Lightweight Mirror Technology for the Next Generation Space Telescope and BEYOND

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Mission Statement

Robust large-aperture low-mass mirrors, that can be rapidly and cost effectively fabricated, are critical for future NASA (space science, planetary & Earth resource) and DoD missions (defense & imaging).

The MSFC Space Optics Manufacturing Technology Center (SOMTC) and its University/Industry Partners are actively developing new enabling techniques for the design, manufacture, test, modeling and control of such mirrors.

The goal is to buy-down technical (weight & performance) and programmatic (schedule & cost) risk for current programs such as NGST as well as future missions.

Agenda

NGST

- Requirements
- Mirror Technology Development Program - Status

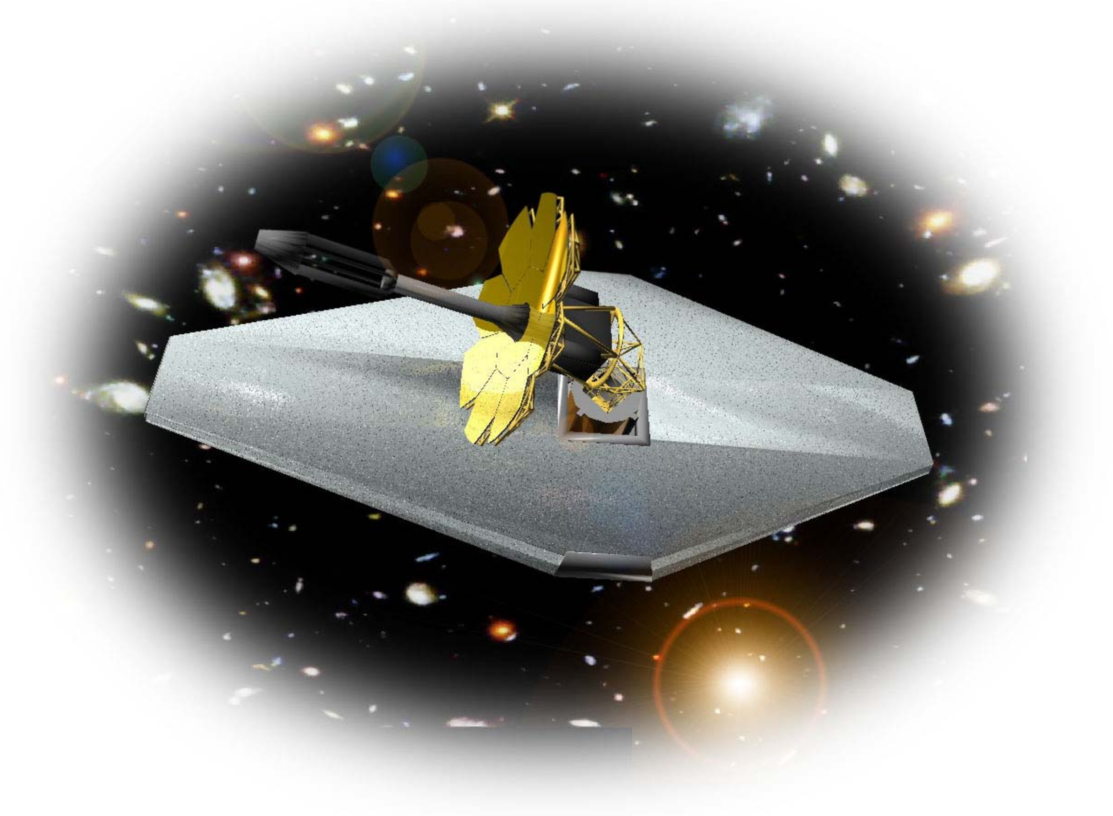
Beyond NGST

- Origins and SEU
- Technology Development Roadmaps

“to detect the first light of the Universe”

In 2010, NASA plans to launch a 6 m diameter NGST to L2 1.5 MKm from Earth.

There, NGST will undertake a 10 year science mission in direct support of the NASA Origins Program.



NGST Requirements

OTA study in summer 1996:

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

8 meter segmented telescope, mirror technology at $\leq$15 kg/m^2.

Current Procurement SOW

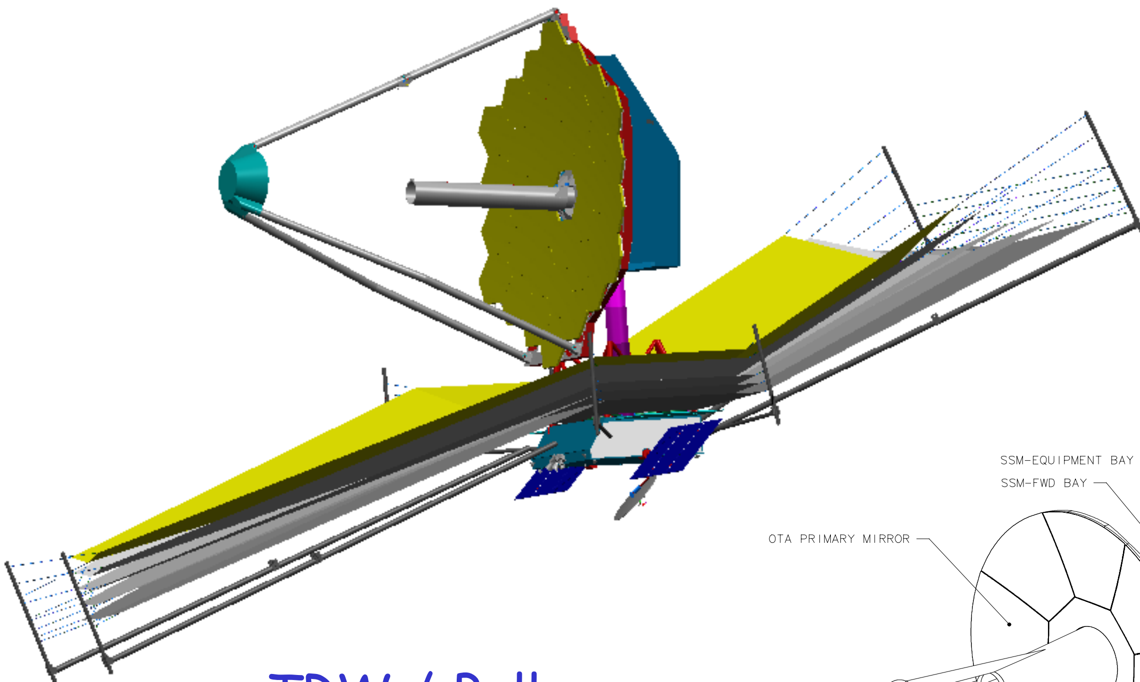
Minimum of 25 m^2 collecting area (>6.25 m diameter)

Areal Density TBD by Contractor (probably 20-24 kg/m^2

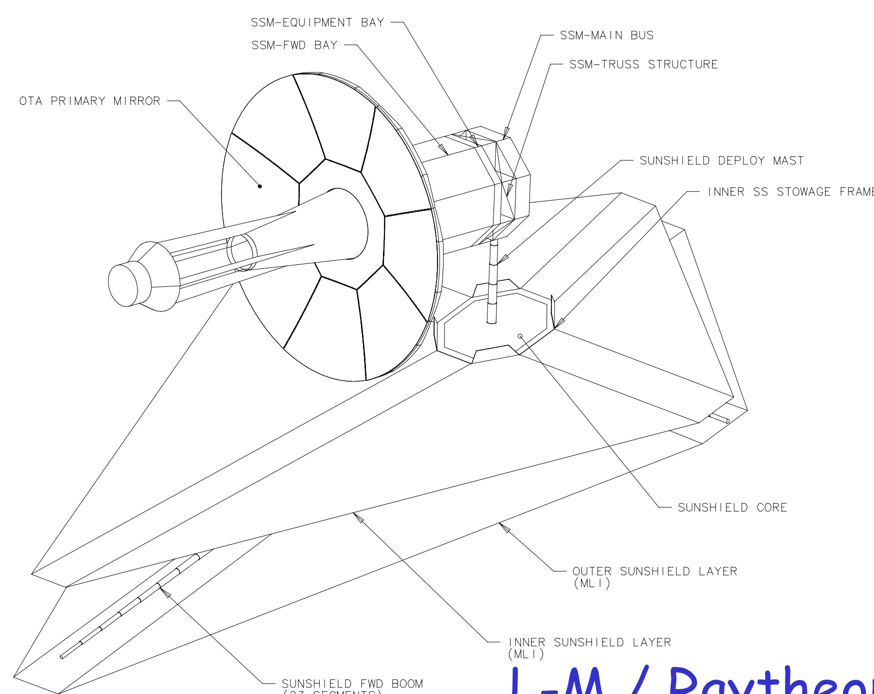
Discovery Space for NGST

NGST

Reference designs

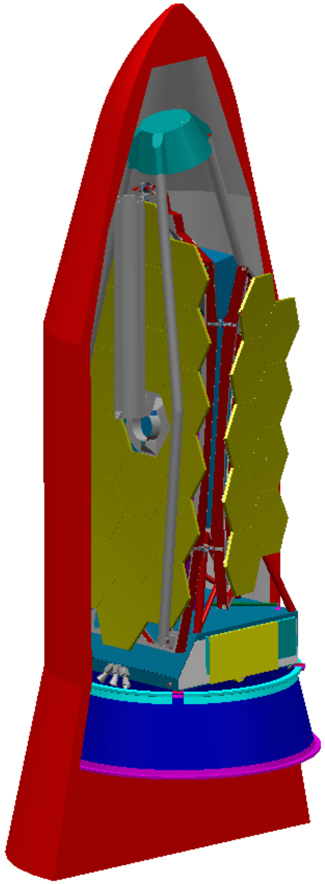


TRW / Ball

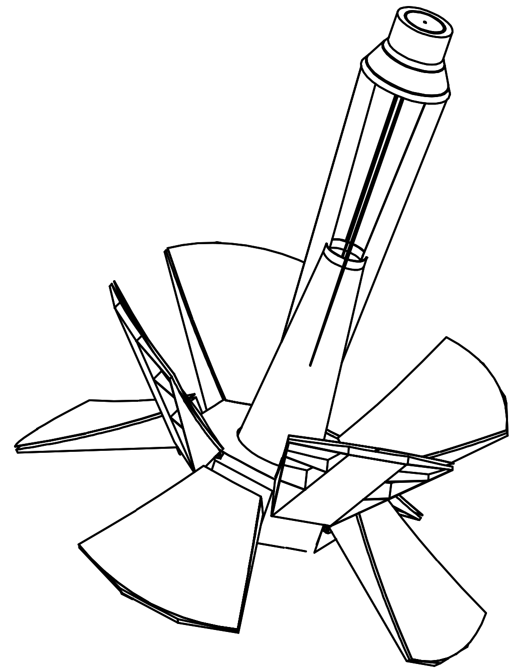


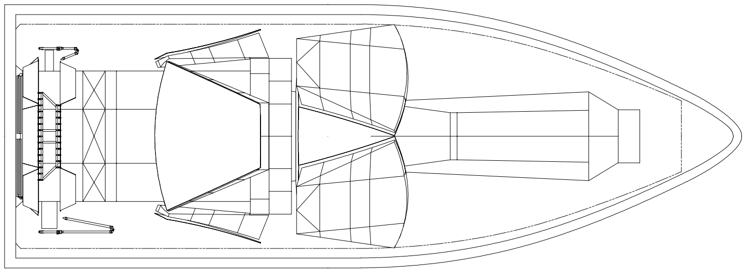
L-M / Raytheon

Packaging for launch



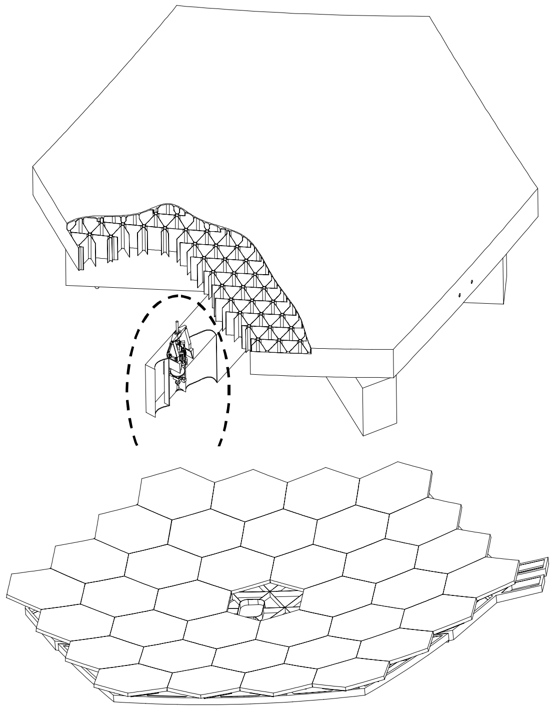
TRW / Ball

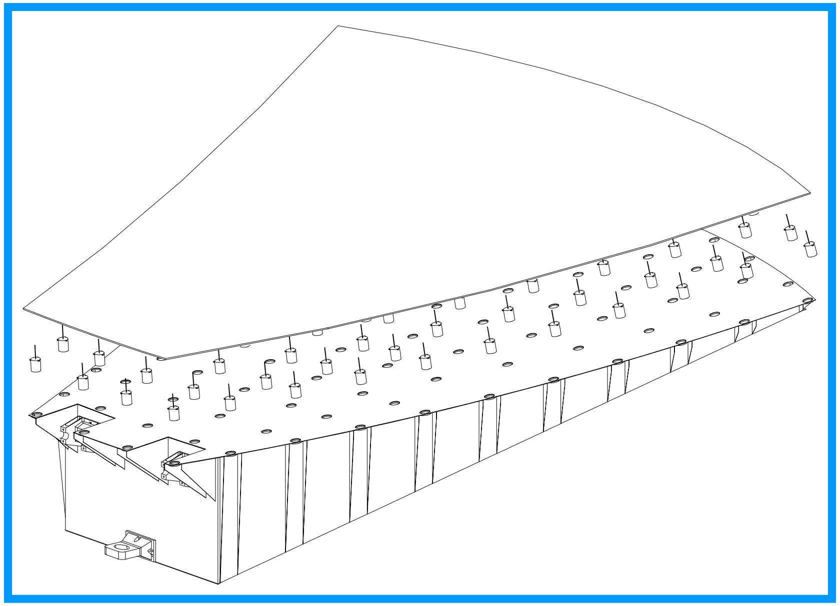




L-M / Raytheon

Primary mirror segments





TRW / Ball

Semi rigid
beryllium
cryogenic null figured,
low authority (ROC only)
1.4 m dia

L-M / Raytheon

Thin meniscus
“glass” (fused silica)
high authority (~90 act/petal)
2 x 3 m

NGST Mirror Technology Development

Large Lightweight Mirrors are a Key Technology for NGST

- Need to be TRL-6 by Non-Advocate Review
- Currently TRL-3/4
- On Critical Path

Technology Development Program Goals:

- Advance Technology and Develop Technical Processes to dramatically reduce Cost, Schedule, and Weight for large-aperture optical systems.
- Determine Cost Scaling Laws
- Mitigate Programmatic Cost, Schedule and Weight Risk.
- Characterize/Understand Ambient/Cryogenic Mirror System Performance.
- Provide Mirrors for NASA & DOD Flight Demonstration Programs.

NGST needs New Technology to make Mission Affordable

Several key technological and manufacturing advances have been developed

Cryogenic Materials – CTE uniformity, dynamic dampening, stiffness, etc.

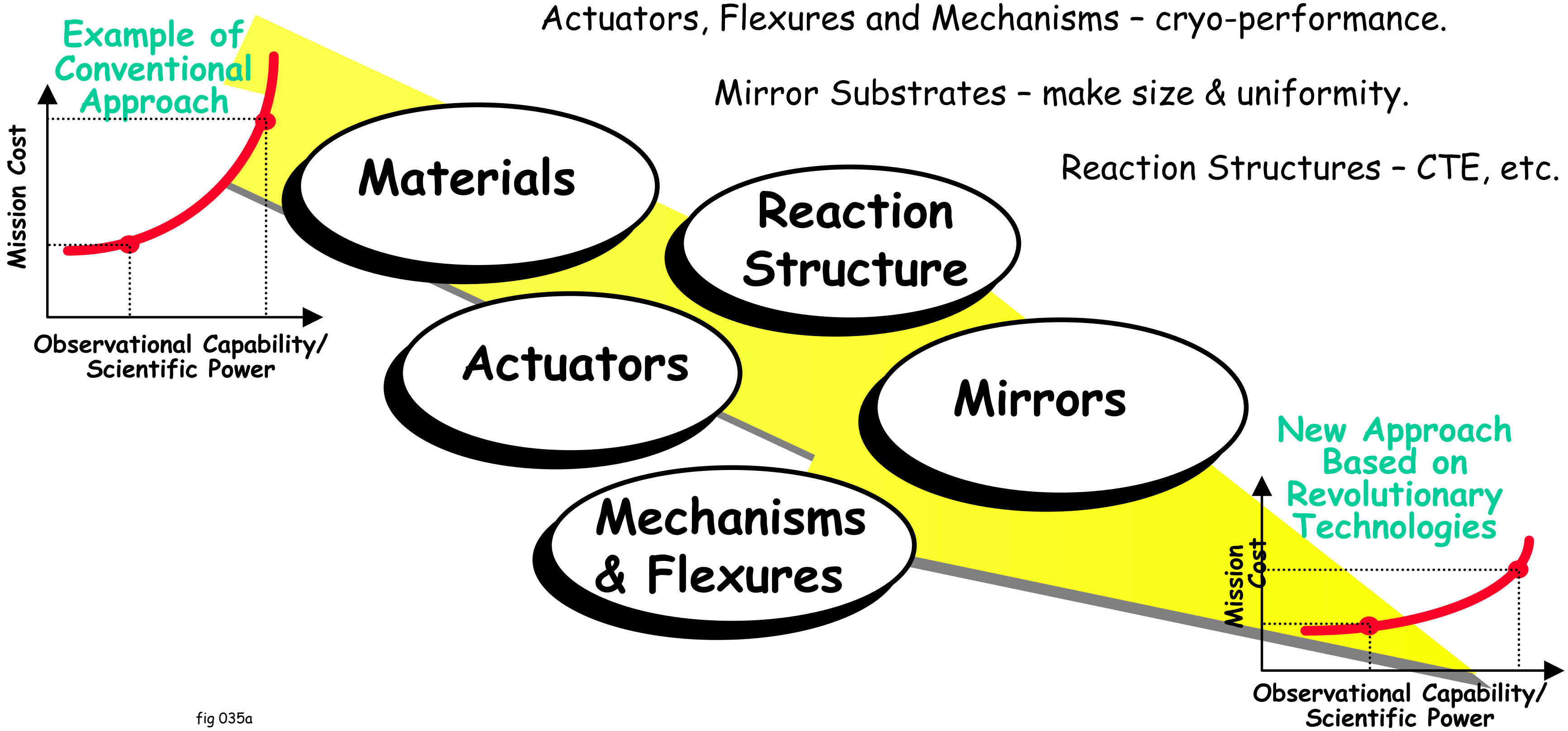
Fabrication Techniques – ability to make size & areal density to required figure.

Cryogenic Performance Characterization – optical testing, cryo-behavior.

Actuators, Flexures and Mechanisms – cryo-performance.

Mirror Substrates – make size & uniformity.

