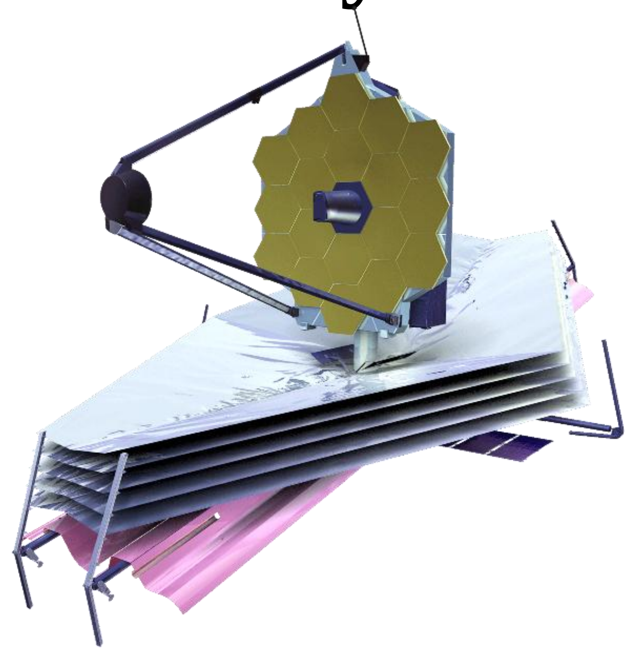
50 years of NASA Mirror Technology Development:

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 … Astronomy has a far greater potential for advancement by the space program than any other branch of physics".

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.

<u>Stratoscope II</u> mirror designed for ‘soft’ balloon flight and not suitable for the more 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)

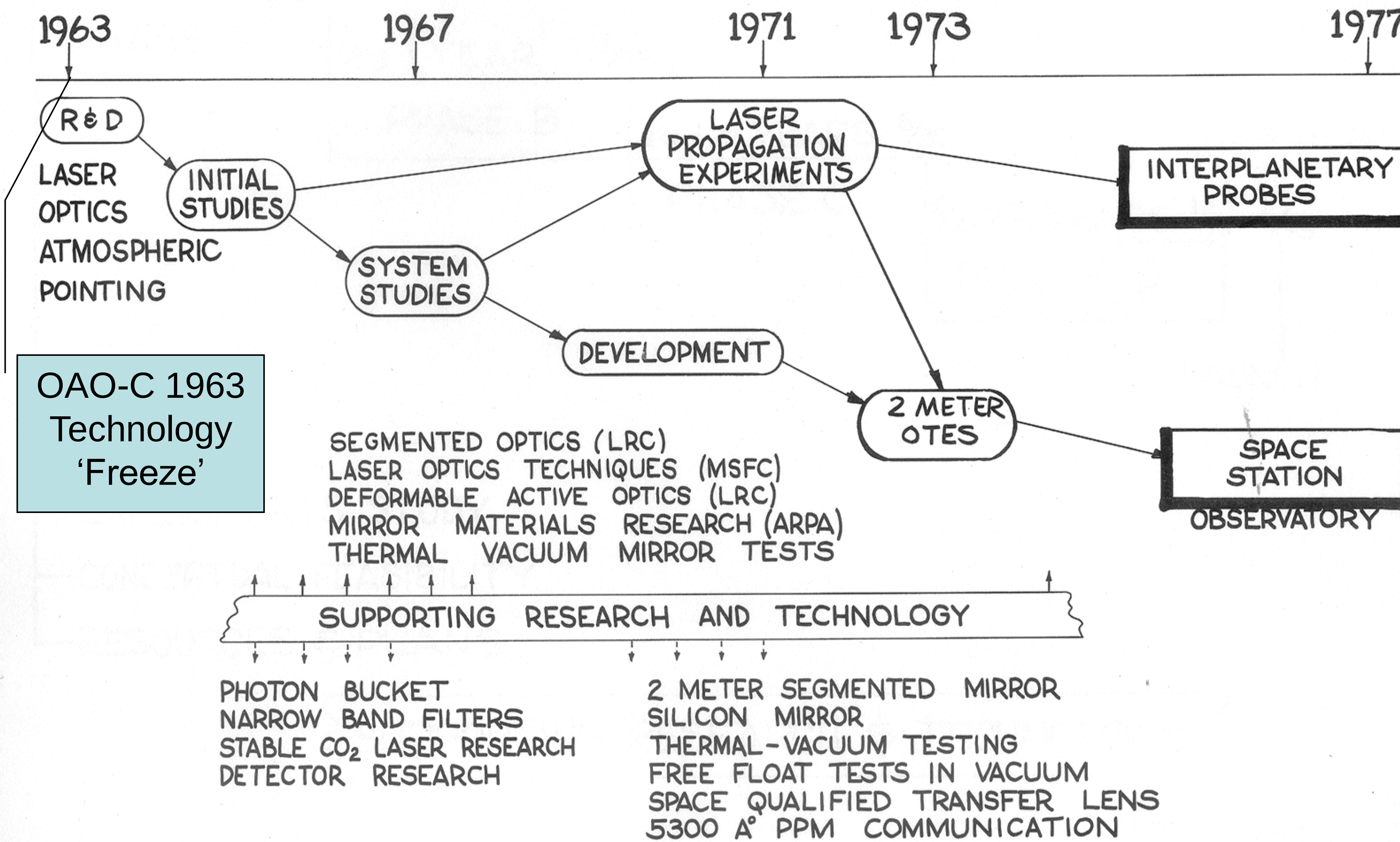
- Conceived by Martin Schwarzchild
- Build by Perkin-Elmer
- 30 cm (12 inch) primary mirror
- Film recording

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



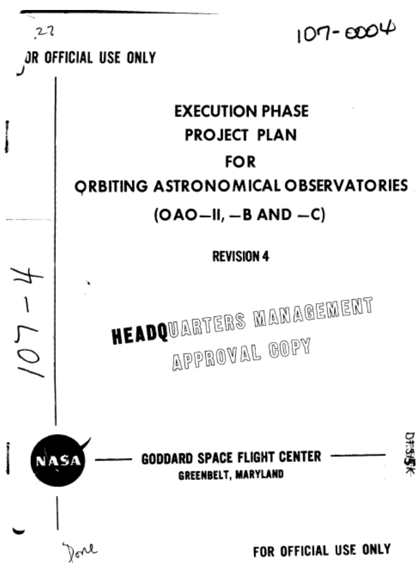
PERKIN-ELMER

Orbiting Astronomical Observatory (OAO) Satellites

OAO started in 1957 after launch of Sputnik to do astronomical science in a universal spacecraft of less than 50 kg. Kick-off meeting was in 1959. Ames defined Requirements, GSFC was lead center, Grumman was Prime.

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 when Atlas Centaur didn't achieve orbit
- OAO-C Aug 1972 to Feb 1981



107-0004

OR OFFICIAL USE ONLY

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

REVISION 4

HEADQUARTERS MANAGEMENT
APPROVAL COPY

107-4

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

Done

FOR OFFICIAL USE ONLY

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-II

OAO-II had two experiment packages

Wisconsin Experiment

7 independent observing sensors

Smithsonian Astrophysics Observatory Experiment

4 independent Schwarzchild Cameras

30 cm aperture

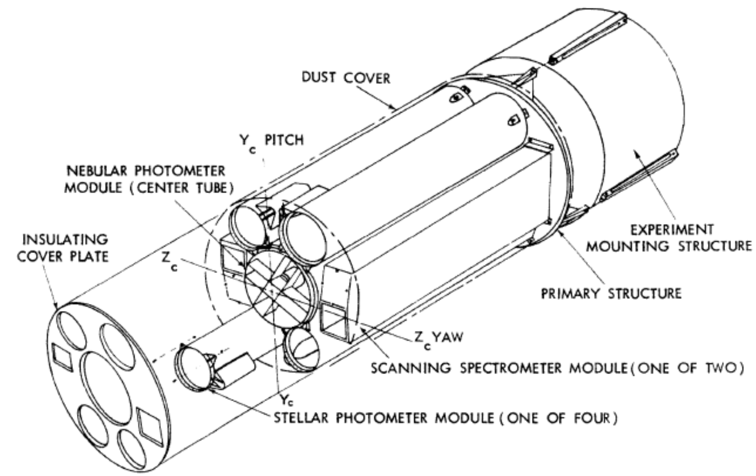


Figure 3. University of Wisconsin Experiment Package

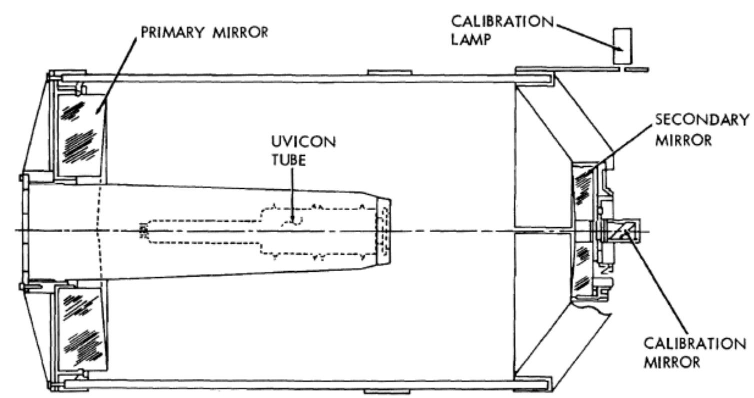


Figure 4. Schwarzchild Camera, SAO


107-0004
FOR OFFICIAL USE ONLY

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

REVISION 4

HEADQUARTERS MANAGEMENT
APPROVAL COPY

107-4

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

Done

FOR OFFICIAL USE ONLY

OAO-GEP (Goddard Experiment Package

OAO-B or OAO-GEP
- 96 cm RC telescope
- PM: S200B Beryllium; electroless Ni
- SM: fused silica; MgF_2
- 7 channel UV Spectrometer
- Guider: 0.2 arc-sec @ +2 mag;
  - 10 arc-sec @ +17 mag

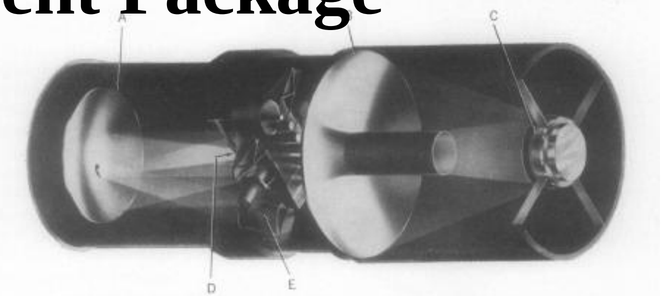
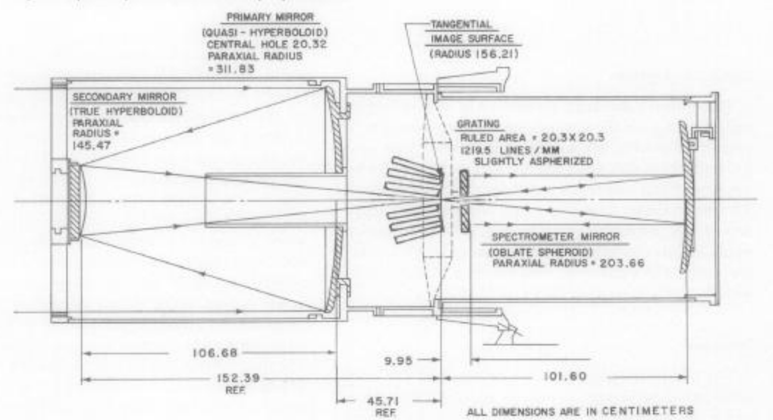


Fig. 4. Drawing of the GEP optical subsystem. A—spectrometer mirror; B—primary mirror; C—secondary mirror; D—grating area (grating not visible); E—fine guidance optics.

Fig. 5. Optical layout of the GEP telescope spectrometer.



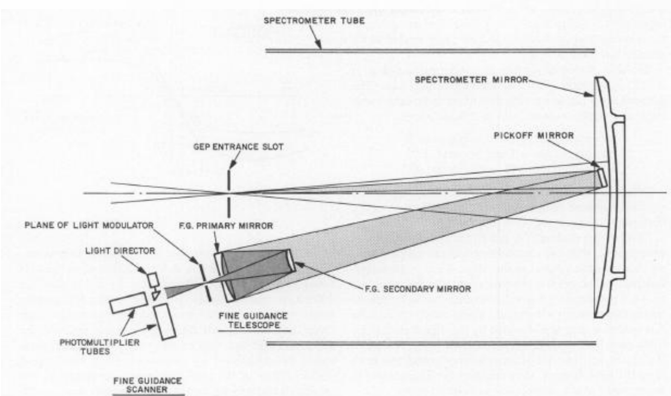
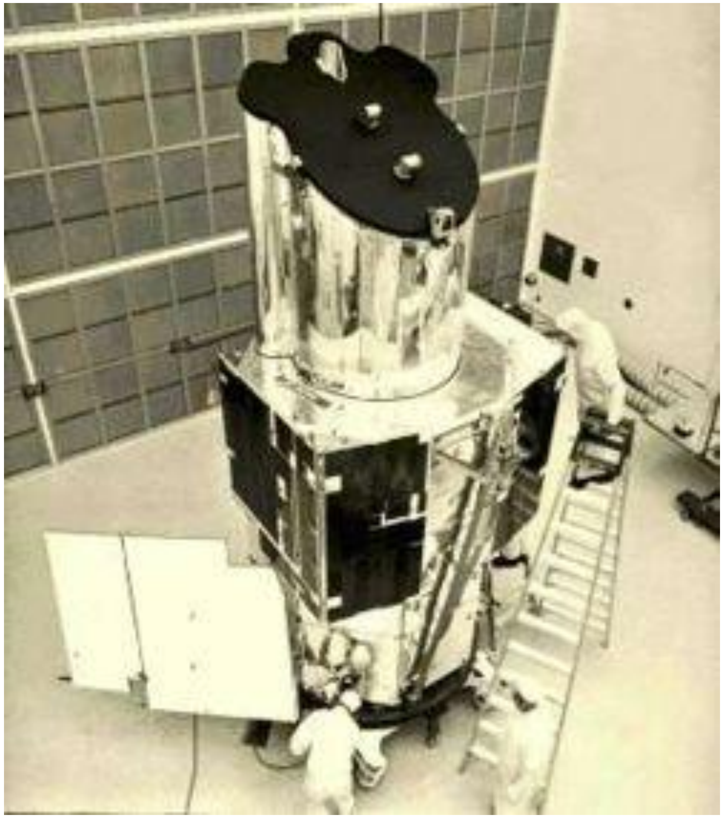


Fig. 6. Layout of the fine guidance optical system.

"The Goddard Experiment Pacakage – 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 (Copernicus)



OAO-C had two Science Experiments

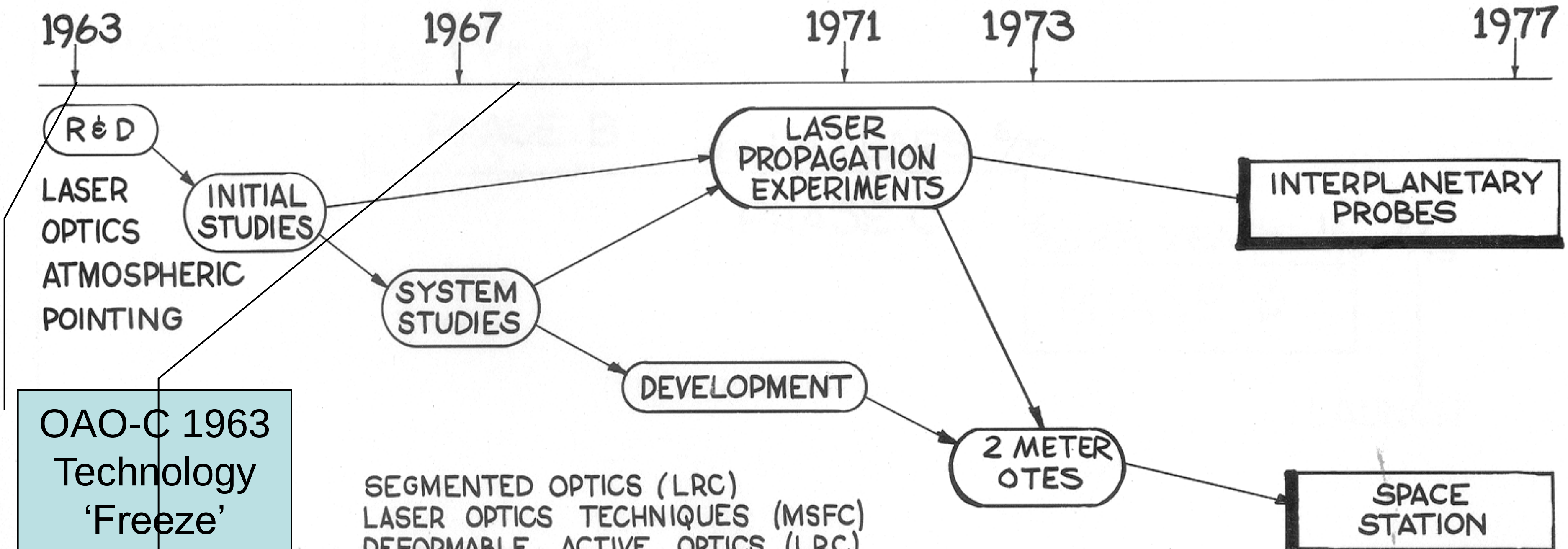
Princeton Experiment Package was a UV Spectrometer

- 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?

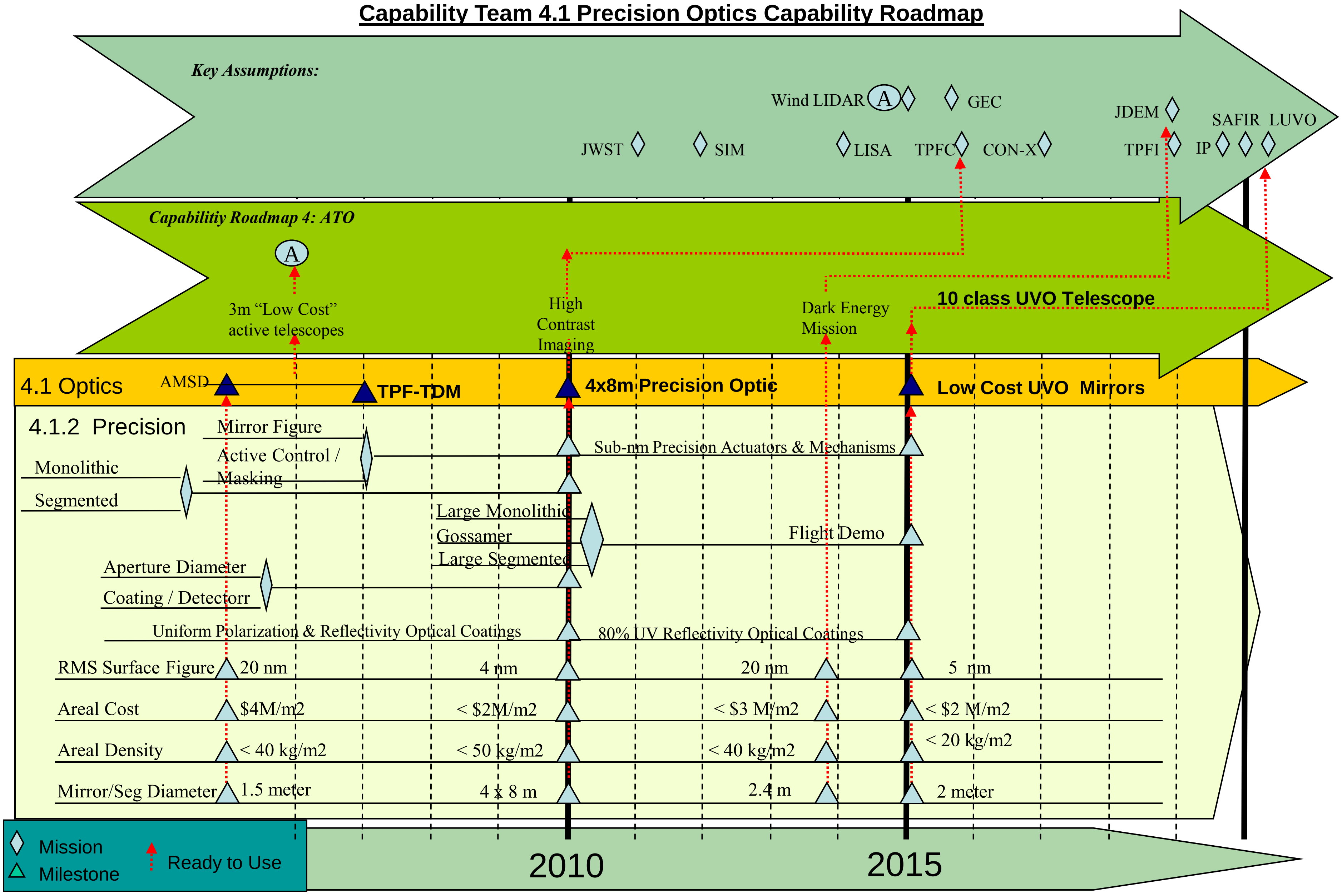
NASA SPACE OPTICS TECHNOLOGY PLAN



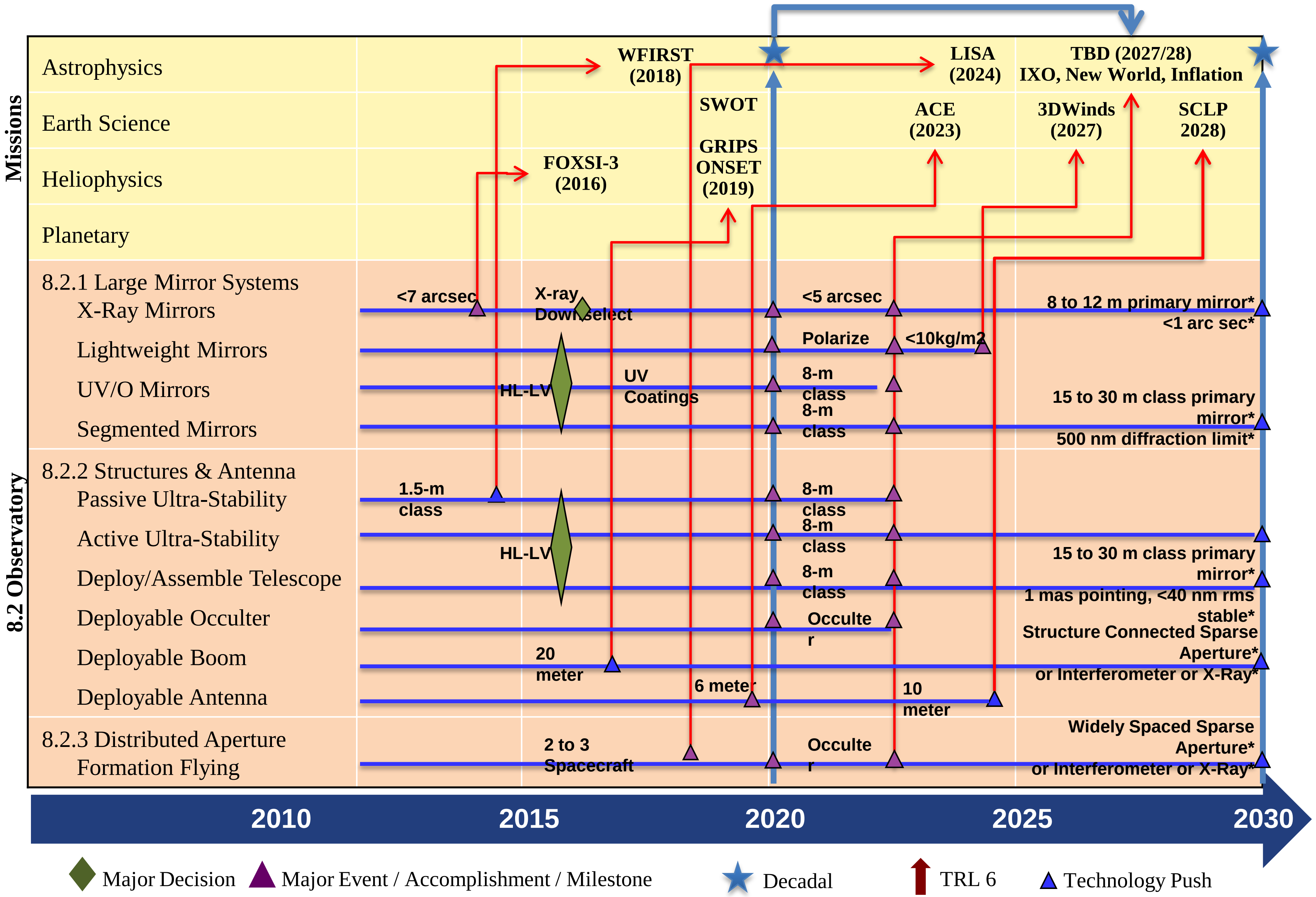
OAO-C 1963
Technology
'Freeze'

"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

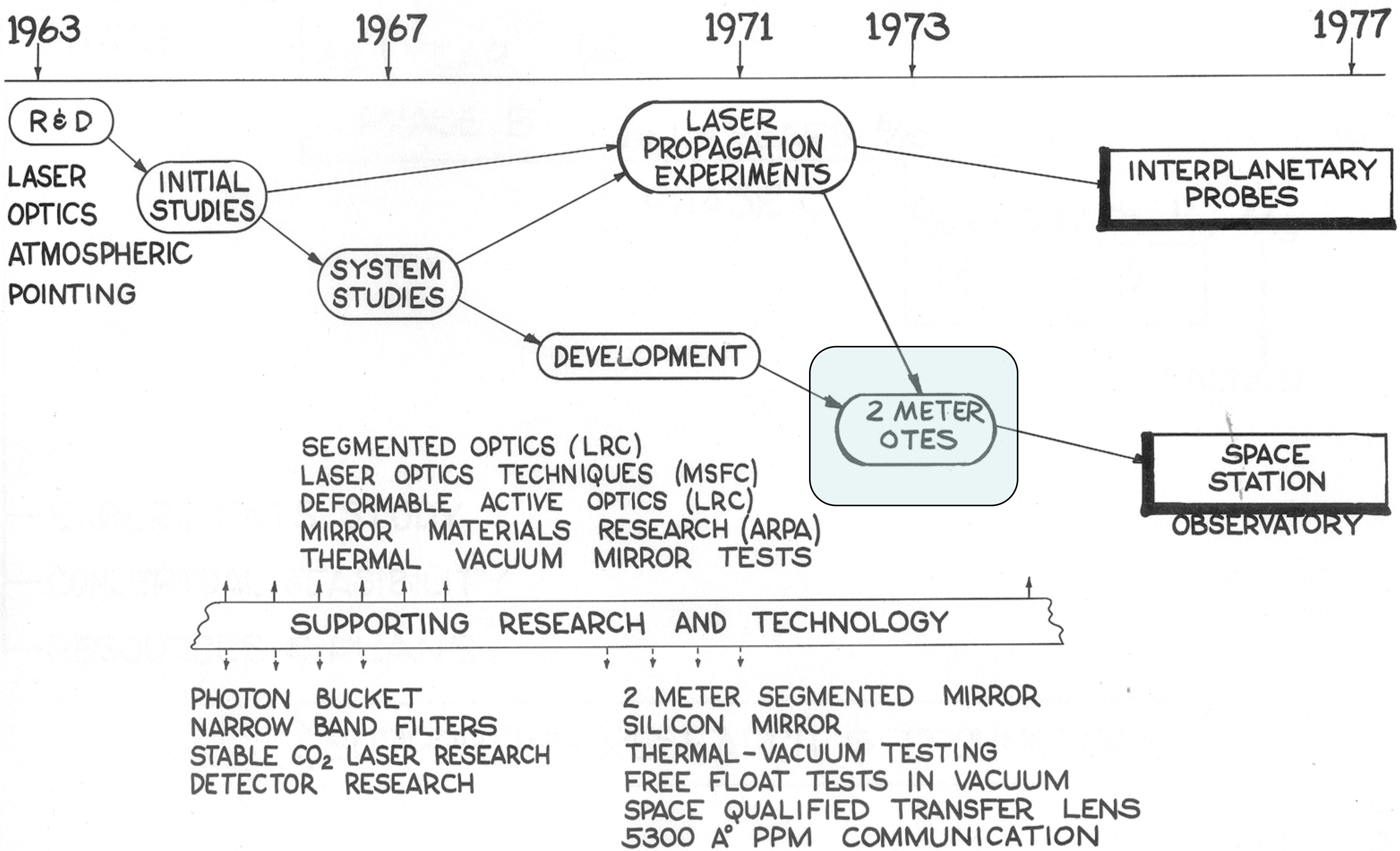
ATO CRM Optics Roadmap (NRC 2005)



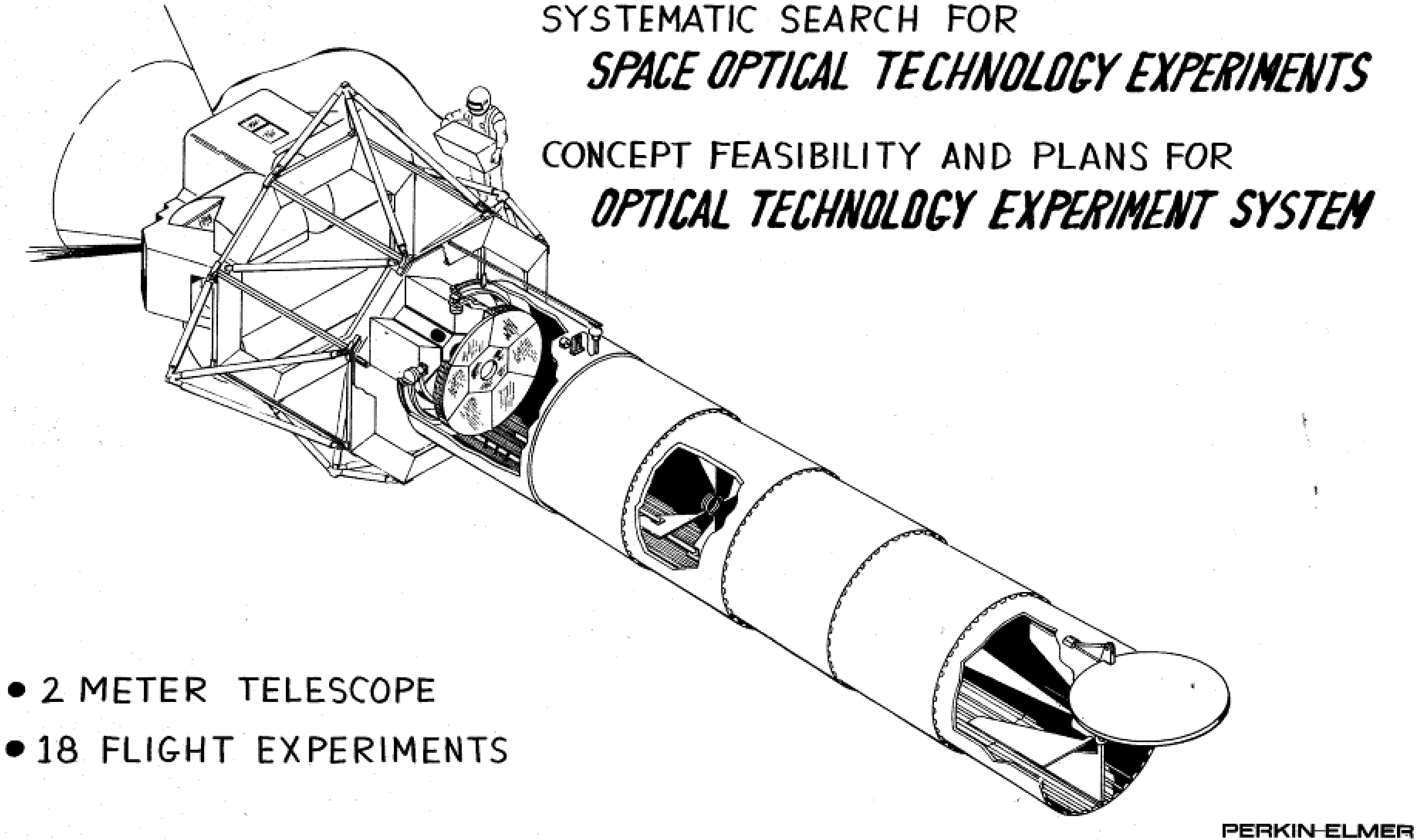
8.2 Observatories Roadmap (OCT, 2011)



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.

