# Showcasing the PhysCOS/COR Technology Investment Portfolio

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NASA/GSFC

January 8, 2024

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# PhysCOS/COR
# Program Office Technology

**The PhysCOS/COR Program Office Technology is an implementation arm of APD/NASA HQ:**

- **Manages various technology investments:**
  - Oversees SAT, ISFM, SMTP, RTF, and directed projects
  - Accepts and reviews deliverables via eBooks
  - Conducts TRL assessments
- **Focuses on strategic alignment with Astro2020**
- **Solicits and prioritizes strategic technology gaps**
- **Publishes Astrophysics Biennial Technology Report**
- **Publishes portfolio reports via Astrophysics database**
- **Tracks and publishes Astrophysics portfolio metrics including technology infusions and TRL advances**
- **Communicates tech updates via website and conferences**
- **Conducts mission concept studies**
- **Supports the GOMaP TAG**

# Habitable Worlds Observatory

## Technologies, Goals, Portfolio, SotA

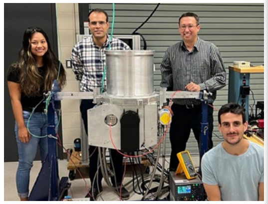
- **Science questions:**
  - Search for Life outside the solar system
  - Transformative Astrophysics
- **Target assumptions:**
  - UV (~0.1 um) to NIR (≲2.4 um)
  - High-contrast imaging/ spectroscopy
  - MOS/IFU/point-source spectroscopy
  - Wide-field Imagers
  - Photometry
- **Targets technology needs via portfolio:**
  - Detectors: low noise, large format, high resolution, high QE
  - Ultra-stable structures
  - High-contrast technologies (ExEP)
  - Microshutters
  - UV gratings
  - Broadband coatings
  - Precision optics: surface quality, thermal control, segment sensing/control, obs disturbance, WFSC modeling

# HWO Detectors

## HgCdTe

### NIR LmAPD: M. Bottom/UH Manoa

- Photon counting
- Megapixel sensor
- 1-2.5 µm (50-70K)



### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| Dark current | 1e-3 e-/pixel/s | 1e-4 e-/pix/s |
| Read Noise | <1 e-/pix/read | 0.3 e-/pix/read (best)<br>0.7 e-/pix/read (typ.) |

## Si MCP

### UV/VIS: O. Siegmund/UCB

- Photon counting
- 50-mm sealed tube
- 20-µm resolution
- 115-400 nm

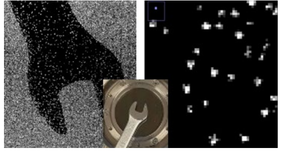
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| Spatial resolution | <25µm FWHM | Better than 20µm |
| Size format | 50mm | 50mm |
| Quantum Efficiency | >25% @ 200nm | 33% @ 200nm |
| Event rate | Multi MHz | >4MHz |
| Stability | >$10^{13}$ events cm$^{-2}$ | >$10^{13}$ events cm$^{-2}$ |

## MCP Readout

### TimePix4 ROIC: J. Vallerga/UCB

- Large-area readout
- 4-side buttable
- GHz rate capability



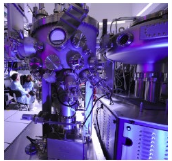
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| Mosaicing | Dicing to 1-2 pixels | Stealth dicing tests good to <15µm accuracy |
| Mosiac Readout | 3X3 Tpx4 mosaic MCP anode | Single Tpx4 anode |
| TSV to BGA outputs | | Demonstrated |

## CCD

### Skipper CCD, EMCCD: S. Nikzad/JPL

- Photon counting
- Large format, UV/O/NIR
- MBE, delta-doped



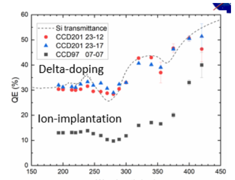
**Skipper CCDs-** Silicon UV detector skipper architecture, delta doping, and detector integrated filters

**EMCCDs**- Combine 2D doping and detector-integrated metal-dielectric filter (DIMDF) coatings for tailored UV applications and out-of-band rejection.

## CMOS

### CMOS imager: M. Hoenk/JPL

- Delta doped
- Multi-gigapixel mosaic focal plane



Delta-doping vs. ion-implantation

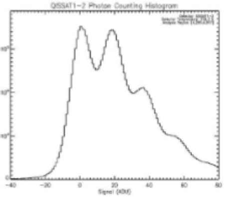
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| Broadband NUV-NIR QE | >50% absolute QE | Si-SiO$_2$ traps cause loss of signal in ion-implanted devices |
| Visible-blind UV detection | In-band QE > 40% with 3-4 orders of magnitude out-of-band rejection | JPL-unique capability with integrated metal-dielectric filters |
| Stability for precision photometry | QE stability better than 1% in radiation environment | Si-SiO$_2$ traps cause instabilities in ion-implanted devices |

## CMOS

### CMOS imager: D. Figer/RIT

- Photon counting
- On-die photon-to-digital conversion
- 300-1000 nm



### Key Performance Param

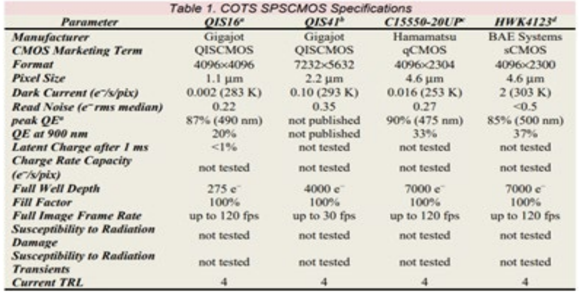


Table 1. COTS SPSCMOS Specifications

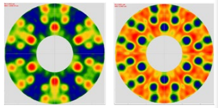
| Parameter | QIS16ᵃ | QIS41ᵇ | C15550-20UPᶜ | HWK4123ᵈ |
|---|---|---|---|---|
| Manufacturer | Gigajot | Gigajot | Hamamatsu | BAE Systems |
| CMOS Marketing Term | QISCMOS | QISCMOS | qCMOS | sCMOS |
| Format | 4096×4096 | 7232×5632 | 4096×2304 | 4096×2300 |
| Pixel Size | 1.1 µm | 2.2 µm | 4.6 µm | 4.6 µm |
| Dark Current ($e^-$/s/pix) | 0.002 (283 K) | 0.10 (293 K) | 0.016 (253 K) | 2 (303 K) |
| Read Noise ($e^-$ rms median) | 0.22 | 0.35 | 0.27 | <0.5 |
| peak QEᵉ | 87% (490 nm) | not published | 90% (475 nm) | 85% (500 nm) |
| QE at 900 nm | 20% | not published | 33% | 37% |
| Latent Charge after 1 ms | <1% | not tested | not tested | not tested |
| Charge Rate Capacity ($e^-$/s/pix) | not tested | not tested | not tested | not tested |
| Full Well Depth | 275 $e^-$ | 4000 $e^-$ | 7000 $e^-$ | 7000 $e^-$ |
| Fill Factor | 100% | 100% | 100% | 100% |
| Full Image Frame Rate | up to 120 fps | up to 30 fps | up to 120 fps | up to 120 fps |
| Susceptibility to Radiation Damage | not tested | not tested | not tested | not tested |
| Susceptibility to Radiation Transients | not tested | not tested | not tested | not tested |
| Current TRL | 4 | 4 | 4 | 4 |

# HWO Optics

## High angular resolution

### UVOIR mirrors: H.P. Stahl/MSFC

- Mirrors w/CTE knowledge for cryo-test & model corr.
- Mirrors w/larger G-sag
- Mirrors to test tailored stiffness designs



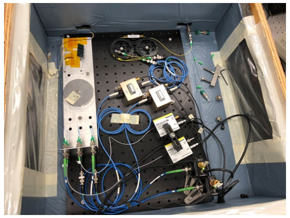
**Key Performance Parameters:**

| For Glass Mirrors | Goal | Current |
|---|---|---|
| Predictable Thermal Stability | 1 pm per mK | 2.5 pm per mK |
| Thermal Control | 2 mK | 2 mK |
| G-Sag Knowledge Uncertainty | 1000 µm rms<br>< 5 nm rms | HSC : 7.6 µm PV to 1.4 nm rms<br>Kepler: 0.17 µm rms to 20 nm rms<br>DOT: 0.60 µm PV to 3 nm rms |
| G-Sag x dia/mass [nm-m/kg] | TBD | Hubble (400 Hz): 22 pv;<br>DOT (80 Hz): 87 pv<br>Kepler: 3 rms |
| G-Sag Correctability % | TBD | TBD |

## High angular resolution

### TechMAST: A. Nordt/Lockheed Martin

- Ultra-stable space telescopes via DFP
- pm-level metrology
- Improved space telesc. dyn. perf. predictions
- Improved mfr techniques for large mirror segments



## High angular resolution

### ULTRA-TM: L. Coyle/Ball Aerospace

- pm-capable independ. metrology/stable env.
  - Edge sensors, actuators
  - Structural dampening
  - Thermal sensing & control

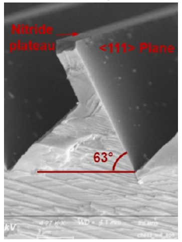
**Key Performance Parameters:**

| | Technical Target | Current Performance |
|---|---|---|
| Mirror segment sensing/control (piston) stability budget | 3.8 pm (0.01-1 Hz)<br>2.3 pm (1-10* Hz) | 3.6 pm (0.01-1 Hz)<br>10 pm (0.01-2.1 Hz)<br>52 pm (0.01-10 Hz) |
| Mirror surface fig. distortion | <1 pm RMS SFE/mK | <0.2 pm RMS SFE/mK |

## UV Gratings

### Reflection gratings: R. McEntaffer/PSU

- e-beam lithography stitching over large curved substrates
- Low blaze angles



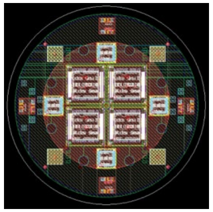
**Key Performan**

| | Technical Target | Current Performance |
|---|---|---|
| Low blaze angle | <1° | 4° |
| High echelle efficiency | >80% | ~70% |
| Aberration control with ebeam | SISTINE & FORTIS requirements | Beasley et al. 2019 |

## Microshutters

### Microshutter MOS: P. Scowen/GSFC

- Electrostatically actuated
- High reliability
- High contrast including in UV



**Key Performance Parameters:**

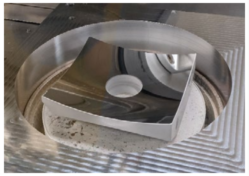
| | Technical Target | Current Performance |
|---|---|---|
| Contrast | $>10^5$ | $10^4$ |
| Radiation rqmt | Survive TID per L2 behind 2.5 mm Al | Not proven |
| Lifetime | >10,000 cycles | Not proven |
| Vibration & shock | Survive GEVS levels | Not proven |

# Other HWO Technologies

## Broadband coatings

### ALD UV coatings: J. Hennessy/JPL

- Determine best way to combine ALD with PVD Al (shared vac. vs. ALE).