Reaction Structures – CTE, etc.



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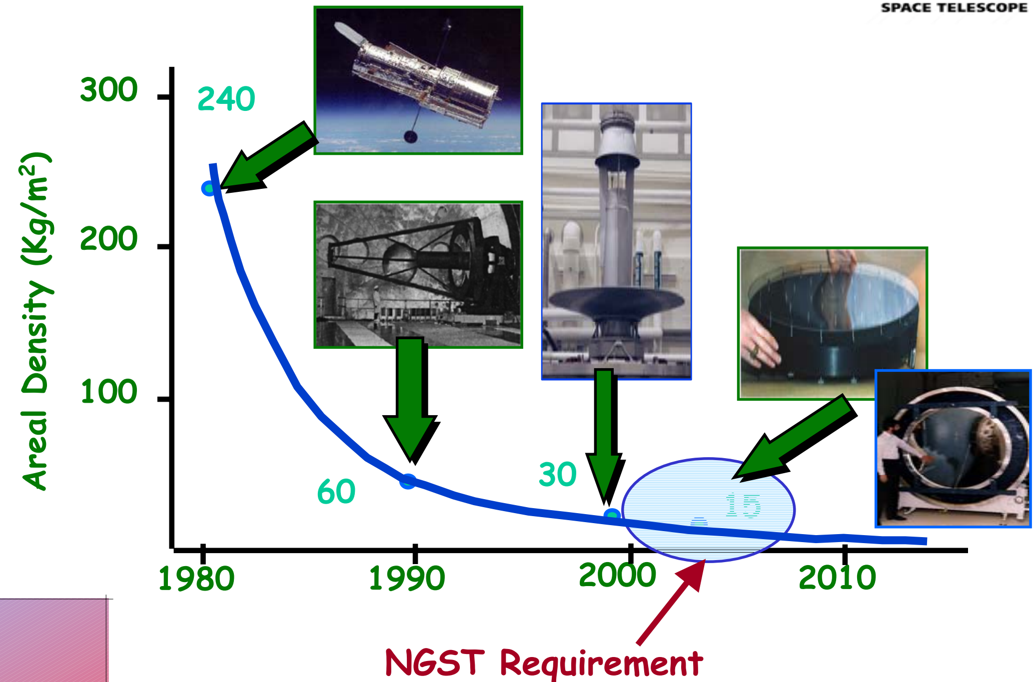
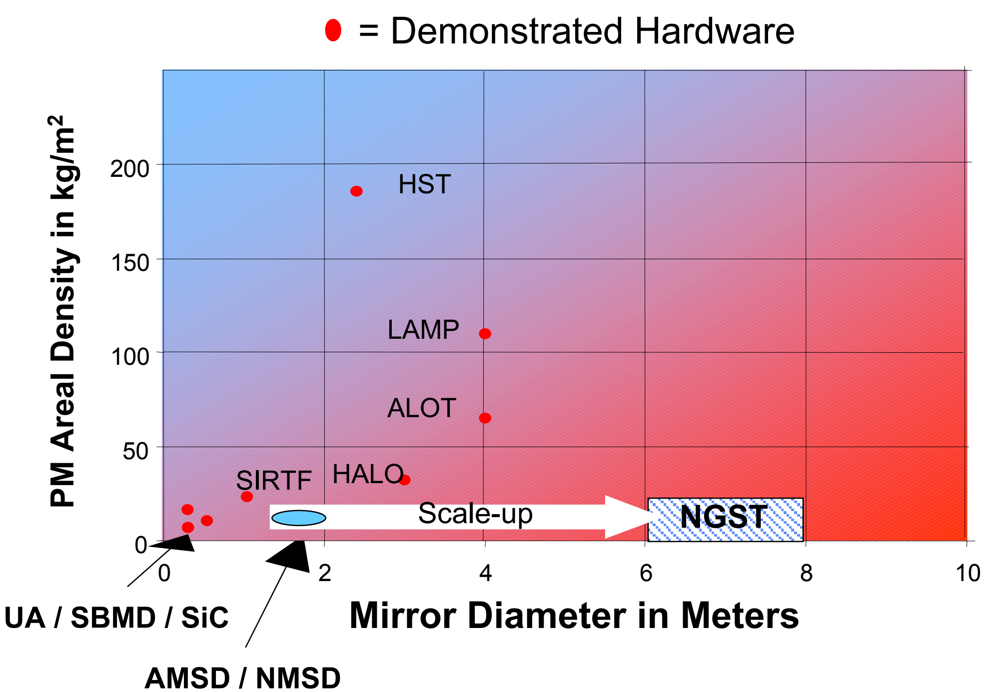
Mirror Technology Program demonstrates that NGST Goals are within reach

At start of Pre-phase A:

Mirror areal density, diameter, cost and schedule were order of magnitude higher than NGST goals

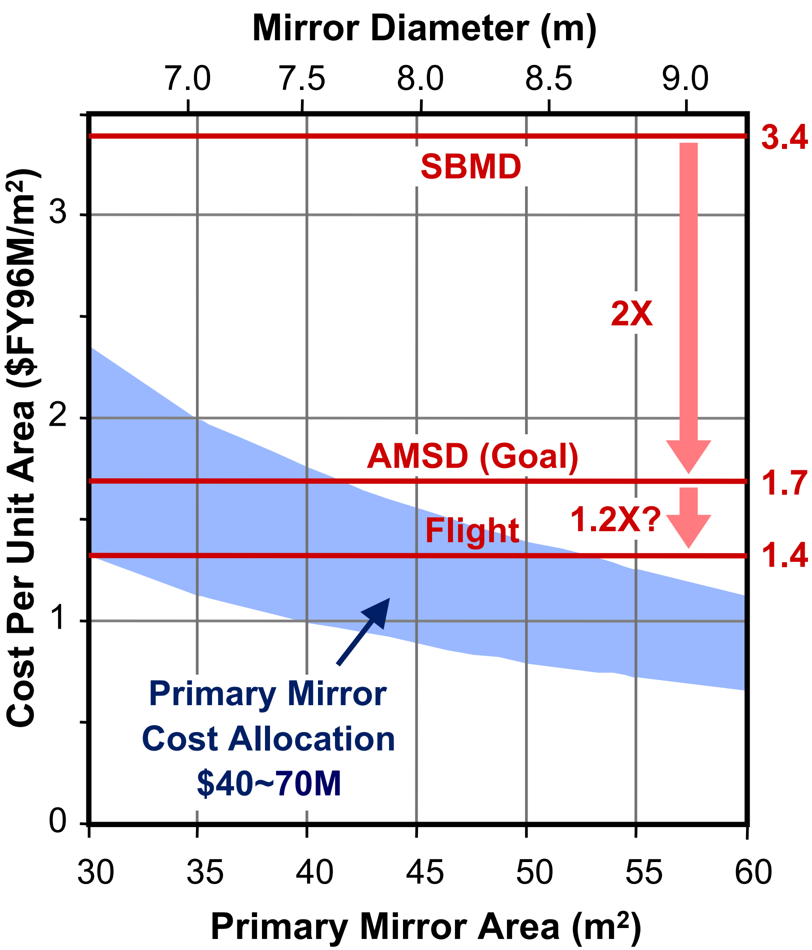


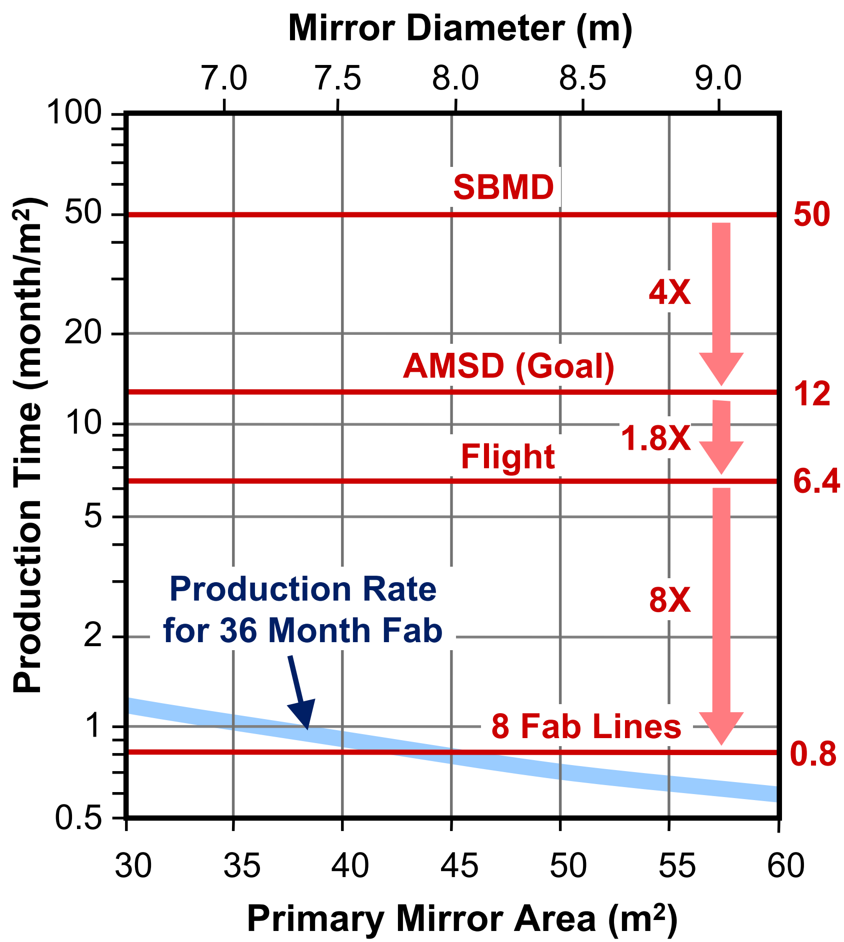


Manufacturing Time/Unit Area

HST (2.4 m)	≈ 1 year/m²
SIRTF (0.9 m)	≈ 3 years/m²
NGST (6 m)	≈ 1 month/m²

Must Break Cost/Schedule Paradigms





Mirror Technology Development Program

NASA and DoD Partners have invested $40M in mirror technology development projects:

- AMSD - Advanced Mirror System Demonstrator
  - Ball Semi-Rigid Low-Authority Be
  - Kodak Semi-Rigid Medium-Authority ULE Glass
  - Goodrich Iso-Grid High-Authority Fused Silica Glass
- NMSD - NGST Mirror System Demonstrator
  - Arizona Meniscus Very-High-Authority Glass
  - COI Rigid Hybrid-Glass-Composite
- SBMD - Small Beryllium Mirror Demonstrator
- IABG C/SiC Mirror
- MER, UltraMet and Xinetics SiC Mirror SBIR's
- JBMD - Joined Beryllium Mirror Demonstrator
- MSFC Nickel Replication

NGST Mirror Development Technology

Wide Variety of Design Solutions are being 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

NGST Mirror Development Technology

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 ($1\text{-}10\ cm^{-1}$)	63 nm	63/32 nm	
RMS Finish	3/2 nm	2/1 nm	4 /2 nm

AMSD Base Requirements Validation Matrix (23 Apr 02)

Item	Basic System Design Requirement	Meas Err	Units	Verify
Physical Properties				
Shape	Hexagonal			Inspect
Areal Density	< 15	$\pm$ 0.05	kg/m^2	Weigh
Petal Size	1.2 to 1.5	$\pm$ 0.0005	meter	Measure
Prescription @ Ambient & Cryo				
Radius of Curvature	10 $\pm$ 0.001	$\pm$ 0.0005	meter	Measure
Radius of Curvature Matching	20	$\pm$ 2	µm	Measure
Radius of Curvature Matching	50	$\pm$ 5	nm sag	Measure
Radius of Curvature vs Temperature		$\pm$ 0.0005	meter	Measure
Conic Constant	-1	$\pm$ 0.0001		Calculate
Vertex Location	2	$\pm$ 0.0001	meter	Calculate
Total Surface Error @ Ambient & Cryo (Over Clear Aperture 15 mm from Edge)				
PV	250/100	$\pm$ 20 rms	nm	Measure
RMS	50/25	$\pm$ 20 rms	nm	Measure
Low Order (Z4-Z36)		$\pm$ 20 rms	nm	Measure
Mid-Spatial (Z36 to 1 mm)		$\pm$ 20 rms	nm	Measure
Roughness (1 to .001 mm)	4/2	$\pm$ .2 rms	nm	Measure
2D PSD Departure (1m to .001 mm)	+10X			Calculate
Operating Temperature				
Ambient	300 $\pm$ 10	$\pm$ 1	Kelvin	Test
Cryogenic	30 to 55	$\pm$ 1	Kelvin	Test
Survival	25	$\pm$ 1	Kelvin	Test
Stiffness (1^{st} 5 Modes)				Measure
Dynamic Environment/Survivability				Model

Total Surface Error

MSFC will use at least two instruments to measure total surface error from Full Aperture to 1.0 micrometer spatial periods.

Phase-measuring interferometer measures from Full Aperture to 3 mm.

Interferometer Sampling	Pixel Size	Spatial Period
1.2 m diameter / 400 pixels	3 mm	6 mm
1.2 m diameter / 800 pixels	1.5 mm	3 mm

For below 3-6 mm periods, change magnification and test sub-apertures.

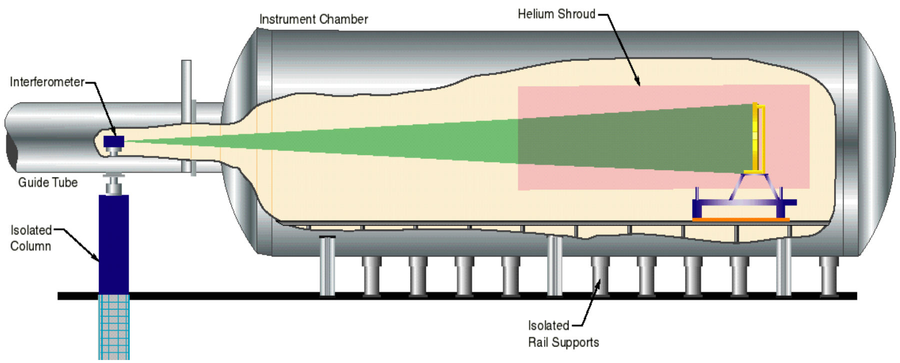
Interference Profiler measures Micro-Roughness from 1 mm to 1 µm.

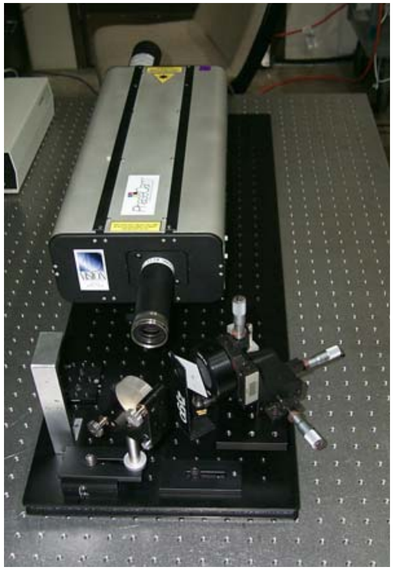
10X Objective	1 mm to 1 µm
5X Objective	2 mm to 2 µm
2.5X Objective	4 mm to 4 µm

Ability to Cryo-Test NGST Segments is TRL 6

Cryogenic Testing at MSFC is Routine

Performed 10+ Tests to 30K , Reduced Test Times from 7 to 5 to 3 weeks

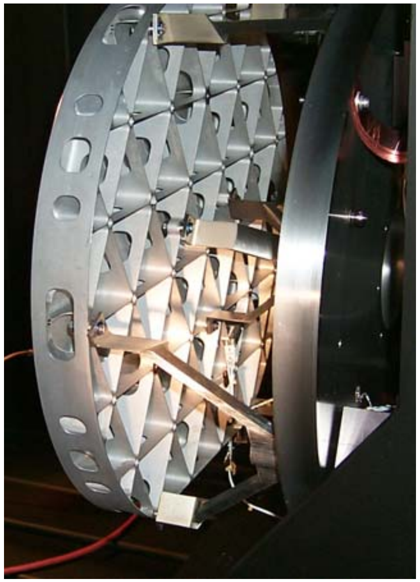




Invested in Special Test Equipment and Procedures

- PhaseCAM Instantaneous Interferometer
  - Stroboscopic Modal Test Interferometry
- Leica Absolute Distance Meter
  - 100X Accuracy/Resolution Improvement
  - Segment Radius of Curvature Matching
- ADE Instantaneous Phase Interferometer

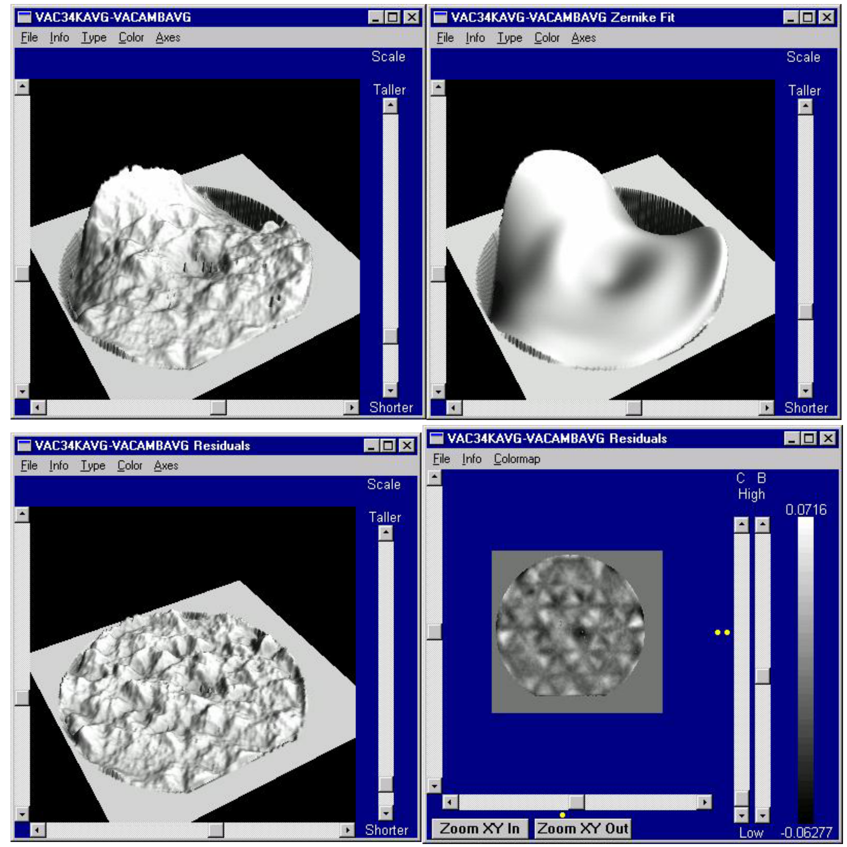
Ball Subscale Beryllium Mirror Demonstrator (SBMD)



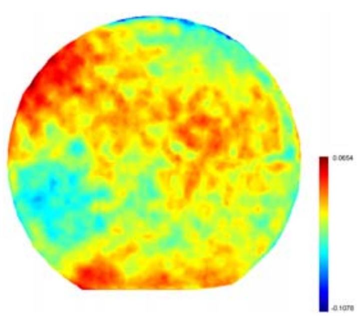
Cryogenic Surface Error (34K -288K)

Total (0.571 μm p-v; 0.063μm rms)

