National Aeronautics and Space Administration

Astrophysics Biennial Technology Report 2024

Astrophysics Division

Science Mission Directorate

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About the Cover

This Astrophysics Biennial Technology Report (ABTR) follows the establishment of the Habitable Worlds Observatory Technology Maturation Project Office, preparing for the next NASA Flagship astrophysics and astronomy mission, planned to launch around 2040. This report provides joint technology reporting from the three thematic Astrophysics Program Offices – Cosmic Origins (COR), Exoplanet Exploration Program (ExEP), and Physics of the Cosmos (PhysCOS). Reflecting this, the front and back covers are an artist's composition of images of the star-forming region of the Orion Nebula (Messier 42) in X-rays from the Chandra X-ray Observatory, visible light from the Hubble Space Telescope, and infrared (IR) from the James Webb Space Telescope's (JWST) near-IR camera (NIRCam) instrument; along with an imagined exoplanet orbiting a nearby star. Overall, the cover references the breadth and majesty of the universe studied by astronomy and astrophysics, enabled by NASA's Astrophysics Division (APD) technology development efforts.

Message from Astrophysics Division Director, Dr. Mark Clampin

I am pleased to present the 2024 ABTR to the astrophysics community. This report covers technology advancements and technology gaps motivated by our science drivers, priorities, and missions.

The ABTR addresses the priorities presented in the National Academies' Decadal Survey in Astrophysics, "Pathways in Astronomy and Astrophysics for the 2020s" (Astro2020). The Decadal Survey provides APD with science priorities for the decade, as well as programmatic guidance to realize those priorities. Every two years, NASA solicits input from the astrophysics community regarding the technology challenges and priorities that require development to address Astro2020 priorities. This ABTR reflects the consolidated input of our science community.

Every assessment of lessons learned from the development of new mission concepts points to the need for early technology investment and maturation to ensure mission success. According to a 2008 Space Review article by J. Mankins, "*…during the first 30 years of the civil space program, no project enjoyed less than a 40% cost overrun unless it was preceded by an investment in studies and technology of at least 5-10% of the actual project budget that eventually occurred.*" The emphasis on moving technology from inception to infusion through a dedicated technology management process has accelerated these transitions into flight technology components and instrumentation. Astrophysics infusion rates into missions, including suborbital payloads, were recently estimated to be about 62% for technology grants in the last decade. We are committed to further increasing these rates by understanding and addressing key obstacles and challenges to successful infusions.

In this ABTR, the emphasis for technology investments follows the key recommendation of the Astro2020 decadal survey – the Habitable Worlds Observatory (HWO). However, with the establishment of a new HWO Technology Maturation Project Office, the focus for the remainder of the decade will revert to a broader range of technologies from gamma rays to far IR.

With the rapid emergence of new technologies in fields such as quantum sensors, artificial intelligence/machine learning (AI/ML), astrophotonics, and meta-materials, it is essential that Astrophysics exploits these new technologies to enable the best scientific outcomes for future instrumentation in small, medium, and large astrophysics missions. Our upcoming workshop in 2025 will survey the opportunity space for applications of emerging technologies to leverage new advances in astrophysics.

Technology development and maturation has always been a key element in the success of new astrophysics missions. This ABTR provides a snapshot of our current activities, successes, and the path forward for Astrophysics technology priorities.

Dr. Mark Clampin (he, him, his)
Director, Astrophysics Division
Science Mission Directorate

Message from the Chief Technologist, Dr. Mario R. Perez

In the last few years, as we worked to articulate and fulfill the technology recommendations of the Astro2020 report, we enjoyed stable and healthy levels of funding for our technology solicitations, such as Astrophysics Research and Analysis (APRA), Strategic Astrophysics Technology (SAT), Roman Technology Fellowship (RTF), Internal Scientist Funding Model (ISFM), and risk-reduction industry contracts, leading to reasonable selection rates (20-30%). We look forward to the results of new technology awards (see, e.g., the new SATs listed on the opposite page) from these solicitations in the 2023 Research Opportunities in Space and Earth Science (ROSES) and expect them to benefit several types of future missions.

For now, the main focus for the SAT solicitation is to advance technologies enabling the development of the first recommended flagship, HWO. As mentioned by Dr. Clampin, this will change in upcoming years, when HWO receives a separate budget line and uses it to develop answers to more specific technology needs and associated development plans.

It has become clear that new and emergent technologies are crucial for APD to support its program of record and comply with the Astro2020 recommendations. In an upcoming community workshop to be held in 2025, we seek to understand and identify potential applications of quantum sensing, AI/ML (as applied to technology development), astrophotonics, and advanced materials; and how they may impact implementation of future instrumentation in small, medium, and large astrophysics missions.

We look to further expand and engage our community in current and emergent technologies to assist us in accelerating the development lifecycle, from inception to infusion, of basic technologies, which normally takes 15 to 20 years or longer. We welcome the user community's enthusiasm, and trust that they will instill new ideas, applications, and approaches to reduce these development times, improve performance, and perhaps decrease development costs

Dr. Mario R. Perez
Chief Technologist, Astrophysics Division
Science Mission Directorate

New Awards

The 2023 SAT program includes 12 new awards (table). These projects include detectors, optics, coronagraphs, mirror coatings, materials, metrology, and readout and control electronics that will enable or enhance multiple strategic Astrophysics missions recommended by Astro2020.

PI Name	PI Org.	Project Title	Managing Program
Timothy Cook	U of Mass., Lowell	A novel asynchronous integrating latching controller for MEMS deformable mirrors (DMs)	ExEP
Juan Estrada	U of Chicago	Single-photon counting with SiSeRO to search for Earth-like planets	COR
Felipe Guzman	U of Arizona	Thermo-optical metrology for exoplanet observatories	ExEP
John Hennessy	JPL	Large-area Atomic-Layer Deposition (ALD)-protected aluminum mirror coatings for HWO	COR
Tracee Jamison-Hooks	ASU	Development of space-qualified signal-processing readout electronics for HWO and Origins Space Telescope detector arrays	COR
Drew Miles	Caltech	New techniques toward the nanofabrication of custom, blazed UV gratings to enable next-generation spectroscopy	COR
Laurent Pueyo	STScI	Laboratory demonstration of high contrast using phase-apodized-pupil Lyot coronagraph with high-order wavefront sensor	ExEP
Mark Schattenburg	MIT	Technology development for a high-resolving-power X-ray spectrometer	PhysCOS
Gene Serabyn	JPL	Optical vortex phase mask development and testing	ExEP
Mark Silver	MIT/LL	Precision high-strain composites for astronomical telescope optomechanics	COR
Johannes Staguhn	JHU	Demonstration of an HgCdTe detector-based ultra-stable mid-IR spectrometer for transit spectroscopy and phase-curve observations of habitable planets around M stars	ExEP
Kyle Van Gorkom	U of Arizona	Technology development in UV coronagraphy to enable characterization of Earth-like exoplanets	ExEP

The APD Technology team in front of the HWO banner at the American Astronomical Society winter meeting in New Orleans. Standing (from left to right) Dominic Benford, Jason Derleth, Omid Noroozian, Brendan Crill, Steve Kendrick, Opher Ganel, and Pin Chen. Kneeling (from left to right) Rachel Rivera, Nick Siegler, and Mario Perez.

Astrophysics Science Programs and Technology Development

About NASA Astrophysics Science Programs

APD undertakes space missions to explore the nature of the universe at its largest scales, earliest moments, and most extreme conditions; missions that study how galaxies and stars formed and evolved to shape the universe we see today; and missions that seek out and characterize planets and planetary systems orbiting other stars. Since such ambitious missions require technologies that exceed today's state of the art, APD established the SAT program to mature key technologies to enable these future missions, from demonstrated feasibility (i.e., Technology Readiness Level, or TRL, of 3), to the point where they can be incorporated into NASA flight missions (i.e., TRL 5).

APD science is organized into three themed Programs, COR, ExEP, and PhysCOS, to address three fundamental questions: “How did we get here?” (COR), “Are we alone?” (ExEP), and “How does the universe work?” (PhysCOS). The COR, ExEP, and PhysCOS Program Offices support their respective Programs, including managing SAT and other mid-TRL-directed projects.

About Astrophysics Technology Development

The three Program Offices serve the critical function of developing concepts and technologies for strategic missions and facilitating science investigations derived from them, specifically:

- Assess and prioritize technology gaps, based on inputs from the community and technology activities.
- Manage projects that mature technologies for strategic missions from initial TRLs of 3 or 4 (and rarely 2 or 5).
- Promote infusion of technologies into missions and projects.
- Conduct and support mission studies and develop mission concepts to enable future scientific discoveries.
- Communicate progress to and coordinate with the scientific and technological community.
- Inform the general public about progress achieved by the Programs (see searchable database of Astrophysics technology development projects at www.astrostrategictech.us).