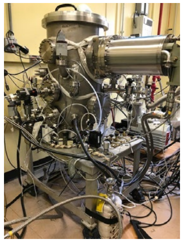
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| Absolute reflectance (LUVOIR) | > 50% R (100–115 nm)<br>> 80% R (115-200 nm)<br>> 88% R (200-850 nm)<br>> 96% R (> 850 nm) | Meets LUVOIR targets, see Hinton et al., Proc. SPIE 11821, 118211B (2021) |
| Reflectance uniformity | HWO coronagraphs may require < 0.1% intra-segment uniformity | Our ALD coatings (Al/$MgF_2$) achieve ~0.05% (1σ) uniformity at 450 nm over 150 mm dia. |

## Broadband coatings

### PVD UV coatings: M. Quijada/GSFC

- Demonstrate rPVD process at m-scale
- Retrofit 2-m GSFC chamber



### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| Avg R (100-200 nm) | > 80% | ~ 81% |
| Avg R (120-3000 nm) | > 90% | ~ 93% |
| Uniformity R (100-200 nm over 6”) | < 1 % | < 1% |
| Uniformity R (300-2500 nm over 6”) | < 0.1 % | < 0.2% |

## Ultra-stable structures

### Ultra-stable structures: B. Saif/GSFC

- Separate test-article response from env. factors
- Manage large data vol. for persistent long-term data collection
- Develop algorithm for processing large data vol. w/o sacrificing uncertainty goals.
- Define relevant stability metrics
- Improve data mgmt for persistence over > 10 min.
- Improve env. influence mitigation

### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| Static measurement uncertainty | <10 pm uncertainty in <10 seconds of data collection in static measurement | <100 pm uncertainty in < 1 hr of data collection in a static measurement |
| Drift measurement over 10 minutes | Continuous data for 1 hr at >1000 Hz sampling rate | Continuous data for >10 minutes at 830 Hz |

# Decadal X-ray Flagship & Probes

## X-Ray-Related Technologies

- **Science questions:**
  - Compact Objects
  - Cosmology
- **Target assumptions:**
  - X-ray (~0.01 – 10 nm)
  - Imaging/spectroscopy/ polarimetry

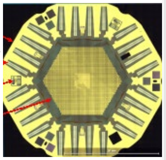
- **Targets technology needs via portfolio:**
  - Detectors: low noise, large format
  - Multiplexing readout schemes
  - Lightweight X-ray optics
  - X-ray optical coatings
  - CAT gratings
  - Sub-Kelvin cooling

# X-ray Detectors

## Advanced µ-calorimeters

### TES µ-calorimeters: S. Smith/GSFC

- Demonstrate full-scale Probe array w/hydras meeting req's.
- Demonstrate 100k array w/ hybridized µwave-muxed r/o



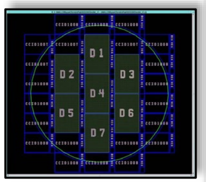
**Key Performance Parameters:**

| | Technical Target | Current Performance |
|---|---|---|
| LEM: energy resolution (single pixels/hydras) | 1.3 eV / 2.5 eV | 1.2 eV / 2.3 eV |
| LEM: array size | 30 arc minutes | 33 arc minutes |
| LEM: hydra position sensitivity | 200 eV – 2keV | 200 eV – 2 keV |
| Lynx: array size | 100k pixels | 50k pixels |

## CCD

### X-ray CCDs: M. Bautz/MIT

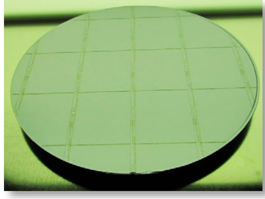
- Large Area
- High Speed
- Excellent Soft Response



**Key Performance Parameters:**

| | Technical Target | Current Performance |
|---|---|---|
| Read Noise | Goal ~1 $e^-$ RMS @ 2 MHz | ~2$e^-$ RMS at 2 MHz |
| Frame Rate | ≥ 5 frames s-1,<br>Goal 20 frames s-1 | 6 frame $s^{-1}$ , 2 Mpix $fr^{-1}$ |

## CCD



### CCD: C. Leitz/MIT-LL

- Sub-keV spectral
- Large Format
- BI Si CCD, MBE passivated
- Uniformity Process controls

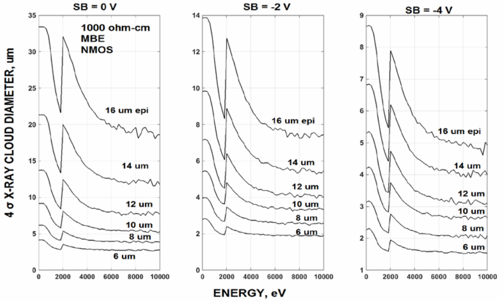
**Key Performance Parameters:**

| | Technical Target | Current Performance |
|---|---|---|
| Spectral Performance | Demonstrate MBE close to Fano Limit | TBD |
| Read Noise | ≤ 3 e- RMS @ 2-4 MPixel s-1 | TBD |
| Radiation | Characterize radiation tolerance | TBD |

## CMOS

### CMOS monolith: A. Kenter/SAO

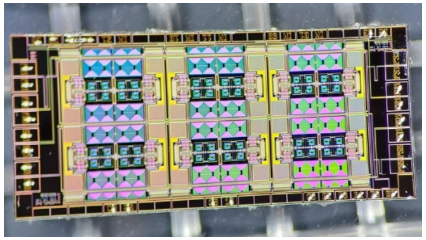
- BI, thicker CMOS using MBE
- Implement external Substrate Bias Voltage to improve QE, spectral response



## SQUID readouts

### SQUID readout: D. Bennett/NIST

- Bump-bond SQUID µmux to large X-ray µ-calorimeter arrays
- Achieve TRL 6 for Probe focal plane concept



# X-ray Optics

## Segmented X-ray Optics

### Thin next-gen X-ray optics: W. Zhang/GSFC

- < 0.5" HPD angular resolution
- Mass, cost at least 10× lower than Chandra per unit effective area

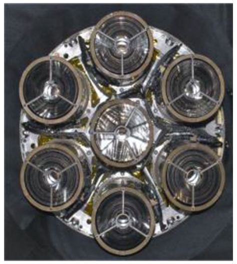
**Key Performance Parameters:**

| | Technical Target | Current Performance |
|---|---|---|
| Mirror segments | <0.3" | <0.6" |
| Coating distortion | <0.1" | <1.0" |
| Bonding distortion | <0.2" | <1.5" |

## Full-Shell X-ray Optics

### Replicated X-ray optics: J. Gaskin/MSFC

- Sub-arcsec replicated full-shell optics
- Thin shells



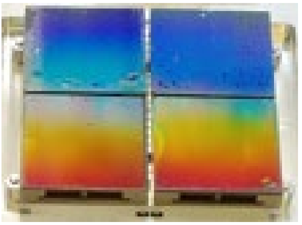
**Key Performance Parameters:**

| | Technical Target | Current Performance |
|---|---|---|
| Ang. Res. – *single full-shell* replicated optic | < 1 arcsec HPD | 4.5 arcsec HPD |
| Ang. res. – optics *module* | < 1 arcsec HPD | 5-6 arcsec HPD |

## X-Ray Gratings

### CAT gratings: M. Schattenburg/MIT

- 200-nm-pitch, ultra-high aspect-ratio freestanding grating bars w/nm-smooth sidewalls



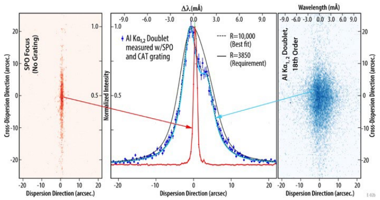
**Key Performance Parameters:**

| | Technical Target (Lynx) | Current Performance |
|---|---|---|
| grating depth | > 5.7 um | > 6 um |
| grating bar duty cycle | ≤ 0.2 | 0.25 |
| geometric transmission | > 0.79 | ≈ 0.5 |
| Diffraction eff. (2.5 nm) | 0.43 | 0.34 |
| Period variation | < 2e-4 | ≈ 1 e-4 |

## X-ray Grating Manufacturing

### CAT X-ray grating mfr.: R. Smith/CfA

- Methods to process Si wafers into CAT gratings suitable for large-scale manufacturing



**Key Performance Parameters:**

| | Technical Target (Arcus) | Current Performance |
|---|---|---|
| grating depth | 4 um | > 6 um |
| grating bar duty cycle | 0.25 | 0.25 |
| geometric transmission | > 0.5 | ≈ 0.5 |
| Diffr. Eff. (2.5 nm) | 0.3 | 0.34 |
| Period variation | < 2e-4 | ≈ 1 e-4 |

# Decadal Far-IR Flagship & Probes

## Far-IR-Related Technologies

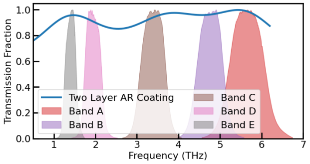
- **Science questions:**
  - ISM and Star/Planet formation
  - Galaxies
- **Target assumptions:**
  - Mid-IR (≥2.4 μm) to Far-IR (≲500 μm)
  - Imaging/spectroscopy
  - Wide-field imagers
  - IFU/MOS/point-source spectroscopy
- **Targets technology needs via portfolio:**
  - Detectors: low noise, high frame rate
  - Multiplexing readout schemes
  - Sub-Kelvin cooling

# Far-IR Technologies

## Low Noise Detector

### MKIDs: J. Austermann/NIST

- Broad 1-6 THz
- TiN Film SOI chip
- RFSoC muxing



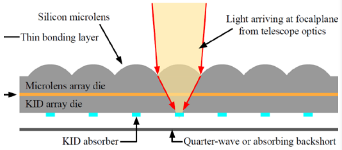
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| Measured target detector NEP | 1e-19W/rt(Hz) | 1e-18 W/rt(Hz) |
| Broadband efficiency | 90% | TBD |
| RfSoC Multiplexing | 1024X | TBD |