Low Order (0.542 μm p-v, 0.062 μm rms)



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



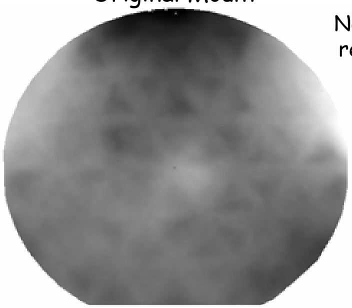
Cryo Tested at MSFC

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

Addition Tests Studied Effects of Mounting & Gold Coating

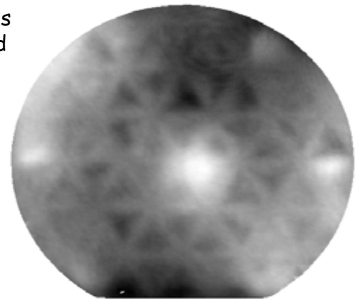
Original Mount

No terms removed



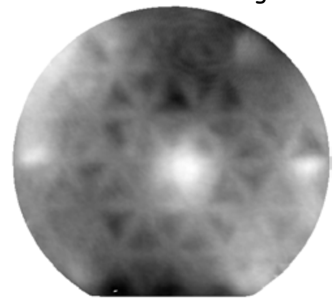
Surface Change = 89 nm rms

New Mount



Surface Change = 53 nm rms

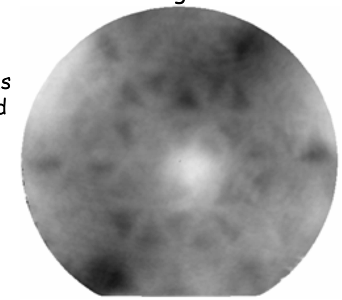
Cryogenic deformation before coating



Surface Change = 53 nm rms

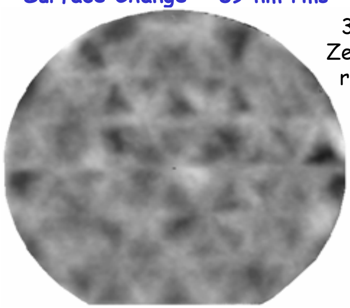
Cryogenic deformation after coating & 2nd mounting modification

No terms removed

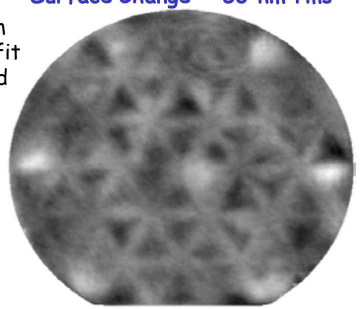


Surface Change = 54 nm rms

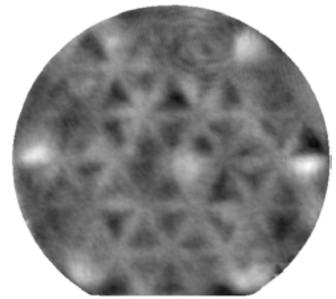
36 term Zernike fit removed



Surface Change = 17 nm rms

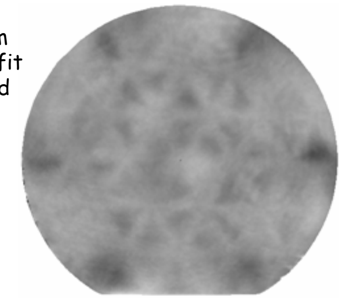


Surface Change = 17 nm rms

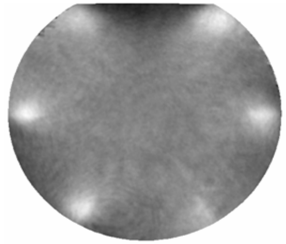


Surface Change= 17 nm rms

36 term Zernike fit removed



Surface Change = 23 nm rms



Change between cryogenic deformation before and after coating and modification of mounting

Surface Change = 35 nm rms

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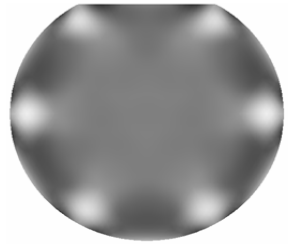

NASTRAN prediction for modified mounting change

Surface Change = 35 nm rms

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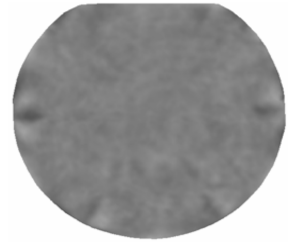
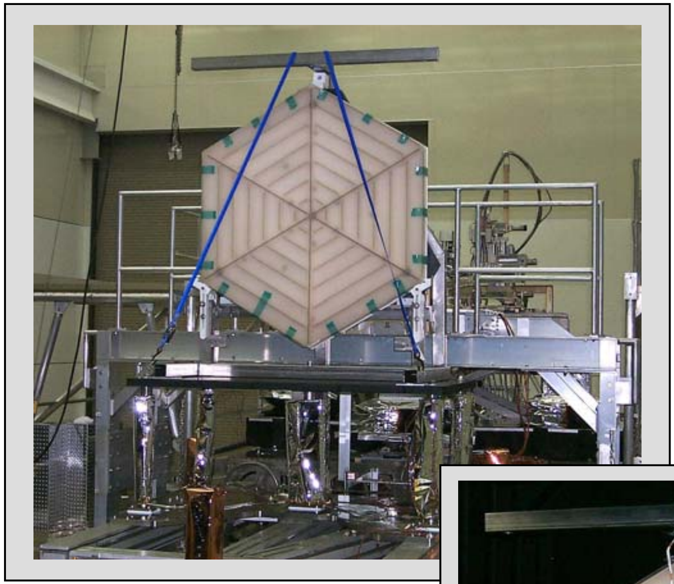


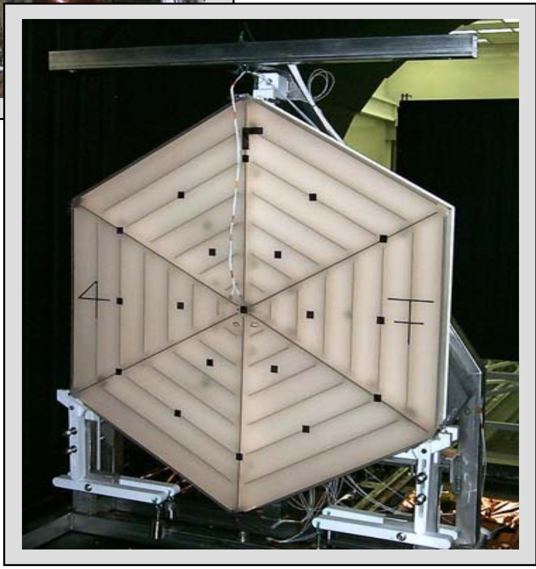
Best estimate of only the coating effects

Surface Change = 9 nm rms

COI Hybrid NGST Mirror System Demonstrator (NMSD)

1.6m Glass (Zerodur) Bonded to Composite Structure





Hybrid Combines Desirable Attributes of Both Glass and Composite

- **Zerodur Facesheet to Meet Optical Requirements**
  - Processable Using Conventional Methods (Grinding, Polishing, Ion Figuring)
- **Carbon/Cyanate-Ester Composite Structural Support for Glass**
  - Low Mass, High Stiffness
  - Matched Thermal Expansion of Zerodur from Ambient to 35K

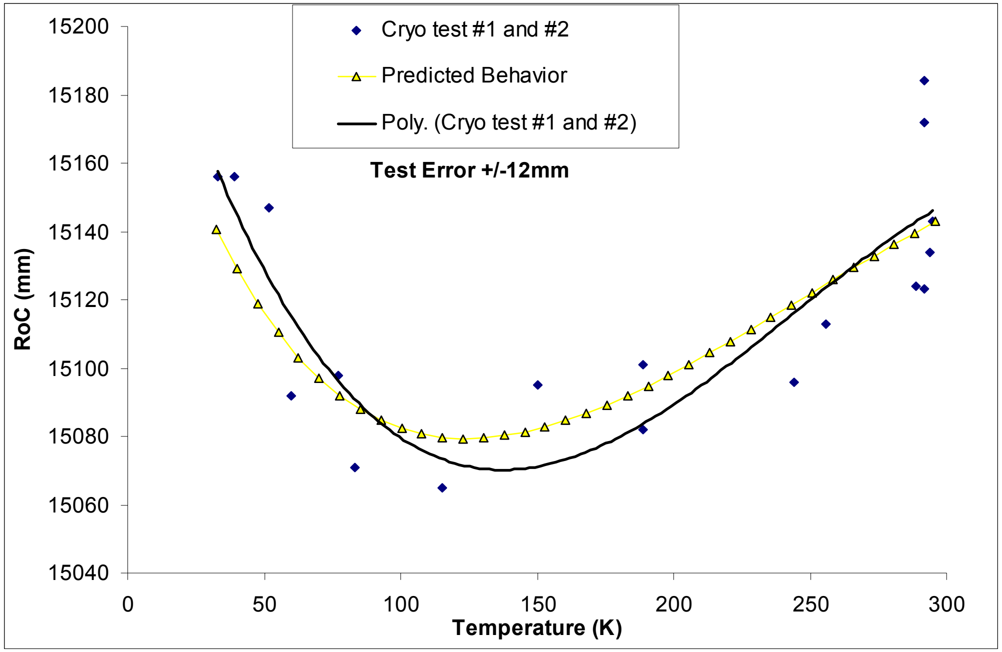
Successful Demonstration at the XRCF

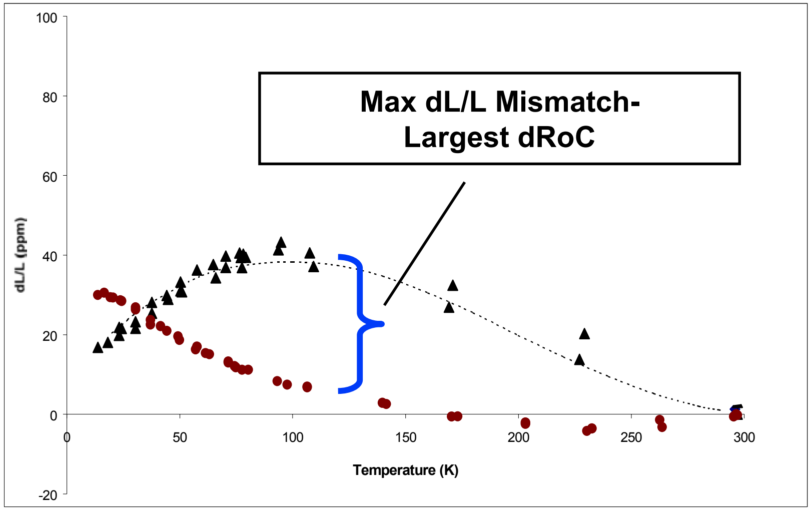
- **Modal Test of Mirror Assembly at Ambient**
- **Cryo/Optical Demonstration to <30K (Two of Three Scheduled Tests are Complete)**

Change in Radius of Curvature

Match CTE of Composite and Zerodur to select Radius of Curvature at Cryo.

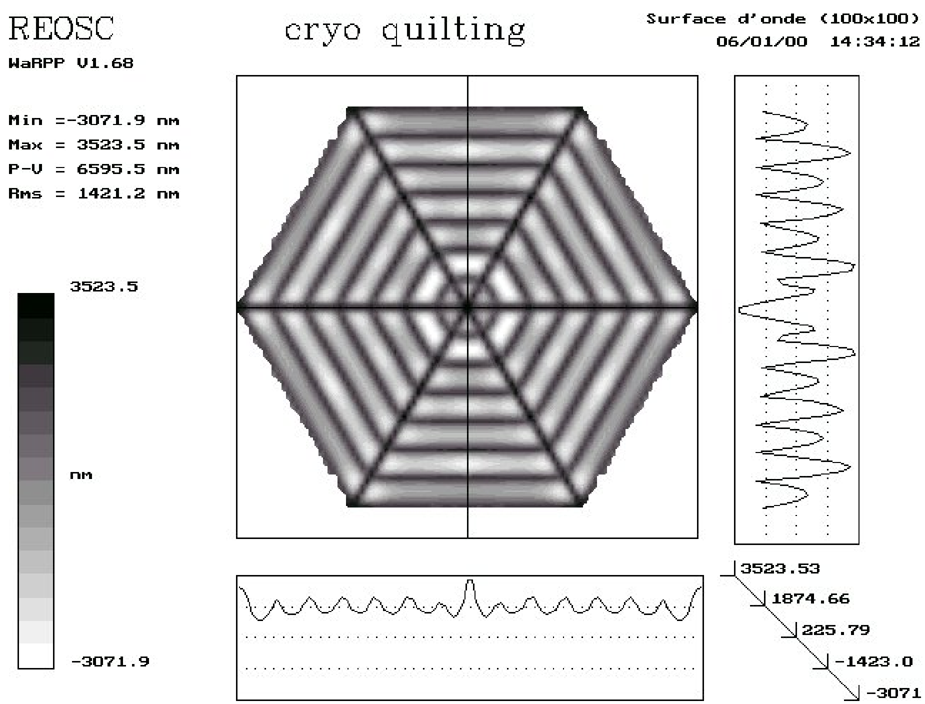
Predicted Change in Radius of Curvature consistent with Cryo Test 1 and 2.



