Deformable Mirror



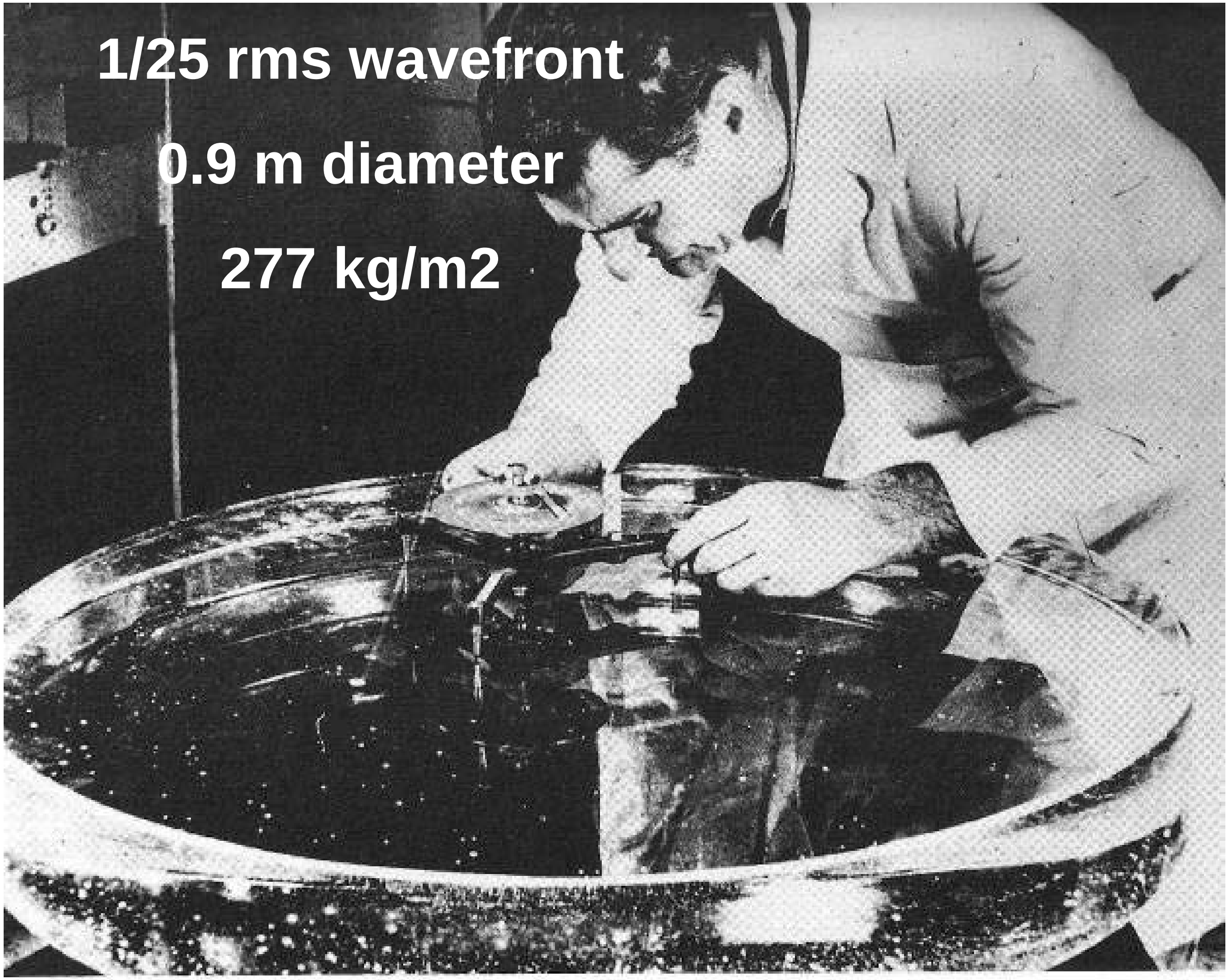
Thin Deformable Mirror — Before Active
Optics System Activated