## Low Noise Detector

### KIDs: Hailey-Dunsheath/Caltech

- 25-250 µm
- Pixel sensitivity
- Large format



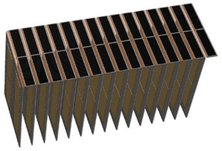
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| NEP at 25um and 215um | 1e-19W/rt(Hz) for 1008 pixels | 1e-19W/rt(Hz) single pixel |
| Microlens optical coupling | Demonstrate at 25um and 215um | Demonstrated at 25um (etched) and 215um (laser ablated) |
| Absorbing film to reduce cosmic ray effects | Cosmic ray deadtime < 10% | TBD |

## Low Noise Detectors

### TES: J. Staguhn/JHU

- Large, tileable arrays
- Compact package
- SQUID readout



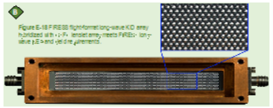
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| R=10 Background Limited FIR Detectors | 4e-19W/rt(Hz) | Better than 1e-18 W/rt(Hz) |
| Pixel Filling factor | 80% | 80% |
| Superconducting Flex Lines | TRL = 5 | TRL = 3 |
| 2-level Multiplexing | TRL = 5 | TRL = 3 |

## Low Noise Detector

### KIDs: C. Bradford/JPL

- 25µm, 200 µm
- Large format
- Optical efficiency



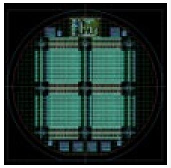
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| NEP at 25um and 2ooum | 1e-19W/rt(Hz) for 1008 pixels | At 200 um 73% yield with NEP below 1e-19 W/sqrt(Hz) |
| Optical Efficiency | 0.65% | TBD |

## Detector Readouts

### TDM Readout: K. Rostem/GSFC

- Read out kilopixel TES arrays
- Reduce # of wires
- SQUID 2-level addressing



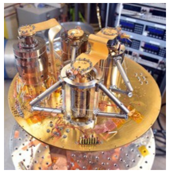
### Key Performance Parameters:

| | Technical Target | Current Performance |
|---|---|---|
| SQUID 2-level TDM | 16 wires | 64 wires |
| TES array with SQUID 2-level TDM | Demonstrate kilopixel TES array with SQUID 2-level TDM | Kilopixel TES single-switch SQUID multiplexer arrays |

## Advanced Coolers

### CADR: A. Jahromi/GSFC

- Continuous cooling
- Sub-Kelvin cooling
- No moving parts, reliable, jitter-free



### Key Performance Parameters:

| Performance Metric | Reqs | Current SOtA of TRL 6+ Coolers | 2017 SAT CADR$^{*}$ | 2021 SAT CADR |
|---|---|---|---|---|
| Cold Stage Operating Temp. (mK) | ≤ 50 | 50 | 50 | 35 |
| Cold Stage Temp. stability (µK) rms | 2 | 1 | TBD more tests | 1 |
| Cold Stage Cooling power @ 50 mK (µW) | 6 | 0.5 | 5.0 | 10$^{+}$ |
| Heat Sink Temperature (K) | 4.5 | 4.5 | 4.0 | 4.5 |

HWO-related technology

# BACK-UP CHARTS

# A22ISFM-0006: UV/Optical to Far-Infrared (UVOIR) Mirror System & Telescope Technology

PI: H. Philip Stahl / MSFC

## Objectives and Significance:

Mature Tier-1 2022 Technology Gaps to enable Habitable Worlds Observatory Mission:

- Coronagraph Stability
  - Ultra-stable Telescope
  - Integrated Model Telescope/Coronagraph System
  - Thermal Sensing and Control
- Mirror Technologies for High Angular Resolution
  - Mirror Substrate and Structure
  - Gravity Sag Off-Loader
  - Coefficient of Thermal Expansion Characterization

## Key Challenges/Tall Poles:

- Need 1.5-m mirrors with better CTE knowledge for Cryo-Testing and Model Correlation
- Need 1.5-m mirrors with larger G-Sag
- Make mirrors to test Tailored Stiffness Designs

## Accomplishments:

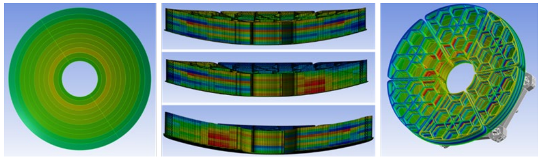
✓Create/Correlate AMTD 'as-built' CTE model

✓Characterize absolute G-sag to < 5 nm rms

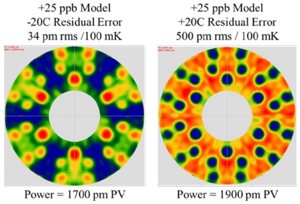
✓Design Tailored Stiffness Mirror for Balloon

## Key Collaborators (MSFC):

Chris Hopkins, Tomasz Lis, Jagan Ranganathan, Stephen Cheney, Ron Eng, William Arnold



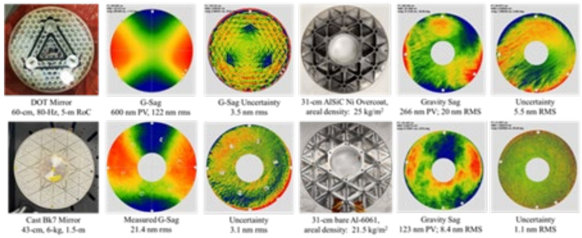
AMTD 'as-built' CTE Model



+25 ppb Model<br>-20C Residual Error<br>34 pm rms /100 mK — Power = 1700 pm PV

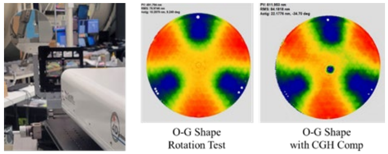
+25 ppb Model<br>+20C Residual Error<br>500 pm rms / 100 mK — Power = 1900 pm PV

Absolutely Measured G-Sag (100 to 600 nm PV) with uncertainty < 5 nm rms



DOT Mirror 60-cm, 80-Hz, 5-m RoC; G-Sag 600 nm PV, 122 nm rms; G-Sag Uncertainty 3.5 nm rms; 31-cm AlSiC Ni Overcoat, areal density: 25 kg/m²; Gravity Sag 266 nm PV; 20 nm RMS; Uncertainty 5.5 nm RMS

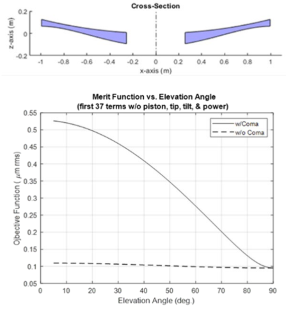
Cast Bk7 Mirror 43-cm, 6-kg, 1.5-m; Measured G-Sag 21.4 nm rms; Uncertainty 3.1 nm rms; 31-cm bare Al-6061, areal density: 21.5 kg/m²; Gravity Sag 123 nm PV; 8.4 nm RMS; Uncertainty 1.1 nm RMS



O-G Shape Rotation Test

O-G Shape with CGH Comp

CGH G-Sag Compensation



Mirror with 'only' Coma vs Elevation Angle

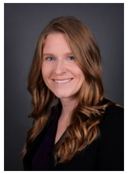
## Key Performance Parameters and Technical Targets:

| For Glass Mirrors | Goal | Current |
|---|---|---|
| Predictable Thermal Stability | 1 pm per mK | 2.5 pm per mK |
| Thermal Control | 2 mK | 2 mK |
| G-Sag Knowledge Uncertainty | 1000 μm rms<br>< 5 nm rms | Hubble : 7.6 μm PV to 1.4 nm rms<br>Kepler: 0.17 μm rms to 20 nm rms<br>DOT: 0.60 μm PV to 3 nm rms |
| G-Sag x dia/mass [nm-m/kg] | TBD | Hubble (400 Hz): 22 pv;<br>DOT (80 Hz): 87 pv<br>Kepler: 3 rms |
| G-Sag Correctability [correctable/total] | TBD | TBD |

**For TRL-5 need $20M+ for 5 yrs.**

# Ultra-Stable Large Telescope Research and Analysis – Technology Maturation (ULTRA-TM)

PI: Laura Coyle/Ball Aerospace & Technologies Corp.



## *Objectives and Significance of Work :*

- Mature the TRL of key components for ultra-stable architectures like the Habitable Worlds Observatory, with a focus on enabling and Low-Mid TRL technology gaps
- Refine spatial/temporal stability requirements set by the coronagraph, which drives the ultra-stability need, and flow down to subsystem/component performance allocations
- Demonstrate component performance in picometer regime and/or with path-to-flight properties.

## *Key Challenges/Remaining Tall Poles:*

- Picometer-capable independent metrology / stable environments can limit performance (our team has implemented various mitigations)

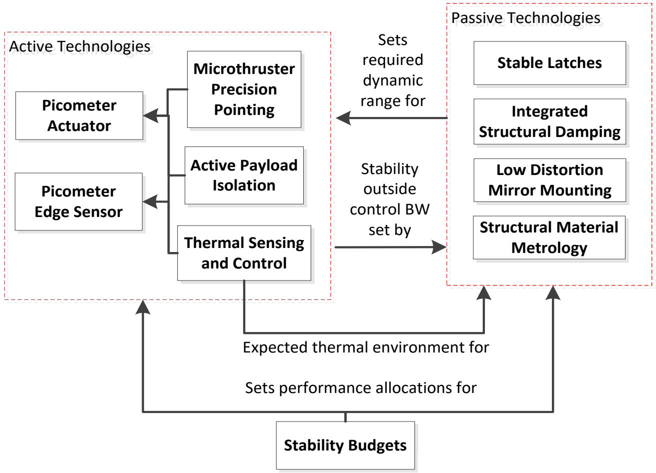
## *Summarize Top Accomplishments:*

- ✓ Advanced 10 technologies by 1 TRL step (primarily from 2→3 or 3→4)
- ✓ Demonstrated closed loop gap stability of a capacitive sensor and 3 ultra-fine actuators
- ✓ Demonstrated mirror mount with reduced surface figure distortion in sub-scale hardware with mapping to flight-like segments
- ✓ Demonstrated increased damping of treated composite to significantly reduce structural dynamic loads

## *Key collaborating institutions/companies:*

- Northrop Grumman, L3 Harris, Space Telescope Science Institute, Smithsonian Astrophysical Observatory, KBR Wyle, Kratos Defense

*The ten technology areas being advanced in ULTRA-TM address gaps identified in the ULTRA study and span the ultra-stable architecture, including passive and active components.*



## *Key Performance Parameters and Technical Targets:*

| | Technical Target | Current Performance |
|---|---|---|
| Mirror Segment Sensing and Control (Piston) | Stability Budget Allocations:<br>3.8 pm (0.01-1 Hz)<br>2.3 pm (1-10* Hz) | 3.6 pm (0.01-1 Hz)<br>10 pm (0.01-2.1 Hz)<br>52 pm (0.01-10 Hz) |
| Mirror Surface Figure Distortion | <1 pm RMS SFE/mK | <0.2 pm RMS SFE/mK |