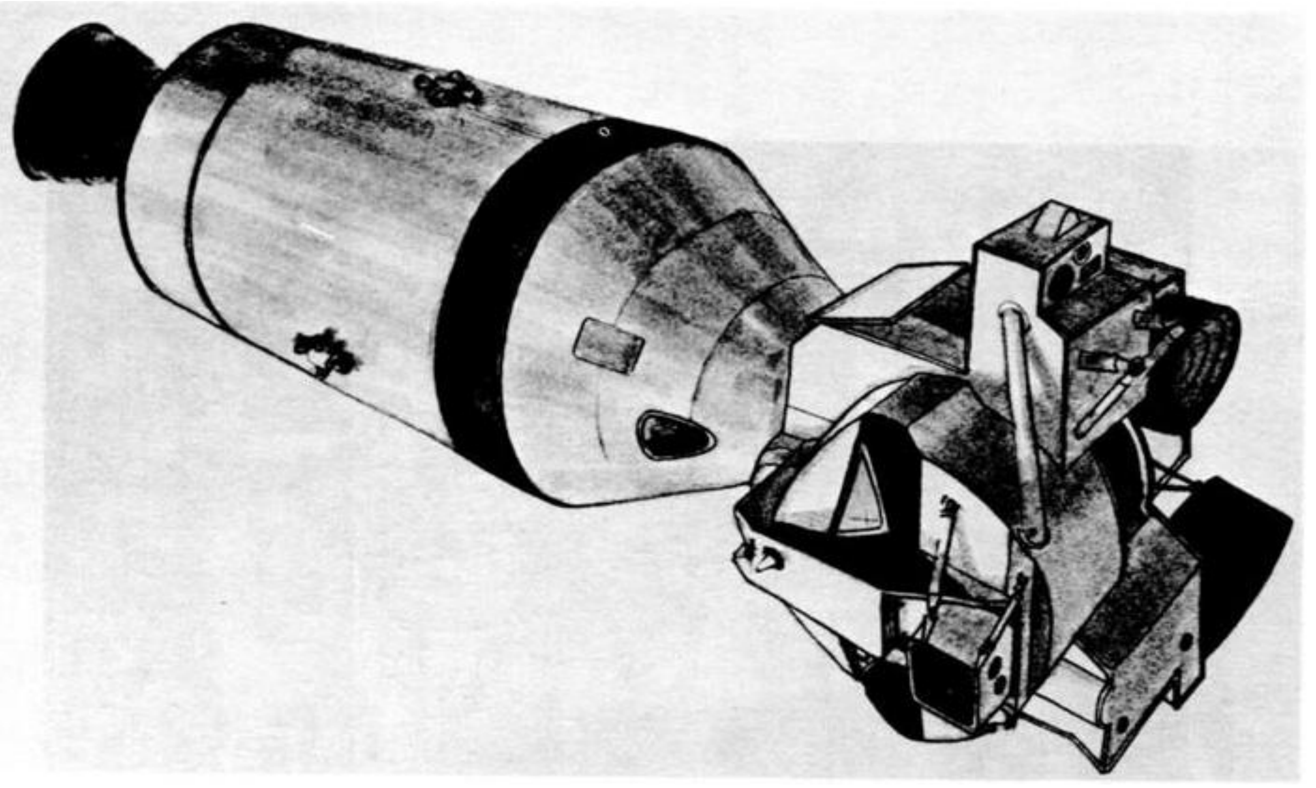
Data … are critical for settling major questions in cosmology:

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.



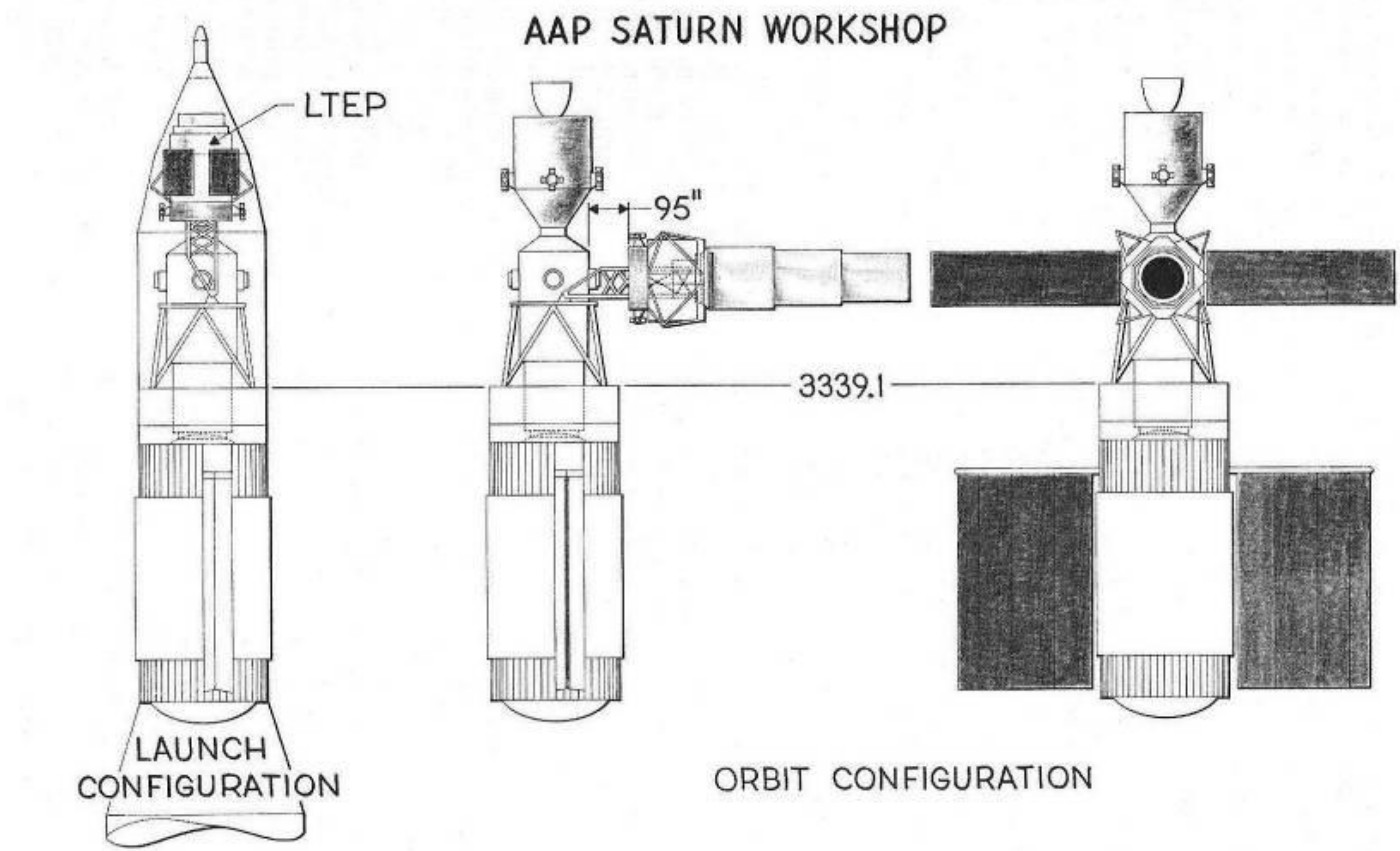
While this particular concept was never built, aspects of the design evolved into Skylap and the Apollo Telescope Mount.

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

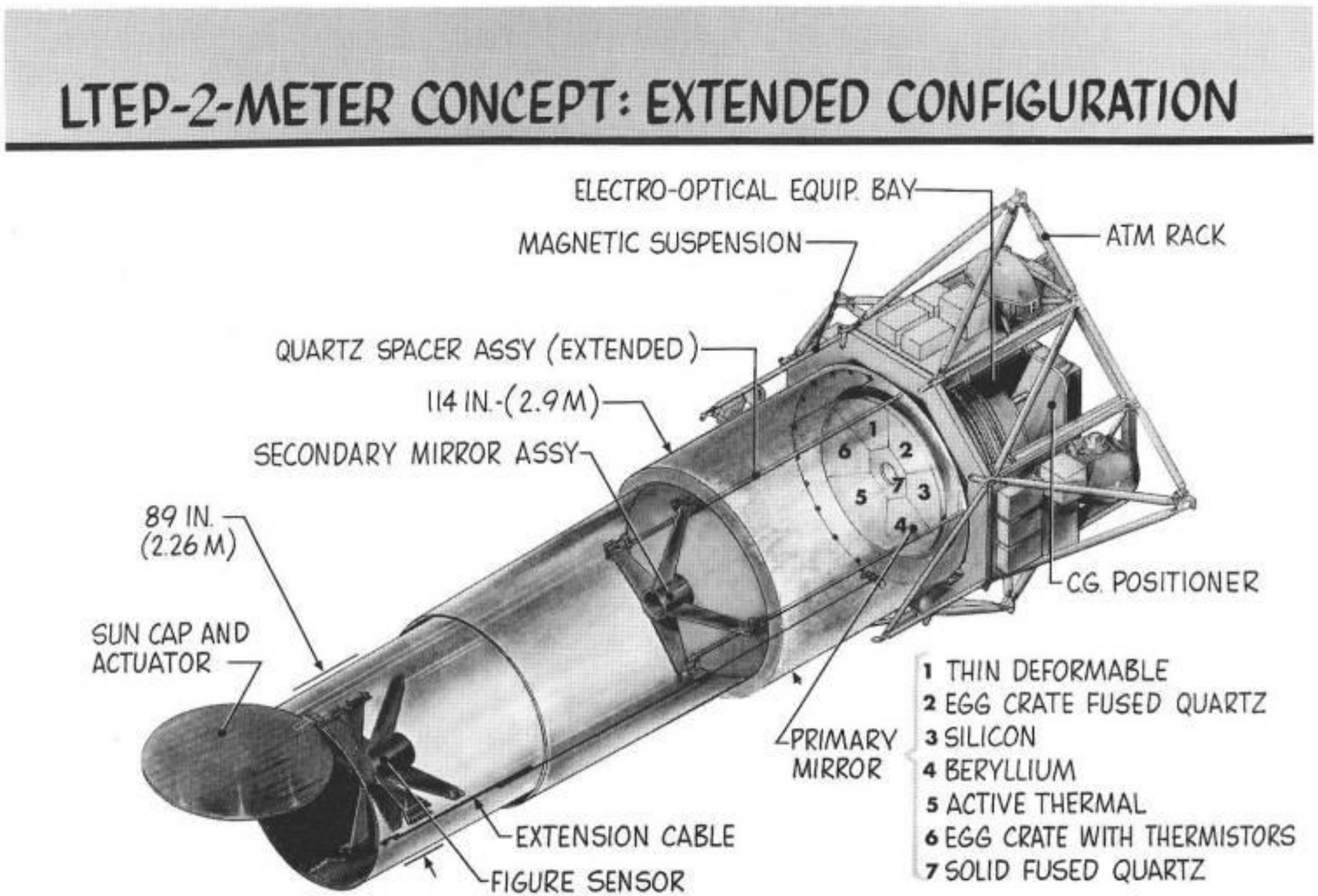
1969 Technology Needs

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

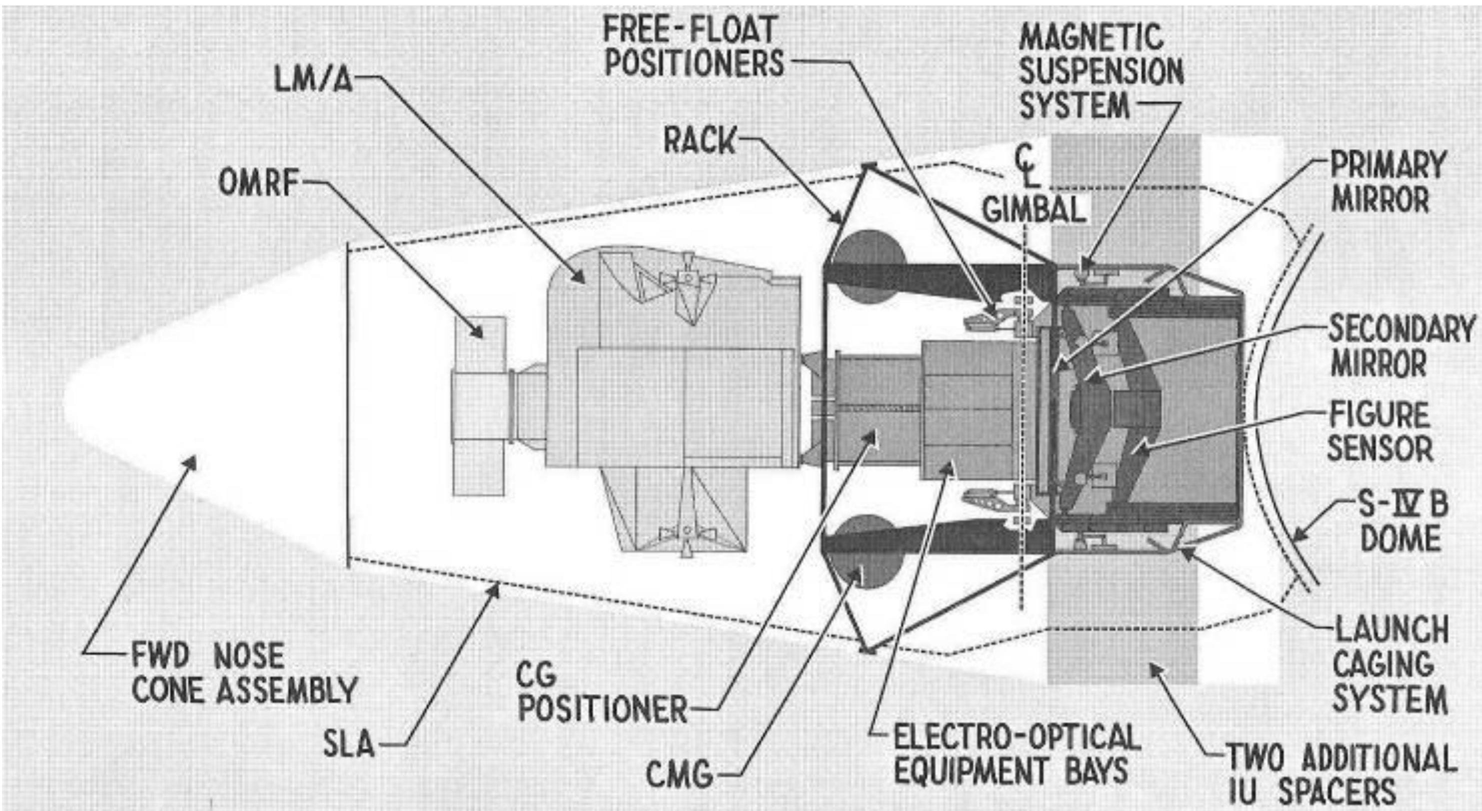
- Precision figuring of 120-inch mirrors to 1/50 wave rms
- Long-term substrate stability to 1/50 wave rms for 120-inch mirrors
- Long-life high-reflectivity ultraviolet mirror coatings
- Stellar pointing to 1/100 arc-second for a 120-inch space telescope
- Space maintenance of large astronomical telescopes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

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

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

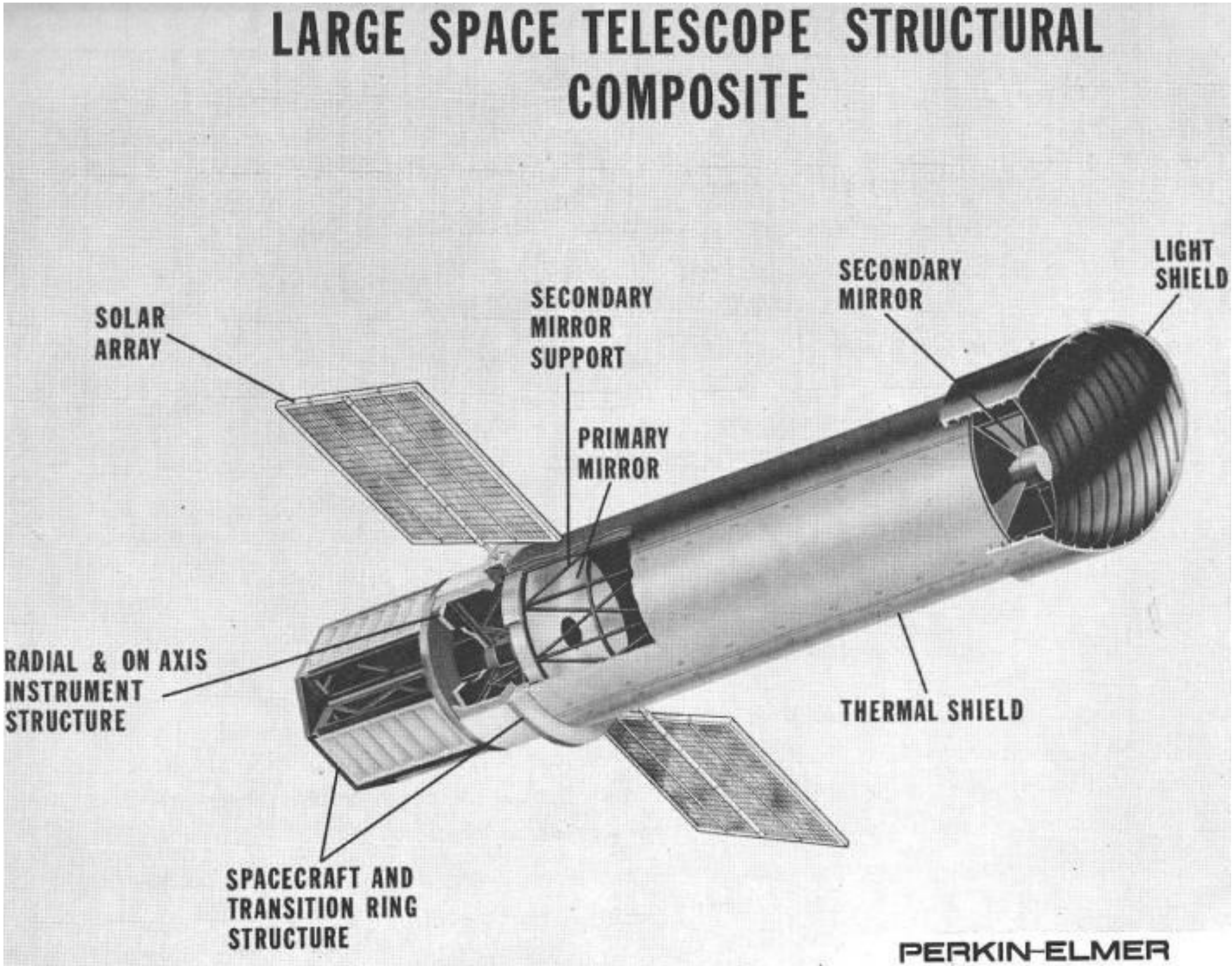


Initial Launch Configuration for Saturn IB



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

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

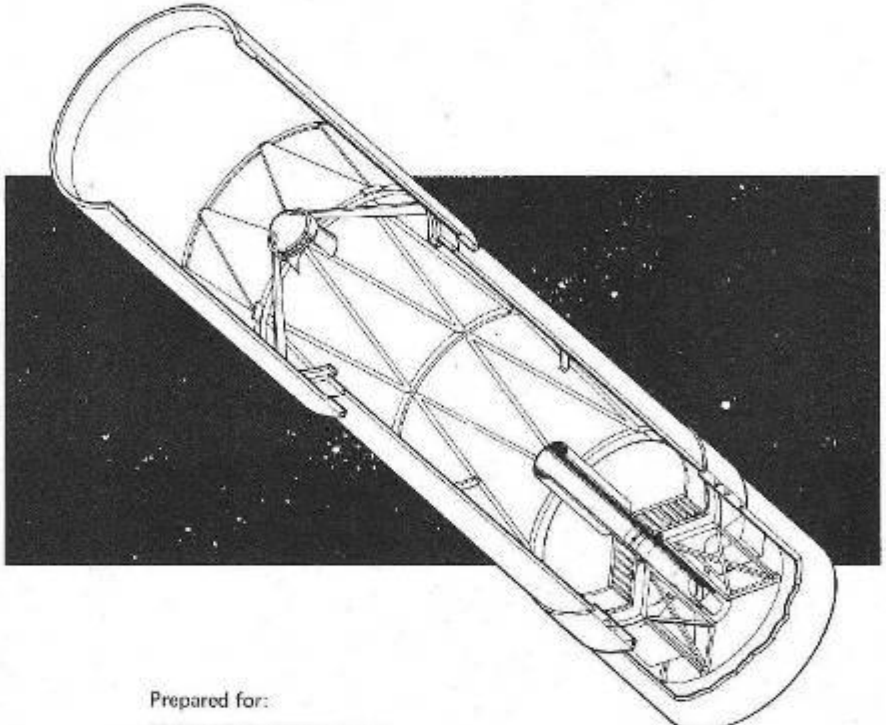


Itek 71-9463-2

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

PFR-71-131

Hubble Deployment April 25 1990

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

Study Results ….

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

Segmented Primary Mirror

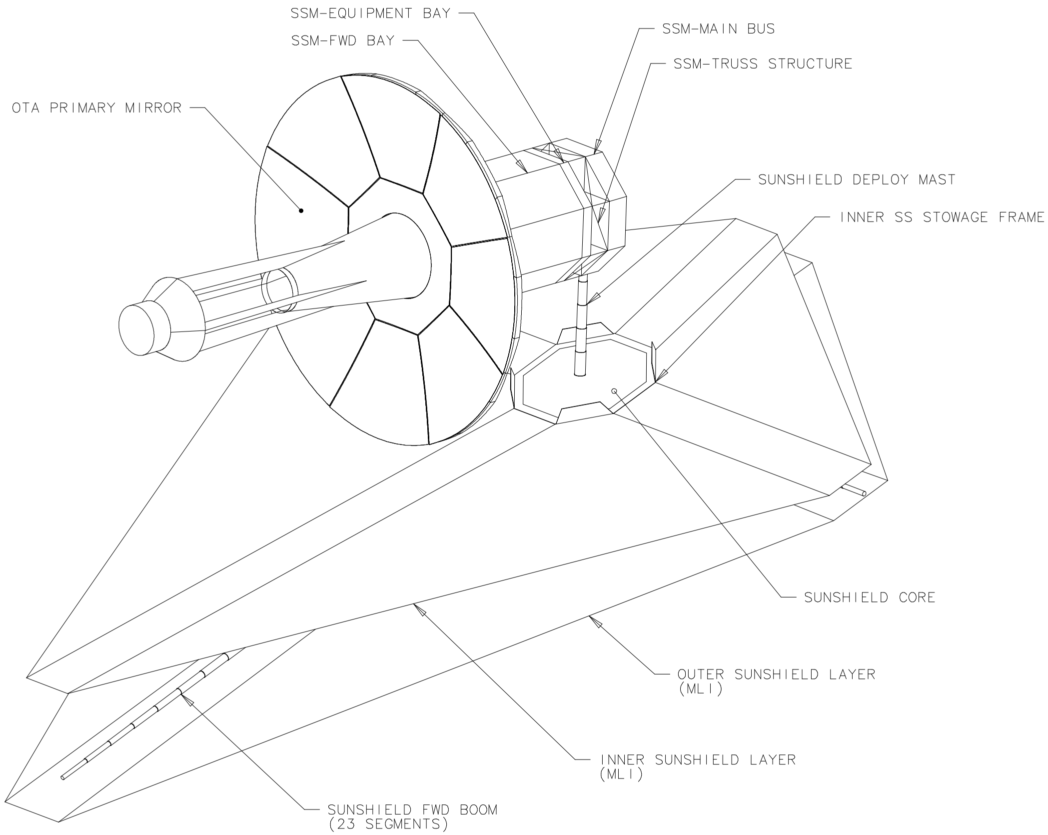
- The only way to put an 8-meter telescope into a 4.5 meter fairing is to segment the primary mirror.

