NASA Small Business Innovative Research (SBIR) Subtopic S2.04

"X-Ray Mirror Systems Technology, Coating Technology: X-Ray, Ultraviolet (UV), Optical and Infrared (IR), and Free-Form Optics"

Ron S. Shiri, GSFC, Sub-Topic Manager
Participating Managers from MSFC and JPL

November, 2019

Outline

- Overview of NASA / GSFC Optics Branch Recent Missions

- SBIR Topic: S2. Advanced Telescope Systems
- SBIR Subtopic: S2.04
  - X-Ray Mirror Systems Technology
  - Optical Coatings from X-Ray, Extreme UV (EUV) to Optical and IR
  - Free-Form Optics Design, Manufacturing and Metrology

Goddard Optics Branch, Code 551

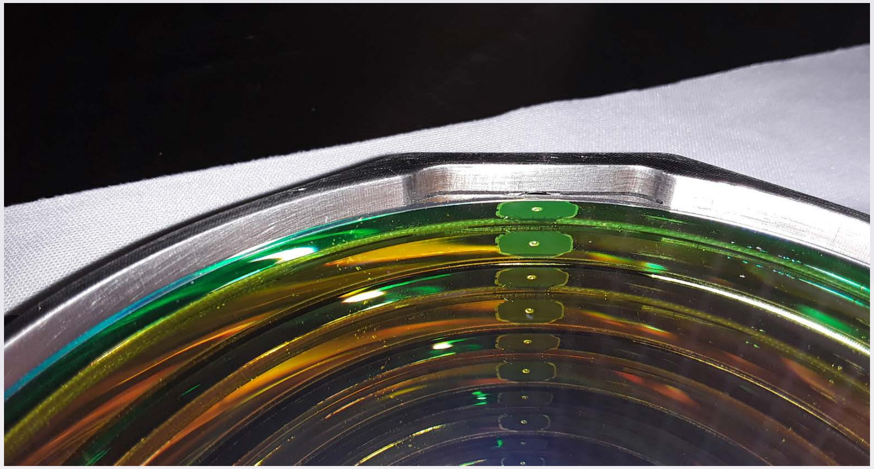
- James Webb Space Telescope Assembly (JWST)
- Wide Field Infrared Space Telescope (WFIRST)
- Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Ocean Color Instrument (OCI)
- Lucy-Ralph
- Origins-Spectral Interpretation-Resource Identification Security--Regolith Explorer (OSIRIS-Rex)
- FUV Coating
  - Faint Intergalactic-medium Redshifted Emission Balloon (Fireball-2)
  - Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet experiment (SISTINE)
  - Cryogenic High Accuracy Refraction Measurement System (CHARMS)
- Black-Silicon Etching
- Free-form Optics

James Web Space Telescope (JWST)

JWST assembled for the first time

Wide Field Infrared Space Telescope (WFIRST) Grism Testing

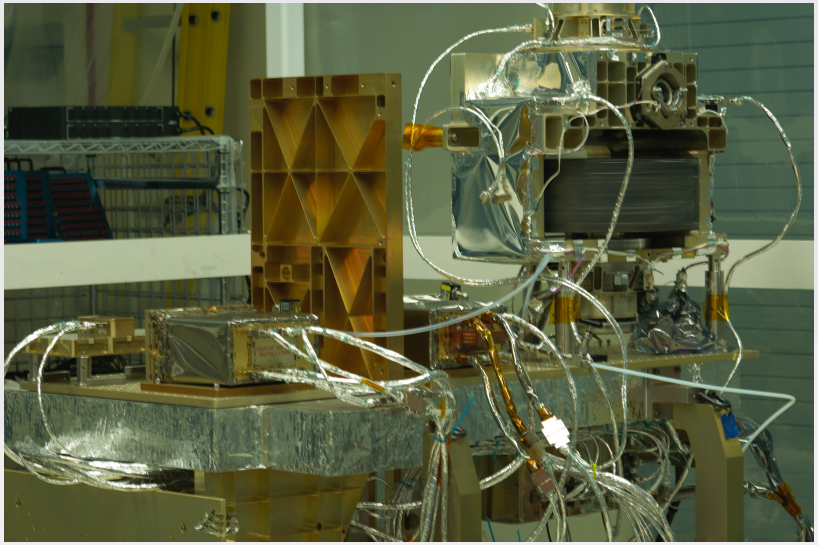
WFIRST Grism Engineering Design Unit on flexure legs while modifying alignment