*Upper frequency value needs additional study

- Estimate of many years (at current-level funding) are needed to reach TRL 5: 5 years for all components (driven by funding profile), additional years for subsystem/system TRL advancement

# TechMAST: Technology Maturation for Astrophysics Space Telescopes

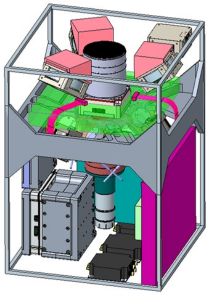
PI: Alison Nordt/Lockheed Martin

## *Objectives and Significance of Work :*

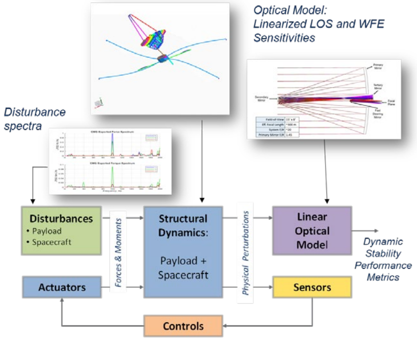
- Enable large and small ultra-stable space telescopes using disturbance free payload technology (DFP)
- Develop compact picometer-level metrology tools for space
- Improve dynamic performance predictions of large space telescopes, integrating optics, structural dynamics and controls
- Improve manufacturing techniques to rapidly produce large telescope mirror segments

## *Summarize Top Accomplishments:*

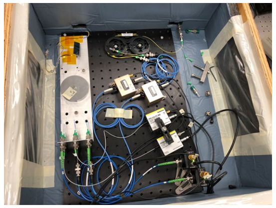
- Developed a payload for a CubeSat to demonstrate DFP in a flight environment in six degrees of freedom over large angles of payload slew, and measure transmissibility
    - Completed CDR, built and tested electronics
- Advanced space qualified, picometer-level metrology with two separate methods: Heterodyne metrology using Photonic Integrated Circuits (PIC) and Tracking Frequency Gauge (TFG) metrology
    - Improved accuracy performance of Heterodyne PIC metrology by addressing noise sources
    - Developed and tested electronics with a path to flight for TFG metrology
- Performed integrated modeling and analysis to predict performance of large telescope architectures under several conditions of disturbance and noise sources
- Developed ultra-smooth finishing process for a light-weighted Capture Range Replicated (CRR) mirror



DFP CubeSat Payload



Integrated Modeling



Metrology Test Bench

## *Key collaborating institutions/companies:*

- Lockheed Martin, University of Florida, Illinois Institute of Technology, Endless Frontiers Associates, L3Harris

## *Key Challenges/Remaining Tall Poles:*

- Integrated Modeling with latest optical architecture
- Minimize impact of cables across DFP interface

## *Key Performance Parameters and Technical Targets:*

| | Technical Target | Current Performance |
|---|---|---|
| DFP | TRL4 | TRL4 |
| PIC Metrology | TRL4 | TRL4 |

- At current funding, would reach TRL5 in 2-3 years

# 21-SAT21-0017: Ultra-stable Structures Test Bed

PI: Babak Saif / GSFC, Code 551

Ultra-stable lab set up with new stable composite bench and environmental enclosure.

## *Objectives and Significance of Work :*

- Develop picometer-level surface metrology of mirrors and structures.
- Develop structures and mirrors with controlled dynamics at picometer levels.
- Acquire static and drifting measurements with unit pm measurement uncertainty in as short a time as possible, and without over-drive testing.
- Application to broad spectrum of test articles, test conditions, and test objectives seeking to understand physical responses and achieved stability to pm scale disturbances.
- Stability and dynamics of large structures and mirrors are required for large space missions such as Habitable Worlds Observatory (HWO) and Exoplanet missions.
- Facilitate design and model validation through testing of HWO critical subsystem demonstrations.

## *Key Challenges/Remaining Tall Poles:*

- Separating article-in-test response from environmental factors affecting the measurements.
- Managing large volume of data to allow persistent data collection over longer periods of time.
- Algorithm development for processing large volume of data without sacrificing uncertainty goals.
- Defining relevant metrics for definition of stability.
- Further improvement on data management to achieve persistent data over times longer than 10 minutes.
- Continuing improvement on mitigating environmental influences.

# 21-SAT21-0017:
# Ultra-stable Structures Test Bed

PI: Babak Saif / GSFC, Code 551

## Major Findings:

- Interferometer measurement standard uncertainty can be less than ±6 pm persistent in time.
- Faster sampling rates may interchange with longer sampling periods for improved measurements.

## Key Performance Parameters and Technical Targets:

| | Technical Target | Current Performance |
|---|---|---|
| Static measurement uncertainty | <10 pm uncertainty in <10 seconds of data collection in static measurement | <100 pm uncertainty in < 1 hr of data collection in a static measurement |
| Drift measurement over 10 minutes | Continuous data for 1 hr at >1000 Hz sampling rate | Continuous data for >10 minutes at 830 Hz |

## Key collaborating institutions/companies:

- Lee Feinberg, Ritva Keski-kuha, Thomas Zielinski, Breann Sitarski : GSFC
- Peter Petrone (Sigma Space)
- Marcel Bluth (KBR)
- Perry Greenfield (STSCI)
- Sang Park (SAO)

## Future funding:

- 2 to 4 years of additional funding is needed to advance the test system to enable other subsystems or components to achieve TRL 5/6 validation.

# 17-SAT17-0017: E-Beam Generated Plasma Etching for Developing High-Reflectance Mirrors for Far-Ultraviolet Astronomical Instrument Applications

Manuel A. Quijada

## *Objectives and Significance of Work:*

- Development of the Large Area Plasma Processing System (LAPPS) at NRL for treatment of aluminum-based mirror coatings with high reflectance over a broad spectral range and particularly in the far-ultraviolet (FUV) spectral region.
- A successful oxide removal and passivation of Al-based coating will enable a large-scale process to the intrinsic high reflectance of Al-based reflectors with high uniformity over a 1-meter class mirror area.

## *Key Challenges/Remaining Tall Poles:*

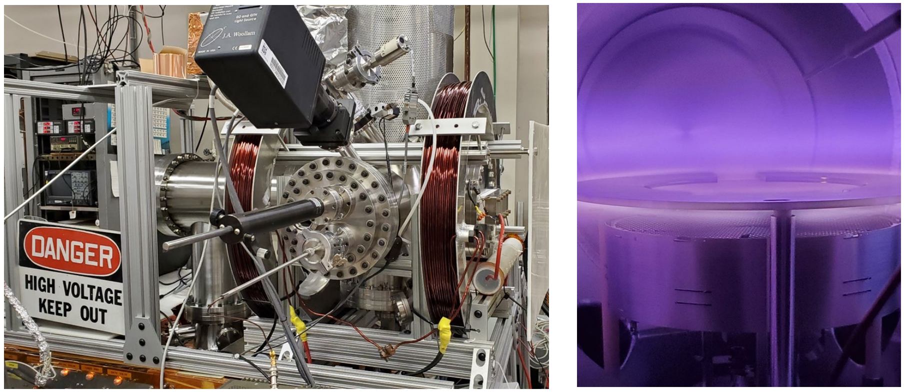
- Demonstration of the plasma-based process on a large scale (up to a 1-meter) area substrate.
- Bring online a 1-meter reactor at NRL.

## *Summarize Top Accomplishments:*

- LAPPS has repeatedly demonstrated oxide removal and fluorine passivation of Al mirrors over 6” diameter area with a precisely controlled growth of a thin $AlF_3$ layer.
- Demonstrated control of FUV reflectance properties of Al with a metal fluoride overcoat ($MgF_2$, $AlF_3$) by varying ion energy, radical density, and plasma exposure time.
- **Start TRL = 3 Final TRL = 4 (TMB vetted)**.

## *Key collaborating institutions/companies:*

- David Boris, Scott Walton (Naval Research Laboratory)
- Luis Rodriguez de Marcos, (Catholic U. of America)
- Ed Wollack, Javier del Hoyo (NASA/GSFC)



Left: Completed UHV LAPPS chamber reactor at NRL with in-situ ellipsometry and a load lock for maintaining chamber cleanliness. Right: Interior view of electron beam generated plasma over the 150mm diameter processing stage.

## *Key Performance Parameters and Technical Targets:*

| | Technical Target | Current Performance |
|---|---|---|
| Average R (100-200 nm) | > 80% | ~ 81% |
| Average R (120-3000 nm) | > 90% | ~ 93% |
| Uniformity R (100-200 nm) (over 6”) | < 1 % | < 1% |
| Uniformity R (300-2500 nm) (over 6”) | < 0.1 % | < 0.2% |

- Estimate of years needed to reach TRL 5: 3 years

# 18-SAT18-0011: High performance, stable, and scalable UV aluminum mirror coatings using ALD

PI: John Hennessy / JPL

## Objectives and Significance of Work :

- Enhancing the long-term stability of Al/LiF (100–2500 nm) mirror systems using atomic layer deposition (ALD) to produce the protective coating.
- Demonstrating scalability towards >1 m size mirrors.
- Study fundamentals of aluminum deposition with respect to birefringence, microstructure, and ALD compatibility.
- Alternative to physical vapor deposition (PVD) methods.

## Key Challenges/Remaining Tall Poles:

- Original challenges were to demonstrate that ALD methods could produces mirror coatings that could meet FUV performance goals.
- Remaining challenges are to determine best method for combining ALD with PVD aluminum (shared vacuum vs. atomic layer etching).

## Summarize Top Accomplishments:

- ALD capping layers on PVD eLiF coatings will be demonstrated on the SPRITE CubeSat and Aspera Pioneers Mission.
- Estimate TRL 4 in context of HWO (PI Asserted).
- All-ALD protective coatings can meet the performance requirements specified by LUVOIR.