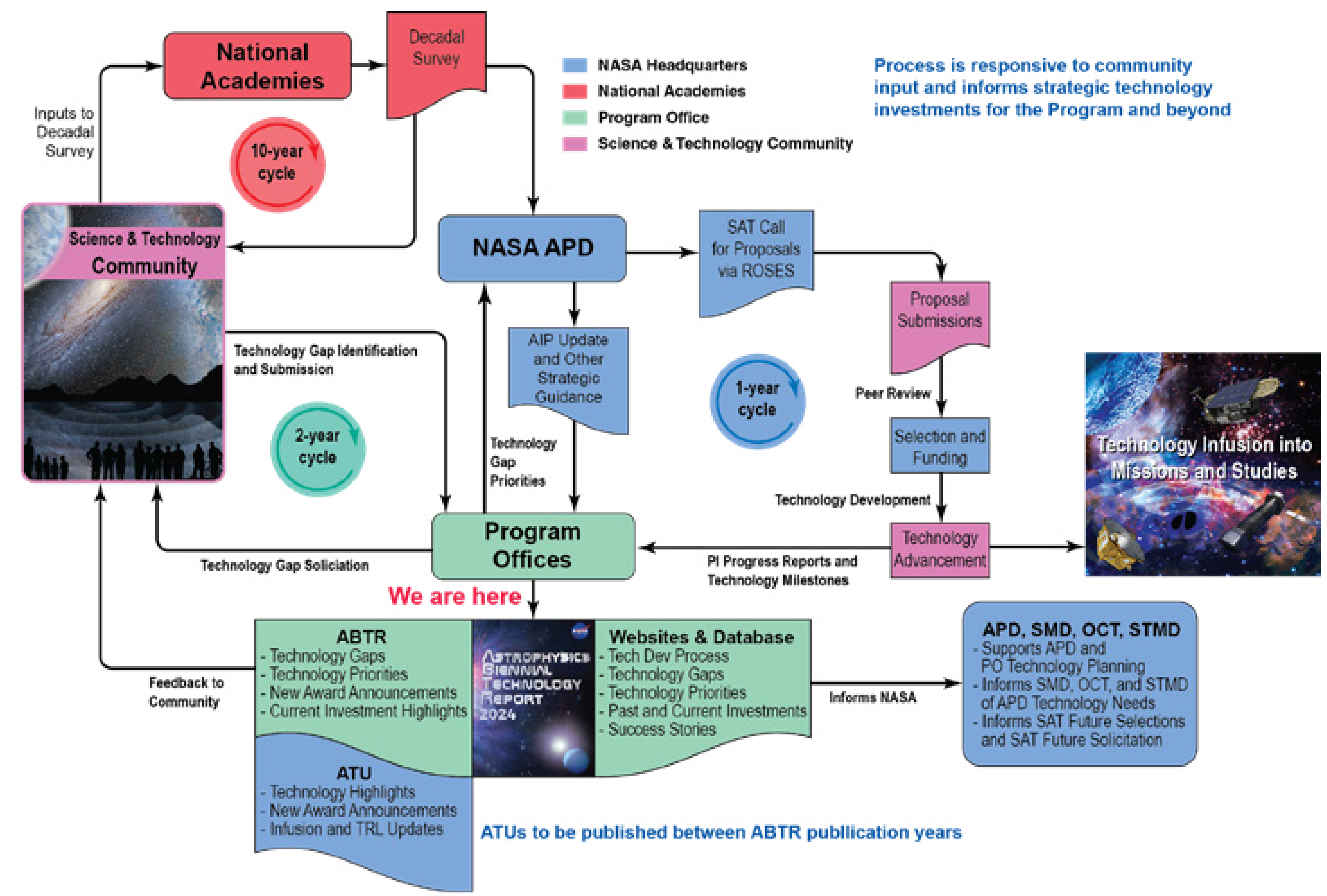
Major astrophysics missions currently in development or being deployed (from left to right: Nancy Grace Roman Space Telescope, RST; Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer, SPHEREx; Advanced Telescope for High ENergy Astrophysics, Athena; and Laser Interferometer Space Antenna, LISA).”

Astrophysics Program Office Technology Maturation

Identifying, soliciting, and funding strategic technologies requires collaboration and cooperation of many bodies and organizations, including the science and technology community, the National Academies' Decadal Survey panels, APD, and the Program Offices, as shown in the flowchart below. This process comprises three interlinked cyclic processes:

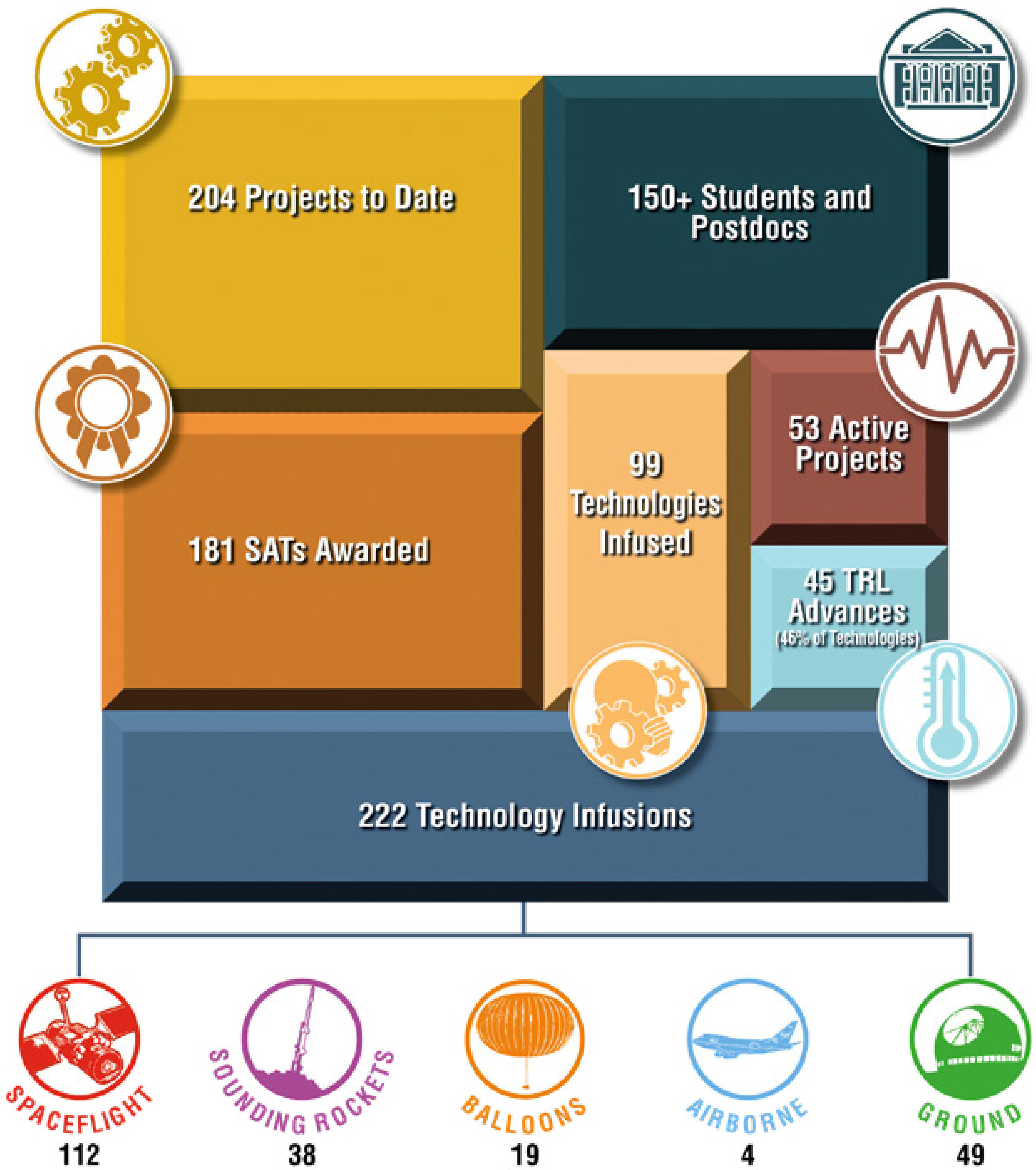
- A 10-year cycle through which the Decadal Survey panels collect and consider input from the community and recommend to APD the highest-priority missions and activities for the coming decade or longer, such as Astro2020;
- A biennial cycle through which the Program Offices collect input from the community and prioritize technology gaps based on APD and Decadal Survey strategic guidance (this ABTR and the Astrophysics Technology Update, or ATU, are the main reporting step of that cycle); and
- An annual process of soliciting, reviewing, and funding technology development proposals.

The proposal and Notice of Intent due dates for technology development and other solicitations are scheduled to enhance responsiveness and enable prompt proposal evaluations and selection decisions. These due dates can be found in the 2024 ROSES webpage.



The Astrophysics strategic technology development process starts with the National Academies’ Decadal Survey recommendations, and APD’s programmatic guidance. Based on these, the process matures and enables infusion of key technologies into Astrophysics missions and beyond.

The Big Picture – Astrophysics Technology Development



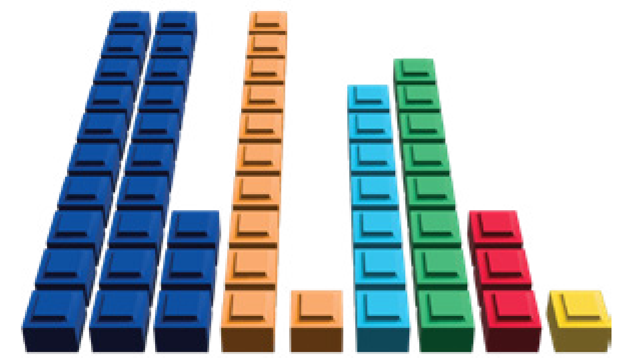
Technology Investment to Date (End of FY 2024)

- 204 technology and related awards to date (53, including 41 SATs, are currently active).
- 181 SAT projects competitively awarded from the 2009 program inception to date, with a 35% proposal win rate in the last three cycles.
- 45 technologies advanced their TRL at least one level to date.
- 99 technologies were infused a total of 222 times into missions or projects (59 technologies 112 times into space missions, 42 technologies 61 times into suborbital missions, and 24 technologies 49 times into ground observatories).
- Over 150 students and postdocs participated in Astrophysics technology projects. Many were then accepted into graduate programs, graduated with a PhD, and/or obtained full-time positions at other institutions or high-tech companies. All these contributed to our technology and academic workforce for decades to come, in astrophysics and beyond.

Current Projects by Signal Type

Signal types addressed by current projects include electromagnetic waves across the spectrum from X-rays to sub-mm. Since future exoplanet observatories are expected to observe across the UV/Optical/IR (UVOIR) spectrum, exoplanet-science-driven projects are deemed here to address that broad band. Projects affecting more than one signal type are assigned to the signal type most affected.

- 23 UVOIR
- 11 X-rays
- 7 UV
- 8 Far-IR/Sub-mm
- 3 N/A
- 1 Mid-IR



Current Projects by Technology Area

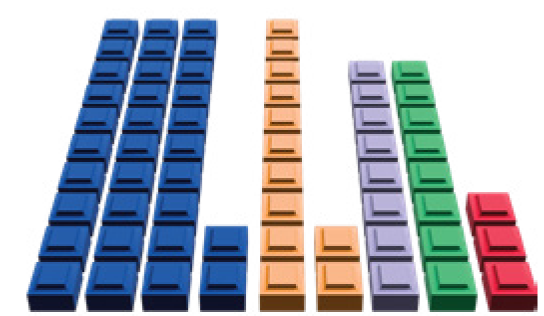
Technology areas funded include detectors, coronagraphs, optics, electronics, optical coatings, starshades, and more with over 73% of projects pursuing detectors, coronagraphs, and optics.

- 19 Detectors
- 14 Coronagraphs
- 6 Optics
- 5 Facilities/Other
- 2 Electronics
- 2 Optical Coatings
- 1 Starshades
- 1 Metrology/Structures
- 1 Micropropulsion
- 1 Radial Velocity Measurement
- 1 Cooling Systems

Current Projects by Missions Supported

Nearly all current projects support at least one strategic mission*, and many support several; therefore the total of mission-support lines is higher than 53.