Thin Deformable Mirror — During Active
Optics System Operation

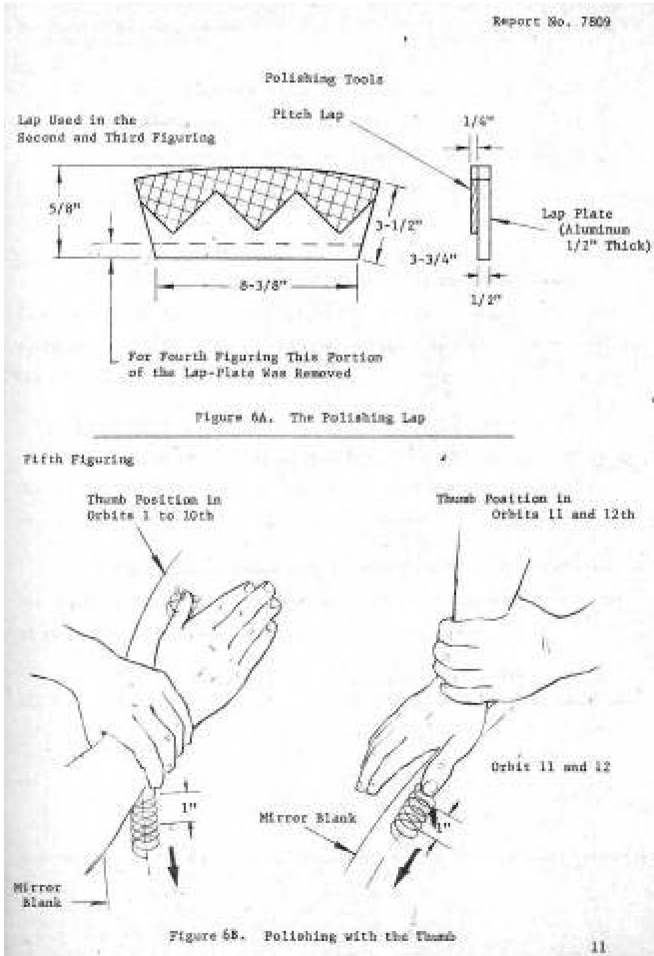
Optical Fabrication

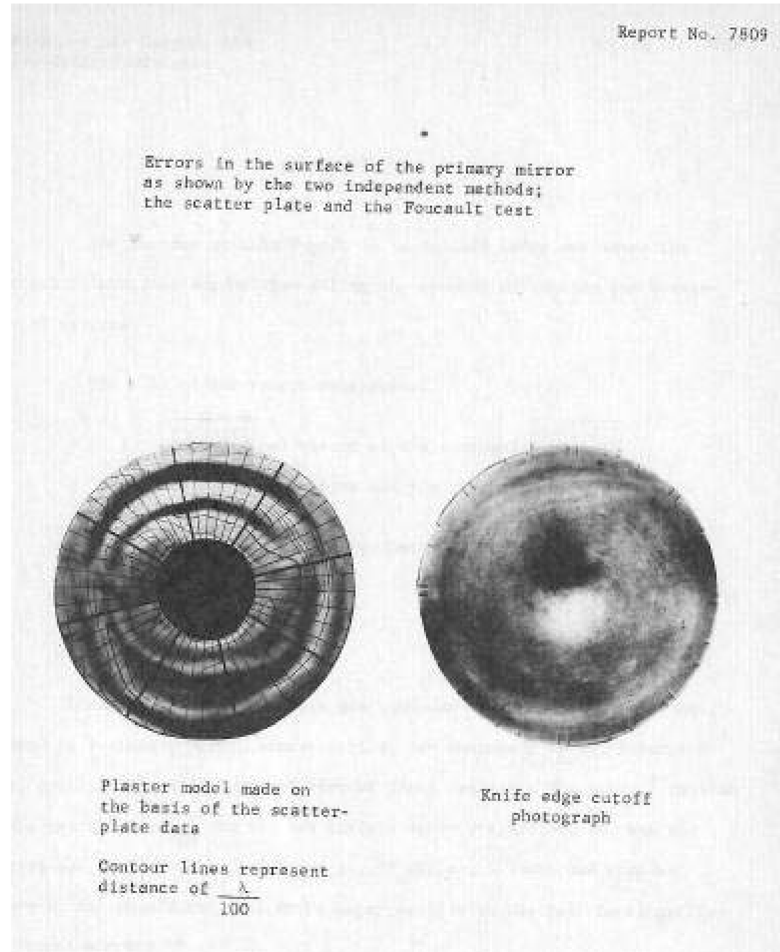
Stratoscope II – Primary Mirror



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

Stratoscope II – Optical Fabrication

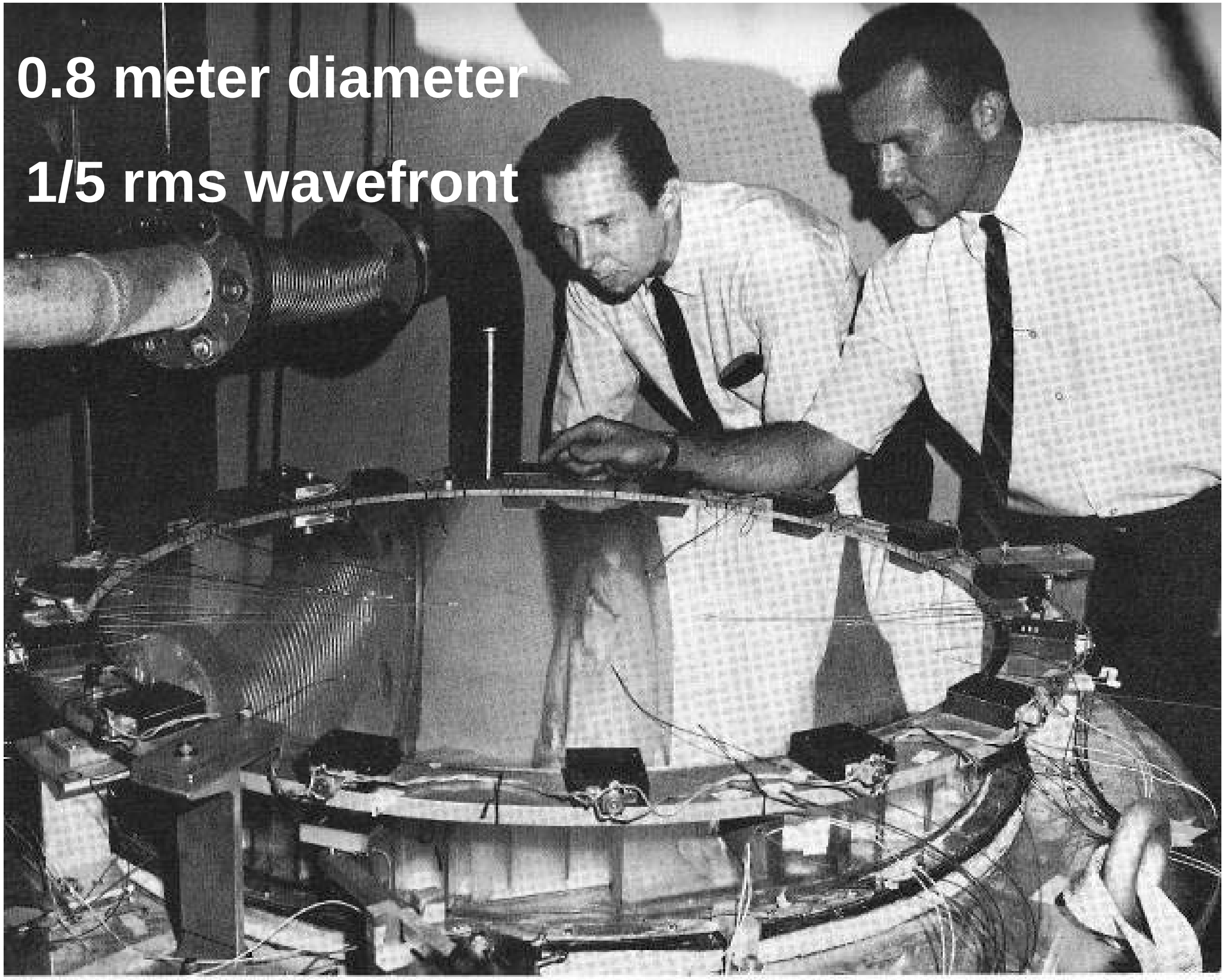




Classical Fabrication Techniques - Shaped Laps and Hand Figuring

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

OAO-C Primary Mirror



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

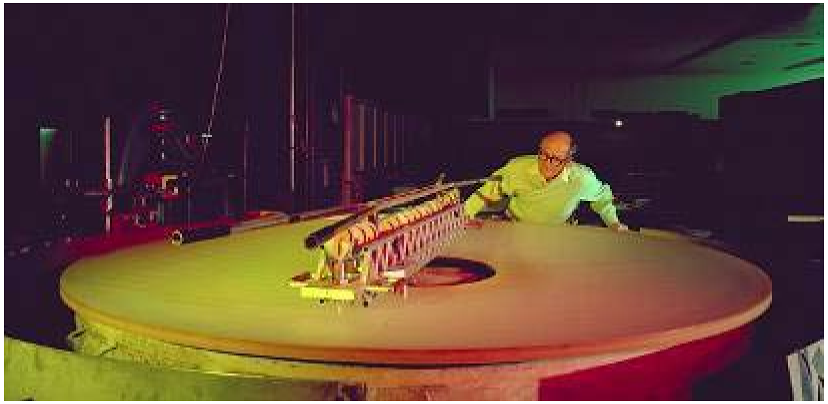
Hubble Primary Mirror Fabrication 1979-1981

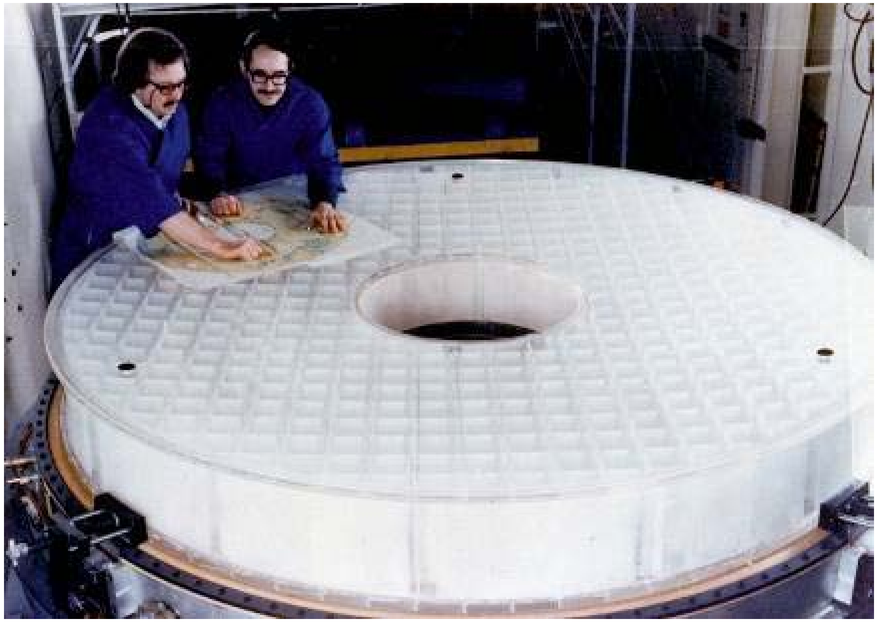



Start of Small Tool Computer Controlled Polishing (I saw this)

NASA Technology for the 1980's

Back-up Primary Mirror Blank





Kodak used conventional full aperture shaped laps

(I also saw some of these)