## Key collaborating institutions/companies:

- JPL, CU Boulder, UC Santa Cruz

A flight candidate primary mirror (16 x 18 x 5 cm) for the SPRITE CubeSat mission receiving an ALD $MgF_2$ overcoat at JPL

## Key Performance Parameters and Technical Targets:

| | Technical Target | Current Performance |
|---|---|---|
| Absolute Reflectance | LUVOIR target:<br>>50% R (100–115 nm)<br>>80% R (115-200 nm)<br>>88% R (200-850 nm)<br>>96% R (> 850 nm) | Meets LUVOIR targets, see Hinton et al., Proc. SPIE 11821, 118211B (2021) |
| Reflectance Uniformity | Coronagraphs may require <0.1% (TBE) intra-segment uniformity on HWO | ALD coatings ($Al/MgF_2$) in this program achieve ~0.05% (1σ) uniformity at 450 nm over 150 mm dia. |

- 1–2 years at current-level funding are needed to reach TRL 5

# Award #22-SAT22-0030: Characterizing Single-photon Counting CMOS Image Sensors for NASA Missions

PI: Donald F. Figer / RIT

## Objectives and Significance of Work :

- Advance commercial-of-the-shelf single-photon sensing CMOS technology to deliver TRL5 photon-counting capability for UV/Vis space missions
- Deliver tier 1 gap technologies to NASA, its partners, and future instrument Principal Investigators
- Characterize and Advance CMOS detector candidates for HWO
- Demonstrate low-light-level imaging/spectroscopy in small packages

## Key Challenges/Remaining Tall Poles:

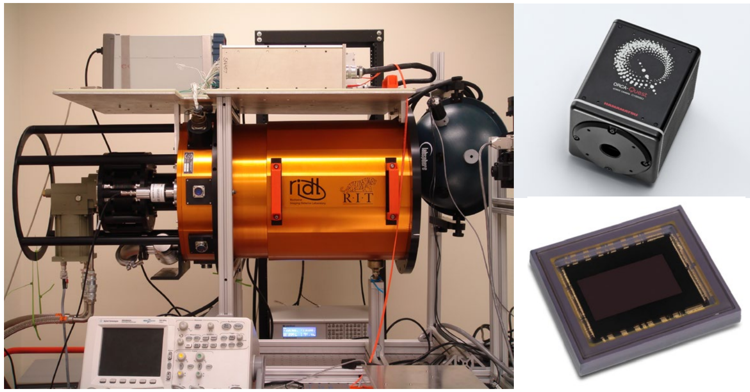
- Achieve high performance for photon-starved NASA science missions
    - On-die photon-to-digital conversion
    - Radiation-hard by design
    - Dark current as low as CCDs
    - High quantum efficiency with direct readout pixels
- Achieve high performance for photon-starved NASA science missions
- CMOS readout integrated circuit (ROIC) is not yet at TRL 5 and requires heavy ion tests

## Summarize Top Accomplishments:

- completed post-radiation characterization of QIS sensor
- vetted pixel technology at TRL5 and ROIC at TRL4
- submitted JATIS manuscript on QIS radiation results
- kicked-off SAT2022 project that will use qCMOS and HWK4123 sensors

## Key collaborating institutions/companies:

- Eric R. Fossum (Thayer School of Engineering at Dartmouth)
- Gigajot Technology Inc.
- Hamamatsu Photonics Inc.
- BAE Systems Electronic Systems (Fairchild Imaging)



The images show one of RIT’s dewar hardware test systems (left) and two different sensor packages that will be used for the project: The Quest qCMOS Camera (top) and the HWK4123 sensor (bottom).

## Key Performance Parameters and Technical Targets:

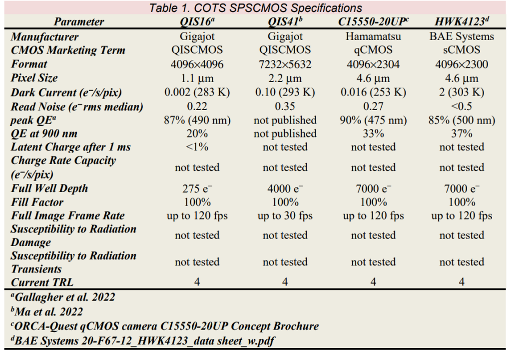


Table 1. COTS SPSCMOS Specifications

| Parameter | QIS16[a] | QIS41[b] | C15550-20UP[c] | HWK4123[d] |
|---|---|---|---|---|
| Manufacturer | Gigajot | Gigajot | Hamamatsu | BAE Systems |
| CMOS Marketing Term | QISCMOS | QISCMOS | qCMOS | sCMOS |
| Format | 4096×4096 | 7232×5632 | 4096×2304 | 4096×2300 |
| Pixel Size | 1.1 µm | 2.2 µm | 4.6 µm | 4.6 µm |
| Dark Current ($e^-$/s/pix) | 0.002 (283 K) | 0.10 (293 K) | 0.016 (253 K) | 2 (303 K) |
| Read Noise ($e^-$rms median) | 0.22 | 0.35 | 0.27 | <0.5 |
| peak QE[a] | 87% (490 nm) | not published | 90% (475 nm) | 85% (500 nm) |
| QE at 900 nm | 20% | not published | 33% | 37% |
| Latent Charge after 1 ms | <1% | not tested | not tested | not tested |
| Charge Rate Capacity ($e^-$/s/pix) | not tested | not tested | not tested | not tested |
| Full Well Depth | 275 $e^-$ | 4000 $e^-$ | 7000 $e^-$ | 7000 $e^-$ |
| Fill Factor | 100% | 100% | 100% | 100% |
| Full Image Frame Rate | up to 120 fps | up to 30 fps | up to 120 fps | up to 120 fps |
| Susceptibility to Radiation Damage | not tested | not tested | not tested | not tested |
| Susceptibility to Radiation Transients | not tested | not tested | not tested | not tested |
| Current TRL | 4 | 4 | 4 | 4 |

[a] Gallagher et al. 2022
[b] Ma et al. 2022
[c] ORCA-Quest qCMOS camera C15550-20UP Concept Brochure
[d] BAE Systems 20-F67-12_HWK4123_data sheet_w.pdf

| TRL Summary (2025 Target) | Entry | Current | Target |
|---|---|---|---|
| Overall System | 3 | 4 | 5 |
| Single-Photon Sensing Pixel | 3 | 4 and 5 | 5 |
| Readout Cluster/ROIC | 4 | 4 | 5 |

# High-Performance Sealed-Tube Cross-Strip Photon-Counting Sensors for UV-Vis Astrophysics Instruments

PI: Oswald Siegmund / UC Berkeley

## *Objectives and Significance of Work :*

- Exploit developments in atomic-layer-deposited (ALD) microchannel plates (MCPs), photocathodes, & cross strip (XS) readout techniques to implement a new generation of large area enhanced-performance sealed-tube photon-counting sensors spanning the 115-to-400-nm regime.
- Establish high resolution, high efficiency, large area MCP detectors for sub-orbital to flagship missions.
- Adopted in a 2023 Probe mission proposal.

## *Key Challenges/Remaining Tall Poles*:

- Configuring into a robust, integrated package using state of the art techniques. – Accomplished.

## *Summarize Top Accomplishments:*

✓ 50mm XS anode in cofired ceramic built and integrated into 2 sealed tubes with ALD MCPs.

✓ Device performance meets expectations, eg ~20µm resolution, environmental tests successful.

✓ 9 papers, 9 talks, undergraduate participants.

✓ Funded to fly on MOBIUS rocket mission.

✓ Established TRL 5 (6) TMB vetted.

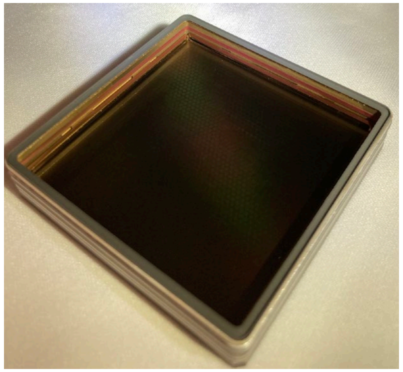
✓ PI, AAS Weber & SPIE Goddard Awards 2021.

## *Key collaborating institutions/companies:*

- Photonis North America.
- Incom Inc.

Planacon 50-mm XS sealed tube with ALD MCPs, completed successful vacuum, vibration and thermal testing.

50mm HTCC XS anode hermetically integrated with the Planacon detector body.



## *Key Performance Parameters and Technical Targets:*

| | Technical Target | Current Performance |
|---|---|---|
| Spatial resolution | <25µm FWHM | Better than 20µm |
| Size format | 50mm | 50mm |
| Quantum Efficiency | >25% @ 200nm | 33% @ 200nm |
| Event rate | Multi MHz | >4MHz |
| Stability | $>10^{13}$ events $\mathrm{cm}^{-2}$ | $>10^{13}$ events $\mathrm{cm}^{-2}$ |

- Reached TRL 5 (TMB, 6 in specific configurations)

# Ultraviolet Spectroscopy for the Next Decade Enabled Through Nanofabrication Techniques

PI: Randall L. McEntaffer/PSU

## Objectives and Significance of Work :

- High-efficiency, low-scatter UV echelle gratings
- Gratings with low blaze angles
- Curved grooves on curved substrates
- High-efficiency echelles and full-sized, curved-substrate, flight-like UV gratings enable spectroscopy for strategic missions such as LUVEX. Also applicable to Explorers, Probes, and rocket missions.
- Investigates a wide range of grating characteristics: large/small periods, low/high blaze angle, parallel/curved grooves, flat/curved substrates, variable line spacing, coating effects, etc.

## Key Challenges/Remaining Tall Poles:

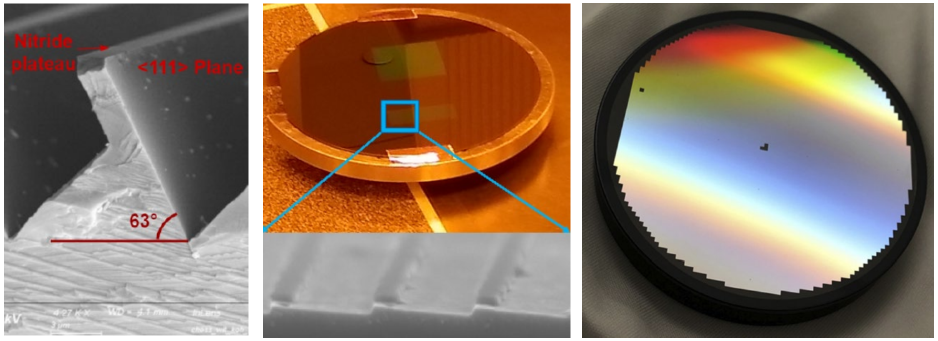
- Electron-beam lithography stitching over large areas on curved substrates

## Summarize Top Accomplishments:

- This award just began with funding in June 2023.
    - Kick-off meetings have been held with early procurements started

## Key collaborating institutions/companies:

- University of Colorado, Boulder; Johns Hopkins University; Caltech; Southwest Research Institute



Caption: Left – a high-blaze-angle echelle made for CHESS; Center – a low-blaze-angle grating made for ESCAPE; Right – polished Si grating, 80 mm diameter, 250 mm radius of curvature, hyperbolic grooves