- 32 HWO
- 12 X-ray Flagship/Probe
- 8 Far-IR Flagship/Probe
- 8 Cosmic Microwave Background (CMB) Probe
- 3 General/Other



* *Strategic astrophysics missions are usually large, multi-purpose observatories that APD is developing, participating in, or interested in, to respond to high-priority science questions or mandates. These missions are generally assigned to a NASA center to implement, with science instruments and platform components selected through open competition.*

COR, ExEP, and PhysCOS Technologies

Current COR Portfolio

"How did we get here?" is the fundamental question the COR Program addresses. COR science objectives include stellar lifecycles and the evolution of the elements, early formation and evolution of planetary systems, archaeology of the Milky Way and its neighbors, history and evolution of galaxies and supermassive black holes, and first light and reionization in the early universe. These are addressed through developing technologies enabling observatories operating across much of the electromagnetic spectrum, from UV through the visible and into the IR. The 21 current technology projects (table) include detectors, multi-object selection, advanced mirror coatings, gratings, large optics, metrology and structures, and advanced cooling.

PROJECT TITLE	PI	PI ORG	TECH TYPE
Low-Noise, Large-Format, Direct-Absorption Far-IR Kinetic Inductance Detector (KID) Arrays	Austermann, J	NIST	Detector
Four-Megapixel Sensor for Ultra-Low-Background Shortwave IR Astronomy	Bottom, M	U Hawaii	Detector
Ultrasensitive Far-IR KID Arrays: Maturation for Flight	Bradford, CM	JPL	Detector
Characterizing Single-Photon-Sensing CMOS Image Sensors for NASA Missions	Figer, D	RIT	Detector
Ultrasensitive Far-IR KID Arrays for Space	Hailey-Dunsheath, S	Caltech	Detector
High-Performance, Stable, and Scalable UV Al Mirror Coatings Using ALD	Hennessy, J	JPL	Coating
Advancing & Qualifying UV Space Technology & Instrumentation	Hoadley, K	U Iowa	UV Facility
High-Performance Far-UV, Near-UV, and UV/Optical CMOS Imagers	Hoenk, M	JPL	Detector
30-mK Continuous Adiabatic Demagnetization Refrigerator (CADR) with Continuous 700-mK Intermediate Heat Intercept	Kimball, M	GSFC	Cooling System
UV Spectroscopy for the Next Decade Through Nanofabrication Techniques	McEntaffer, R	PSU	Optics
High-Performance UV Photon-Counting Detector for Strategic Astrophysics Missions	Nikzad, S	JPL	Detector
Large-Format, High-Efficiency, UV/Optical/Near-IR Photon-Counting Detectors	Nikzad, S	JPL	Detector
Advanced Al Mirrors with Passivated LiF for Environmentally Stable m-Class UV Space Telescopes	Quijada, M	GSFC	Coating
Advancing Readout of Large-Format Far-IR Transition-Edge Sensor (TES) Arrays	Rostem, K	GSFC	Electronics
Ultra-Stable Structures Development and Characterization Using Spatial Dynamic Metrology	Saif, B	GSFC	Metrology/ Structure
Ames Laboratory Astrophysics Directed Work Package Round 2 ISFM	Sciamma-O'Brien, E	ARC	Lab Astrophysics
Scalable Microshutter Systems for Multi-Object Spectroscopy	Scowen, P	GSFC	Optics
Large Low-Noise TES Arrays for Future Far-IR Space Missions	Staguhn, J	JHU	Detector
UV/Optical to Far-IR Mirror and Telescope Technology Development	Stahl, HP	MSFC	Optics
Large-Format, High-Dynamic-Range UV Micro-Channel-Plate (MCP) Detectors and Timepix4 Readouts	Vallerga, J	UCB	Detector
The Advanced Astrophysics Spectroscopy Lab at LASP	Vorobiev, D	LASP	UV Facility

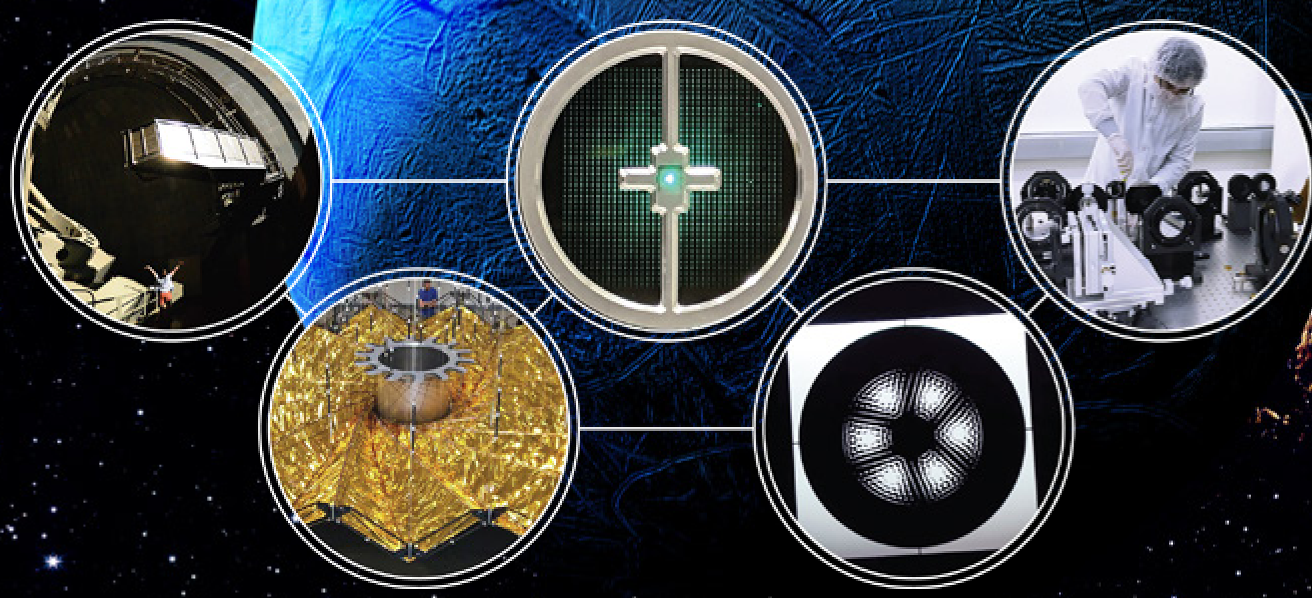
For more information see www.astrostrategictech.us

Current ExEP Portfolio

"Are we alone?" is the fundamental question for ExEP, which is addressed by detecting and characterizing planets around our stellar neighbors, especially Earth-like planets in their stars' habitable zones, searching for signatures of life. ExEP is thus primarily interested in technologies that enable such observations. This includes 19 projects (table) developing coronagraphs, starshades, detectors, and stability-enhancing technologies.

PROJECT TITLE	PI	PI ORG	TECH TYPE
Starshade Petal Fabrication & Accuracy Demonstration at Full-Scale for IR/Optical/UV Great Observatory	Arya, M.	Stanford	Starshade
Development of a Method for Exoplanet Imaging in Multi-Star Systems	Belikov, R	ARC	Coronagraph
Laboratory Demonstration of High Contrast Using Phase-Induced Amplitude Apodization Complex Mask Coronagraph on a Segmented Aperture	Belikov, R	ARC	Coronagraph
Laboratory Demonstration of Multi-Star Wavefront Control (WFC) in Vacuum	Belikov, R	ARC	Coronagraph
Adaptive High-Order WFC Algorithms for High-Contrast Imaging on the Decadal Survey Testbed	Cahoy, K	MIT	Coronagraph
Segmented Coronagraph Design and Analysis study	Chen, P	JPL	Coronagraph
Linear WFC for High-Contrast Imaging	Guyon, O	U Arizona	Coronagraph
Robust Deep-Contrast Imaging with Self-Calibrating Coronagraph Systems	Guyon, O	U Arizona	Coronagraph
Colloid Thruster Life Testing and Modeling	Marrese-Reading, C	JPL	μ-propulsion
Optimal Spectrograph and WFC Architectures for High-Contrast Exoplanet Characterization	Mawet, D	Caltech	Coronagraph
Laboratory Demonstrations of High Contrast with Black Silicon Coronagraph Masks	Riggs, AJ	JPL	Coronagraph
Vortex Coronagraph High-Contrast Demonstrations	Serabyn, E	JPL	Coronagraph
System-Level Demonstration of High Contrast for Segmented Space Telescopes	Soummer, R	STScI	Coronagraph
Ultra-Stable Mid-IR Detector Array for Space-Based Exoplanet Transit Spectroscopy	Staguhn, J	JHU	Detector
Demonstration of Advanced WFC for Segmented-Aperture Telescopes	Tesch, J	JPL	Coronagraph
Low-Order Hardware Implementation for Sensing and Control in Exoplanet Imaging	Trauger, J	JPL	Coronagraph
Super Lyot ExoEarth Coronagraph	Trauger, J	JPL	Coronagraph
A Novel Optical Etalon for Extreme-Precision Radial Velocity (EPRV) Measurements	Vasisht, G	JPL	EPRV
Dual-Purpose Coronagraph Masks for Enabling High-Contrast Imaging with an IR/Optical/UV Flagship Mission	Wallace, K	JPL	Coronagraph

