Lightweight Optics: Optical to IR

to:

Astrophysics Subcommittee
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What is 'Status' of Lightweight Optics

Answering whether Lightweight mirrors are at TRL-3 or TRL-6 depends on knowing the boundary constraints:

- What Science must the mirrors perform?
  - Different science requires different system capabilities
  - Nearly all science wants larger aperture telescopes
  - BUT most important for LUVOIR/HabEx is Stability.
- What Launch Vehicle will be used?
  - If SLS & we design accordingly, then Areal Density is OK.
  - If not SLS, then we need long-term sustained investment to develop either lower mass telescopes or on-orbit assembly.
- What is the Available Budget?
  - Depending on Aperture Diameter, current Areal Cost is either OK or too High by 2X.

Science Driven Systems Engineering

Science Requirement	Engineering Specification	Launch Vehicle	Engineering Specification	Program
Wavelength	Diffraction Limit (WFE)			
	Temperature			
		Mass	Areal Density	Areal Cost
Resolution	PM Diameter	Volume	Segmented?	
	Pointing Stability (Structure)			
Contrast	WFE Stability (Structure) (Vibration) (Thermal)			

NOTE: Exoplanet WFE Stability 'maybe' beyond State of Art

What is 'Status' of Lightweight Optics

Stahl's Rules of Thumb		
Parameter	Easier (less $)	Harder (more $)
Diffraction Limit	Longer (20 μm; Far-IR)	Shorter (500 nm; UVOIR)
Temperature	Warm (300 K;UVOIR)	Cold (10 K; Far-IR)
Aperture	Monolithic	Segmented
Seg/Mirror Size	2 meter	4 meter
Areal Density	100 kg/m^2	10 kg/m^2

In my opinion, the most important issues are:

- Wavefront Stability
  - Primary Mirror Assembly (PMA) Stiffness
  - Primary Mirror Assembly (PMA) Thermal Stability
- Areal Cost (PMA cost / Collecting Area)

Definitions

Optical Telescope Assembly

- Primary Mirror Assembly
- Secondary Mirror Assembly
- Optical Bench Structure

Primary Mirror Assembly

- Primary Mirror and/or Segments
- Primary Mirror Support Structure

HST

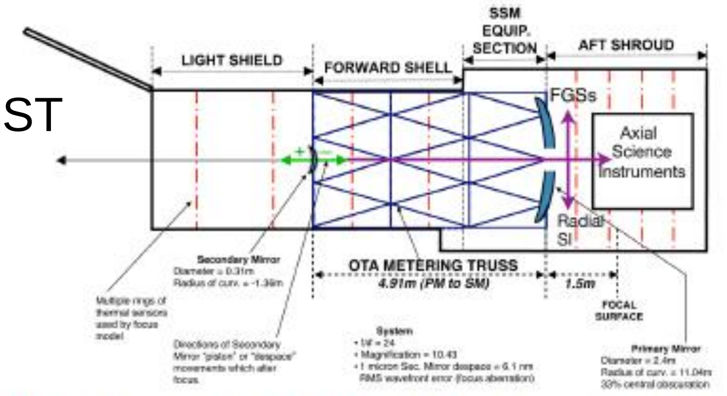
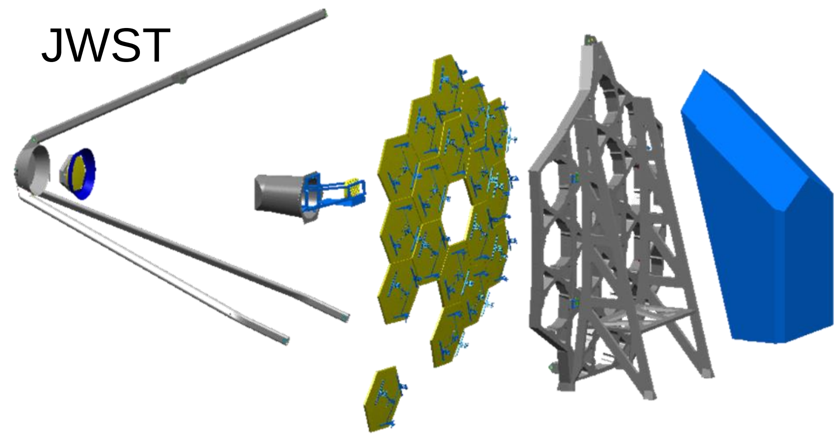
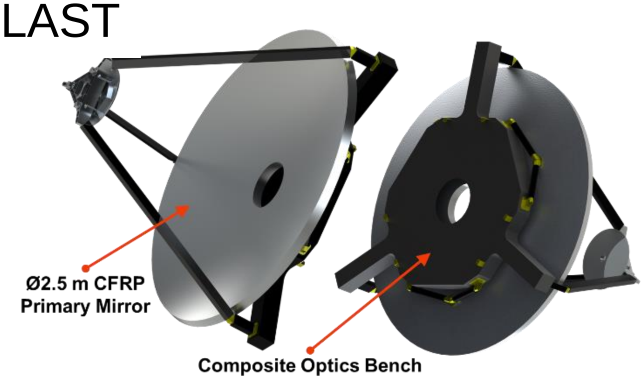


Fig. 3 Simplified HST schematic, showing relevant optical quantities and overall physical layout (see also Table 1).