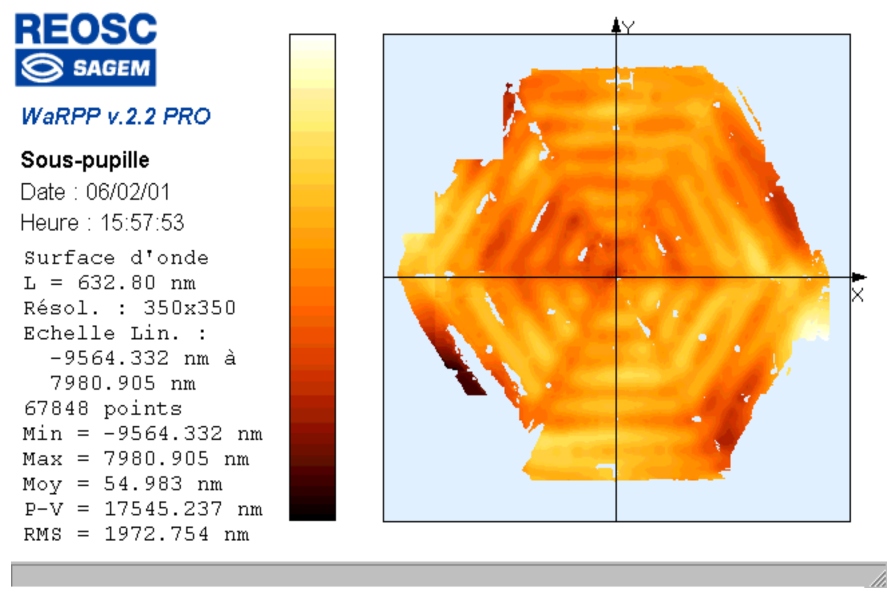


Cryo Quilting

Predicted

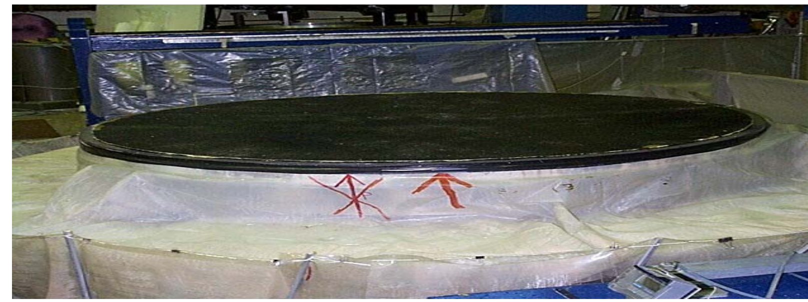


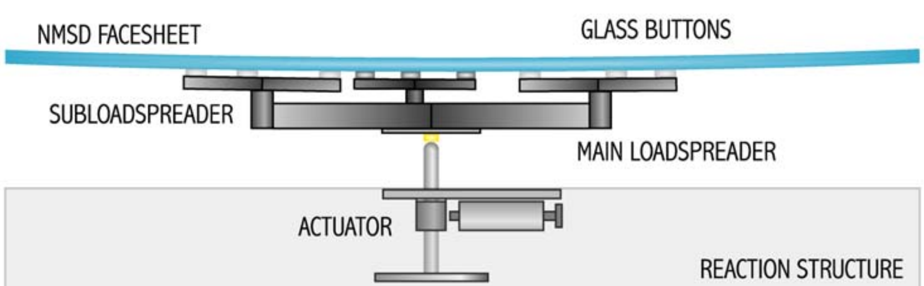
Ambient to 39K Measured

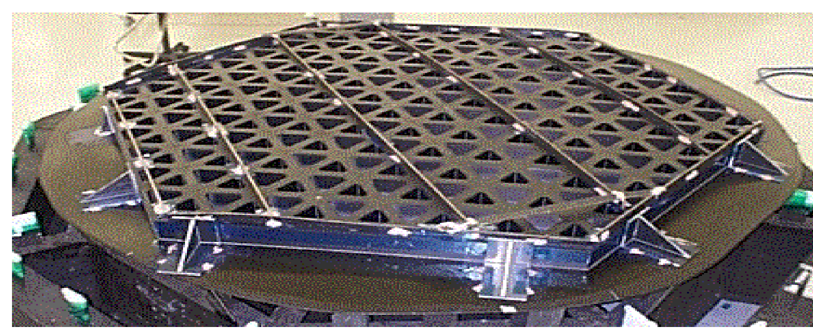


University of Arizona NGST Mirror System Demonstrator

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

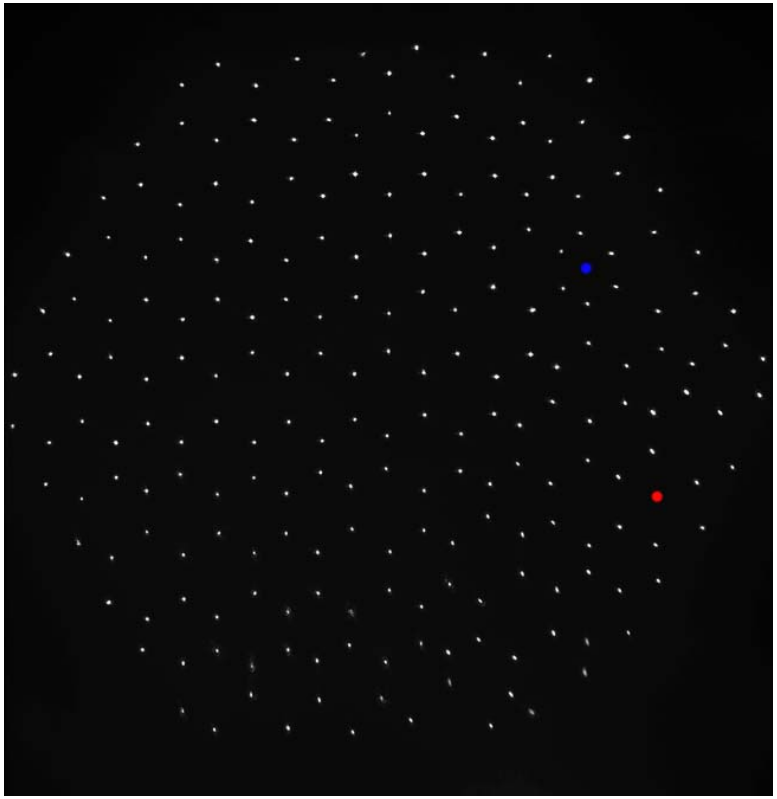






System Testing

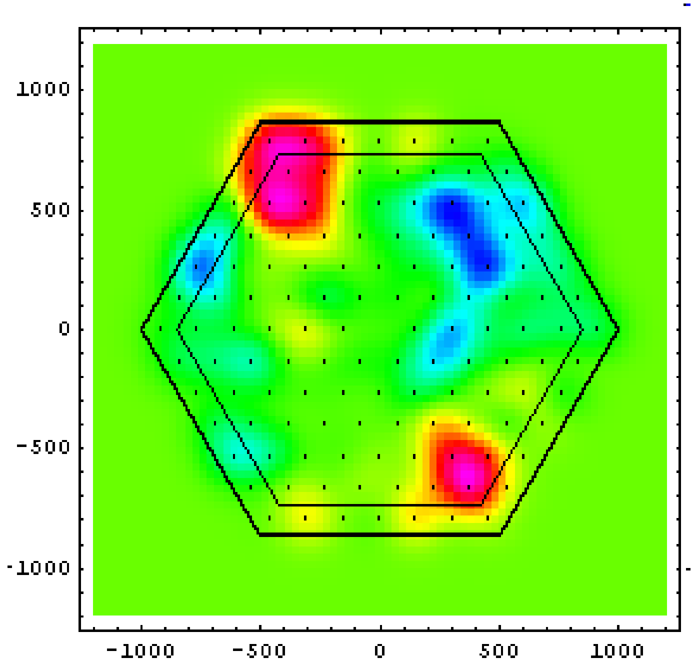
Metrology - The Hartmann Test



Each actuator is surrounded by 6 spots

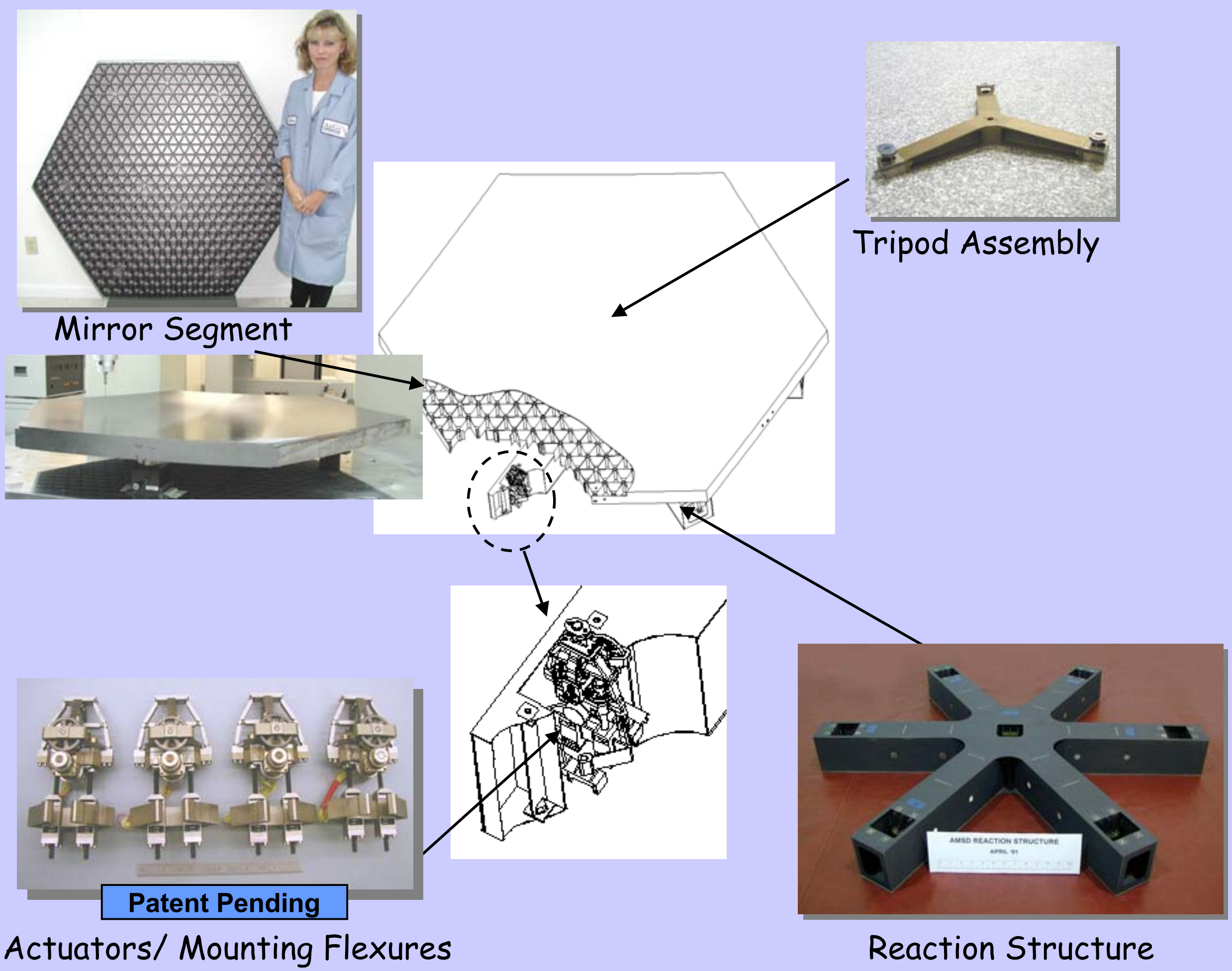
Blue - too low

Red - too high



Ball AMSD Mirror

Ball's Beryllium Semi-Rigid Design for AMSD



- 1.39-m point-to-point 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
- 7 Ball IRAD Actuators (6-rigid body and a ROC), 9 points.
- Major Subcontractors: SVG Tinsley, AXSYS, Brush-Wellman, COI

Kodak AMSD Mirror

1.4 m Diameter Semi-Rigid ULE Closed-Back Mirror

Graphite Epoxy (M55J) Reaction Structure by COI.

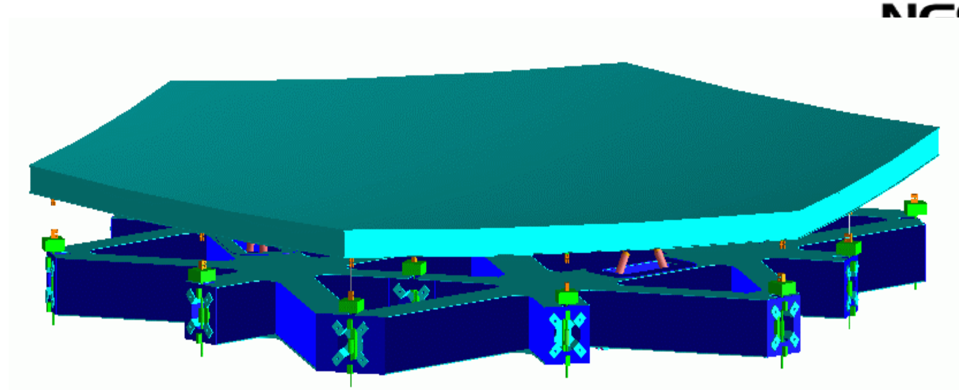
Reaction structure complete

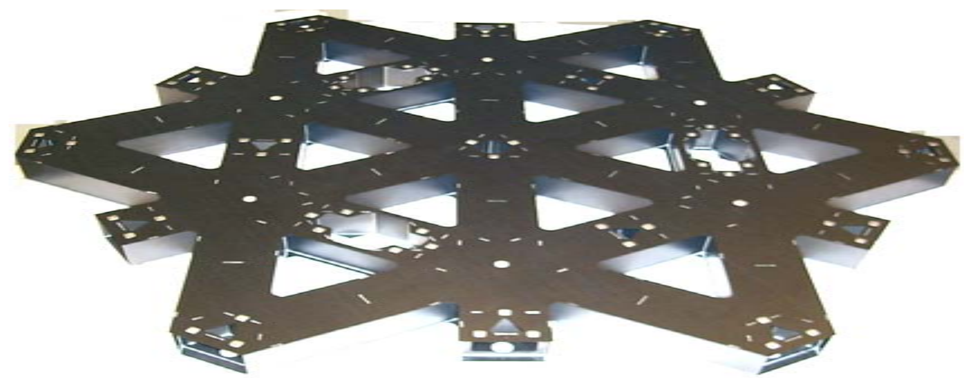
- Thermal cycled to 113°K

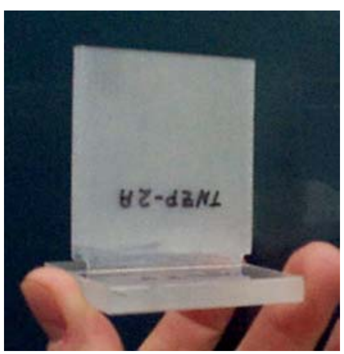
16 Force Actuators by Moog

- 7 for wavefront & radius
- 9 for gravity offloading

Identified Cause of Low Temperature Fusion (LTF) Failure





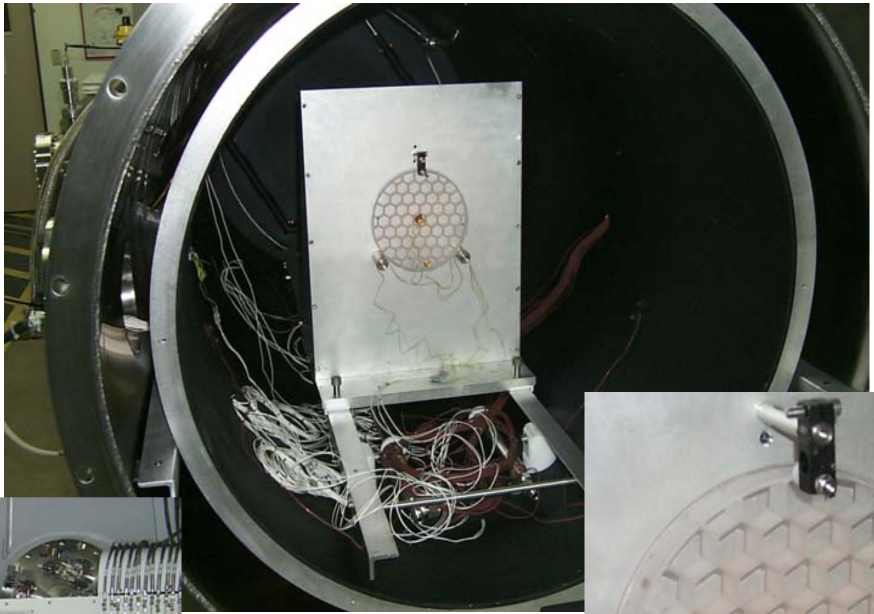


T-Sample cut from T-Box

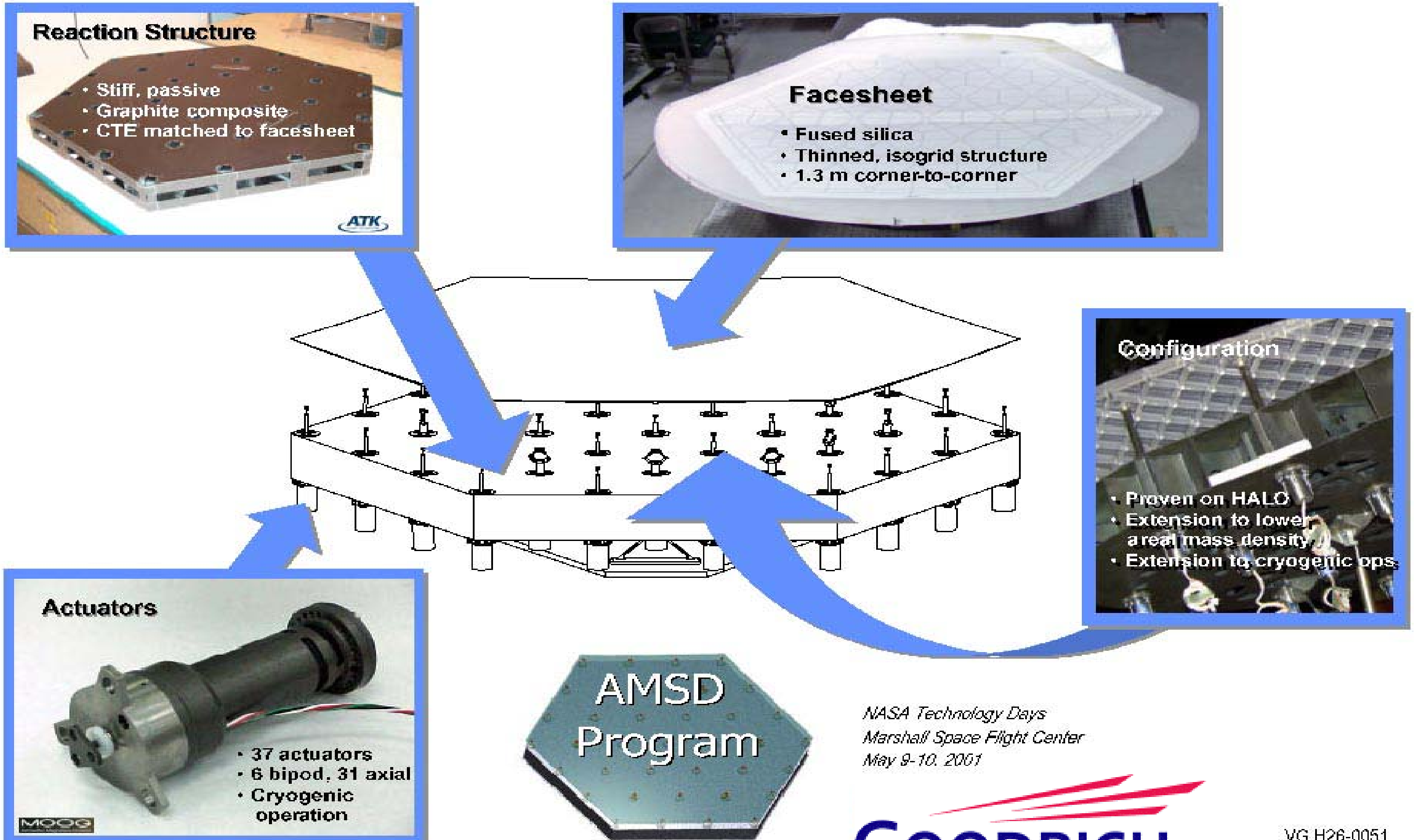
Kodak 23 cm Fused Silica Pathfinder Mirror