For more information see www.astrostrategictech.us

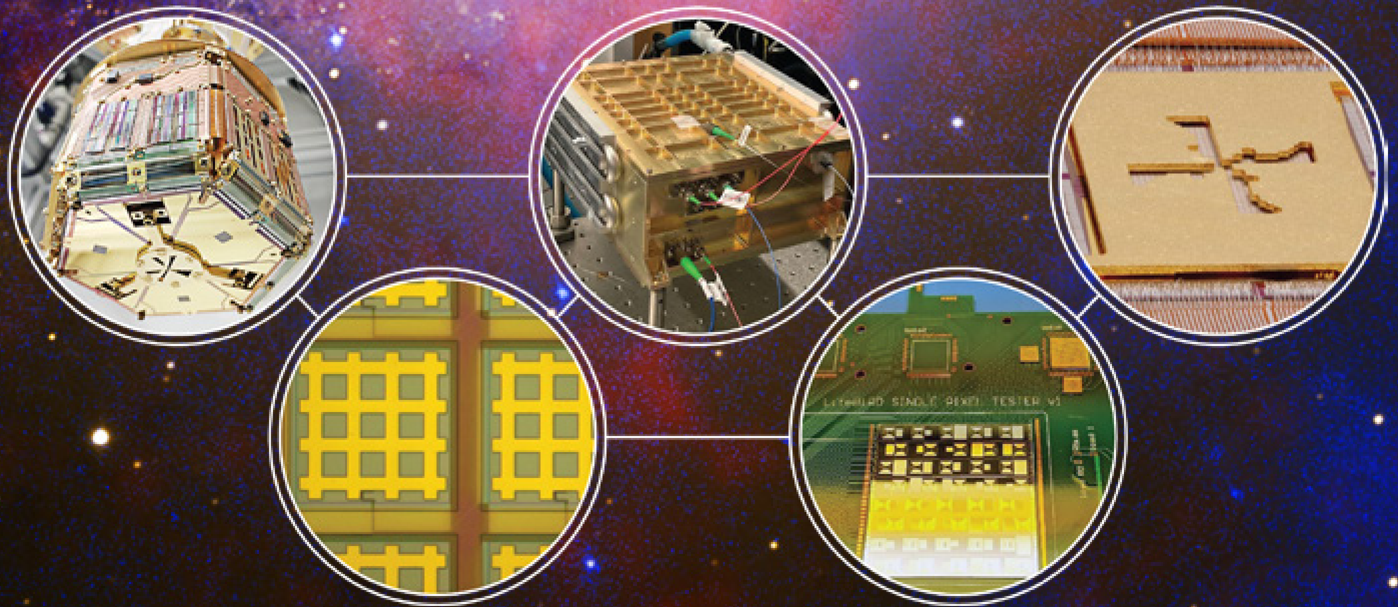


Current PhysCOS Portfolio

"How does the universe work?" is the fundamental question driving PhysCOS science, including testing the validity of Einstein's General Theory of Relativity and understanding the nature of space-time, the behavior of matter and energy in extreme environments, the cosmological parameters governing inflation and the evolution of the universe, and the nature of dark matter and dark energy. The key technologies currently pursued by this Program in 13 projects (table) include X-ray detectors, readout electronics, mirrors, and gratings; as well as software and other tools.

PROJECT TITLE	PI	PI ORG	TECH TYPE
Magnetically Coupled Calorimeters	Bandler, S	GSFC	Detector
Extremely Low-noise, High-Frame-Rate X-ray Image Sensors	Bautz, M	MIT	Detector
Microwave Superconducting QUantum Interference Device (SQUID) Readout Technology for X-ray Missions	Bennett, D	NIST	Electronics
Rapid Electron-Beam Lithography Patterning for Customized Reflection Gratings	DeRoo, C	U Iowa	Optics
MSFC Advanced X-Ray Optics: Formulation to Flight	Gaskin, J	MSFC	Optics
Advanced Pixelated Si Sensors for the Next Generation of X-ray Observatories	Kenter, A	SAO	Detector
Optimized Soft-X-ray Sensors for Strategic X-ray Astrophysics Missions	Leitz, C	MIT/LL	Detector
Advanced X-Ray Microcalorimeters: Laboratory Astrophysics	Porter, S	GSFC	Lab Astrophysics
General Coordinates Network	Racusin, J	GSFC	Software
High-Sensitivity and High-Resolving-Power X-ray Spectrometer	Schattenburg, M	MIT	Optics
Advanced X-Ray Microcalorimeters: TESs	Smith, S	GSFC	Detector
MSFC Relativistic Astrophysics – Multi-Messenger Astrophysics Community Tools and Support	Wilson-Hodge, C	MSFC	Software
Next-Generation X-ray Optics: High Resolution, Light Weight, and Low Cost	Zhang, W	GSFC	Optics

For more information see www.astrostrategictech.us



Astrophysics Technology Developers at Work

Astrophysics technologies cannot be developed without dozens of teams of technology developers, such as those seen below working in their labs on strategic technologies that will enable and enhance the compelling missions envisioned by Astro2020.

Strategic Astrophysics Technology Gap Prioritization

Since 2019, the COR, ExEP, and PhysCOS Program Offices biennially generate a joint list of strategic Astrophysics technology gaps. The full details of the process can be found on our technology website (URL on p. 30). Briefly, the Program Offices start from the previous cycle's list, remove old non-strategic gaps, add new entries of technology gaps relevant to strategic Astrophysics missions, merge entries that overlap, and score each remaining gap on four criteria: (a) strategic alignment, (b) benefits and impacts, (c) urgency, and (d) scope of applicability.

This prioritization cycle is informed by the Astro2020 report and the recently concluded work of the HWO Science, Technology, and Architecture Review Team (START) and Technical Assessment Group (TAG). Astro2020 provides a sweeping and compelling vision of polychromatic electromagnetic and GW observatories peering deep into the cosmos, providing time-domain and multi-messenger observations of general astrophysics phenomena, as well as searching for and imaging and characterizing exo-Earths.

Astro2020 recommended the following strategic space observatories:

- A 6m-class IR/Optical/UV observatory to be launched during the first half of the 2040s (HWO);
- A Far-IR Flagship to be launched later than the 2040s;
- An X-ray Flagship, also to be launched later than the 2040s (before, after, or in parallel to the Far-IR Flagship);
- A Far-IR or X-ray Probe mission to be launched in the early 2030s; and
- A second Probe to be launched about 10 years later, either X-ray or Far-IR (whichever isn't selected as the first Probe) or a CMB Probe, with another Probe to be launched each decade thereafter.

Astro2020 recommends investing in strategic technologies for HWO throughout this decade, and for the Probes starting later in the decade. Technologies for the Far-IR and X-ray Probes will likely also be applicable to the Flagships planned for the same wavelengths. With the first Probe expected to launch within 7-10 years, technologies enabling it will already need to be fairly mature, with some work possible if funded directly.

The 2024 Technology Gap Prioritization

This cycle, the Program Offices assessed 49 technology gaps from 2022 (all but the eight non-strategic gaps), plus 29 gaps from the HWO START/TAG, and 33 community entries – for a total of 111 gaps. These 111 gaps were assigned to the three Programs – 40 to COR, 35 to ExEP, and 36 to PhysCOS. The Executive Committees (ECs) of COR's Program Analysis Group (COPAG) and PhysCOS's Program Analysis Group (PhysPAG) reviewed the gaps assigned to their respective programs. ExEP technologists also reviewed their assigned gaps, during which they added two new gaps. The COPAG EC merged or removed 15 gaps deemed not strategic technology gaps within APD's payload focus, leaving 25 COR gaps. The PhysPAG EC similarly merged or removed 13 gaps, leaving 23 PhysCOS gaps. ExEP technologists defined 13 top-level gaps, moving other gaps to be sub-gaps. Each of the three Program Offices then prioritized its remaining gaps with the participation of managers; scientists, technologists, and subject matter experts from APD and all three Program Offices; as well as independent reviewers. Finally, the three resulting gap lists were merged into the unified, prioritized Astrophysics Technology Gap List of 61 gaps shown on the right. This list will inform APD technology development planning as well as decisions on what technologies to solicit, and will be considered when making funding decisions.

Technology Gap Priorities

The four gap priority tiers are in descending priority order. Gaps within any given tier are arranged alphabetically, as they are considered to be of equal priority. The Program Offices recommend soliciting proposals to close as many Tier-1 gaps as possible, soliciting proposals to close Tier-2 gaps as resources allow, and deferring work on Tier-3 gap technologies for the time being. Non-strategic gaps are ones deemed not relevant for any strategic mission or activity.

Tier-1 Technology Gaps

Coronagraph Contrast and Efficiency in the Near IR
Coronagraph Contrast and Efficiency in the Near UV
Coronagraph Stability
Cryogenic Readouts for Large-Format Far-IR Detectors
Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
High-Bandwidth Cryogenic Readout Technologies for Compact and Large-Format Calorimeter Arrays
High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blazed-Angle UV Gratings
High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
High-Performance Sub-Kelvin Coolers
High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
High-Resolution, Lightweight X-ray Optics
High-Throughput, Large-Format Object-Selection Technologies for Multi-Object and Integral-Field Spectroscopy
Integrated Modeling for HWO: Multi-Physics Systems Modeling, Uncertainty Quantification, and Model Validation
Large-Format, High-Resolution Far-UV (100 - 200 nm) Detectors
Large-Format, High-Resolution Near-UV (200 - 400 nm) Detectors
Low-Stress, Low-Roughness, High-Stability X-ray Reflective Coatings
Mirror Technologies for High Angular Resolution (UV/Visible/Near IR)
Optical Blocking Filters for X-ray Instruments
Scaling and Metrology for Advanced Broadband Mirror Coatings for HWO
Segmented-Pupil Coronagraph Contrast and Efficiency in the Visible Band
UV Multi-Object Spectrograph Calibration Technologies
UV Single-Photon Detection Sensitivity
Visible/Near-IR Single-Photon Detection Sensitivity

Tier-2 Technology Gaps

Advanced Cryocoolers
Broadband X-ray Detectors
Compact, Integrated Spectrometers for 100 to 1000 µm
Cryogenic Far-IR to mm-Wave Focal-Plane Detectors
Far-IR Imaging Interferometer for High-Resolution Spectroscopy
Far-IR Spatio-Spectral Interferometry
Heterodyne Far-IR Detector Systems
High-Performance Computing for Event Reconstruction
High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths
High-Throughput Focusing Optics for 0.1-1 MeV Photons
High-Throughput UV Bandpass Standalone and Detector-Integrated Filters and Bandpass Selection
Improving the Calibration of Far-IR Heterodyne Measurements
Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays
Large-Format, Low-Noise and Ultralow-Noise, Far-IR Direct Detectors
Low-Power Readout and Multiplexing for CMB Detectors
Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
Optical Elements for a CMB Space Mission
Starshade Deployment and Shape Stability
Starshade Starlight Suppression and Model Validation
Stellar Reflex Motion Sensitivity: Astrometry
Stellar Reflex Motion Sensitivity: Extreme Precision Radial Velocity
Warm Readout Electronics for Large-Format Far-IR Detectors

Tier-3 Technology Gaps

Broadband X-ray Polarimeter
Charged-Particle-Discriminating X-ray/Gamma-Ray Detectors
Dynamic Switching for Ultra-Low-Power, High-Resolution Charge Readout
High-Energy-Resolution Gamma-Ray Detectors
Large-Aperture Deployable Antennas for Far-IR/THz/sub-mm Astronomy for Frequencies Above 100 GHz
Large Cryogenic Optics for the Mid IR to Far IR
Large Field-of-View and Effective-Area Gamma-Ray Detectors
Low-Power, Low-Cost Semiconductor Detectors
Low-Power Readout for Silicon Photomultipliers
Photometric and Spectro-Photometric Precision of Time-Domain and Time-Series Measurements
Precision Timing Measurement Technology
Radiation-Tolerant, Photon-Counting Light Detectors
Sensitive Spectrometer for CMB Spectrum Measurement
UV/Optical/Near-IR Tunable Narrowband Imaging Capability

Non-Strategic

Advancement of X-ray Polarimeter Sensitivity
Detection Stability in Mid-IR

For full information on these technology gaps, visit the PhysCOS/COR or ExEP Program Office website (see page 30).