JWST



BLAST

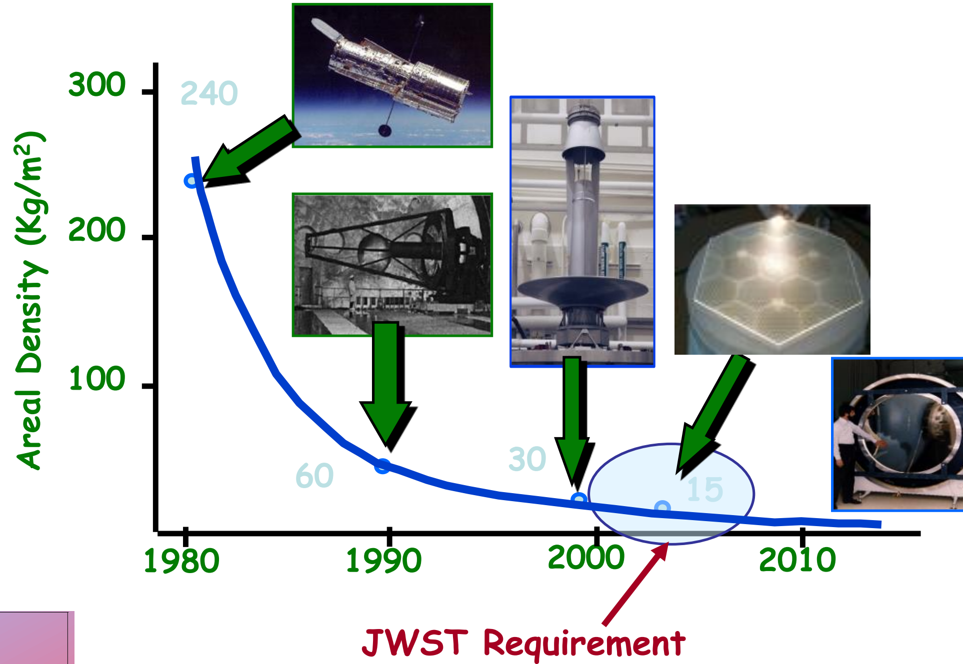


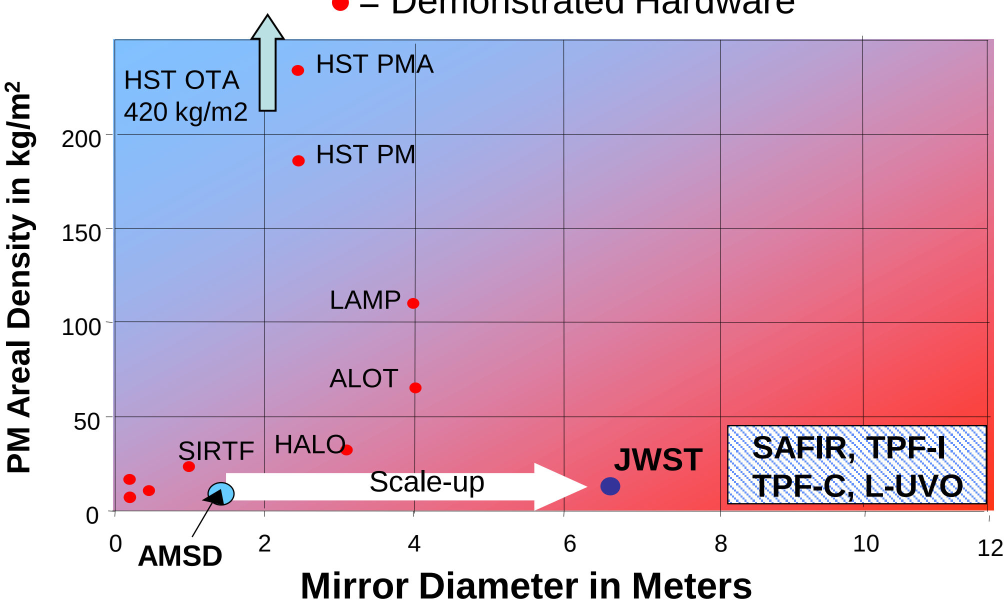
JWST Mirror Technology Development 1999

Challenges for Space Telescopes:

20X Areal Density reduction relative to HST to enable up-mass.

5X Cost & Schedule Improvement relative to HST.