Validate to 35K at MSFC cryo-performance of NGST Traceable Fused Silica Mirror

- 0.23 m diameter
- 1.6 m Rcv
- Low Temperature Fusion Fabrication



Goodrich Figure-Controlled AMSD Mirror

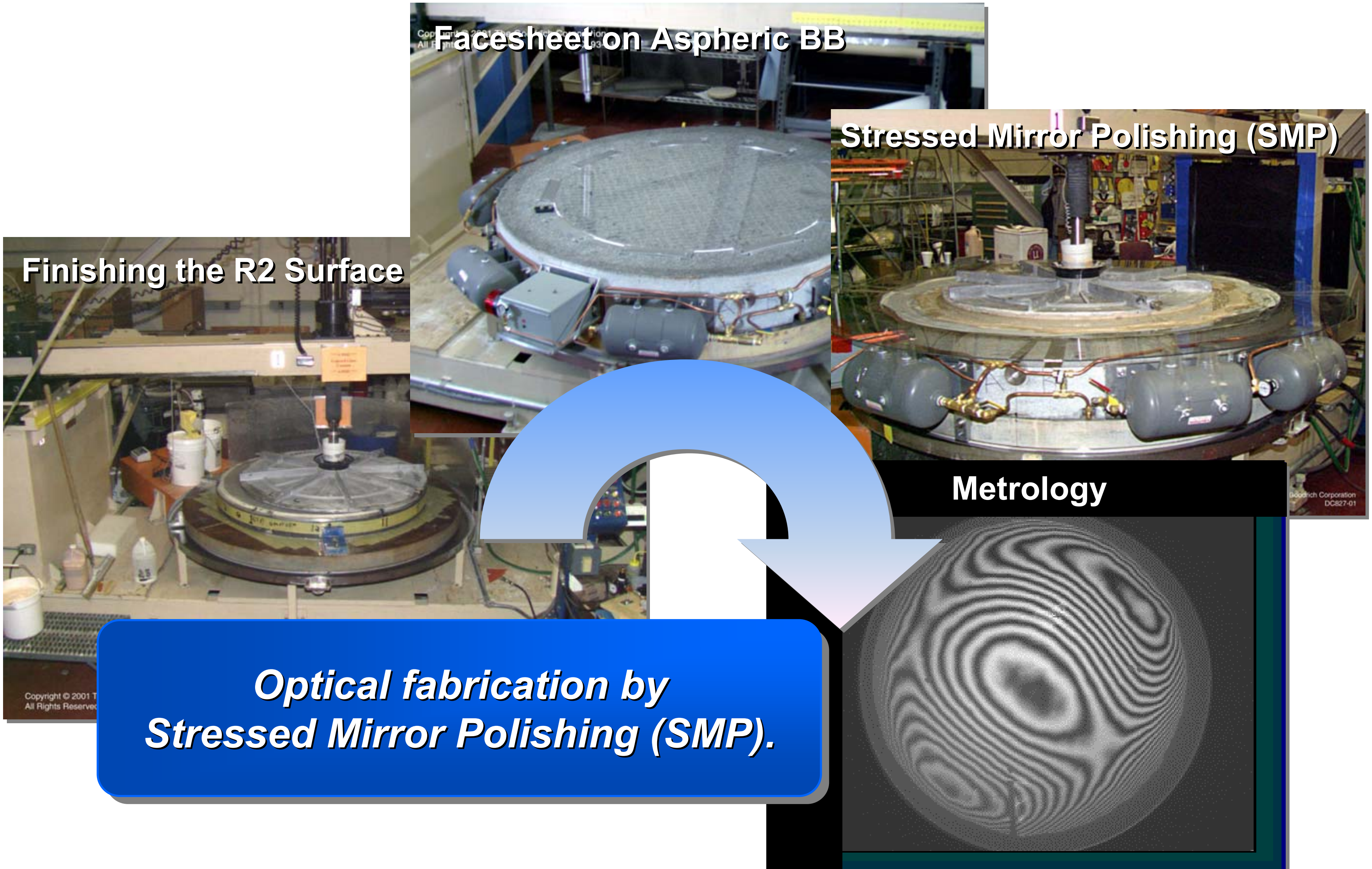


NASA Technology Days
Marshall Space Flight Center
May 9-10, 2001

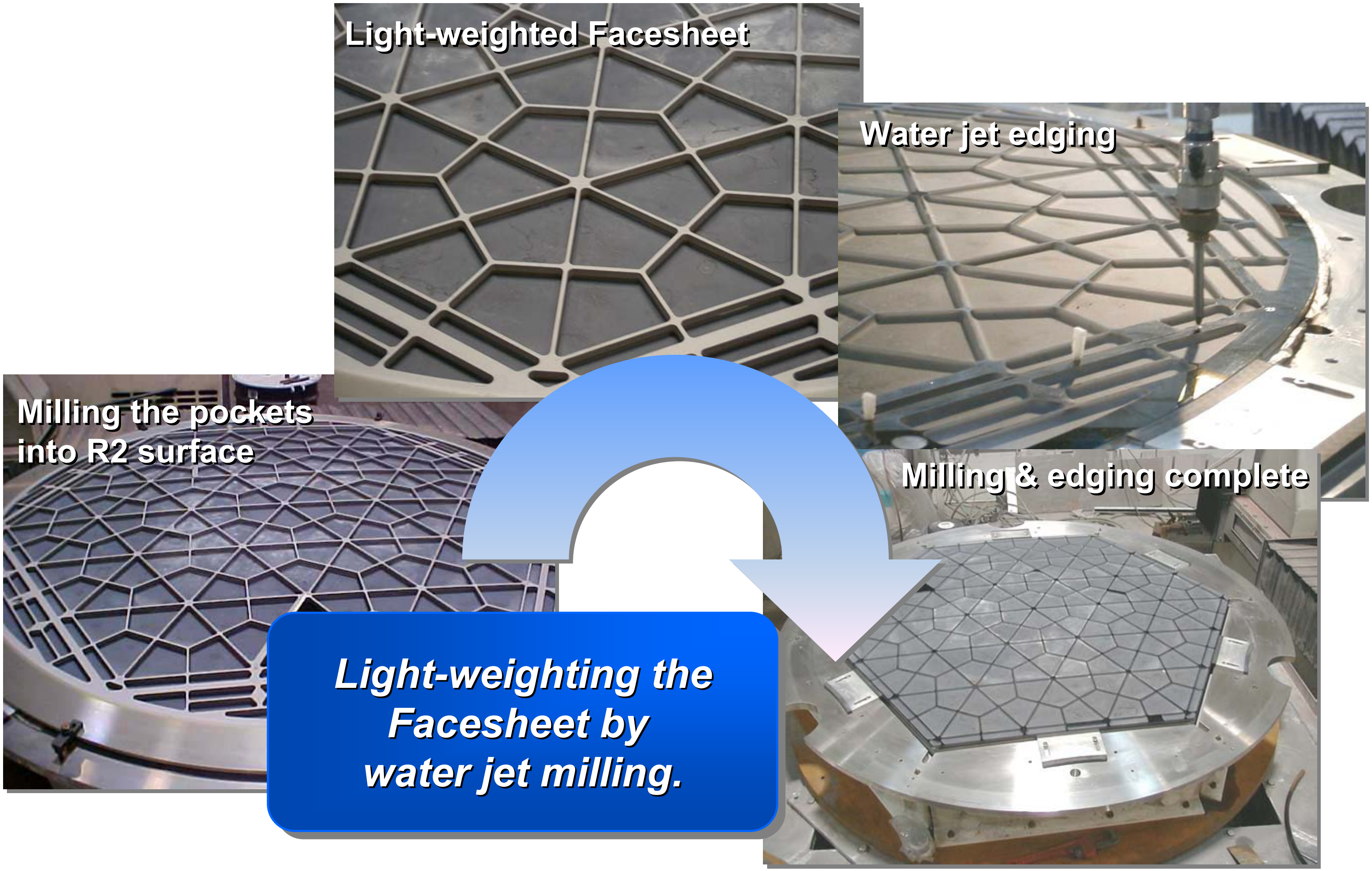
GOODRICH

VG H26-0051

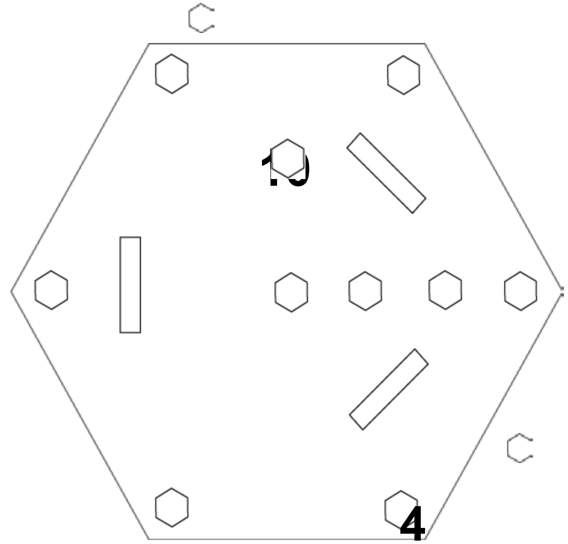
Stress Mirror Polishing



Light-Weighting and Edging by Water Jet Milling



Cryo-Deformation of Goodrich reaction structure

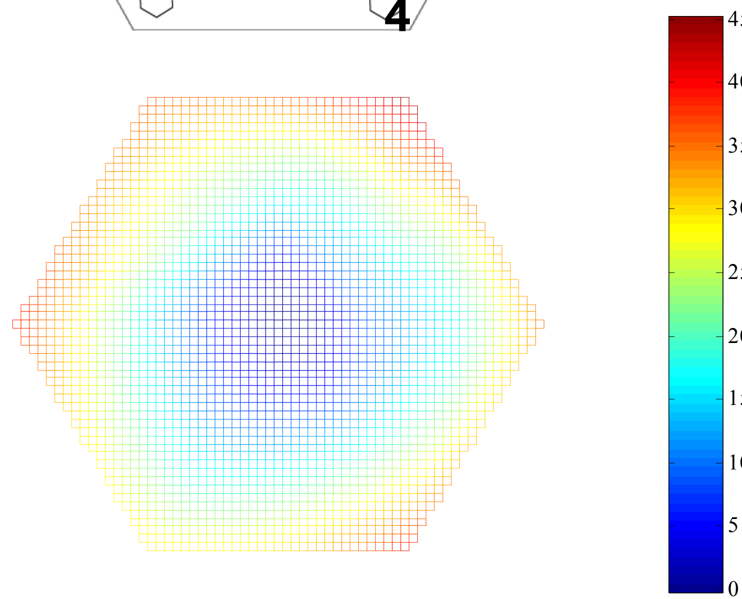


To measure reaction structure cryo-change

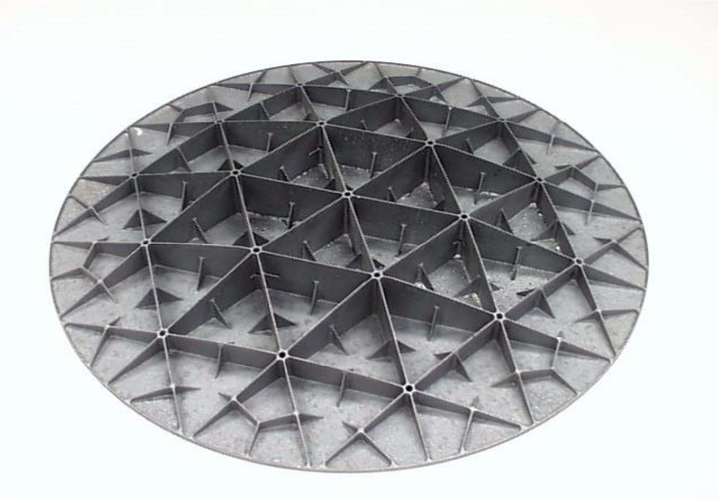
Instrument with corner cubes

Characterize with Leica ADM

30 micrometer change from Ambient to 25K



IABG 0.5 m 20 m Rcv Carbon Silicon Carbide

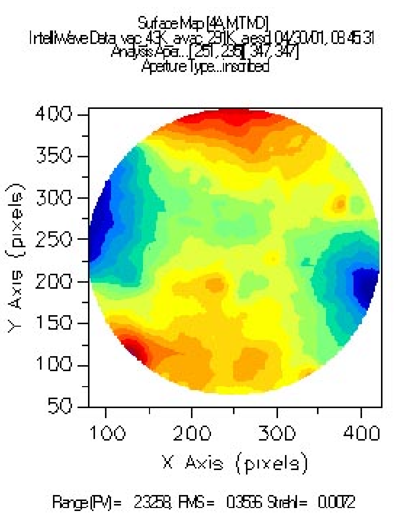


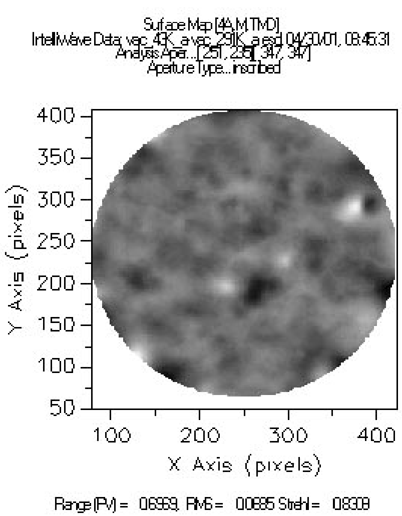
IABG Carbon Silicon Carbide Mirror C/SiC
- 0.5 m Diameter
- 20 m Rcv
- 7.8 kg/m^2 Areal density

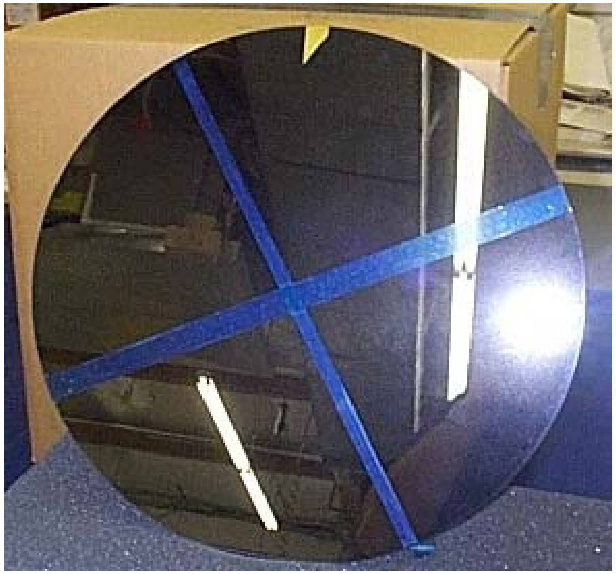
Blank polished at General Optics
- Figure of ½ wave PV
- Finish of 100 Angstroms RMS

Mirror tested to 120K at Kodak (Sept 99)
- 2.53 µm PV, 0.28 µm RMS Cryo-Figure Change

Mirror tested to 30K at MSFC
- 2.32 µm PV, 0.35 µm RMS Cryo-Figure Change (Apr 01)
- 2.40 µm PV, 0.43 µm RMS Cryo-Figure Change (Apr 02)







Xinetics 0.5 m 20 m Rcv Silicon Carbide

Xinetics Silicon Carbide Mirror SiC

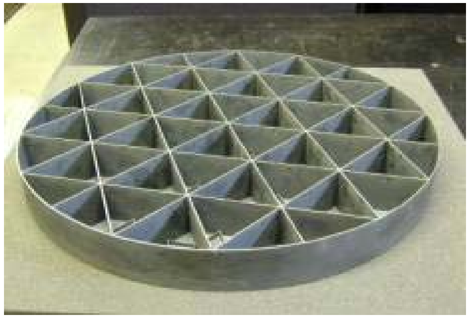
- 0.5 m Diameter
- 20 m Rcv
- 20 kg/m^2 Areal density

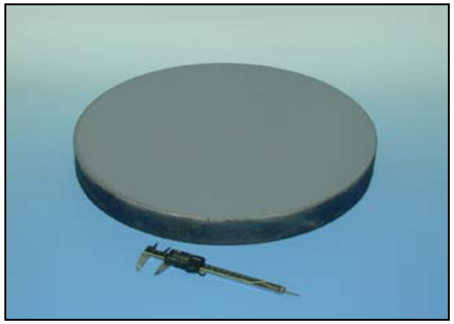
Blank polished at Kodak

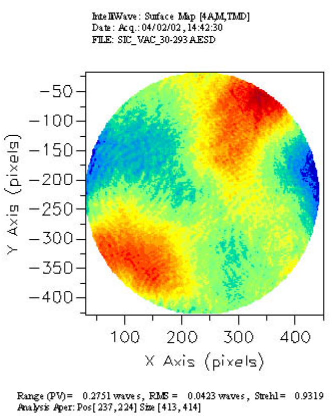
- Figure of 2.5 wave PV, 0.5 wave RMS
- Finish of 16 Angstroms RMS

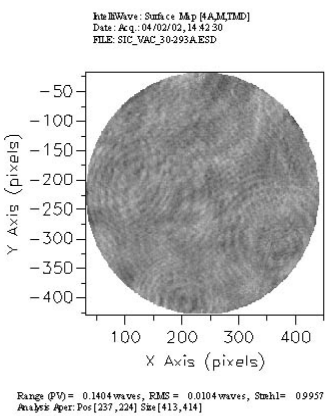
Mirror tested to 30K at MSFC (Apr 02)

- 0.17 µm PV, 0.027 µm RMS Cryo-Figure Change









Mirror	Company	Polishing Method	Figure (PV,waves)	Surface Rough (A)	Cost
Previous Program	Zygo	Spindle Bare SiC	λ /17 PV	16 A rms	$7650.
8 inch #1	Zygo	Spindle + MRF (Bare)	λ /35 PV	Before 19 A rms MRF 181 A rms	N/A
8 inch #2	Wave Precision	Planetary Bare SiC	λ/33 PV (90%)	11A rms	$1500.
8 inch #3	Wave Precision	Planetary Si Clad	λ /19 PV (90%)	2 A rms	$2500.
8 inch #4	Kodak	Planetary Bare SiC	λ /7 PV	16 A rms	$5625.
20 inch #1	Kodak	Spherical Bare SiC	TBD	TBD	$45000.

Beyond NGST

NASA's Origins and Structures and Evolution of the Universe (SEU) Themes have defined a series of future missions. Many require large optics that are more challenging than anything demonstrated to date.

For Example:

- Single Aperture Far-IR (SAFIR) requires a 10 meter segmented telescope diffraction limited at 40 micrometers actively cooled to 4K.
- Space Ultra-Violet Observatory (SUVO) requires a 4 meter monolithic telescope diffraction limited at 0.5 micrometers.
- Terrestrial Planet Finder (TFP) coronagraph requires a monolithic 4 x 8 meter elliptical primary mirror.

Optic is used broadly at NASA

NASA is divided into Program Offices

- Space Science (Code S)
- Earth Science (Code Y)
- Microgravity Science (Code U)
- etc

Space Science is responsible for programs such as Hubble & Chandra.

Earth Science is responsible for programs such as LANDSAT and a series of EOS (Earth Observation Satellite) Missions.

Microgravity performs materials and fluid experiements on the Space Shuttle and Station (such as STDCE, PHaSE, PCS, TIPMPS, etc.)

All have Optics Requirements: Components, Telescopes, Detectors, Cameras, Spectrometers, Metrology Systems, Visions Systems, etc.

Optic Requirements for Space Science

Space Science has two Major Initiatives:

- Origins
- Structure and Evolution of the Universe

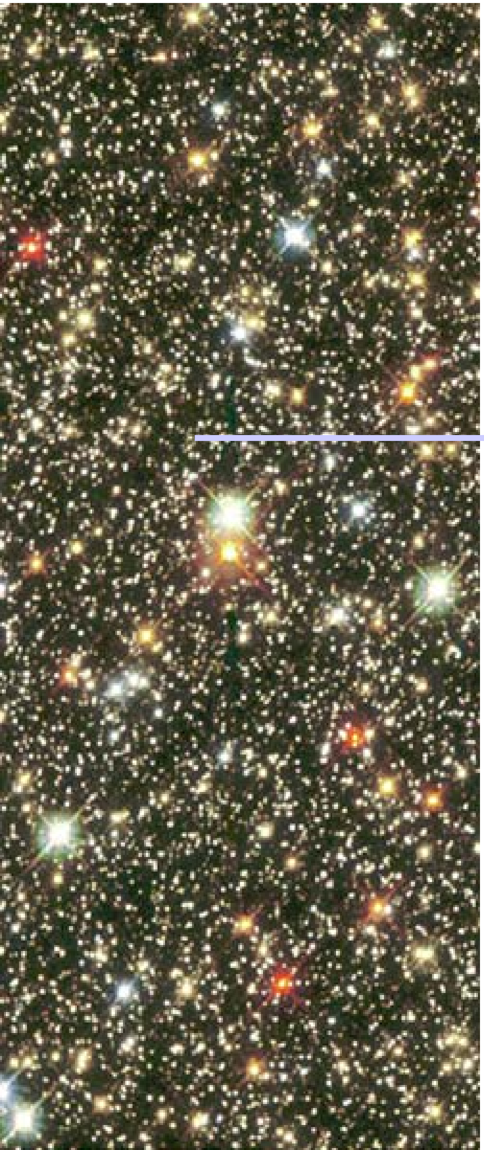
While the Origins Initiative is well known – includes NGST.

The SEU Initiative is just being defined.

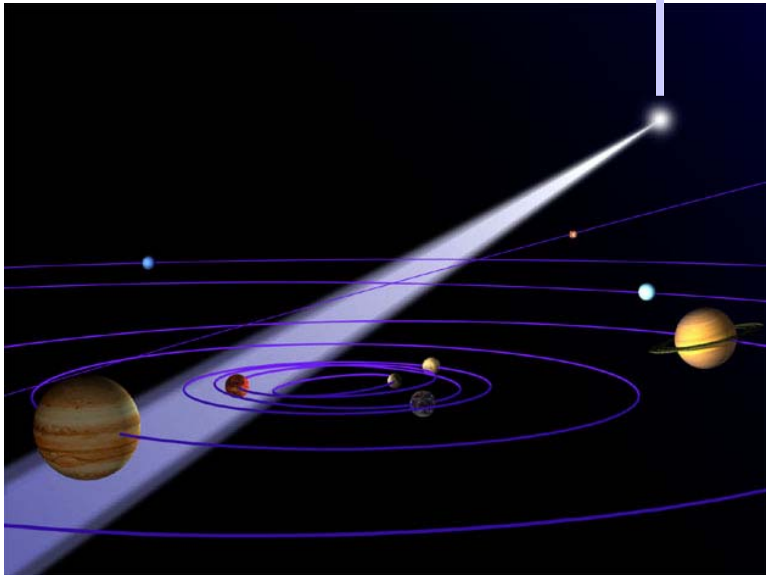
And, given that both overlap, there may be some merging.

Origins Theme Technology Roadmap

Origins Theme's ***Two*** Fundamental Questions



- How Did We Get Here?
- Are We Alone?



How Did We Get Here?

Trace Our Cosmic Roots

Formation of galaxies

Formation of stars

Formation of heavy elements

Formation of planetary systems

Formation of life on the early Earth

Are We Alone?