WFIRST Grism Propagating Reflection

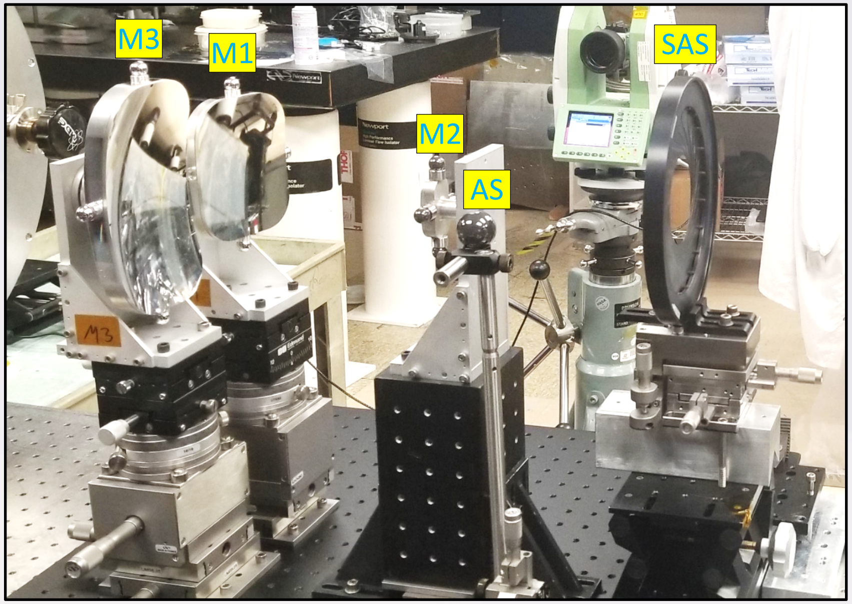
Ocean Color Instrument (OCI)

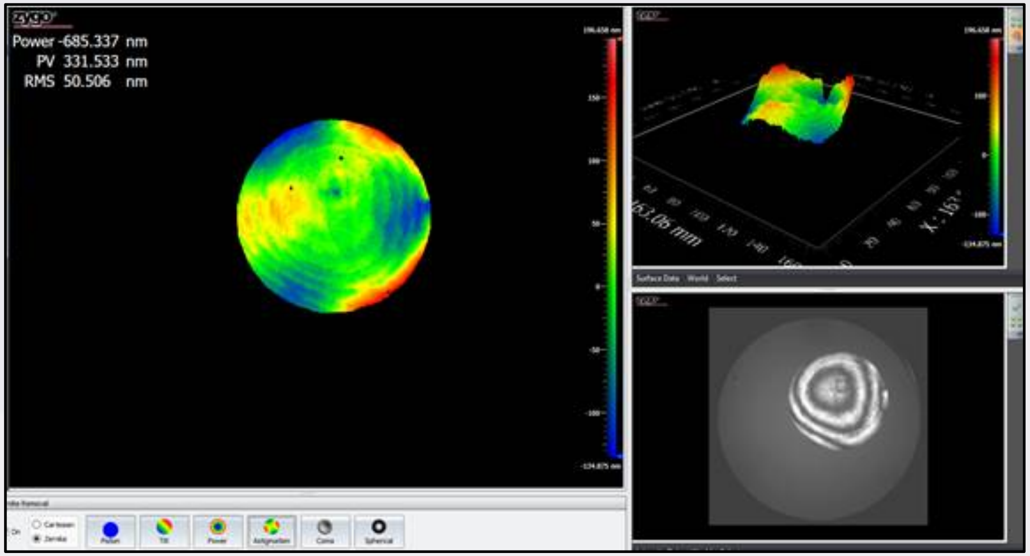
DAU de-integration/removal from the Functional Bench; OCI ETU FlatSat End-to-End Electrical System Test – Electrical Integration



FlatSat Spinning test for OCI at Optical Characterization Lab (OCL)