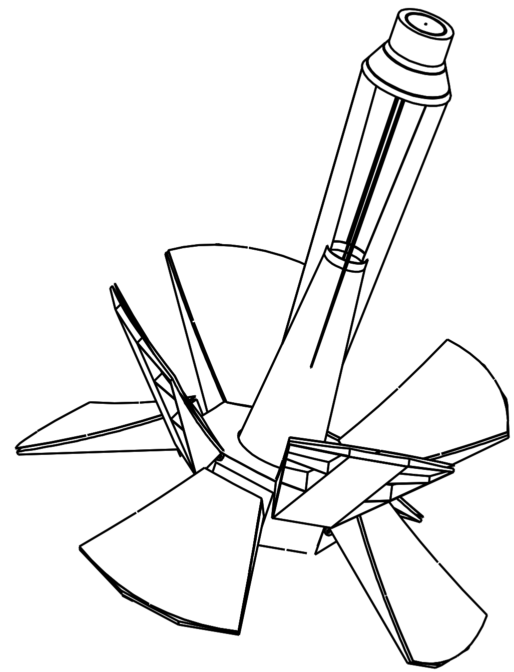
Mass Constraint

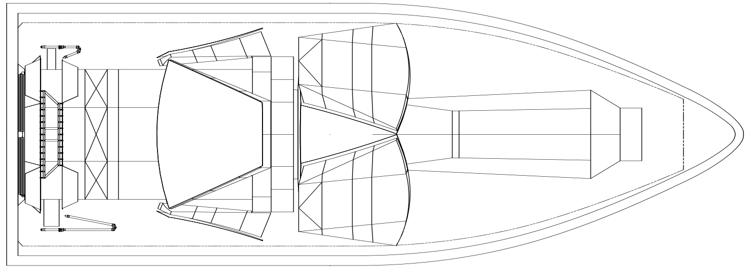
- Because of severe launch vehicle mass constraint, the primary mirror cannot weight more than 1000 kg for an areal density of < 20 kg/m2

Such mirror technology did not exist

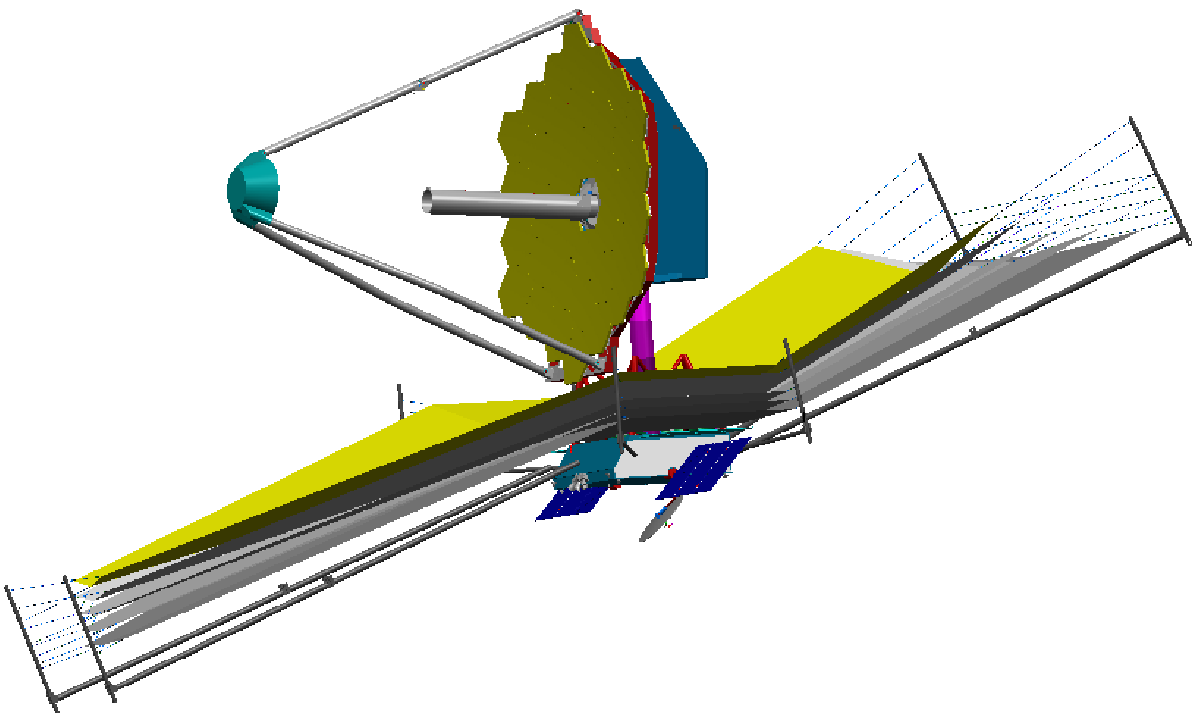
Reference design – Lockheed / Raytheon

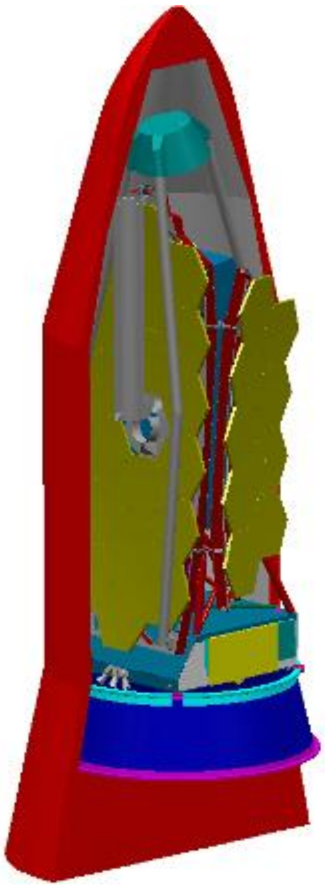






Reference design – TRW/Ball





LAMP Telescope - 1996

Optical Specifications

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

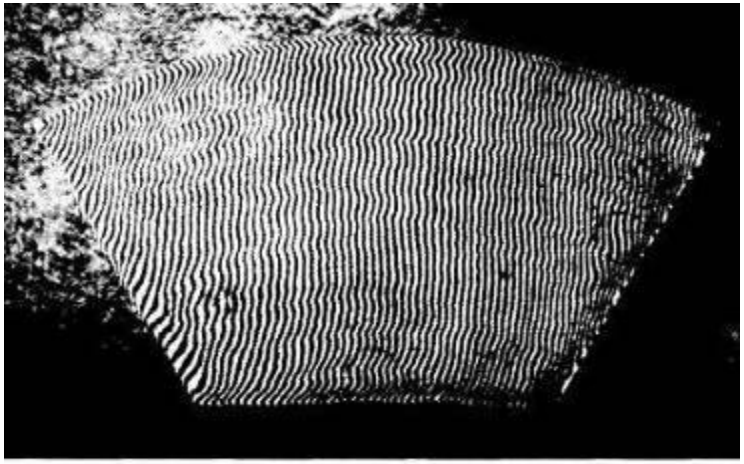
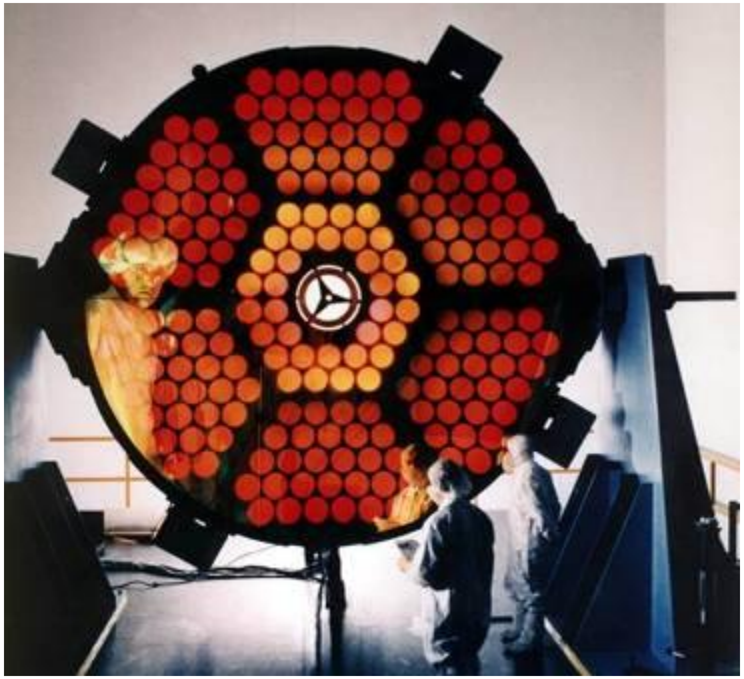


Fig. 12. Facesheet 3 final interferogram

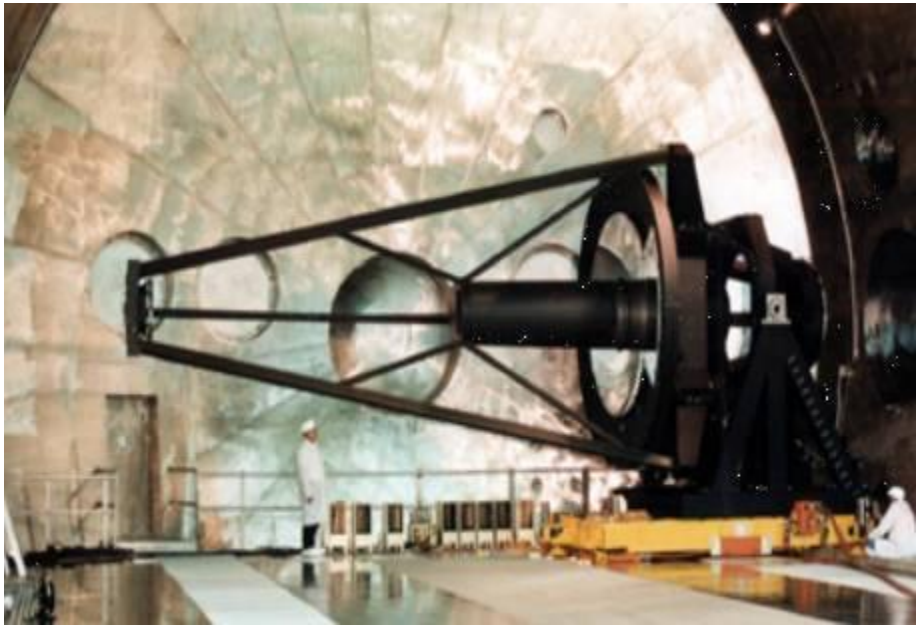


ALOT Telescope - 1994

GOODRICH

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

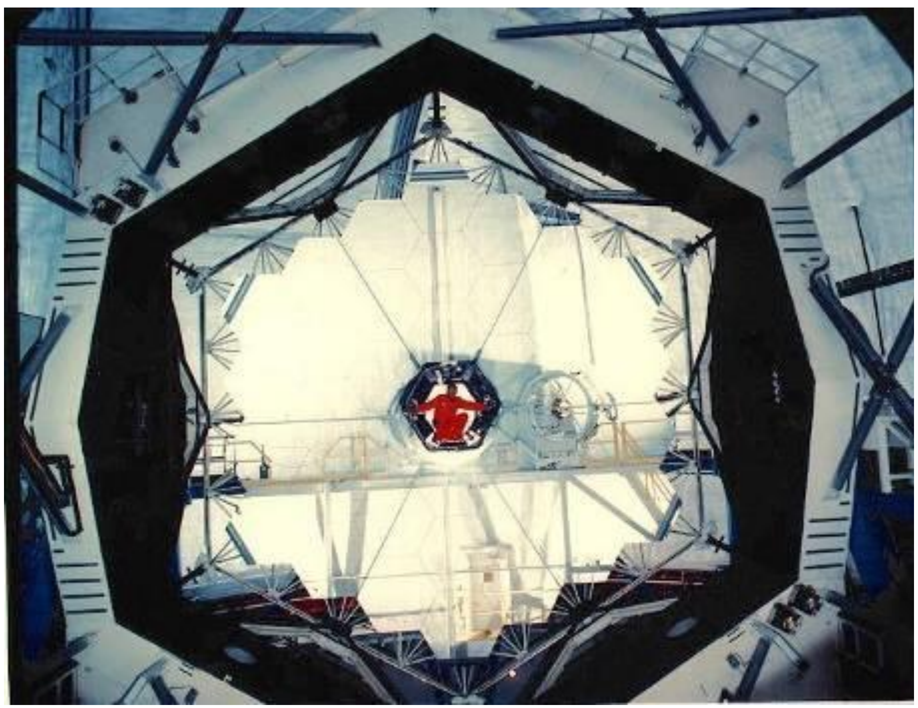
Keck Telescope - 1992

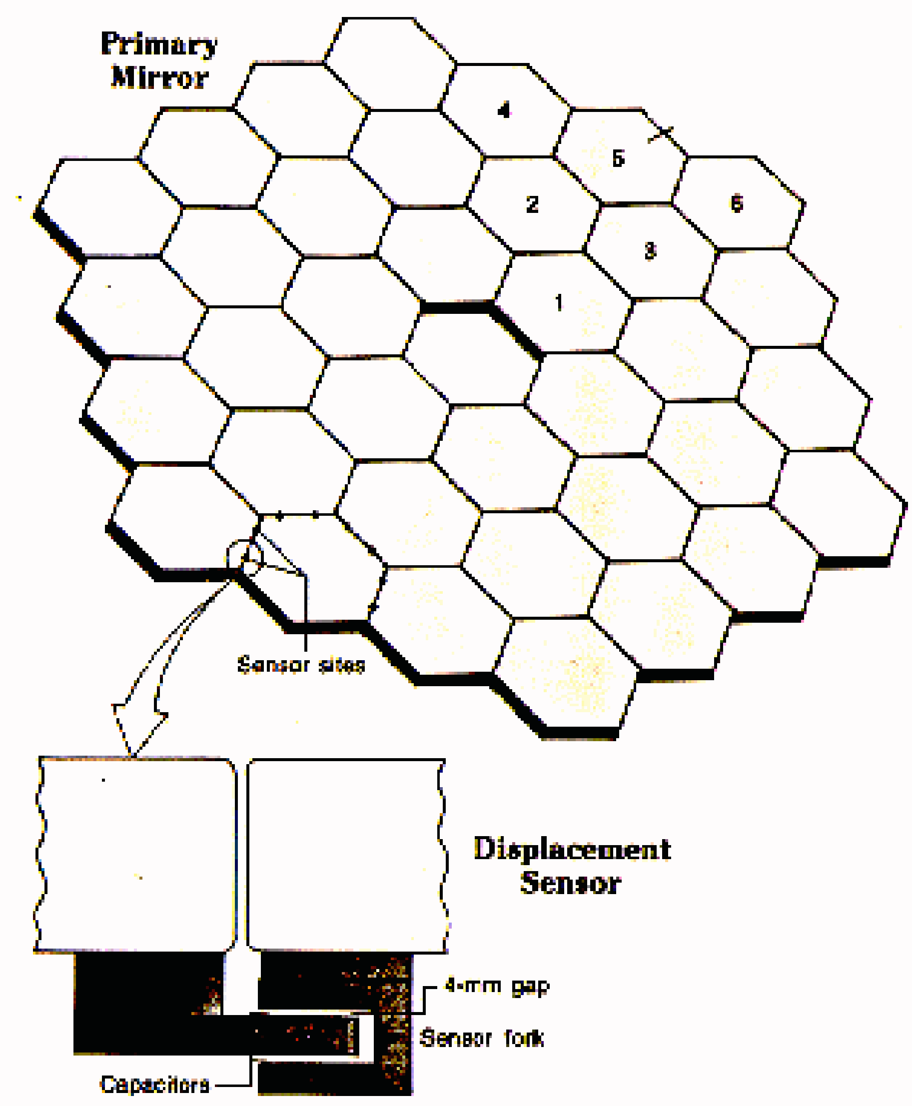
10 meter diameter

36 segments

Capacitance Edge Sensors

Diffraction Limited ~ 10 micrometers

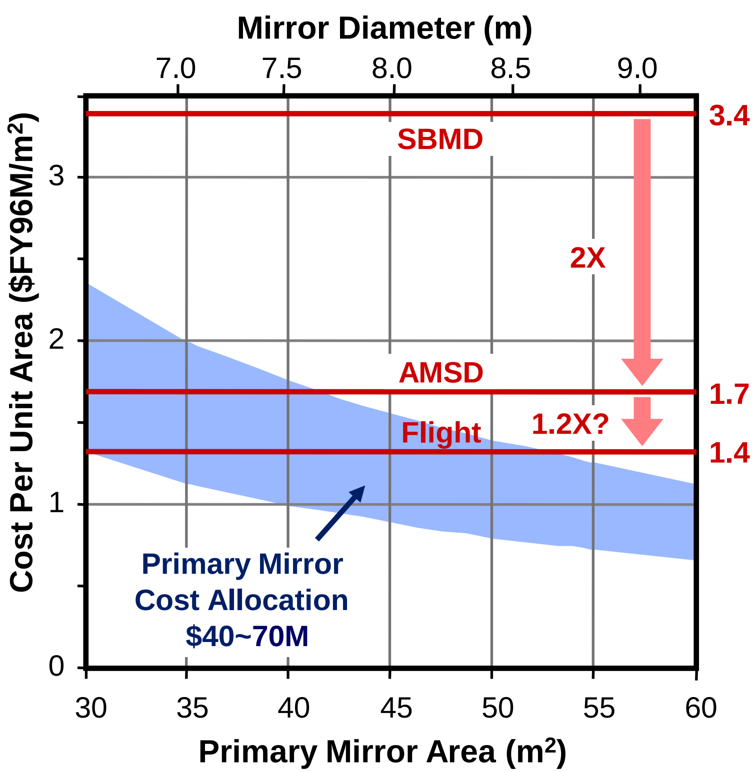


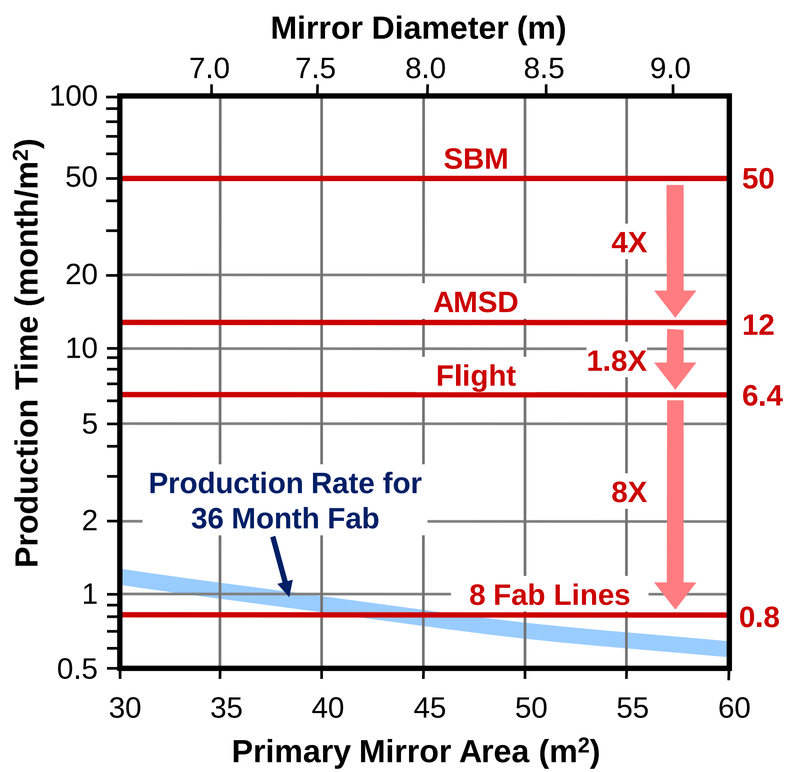


Programmatic Challenge of NGST

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

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





Programmatic Challenge of NGST

TEXT which 'went' with this slide

HST cost far more than it was initially expected, and far more than NGST can be allowed to cost. Nevertheless, NGST must be much larger and more capable. Design choices can be made to reduce difficulty and expense. The most important is to reduce weight. Experience shows that total weight is an important predictor of cost, but to reduce the weight requires new technology, and construction should not be started until it is ready. Shuttle costs were also high. HST had to be man-rated, and the complexity of the servicing missions was as expensive as it was important. NGST would not be serviceable because it is too far from Earth. To compensate for this risk, the NGST would be adjustable, so that it is not necessary to achieve optical perfection before launch. HST required extreme effort to achieve accurate absolute pointing, but the scientific goals of NGST do not require that. HST operates close to the Earth where it can observe most objects for only a few minutes before the Earth blocks the view, and it is complex and expensive to operate. NGST would be far from Earth and would require only occasional commands.

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

- 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

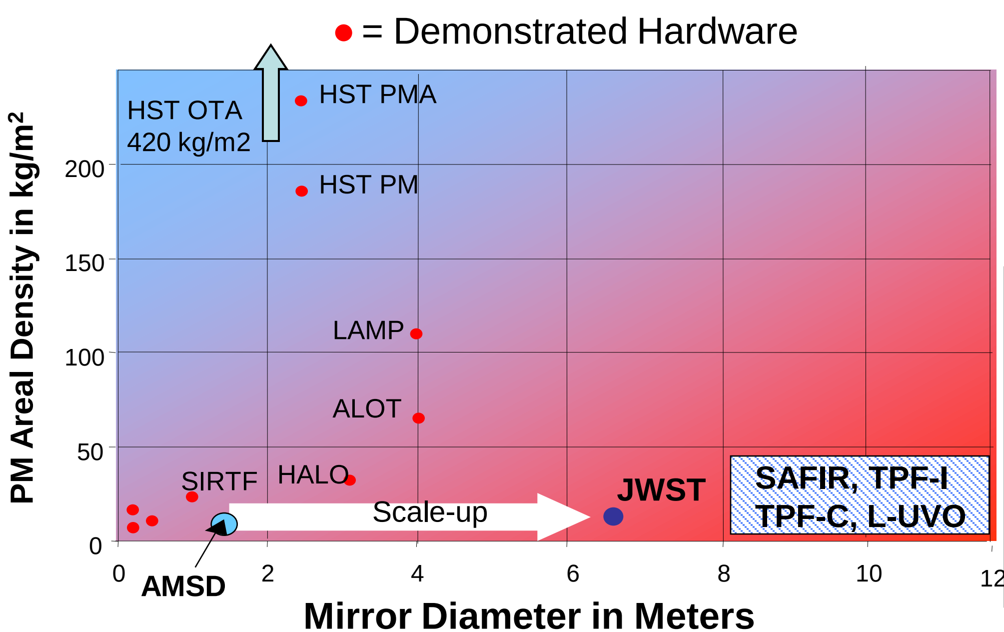
When I joined NASA is 1999, the over riding mantra for Space Telescopes was Areal Density, Cost & Schedule

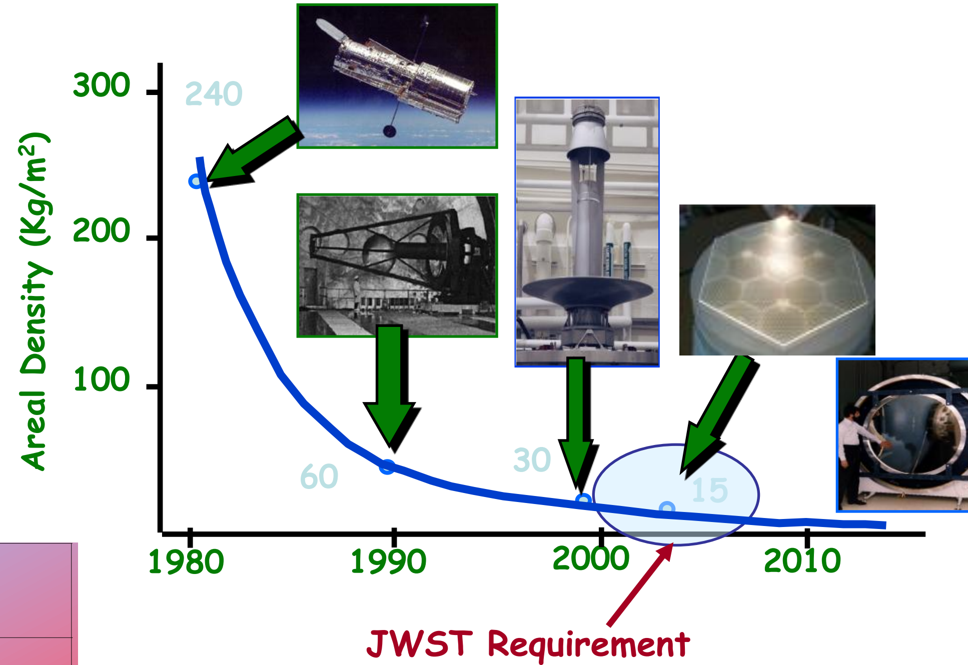
Challenges for Space Telescopes:

Areal Density to enable up-mass for larger telescopes.

Cost & Schedule Reduction.

Are order of magnitude beyond 1996 SOA





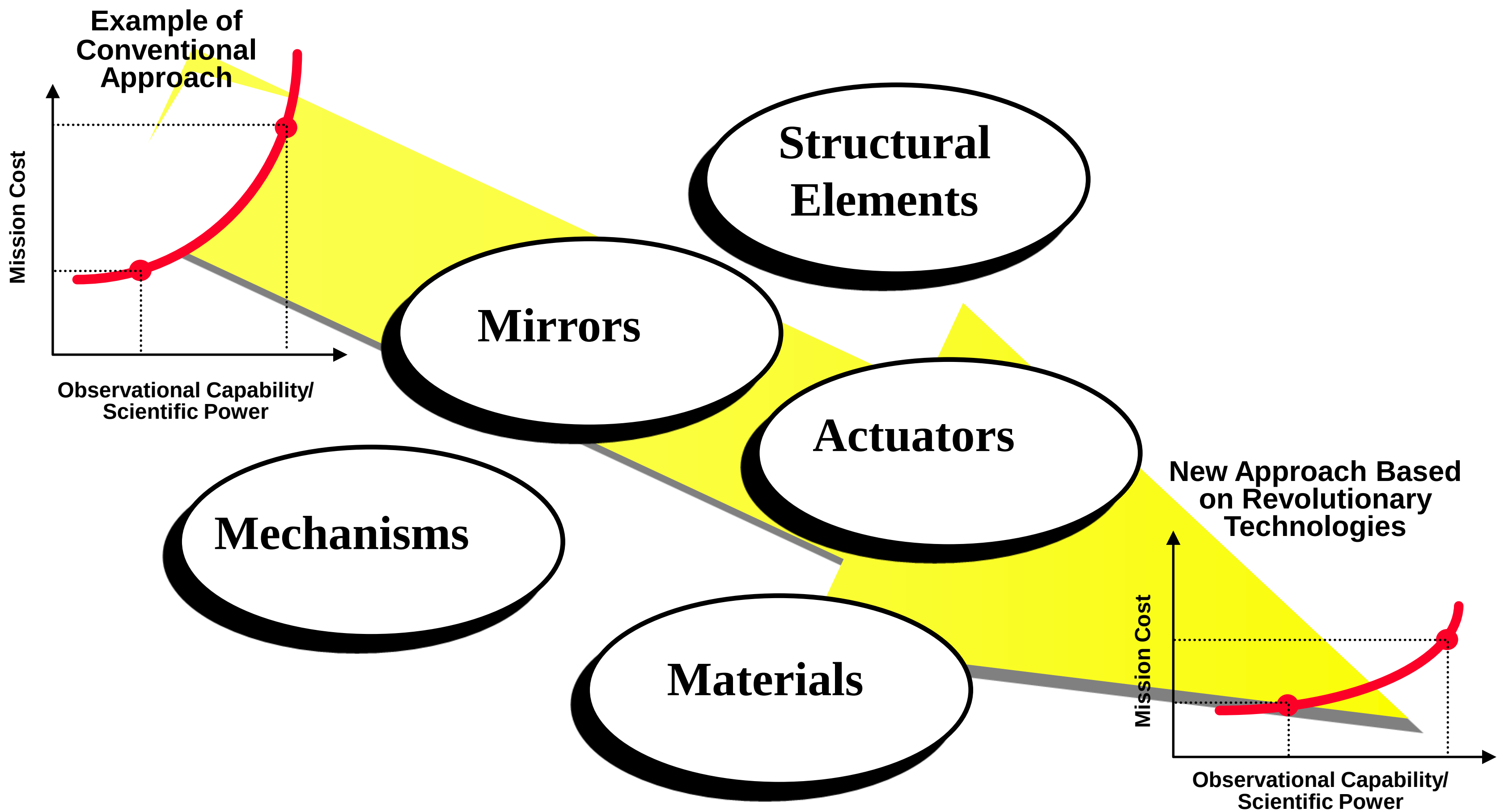
Primary Mirror	Time &	Cost
HST (2.4 m)	≈ 1 m^2/yr	≈ \$10M/m^2
Spitzer (0.9 m)	≈ 0.3 m^2/yr	≈ \$10M/m^2
AMSD (1.2 m)	≈ 0.7 m^2/yr	≈ \$4M/m^2
JWST (8 m)	> 6 m^2/yr	< \$3M/m^2

Note: Areal Cost in FY00 $

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
- Metrology Tools (funded by MSFC)
  - PhaseCAM Interferometer
  - Absolute Distance Meter
- Advanced Mirror System Demonstrator Project (AMSD)
  - funded by NASA, Air Force and NRO

Substrate Material

BRUSH WELLMAN
ENGINEERED MATERIALS

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:

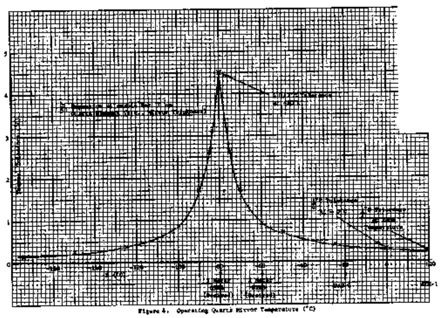
- It provides a surface quality unavailable to Spitzer, both in terms of RMS surface figure and also in scatter.

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

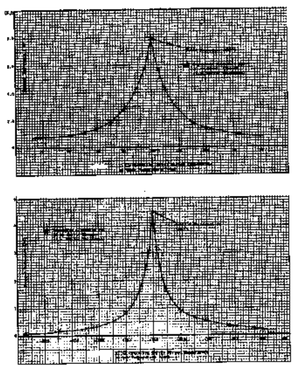
Full production capability in sufficient quantities for JWST on-line in 1999/2000.