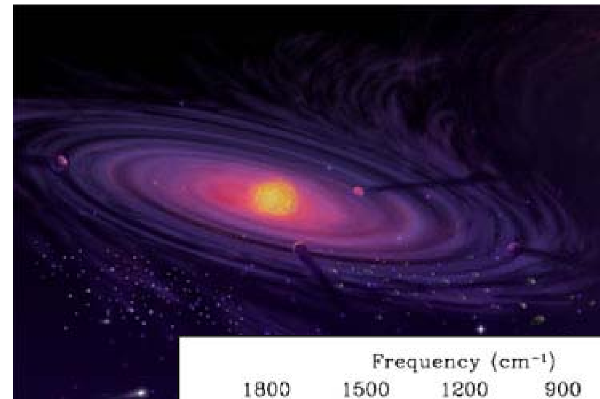
Search for life outside the solar system

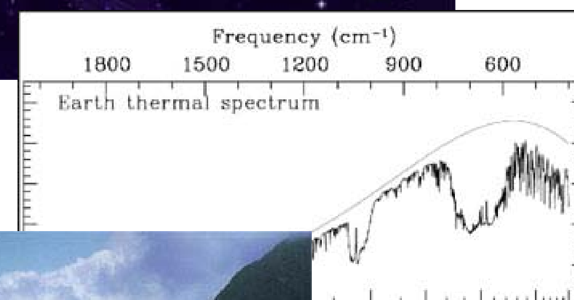
Search for other
planetary systems

Search for habitable planets

Identify remotely detectable bio-signatures

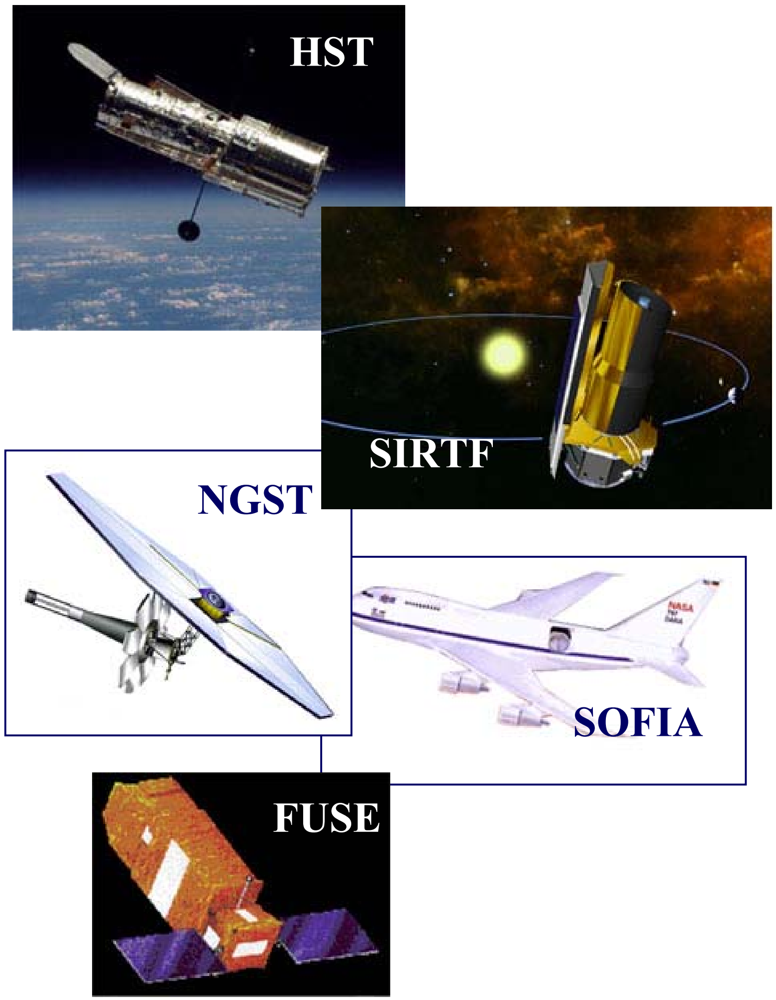
Search for "smoking guns" indicating biological activities





Missions Supporting the Origins Goals

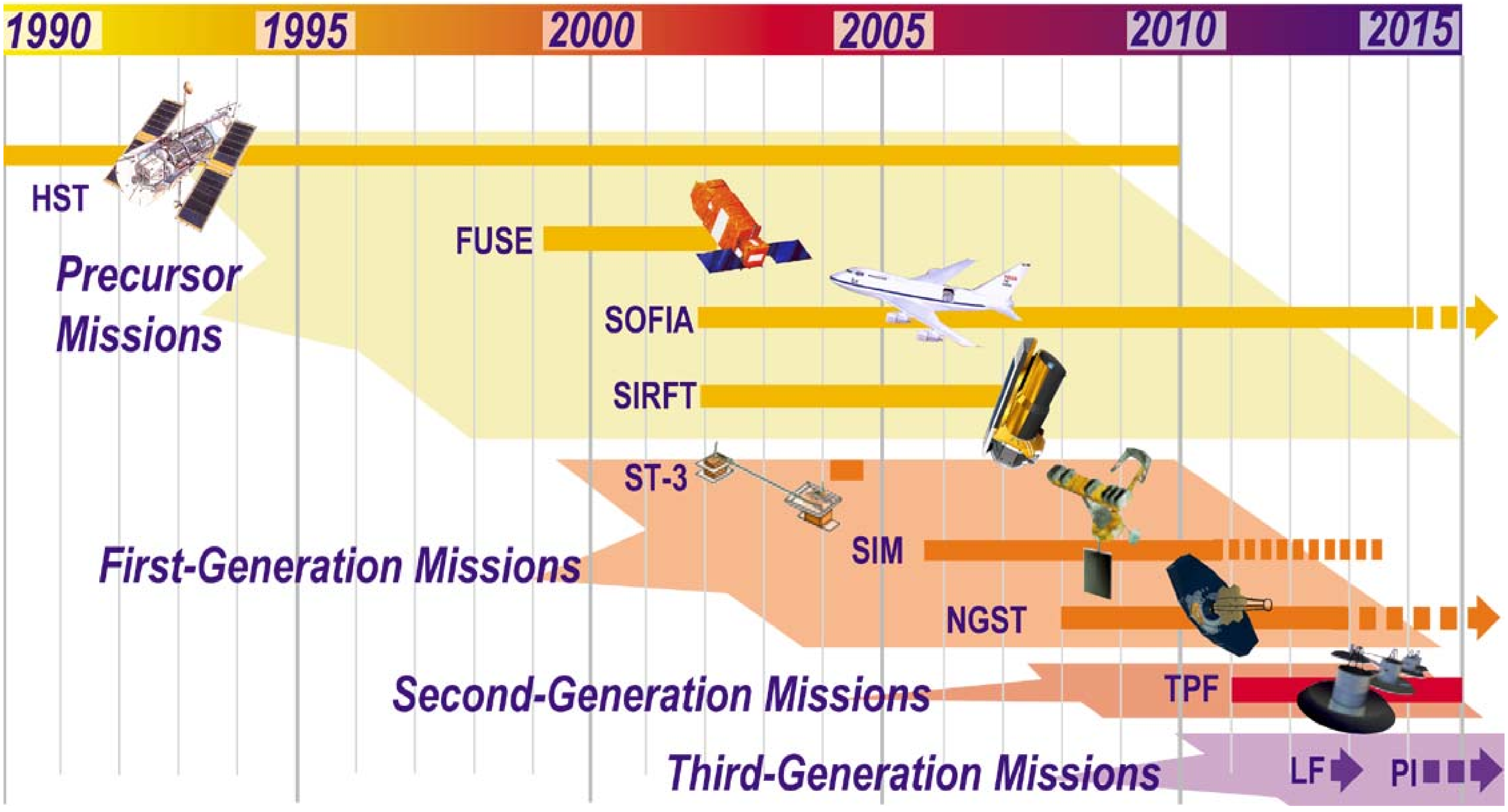
How Did We Get Here?



Cross Feed Science & Technology

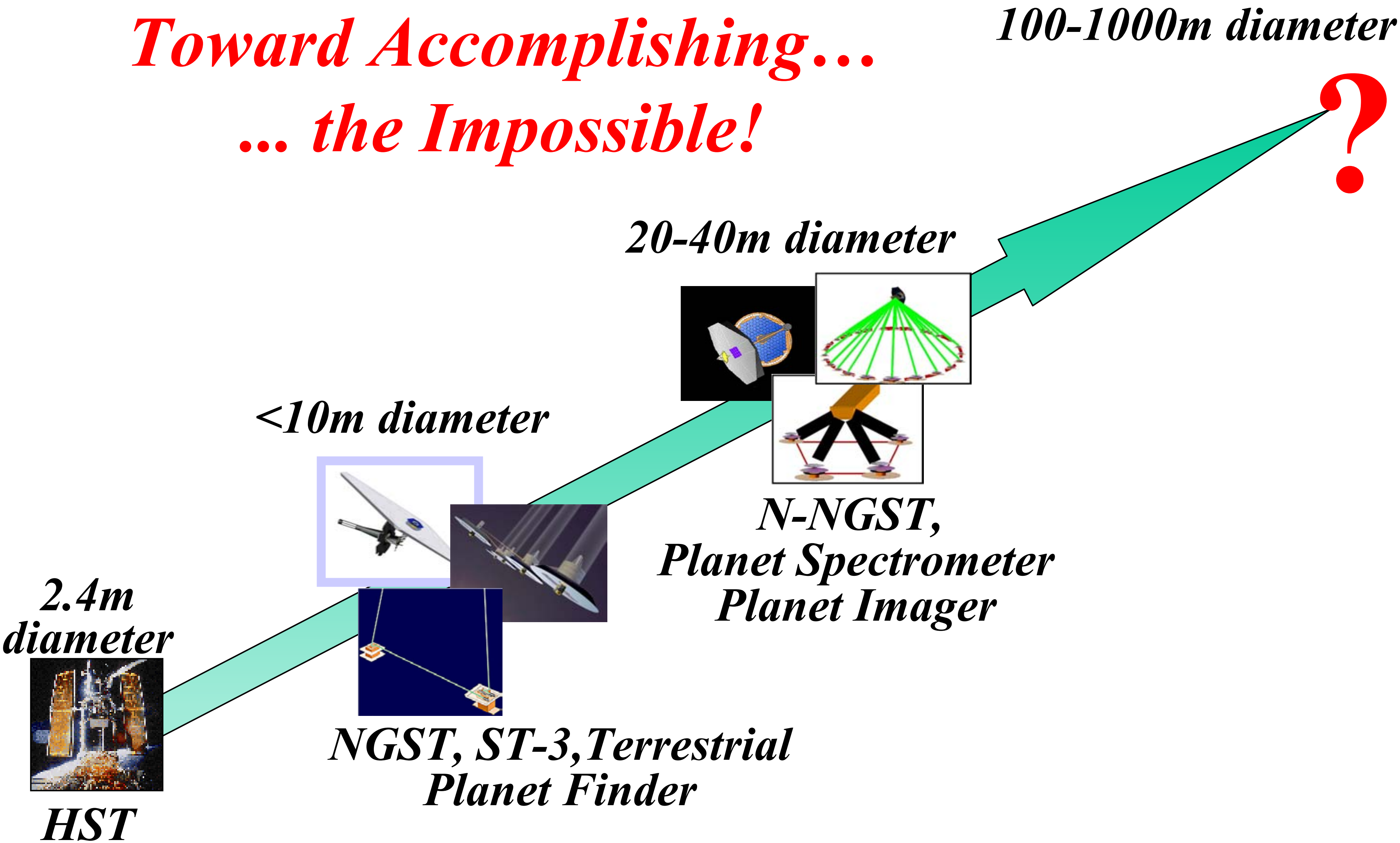
Are We Alone?

Mission Timeline



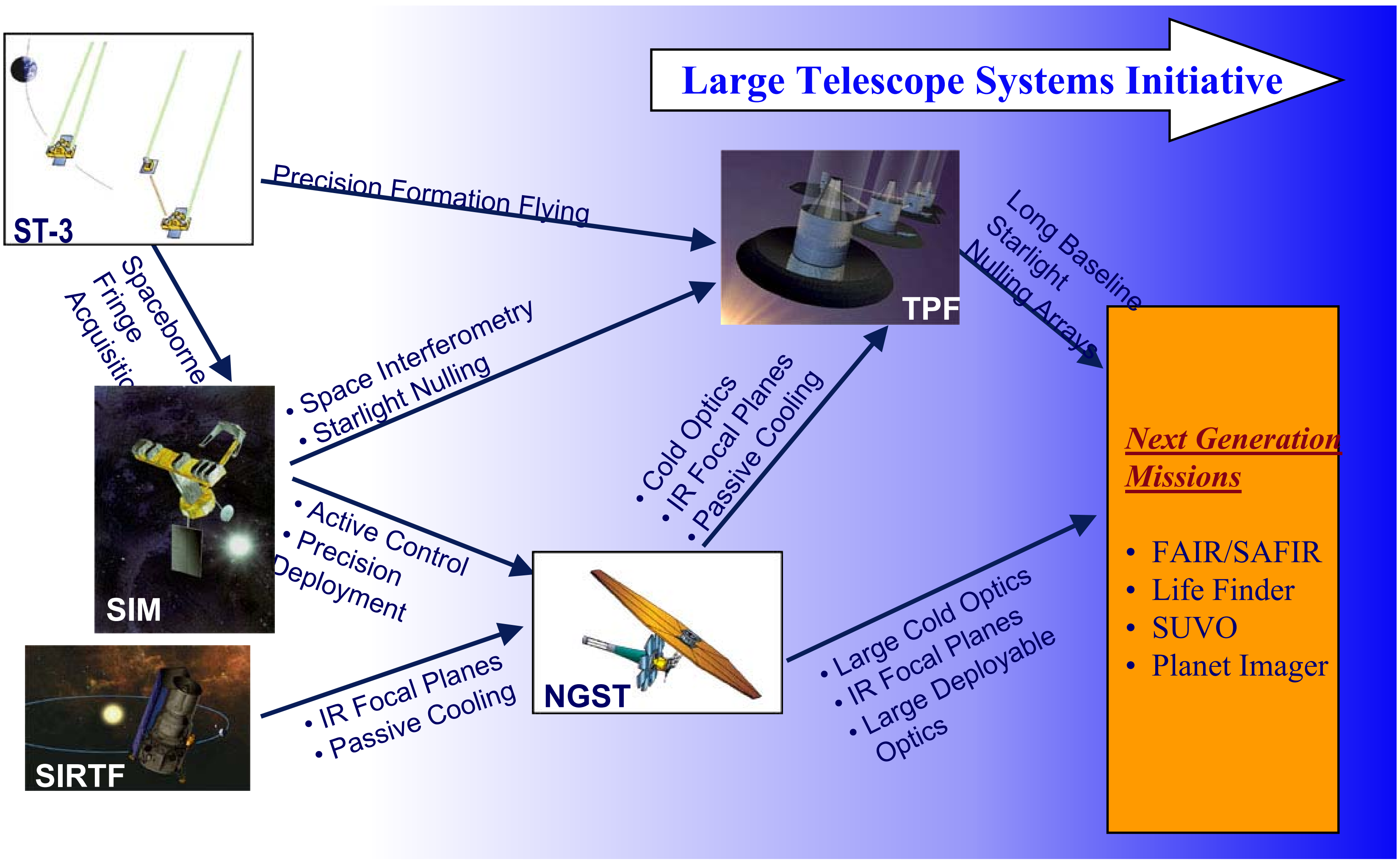
A Vision for Large Telescopes & Collectors

Toward Accomplishing…
... the Impossible!



Operational Developmental Conceptual Unimaginable

Strategic Technologies Are the Enabling Threads Between the Origins Missions



SEU Technology Roadmap

Structure and Evolution of the Universe (SEU) has defined two 'focused' themes for the next 10 years:

- Beyond Einstein
- Cycles of Matter

Each Theme has defined

- Major Missions ($1B class),
- Cosmic Probe Missions ($350M class), and
- 'Vision' Missions that might become practical in 20 years.

Each Theme will have a technology funding line (similar to NGST) to enable technology for all missions.

- NGST invested 33% (or approx $150M) of the projected mission cost.
- Major Challenges include optics, detectors and cryogenics.

Beyond Einstein Theme

Beyond Einstein probes the physics of 'beginning and end of time' and black hole horizons. Its two major missions are:

- Constellation-X
- LISA

Three smaller 'Cosmic Probe' missions are defined to study:

- Nature of dark energy – could be the proposed SNAP.
- Effect of Big Bang gravitational wave background on the Cosmic Background Microwave radiation Polarization – could be the proposed CMB-POL.
- Obscured black holes in the nearby universe – could be the proposed EXIST.

Actual missions will competed via NASA Research Announcement (NRA)

Possible 'Vision' missions include the proposed:

- MAXIM – an x-ray interferometer mission to image black holes

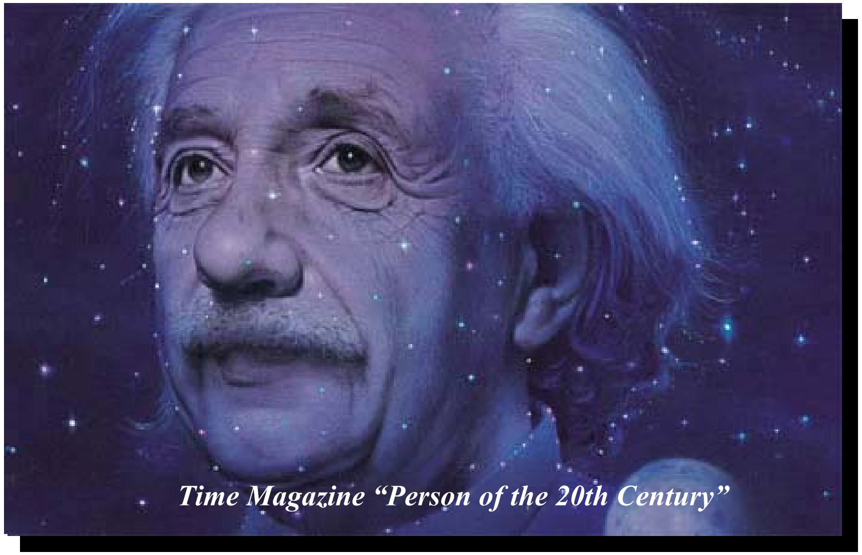
Beyond Einstein

There are pressing questions related to, or left over from Einstein's work, that challenge the foundations of physics:

What is the nature of gravity, space and time?

What is the Universe made of?

What powered the big bang?

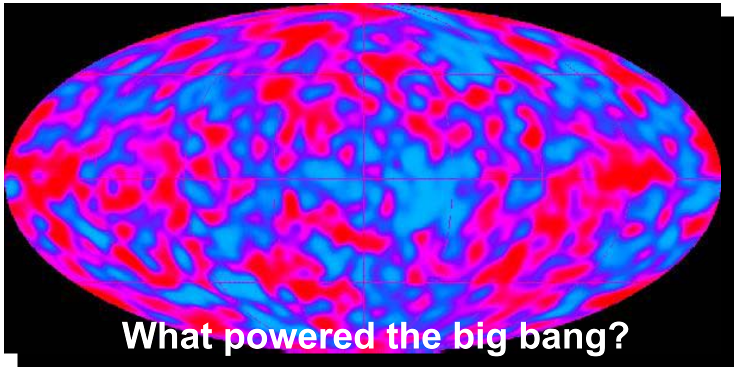


Answering these questions is the major challenge facing Physics and Astronomy for the 21st century

The Three Extremes of Gravity

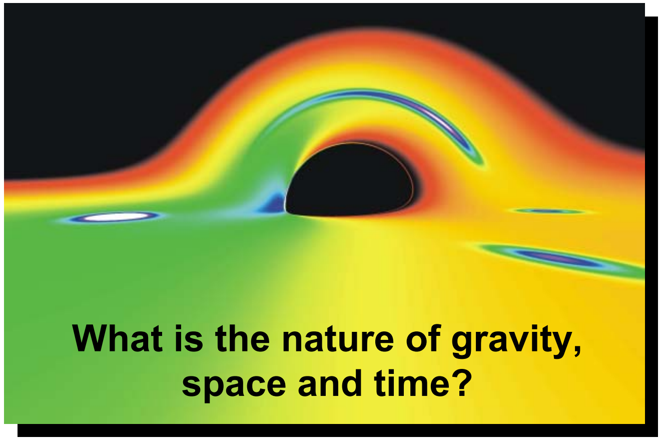
Gravity on the universal scale

X-ray Spectroscopy



Gravity in the early universe

Cosmic Microwave Background



Gravity in the vicinity of black holes

x-ray interferometry

Roadmap to a Black Hole

Now

Chandra

XMM-Newton

RXTE

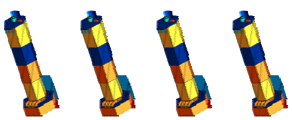
Find them & Probe properties

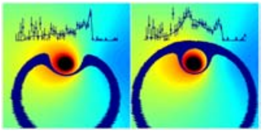
LISA

Gravitational Waves Black Hole mergers

2010-2011

Constellation-X



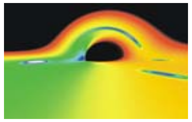


X-ray Spectroscopy at the event horizon

Evolution & environment at the event horizon

MAXIM

10 million times Chandra angular resolution



Black hole imager!