Mirror Constructed of Corning ULE^{TM}

Lightweight, High Temperature Fused Construction

2.4-meter Aperture

Spitzer PM Fabrication – ITTT Program

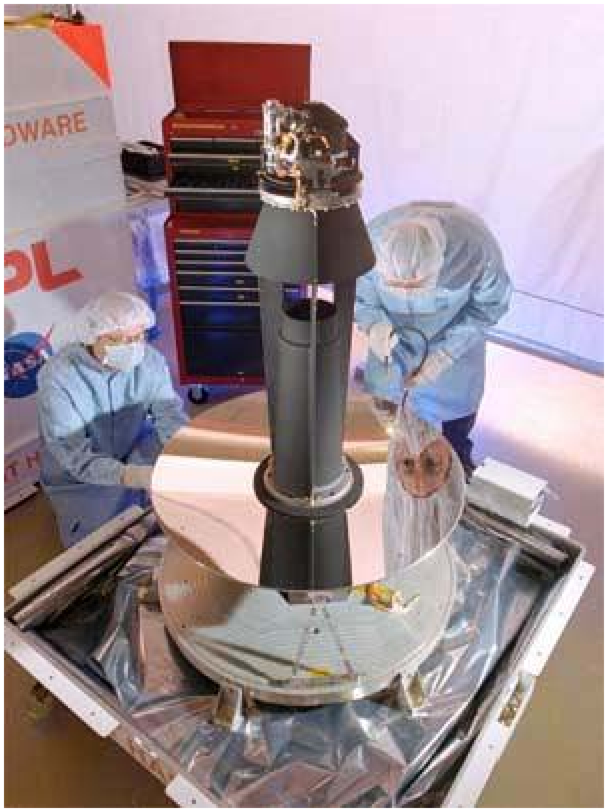
Spitzer PM Fabrication

GOODRICH

PM used Small Tool Computer Controlled Polishing

SM used Full Aperture Shaped Laps and Zonal Laps

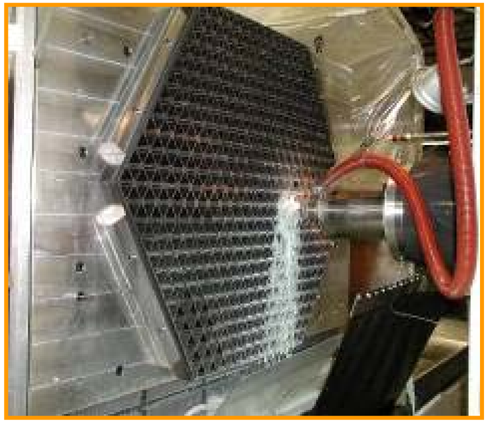
Spitzer Optical Telescope Assembly and Primary Mirror



JWST Mirror Manufacturing Process

Blank Fabrication

HIP Vessel being loading into chamber

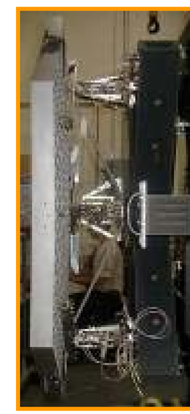


Machining of Web Structure

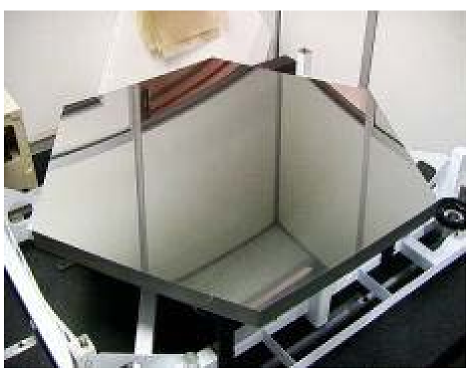
Machining

Machining of Optical Surface

Completed Mirror Blank



Polishing

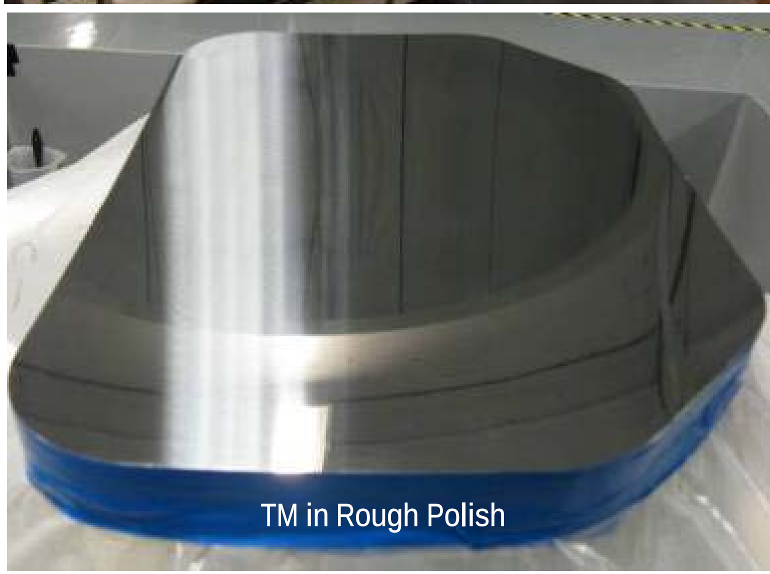


Mirror System Integration

Mirror Fabrication at L-3 SSG-Tinsley


Primary Mirror EDU Post Fine Polish


SM in Rough Polish


TM in Rough Polish

EDU Shipped to BATC for Cryo Testing

Optical Testing

Optical Testing

you cannot make what you cannot measure

In 1999, the NGST program had a problem.

To produce cryogenic mirrors of sufficient surface figure quality, it was necessary to test large-aperture long-radius mirrors at 30K in a cryogenic vacuum chamber with a high spatial resolution interferometer.

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

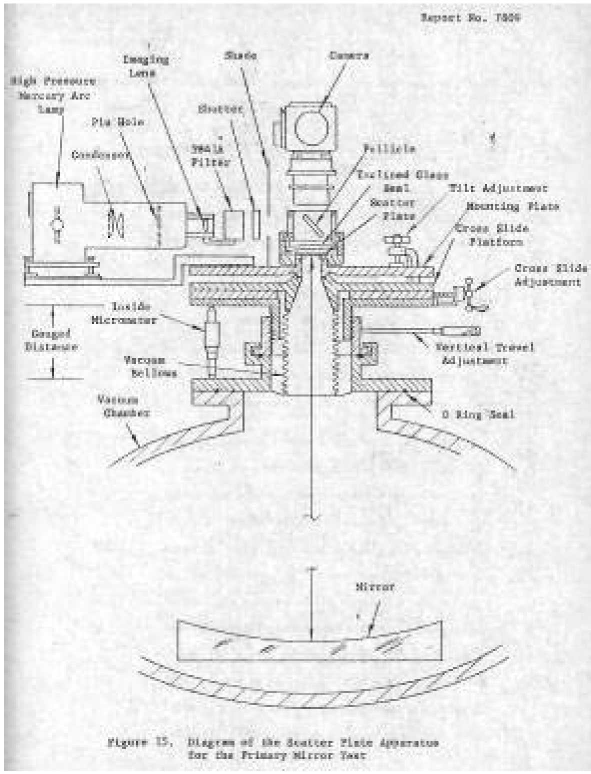
Spatial resolution was acceptable, but mechanical vibration made temporal phase-modulation impossible.

But this problem is nothing new …..

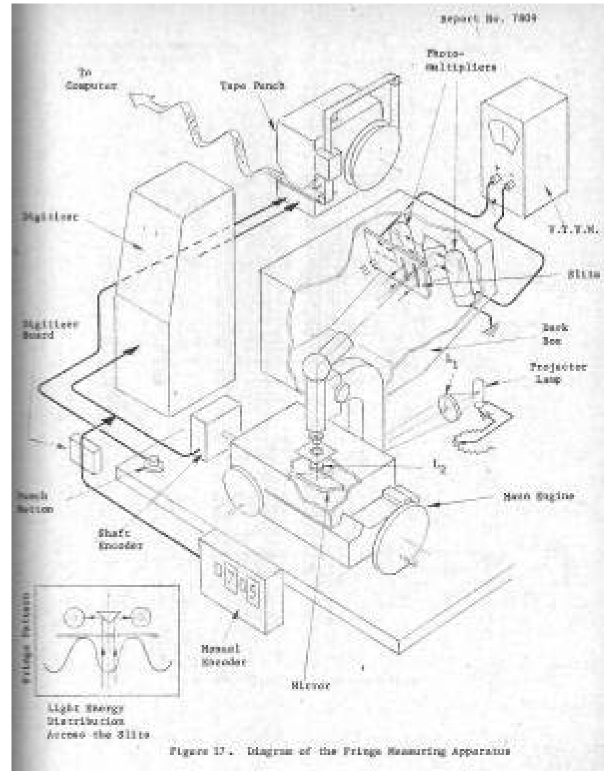
Stratoscope II – Optical Testing

One solution is common path interferometry

Scatterplate Interferometer



Fringe Scanning Digitizer



(And, in grad school I thought scatterplate interferometer was a laboratory curiosity.)