1960 Material Property Studies

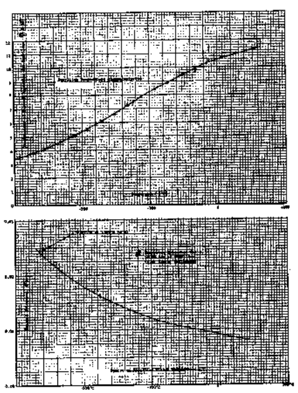
PRIMARY MIRROR MATERIALS



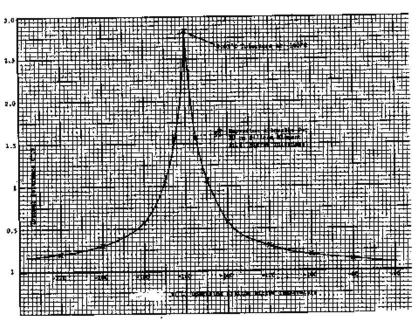
FUSED QUARTZ



CERVIT



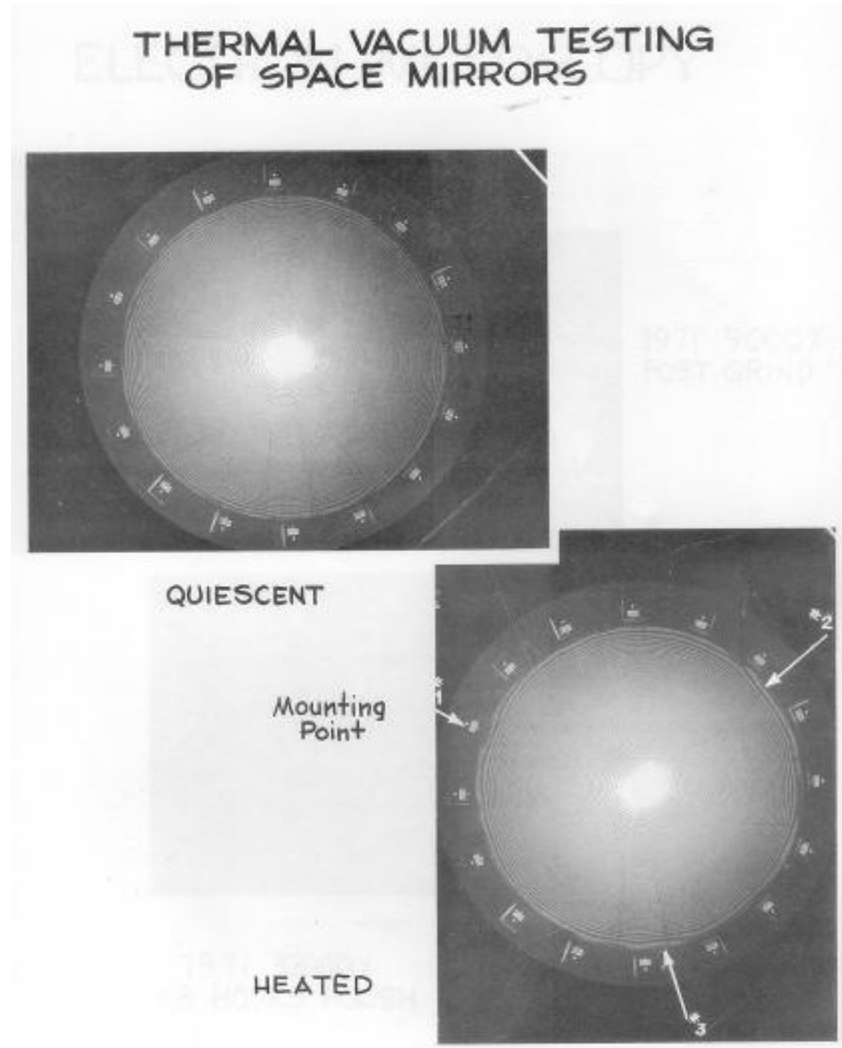
BERYLLIUM



SILICON

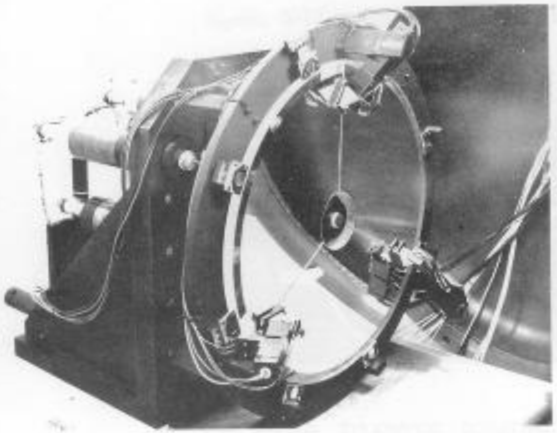
PERKIN-ELMER

Thermal Stability was Significant Concern



Solution to Thermal Instability was Segmented Mirror

SEGMENTED ACTIVE OPTICS



REFER TO
OTES
EXPERIMENT
NO. 1

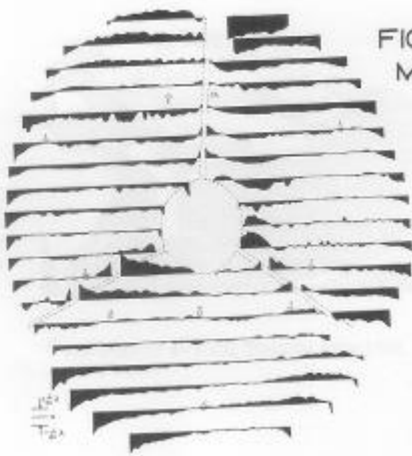
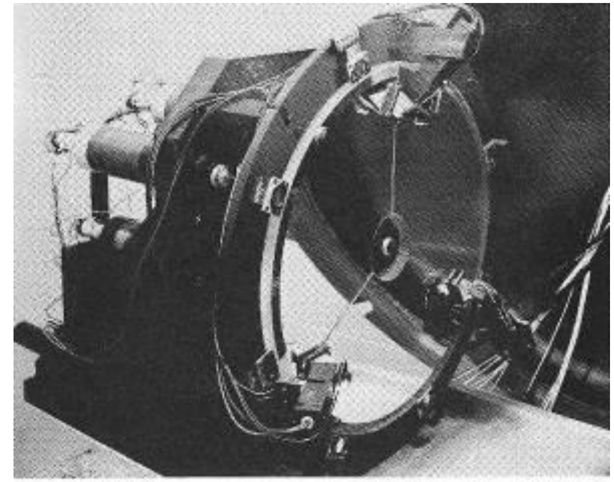


FIGURE ERROR
MEASUREMENT

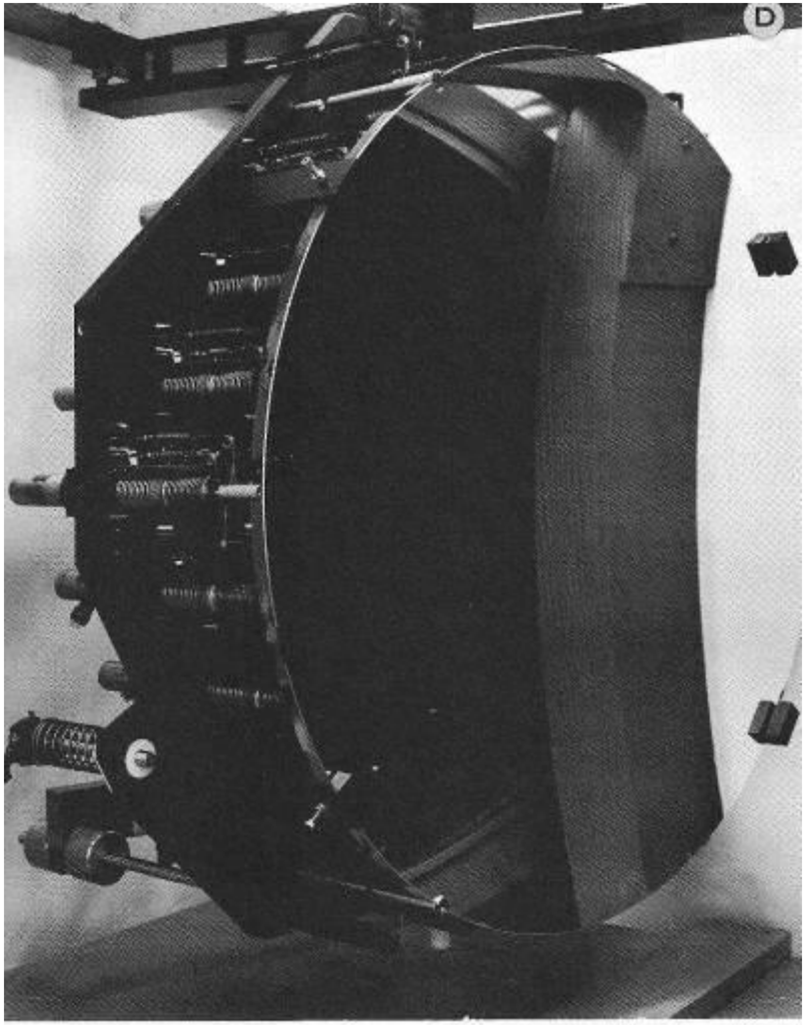
Raster Scan of Figure Error for Composite Active Optics Mirror with Automatic Alignment in Operation



Segmented Mirror

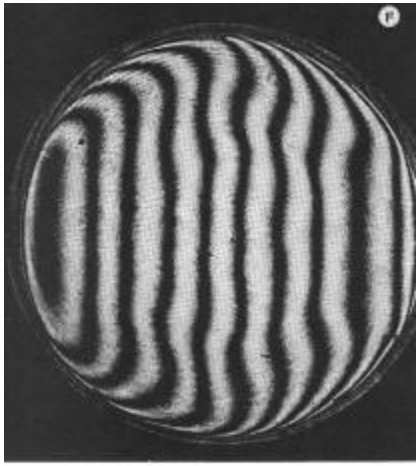
Interferogram of Active Segmented Mirror
Active Segmented Optics

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

Solution

The final solution was to develop better mirror materials:

Cervit,

ULE,

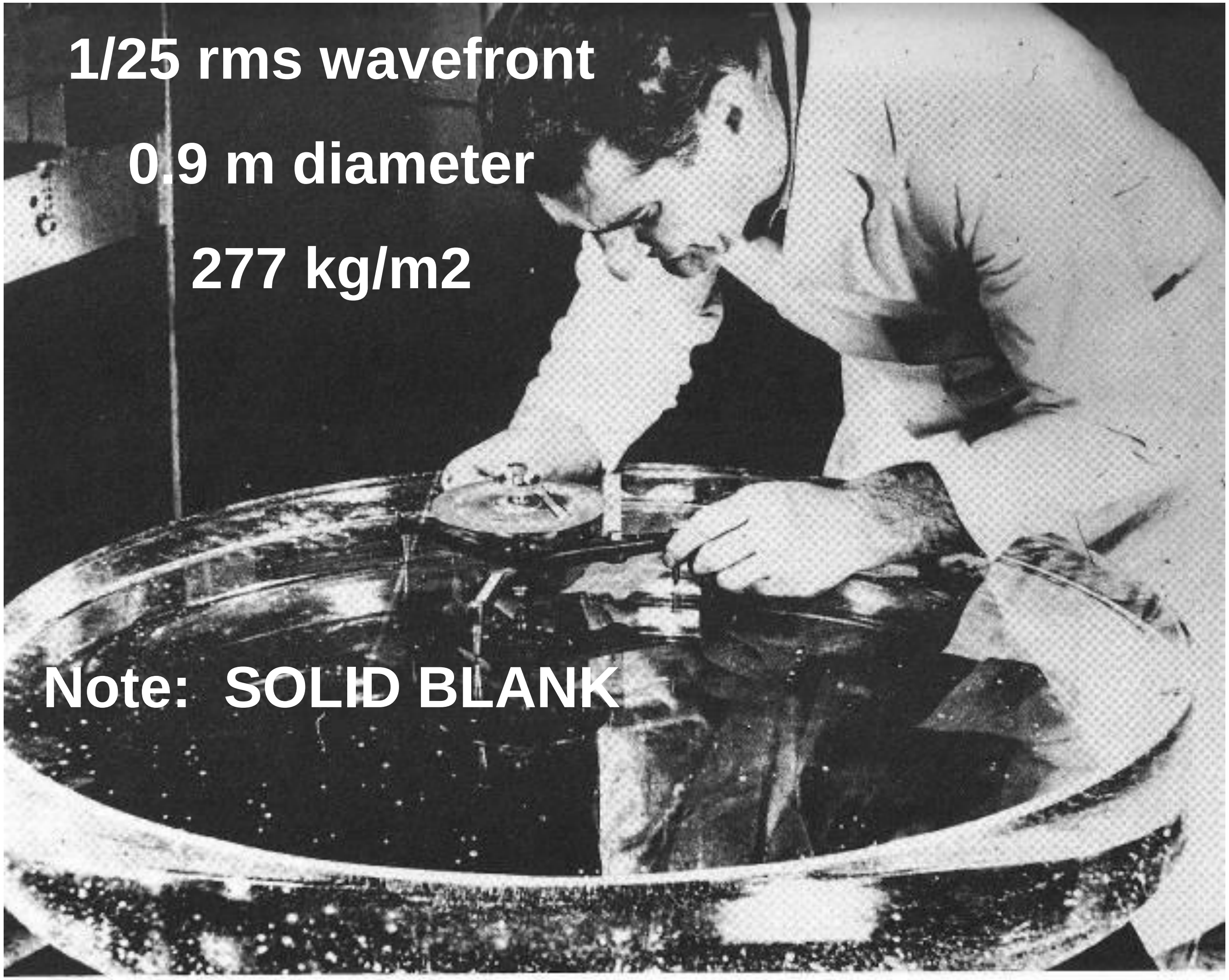
Zerodur

which enabled a passive monolithic space telescope mirror

Mirrors:

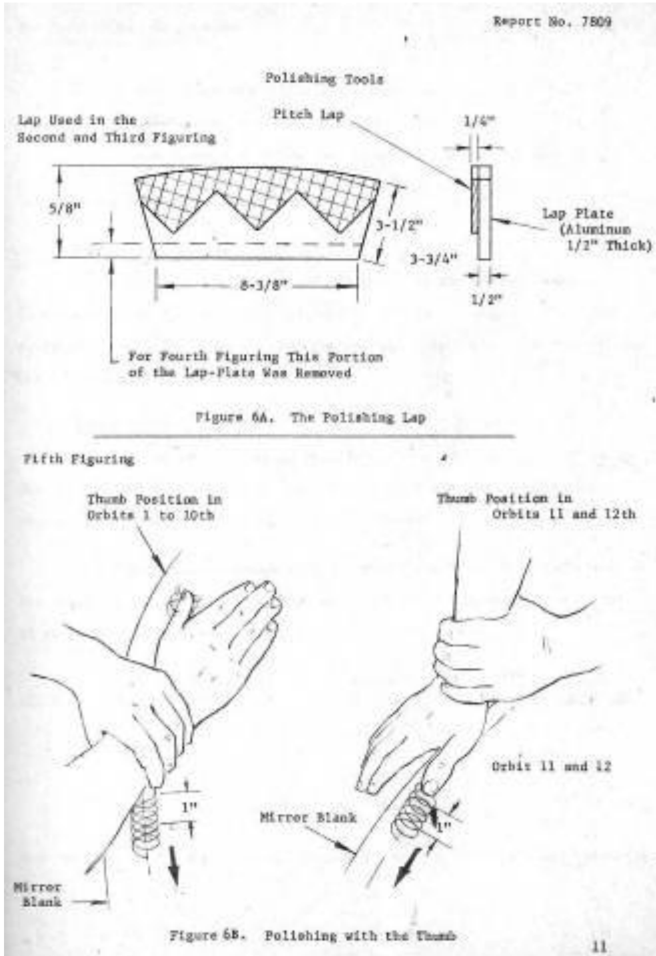
Substrate Technology & Optical Fabrication

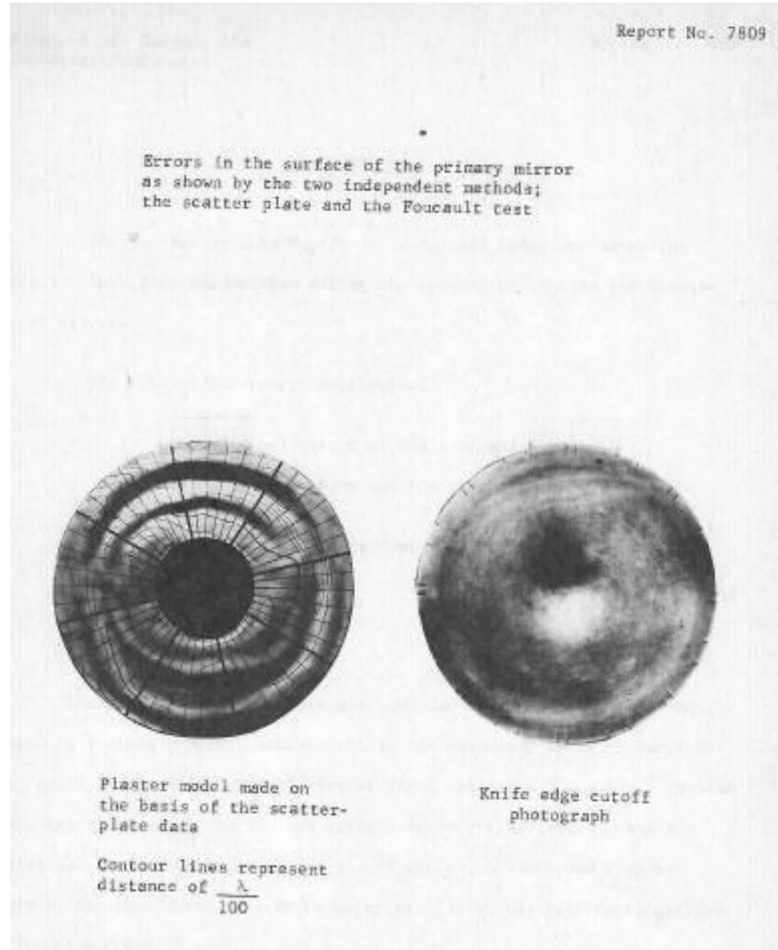
Stratoscope II – Primary Mirror



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-B Primary Mirror

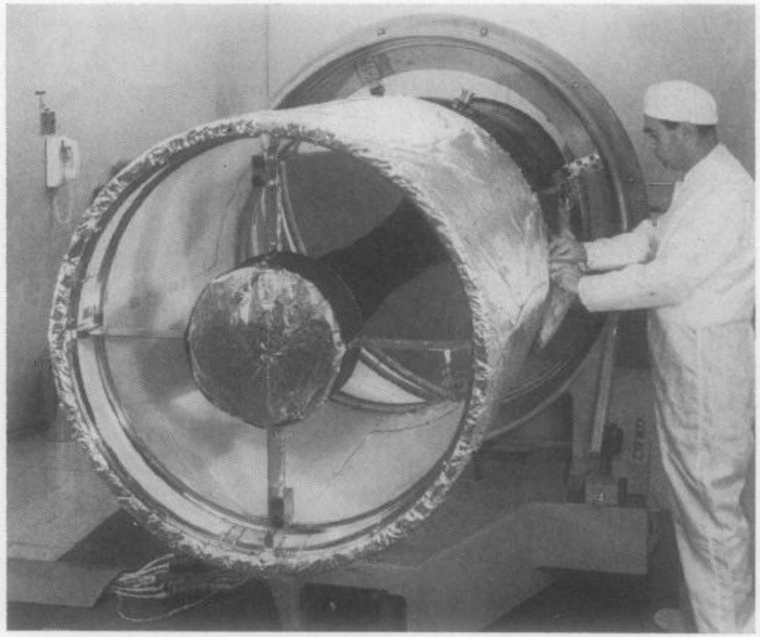


Fig. 1. View of the 38-inch GEP space telescope.

State of Art (6:1 solid blank) fused silica mirror would have had a mass of 310 kg (680 lbs).

Beryllium (S200B) thin meniscus (25:1) substrate with electroless nickel overcoat was fabricated. Its mass was 57 kg (125 lb). Its stiffness minimized gravity sag

"The Goddard Experiment Pacakage – 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

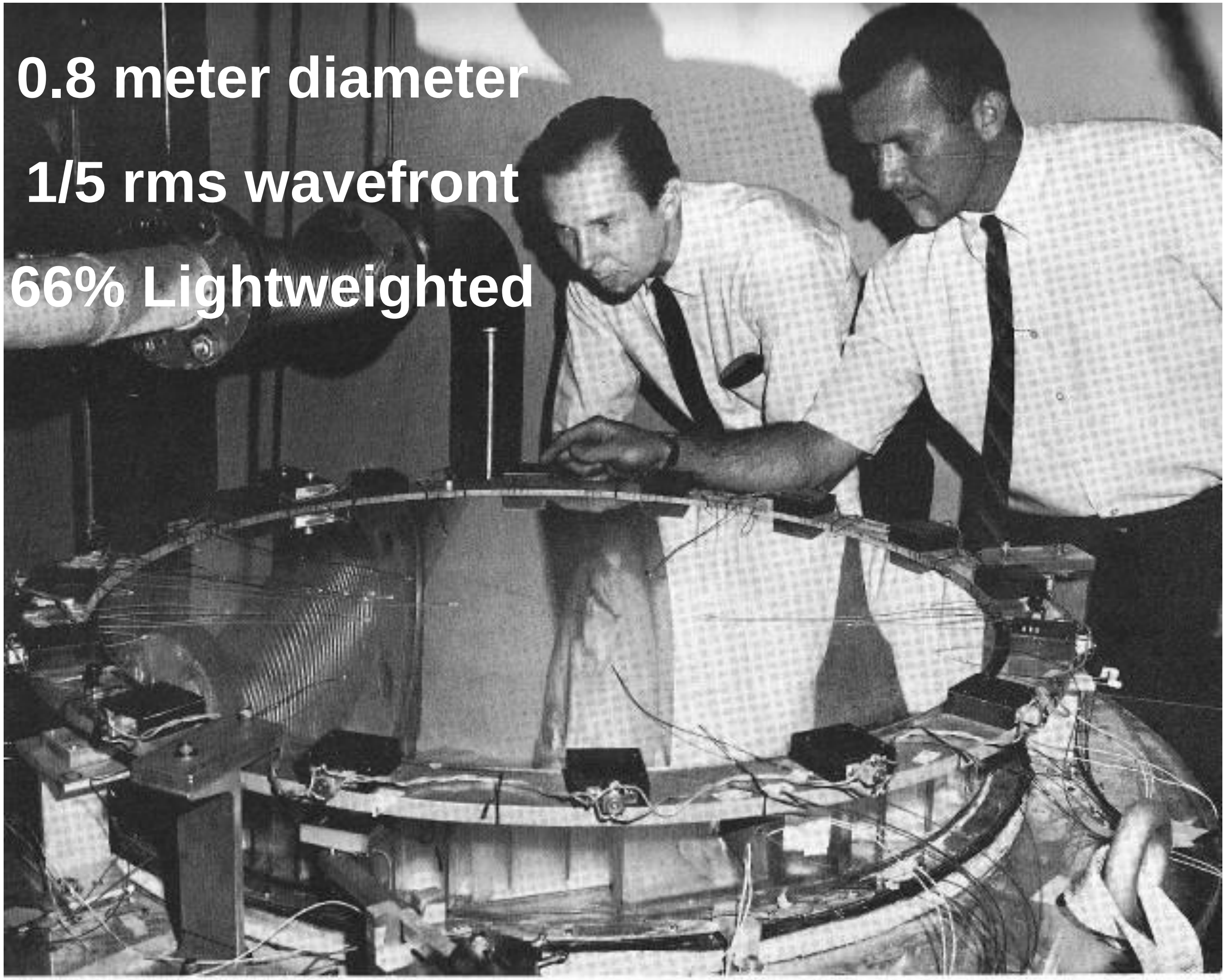
OAO-C Primary Mirror

Fig. 4 Primary mirror before coating.

NASA is developing lightweight Egg-Crate Glass Mirror Substrates

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

OAO-C Primary Mirror



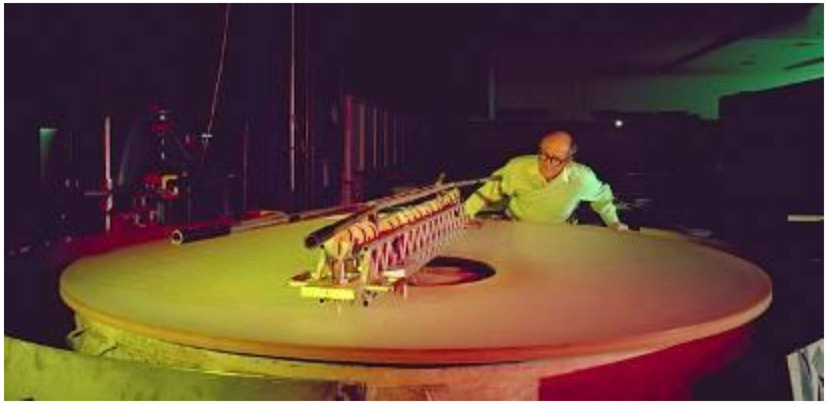
32 Inch Diameter OAO-C Princeton University Eggcrate Mirror
(Thermal/Deformation Test Instrumentation)

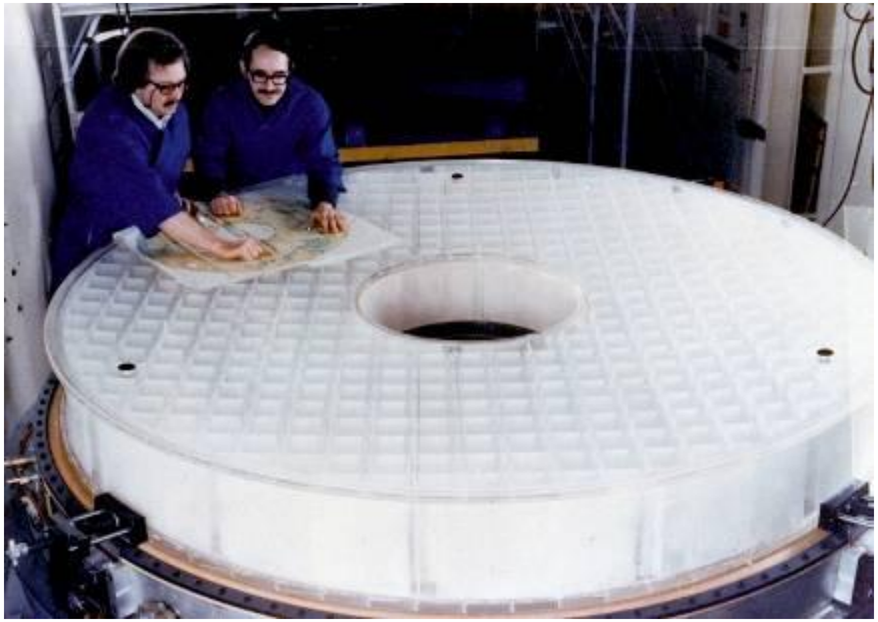
Hubble Primary Mirror Fabrication 1979-1981

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™

Lightweight, High Temperature Fused Construction

2.4-meter Aperture

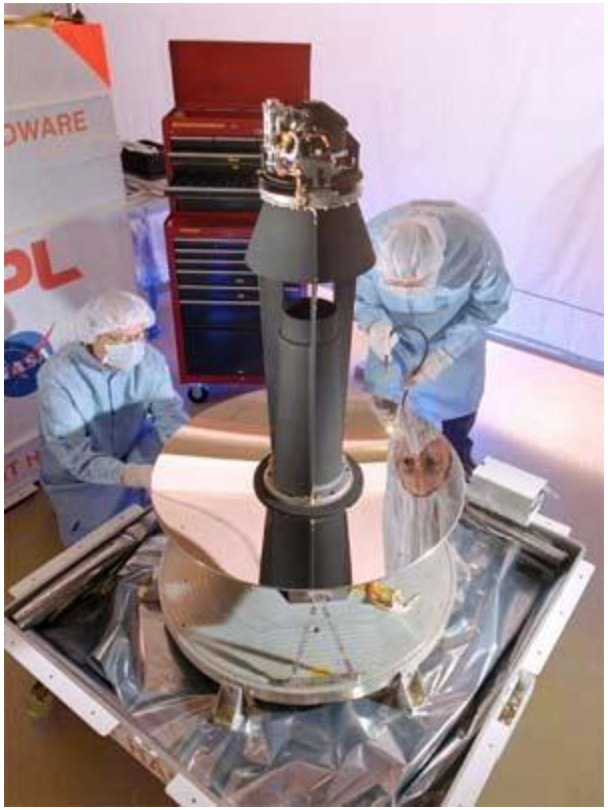
Spitzer PM Fabrication – ITTT Program GOODRICH

Spitzer PM Fabrication

PM used Small Tool Computer Controlled Polishing

SM used Full Aperture Shaped Laps and Zonal Laps

Spitzer Optical Telescope Assembly and Primary Mirror

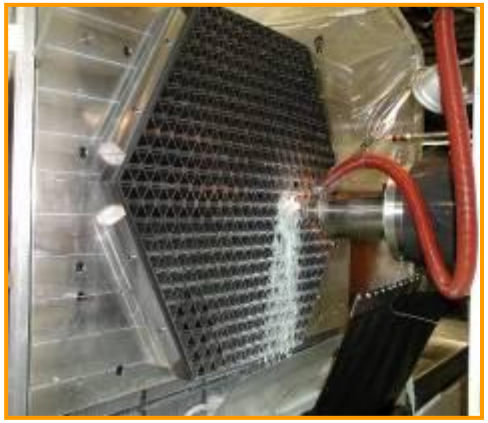


JWST Mirror Manufacturing Process

Blank Fabrication

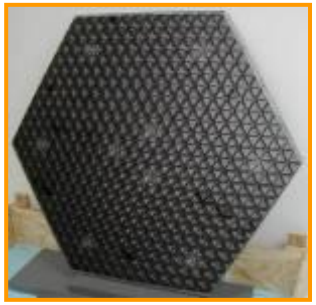
HIP Vessel being loading into chamber

Machining



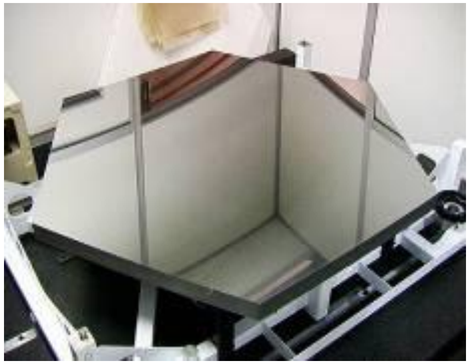
Machining of Web Structure

Machining of Optical Surface

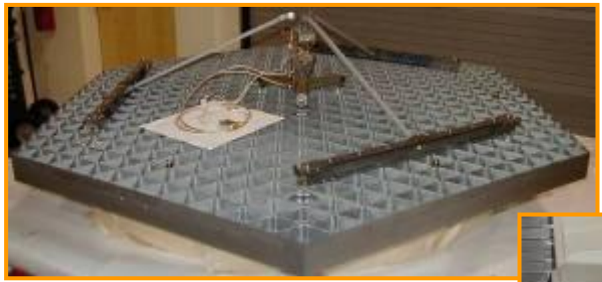


Completed Mirror Blank

Polishing



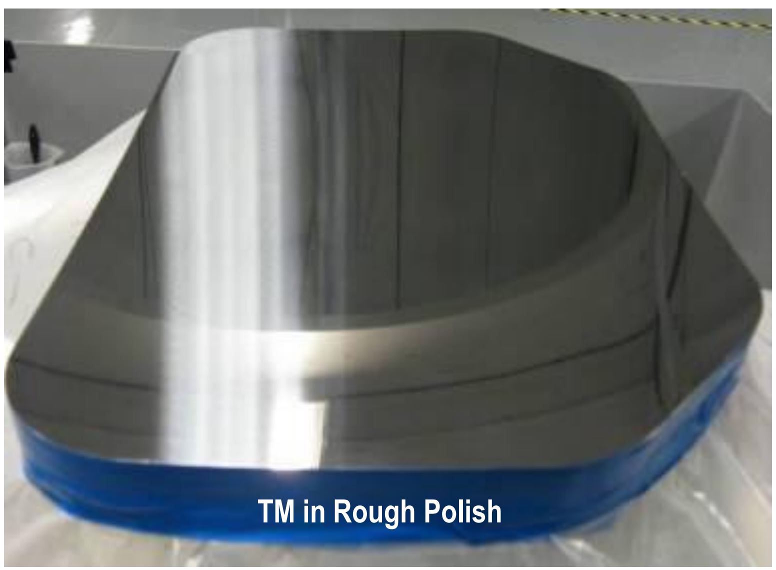
Mirror System Integration



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.