Lucy-Ralph Three Mirror Anastigmat Alignment



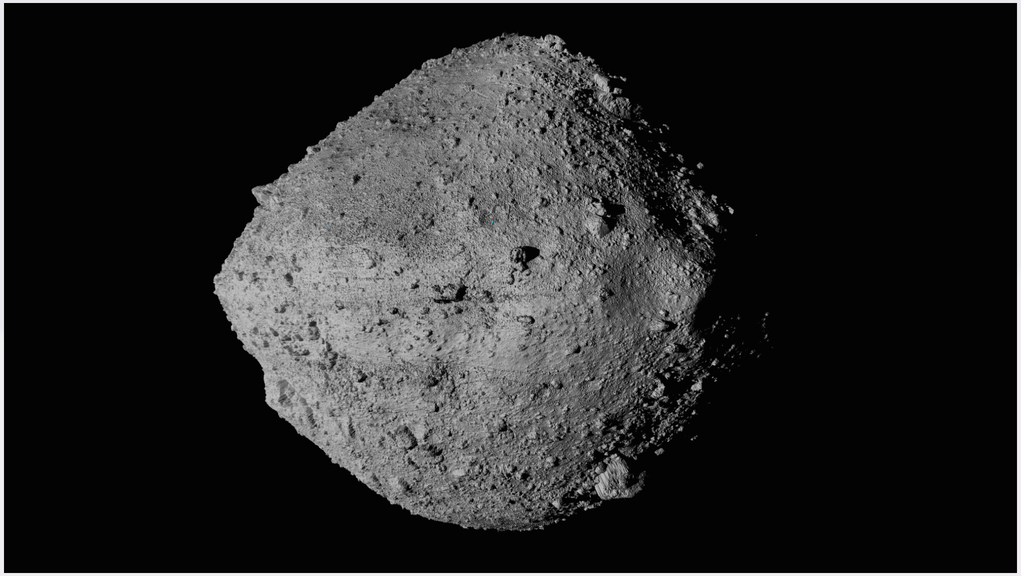


Breadboard with fixed SAS, M2, and AS at front of Zygo Fizeau interferometer. Non-contact Coordinate Measurement Machine (CMM) combined as built prescription and four tooling ball fiducials per mirror.

Single-pass Wavefront of Flight Mirrors Set #1 after 2nd iteration using 6-DoF adjustments of M1 & M3 only. . . mainly Dz, Rx, Ry. Small trefoil from *nominal design residuals*.

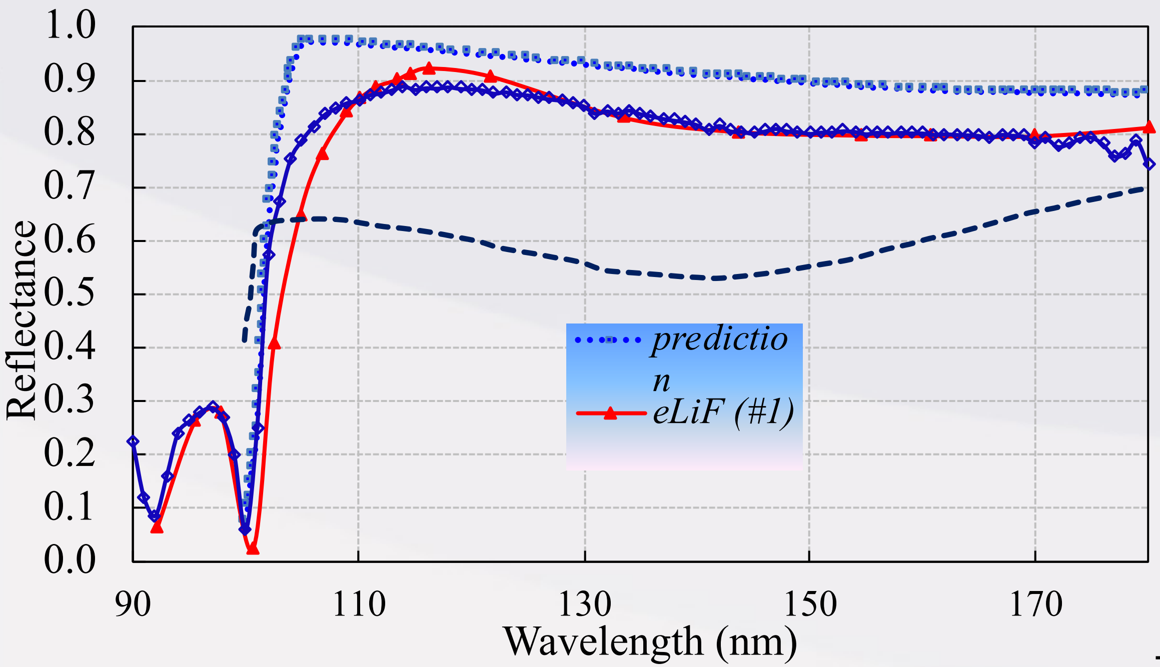
Origins-Spectral Interpretation-Resource Identification Security--Regolith Explorer (OSIRIS-Rex)