## Key Performance Parameters and Technical Targets:

| | Technical Target | Current Performance |
|---|---|---|
| Low blaze angle | <1° | 4° |
| High echelle efficiency | >80% | ~70% |
| Aberration control with ebeam | Requirements for SISTINE and FORTIS | Beasley et al. 2019 |

- 2-3 years (at current-level funding) are needed to reach TRL 5

# Photon Counting NIR LmAPD Arrays for Ultra-low Background Space Observations

Michael Bottom, University of Hawaii

## Objectives and Significance of Work :

- Objective: qualify to TRL-5 a megapixel, ultra-low-noise (dark current < 1e-3 e-/pix/s, read noise <<1 e-/pix/frame) infrared (1-2.5 um) array
- This work develops linear-mode avalanche photodiodes, which are semiconductors only requiring "easy" cryogenics (50-70K)
- Relevant to HabWorlds (no infrared detectors currently capable of doing exoplanet spectroscopy)

## Key Challenges/Remaining Tall Poles:

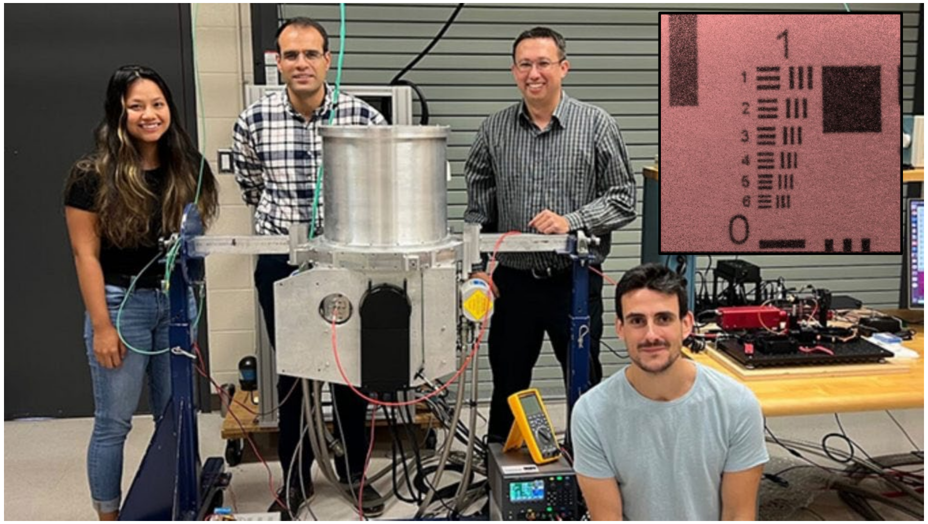
- Achieve low dark current and low read noise simultaneously.
- Radiation testing remains

## Summarize Top Accomplishments:

- TRL 3→4 (TMB verified)
- Promising results obtained. Outperforms state of the art HAWAII-xRGs > 10x
- SAT 2023 awarded for development of 4 megapixel sensor.

## Key collaborating institutions/companies:

- Leonardo Corporation, Hawaii Aerospace, Markury Scientific



## Key Performance Parameters and Technical Targets:

| | Technical Target | Current Performance |
|---|---|---|
| Dark current | 1e-3 e-/pixel/s | 1e-4 e-/pix/s |
| Read Noise | <1 e-/pix/read | 0.3 e-/pix/read (best)<br>0.7 e-/pix/read (typ.) |

- 0.5 years required to reach TRL 5 (est)

# High Performance FUV, NUV, and UV/Optical CMOS Imagers

PI: Michael Hoenk / JPL

## Objectives and Significance of Work :

- Development and maturation of delta-doped CMOS imaging detectors using nanoscale surface engineering for ultra-precise photometry in space.
- Astro2020 science goals require multigigapixel mosaic focal planes capable of precision photometry in challenging radiation environments.

## Key Challenges/Remaining Tall Poles:

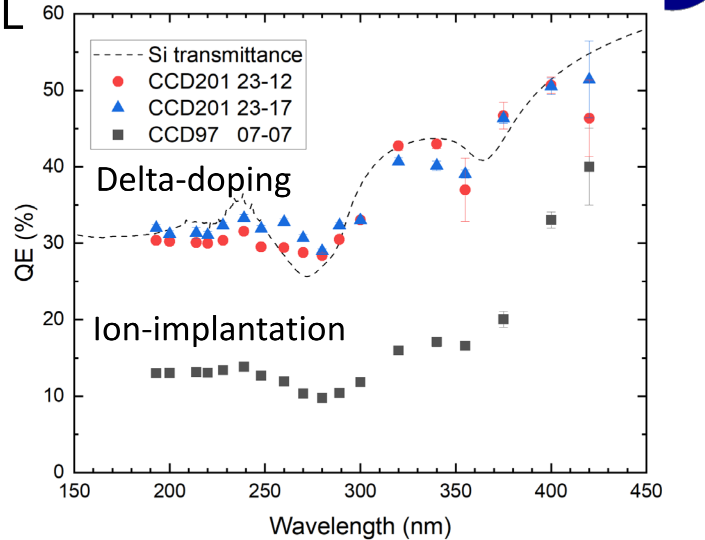
- Performance and radiation testing of delta-doped CMOS detectors using JPL's Precision Projector Laboratory (PPL).
- On-sky observations at Kitt Peak by Columbia University.

## Summarize Top Accomplishments:

- Fabrication and initial testing of delta-doped Te2v CIS120 detectors and SRI MkxNk detectors.
- Design and build of CIS120 camera is underway.
- Initiated design study for far ultraviolet cubesat.

## Key collaborating institutions/companies:

- Prof. David Schiminovich, Columbia University
- Prof. Kevin France, University of Colorado LASP
- Teledyne e2v
- SRI International



Delta-doping vs. ion-implantation
Hoenk *et al.*, SPIE Proc. 12191-38 (2022)

## Key Performance Parameters and Technical Targets:

| | Technical Target | Current Performance |
|---|---|---|
| Broadband NUV-NIR QE | >50% absolute QE | Si-SiO$_2$ traps cause loss of signal in ion-implanted devices |
| Visible-blind UV detection | In-band QE > 40% with 3-4 orders of magnitude out-of-band rejection | JPL-unique capability with integrated metal-dielectric filters |
| Stability for precision photometry | QE stability better than 1% in radiation environment | Si-SiO$_2$ traps cause instabilities in ion-implanted devices |

- Three years to reach TRL 5 at current-level funding

# Large format, high dynamic range UV detector using MCPs and Timepix4 readouts

PI: John Vallerga, Space Sciences Laboratory, U.C. Berkeley

## Objectives and Significance of Work :

- A mosaic of large format Timepix4 (Tpx4) ROICs as the readout anode for large area MCP detectors can provide the 200x200mm FUV detectors required for the upcoming Habitable Worlds Observatory.
- Such a detector provides FUV photon counting at ~GHz rates with high spatial and temporal resolution, no cryogens and minimal HV (<1500V)

## Key Challenges/Remaining Tall Poles:

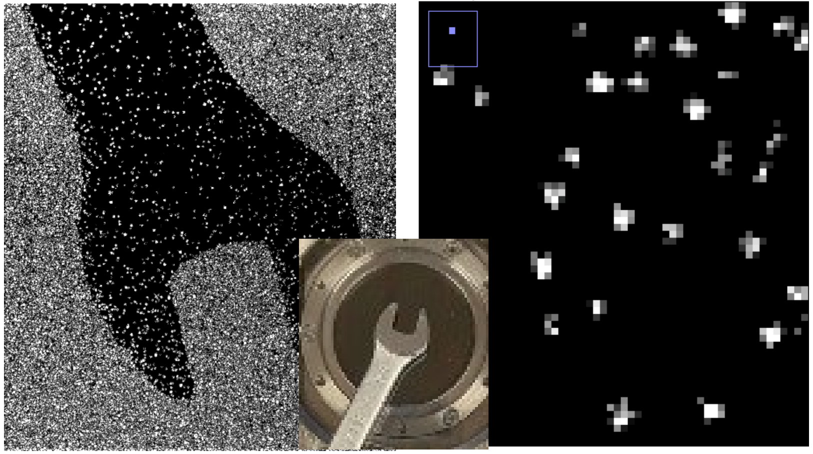
- Tpx4 mosaicing requires “Through Silicon Via” technology to avoid wirebonding and allow 4 side buttable dies.
- Must demonstrate 4 side mosaicing while minimizing gaps between dies to 1-2 pixels using techniques such as “stealth dicing”

## Summarize Top Accomplishments:

- First light demonstration of a single Tpx4 as readout for single MCP (see figure)
- First Tpx4 with TSV outputs has just been successfully tested last month

## Key collaborating institutions/companies:

- The Timepix4/Medipix4 collaboration and CERN



**First Light!** Left: *UV shadow image of a wrench using the TPX4 MCP detector.* Right: *Individual photon events appearing as small pixel clusters. The centroids of these clusters represents the location of the detected UV photons.*

## Key Performance Parameters and Technical Targets:

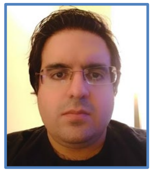
| | Technical Target | Current Performance |
|---|---|---|
| Mosaicing | Dicing to 1-2 pixels | Stealth dicing tests good to <15µm accuracy |
| TSV to BGA outputs | | Demonstrated |
| Mosaic readout | 3 x 3 Tpx4 mosaic MCP anode | Single Tpx4 anode |

Far-IR-related technology

# BACK-UP CHARTS

# Development of an ultra-low temperature Continuous Adiabatic Demagnetization Refrigerator (CADR) with a continuous intermediate stage for heat intercept

PI: Amir Jahromi / GSFC-code 552



## Objectives and Significance of Work :

- Bring to TRL 6 a cooling system that provides:
  - Continuous cooling at 35 mK with a cooling power of 3 µW
  - Continuous cooling at an intermediate temperature of 1 K with a cooling power of 1.5 mW (total)
  - Low external magnetic field of less than 2 µT
  - Simple, efficient, vibration-free operation
  - Proven reliability; no moving parts
  - Improve control algorithm of low temperature stage