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

OAO-C also used scatter plate interferometry

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

Hubble Testing

Another solution is 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
- PE tested in the vertical ‘Ice-Cream Cone’ vacuum chamber

Even in the 1990’s when I worked at PE (then Hughes) I would hand digitize meter class prints of interferograms.

Hubble Primary Mirror Optical Testing

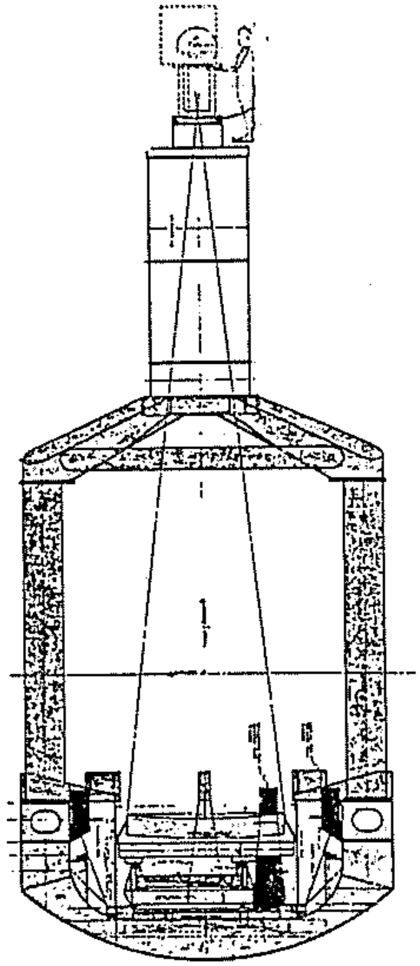
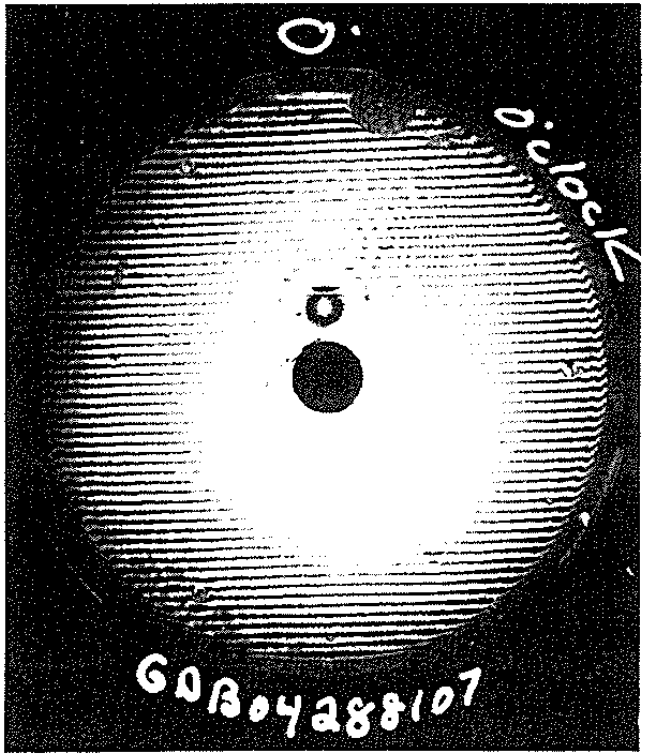


Figure 2. Primary mirror test configuration.



OG-768-83

Figure 13. Interferogram of finished primary mirror.

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

Hubble Interferogram Digitization & Analysis

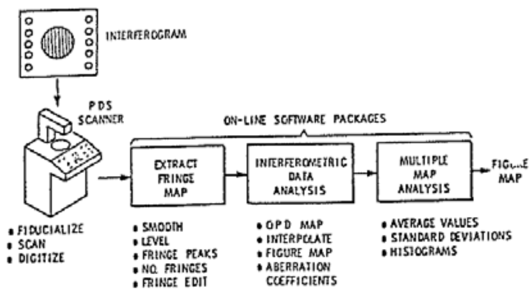


Figure 14. Interferogram analysis facility.

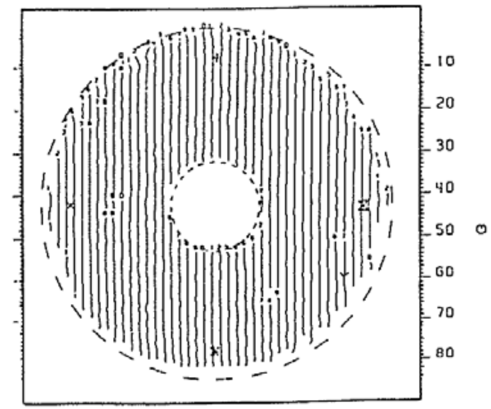


Figure 15. Fringe map.

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.

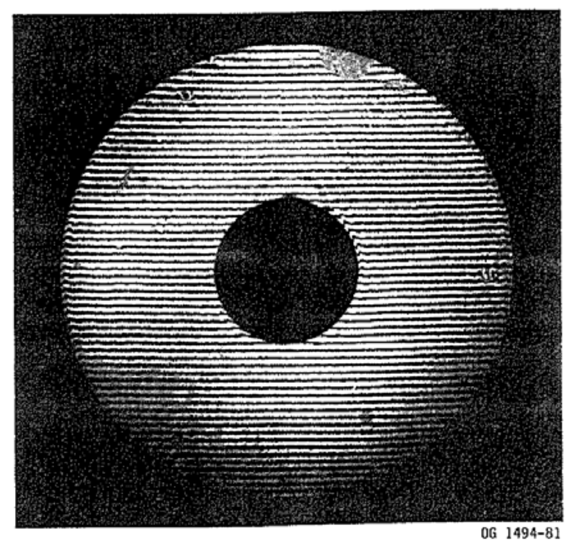


Figure 17. Interferogram of finished primary mirror masked to its clear aperture.

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

GOODRICH

Another solution is structurally connect interferometer and test.

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

PhaseCAM

At BRO, I designed, built and wrote the software for a 480 Hz common path phase-measuring Twyman-Green interferometer that was used to test all the Keck segments at ITEK.

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.

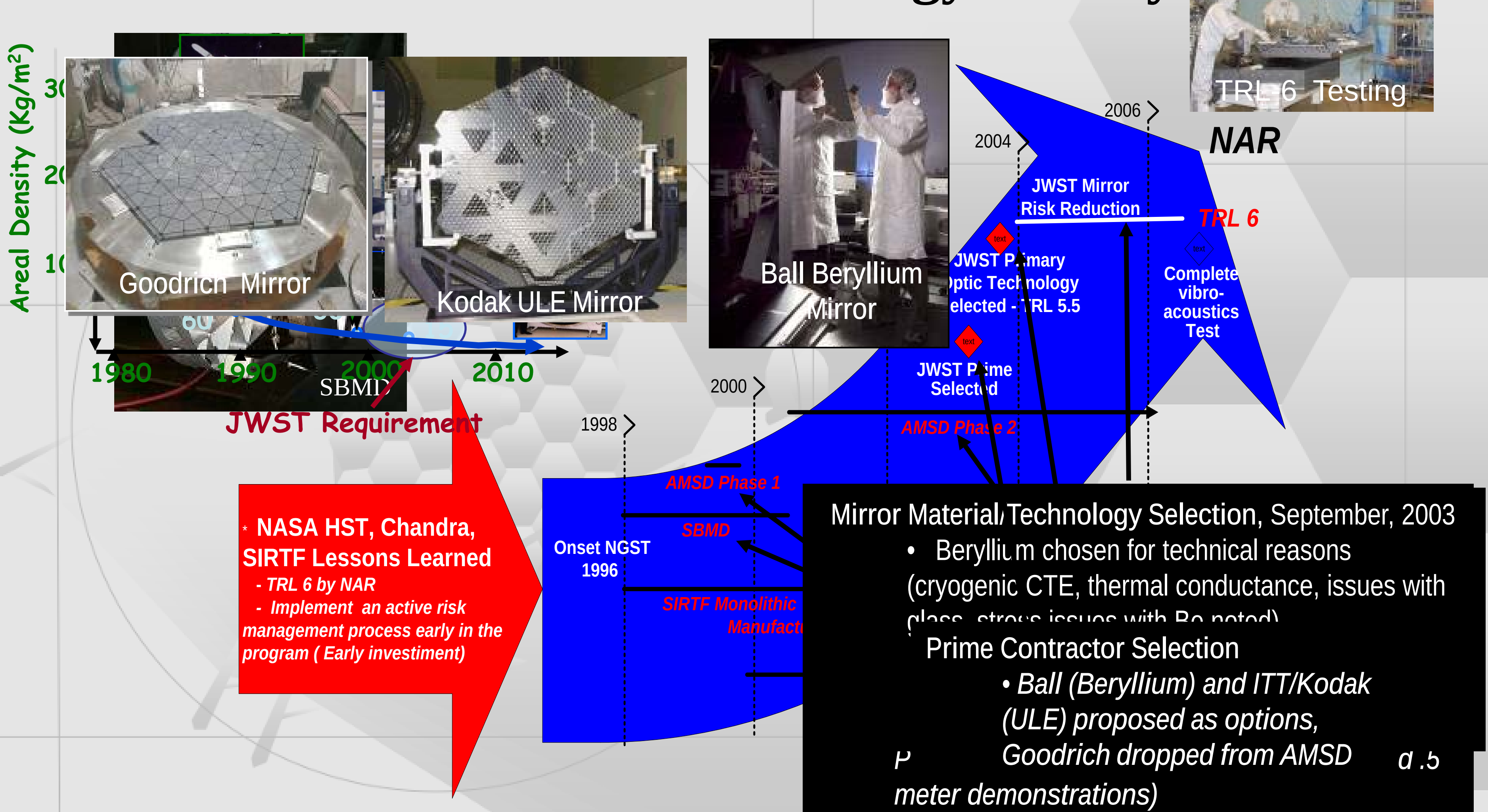
When I got to NASA I defined the specifications for and ordered the first PhaseCAM interferometer.