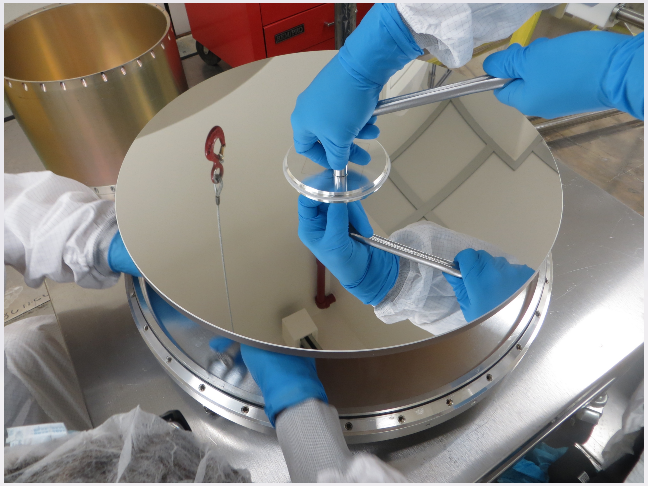
Composite image acquired by NavCam 1 on January 6, 2019 that shows Bennu ejecting particles.



Four landing sites the OSIRIS-Rex is considering sampling next summer

Optimization Al+LiF (eLiF) Hot Coatings

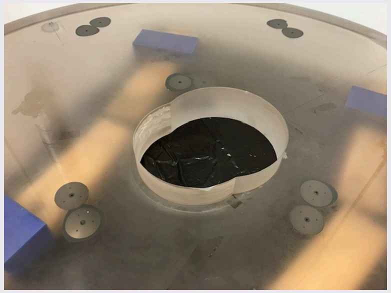


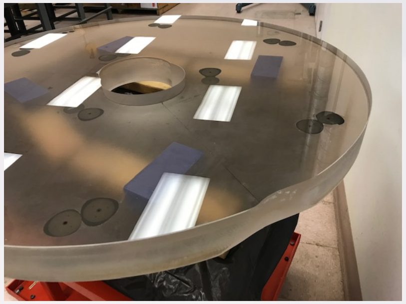


The 2-meter chamber was used to successfully the 0.5-meter Suborbital Imaging Spectrograph for Transition Region Irradiance from Nearby Exoplanet (SISTINE) primary (Sounder Rocket project led by PI Kevin France from U. of Colorado).

The SISTINE primary mirror after coating with Al+LiF in 2-meter chamber at GSFC.

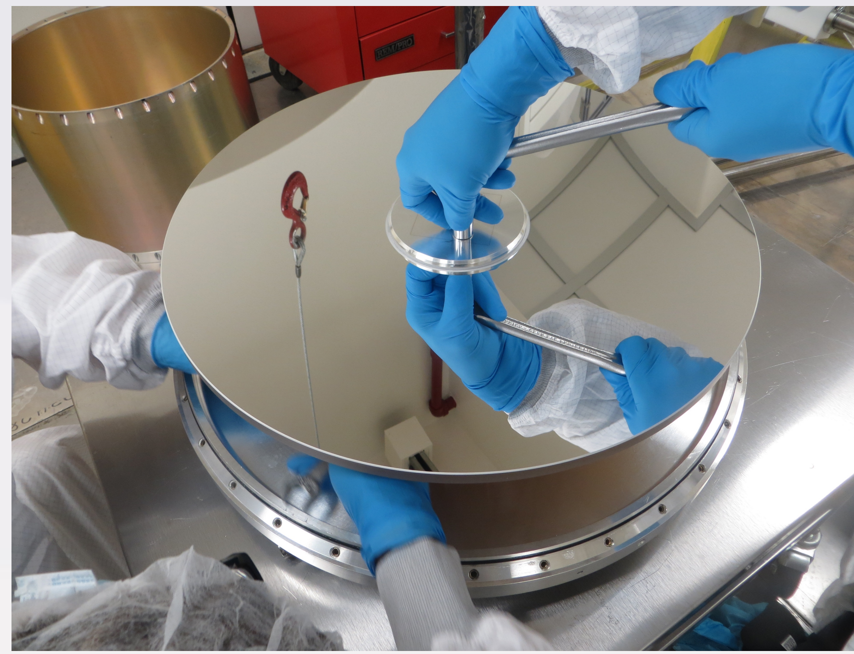
Faint Intergalactic-medium Redshifted Emission Balloon (FIREBALL-2) Primary Mirror Re-coating