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

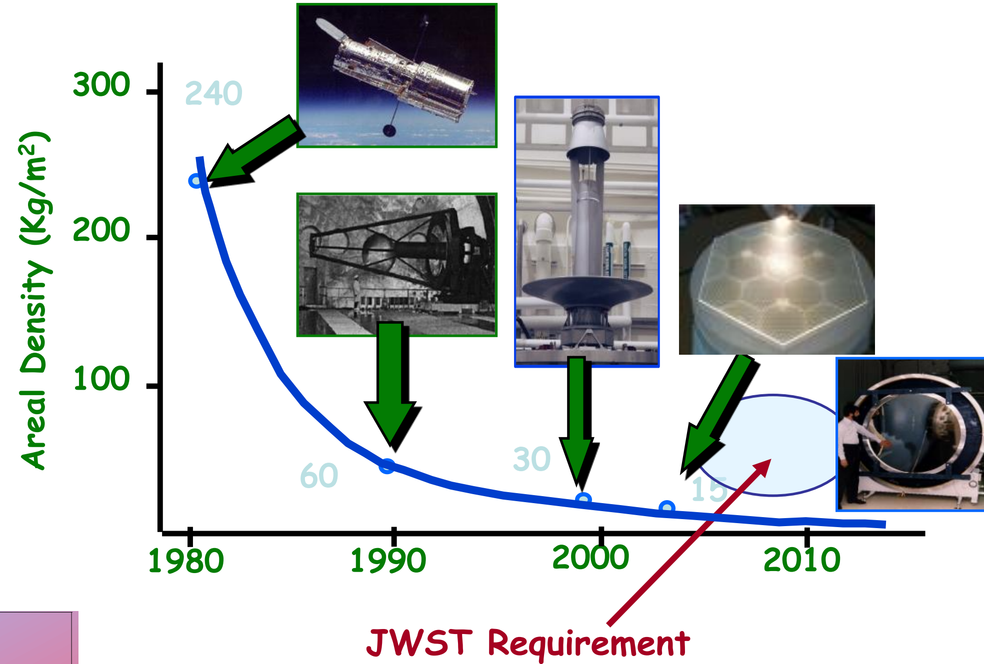
Note: Areal Cost in FY00 $

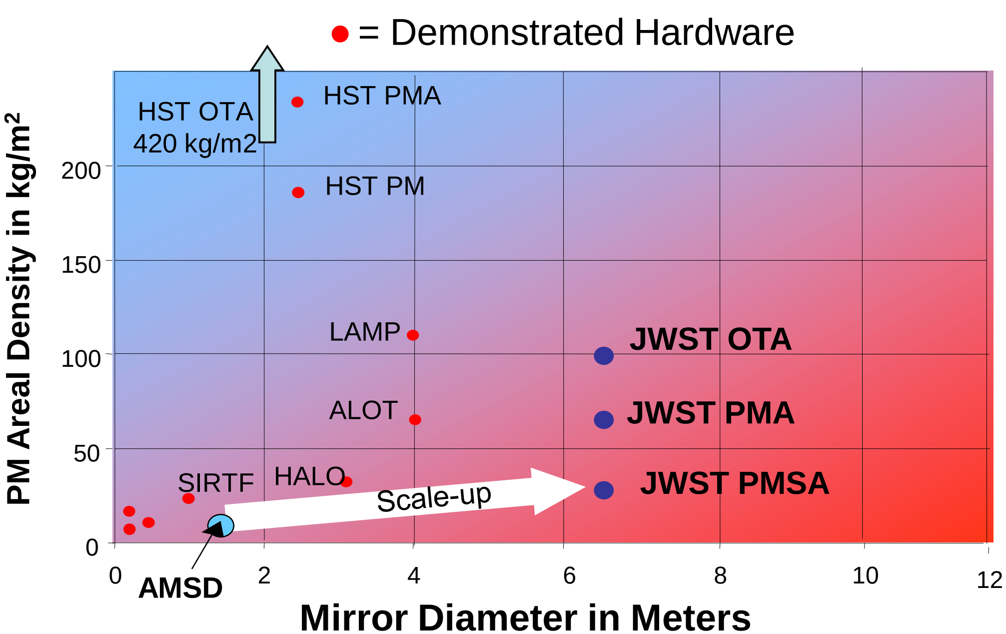
JWST Mirror Technology Lessons Learned

Based on Lessons Learned from JWST

Mirror Stiffness (mass) is required for launch loads & performance

2X Cost & Schedule reductions achieved but need another 5X reduction for even larger telescopes





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

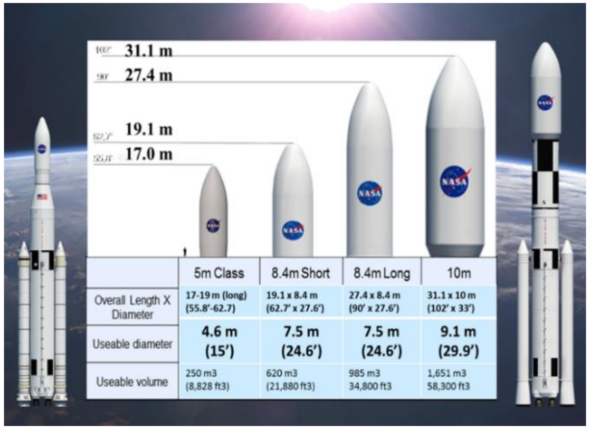
Note: Areal Cost in FY10 $

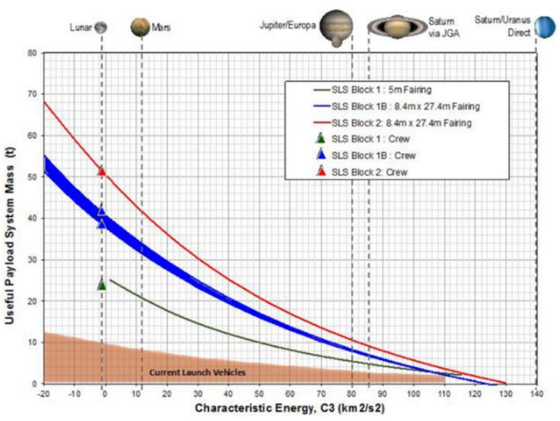
PMA Mass budget depends on Launch Vehicle Independent of architecture (monolithic vs segmented)

	Primary Mirror Areal Density as function of Diameter and Launch Vehicle						
Launch Vehicle	HST	JWST	EELV	SLS-1B	SLS-2	SLS-2B	Units
Payload Mass	11,100	6,500	6,500	24,500	31,500	38,500	kg
PMA Mass	1,860	1,750	2000*	8,500*	11,000*	13,000*	kg
PM Mass	740	750					kg
PMA Areal Density	460	70					kg/m^2
PM Areal Density	170	30					kg/m^2
4-m PMA ($12.5m^2$)			160	675	875	1000	kg/m^2
8-m PMA ($50\ m^2$)			40	170	220	260	kg/m^2
12-m PMA ($100\ m^2$)			20	75	100	115	kg/m^2
16-m PMA ($200\ m^2$)			10	42	55	65	kg/m^2