System will exceed requirements of currently conceived cryogenic detector arrays

## Key Challenges/Remaining Tall Poles:

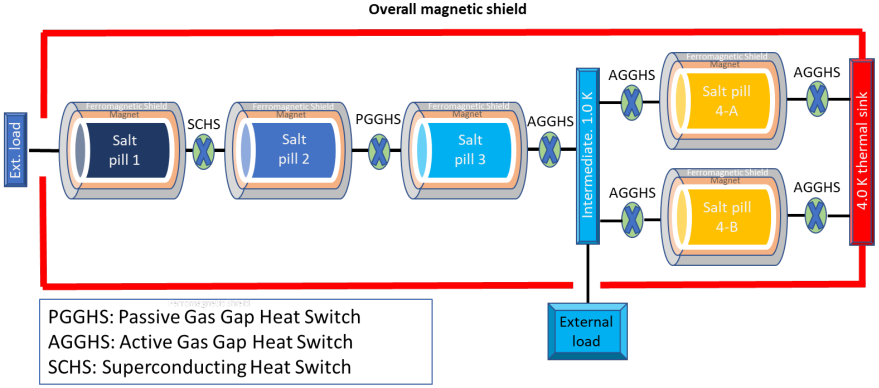
- Continuous cooling demonstration at 35 mK with tight temperature stability (i.e. 1 µK RMS)
- Continuous cooling demonstration at intermediate temperatures (e.g. 1 K) with tight temperature stability (i.e. 1 mK RMS)
- Magnetic shielding to levels lower than few µT outside the CADR envelope

## Summarize Top Accomplishments:

- Entire system high fidelity model completed
- Closed design of stages 4A/4B
- Parts for above stages either completed or nearing end of fabrication
- Characterized overall high permeability magnetic shield
- AGGHS underwent full thermal characterization
- Received single crystal GLF and YbGG vital for the higher temperature ADR stages → will characterize soon

## Key collaborating institutions/companies:

- SYNOPTICS division of Northrop Grumman
- University of Maryland College Park



PGGHS: Passive Gas Gap Heat Switch
AGGHS: Active Gas Gap Heat Switch
SCHS: Superconducting Heat Switch

5-stage Continuous Adiabatic Demagnetization Refrigerator configuration

## Key Performance Parameters and Technical Targets:

| Performance Metric | Requirements | Current SOA of TRL 6+ Coolers | 2017 SAT CADR$^{*}$ | Proposed New CADR |
|---|---|---|---|---|
| Cold Stage Operating Temp. (mK) | ≤ 50 | 50 | 50 | 35 |
| Cold Stage Temp. stability (µK) rms | 2 | 1 | TBD more tests | 1 |
| Cold Stage Cooling power @ 50 mK (µW) | 6 | 0.5 | 5.0 | 10$^{\dagger}$ |
| Heat Sink Temperature (K) | 4.5 | 4.5 | 4.0 | 4.5 |
| Intermediate Stage Stability at Operating Temperature (mK@K) | 1@0.7 | 1@1.4 | N/A | 1@0.7 |
| Mag. Field outside ADR shield assembly (µT) | 5 | 250 | 2$^{**}$ | <1 |
| Lifetime (years) | >10 | >10 | >10 | >10 |
| Mass (kg) | <25 | 15 | 18$^{\ddagger}$ | 22$^{\ddagger}$ |

*Results to date as of August 2023

** Designed and fabricated but not demonstrated during operation

† Cooling power of 3 µW at the proposed 35 mK

‡ Mass includes 6 kg mounting plate that can easily be light-weighted for flight

- 3 years at current level funding to reach TRL-5

# SAT21-0030:Demonstrating Large Low Noise Transition Edge Sensor Arrays for Future FIR Space Missions

PI: Johannes Staguhn / JHU & GSFC

## *Objectives and Significance of Work :*

- Demonstrate large, tileable array with latest version of Time Domain Superconducting Quantum Interference Device (SQUID) multiplexers
- Deliver background noise-limited, large TES arrays for FIR Probes and FIR flagship mission.
- Superconductung Flexlines for compact design
- Enabling large detector arrays for major suborbital and space-based Far-IR observatories

## *Key Challenges/Remaining Tall Poles:*

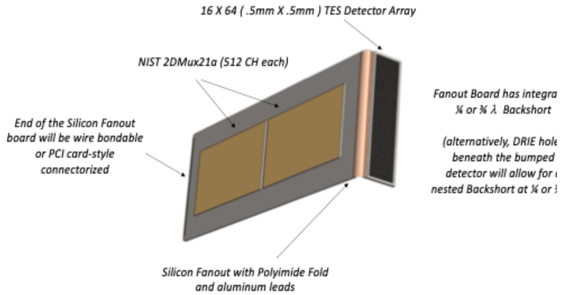
- < What are the main challenges originally faced?>
- < What are the remaining tall poles?>

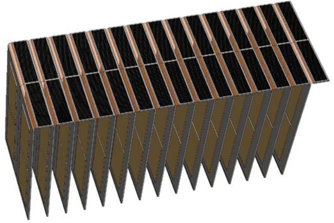
## *Summarize Top Accomplishments:*

- Initial detector designs, mechanical tests successful, flexlines demonstrated
- Expect delivery of TRL 5 detector arrays
- Expected to meet/exceed sensitivity requirements for detectors

## *Key collaborating institutions/companies:*

- NASA/Goddard Space Flight Center, NIST/Boulder, Princeton University
- DeepSpace Technologies





Detector unit: The array consists of 16x64 pixels with 0.5 mm pitch. A 90° flex connection to the SQUID multiplexer board allows for the readout board to be 90 degrees rotated with respect to the detector fanout, allowing for the tileability of the detector array.

## *Key Performance Parameters and Technical Targets:*

| | Technical Target | Current Performance |
|---|---|---|
| R=10 Background Limited FIR Detectors | 4e-19W/rt(Hz) | Better than 1e-18 W/rt(Hz) |
| Pixel Filling factor | 80% | 80% |
| Superconducting Flex Lines | TRL = 5 | TRL = 3 |
| 2-level Multiplexing | TRL = 5 | TRL = 3 |

- 2.5 more years required to reach TRL 5

X-ray related technology

# BACK-UP CHARTS

# ISFM: Advanced X-ray Microcalorimeters - Transition-Edge Sensor (TES) Sub-package

PI: Stephen Smith / GSFC 662

## Objectives and Significance of Work :

- Very large format microcalorimeter arrays provide high-resolution imaging and spectroscopy, needed for next generation X-ray observatories.
- Technology maturation for Lynx like strategic mission and X-ray probe missions, highlighted as decadal priorities.
- Will develop arrays of transition-edge sensors (TESs) for X-ray probe concept called the Line Emission Mapper (LEM)
- Will develop arrays of TESs on scale needed for a Lynx-like strategic mission (>100,000 pixels).

## Key Challenges/Remaining Tall Poles:

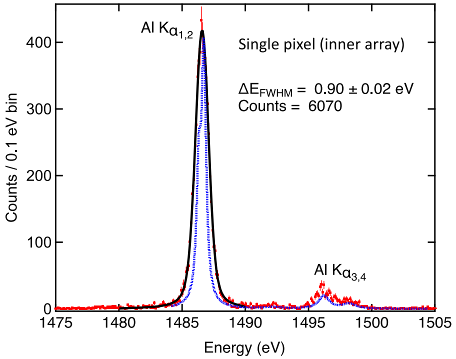
- Demonstrating full scale LEM array containing single pixel and 4-pixel hydras that meets all requirements.
- Demonstrating 100k Lynx array with hybridized bump-bonded microwave multiplexed readout.

## Summarize Top Accomplishments:

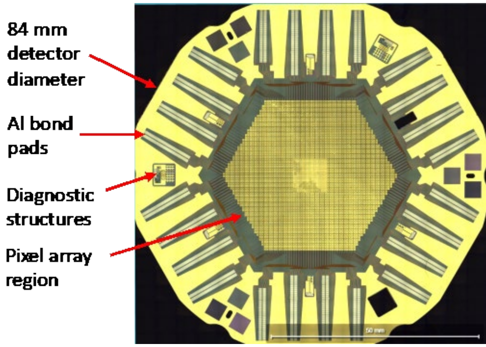
- Demonstrated prototype LEM detectors meet key requirements.
- Fabricated 1st full-scale prototype LEM array of 14-k pixels
- LEM detectors confirmed at TRL-5 (TMB reviewed).

## Key collaborating institutions/companies:

- J. Adams, S. Bandler, F. Finkbeiner, S. Hull, C. Kilbourne, S. Porter, K. Sakai, N. Wakeham, J. Fuhrman (GSFC/662)
- J. Chervenak, R. Borelli, J. Mateo, H. Muramatsu (GSFC/553). K. Ryu (MIT Lincoln Laboratory), D. Bennett (NIST/Boulder).



Measured spectral performance on a LEM single pixel showing 0.9 eV energy resolution at an energy of 1.5 keV.



Photograph of completed full-scale LEM array

## Key Performance Parameters and Technical Targets:

| | Technical Target | Current Performance |
|---|---|---|
| LEM - energy resolution (single pixels/hydras) | 1.3 eV / 2.5 eV | 1.2 eV / 2.3 eV |
| LEM - array size | 30 arc minutes | 33 arc minutes |
| LEM - position sensitivity in hydras | 200 eV – 2keV | 200 eV – 2 keV |
| Lynx – array size | 100k pixels | 50k pixels |

- LEM: ~ 2 years needed to reach TRL-6.
- Lynx: ~ 4 years needed to reach TRL-5.

# A22ISFM-0008: *MSFC Advanced X-Ray Optics: Formulation to Flight*

PI: Jessica A. Gaskin/ ST12

## *Objectives and Significance of Work :*

- Primary goals are to: *Develop the next generation of sub-arcsecond full-shell replicated mirrors and assemblies; Continue to supply low-cost, moderate-resolution flight mirrors and assemblies; Enhance the performance of full-shell and segmented optics through low-stress coatings.*
- Replicated full-shell X-ray mirrors are relatively inexpensive, thin, and have advantages regarding alignment, mounting, and coating.
- Addresses Tier 1 Tech Gap for high-resolution, Lightweight X-ray Optics and is relevant to realizing multiple future astrophysics missions of all classes.