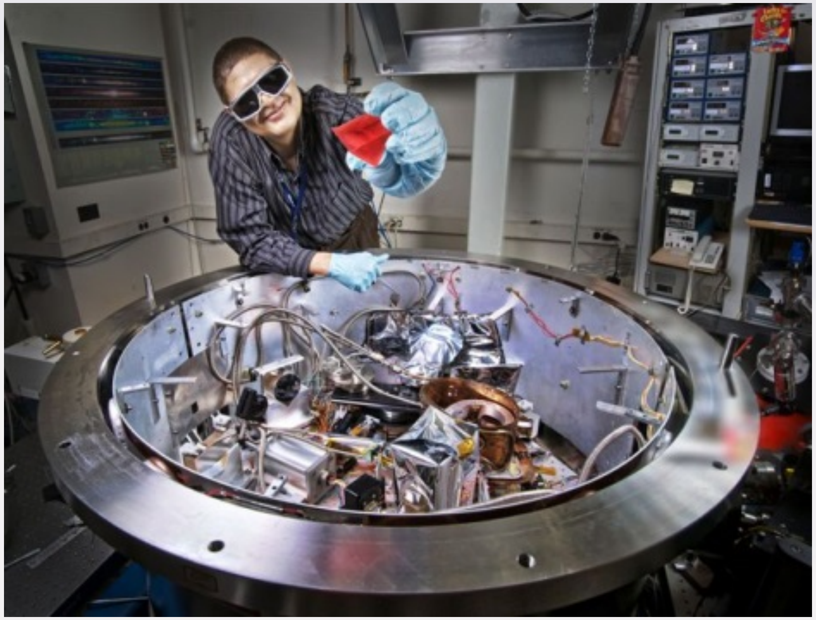
- Balloon-borne 1m telescope coupled to an ultraviolet fiber-fed spectrograph.
- Designed to study the faint and diffuse emission of the intergalactic medium.
- Primary mirror is at GSFC going through re-polishing and re-coating with $Al+MgF_2$ in preparation for launch in 2020.

Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet experiment (SISTINE) Primary Mirror Coating



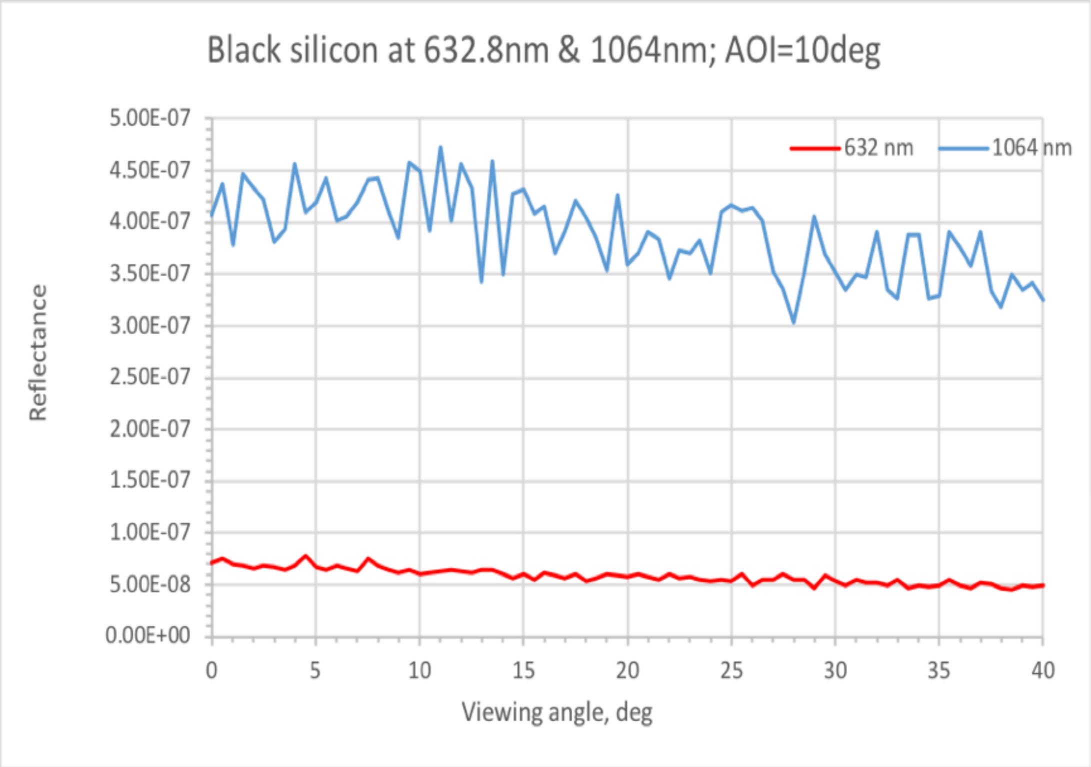
Mirror after application of Al+LiF (eLiF) coating with enhanced performance in the Far Ultra Violet (FUV) spectral range