Areal Density ~100 kg/m^2 is easier (less $) than ~10 kg/m^2

Low-Cost Ground Telescope Mirror are 150 to 300 kg/m^2

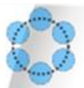
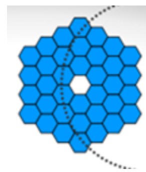
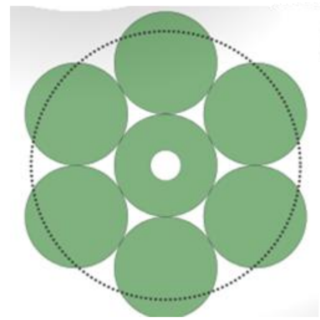
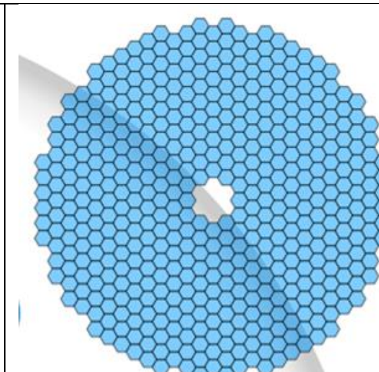


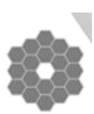
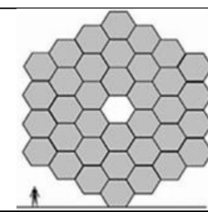


* PMA Mass for EELV is round up from JWST. PMA Mass for SLS is approx. 33% of Payload (SLS max – 43% Reserve).

Segmented versus Monolithic

Historically, only use Segmented when cannot use Monolithic

						
Telescope	Hale	MMT	Keck	Gemini	GMT	TMT
Aperture	5m	4.5m	10m	8.1m	25m	30m
Segment		1.8m	1.8m		8.4m	1.4m
Year	1948	1979	1993	1999	2020	2022

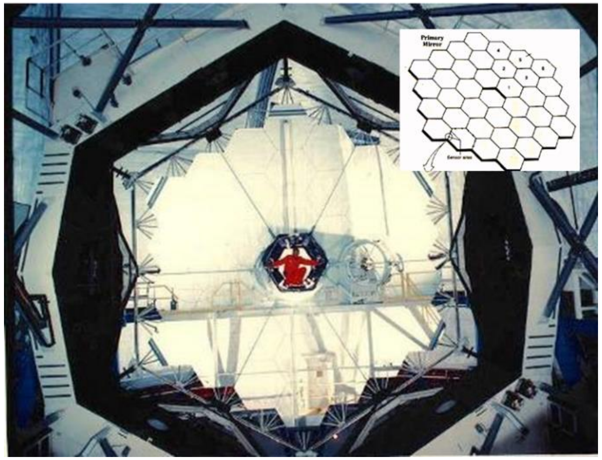
				
Telescope	HST	JWST	ATLAST-8	ATLAST-16
Aperture	2.4	6.5m	8m	16m
Segment		1.5m		2.5m
Year	1990	2018	(TBD)	(TBD)

Do it on the Ground before doing it in Space

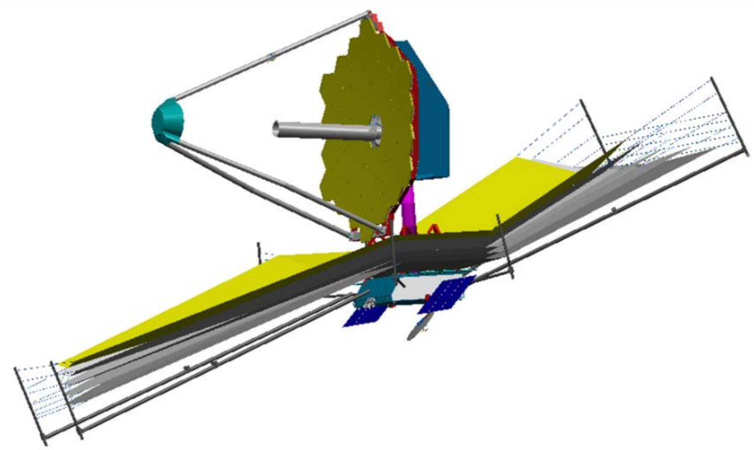
Example of ‘Do it first on ground”: JWST

JWST 1996 Reference Designs based on ‘ground’ telescopes:

Keck Telescope - 1992

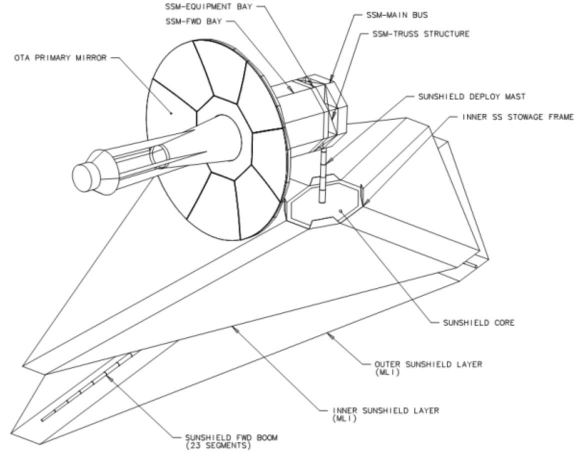


TRW/Ball



LAMP Telescope - 1996

Lockheed / Raytheon



Segmented is harder (more $) than Monolithic

Technology Development Needed for 0.5 μm DL Segmented

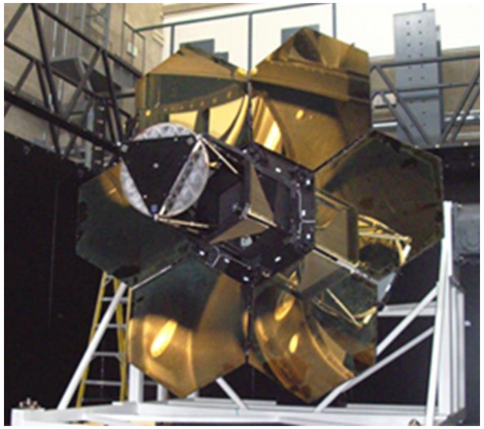
	System Specifications for Potential and Historical Telescopes										
Parameter	LUVOIR	HabEx	FIR	HST	Hershel	JWST	Keck	SMT	LAMP	Gemini	Units
Aperture	12	4		2.4	3.5	6.5	10	3	4	8	Meters
Segmented	Yes	No		1	1	18	36	6	7	1	Number
PMA Areal Density				460	33	70	190	20	140	440	kg/m^2
Diffraction Limit	0.5	0.5	20	0.5	80	2	10	5	NA	1	μm
Surface Error	< 5/seg	< 7	< 200	6.3	~ 800	< 20/seg	< 20/seg	15	NA	< 8	nm rms
WFE Stability	10 pm / 10 min		NA				NA				pm/min
Temperature	300	300	10	300	80	50	300	300	300	300	K
First Light	?	?	?	1993	2009	2018	1992	2005	1996	1999	Year

Segmented Telescope Technology Development needed for:

- Making segments to < 5 nm rms to allow for phasing uncertainty
- Phasing segments to nanometer accuracy
- Having ultra-stable primary mirror structure

To my knowledge:

- At 2 μm DL, JWST will be the best segmented telescope ever made.
- SMT was to be 0.5 μm but only achieved 5 μm due to segment errors, thermal & structure instability.



Areal Cost

- Areal cost has declining with mirror technology development.
- More reduction is needed to make larger telescopes affordable

Areal Cost versus Time and Development versus Flight			
Telescope	Year	PMA Cost	Areal Cost
HST	1992	~ $ 54 M (2012)	$ 12 M/m^2
AMSD	2002	$ 5 M (2002)	$ 5 M/m^2
JWST	2012	~ $ 150 M (2012)	$ 6 M/m^2
AMTD	2015	$2.5 M (2015)	$ 1.5 M/m^2
4-meter	-	$ 75 M Goal	$ 6 M/m^2
8-meter	-	$ 150 M Goal	$ 3.0 M/m^2
12-meter	-	$ 150 M Goal	$ 1.5 M/m^2
16-meter	-	$ 200 M Goal	$ 1.0 M/m^2

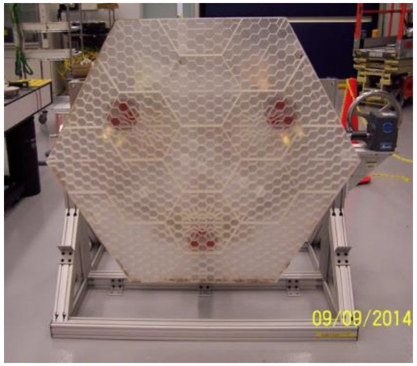
Infrastructure

- Both Corning and Schott can make up to 4-m substrates.

State of Art

Current light-weight space mirror technology

- JWST 1.4-m Segment
  - Areal Density ~ 30 kg/m^2
  - Areal Cost ~ \$6M/m^2
- WFIRST 2.4-m Mirror
  - Areal Density ~ 40 kg/m^2
- MMSD 1.4-m Segment
  - Areal Density ~ 10 kg/m^2
- Schott Extreme-Lightweight 1.2-m Mirror
  - Areal Density ~ 40 kg/m^2



Current low-cost ground mirror technology.

- **TMT 1.44-m Mirror Segment**
  - **Areal Density ~ 150 kg/m^2**
  - **Areal Cost ~ \$0.3M/m^2**
- **Arizona 8.4-m Mirror**
  - **Areal Density ~ 300 kg/m^2**
  - **Areal Cost ~ \$0.5M/m^2**

Flight needs higher Areal Density than Tech Demo

State of Art for Space Telescope Mirror and Segment Substrates							
Parameter	Material	Size [m]	Areal Density [kg/m^2]	Surface Error [nm rms]	Stiffness [Hz]	Areal Cost [$M/m^2]	Year
LUVOIR	ULE or Zerodur	1.5 to 4.0	50	5	400	1.5	
HabEx	ULE or Zerodur	4.0	200	7	200	6	
HST	ULE	2.4	180	6.3		12	1993
AMSD-1	Beryllium	1.2	15	20	180	5	2003
AMSD-2	ULE	1.3	12	20	180	5	2003
AMSD-3	Fused Silica	1.3	15	20	180	5	2003
JWST	Beryllium	1.4	30	15	220	6	2012
WFIRST	ULE	2.4	40	12			
Kepler	ULE	1.4	50	NA	NA	NA	2009
MMSD-1	SiC	1.3	10	15	180		
MMSD-2	ULE	1.3	10	8	180		
AMTD-1	ULE	0.43	60	5.3	2000	1.5	2013
AMTD-2	ULE	1.5	60	NA	400	1.5	2016
Herschel	SiC	3.5	30	800	NA	~1 (estimate)	2009
BLAST	CFRP	2.5	20	5,000	35	0.1	2016
LAMP	Zerodur	2.0	140	classified	NA	NA	1996