Today they are critical to JWST.

Tech Days 2001

Mirror Technology Development

JWST Mirror Technology History



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

AMSD – Ball & Kodak

Specifications

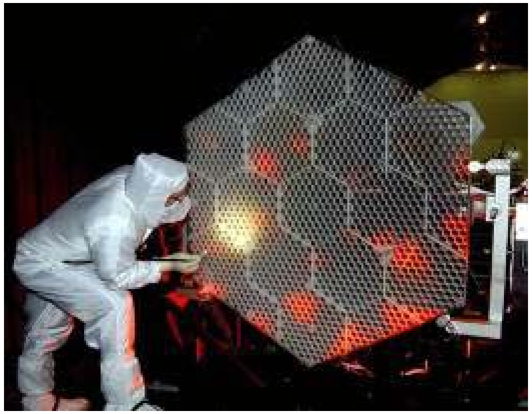
Diameter	1.4 meter point-to-point
Radius	10 meter
Areal Density	< 20 kg/m2
Areal Cost	< $4M/m2

Beryllium Optical Performance

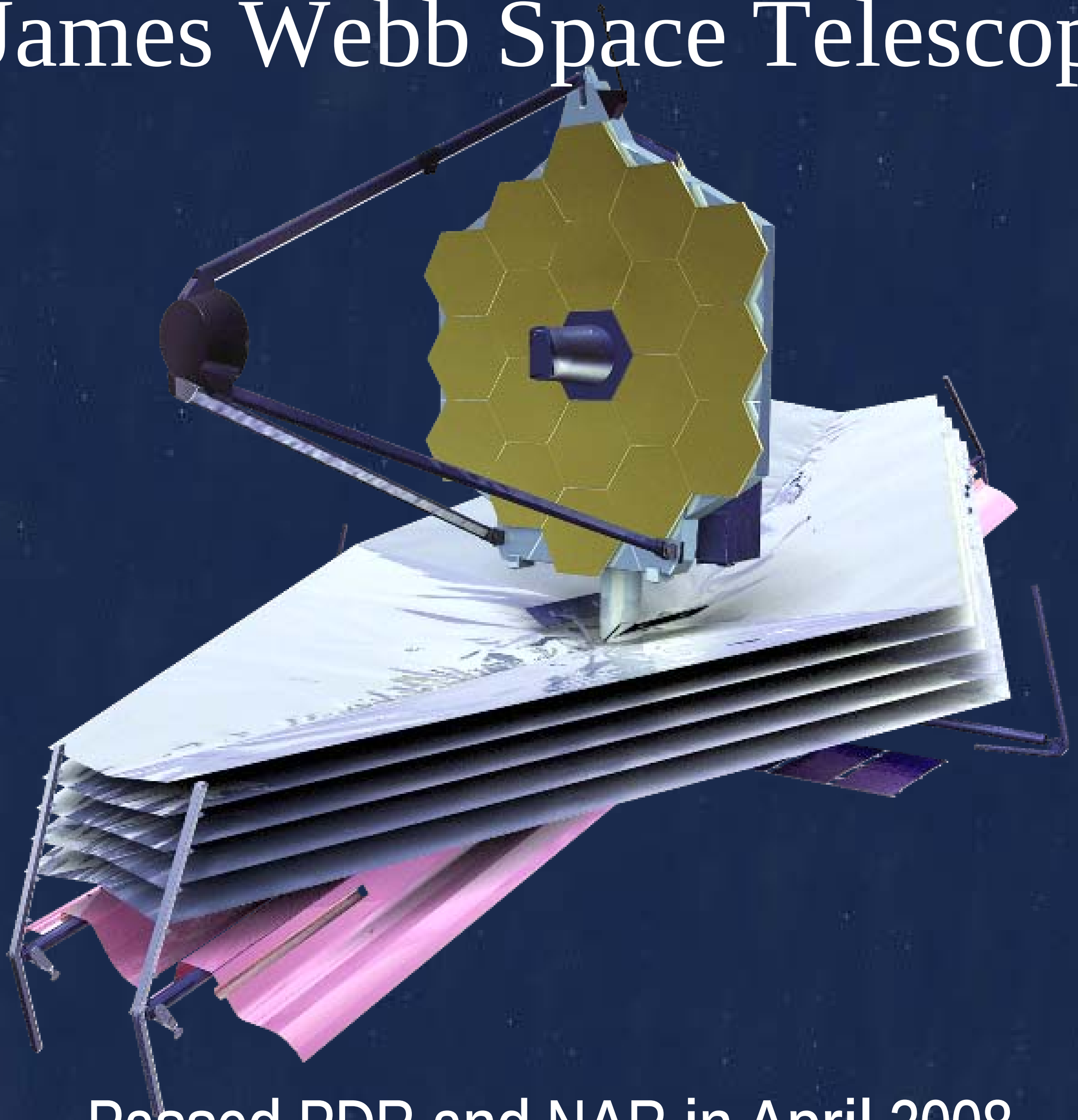
Ambient Fig	47 nm rms (initial)
Ambient Fig	20 nm rms (final)
290K – 30K	77 nm rms
55K – 30K	7 nm rms