Cryogenic High Accuracy Refraction Measurement System (CHARMS)



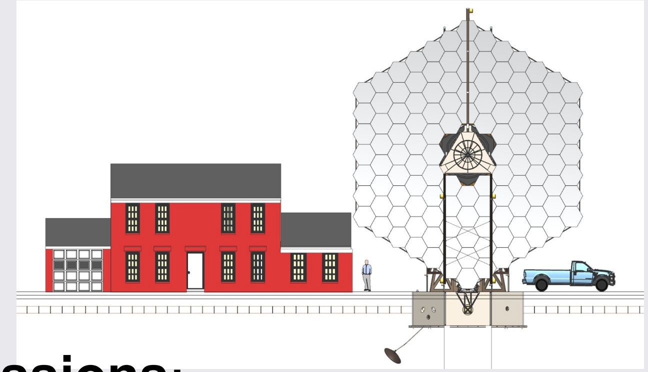
- CHARMS is a unique facility location in the Optics Branch of NASA GSFC that offers unprecedented accuracy in cryogenic refractive index from 0.4 to 6.0 microns
- List of flight projects and external customers (past and present) have been supported:
    - JWST (NIRCam)
    - Transiting Exoplanet Survey Satellite (TESS)
    - WFIRST (Wide Field Instrument)
    - Max Planck Institute (EUCLIDE)
    - Ball Aerospace Corp.
    - Giant Magellan Telescope Office
    - Extra-Large Telescope (ELT)

Black-Silicon Etching



BRDF specular reflectance of Black Silicon at 632 nm and 1064 nm with angle of incident = 10 degrees

Freeform optics



Freeform Optics Enable:

- Faster systems with larger field of view
- Size/volume reduction of instruments
- Improved image quality

Applications in 2020 Decadal Survey missions:

- LUVOIR LUMOS-improved UV image quality, smaller volume, fewer mirrors
- LUVOIR Coronagraph-improved image quality with single mirror off-axis corrector
- LUVOIR HDI-improved image quality UV-VIS, wider FOV, reduced volume
- OST OSS: wider FOV spectroscopy in IR
- OST FIP: improved image quality IR, wider field of few, reduced volume
- OST MISC: wide FOV stable IR spectroscopy
-

Tech Challenge: UV grade freeform mirrors and freeform surface

14

SBIR Subtopic S2.04

- X-Ray Mirror Systems and Components Technology
- Optical Coatings from X-Ray, EUV to Optical and IR
- Free-Form Optics Manufacturing and Metrology

X-Ray Mirror Systems Technology

- Optical Components, systems, and instrument for X-Ray missions
- Light-weight, low-cost, ultra-stable mirrors for large X-Ray observatories
- Stray-light suppression systems (baffles) for large advanced X-Ray observatories
- **Horizon:** 1 to 3 years, mature the technology in advance of decadal 2020 proposal call
- **State of Art:** costly and time consuming to produce X-Ray mirrors. Require improvement to about 0.5-1.0 arc-seconds of angular resolution
- The current stray light suppression is bulky and ineffective for wide-field of view telescopes. We seek significant reduction in both expense and time
- **Importance:** Very-high value, critical need where no feasible competitor and only government is the major player in this technology

Subtopic:	(S2.04, X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics)
Manager:	(Ron Shiri / GSFC, Kunjithapatham Balasubramanian / JPL, Philip Stahl / MSFC, David Broadway/ MSFC)
Center(s):	(GSFC, JPL, MSFC)