SOA for UVOIR mirrors is ULE or Zerodur

SOA for Far-IR mirrors is SiC or CFRP or Aluminum

Technology Development – Lessons Learned

Technology Development requires a long 'sustained' time

- From Start to Launch
  - HST – 27 years (1963 to 1990)
  - JWST – 22 years (1996 to 2018)
- Mirror Technology Development
  - HST – 10 years (1963 to Phase A start in 1973)
  - JWST – 11 years. (TRL-3 in 1996 to TRL-6 in 2007)

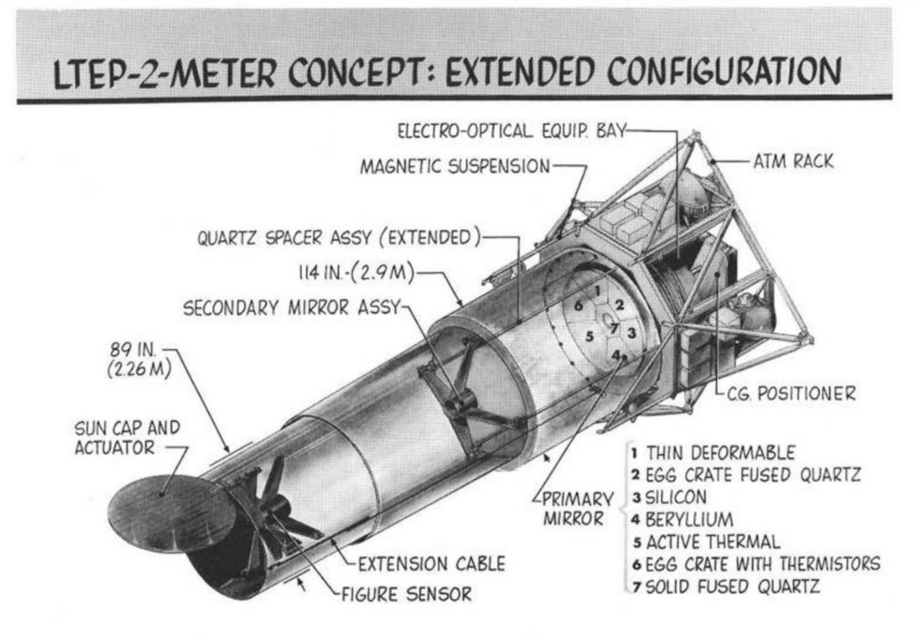
Both JWST and HST required Technology Development in:

- Mirror Material – Homogenous CTE
  - HST –ULE
  - JWST – O-30 Beryllium
- Optical Fabrication of Lightweight Mirrors
- Optical Testing

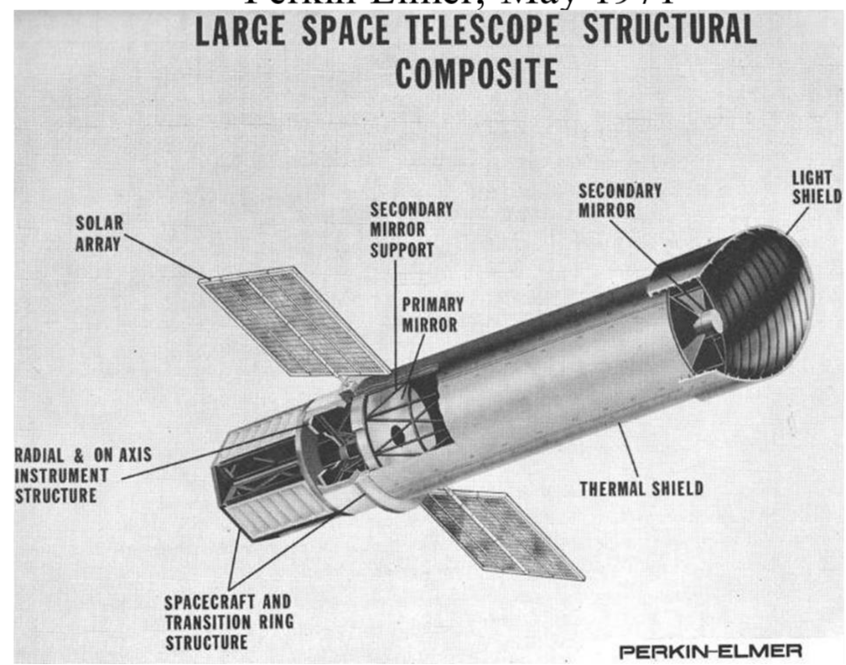
Example of importance of Material: HST

HST was originally segmented because inability to make large thermally-stable lightweight glass mirrors. Solution was ULE.