ULE Optical Performance

Ambient Fig	38 nm rms (initial)
290K – 30K	188 nm rms
55K – 30K	20 nm rms



James Webb Space Telescope



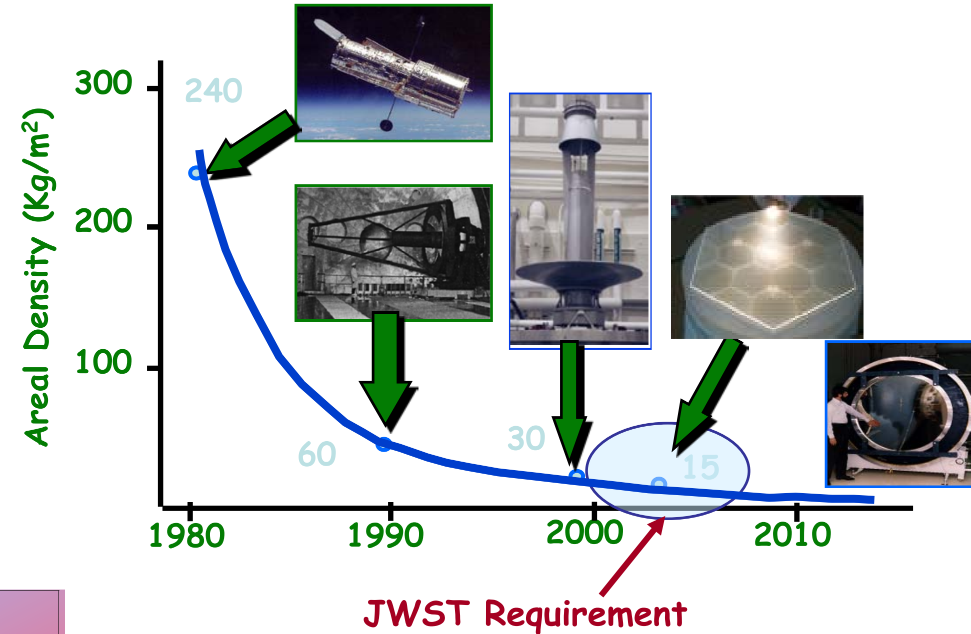
Passed PDR and NAR in April 2008

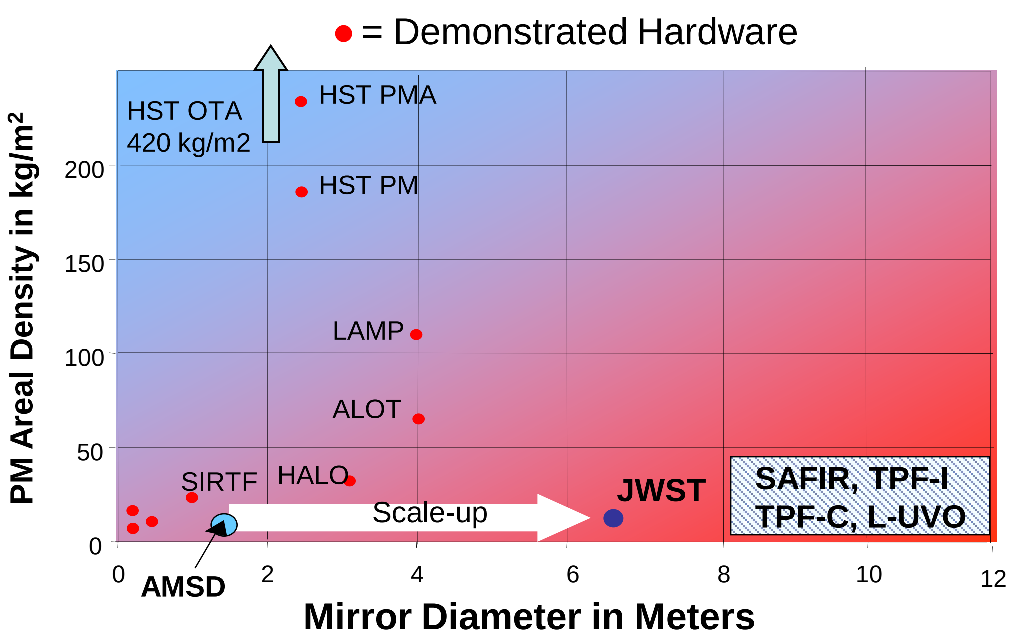
Mirror Technology Development - 2000

Challenges for Space Telescopes:

Areal Density to enable up-mass for larger telescopes.

Cost & Schedule Reduction.