Optical Components, Systems, and Stray Light Suppression for X-Ray Missions -Light-weight, low-cost, ultra-stable mirrors for large X-Ray observatory -Epoxies to bond silicon mirrors to absorb IR radiation between 1.5 to 6 microns that traverses silicon with little or no absorption and cured quickly - Stray light suppression systems (baffles) for large advanced X-Ray observatories -Ultra-stable low-cost light-weight X-Ray telescope using grazing-incidence optics for high altitude balloon-borne and rocket-borne mission	**Science Traceability**	The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (LYNX) The NRC NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.
	Need Horizon	1 to 3 years, Need to mature technology in advance of proposal Decadal 2020
	State of Art	It's very costly and time consuming to produce X-Ray mirrors. Most of SOA requiring improvement is 0.5-1.0 arc-seconds angular resolution. SOA stray light suppression is balky and ineffective for wide-field of view telescopes. We seek significant reduction in both expense and time. Reduce the areal cost of telescope by 2X such that the larger collecting area can be produced for the same cost or half the cost.
	Importance	Very high – Critical need, no feasible competitors. X-Ray mirror technology is inherently in government. There is no commercial application.

Coating Technology: X-Ray, Extreme UV to Visible and IR

- Metrics for X-Ray:
  - Multilayer high-reflectance coatings for hard X-Ray mirrors
  - Multilayer depth gradient coatings for 5 to 80 keV with high broadband reflectivity
  - Zero-net stress coating of iridium or other high reflectance elements on thin substrates (< 0.5 mm)
- Metric for EUV:
  - Reflectivity greater than 90% from 6 nm to 200 nm and depositable onto < 2 meter mirror substrate
- Metric for UVOIR:
  - Broadband reflectivity greater than 60% and uniform polarization from 90 nm to 2500 nm and depositable onto 2, 4, and 8 meter mirror substrate
- Non-Stationary Optical Coating:
  - Used in both reflection transmission that vary with location on the optical surface. The variation refers to ratio of reflectivity transmissivity, optical field amplitude , phase, and polarization change.
  - The optical surface range of diameter is 0.5 cm to 6 cm that could either be flat, conic or free-form
- Carbon Nanotube (CNT) & Black-Silicon Coating:
  - Broadband visible to NIR, Total hemispherical reflectivity of 0.01% or less, adhere to the multi-layer dielectric or metal protected coating

Coating Technology: X-Ray, Extreme UV to Visible and IR (Continued)

- **Horizon:** 1 to 3 years, mature the technology in advance of decadal 2020 proposal call
- **State of Art:** costly and time consuming to produce X-Ray mirrors. Require improvement to about 10 arc-seconds of angular resolution
- The current stray light suppression is balky and ineffective for wide-field of view telescopes. We seek significant reduction in both expense and time
- **Importance:** Very-high value, critical need where no feasible competitor and only government is the major player in this technology

Mirror Technology Days 2019

Subtopic:	(S2.04, X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics
Manager:	(Ron Shiri / GSFC, Kunjithapatham Balasubramanian / JPL, Philip Stahl / MSFC, David Broadway/ MSFC)
Center(s):	(GSFC, JPL, MSFC)

Optical Coatings for X-Ray, EUV, LUV, UV, Visible, and IR Telescopes

- Meet low temperature operation requirement

Metrics for X-Ray:

- Multilayer high-reflectance coatings for hard X-Ray mirrors

- Multilayer Depth Gradient Coatings with a reflective spectral response from 1 to 150 KeV or higher

- Near-zero-residual stress single & multilayer thin-film coatings on thin substrates (< 0.5 mm)

Metrics for EUV:

- Meet temperature requirement, 35 Kelvin
- Reflectivity > 90% from 6 nm to 90 nm onto a < 2 meter mirror substrate

Metrics for LUVOIR:

- Meet temperature requirement, 35 Kelvin
- Broadband Reflectivity > 70% from 90nm-120nm (LUV) and > 90% from 120nm-2.5um (VUV/Visible/IR).Reflectivity Non-uniformity < 1% 90nm-2.5um
- Induced polarization aberration < 1% 400nm-2.5um depositable onto a 1-8m substrate

Non-stationary Optical Coatings:

- Used in reflection & transmission that vary with location on the optical surface

Carbon Nanotube (CNT) Coatings:

- Broadband Visible to NIR, Reflectivity of 0.1% or less, adhere to the multi-layer dielectric or protected metal coating