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



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

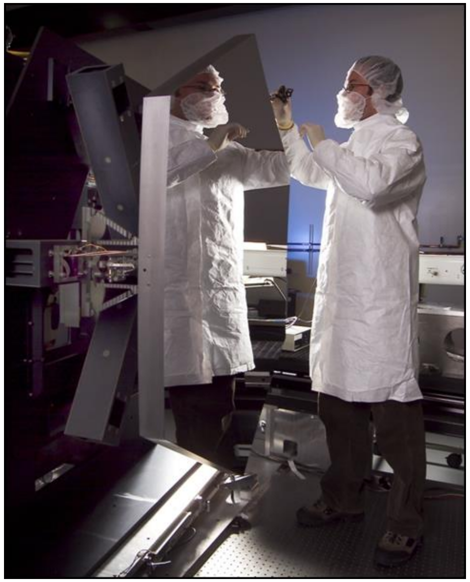


JWST Mirror Technology Development

Systematic $40M+ development program:

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

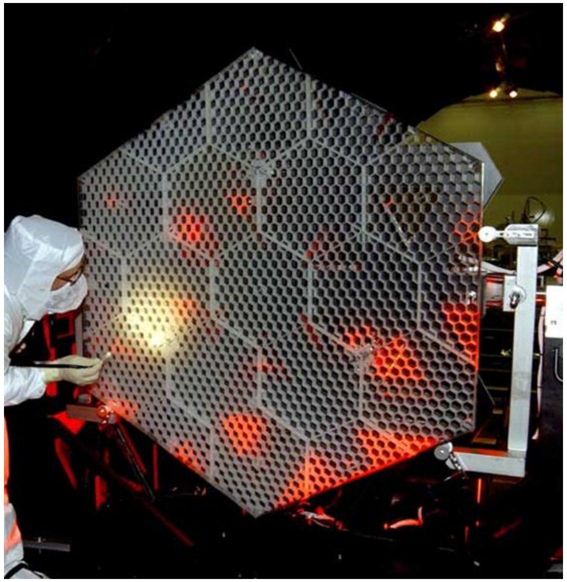
to dramatically reduce cost, schedule, mass and risk for large-aperture space optical systems.



Competition was Critical:

- **remarkably rapid TRL advance**
- **significant reductions in cost and schedule**

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



Predict it will take more $ and longer time to mature technology for an ultra-stable segmented UVOIR telescope.

Advanced Mirror Technology Development

AMTD's objective is to mature critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

Very Smooth Surfaces	< 10 nm rms
Thermal Stability	Low CTE Material
Mechanical Stability	High Stiffness Mirror Substrates

AMTD uses Science Driven Systems Engineering – solve problems that have the biggest impact on performing science.

AMTD: Key Accomplishments

- Derived System Specifications from Science Requirements:
  - Surface < 7 nm rms (low ~5 nm, mid ~5 nm, high ~3 nm)
  - **Stability< 10 picometers rms per 10 minutes**
- Demonstrated, ability to make mechanically stiff, i.e. stable, UVOIR traceable mirrors:
  - <6 nm rms surface
  - 60-kg/m2
  - 0.43 m x 400-mm deep-core substrate

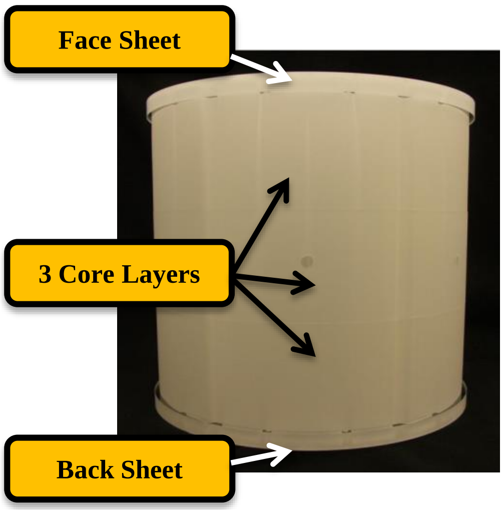
using the stack-core low-temperature-fusion/low-temperature-slumping (LTF/LTS) process.

- Developed Tools for Integrated Modeling & Verification
  - Quickly generate point designs and perform trade studies.

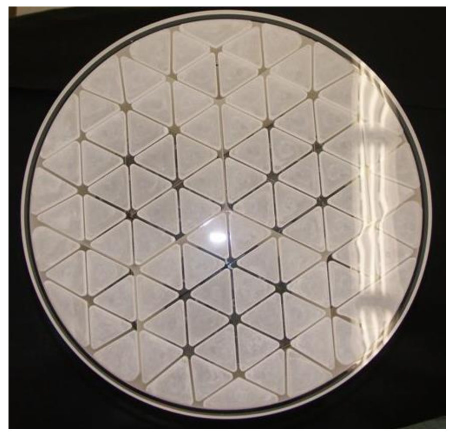
43 cm Deep Core Mirror

Harris successfully demonstrated 5-layer ‘stack & fuse’ technique which fuses 3 core structural element layers to front & back faceplates.

Made 43 cm ‘cut-out’ of a 4 m dia, > 0.4 m deep, 60 kg/m^2 mirror substrate.



Post-Fusion Side View
3 Core Layers and Vent Hole Visible



Post-Fusion Top View
Pocket Milled Faceplate

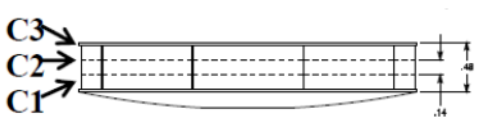
Post Slump:
2.5 meter Radius of Curvature

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

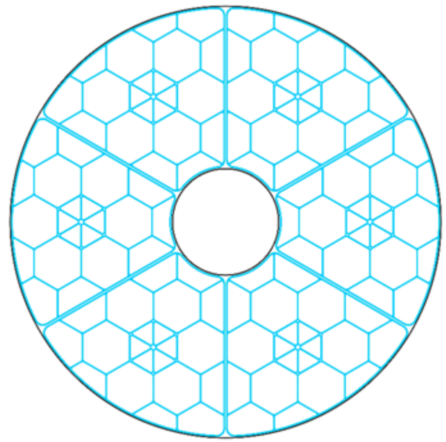
Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.