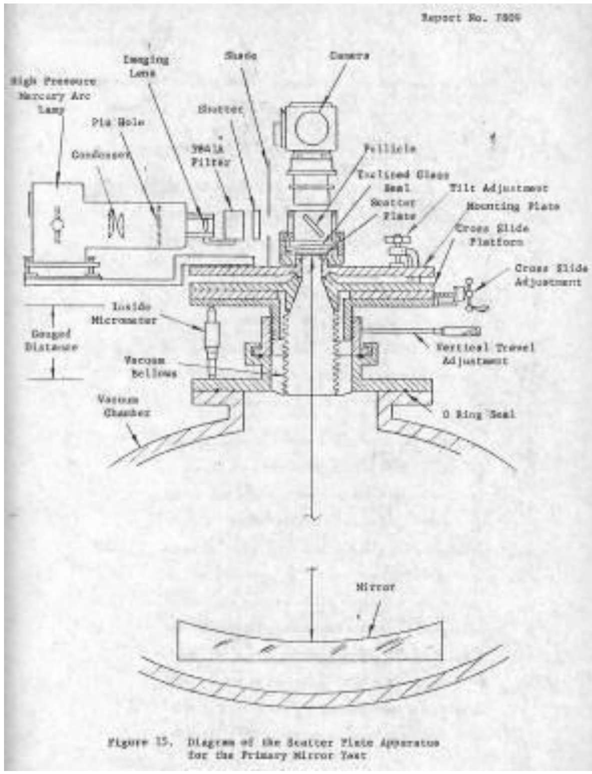
Spatial resolution was acceptable, but mechanical vibration made temporal phase-modulation impossible.

But this problem is nothing new …..

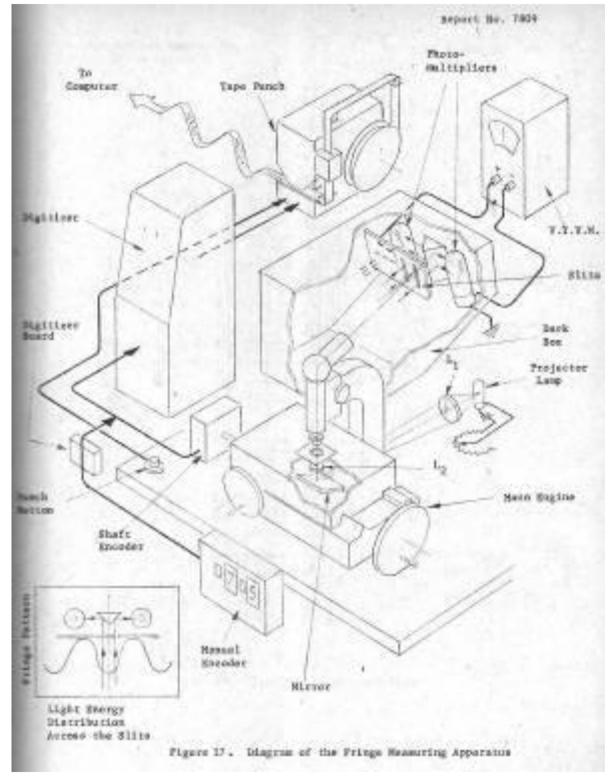
Stratoscope II – Optical Testing

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

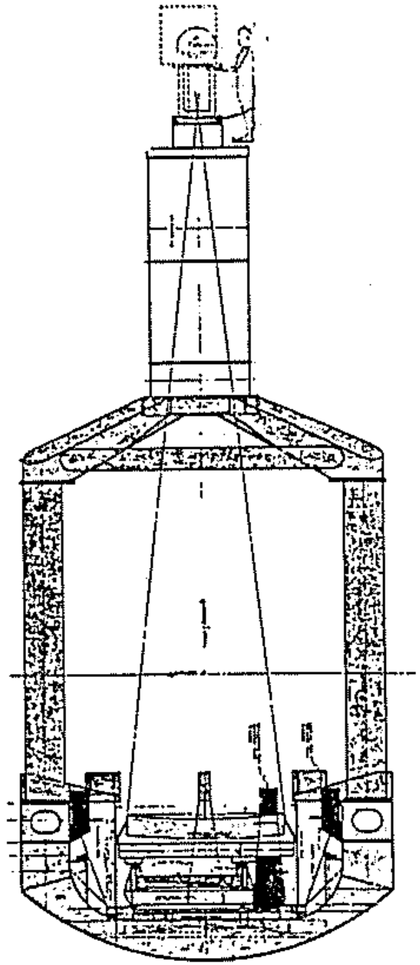
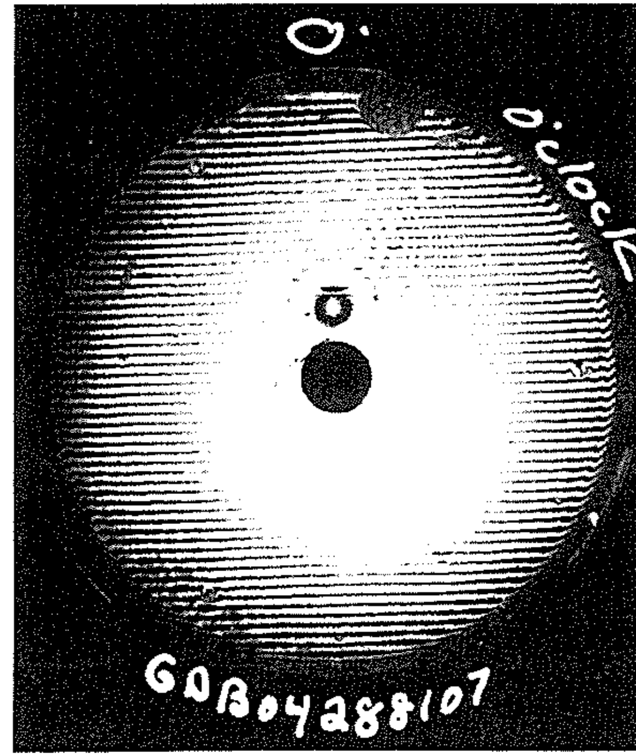


Figure 2. Primary mirror test configuration.



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

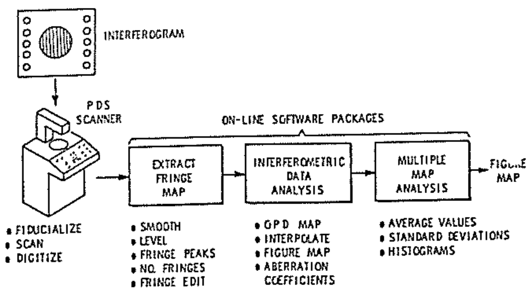


Figure 14. Interferogram analysis facility.

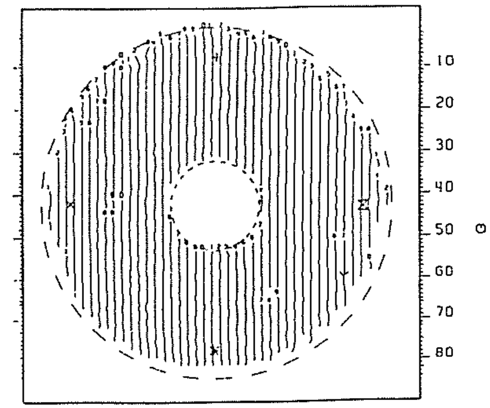


Figure 15. Fringe map.

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.

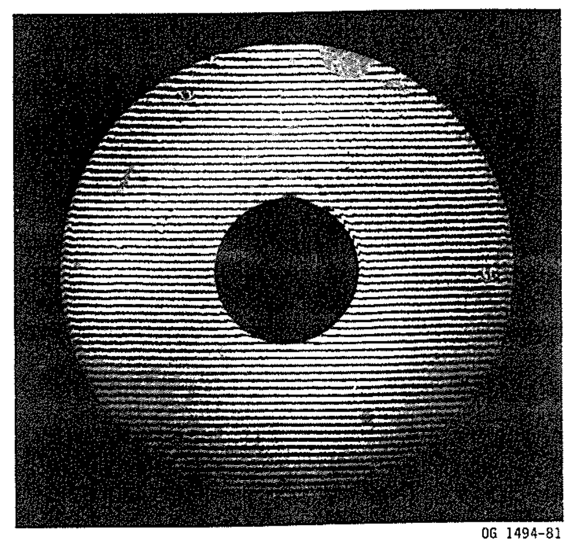
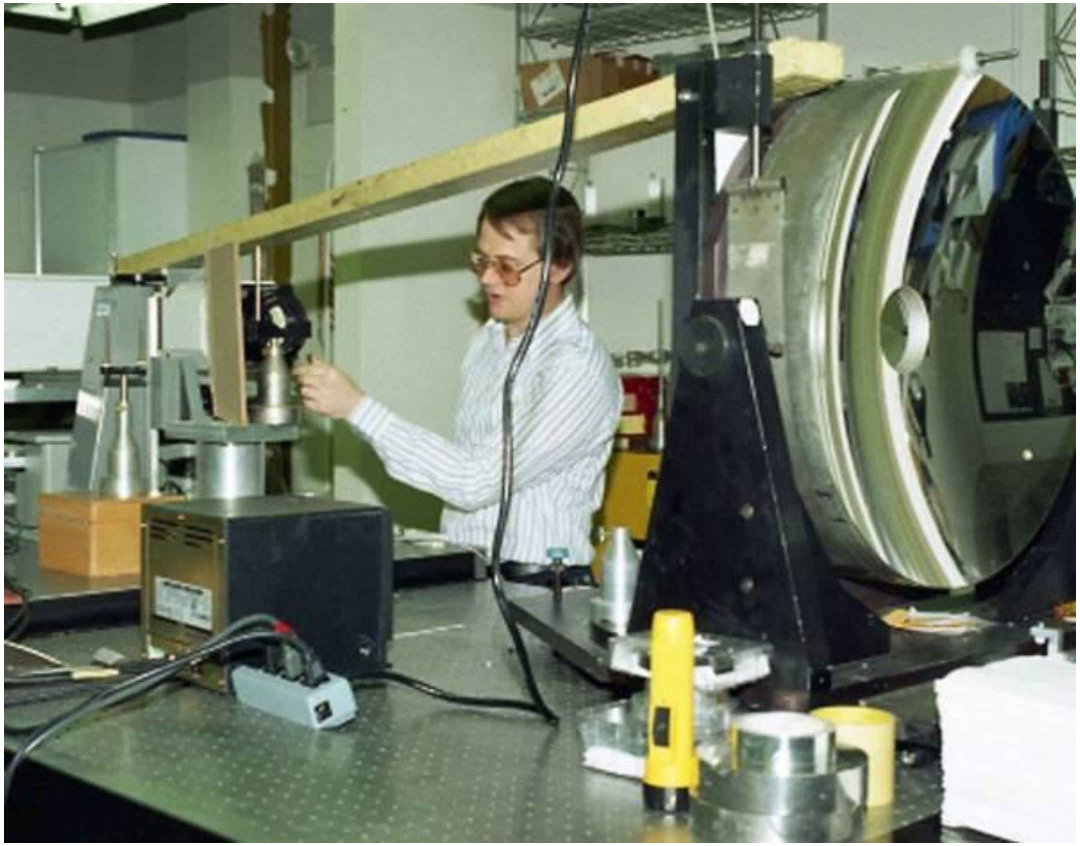


Figure 17. Interferogram of finished primary mirror masked to its clear aperture.

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

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.

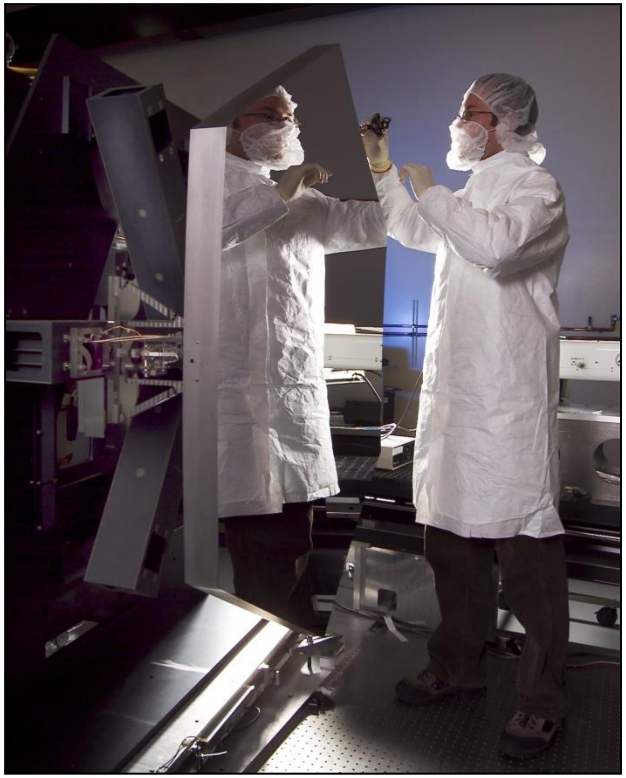
As I prepared to leave Danbury for NASA, I was visiting Metrolaser where I saw a breadboard device taking phase-maps of a candle flame.

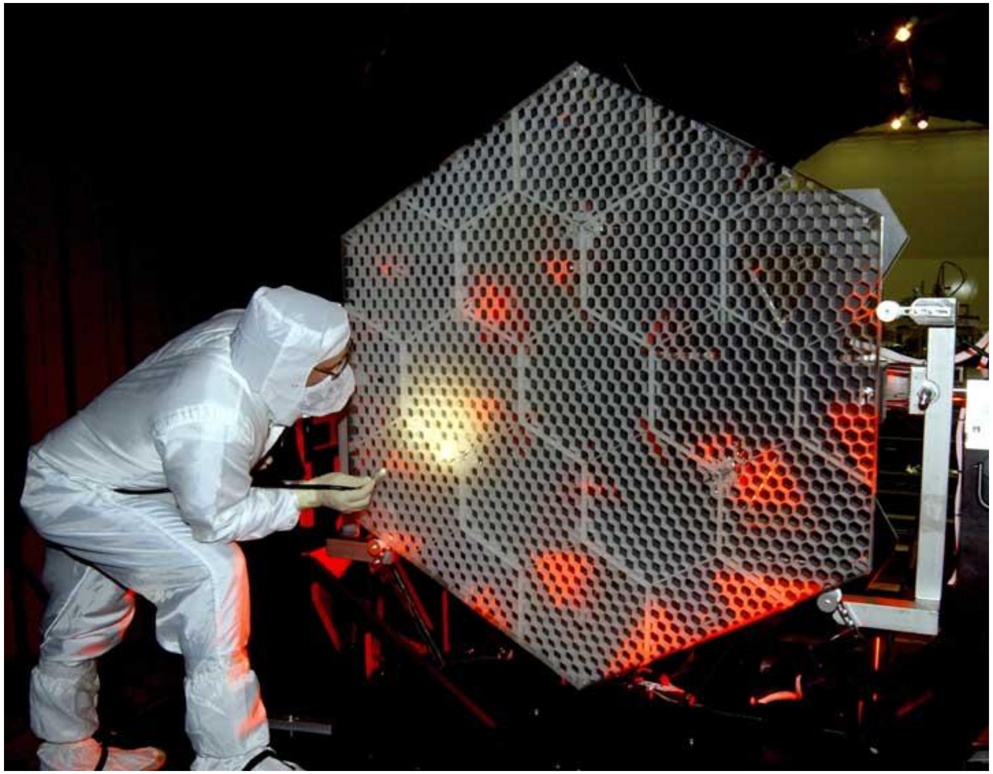
When I got to NASA I defined the specifications for and ordered the first PhaseCAM interferometer.

Today they are critical to JWST.

Tech Days 2001

Mirror Technology Development Program





Mirror Technology Development

Systematic Study of Design Parameters

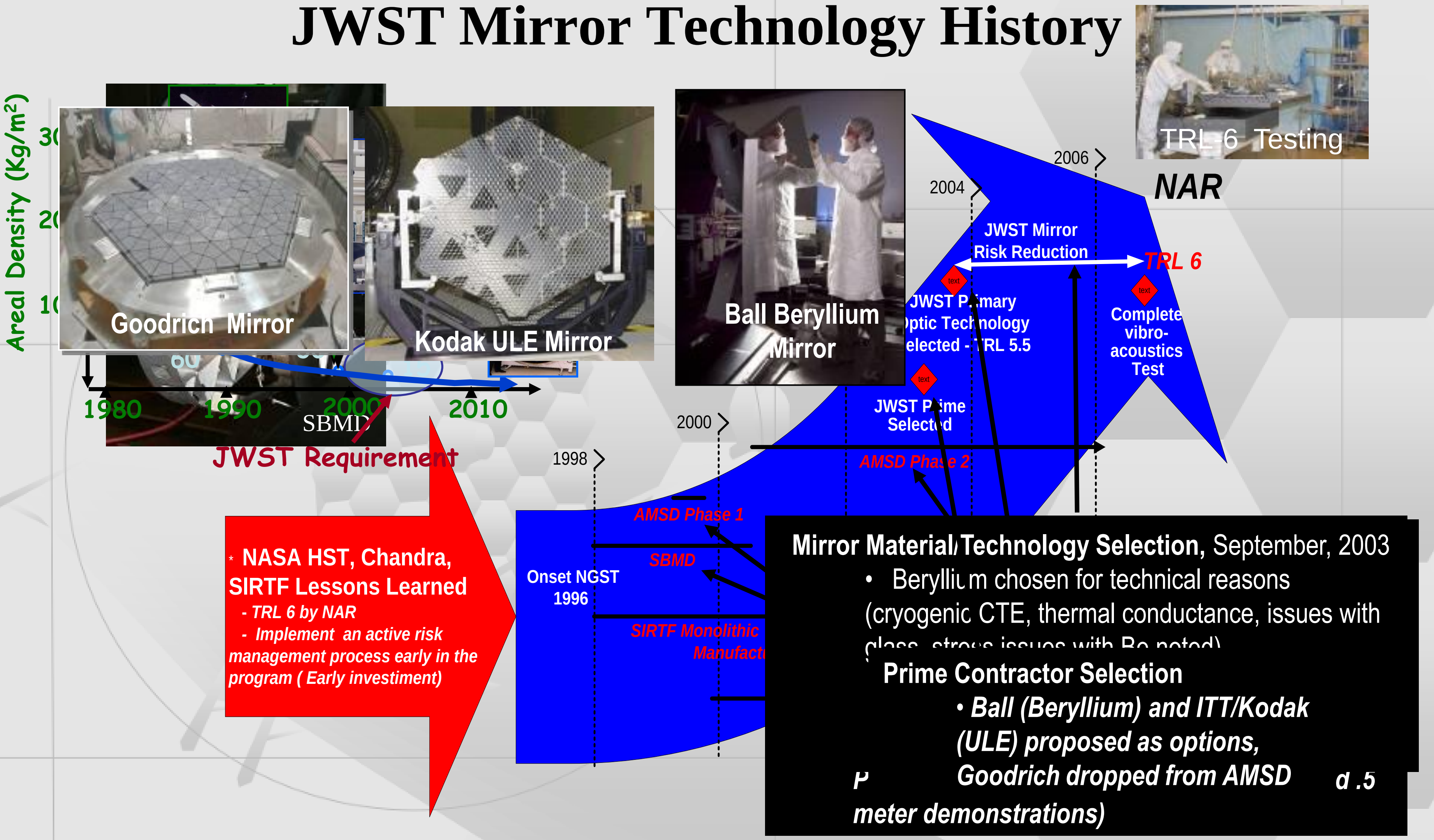
Item	SBMD	NMSD	AMSD
Form	Circle w Flat	Hex	Hex
Prescription	Sphere	Sphere	OAP
Diameter	>0.5 m	1.5 - 2 m	1.2 - 1.5 m
Areal Density	< 12+ kg/m2	<15 kg/m2	<15 kg/m2
Radius	20 m	15 m	10 m
PV Figure	160 nm	160/63 nm	250/100 nm
RMS Figure			50/25 nm
PV Mid	63 nm	63/32 nm	
(1-10 cm^{-1})			
RMS Finish	3/2 nm	2/1 nm	4 /2 nm

Mirror Technology Development

Wide Variety of Design Solutions were Studied

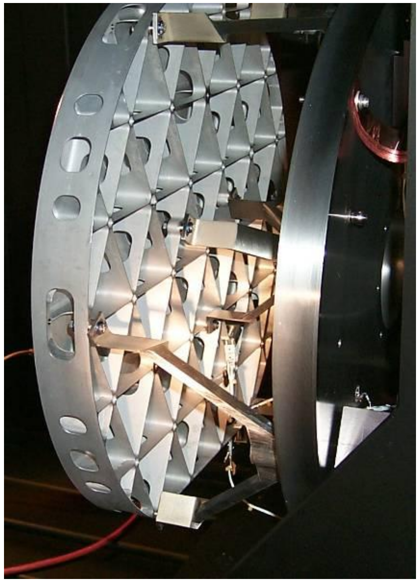
Item	SBMD	NMSD	AMSD
Substrate Material	Be (Ball)	Glass (UA) Hybrid (COI)	Be (Ball) ULE Glass (Kodak) Fused Silica (Goodrich)
Reaction Structure	Be	Composite	Composite (all)
Control Authority	Low	Low (COI) High (UA)	Low (Ball) Medium (Kodak) High (Goodrich)
Mounting	Linear Flexure	Bipods (COI) 166 Hard (UA)	4 Displacement (Ball) 16 Force (Kodak) 37 Bi/Ax-Flex (Goodrich)
Diameter	0.53 m	2 m (COI) 1.6 m (UA)	1.3 m (Goodrich) 1.38 m (Ball) 1.4 m (Kodak)
Areal Density	9.8+ kg/m2	13 kg/m2	15 kg/m2

JWST Mirror Technology History

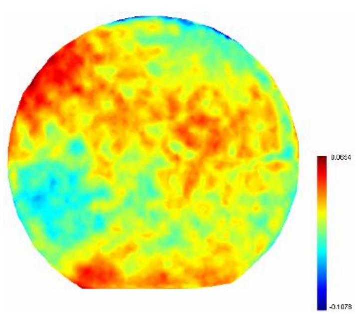


Based on lessons learned, JWST invested early in mirror technology to address lower areal densities and cryogenic operations

Ball Subscale Beryllium Mirror Demonstrator (SBMD)

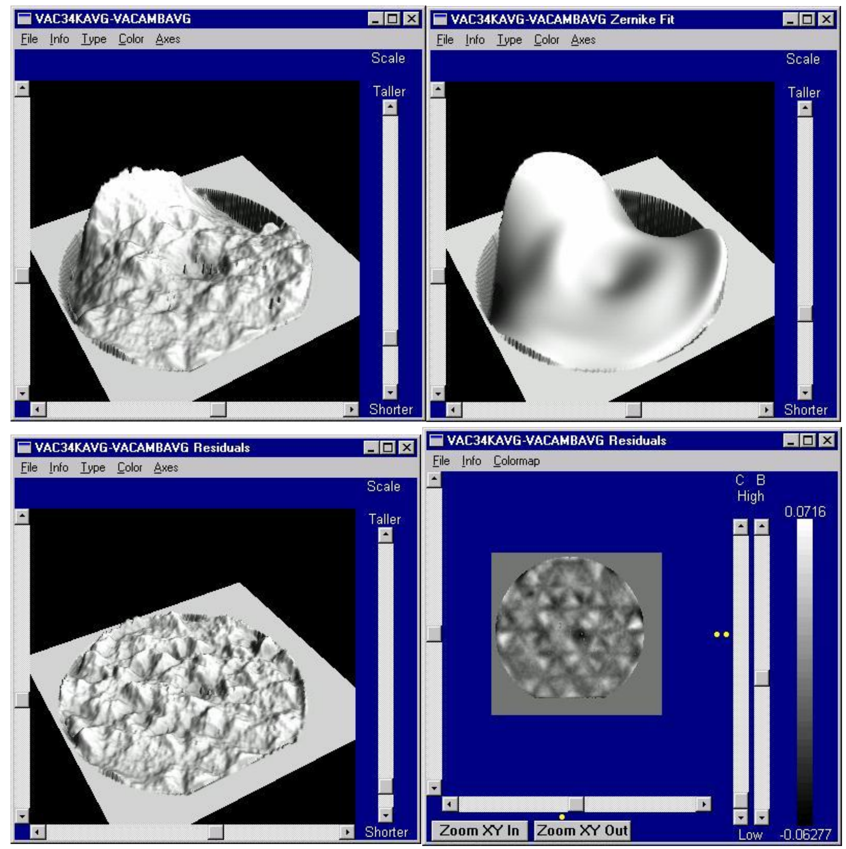


0.5 m diameter, 20 m ROC,
9.8 kg/m^2 areal density, O-30
Beryllium Mirror



Cryo Tested at MSFC

Cryogenic Surface Error (34K -288K)
Total (0.571 µm p-v; 0.063µm rms)
Low Order (0.542 µm p-v, 0.062 µm rms)



Higher Order Residual (0.134 µm p-v; 0.012 µm rms)

SBMD Lessons Learned

SBMD’s cryo-deformation was interesting:

- Initially, we were unable to model the quilting
- Mounting design issues introduced low-order error
- Interface issues resulted in a non-stable deformation

Lessons Learned:

- Learned how to optimize substrate light-weighting to minimize quilting
- Support structure design and interface to substrate is critical
- Very high stiffness of small mirrors means that extrapolating their results to large (low-stiffness) mirrors is unreliable

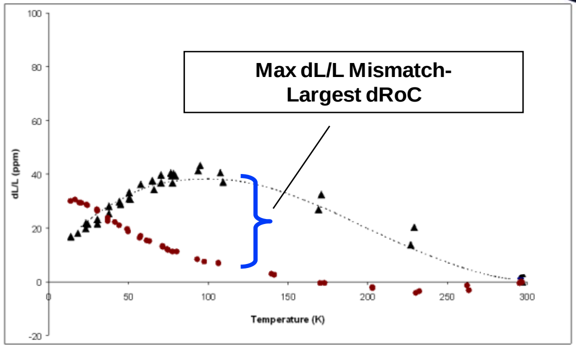
COI Hybrid NGST Mirror System Demo (NMSD)

Hybrid Concept

- **Zerodur Facesheet to Meet Optical Requirements**
  - Conventional Grind/Polish Fab Methods
- **Composite Structural Support for Glass**
  - Low Mass, High Stiffness
  - Match Thermal Expansion from Ambient to 35K

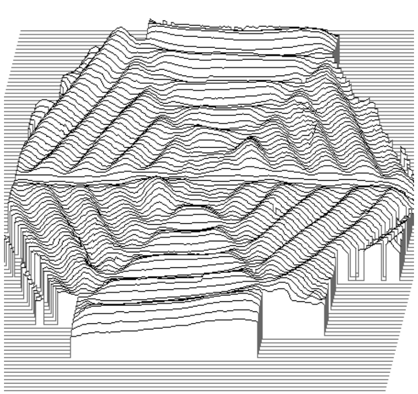
Specifications

Diameter	1.6 meter
Radius	20 meter
Areal Density	< 15 kg/m2
Areal Cost	< $2.5M/m2

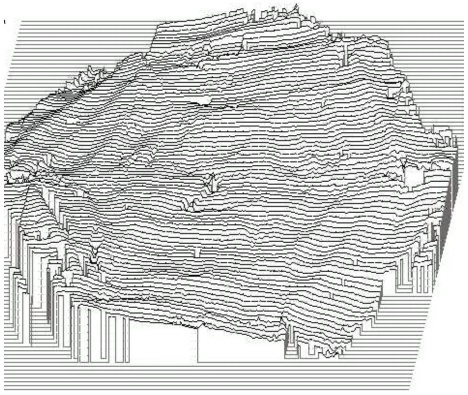


Delivered Polished with Cryo-Null Figure

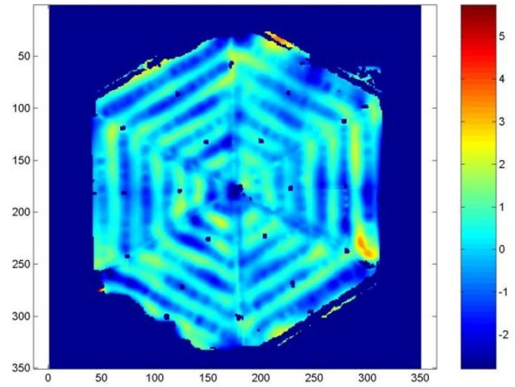
25K Figure	800 nm rms



Ambient Surface



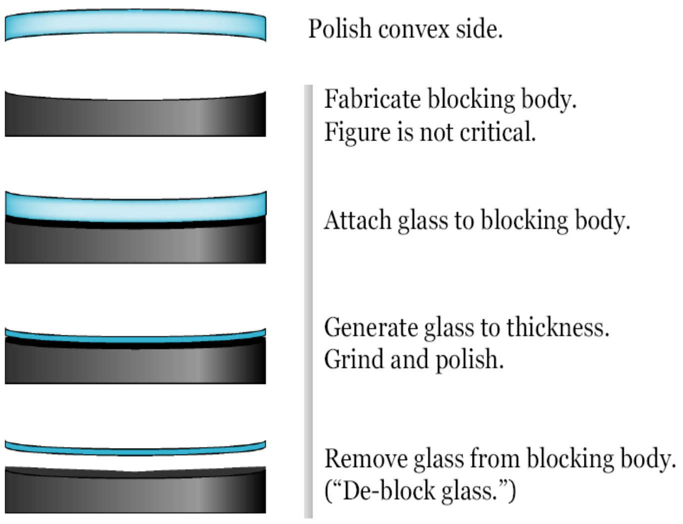
Surface at Cryo

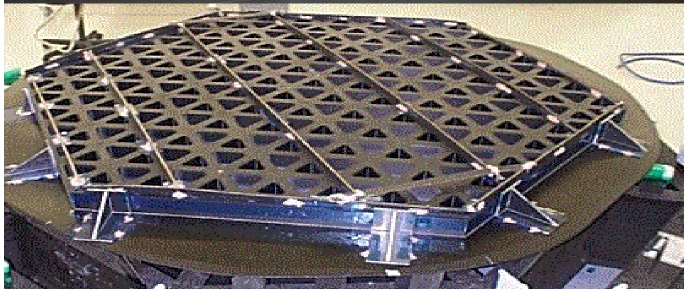


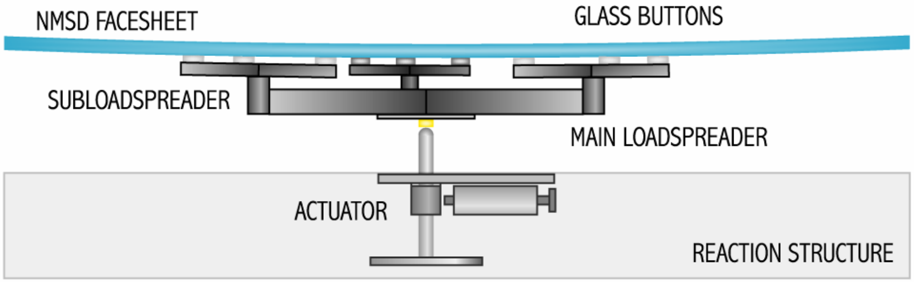
25K Figure (Low Order Zernikes Removed)
0.8micron RMS Full Aperture

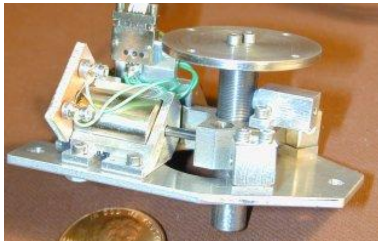
University of Arizona NGST Mirror System Demonstrator

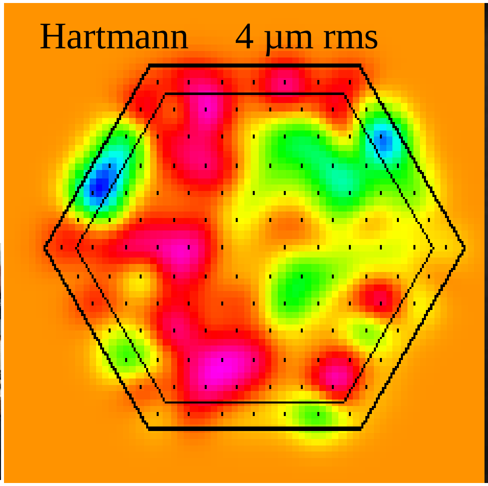
2m Dia 2 mm Thick Glass with Backplane, 166 Actuators, 9 Point Load Spreader

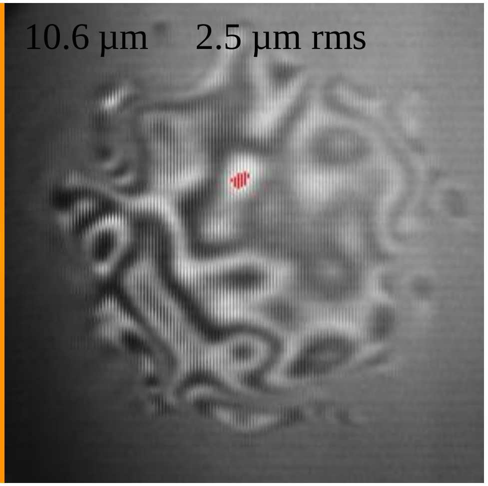












NMSD Lessons Learned

Both NMSD mirrors took significantly longer than expected and achieved significantly lower performance than expected.