Science Traceability	Astrophysics Decadal specifically calls for optical coating technology investment for: Future UV/Optical and Exoplanet missions (HabEX or LUVOIR) Heliophysics 2009 Roadmap identifies optical coating technology investments for: Origins of Near-Earth Plasma (ONEP); Ion-Neutral Coupling in the Atmosphere (INCA); Dynamic Geospace Coupling (DGC); Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS); Reconnection and Micro-scale (RAM); & Solar-C Nulling polarimetry/coronagraph for exoplanet imaging and characterization, dust and debris disks, extra-galactic studies and relativistic and non-relativistic jet studies
Need Horizon	1 to 3 years Affordable high-performance optical component system technology needs to achieve TRL-4-5 by approximately 2018 to support the 2020 Astrophysics Decadal process. Heliophysics missions need mirror technology sooner. Historically, it takes 10 years to mature mirror technology from TRL-3 to 6. To achieve these objectives requires sustained systematic investment. 1 to 5 years for CNT coating applications.
State of Art	Current X-Ray is defined by NuSTAR and Chandra Current EV is defined by Heliophysics (80% reflectivity from 60 to 200 nm) Current UVOIR is defined by Hubble. MgFl2 over-coated Aluminum on a 2.4 meter mirror. This coating has birefringence concerns and a marginally acceptable reflectivity between 100 and 200 nm.
Importance	Very High – optical technology is mission enabling. The technical capabilities of the optical systems will determine performance and science return.

Free-Form Optics: Design, Manufacturing, Metrology

- Freeform Optical Surfaces
  - 0.5 cm to 6 cm diameter optical surfaces (mirrors) with free form optical prescriptions with surface tolerances about 1-2 nm rms
  - Freeform refers to either 2^{nd} order conic prescription with higher order surface polished onto it or without underlying conic prescription but such that is no steps in the surface.
  - The optics with underlying conic prescription would need to be in F/# range of F/2 or F/20
- Metrology of Freeform Optics
  - Component metrology is difficult because of very large departure from the planar or spherical shapes that can be accommodated by conventional interferometric testing
  - New Methods such as multibeam low-coherence optical probe and slope sensitive optical probe are highly desirable
- **Horizon:** 3 to 5 years
- **State of Art:** Never been done before
- **Importance:** Highly desirable, allows efficient, small package, and lower cost that expands operational temperature range in un-obscured system. It allows coronagraphic nulling without shearing and increases the useful science field-of-view

Subtopic:	(S2.04, X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics
Manager:	(Ron Shiri / GSFC, Kunjithapatham Balasubramanian / JPL, Philip Stahl / MSFC, David Broadway/ MSFC)
Center(s):	(GSFC, JPL, MSFC)

Free-Form Optical Surfaces

-0.5 cm to 6 cm diameter optical surfaces (mirrors) with free form optical prescriptions with surface tolerances are 1-2 nm rms.

-The Optics with large field of view and fast F/#s to provide non-rotationally symmetry. Optical freeform surfaces enabling additional degrees of freedom to reduce volume and eliminate traditional design constraints on the surface.

-Metrology of ‘freeform’ optical components is difficult. New methods such as multibeam low-coherence optical probe and slope sensitive optical probe are highly desirable

-Optics design, fabrication, and metrology for package constrained imaging systems

-Integrated SWIR imaging spectrometer

Science Traceability	NASA missions with alternative low-cost science and small size payload are increasing. However, the traditional interferometric testing as a means of metrology are unsuited to freeform optical surfaces due to changing curvature and lack of symmetry. Metrology techniques for large fields of view and fast F/#s in small size instruments is highly desirable specifically if they could enable cost-effective manufacturing of these surfaces for constrained imaging systems. (CubeSat, SmallSat, NanoSat, various coronagraphic instruments)
Need Horizon	3 to 5 years
State of Art	Early stages of development. Improve optical surfaces with large field of view and fast F/#s. Reduce design and fabrication cost of freeform surfaces.
Importance	High – Highly desirable, allows efficient, small package, and lower cost that expands operational temperature range in un-obscured system. Can allow new coronagraphic instruments that adhere to high-contrast imaging while maintains high throughput.

Conclusion

- GSFC has a robust and productive SBIR program in the Optics, with high quality proposals being submitted every year, leading to advances in key Optics Technologies. Companies with successful SBIR efforts have submitted high quality New Technology Reports (NTRs)
- Focus areas,
  - X-Ray Optical Systems, Mirrors, Coating, and Components
  - Optical Coating from X-Ray to UV + Optical + IR
  - Freeform Optics Design, Development, and Metrology