Technology Infusions

Space Missions

Implemented

Directly deposited optical blocking filters flying on OSIRIS-REx/OSIRIS-APEX • High-precision mirror-shell alignment and mounting used for IXPE • Si-thermistor/HgTe microcalorimeter array flew on Hitomi and flying on XRISM • Phasemeter flying on GRACE Follow-On • UV coatings flying on GOLD and ICON • High-Energy Replicated Optics contributed to IXPE and SRG (ART-XC) optics • Adiabatic Demagnetization Refrigerator (ADR) flew on Hitomi and flying on XRISM • APD-funded MCPs flying on ICON, GOLD, Juno, JUICE, and Solar Orbiter • X-Ray test processes and techniques used for IXPE and SRG (ART-XC) • Slumped-glass X-ray mirrors flying on NuSTAR

Upcoming

Multi-star Wavefront Sensing and Control to fly on RST • Charge Management Device developed as NASA contribution for LISA • Protected enhanced LiF (eLiF) mirror coatings and MCP anti-coincidence shielding to fly on SPRITE • Electron-beam-lithography-ruled gratings to be flown on MANTIS • ALD UV coatings to fly on SPRITE, Aspera, and UVEX • Multilayer Al dielectric filters for UV detectors to fly on SPARCS • Delta-doped SRI 4kx4k CMOS image sensors to fly on UVEX • Wavefront Control with two DMs baselined for RST • TES Microcalorimeter arrays and Time-Domain Multiplexing (TDM) baselined for ATHENA X-IFU • End-to-end Coronagraph models baselined for RST • CMB detectors baselined for LiteBIRD • Telescope developed as NASA contribution for LISA • Advanced CCD detectors baselined by SPARCS • Physical Vapor Deposition in support of ALD UV Coatings to fly on SPRITE and Aspera • H4RG IR detectors baselined for RST • Radiation-Tolerant, Photon-Counting, Visible/near-IR Detectors to fly on DarkNESS and DAVINCI • MCPs planned to fly on SPRITE, Aspera, Europa Clipper, GLIDE, Galileo, and MANTIS • Hybrid Lyot Coronagraph baselined for RST • Timepix2 ASICs to fly on PADRE • Feedhorn-coupled symmetric-OMT architectures adopted by LiteBIRD • Laser technology developed as NASA contribution for LISA

Strategic Concept

Directly deposited optical blocking filters baselined for Lynx • Advanced CCD detector baselined by AXIS and Star-X • Multi-star Wavefront Sensing and Control for HabEx and LUVOIR • PIAACMC Coronagraph for HabEx and LUVOIR • MEMS DMs are baselined for HabEx and LUVOIR • CMB detectors and antenna-coupled detectors baselined for PICO • MCP Anti-coincidence shielding baselined for LUVOIR • Next-gen microshutter arrays baselined for HabEx, LUVOIR, and CETUS • Linear wavefront control for HabEx and LUVOIR • Predictive wavefront control and sensor fusion for HabEx and LUVOIR • Avalanche Photodiode HgCdTe near-IR detectors baselined for HabEx and LUVOIR • Delta-doped SRI 4kx4k CMOS image sensors baselined by CASTOR • Starshade technologies baselined for Starshade-RST Rendezvous Probe • CMB detectors baselined for PICO • FPGA-based readout electronics for superconducting arrays baselined for PICO, Origins, GEP, and Cosmic Dawn • Low-blaze-angle grating baselined by ESCAPE • Delta-doped EMCCDs baselined for HabEx • Delta-doped CMOS detector arrays baselined for LUVOIR • Critical-Angle-Transmission (CAT) X-ray gratings baselined for Lynx • Thermal oxide coating-stress compensation for Lynx, AXIS, and TAP mirrors • Vortex Coronagraph baselined for HabEx and LUVOIR • Cross-strip MCP detector systems baselined for HabEx, LUVOIR, and CETUS • MCP detectors baselined for HabEx, LUVOIR, CETUS, ESCAPE, and MAGIC • Electroforming Process Modeling used for MiXO for CubeX • Apodized Pupil Lyot Coronagraph baselined for LUVOIR • Superconducting kilo-pixel far-IR detector architecture baselined for Origins • PTC as pathfinder for zonal thermal control in HabEx • X-Ray test processes and techniques used for MiXO for CubeX • CADR is baselined for Lynx, Origins, PICO, and GEP • Microwave SQUID multiplexers baselined for Lynx and Origins • Time-division SQUID multiplexers baselined for PICO • Single-crystal-silicon X-ray mirrors baselined for Lynx, AXIS, TAP, and STAR-X • Micro-Newton thrusters are baselined for HabEx fine pointing and jitter suppression

Infusion-Ready (TRL 5)

Ultrasensitive Far-IR KID Arrays • Fast X-ray Event Recognition • Single-photon-sensing and photon-number-resolving detector

Sounding Rockets

Implemented

Electroformed X-ray mirror shells flew on FOXSI-4 • High-precision mirror shell alignment and mounting used by FOXSI-4 • Electroformed X-ray mirror shells flew on MaGIXS-2 • Image Slicer flew on INFUSE • Next-gen microshutter arrays flew on FORTIS • Single and multilayer coating techniques used by FOXSI-4 • Si-thermistor/HgTe microcalorimeter array flew on XQC • X-ray reflection grating flew on WRXR and tREXS • ALD mirror coating flew on SISTINE • Superlattice-doped detector flew on SHIELDS • Blazed soft-X-ray reflection grating flew on MaGIXS • MCPs flew on FIRE, SLICE, EUNIS, FORTIS, VeSpR, CHESS, SISTINE, INFUSE, and DEUCE • Electroforming Process Modeling used by FOXSI-4 • X-Ray test processes and techniques used by FOXSI-4 • TES microcalorimeters and Time-division SQUID multiplexers flew on Micro-X • Tpx3 CdTe detector flew on FOXSI-4 • DMDs flew on INFUSE

Upcoming

Electroformed X-ray mirror shells to fly on REDSoX • Electron-beam-lithography-ruled gratings to fly on OAxFORTIS and MOBIUS • Multilayer Al dielectric filters for UV detectors and ALD UV coatings to fly on FLUID • X-ray reflection gratings to be flown on OGRE • Far-UV coatings to fly on FORTIS • X-ray CAT grating baselined for REDSoX • Next-gen microshutter arrays to fly on OAxFORTIS • MCP detectors to fly on MOBIUS, FORTIS, and FLUID • Single-crystal silicon X-ray mirrors to be flown on OGRE

Balloons

Implemented

Antenna-coupled detectors flew on SPIDER • 4.7 THz local oscillator flew on STO-2 and GUSTO • Heterodyne detectors flew on STO-2 • Heterodyne-detector-related C&DH and ASIC flew on HASP • Advanced CCD detectors flew on FIREBall 2 • Broadband Light Rejection with Optical Vortex Coronagraph flew on PICTURE-C • Far-IR large-format detectors flew on PIPER • Time-division SQUID multiplexers flew on SPIDER and PIPER • TiN KIDs were integrated into BLAST-TNG

Upcoming

Microwave SQUID multiplexer firmware and parameters baselined for DR. TES • Setup for Ultra-Sensitive Bolometers to fly on TIM • Far-IR heterodyne technology to fly on ASTHROS • RFSoC readout baselined for EXCLAIM, PUEO, and TIM • Low-loss transmission lines and micromachined packaging and Absorptive mixtures and glint reduction coatings to be implemented on EXCLAIM

Airborne

Implemented

TES Bolometers for the HAWC+ flew on SOFIA • Time-division SQUID multiplexers for the HAWC+ flew on SOFIA • Absorptive mixtures and glint reduction coatings for HAWC+ flew on SOFIA

Upcoming

IF Board to be flown in ONR airborne KID instrument

Ground-Based

Implemented

Microwave SQUID multiplexer crosstalk avoidance implemented at Simons Observatory • Antenna-coupled detectors were deployed on BICEP2, BICEP3/Keck, and BICEP Array • Near-IR LmAPD implemented in U Hawaii 2.2m telescope ULBCam • Ultra-Sensitive Bolometers were deployed at Kitt's Peak • Linear Wavefront Control deployed to Subaru Observatory • Mandrel used to form NIF X-ray microscope optic • RFSoC readout used in Toltec camera at LMT • Spectrograph and Wavefront Control Architectures were deployed on Keck Planet Imager and Characterizer • Delta-doped CCDs placed at Palomar-WaSP and ZTF as permanent facilities • DMDs were deployed on the 4.1-m SOAR Telescope • Electroformed X-ray mirror shell techniques used for NIST Neutron Microscope optics • Vortex coronagraph deployed to Palomar, Keck, and Subaru Observatories • TES bolometers used in the IRAM bolometer camera at the IRAM 30m Telescope • Microwave SQUID multiplexers deployed on GBT MUSTANG2 and Simons Observatory • OMT-coupled TES bolometers deployed on ABS, ACTPol, AdvancedACT, ALI-CPT, GBT MUSTANG2, SPTPol, and Simons Observatory • TES bolometers deployed on JCMT SCUBA2 • Time-division SQUID multiplexers deployed on ABS, ACT, ACTPol, AdvancedACT, BICEP2, BICEP3/Keck, and JCMT SCUBA2 • TiN KIDs were deployed on Toltec Camera at LMT • Feedhorn-coupled symmetric-OMT architectures implemented on ABS, ACTPol, Advanced ACTPol, CLASS, and Simons Observatory • Feedhorn-coupled symmetric-OMT focal planes and absorptive mixtures and glint reduction coatings deployed on CLASS

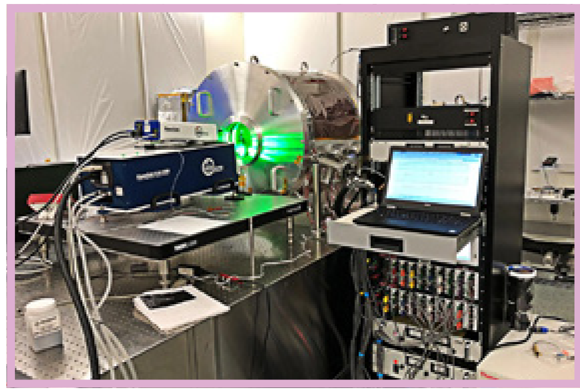
Upcoming

Next generation Near-IR LmAPD implemented in Subaru Observatory • AstroPix CMOS Monolithic Active Pixel Sensors to be implemented at the Electron-Proton/Ion Collider (ePIC) at BNL • RFSoC readout to be used in Toltec camera at CCAT-prime • GISMO to be deployed to GLT • OMT-coupled TES bolometers baselined for CMB-S4 • EPRV etalon to be deployed on Keck Planet Finder • Feedhorn-coupled symmetric-OMT architectures adopted by CMB-S4

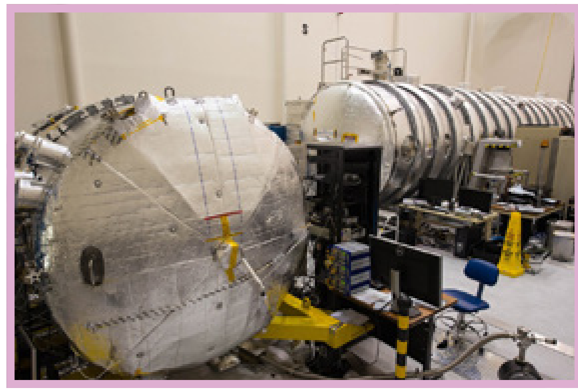
APD's technology development investments have advanced TRLs of dozens of technologies, and led to 160 infusions and over 60 potential infusions into space, suborbital, and ground-based missions and projects.