2020-2025?

Direct observation of GR effects

Constellation-X: Mission Parameters

Collecting Area: 30,000 cm^2 at 1keV

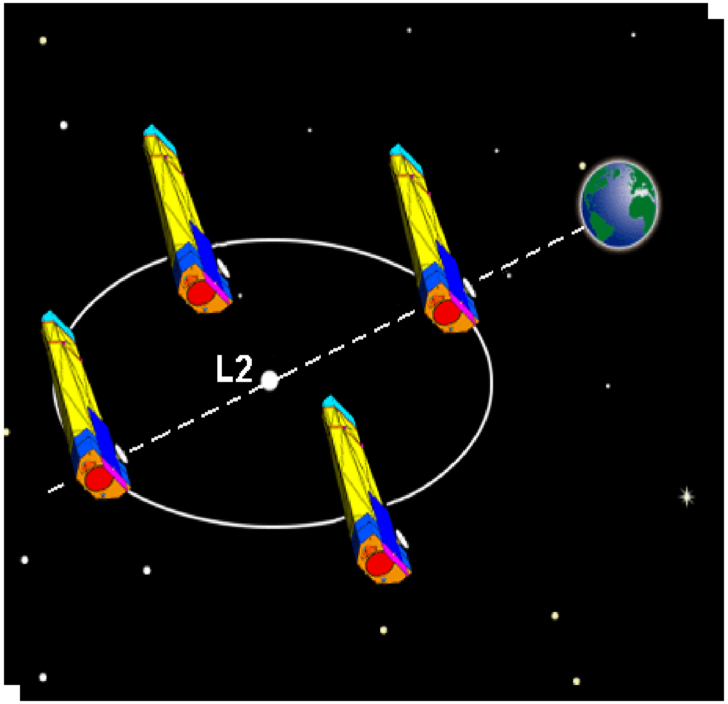
- 25-100X Chandra & XMM for high resolution spectroscopy
- 4 Identical Space Craft – launched 2 at a time.

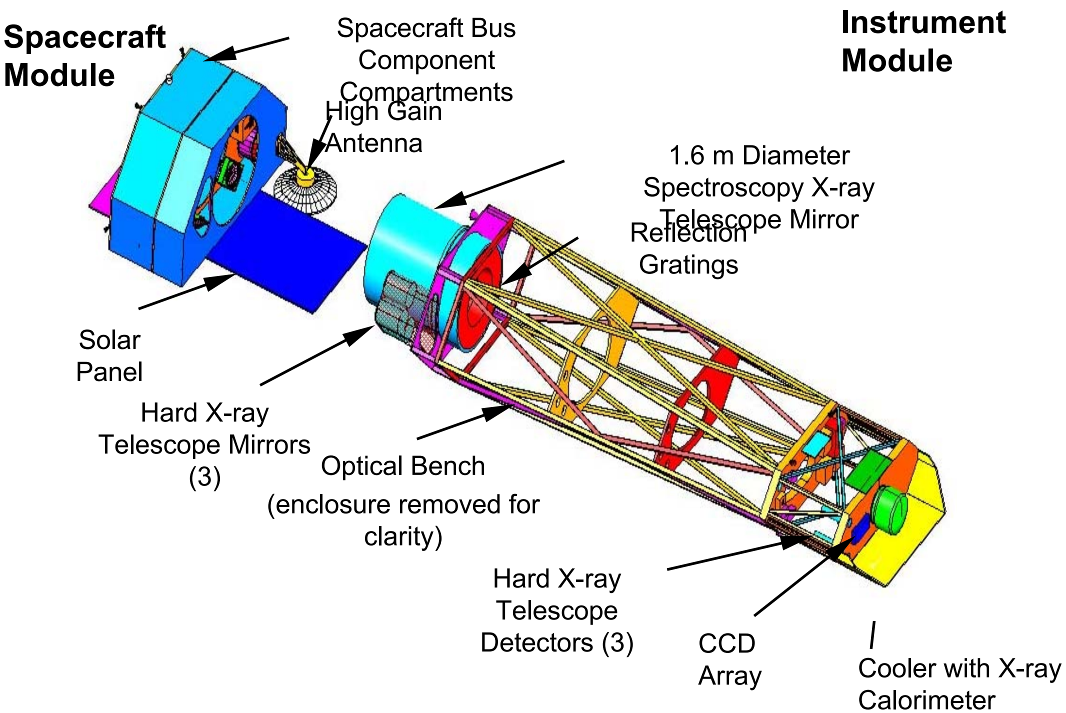
Band Pass: 0.25 to 40 keV

- 100X more sensitive than Rossi XTE at 40 keV

Angular Resolution

- Soft X-Ray Telescope < 15 arc-sec - Mirror Figure and Alignment
- Hard X-Ray Telescope < 1 arc-min - Mirror Figure and Coatings





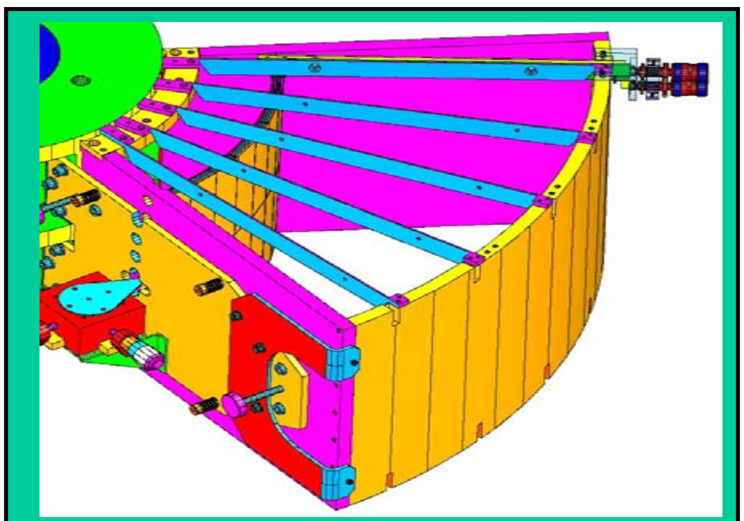
Constellation-X SXT Mirror

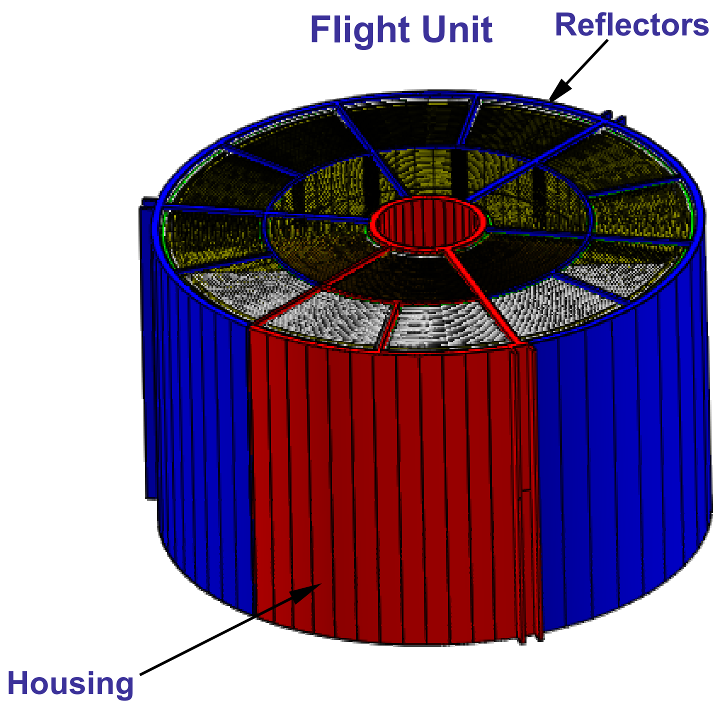
Constellation-X consists of four identical spacecraft and sets of instrumentation.

Each SXT mirror is a Wolter I grazing incidence mirror with a 10 m focal length and a 1.6 m diameter.

The mirror is composed of many (100-250) nested Wolter-I reflectors.

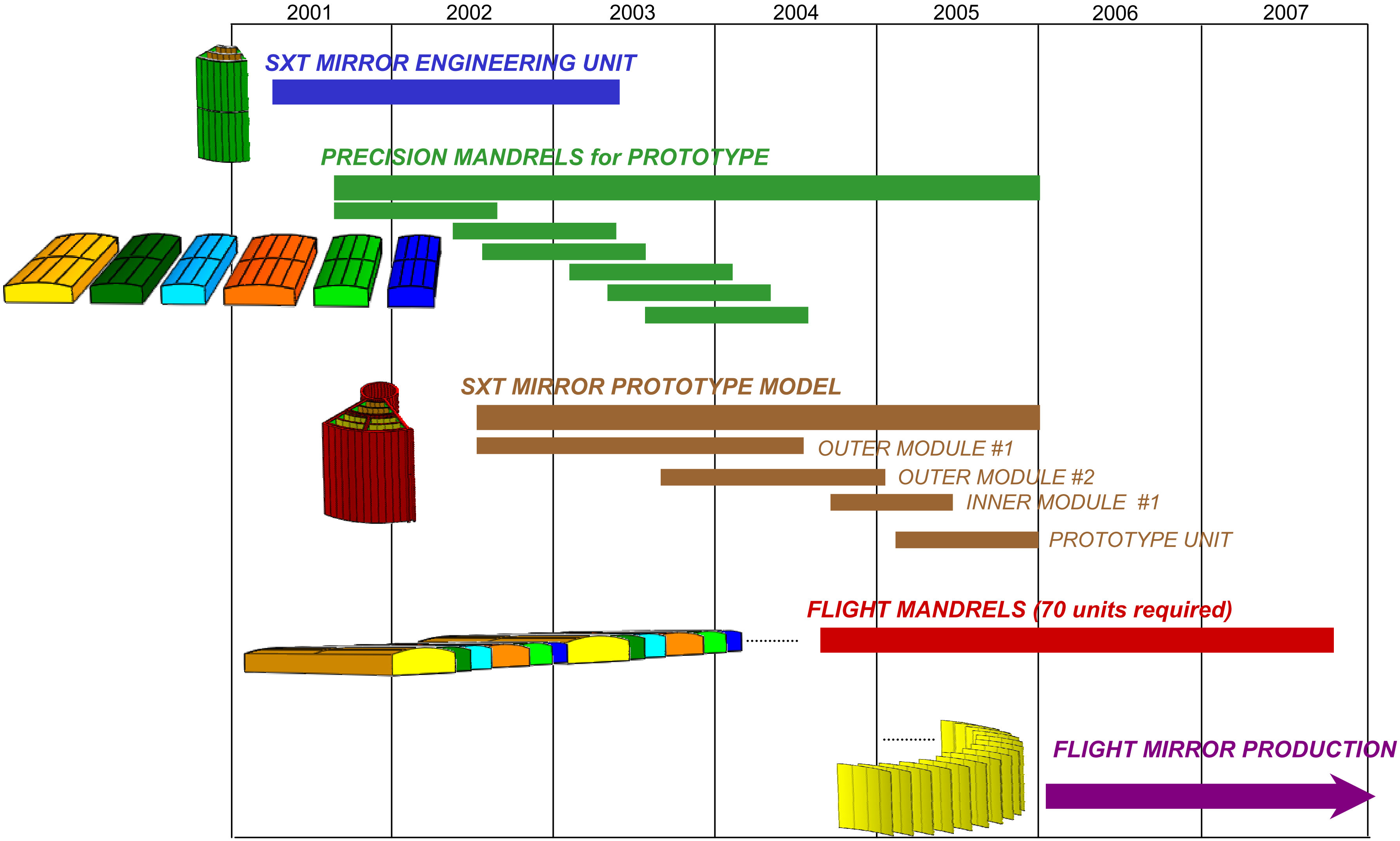
The SXT mirror is azimuthally segmented and gang aligned.





1.6 m outer diameter
10 m focal length
20-50 cm reflector length
18 Small Modules
(6 inner, 12 outer)
70-250 nested reflector pairs
mirror mass ≤500 kg

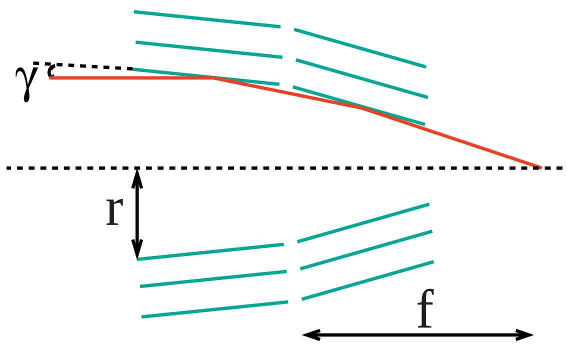
SXT Technology Roadmap

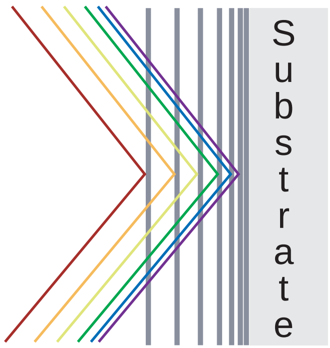


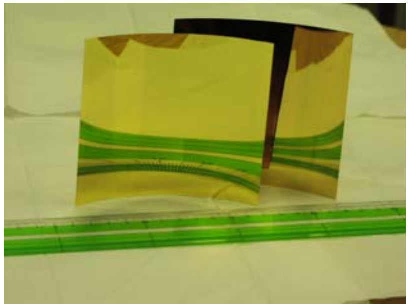
HXT Technologies

Depth-graded multilayer mirrors

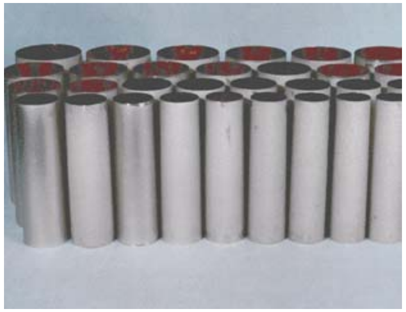
Conic-approximation grazing-incidence optics
Highly-nested thin shells (replicated full-shell or segmented)
Graded multilayer coatings extend energy range to E≥50 keV







Replicated formed glass



Ni replica shells

Key Technical Issues to be Demonstrated

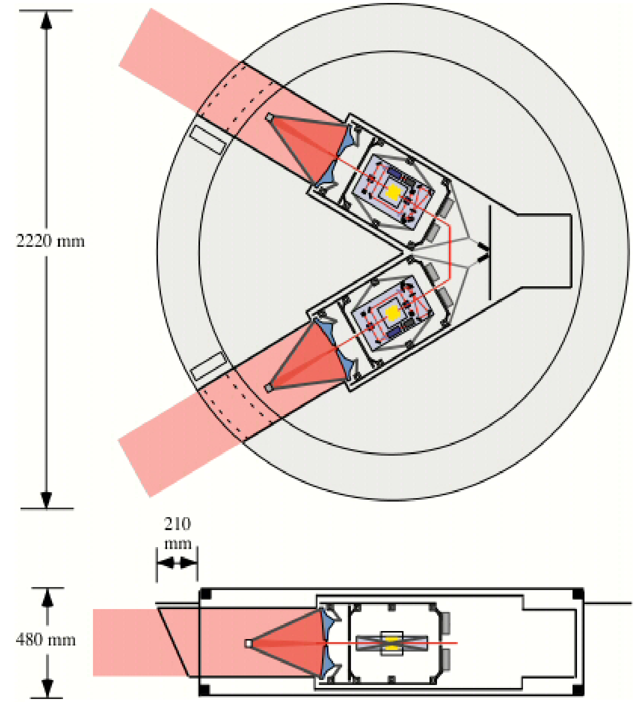
Thin Ni shells yet to be produced in required dimensions
Epoxy replicated foils have not been mounted using precision technique
Neither Ni nor thin glass have demonstrated desired resolution
Replication of multilayers from mandrels must be demonstrated for Ni
Surface roughness of epoxy replicas must be improved

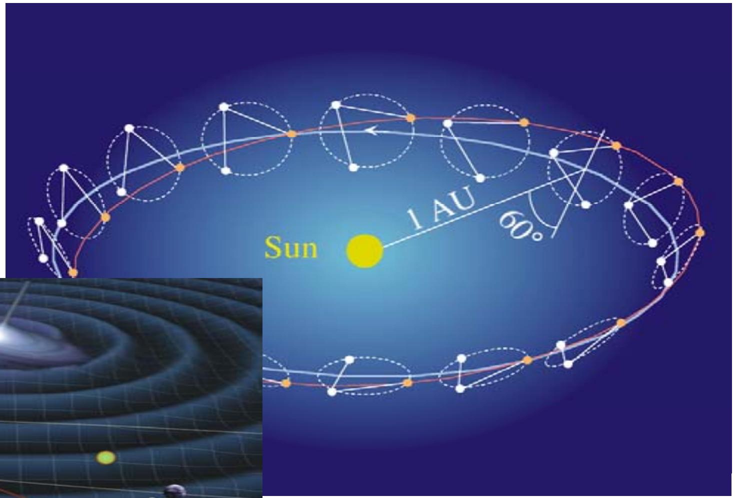
Laser Interferometer Space Antenna (LISA)

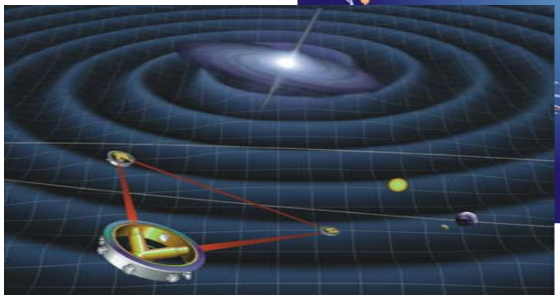
LISA uses a laser based Michelson interferometer to monitor the separation between proof masses in separate spacecraft