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

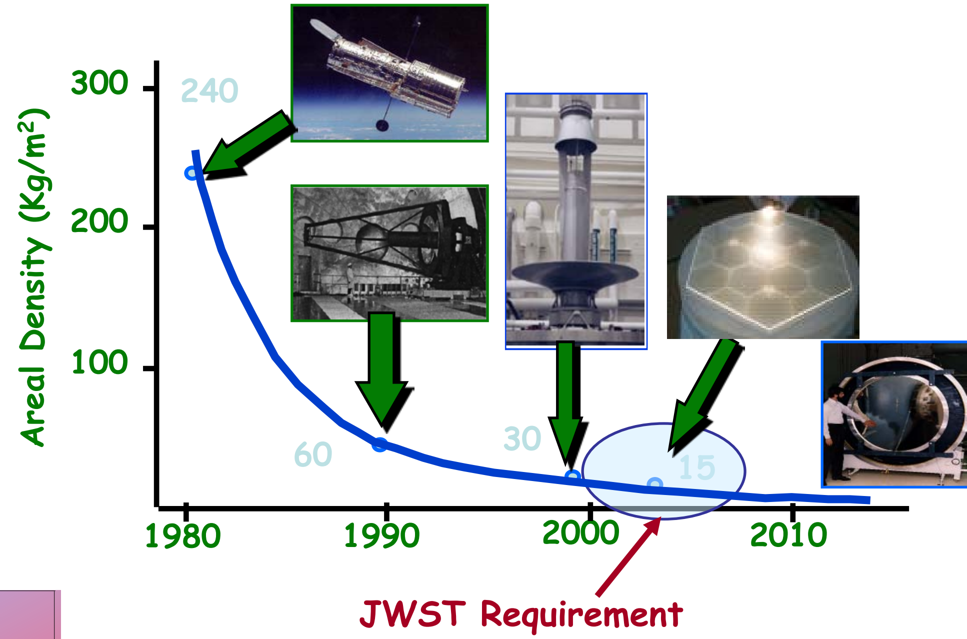
Note: Areal Cost in FY00 $

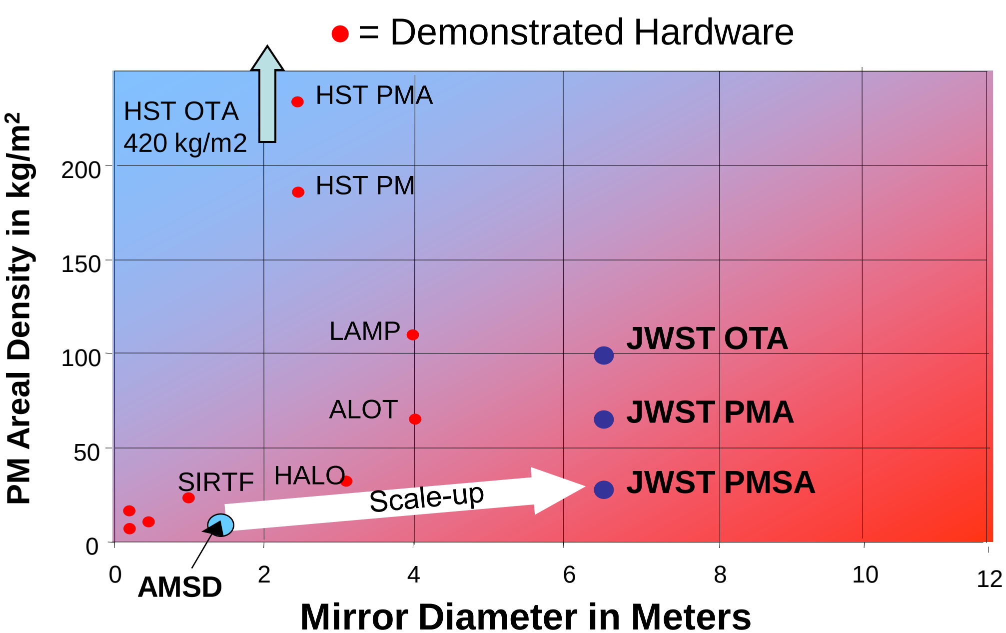
Mirror Technology Development 2008

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



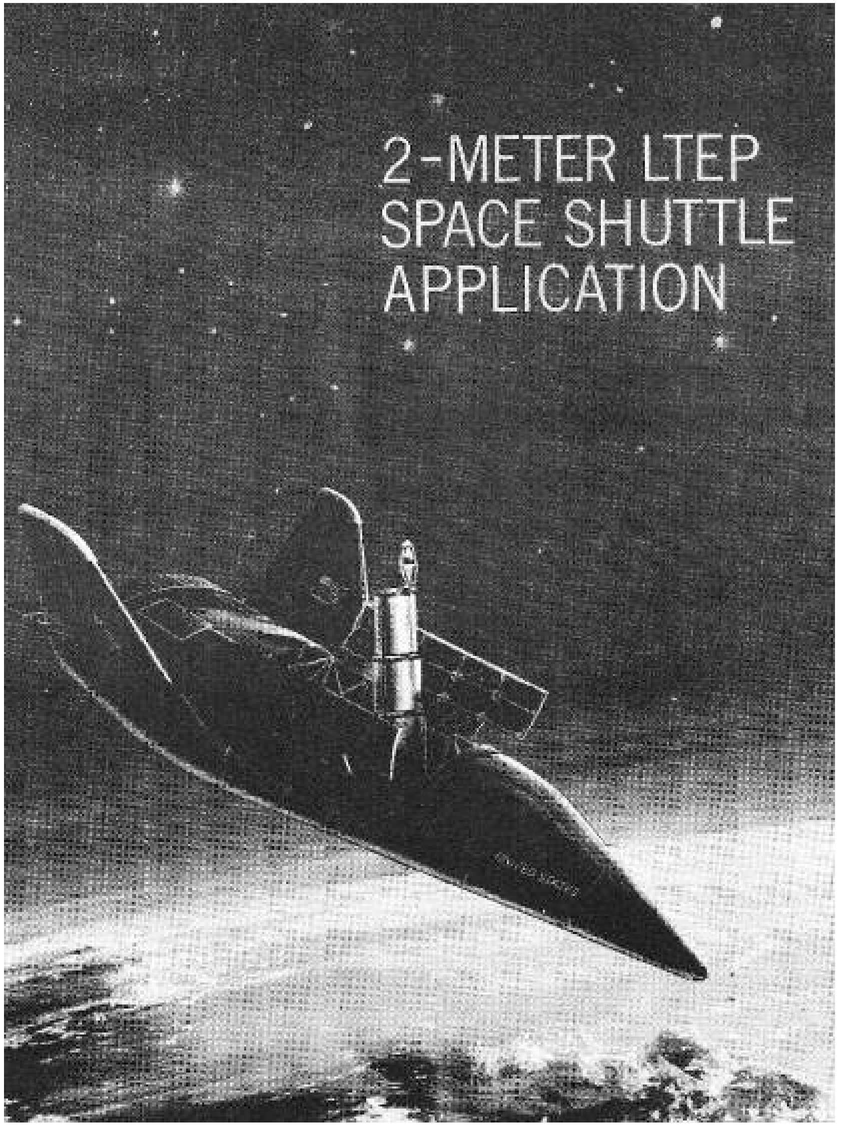


Primary Mirror	Time &	Cost
HST (2.4 m)	≈ 1 m^2/yr	≈ \$12M/m^2
Spitzer (0.9 m)	≈ 0.3 m^2/yr	≈ \$12M/m^2
AMSD (1.2 m)	≈ 0.7 m^2/yr	≈ \$5M/m^2
JWST (6.5 m)	≈ 5 m^2/yr	≈ \$6M/m^2

Note: Areal Cost in FY08 $

Chickens, Eggs and the Future

Was Shuttle designed to launch Great Observatories or were Great Observatories designed to be launched by the shuttle?



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

Design Synergy

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

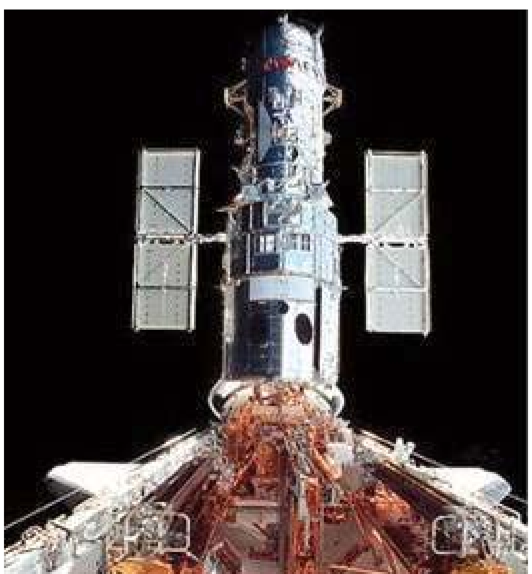
Generic Shuttle-based carriers to berth and service on-orbit

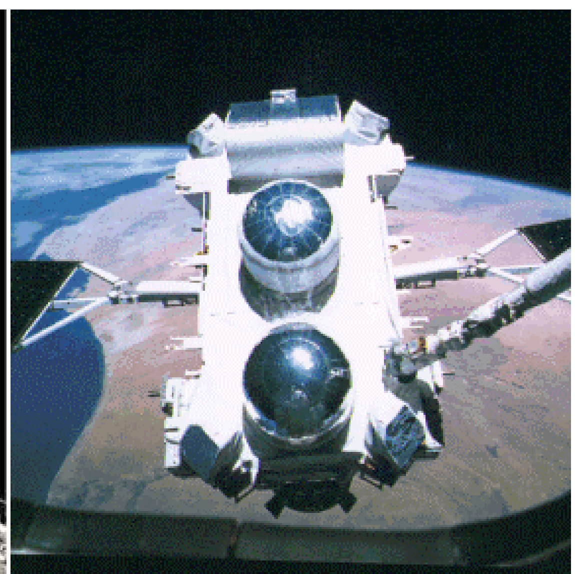
Chandra and Spitzer were originally intended to be serviceable.

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)			