Technology Development and Test Facilities

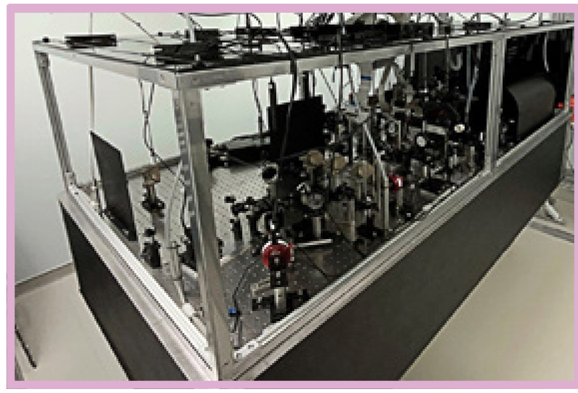
Beyond investments in maturing technologies, APD funds a variety of technology development and test facilities.



Ultrastable Structures Lab (GSFC): This lab has a long history of making precise metrology measurements of specular and diffuse targets to advance the TRL of critical flagship mission components, e.g., optical tests of the JWST Backplane Stability Test Article using a high-speed electronic speckle interferometer proved the backplane stiffness met requirements. The lab maximizes stability using high-performance acoustic tiles, sand-filled walls, piezo isolators supporting a large Invar optical bench, and precision thermal control (±75 μK thermal stability over an hour). Recent in-air results demonstrated few-pm stability for mid-spatial, relative measurements of a 3” test article over multiple two-minute datasets.



High-Contrast Imaging Testbed (HCIT) Laboratory (JPL): HCIT is the world’s premiere facility for demonstrating and advancing space coronagraphs, hosting two vacuum testbeds and one in air, with lasers, DMs, and other optical equipment. The facility was used to demonstrate technology for the RST Coronagraph as well as SAT-funded starlight-suppression technologies that will be needed by HWO.

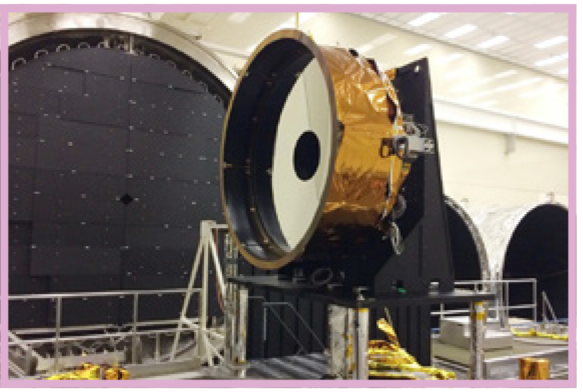


High-Contrast Imager for Complex Aperture Telescopes (HiCAT) Testbed (STScI): HiCAT enables system-level demonstration of coronagraphy for exoplanet direct imaging with HWO. It includes an active, segmented telescope simulator, a coronagraph, and metrology systems. To date, it’s the only testbed able to demonstrate high-contrast coronagraphy with a truly segmented aperture, as required for HWO, albeit limited to ambient conditions. Recent results include 6×10^{-8} (90% confidence interval, CI) contrast in 9% bandpass in a 360° dark hole with inner and outer working angles of $4.4\lambda/D_{pupil}$ and $11\lambda/D_{pupil}$, respectively. Narrowband contrast (3% bandpass) reached 2.4×10^{-8} (90% CI).

Hoadley UV Space Laboratory (U of Iowa): The facility measures intensity of monochromatic UV light to understand how well different materials and gratings reflect, transmit, or diffract UV light. It includes a UV lamp and a monochromator housing a rotatable grating to direct different wavelengths through a small slit to the rest of the system. The color passing through the slit enters a collimator where two mirrors with UV-sensitive $Al+MgF_2$ coating focus/collimate the beam toward a large sample chamber housing a UV detector to record the UV intensity and the optic or material being measured. Between the collimator and sample chamber is a polarizer that can be moved in and out of the beam, giving additional polarization-sensitivity data for UV optics, gratings, and cameras.

Vacuum UV Optical Characterization Testbed (LASP, U of Colorado): The facility optically characterizes advanced optical components, e.g., micromirror arrays, optical fiber bundles, and large mirror segments in the vacuum UV. The testbed measures reflectance and scatter of small optics and advanced optical devices with far-UV coatings, including the throughput and scattered-light properties of digital-micromirror-device (DMD) arrays and two-axis micromirror arrays in the 100-200 nm regime. The LASP team also uses this facility to explore and develop techniques for the optical characterization of large mirror segments with advanced UV mirror coatings ($Al/eLiF/MgF_2$, XeLiF, etc) required for HWO.

Center for Mirror System Characterization & Acceptance Testing (MSFC): Provides thermal-vac performance characterization and analysis services for missions ranging from HWO to X-ray and far-IR Flagships and Probes. This includes XRCF and Marshall-100 (below), as well as a Precision Thermal Control (PTC) Testbed, vertical tower to test mirror gravity sag vs. elevation angle, and extensive metrology instrumentation. The PTC Testbed has sensed, compensated, and controlled a 1.5-m ULE® mirror to 2 mK under large external thermal stimuli, and its sensing system is being updated for sub-mK control stability. Characterizing and qualifying flight mirror systems is of particular importance to HWO, where performance will be limited by thermal stability.

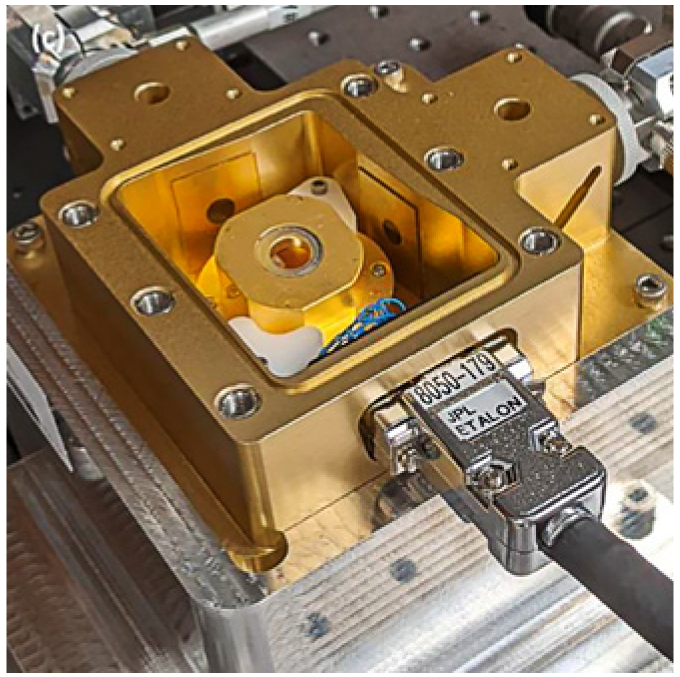


X-Ray & Cryogenic Facility (XRCF, MSFC): With a 500-m beam line and 7×23-m vacuum chamber, XRCF is the world’s largest X-ray optic calibration facility and NASA’s premier thermal optical test facility. A 6,000 square-foot clean room facilitates flight mirror integration, and the chamber can test 6-m-class mirrors to 20 K. XRCF was built to calibrate the Chandra telescope and contributed to multiple X-ray missions. For JWST, MSFC performed cryogenic primary-mirror and backplane structure testing, life-cycle-tested candidate mirror actuators, characterized flight mirror segments, cryo-cycled structure and acceptance-tested mirror assemblies. Recent enhancements allow calibration of Athena X-ray optics via partial illumination in a diverging beam.

Marshall-100 (MSFC): This highly capable, low-overhead test facility for calibrating X-ray optics, detectors, and telescopes consists of a 97-m-long horizontal beamline that terminates at a 3×12-m thermal-vacuum instrument chamber with a -40°C chiller. It provides users with a collimated, 1.3-m-diameter X-ray beam at 0.25-110 keV and a complement of detectors and test stages. An additional vacuum chamber can be attached to the instrument chamber through a gate valve, allowing rapid testing of small optics without re-pressurizing the entire line. The facility allows standard sounding-rocket payload skins to be mounted to the instrument chamber gate valve and aligned to the X-ray beam for end-to-end testing of sounding-rocket payloads.

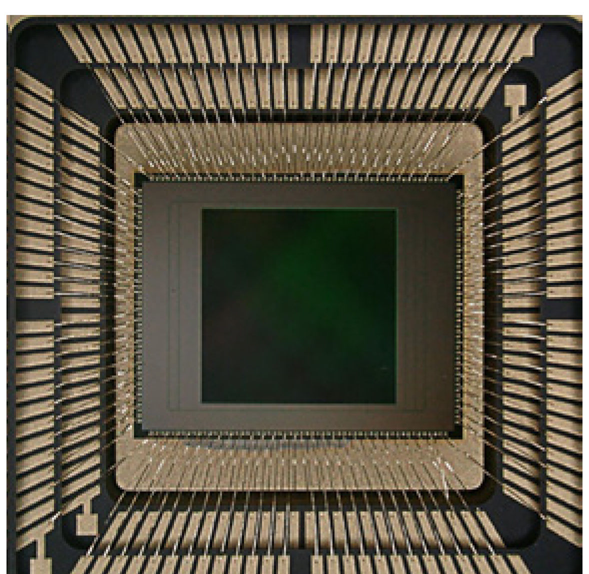
Project Highlights

The following is a selection of current technology development projects addressing a wide range of challenges to enable the gamut of strategic Astrophysics missions. Each of the missions enabled is expected to provide breakthrough science measurements that will push forward the limits of human knowledge of the universe and our place within it. Details of these and our other projects are available through the Astrophysics database at www.astrostrategictech.us.