CTE matching is difficult for a Cryo-Mirror.

Stiffness is much more important than Areal Density.

Stiffness is required for multiple reasons:

- Substrate/Facesheet Handeling
- Standard Fabrication Processes assume a given Stiffness
- Figure Adjustment and Stability

Expect a high infant mortality rate (~30%) on Actuators

Standard Processes and Intuition no not scale for large aperture low stiffness mirrors.

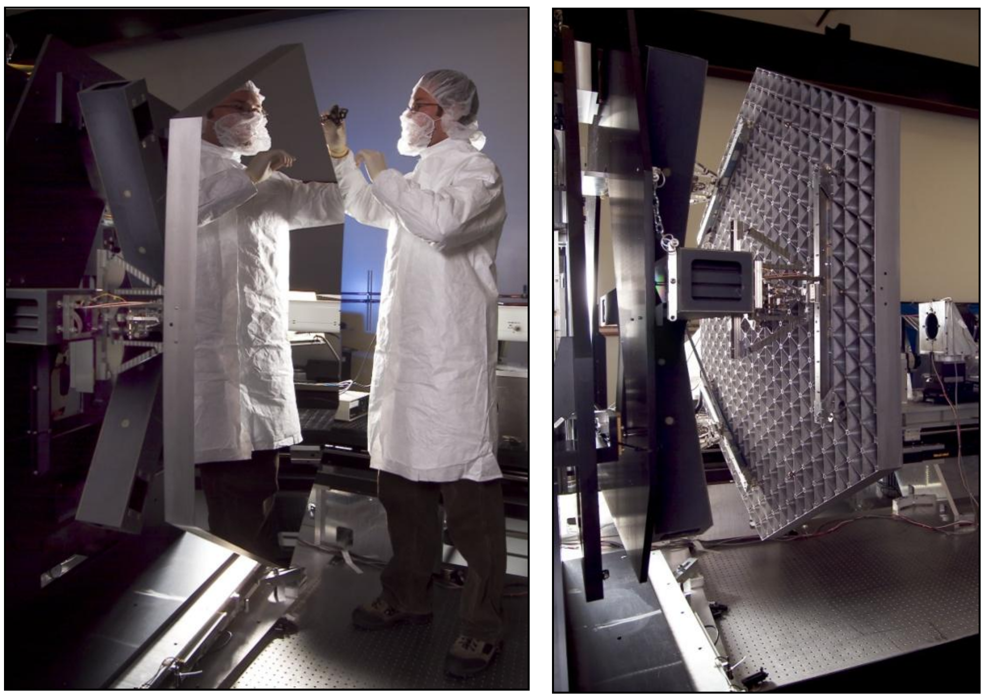
- Stiffness decreases with Diameter^2
- Stiffness increases with Thickness

Advanced Mirror System Demonstrator

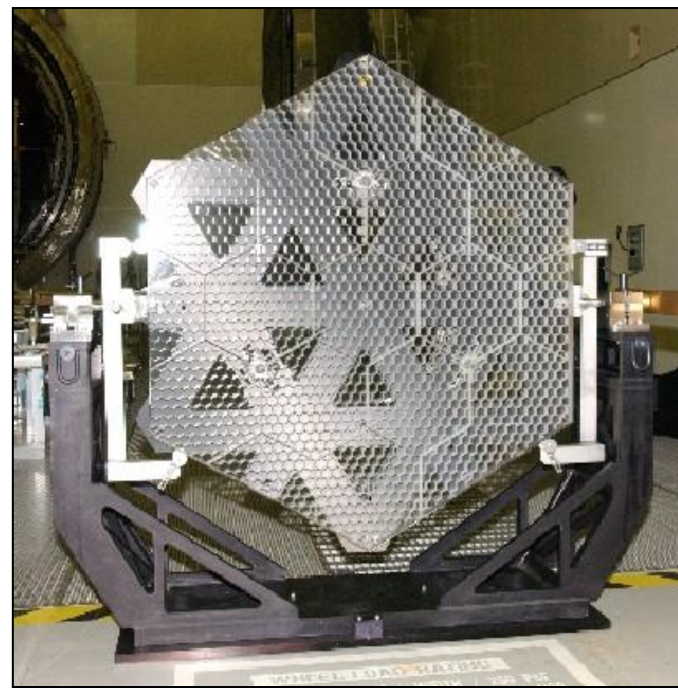
AMSD was a joint NASA, Air Force & NRO program.

AMSD developed two mirror technologies for JWST yielding data on:

- Ambient and Cryogenic Optical Performance
- Manufacturability
- Cost
- Schedule

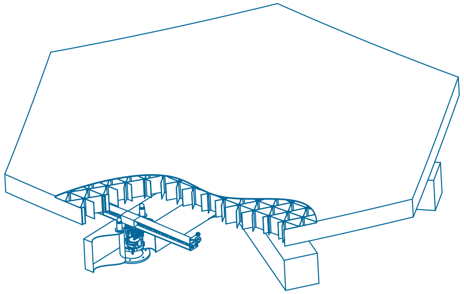


Beryllium AMSD Mirror



ULE Glass AMSD Mirror

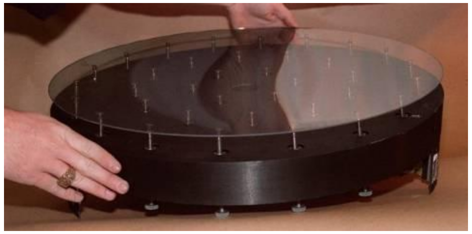
AMSD was Phased Down Select Program



Beryllium

AMSD PHASE I

MAY-SEPT. 1999

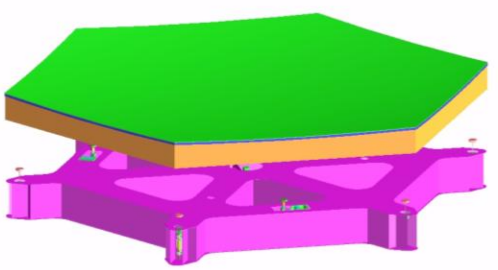


Glass Meniscus

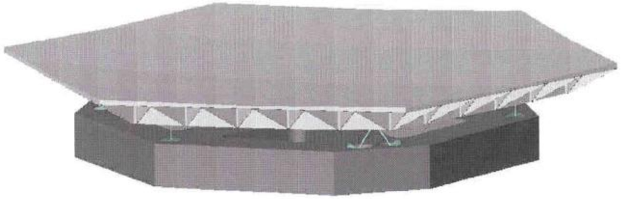
5 Contractors

8 Mirror Designs

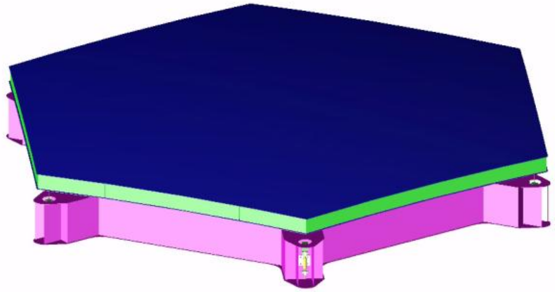
Raytheon(3)
Ball
Kodak(2)
COI
UOA



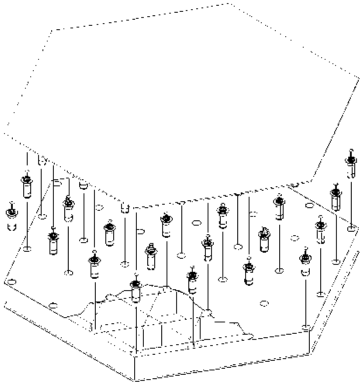
Hybrid



CSiC



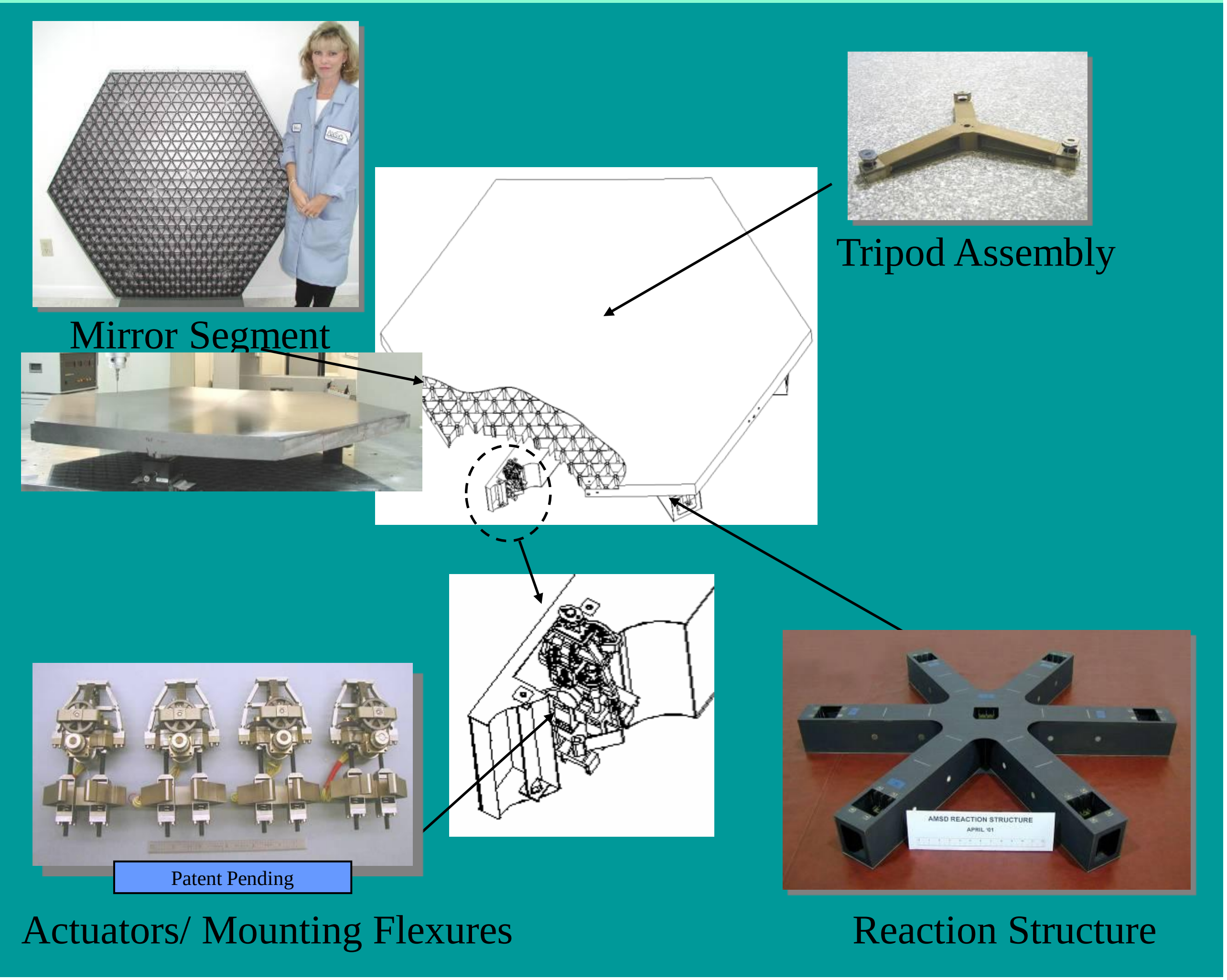
Glass



SiC,Be,Glass Meniscus

Ball AMSD Mirror

Ball's Beryllium Semi-Rigid Design for AMSD



1.39-m point-to-point open back light-weighted O-30 beryllium semi-rigid mirror

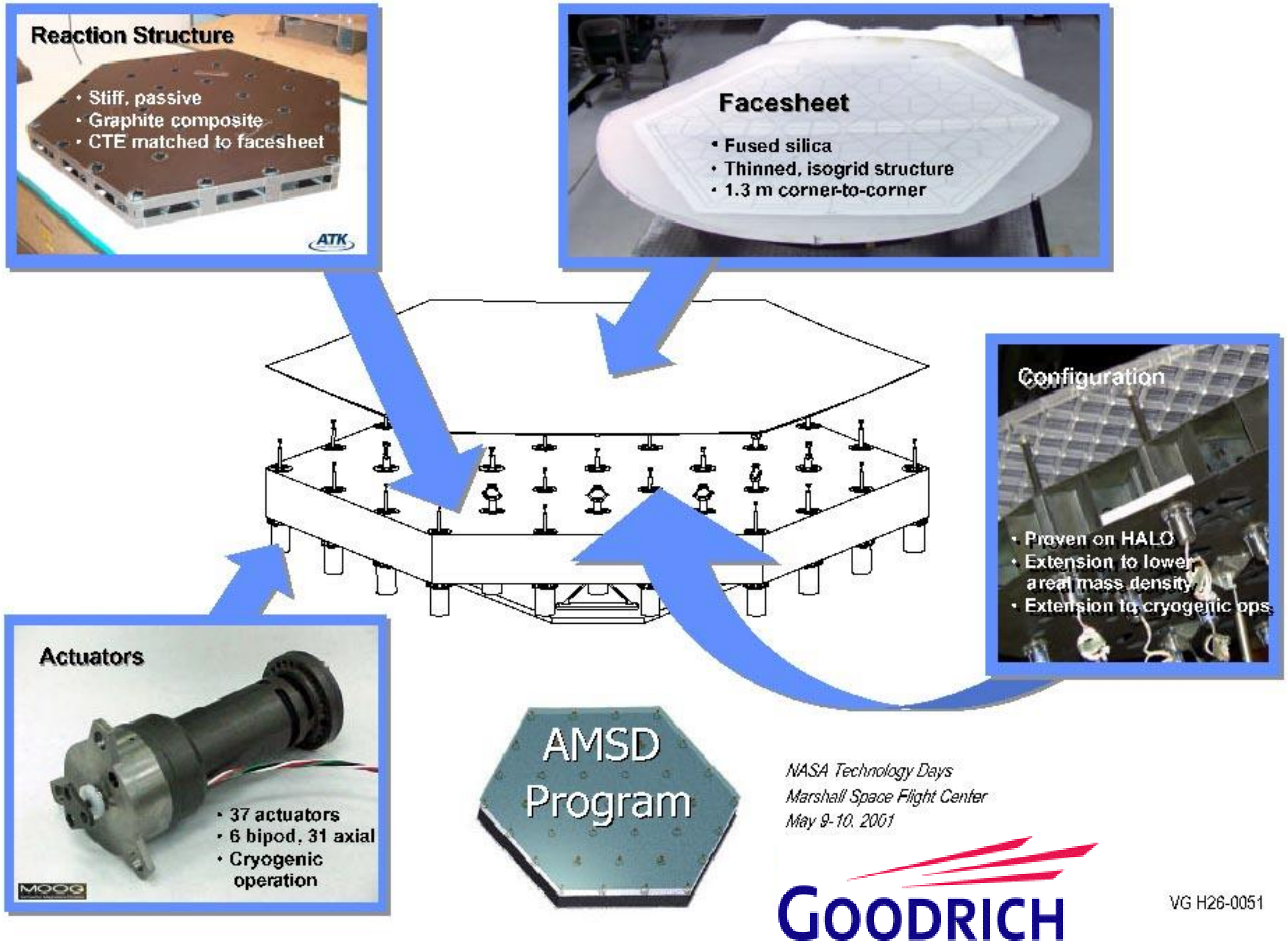
< 15 kg/m^2 areal density for mirror system including mirror, reaction structure, flexures, and actuators

Graphite Epoxy (M55J) Reaction Structure

4 Ball Actuators (3-rigid body and one for ROC).

Major Subcontractors: SVG Tinsley, AXSYS, Brush-Wellman, COI

Goodrich AMSD Mirror



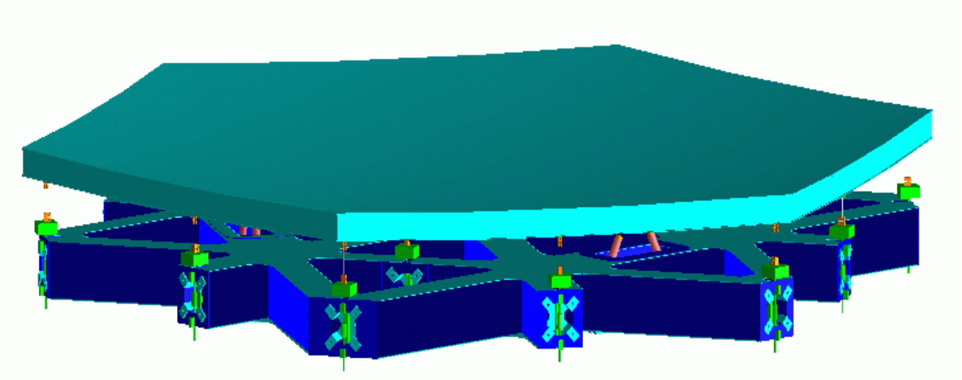
1.3 m SiO2 Iso-Grid Thin Meniscus Mirror

Graphite Composite Reaction Structure from ATK

37 Displacement Actuators from Moog

Kodak AMSD Mirror

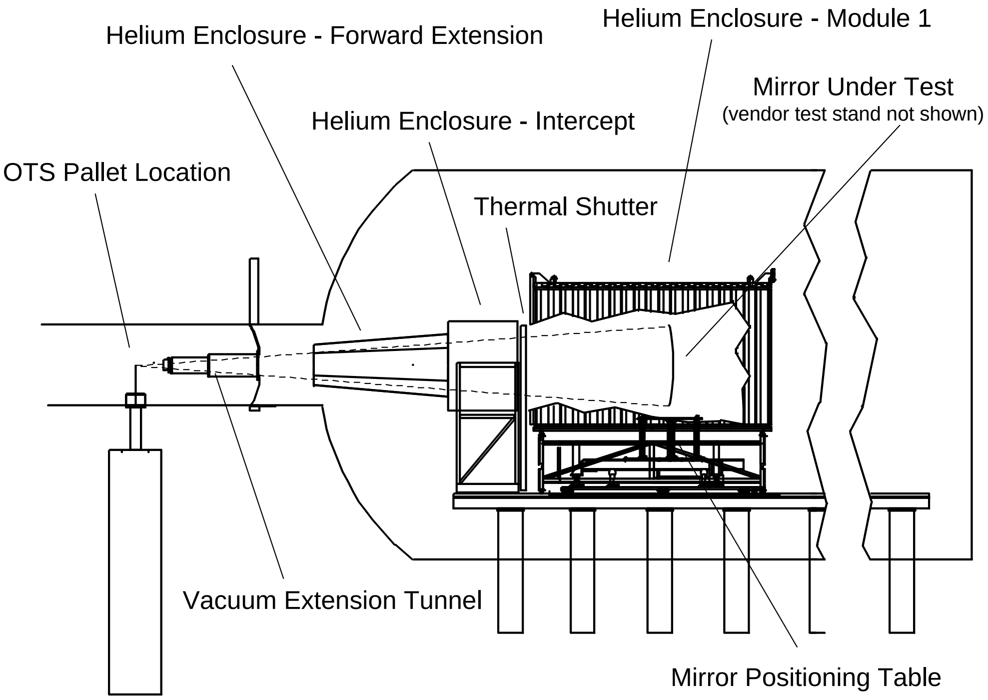
- 1.4 m Diameter Semi-Rigid ULE Closed-Back Sandwich Construction Mirror
  - Low Temperature Fusion into a Flat Substrate
  - Grind Facesheets to Final Mass
  - Low Temperature Slump into Sphere
- Graphite Epoxy (M55J) Reaction Structure by COI
- 16 Force Actuators by Moog
  - 7 for wavefront & radius
  - 9 for gravity offloading
  - No Rigid Body Adjustments

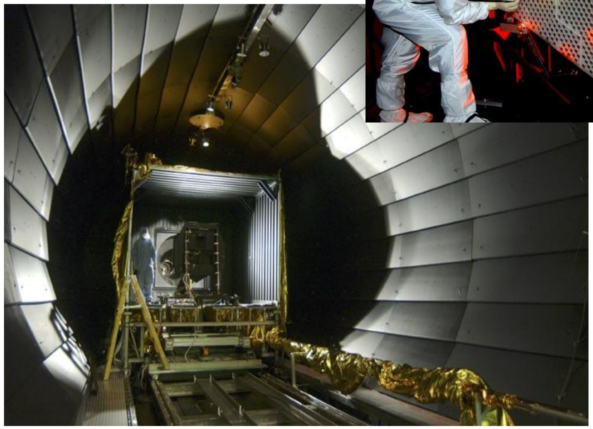


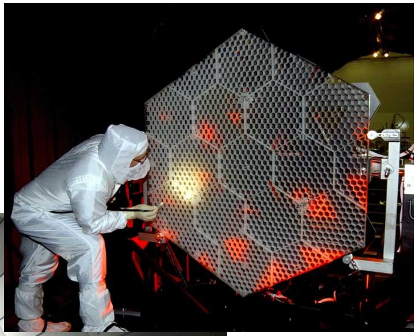
Performance Characterization

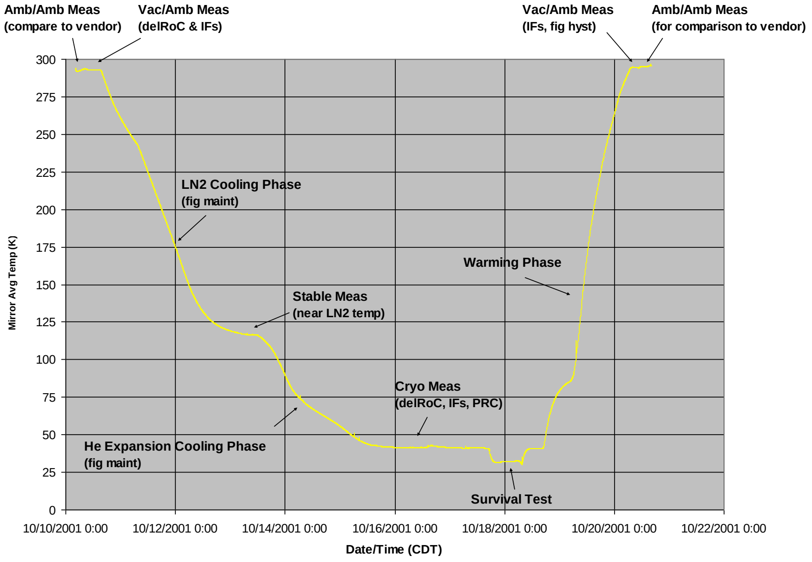
Ambient and Cryogenic Optical Performance was measured at XRCF.