## *Key Challenges/Remaining Tall Poles*:

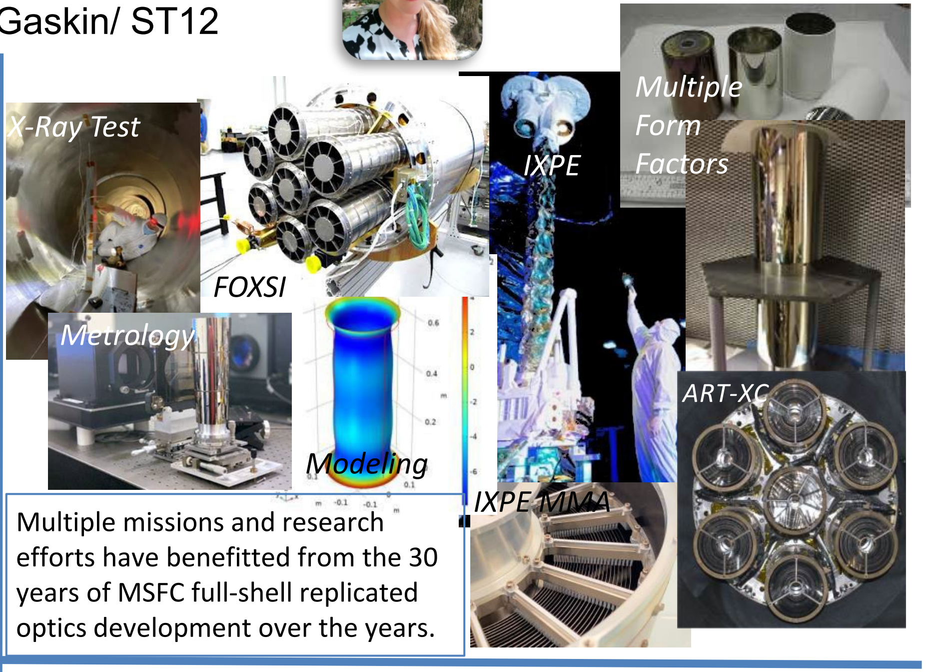
- Reducing stresses induced in the optic during the replication and mirror separation processes.
- No showstoppers

## *Summarize Top Accomplishments:*

- Infusions: HERO/ES, IXPE, ART-XC, NIF, NIST, FOXSI, REDSoX
- TRL: 3-4 (PI Asserted) for high-res full-shell module
- Modeling the plating bath geometry (gaskets & shields) allowed for better understanding and improved process. Improved alignment and mounting, X-ray testing, and test analysis all contributed to improved performance.

## *Key collaborating institutions/companies:*

- SAO, U of Minnesota, Caltech, NIF, NIST, Aerospace Corp., U. of Colorado, and many others that we are in the proposal process with.



Multiple missions and research efforts have benefitted from the 30 years of MSFC full-shell replicated optics development over the years.

## *Key Performance Parameters and Technical Targets:*

| | Technical Target | Current Performance |
|---|---|---|
| Angular Resolution – *single full-shell* replicated optic | < 1 arcsec HPD | 4.5 arcsecs HPD |
| Angular Resolution – Optics *Module* (in-space performance) | < 1 arcsec HPD | 5-6 arcsecs HPD |

- Estimate how many years (at current-level funding) are needed to reach TRL 5: **4 years**
- Goals for FY23-25 are to fabricate, coat, assemble, and test a two-shell mirror module using thin full-shell optics that achieves ~4” HPD, and establish an error budget and roadmap to achieve < 1” HPD mirror-module performance.

# Next-Generation X-ray Optics: High Resolution, Light Weight, and Low Cost

PI: William W. Zhang / GSFC

## *Objectives and Significance of Work :*

- Develop an X-ray mirror technology that achieves better than 0.5” Half-Power Diameter (HPD) angular resolution, while reducing mass and production cost by at least an order of magnitude on a per-unit effective area basis.
- Enables significant increase in effective collection area for high-performance X-ray telescopes under given mass and cost constraints.

## *Key Challenges/Remaining Tall Poles:*

- Fabrication of mirror segments
- Coating of mirror segments
- Alignment and bonding of mirror segments

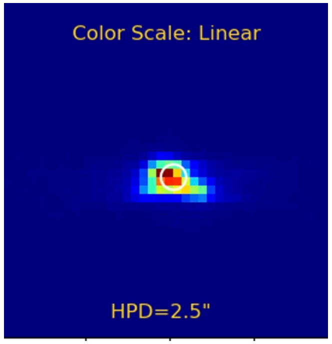
## *Summarize Top Accomplishments:*

- Developed processes to fabricate, coat, align, and bond lightweight X-ray mirror segments.
- Built mirror modules that achieve image quality of 2.5” HPD and pass all environmental tests: thermal vacuum and vibration.
- Technology baselined for Lynx, AXIS, HEX-P, & STAR-X

## *Key collaborating institutions:*

- NASA Goddard Space Flight Center
- KBR & UMBC

Technology Development Module (TDM) containing 3 parabolic-hyperbolic mirror pairs co-aligned and bonded.



Full illumination X-ray image with 2.5-arcsec HPD

## *Key Performance Parameters and Technical Targets:*

| | Technical Target | Current Performance |
|---|---|---|
| Mirror Segments | <0.3” | <0.6” |
| Coating Distortion | <0.1” | <1.0” |
| Bonding Distortion | <0.2” | <1.5” |

This technology

- Is currently at TRL-5 for building 2.5” telescopes.
- Will be at TRL-5 for 1” telescopes by 12/2024.
- Will be at TRL-5 for 0.5” telescopes by 12/2026.

# Readying X-ray Gratings and Optics for Space Applications: Manufacturability & Alignment

PI: Randall Smith / CfA

## Objectives and Significance of Work :

- CAT gratings combine high-efficiency with high-resolution in soft X-rays (0.1-1.5 keV). Individual Critical-Angle Transmission (CAT) gratings have been fabricated and tested, but large-scale adoption requires manufacturing techniques
- Science includes mapping missing baryons, and observing feedback around black holes

## Key Challenges/Remaining Tall Poles:

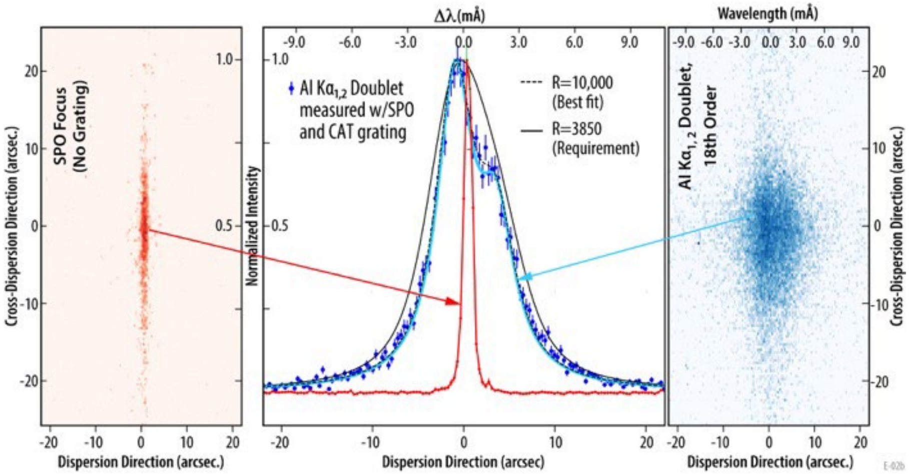
- Develop methods to process Si wafers into CAT gratings that are suitable for large-scale manufacturing.

## Summarize Top Accomplishments:

- Demoed aligning front and back of wafers
- Demoed backside mask processing on full wafer
- Measured tilt-bar angle on grating wafer
- Finished processing to create final grating wafers
- Characterized grating performance/efficiency
- Align & mount wafers to create full CAT grating
- X-ray test at PANTER beamline

## Key collaborating institutions/companies:

- SAO, MIT, MIT/Lincoln Lab, Izentis, MPE (Germany)



## Key Performance Parameters and Technical Targets:

| | Technical Target (Arcus) | Current Performance |
|---|---|---|
| grating depth | 4 um | > 6 um |
| grating bar duty cycle | 0.25 | 0.25 |
| geometric transmission | > 0.5 | ≈ 0.5 |
| Diffraction efficiency (2.5 nm) | 0.3 | 0.34 |
| Period variation | < 2e-4 | ≈ 1 e-4 |

- Technical requirements met at Arcus Probe requirements.
- 2-3 more years required to demonstrate MRL 6, meeting yield and processing time needs.

# Technology maturation for a high-sensitivity and high-resolving power x-ray spectrometer

PI: Mark Schattenburg/MIT
Co-I: Ralf Heilmann/MIT

## Objectives and Significance of Work :

- Develop key technology to enable a Critical-Angle X-ray Transmission Grating Spectrometer (CAT-XGS), advancing to TRL 6 in preparation for proposed mid- and large-size missions over the next decades
- Much improved diffraction efficiency and resolving power compared to current x-ray spectrographs
- Addresses gaps in high-resolution x-ray spectroscopy; applicable to X-ray Probe and *Lynx*-like next-generation X-ray Flagship

## Key Challenges/Remaining Tall Poles:

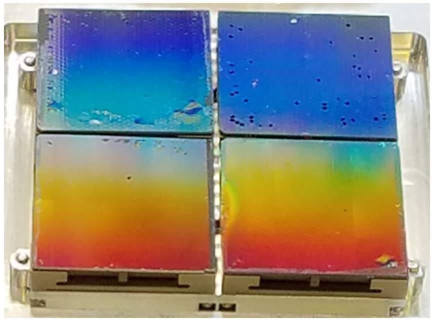
- Challenge: Fabrication of 200 nm-pitch, ultra-high aspect-ratio freestanding grating bars with nm-smooth sidewalls
- Pole: Efficient volume manufacturing

## Summarize Top Accomplishments:

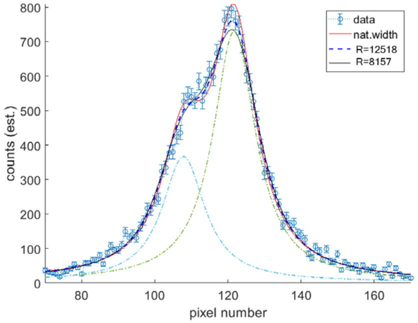
- Infusion of CAT gratings in *Lynx* mission concept study and *REDSoX* mission
- TRL 4 (2016, TMB-vetted), 5-6 (2022, Arcus-level, asserted)
- Demonstrated diffraction efficiency in agreement with model predictions; demonstrated resolving power $\lambda/\Delta\lambda > 10{,}000$ with co-aligned gratings ($\Delta\lambda < 90$ picometer)
- 9 internal funding awards within last 10 years

## Key collaborating institutions/companies:

- SAO, MIT Lincoln Lab, NASA GSFC, NASA MSFC, MPE (Germany)
- Izentis, LLC



Grating window with four 32x32.5 mm$^2$ grating facets



18th order Al-K$_\alpha$ diffraction peak from simultaneous illumination of two grating facets

## Key Performance Parameters and Technical Targets:

| | Technical Target (Lynx) | Current Performance |
|---|---|---|
| grating depth | > 5.7 um | > 6 um |
| grating bar duty cycle | ≤ 0.2 | 0.25 |
| geometric transmission | > 0.79 | ≈ 0.5 |
| Diffraction efficiency (2.5 nm) | 0.43 | 0.34 |
| Period variation | < 2e-4 | ≈ 1 e-4 |

- Estimated time to reach *Lynx*-like TRL 5: 3-4 years