A Novel Optical Etalon for Precision Radial Velocity (G. Vasisht, JPL)

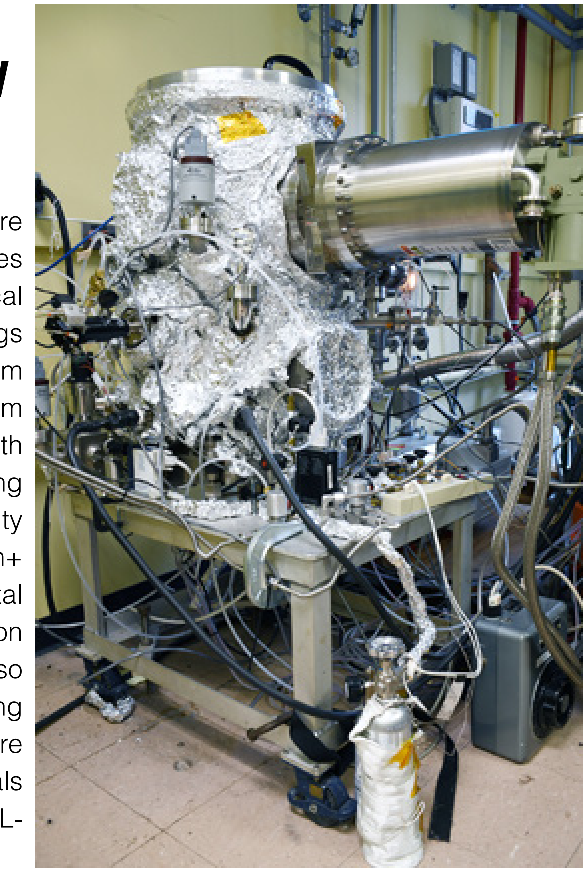
Measuring the mass of Earth-like exoplanets is critical to interpreting spectral measurements of biosignature gases in exoplanet atmospheres, but 10-cm/s sensitivities to the reflex motion of stars due to orbiting planets are needed. Measurement of a star's velocity to this level using radial-velocity doppler shifts requires exquisite wavelength calibration that is stable over long periods. This project designed, built, and is characterizing a whispering-gallery-mode resonator etalon to act as a calibration source. The etalon uses a special technique called “TE-TM lock” to maintain this long period stability, currently at ~1 cm/s levels.



A Single-Photon-Sensing and Photon-Number-Resolving Detector for NASA Missions (D. Figer, RIT)

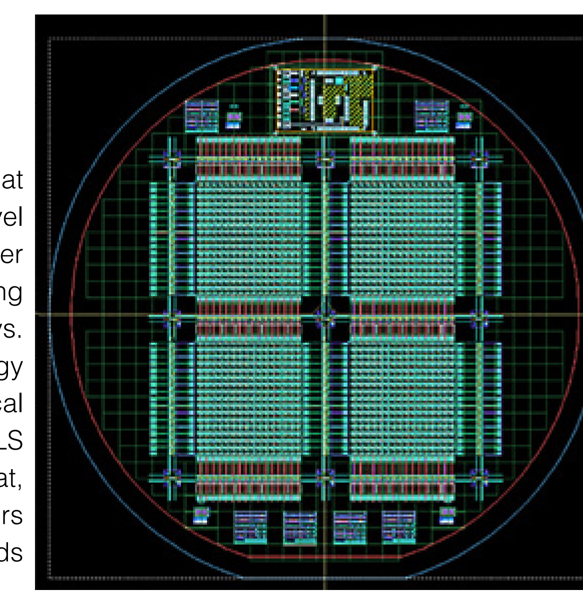
This project and its successor seek to deliver radiation-hard, low-noise, high-quantum-efficiency (QE), photon-counting capability for UV/Visible space missions, including on-die photon-to-digital conversion. The detectors are tested and characterized both in the lab and in on-sky telescope measurements. The team recently completed cryogenic testing and post-radiation characterization, achieving TRL 5 for the detector layer, with the readout planned to reach that level as part of a new SAT cycle.

Advanced Al Mirrors with Passivated LiF for Environmentally Stable 1-m-Class UV Space Telescopes (M. Quijada, GSFC)

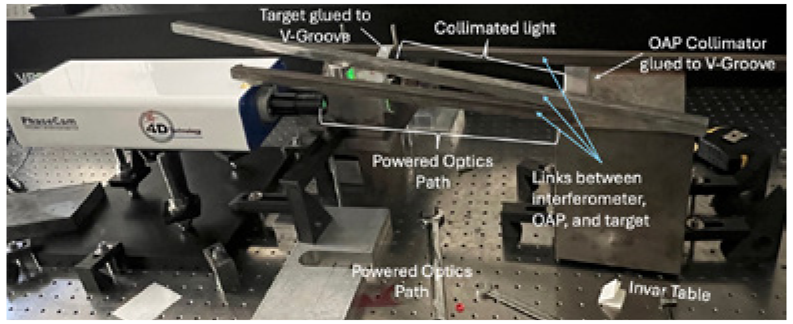


Optical coatings with high broadband reflectivity into the far UV are an enabling technology for HWO and other space observatories performing UV observations. This project develops reactive Physical Vapor Deposition (rPVD) of protected Al-based mirror coatings with the requisite broadband reflectivity performance. Using a 2-m chamber, the team demonstrates rPVD coating of optics up to 1-m diameter. The project rPVD-coats samples of protected Al with a metal-fluoride overcoat using XeF_2 as fluorination agent during the coating process to demonstrate stability and coating uniformity of scaled-up rPVD with XeF_2 fluorination processing over a 1-m+ diameter. The team is upgrading the 2-m chamber. Environmental studies demonstrate Al+XeLiF coatings show little degradation when stored in T < 21°C and relative humidity <50-60%. They also demonstrate minimal native SiO_2 is sufficient to prevent XeF_2 etching on Si-based gratings. Al+XeLiF and Al+$XeMgF_2$ samples are ready to be sent to the International Space Station for the Materials International Space Station Experiment 20 as part of their TRL-advancement efforts.

Advancing Readout of Large-Format Far-IR TES Arrays (K. Rostem, GSFC)

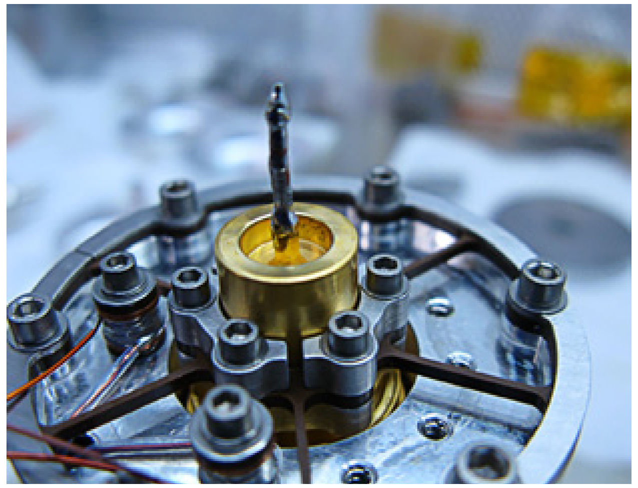


This project works to advance TDM technology for large-format TES bolometers. Specifically, the goal is to implement two-level pixel-address switching (TLS) to significantly reduce the number of cryogenic wires required to read a TES array, thereby reducing the cryogenic power required to read such large-format arrays. Switches are flux-actuated, using the same SQUID TDM technology currently in use in suborbital and ground-based astronomical millimeter and far-IR instruments. The team recently integrated TLS capability in a TDM array design of 16 (row) × 16 (column) format, demonstrated compatibility of warm readout with TLS multiplexers using TES bolometers, and designed cold electronics boards to match TLS multiplexer array readouts.



Development and Characterization of Ultra-Stable Structures Using Spatial Dynamic Metrology (B. Saif, GSFC)

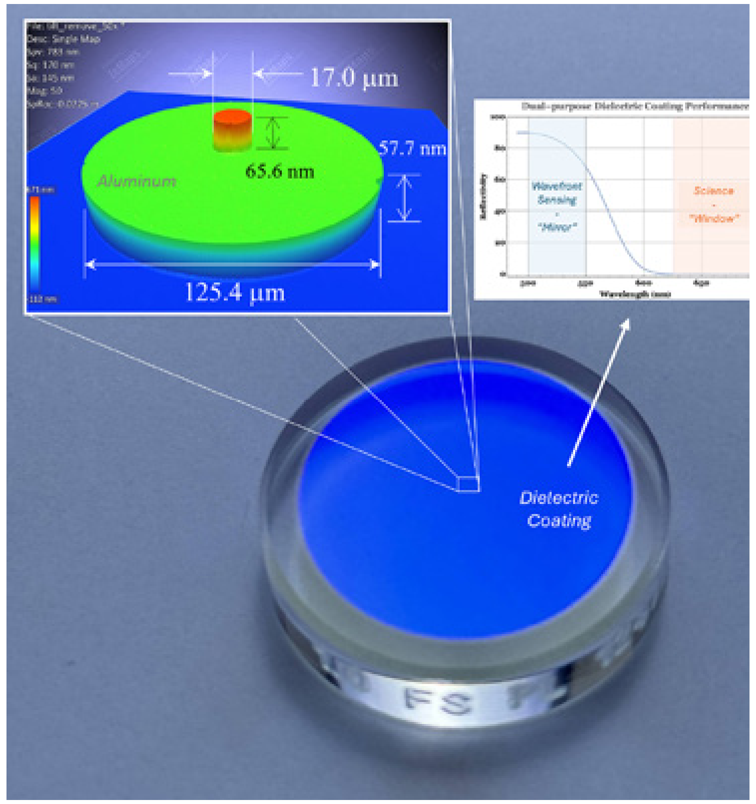
Coronagraphic observations in direct imaging and characterization of habitable planets require actively and passively correcting wave-front errors of large telescopes and keeping them stable to 10 pm (1/5 the radius of a hydrogen atom) for the duration of a science observation (about 10 minutes). The picometer-level metrology testbed developed by this project enables the characterization of thermal and dynamic behavior of optical systems, crucial for missions such as HWO (see facilities description above). The team works with a vendor to develop a Dynamical Digital Speckle Pattern Interferometer with picometer precision, and developed an isolated table-top setup to measure dynamics and drift of material and small structures. The team recently demonstrated an approach for reducing background noise power by eight orders of magnitude, and designed and procured new thermal-control hardware for a test chamber that will enable the necessary authority for testing candidate mirror materials.