Each mirror tested multiple times below 30K









AMSD – Ball & Kodak

Specifications

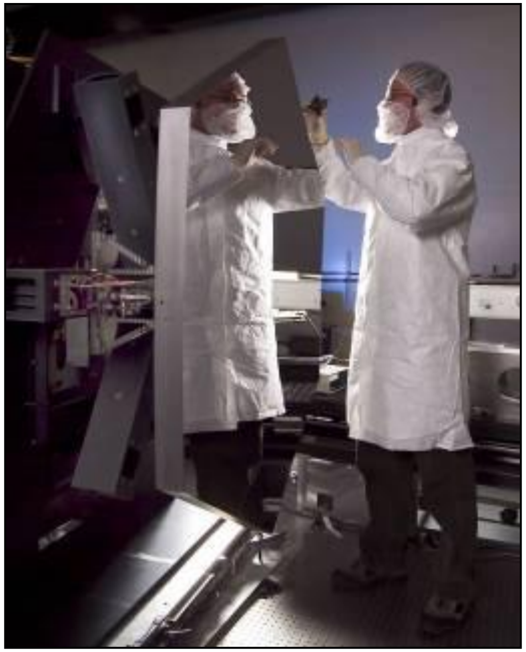
Diameter	1.4 meter point-to-point
Radius	10 meter
Areal Density	< 20 kg/m2
Areal Cost	< $4M/m2

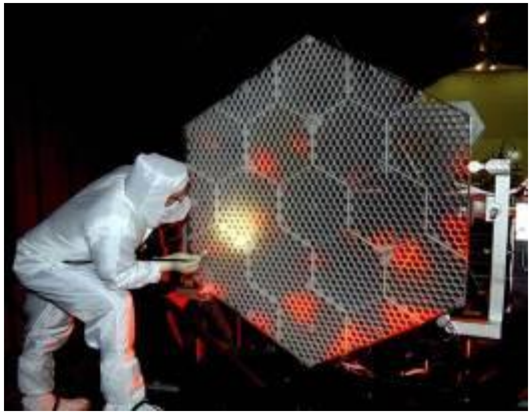
Beryllium Optical Performance

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

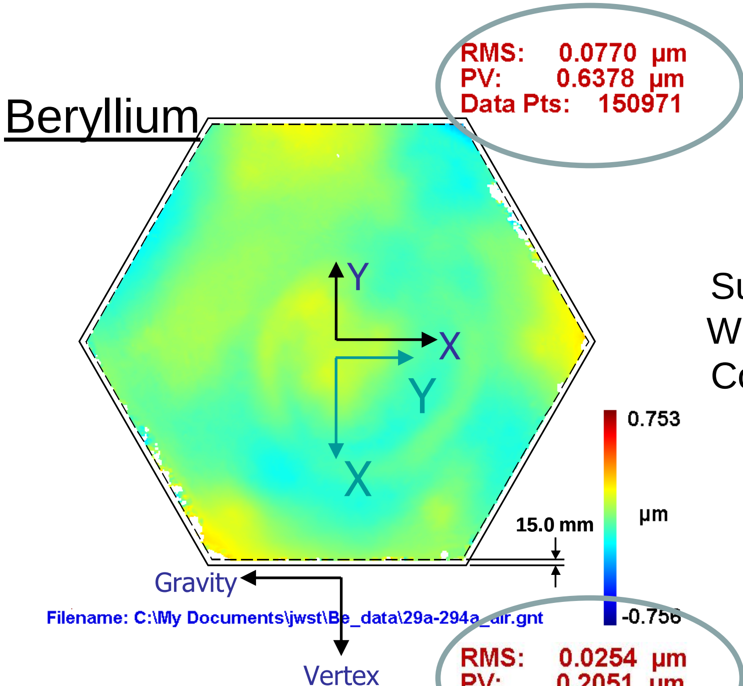
ULE Optical Performance

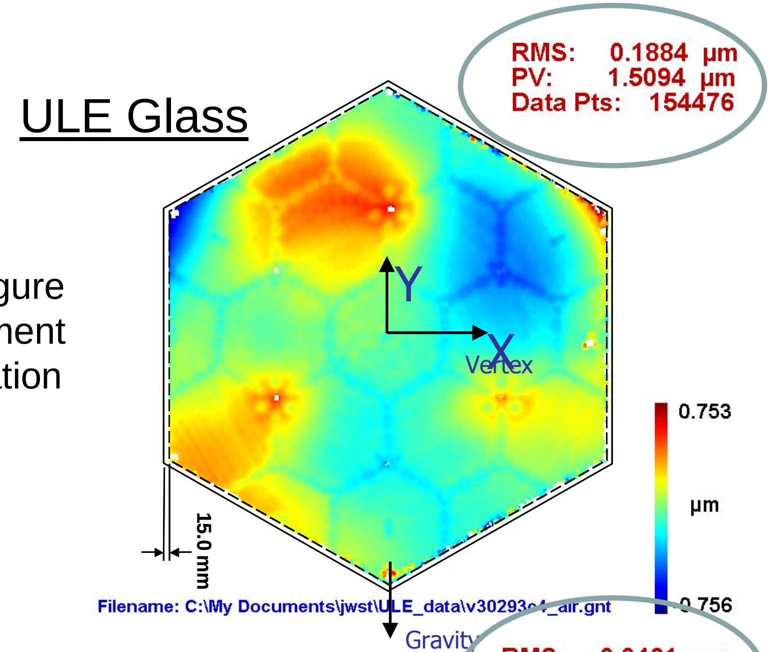
Ambient Fig	38 nm rms (initial)
290K – 30K	188 nm rms
55K – 30K	20 nm rms



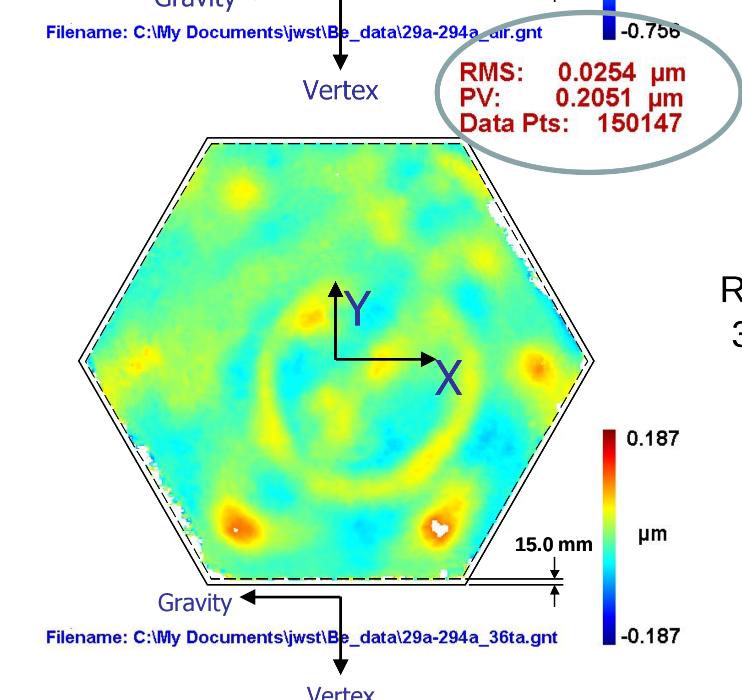


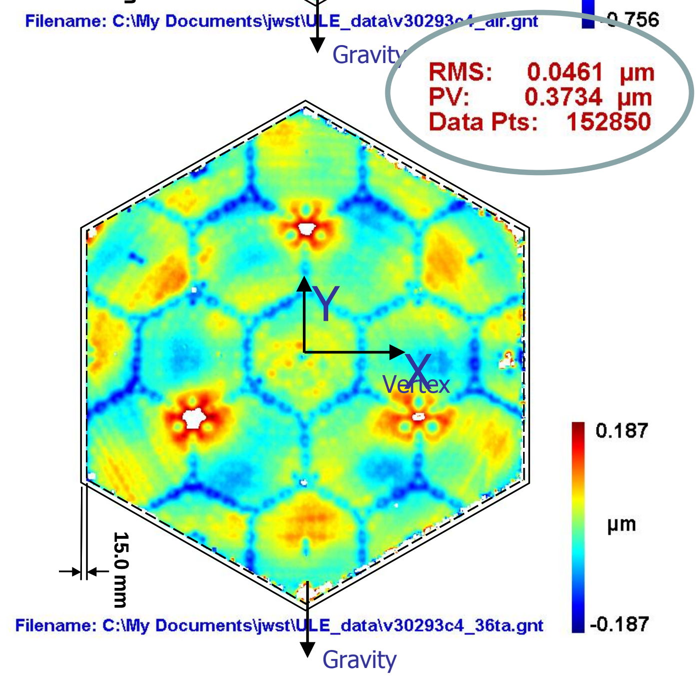
AMSD Figure Change: *Ambient-to-Cryo (30 K)*





Surface Figure With Alignment Compensation





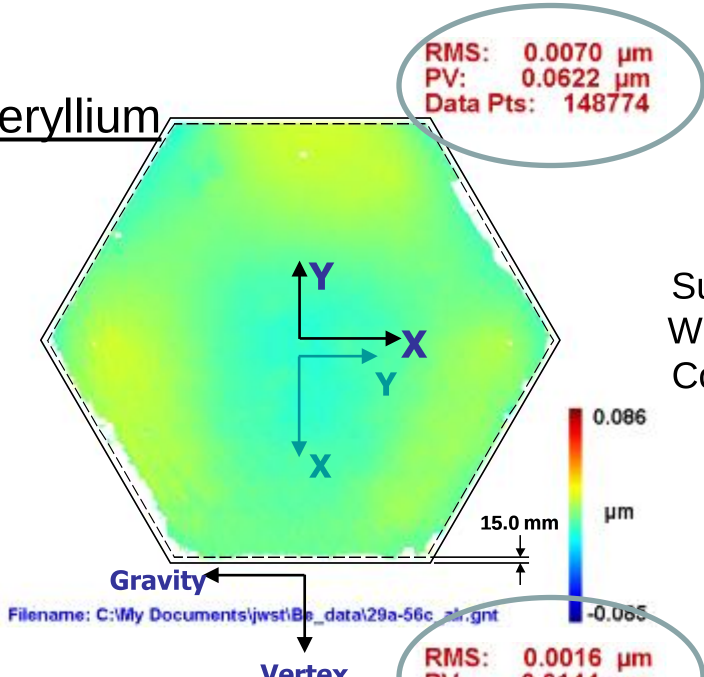
Residual with 36 Zernikes Removed

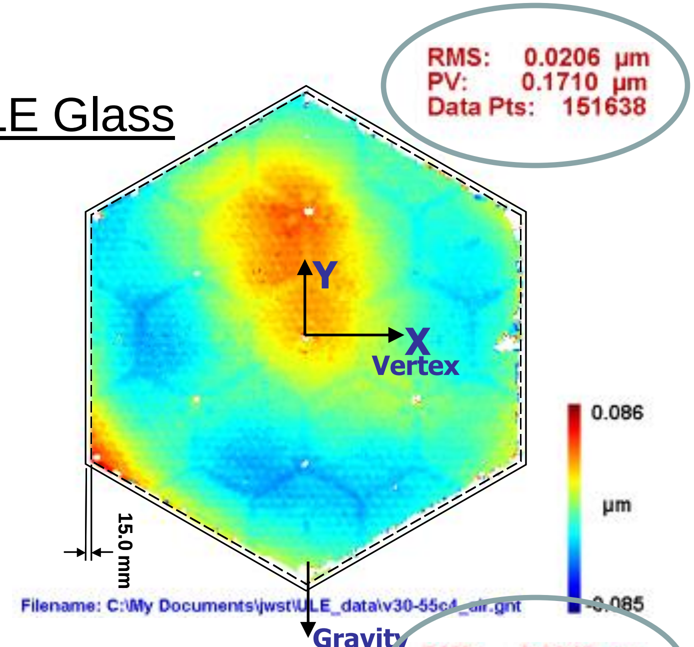
AMDS Figure Change: *30-55K Operational Range*

Beryllium

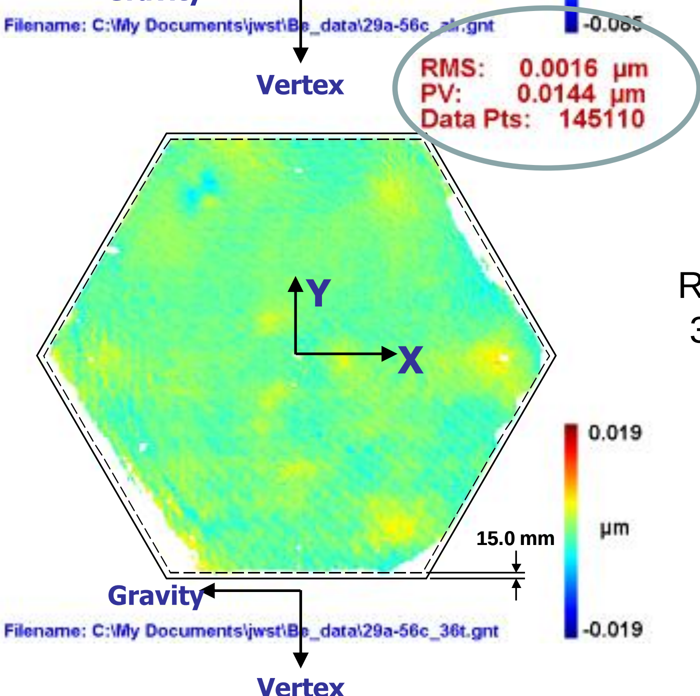
ULE Glass

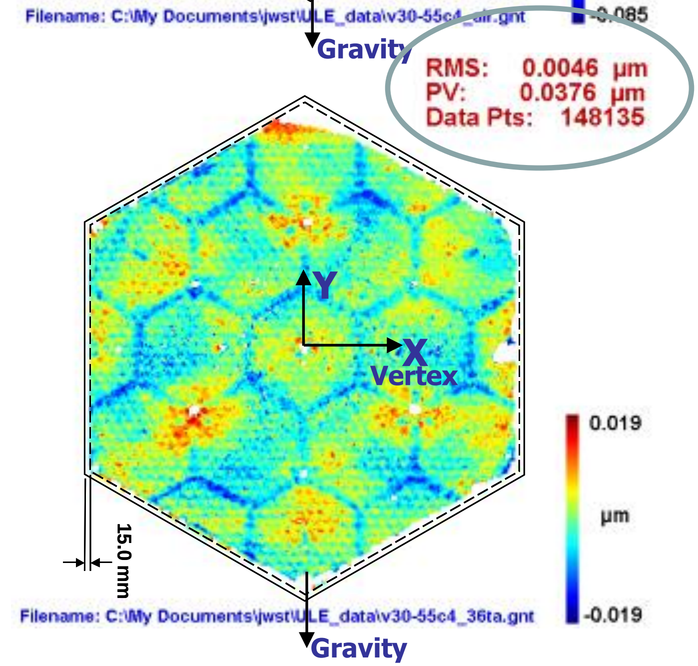
Surface Figure With Alignment Compensation



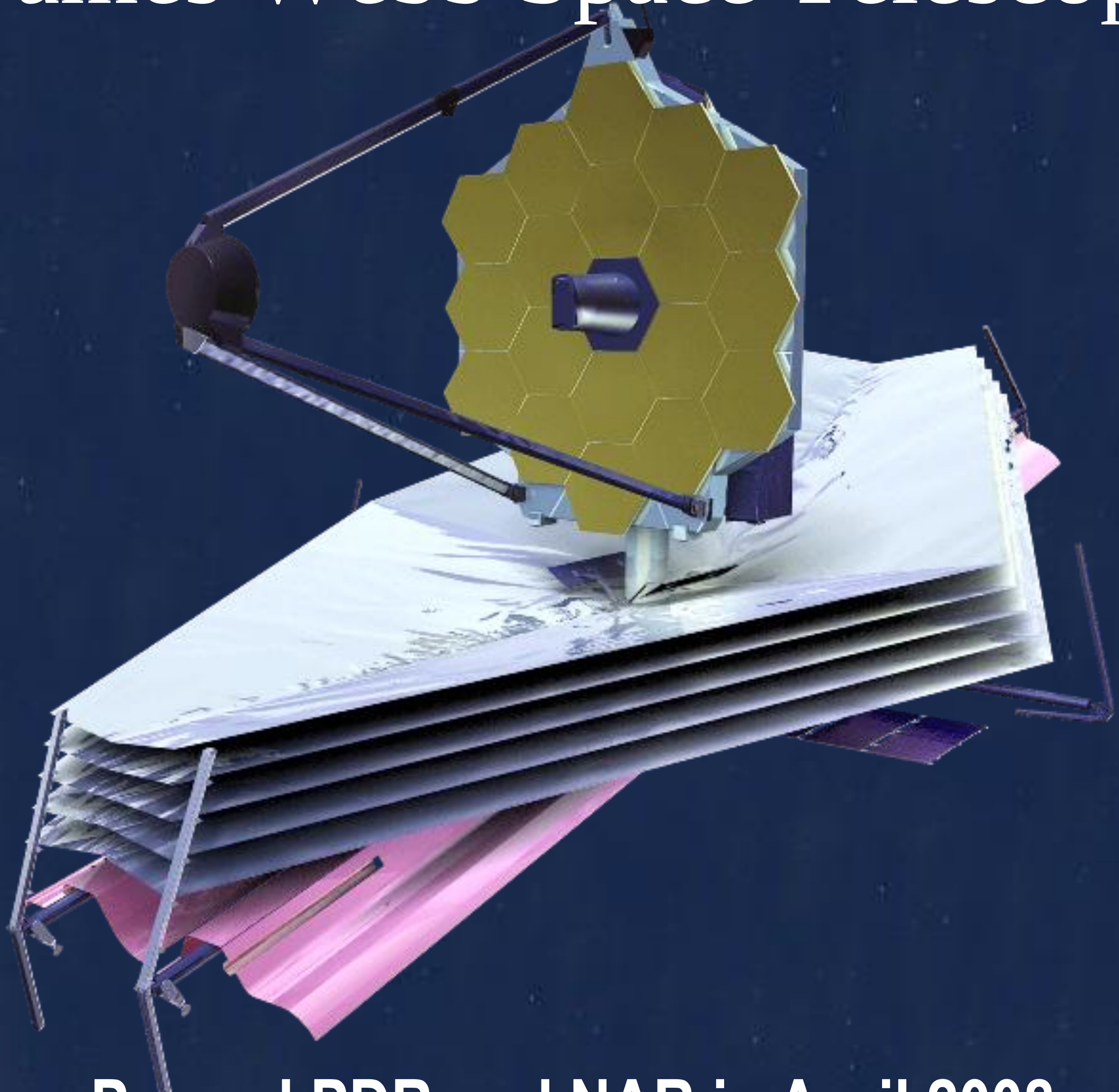


Residual with 36 Zernikes Removed





James Webb Space Telescope



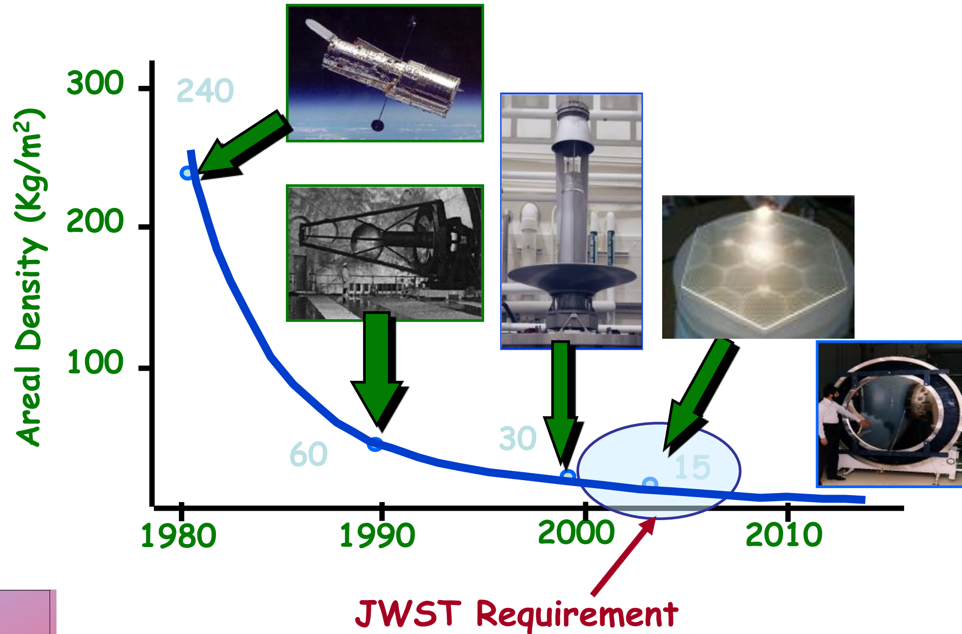
Passed PDR and NAR in April 2008

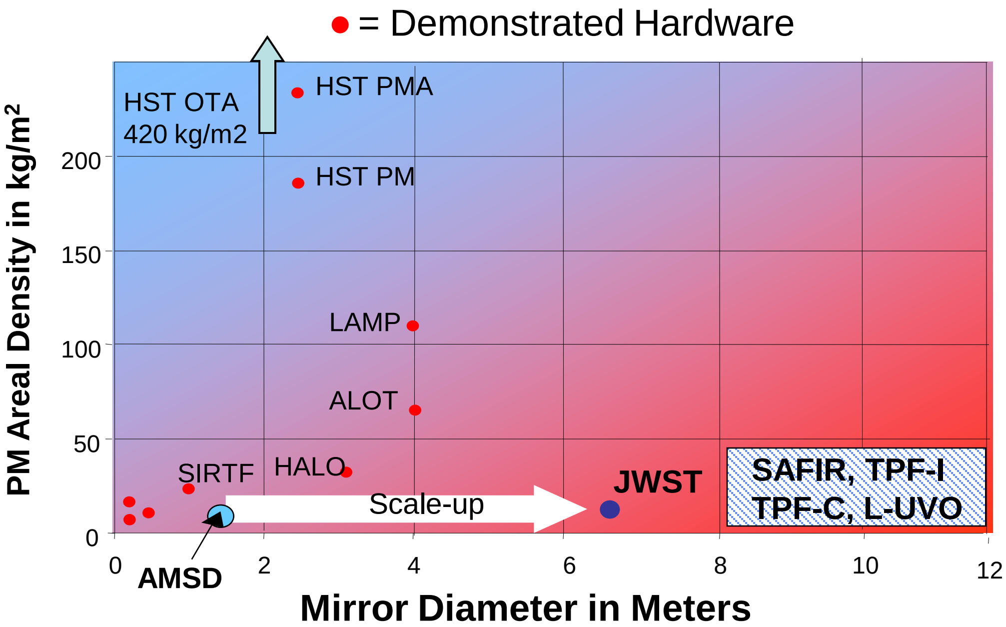
Mirror Technology Development - 2000

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 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

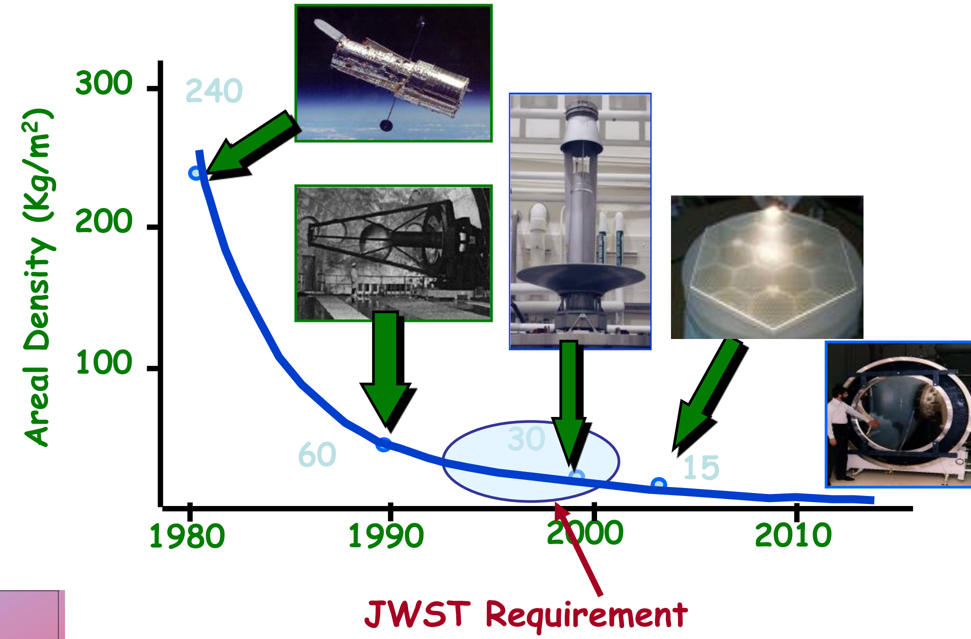
Note: Areal Cost in FY00 $

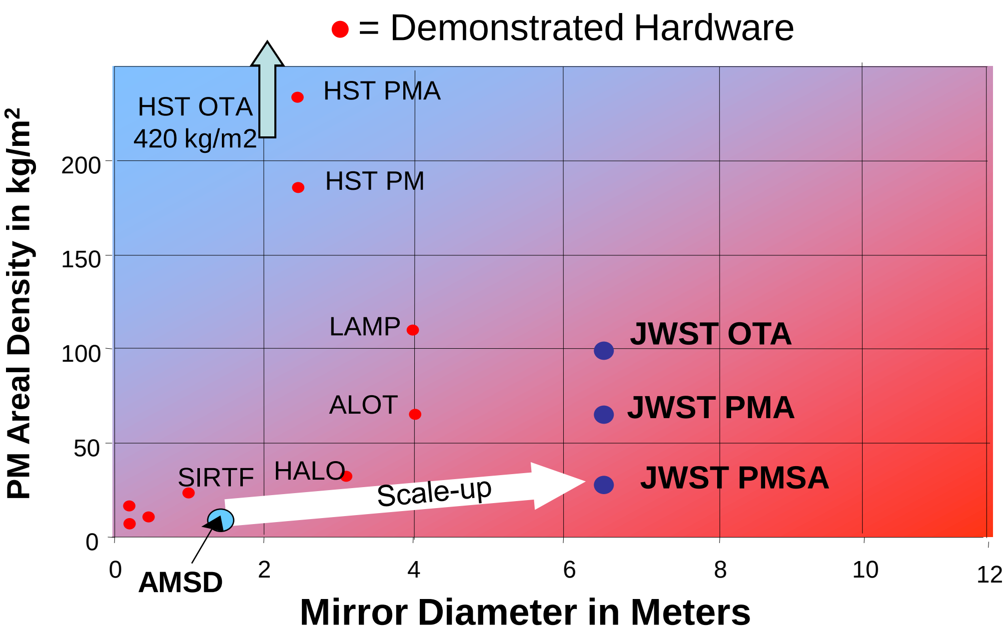
Mirror Technology Development 2010

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



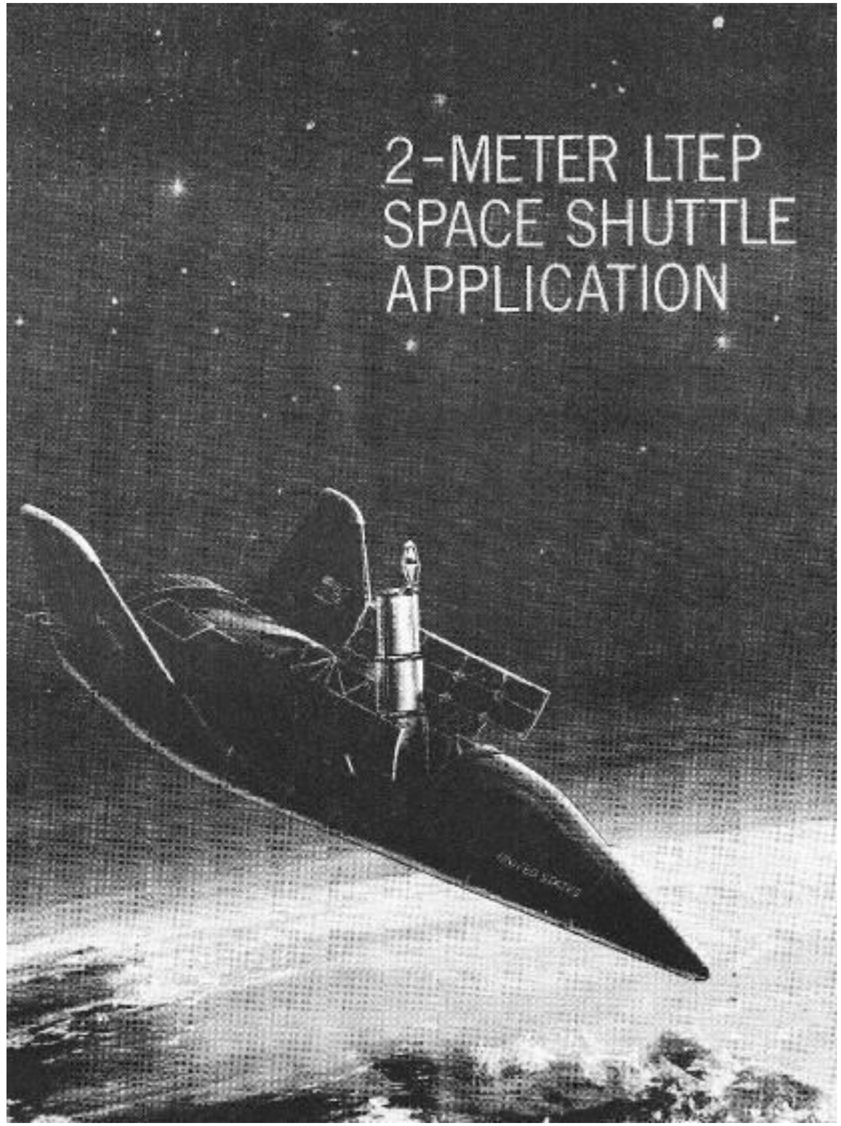


Primary Mirror	Time	& Cost
HST (2.4 m)	≈ 1 m^2/yr	≈ \$12M/m^2
Spitzer (0.9 m)	≈ 0.3 m^2/yr	≈ \$12M/m^2
AMSD (1.2 m)	≈ 0.7 m^2/yr	≈ \$5M/m^2
JWST (6.5 m)	≈ 5 m^2/yr	≈ \$6M/m^2

Note: Areal Cost in FY10 $

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

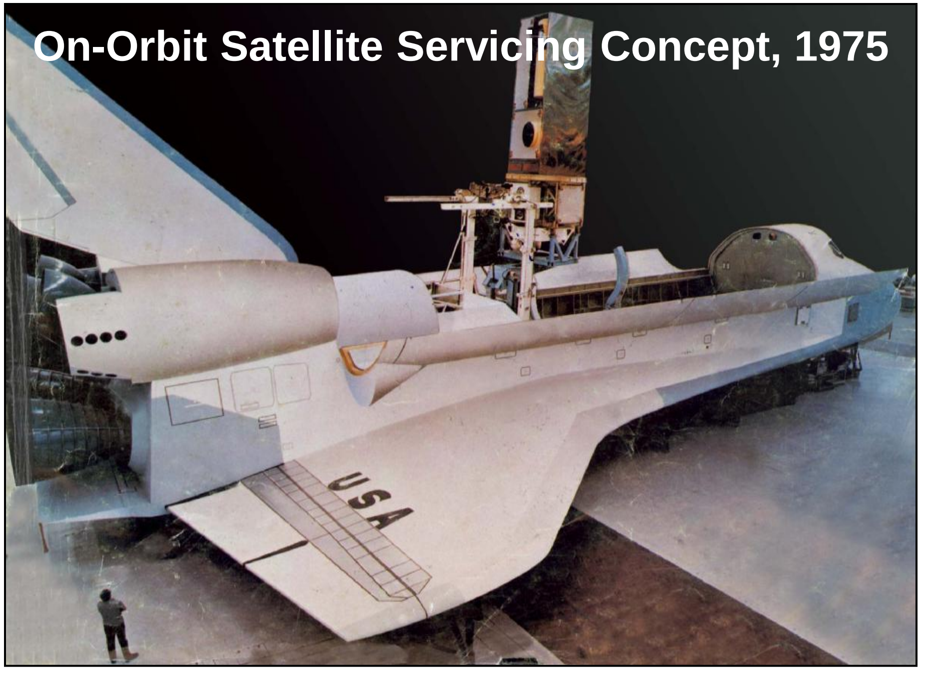
Design Synergy

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

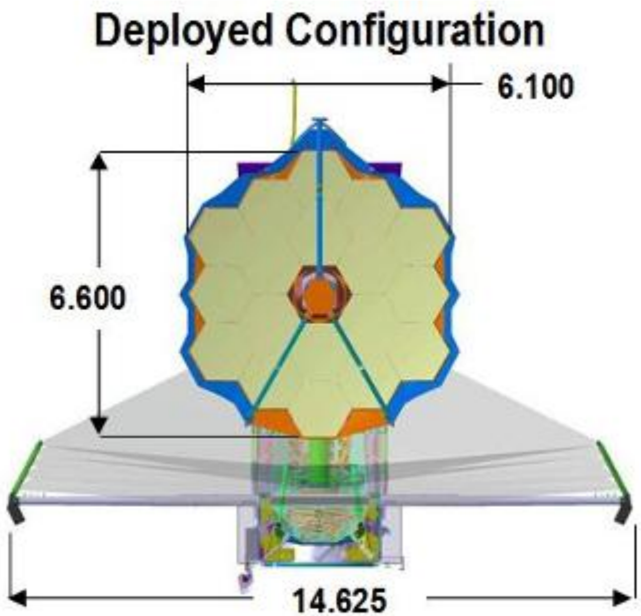
Hubble, Compton and Chandra were specifically designed to match Space Shuttle's payload volume and mass capacities.