AMTD Phase 2: ULE and Zerodur

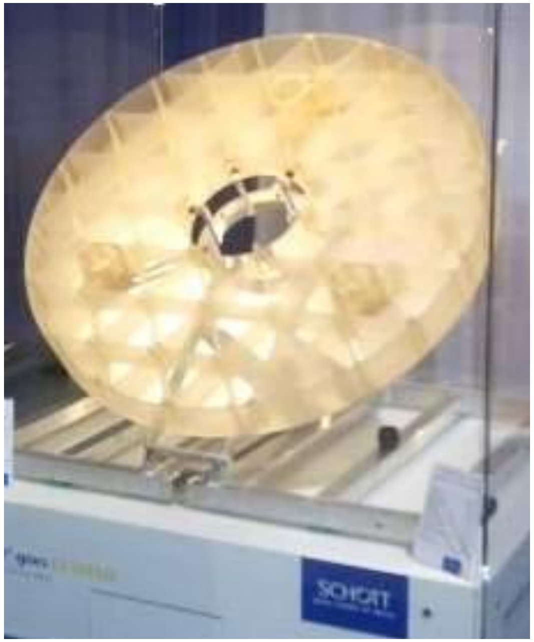
To demonstrate lateral scalability of stack core technology, Harris is making a 1.5 m x 165 mm thick (1/3rd scale of 4-m) 400 Hz ULE mirror.



4m PM Conceptual Layout


Courtesy: Harris

Also, so that we can characterize its performance, AMTD is polishing the Schott 1.2-m Extreme Lightweight Zerodur Mirror.



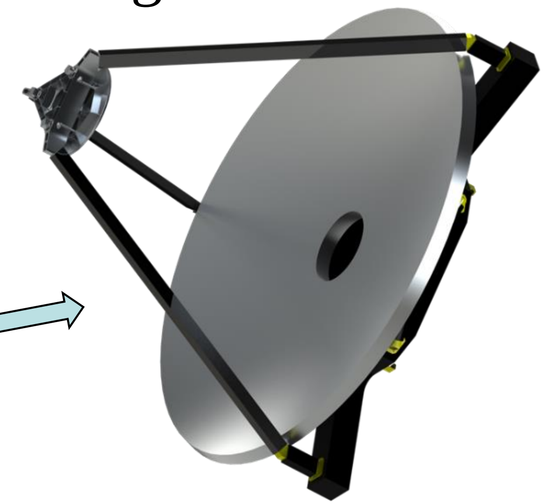
SBIR Mirror Technology Developmet

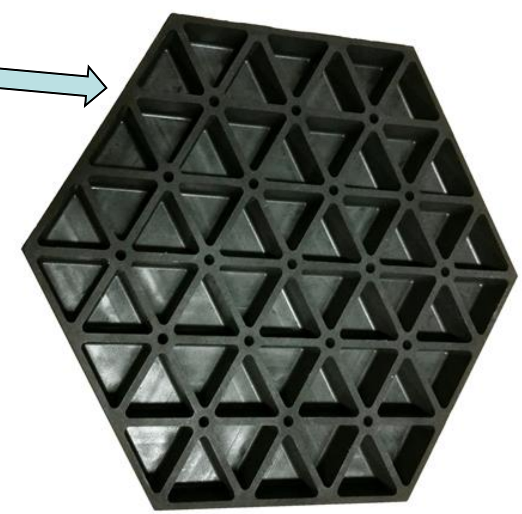
As an SBIR Sub-Topic Manager, I invest in technologies to compete with incumbent approaches.

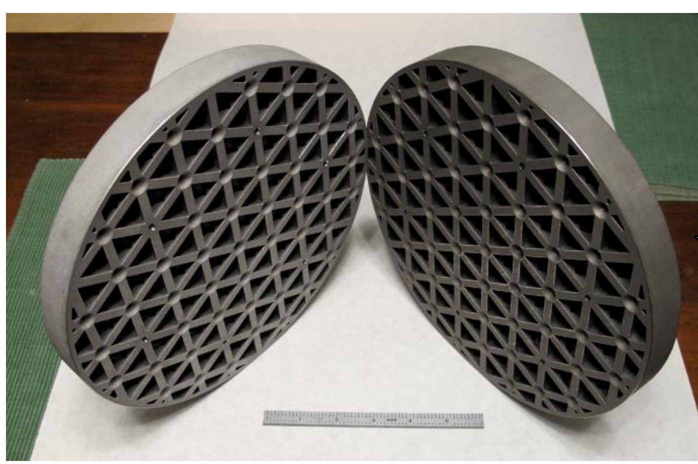
- Incumbent for UVOIR are ULE and Zerodur
- Incumbent for IR is Be and Far-IR is Aluminum

SBIR is currently investing in:

- 2.5-m CFRP Telescope for BLAST
- ‘Zero’ CTE SiC using nanotechnology
- New Materials (SiOC)
- Additive Manufacturing of Aluminum Mirrors







Any Question?