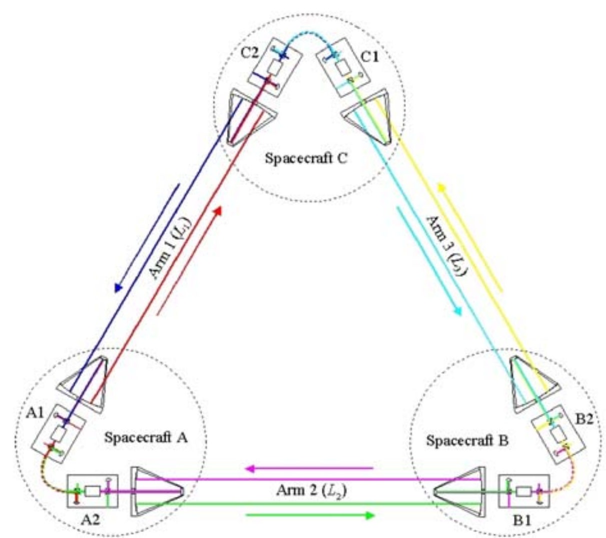
Three "drag free" spacecraft separated by 5 million km

Precision ranging to an accuracy of 20 pico-meters every second ***50X smaller than atom!***





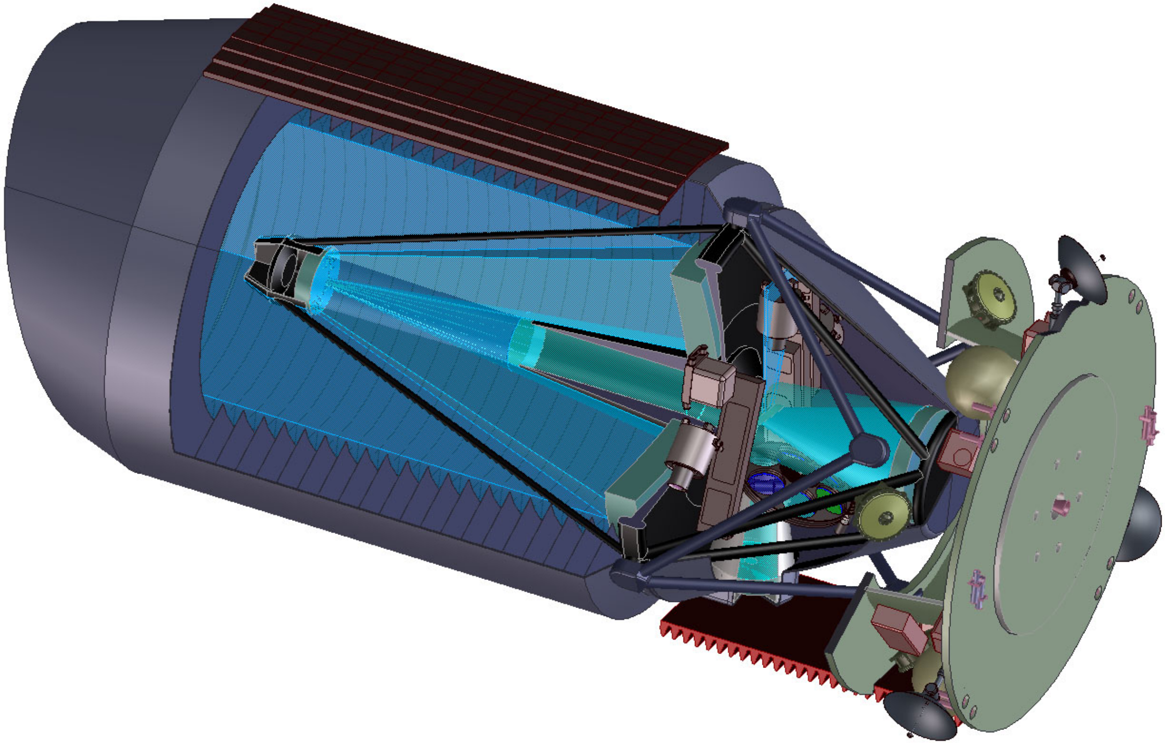




SNAP Mission Design

SNAP a simple experiment to study the dark energy

- Dedicated instrument, essentially no moving parts
- Telescope: 2 meter aperture, diffraction limited beyond 1 micron
- Photometry: with 1deg FOV half-billion pixel mosaic camera, high-resistivity, rad-tolerant p-type CCDs and HgCdTe arrays. (0.4-1.7 μm)
- Integral field optical and IR spectroscopy: 0.4-1.7 μm, 2”x2” FOV



Cosmic Microwave Background Polarization

CMB Polarization test the inflation paradigm by measuring primordial gravity waves.

Precursor Missions:

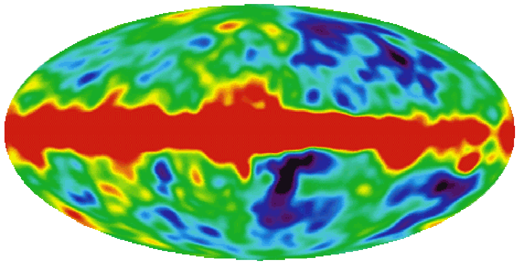
- COBE – 0.2 m, 1.5 K
- MAP – 1.4 m, 70 K

CMB Pol Requirements:

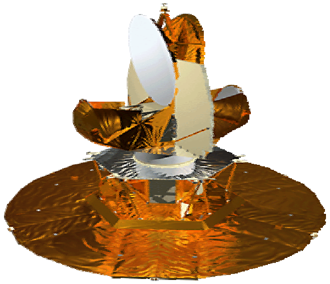
- 2 m diameter
- Diffraction Limited at 0.5 mm
- 10K Operational Temp
- Low Cost

COBE 1992

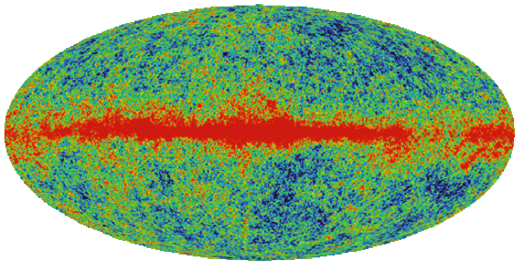
COBE 4-Year Full Sky Coverage



MAP 2001



MAP Simulated Full Sky Coverage



Could use technique with AMD as demonstrated on AMSD Reaction Structure to Test CMBPol Mirror at 10K.

The MAXIM Black Hole Imager

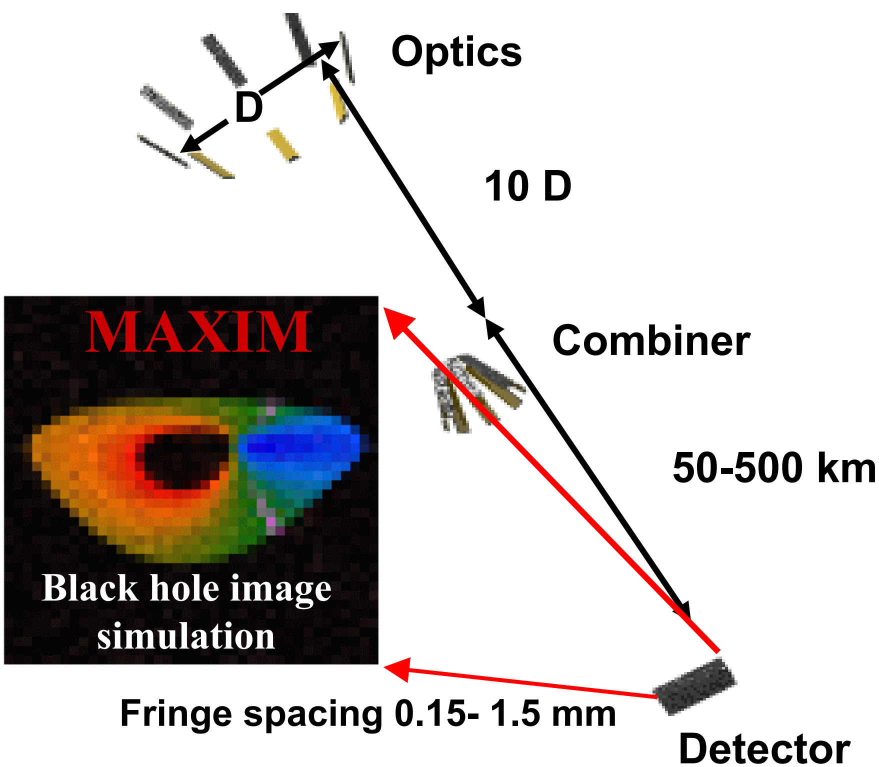
To achieve sub-micro arc second angular resolution will require X-ray interferometry

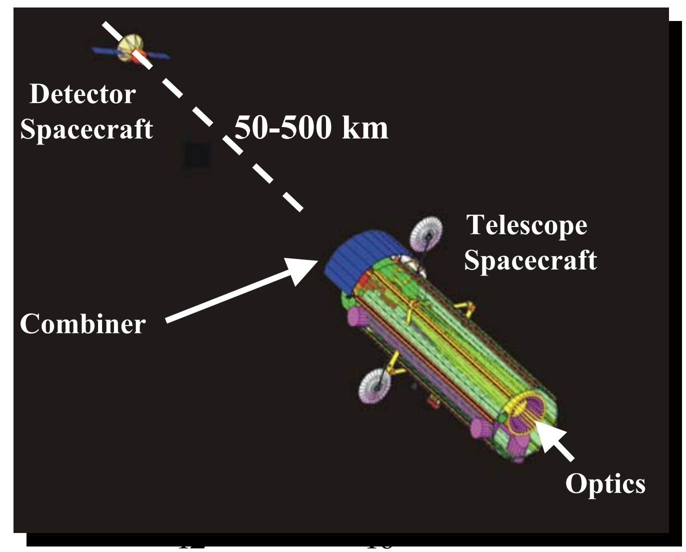
Multiple spacings & rotation angles needed simultaneously to sample UV plane

32 flats (300 × 10 cm) held to 20 nm precision

Resolution @ 1 nm (1.2 keV)

D (m)	*μ arc sec*	*Mission*
1	100	Pathfinder
10	10	
100	1	
1000	0.1	MAXIM



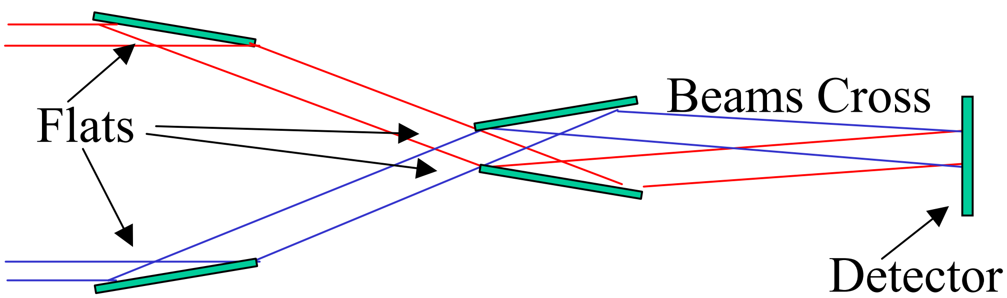


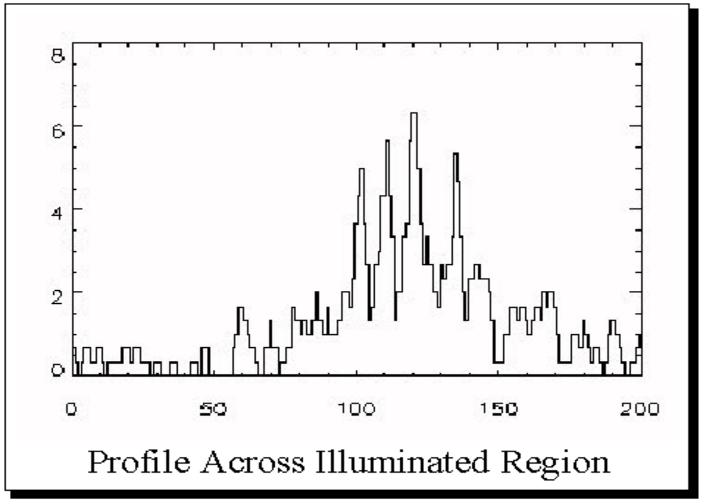
MAXIM Pathfinder with 1m baseline will demonstrate X-ray imaging from interferometry

1,000 times increased resolution over Chandra!

X-ray Interferometry

Laboratory demonstration of the feasibility of X-ray Interferometry with 1 mm baseline





Actual Lab Data @ 1nm

This laboratory experiment is scalable to an on-orbit telescope!

Advantage: Flat optics are MUCH easier to make

Credits: Webster Cash, Marshall Joy, David Zissa

Cycles of Matter Theme

Cycles of Matter studies the 'creation and lifecycles of matter'.

- Where are the Baryons – the rest of the Universe
- How and when were Galaxies, Stars, Solar Systems & Planets formed
- How and when were Elements formed

Its missions include:

- SAFIR – Single Aperture Far Infrared
- SUVO – Space Ultra Violet Observatory
- ACT – Advanced Compton Telescope (detector only)

SUVO – Space UV Observatory

"Emergence of the Modern Universe"

Study fundamental processes of star & planetary system formation at a level of detail only observable locally.

Relate these to their early universe higher-redshift analogs.

Primary Mirror Requirements

4 meter Diameter Monolith – existing launch fairings

Diffraction Limited at 0.5 micrometers (~30 mas).

High Encircled Energy in 0.3"-1.0" for UV Point Spectroscopy

Areal Density ~15 kg/m^2.

SUVO could be combined with TPF Coronagraph Mission which prefers a 4 x 8 meter monolithic mirror architecture.

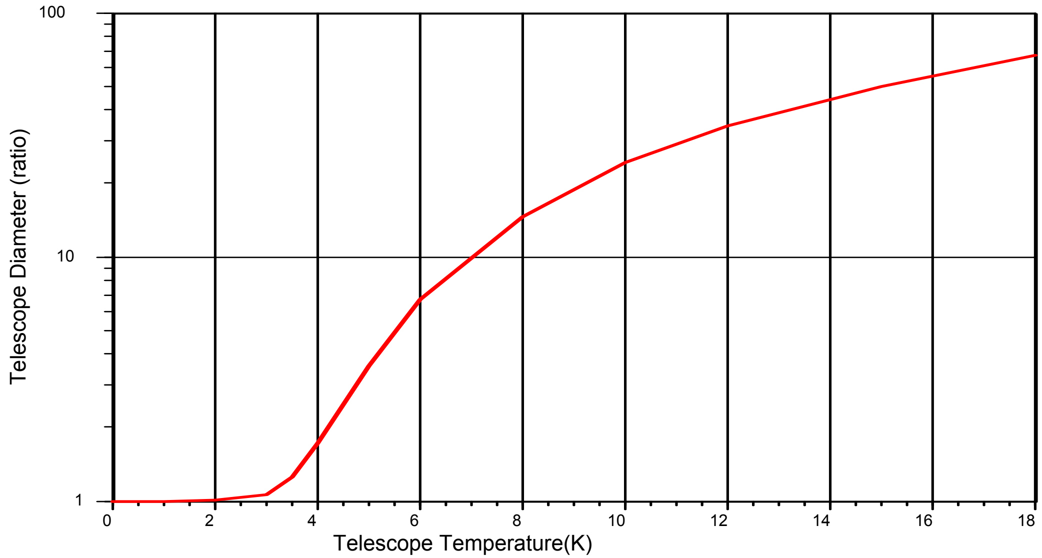
SAFIR – Single Aperture Far IR

SAFIR…will:

- Study important and relatively unexplored region between 30 and 300µm.
- Enable the study of galaxy formation and the earliest stage of star formation by revealing regions too enshrouded by dust to be studied by NGST
- Be more than 100 times as sensitive as SIRTF or Herschel [ESU] missions.

Technical Requirements:

- 10 meter Diameter
- Diffraction Limited at 40 µm
- Transmission Range 10 µm to 1 mm
- 4K Operational Temperature
- Straylight below Zodiacal for all wavelengths



Making telescope a little warmer (noisier) requires making it a lot bigger.

SPICA Mission

Japanese mission

3.5m monolith at 4.5K

Launch in ~2010

Instruments similar to SIRTF

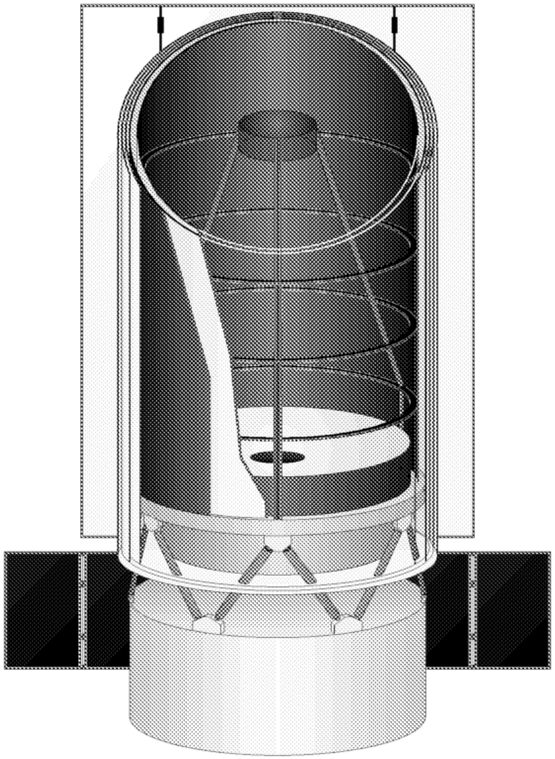


Figure 1. Conceptual design of the SPICA mission with a 3.5 m primary mirror.

Image courtesy of Takao Nakagawa

Mirror Technology Development Roadmap

Leverage an orderly development of achievable technology to maximize science return at a minimum risk.

Cryogenic Optics
- NGST – 6 m, <50K, 2 μm
  - Segmented Mirrors
    - Mechanical Deployment Mechanisms & Strategies
    - Optical Alignment, Figuring & Phasing
  - Lightweight Cryogenic Mirrors
    - Design & Fabrication
    - Cryogenic Performance Characterization
  - Cryogenic Actuators and Mechanisms
- CMBPOL – 2 m, 10K, 0.5 mm
  - Cost & Schedule – Rapid Fabrication, Replication, Etching
  - Cryogenic Material Properties – CTE, Stability, Survival
- SAFIR – 10 m, 4K, 40 μm
  - Cost & Schedule – Rapid Fabrication, Replication, Etching
  - Cryogenic Material Properties – CTE, Stability, Survival

Mirror Technology Development Roadmap

Ambient optics

- NGST Mirror Technology Development Program
  - Lightweight Mirrors
  - Actuators and Mechanisms
  - Figure Control and Performance
- LISA – 0.3 m, 0.5 µm
  - Incredible Thermal Stability
- SNAP – 2 m, 0.5 µm
  - Cost & Schedule – Rapid Fabrication, Replication, Etching
- SUVO – 4 m, 0.5 µm
  - Optical Wavefront – Surface Figure and Roughness, Correctability

Continue Polishing AMSD mirrors to SUVO Specification

Lots of Opportunity for Optics at NASA

Optics is an enabling technology for a variety of NASA Missions:

- Space Science
  - Origins
    - NGST
    - TPF
  - Structure and Evolution of the Universe
    - CON-X
    - LISA
    - SNAP
    - SAFIR
    - SUVO
- Earth Science
- Microgravity Science

While Origins Initiative is well known, SEU Initiative is being defined. Given that both overlap, there may be some merging.