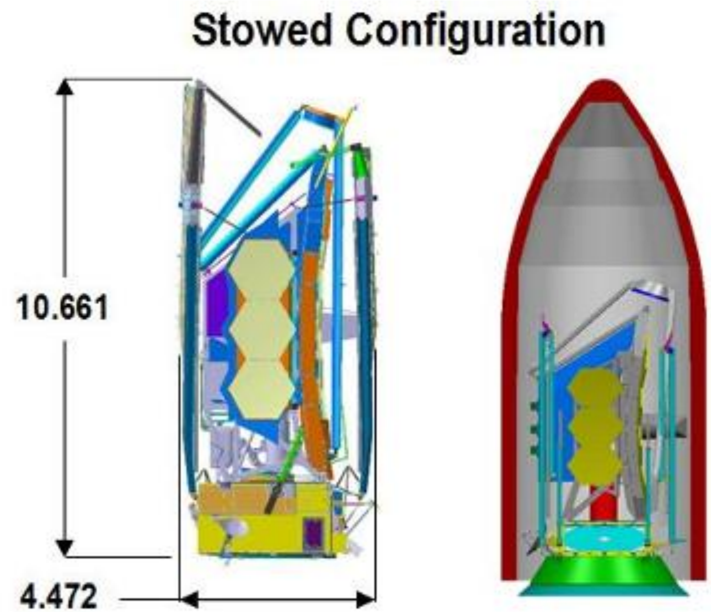
	Launch	Payload Mass	Payload Volume
Space Shuttle Capabilities		25,061 kg (max at 185 km) 16,000 kg (max at 590 km)	4.6 m x 18.3 m
Hubble Space Telescope	1990	11,110 kg (at 590 km)	4.3 m x 13.2 m
Compton Gamma Ray Observatory	1991	17,000 kg (at 450 km)	
Chandra X-Ray Telescope (and Inertial Upper Stage)	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 …..

A Heavy Lift Launch Vehicle would be a Disruptive Capability which would offers the potential for completely new Mission Concepts

SLS vs Ares V

First it was Ares V, now it is SLS (Space Launch System)

While these charts are for Ares V, the reported SLS capabilities are similar.

SLS ‘lite’ will have between 80 and 100 mt to LEO.

SLS ‘heavy’ will have 140 mt to LEO (very similar to Area V)

Ares V delivers 6X more Mass to Orbit

Sun

Earth

Moon

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

L2

1.5 M km from Earth

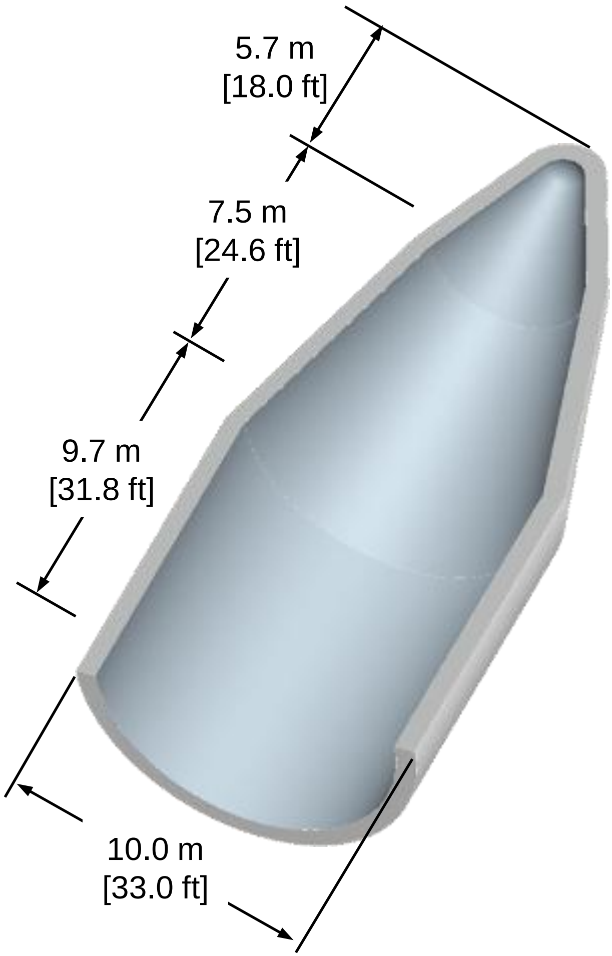
Ares V Performance for Selected Missions

Mission Profile	Target	Payload Mass (kg)
Sun-Earth L2	**C3 of -0.7 km^2/s^2 @ 29.0 degs**	**55,800**
GTO Injection	**Transfer DV 8,200 ft/s Final Orbit: 185 km X 35,786 km @ 27 deg**	**70,300***
GEO	**Transfer DV 14,100 ft/s Final Orbit: 35,786 km Circular @ 0 degrees**	**36,200**
Cargo Lunar Outpost (TLI Direct)	**C3 of -1.8 km^2/s^2 @ 29.0 degs**	**56,800**

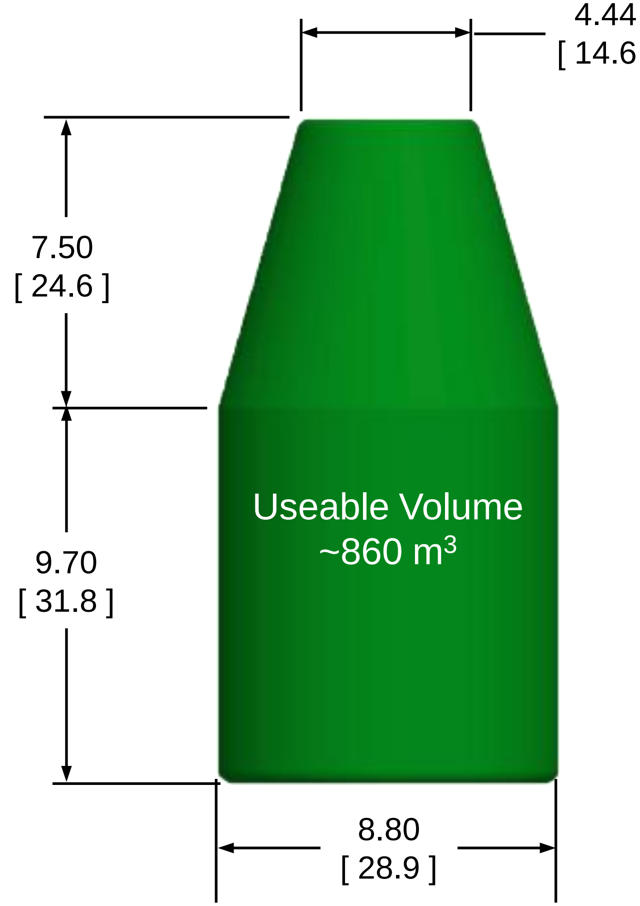
* Performance impacts from structural increases due to larger payloads has not been assessed

Current Ares V 10 meter Shroud - Biconic

Shroud Dimensions



Usable Dynamic Envelope

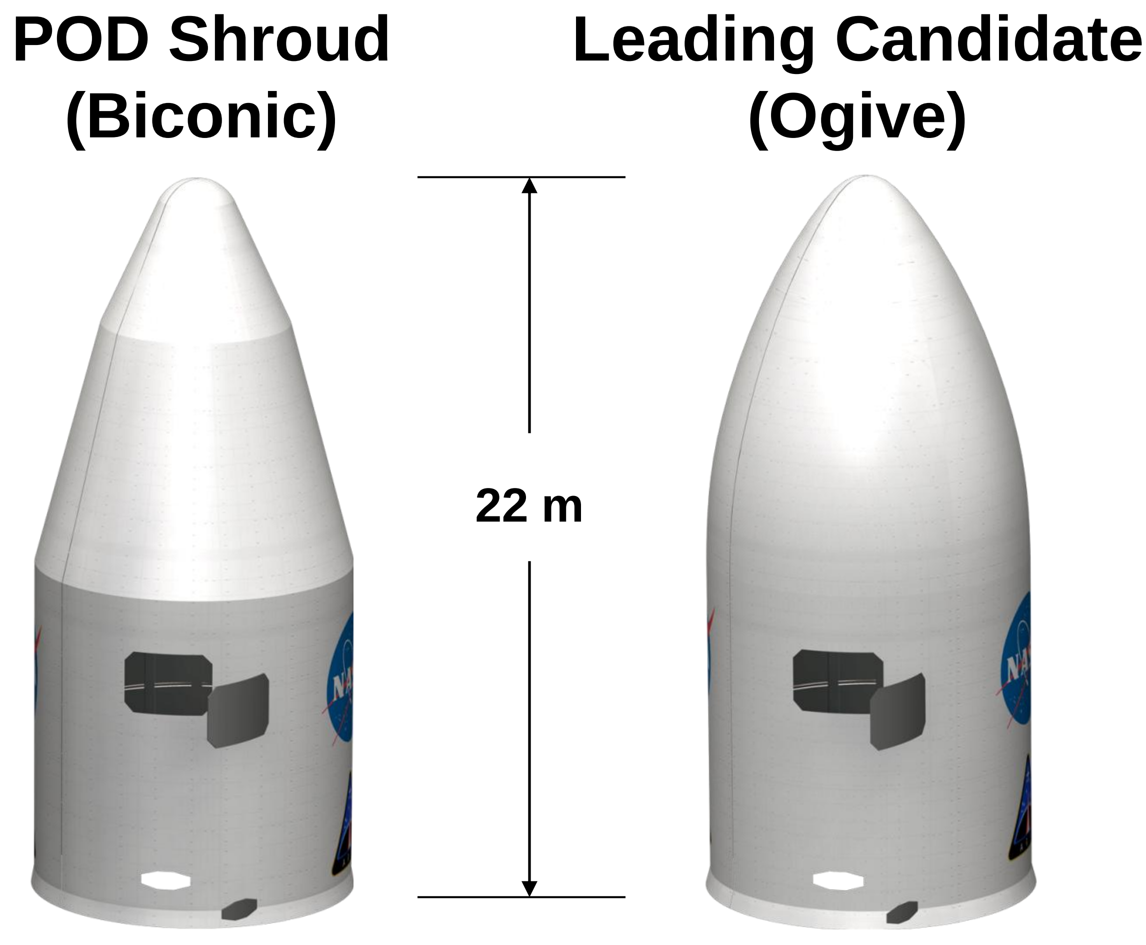


Mass: 9.1 mT (20.0k lbm)

Total Height: 22 m (72 ft)

meters [feet]

Alternative Payload Shroud Design Concept



Ogive Shroud provides more usable vertical payload height than Biconic

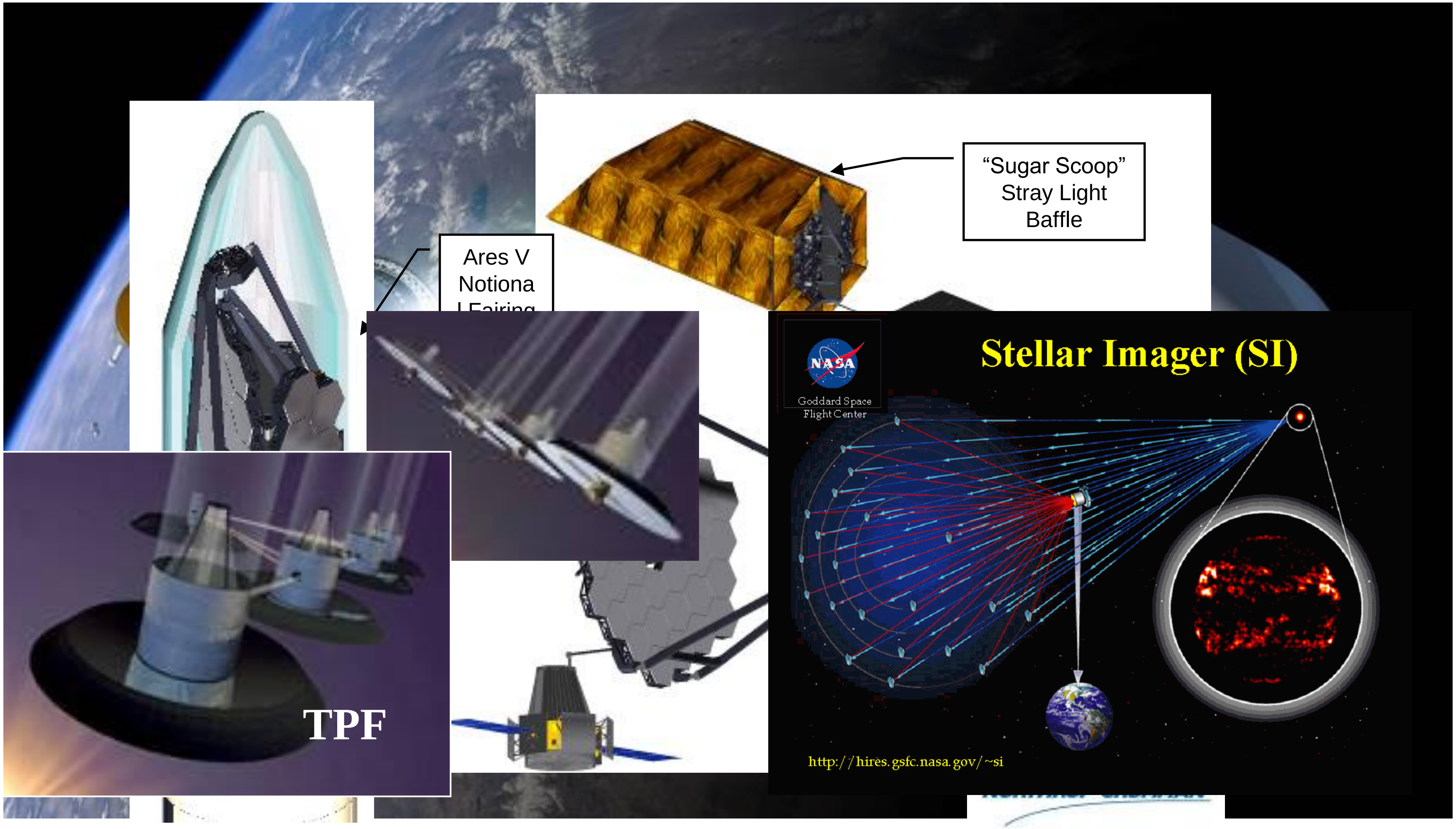
Payload interface adapter to Ares V (@ 10 m diameter) must fit inside shrouds

Max Shroud height is limited by height of KSC Vehicle Assembly Building

SLS Changes Paradigms

SLS Mass & Volume enable entirely new Mission Architectures:

– 8 meter class Monolithic UV/Visible Observatory



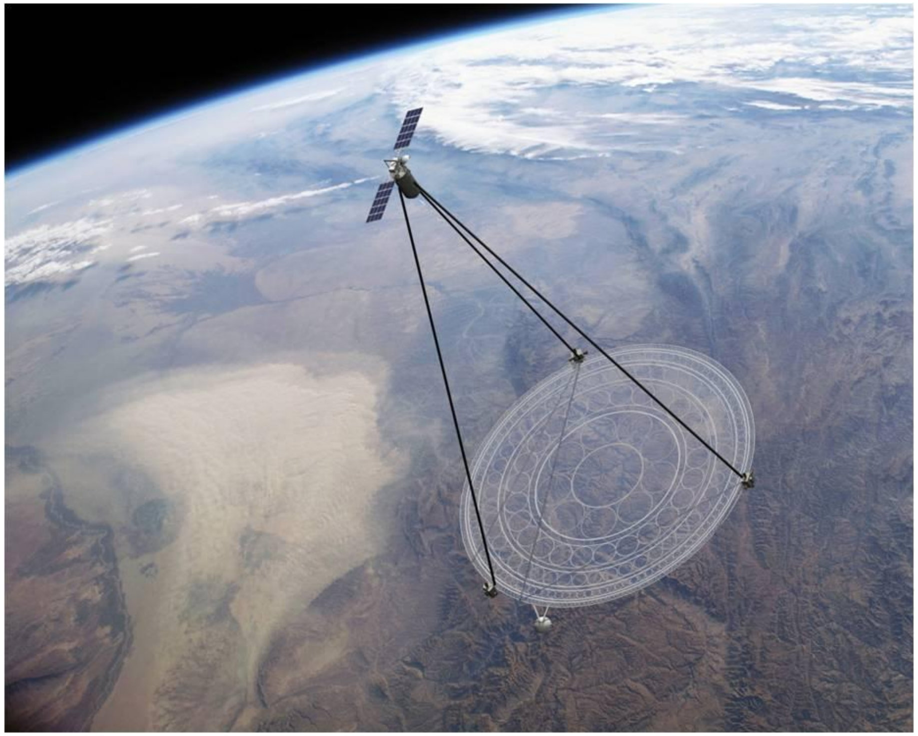
And now for something completely different ….

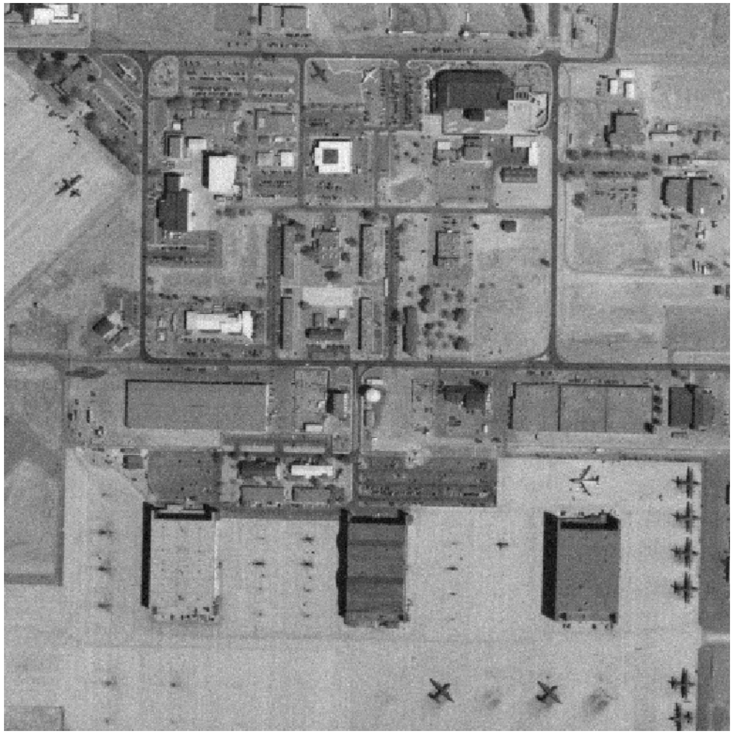
Giant Telescopes without mirrors

MOIRE 20 meter Diffractive Telescope

Design Reference Mission Performance Goals

- Persistence – 24/7
- Missile launch detection & vehicle tracking
- Ground Sample Distance -- ~ 1m
- Visible/IR Video @ > 1 Hz
- Field of View > 100 sq km
- Field of Regard – 15,000 km by 15,000 km (without slewing)
- < $500M/copy (after R&D)





Consider what you could do with Multi-Spectral Fiber Detectors

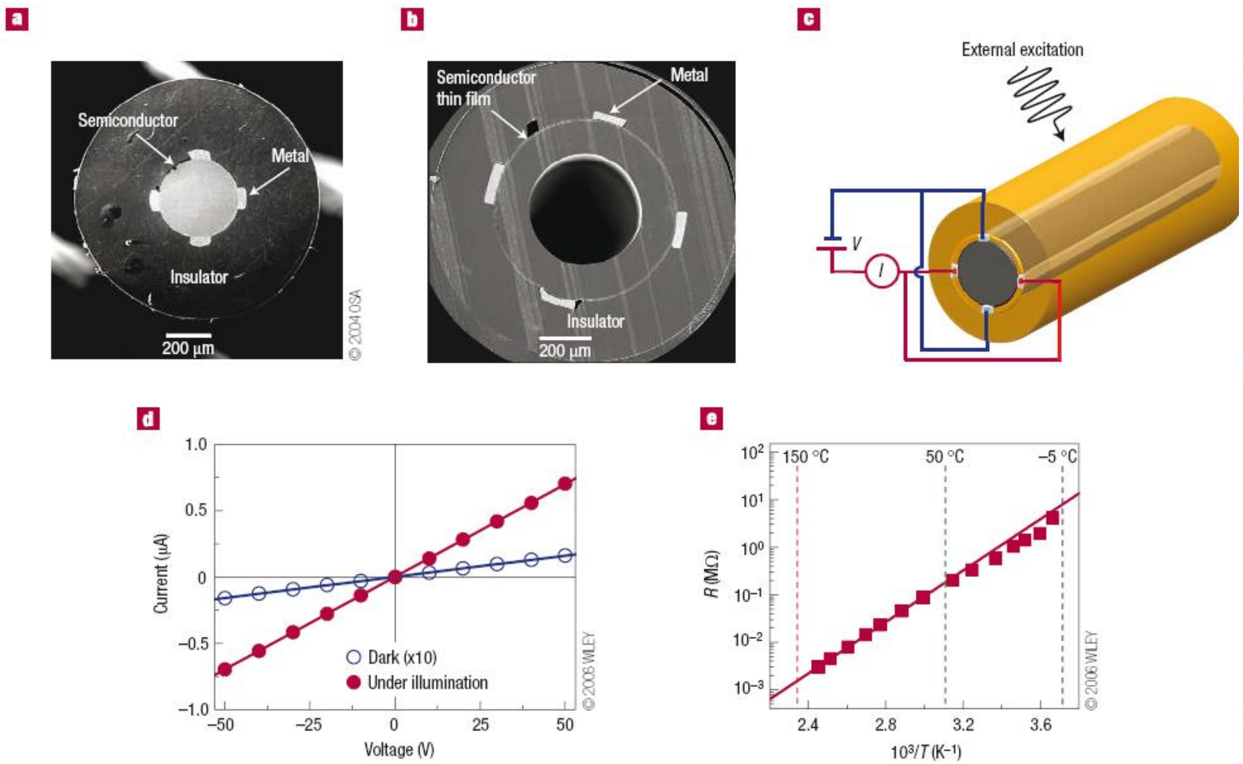


Figure 3 Metal–semiconductor–insulator fibre devices. **a**, SEM micrograph of a cross-section (the semiconductor is $As_{40}Se_{50}Te_{10}Sn_5$, the insulator polymer is PES, and the metal is Sn). Image reprinted from ref. 26. **b**, SEM micrograph of a thin-film fibre device (the semiconductor is As_2Se_3, the insulator polymer is PES, and the metal is Sn). **c**, Electrical connection of the four metal electrodes at the periphery of the fibre to an external electrical circuit. **d**, The current–voltage characteristic curve of a photosensitive solid-core fibre device (980 μm outer diameter, 15 cm long). The conductivity increases upon illumination (20 mW, white light) when compared with dark conditions. **e**, The resistance of a thermally sensitive solid-core fibre device (1,150 μm outer diameter, 9 cm long) as a function of temperature. **c–e** reprinted with permission from ref. 28.

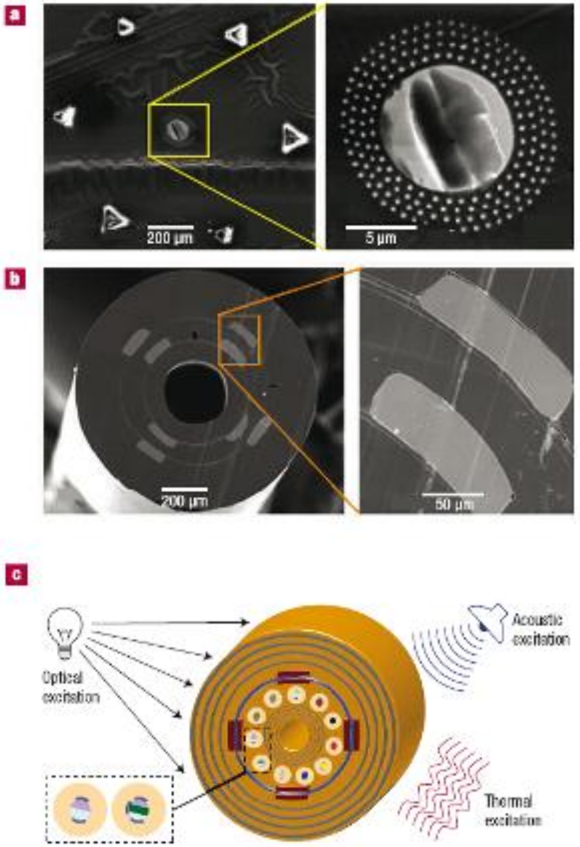


Figure 8 Fibre-device integrated bundles produced by stacking and redrawing. **a**, An array of chalcogenide-glass nanowires surrounding a solid-core of highly nonlinear chalcogenide glass. **b**, Two concentric thin-semiconductor-film devices integrated into the same fibre. **c**, Future vision of integrated fibre-device bundles. A single fibre consists of a hollow core lined with an omnidirectional reflector for optical-power transmission. The fibre is surrounded with another omnidirectional reflector, which may contain multiple cavities, for spectral filtering of externally incident radiation. The fibre contains thin-film semiconducting devices, and also multiple devices distributed over the cross-section, with each device sensitive to a different environmental parameter (light, heat, acoustic waves and so on). Logical operations may also be implemented with simple semiconductor junctions, two of which are shown in the inset.

Abouraddy, et al., "Towards multimaterial multifunctional fibres that see, hear, sense and communicate", Nature Materials, Vol 6, pp.336, May 2007.

Computed Axial Tomography Astronomy (Astro-CAT)

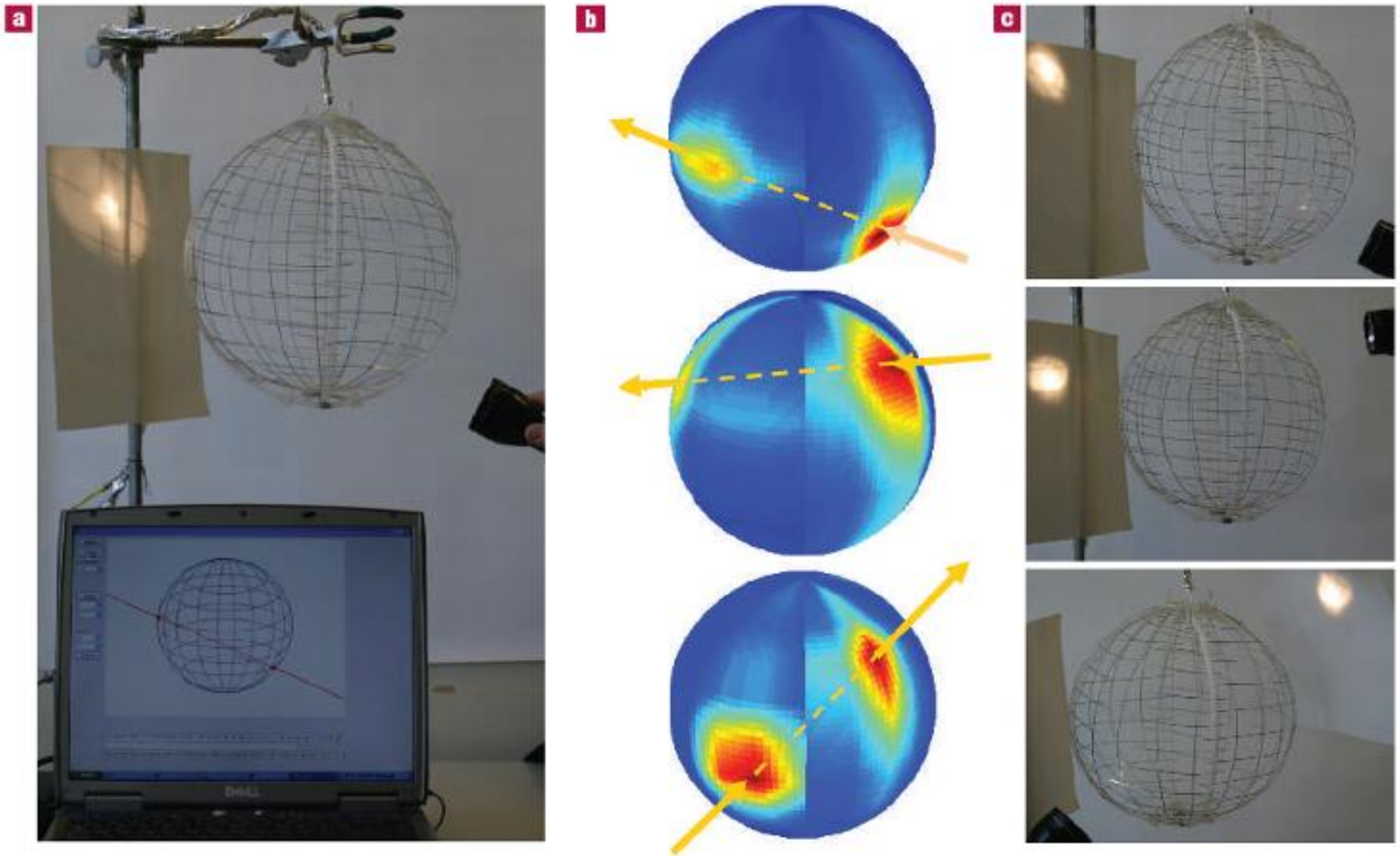


Figure 2 Omnidirectional light detection. **a**, A closed spherical fibre web is an omnidirectional photodetector which detects the direction of the beam throughout a solid angle of 4π. The spherical web is sufficiently transparent to see through and for a beam of light to traverse unimpeded. **b**, The distribution of the electrical signals detected by the fibres for a light beam incident in three different directions. The arrows indicate the direction of the beams, and the dashed portion of each arrow corresponds to the beam's path inside the sphere. **c**, Photographs of the three beam trajectories that resulted in the signal distributions shown in **b**.

Abouraddy, et al., “Large-scale optical-field measurements with geometric fibre constructs”, Nature Materials, Vol 5, pp.532, July 2006.

Acknowledgements

Mark Stier and Dave Chadwick
of Goodrich Danbury

Gary Mathews of ITT

Tom Parsonage of Brush-Wellman

Jim Bilbro retired NASA
and his historical reports

Any Question?