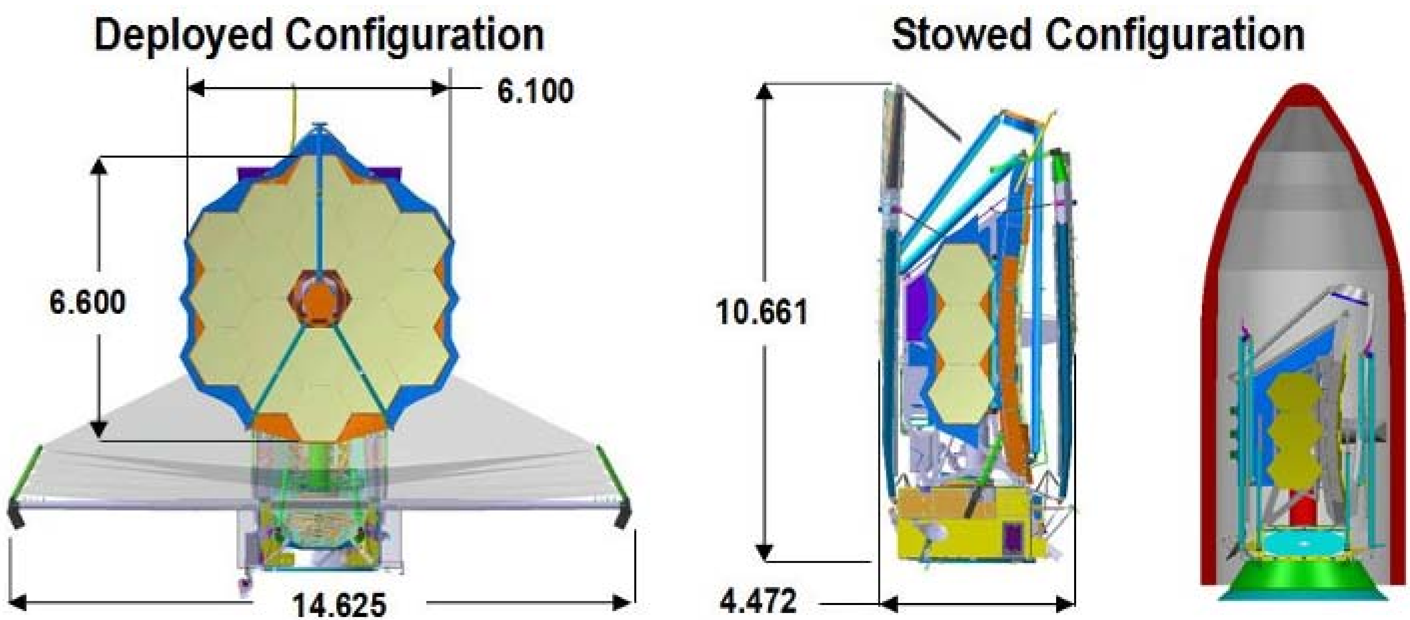




Launch Vehicles Continue to Drive Design

Similarly, JWST is sized to the Capacities of Ariane 5

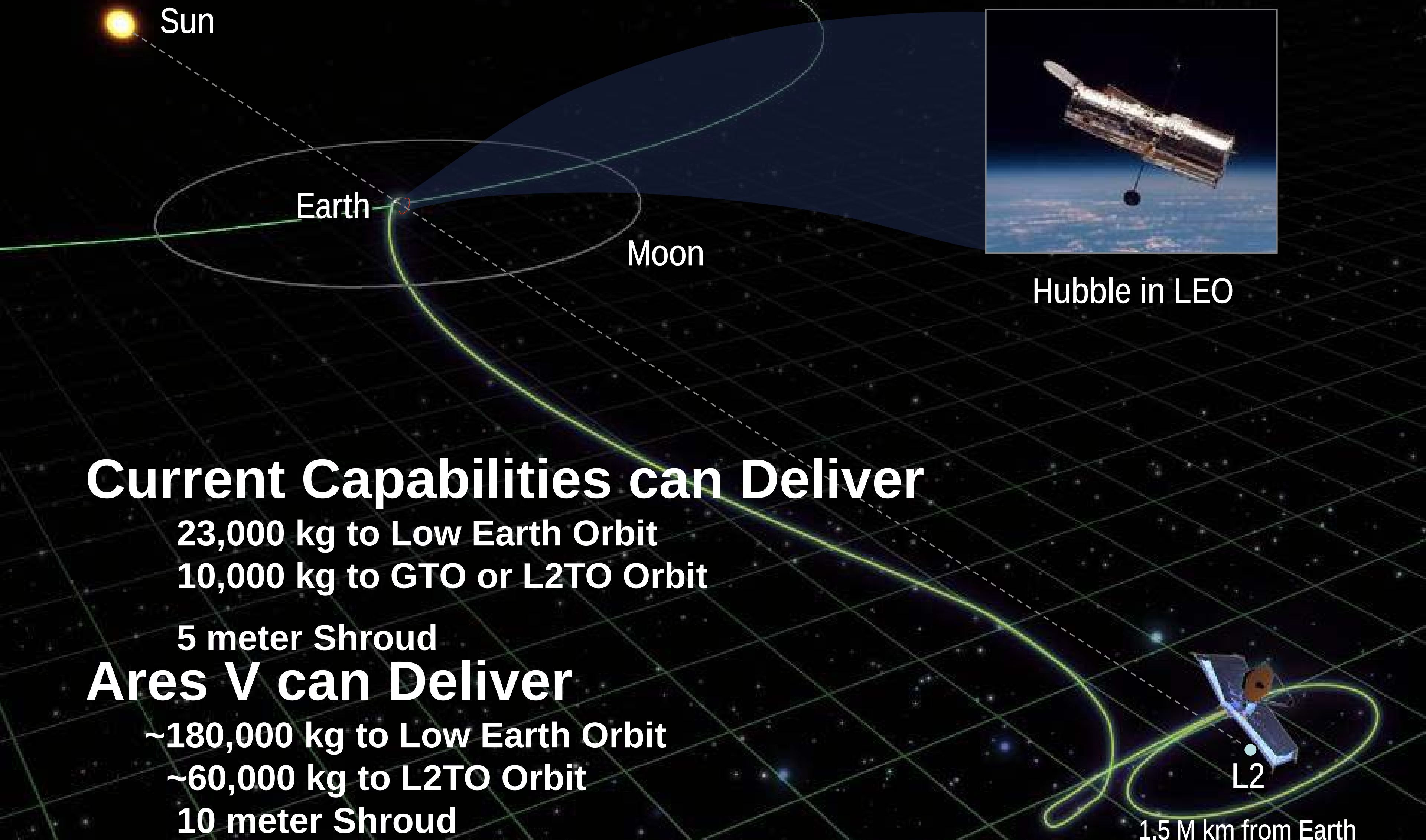
	Payload Mass	Payload Volume
Ariane 5	6600 kg (at SE L2)	4.5 m x 15.5 m
James Webb Space Telescope	6530 kg (at SE L2)	4.47 m x 10.66 m



And now the FUTURE …..

Ares V is a Disruptive Capability which offers the potential for completely new Mission Concepts

Ares V delivers 6X more Mass to Orbit



Hubble in LEO

Current Capabilities can Deliver

23,000 kg to Low Earth Orbit
10,000 kg to GTO or L2TO Orbit

5 meter Shroud

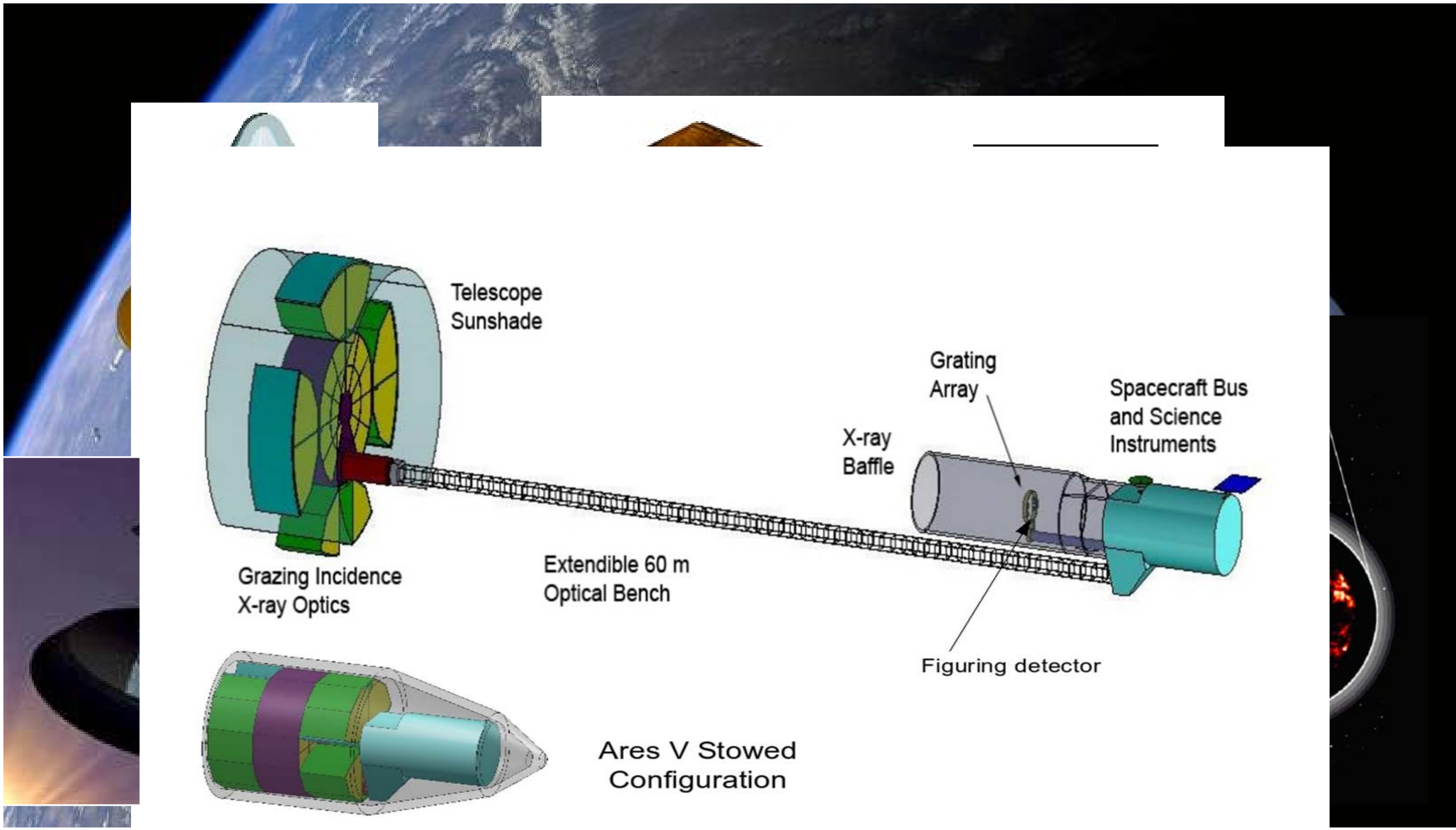
Ares V can Deliver

~180,000 kg to Low Earth Orbit
~60,000 kg to L2TO Orbit
10 meter Shroud

Ares V Changes Paradigms

Ares V Mass & Volume enable entirely new Mission Architectures:

- 8 meter class Monolithic UV/Visible Observatory



Acknowledgements

Mark Stier and Dave Chadwick
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Tom Parsonage of Brush-Wellman

Jim Bilbro retired NASA
and his historical reports

Any Question?