Development of an Ultra-Low-Temperature Continuous ADR (CADR) with a Continuous Intermediate Stage for Heat Intercept (M. Kimball, GSFC)

Future astrophysics observatories such as Origins, Lynx, and PICO are expected to include large superconductor-based focal planes cooled to near absolute zero (below -459°F!). Such observatories require unprecedentedly high cooling power at lower operating temperatures. Achieving this without liquid helium (which runs out, ending the mission), and without jitter that disturbs sensitive measurements, is extremely challenging. This project is developing CADR technology with a heat lift of 3 μW at 30 milliKelvin and 1.5 mW at 1 K, and stray magnetic fields of less than 2 μT, to enable such missions. The above three mission concepts all baselined this technology into their reference designs. The team recently assembled and characterized stage 4a, processed stage-4b parts, procured a new paramagnetic material and integrated it as a drop-in replacement salt pill for their older CADR system, completed hysteresis heat measurements from the superconducting magnets, and is conducting a test program to deepen their understanding of the passive gas-gap heat switches used in the system.

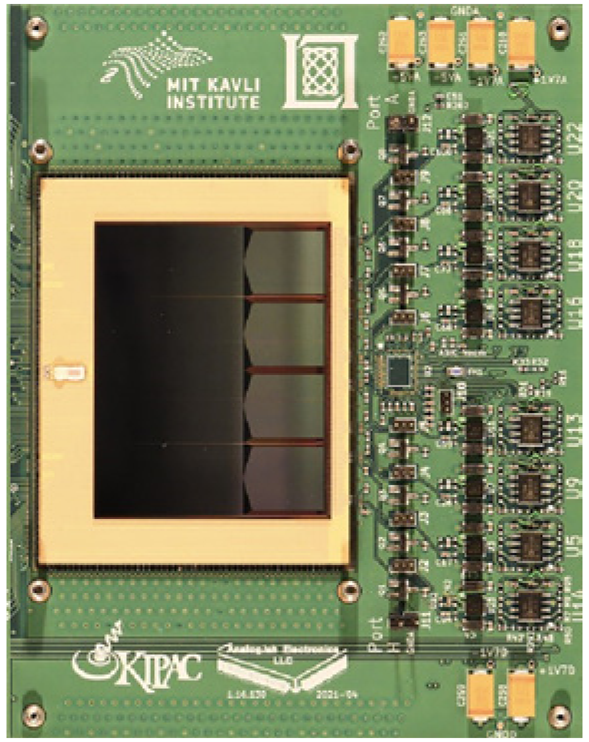
Dual-Purpose Coronagraph Masks (K. Wallace, JPL)

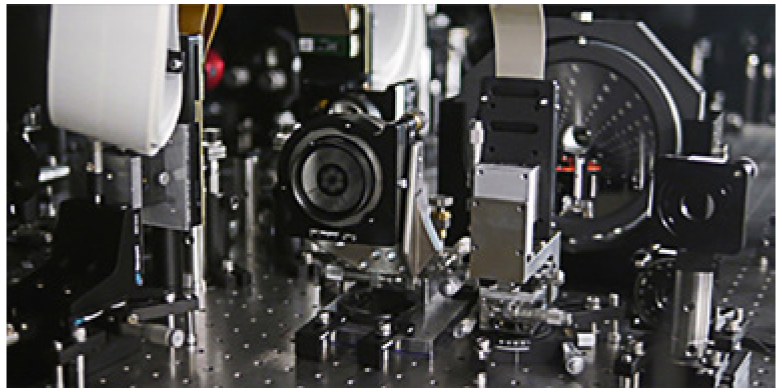


To directly image exo-Earths, space coronagraphs must achieve 10^{-10} contrast performance and maintain it long enough for spectroscopy of very faint planets, requiring adaptive optics. Picometer-level measurement of wavefront errors is needed to drive the adaptive optics correction. This project designs and demonstrates coronagraph masks that simultaneously measure the wavefront error at the coronagraph mask with Zernike wavefront sensing while also performing the starlight suppression function. The first of these dual-purpose focal plane masks was manufactured and demonstrated to achieve $5{\times}10^{-10}$ contrast with simultaneous wavefront sensing at the 10-pm level.

Extremely Low-Noise, High-Frame-Rate X-ray Image Sensors (M. Bautz, MIT)

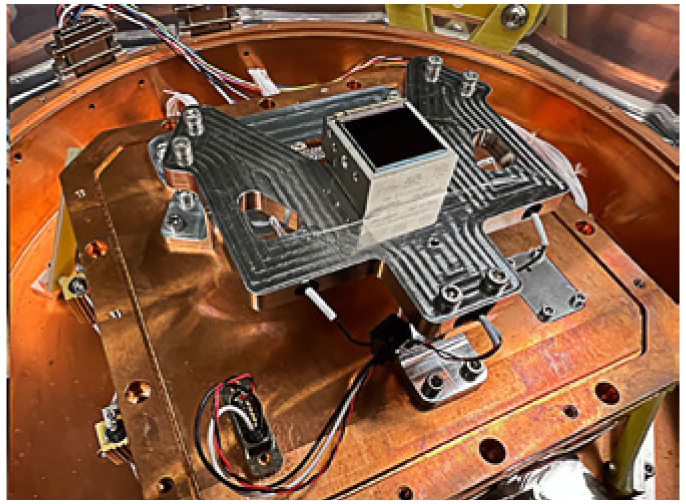
X-ray missions, including an X-ray Great Observatory and X-ray Probe, both recommended by Astro2020, as well as X-ray spectrometer-based Explorers, would all benefit from fast, low-noise, X-ray image sensors. The project is building on an existing MIT Lincoln Laboratory (MIT/LL) advanced-CCD program developing low-noise, low-power, high-frame-rate CCDs. The team, which also includes researchers at Stanford University, recently began fabricating prototype and noise-reduction test sensors significantly exceeding the requirements of the proposed Advanced X-ray Imaging Satellite (AXIS) X-ray Probe.





First System-Level Demonstration of High Contrast for Future Segmented Space Telescopes (R. Soummer, STScI)

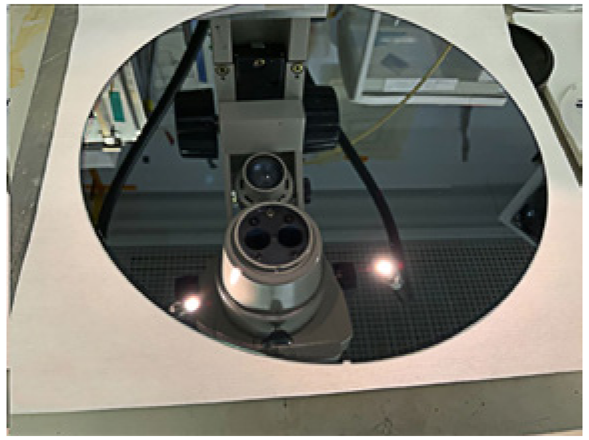
A space coronagraph must achieve 10^{-10} contrast performance to directly image and characterize terrestrial exoplanets as part of an observatory system that includes a segmented-primary-mirror telescope. This project developed a unique optical testbed for prototype demonstrations of a coronagraph system that includes the wavefront-error instability due to hexagonal mirror segments and wavefront sensing and control to mitigate them. The team demonstrated 4×10^{-8} contrast performance over a 9% band from 2-13 λ/D in the presence of dynamic segment misalignments, using a Phase-Apodized Pupil Lyot Coronagraph, paving the way for demonstrations of a future space coronagraph system.



Four-Megapixel Sensor for Ultra-Low-Background Shortwave Infrared Astronomy (M. Bottom, U of Hawaii)

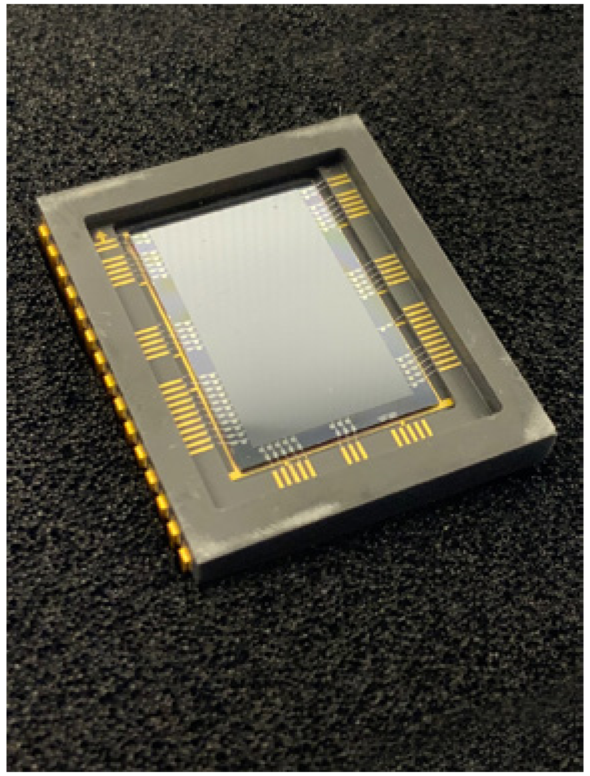
The project's objective is to mature low-noise, large-format, linear-mode avalanche photodiode (LmAPD) detectors suitable for very sensitive IR space astronomy applications, including spectroscopy of exoplanets. LmAPDs hold the potential for significant improvements in readout noise and dark current compared to the current state-of-the-art. The team recently managed to manufacture a megapixel-format chip with negligible glow and dark current, and read noise at least 10 times better than the state-of-the art. Future work will implement a design aimed at reducing persistence.

High-Performance Far-UV, Near-UV, and UV/Optical CMOS Imagers (M. Hoenk, JPL)



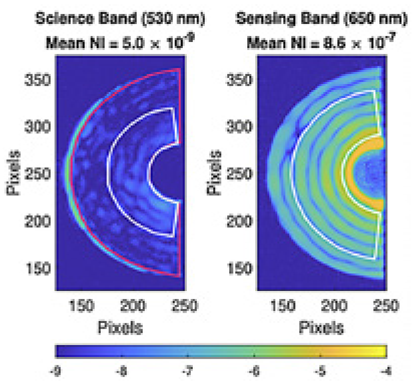
This project's objectives are to fabricate, characterize, and mature CMOS detectors using nanoscale surface engineering to enable HWO requirements for multi-gigapixel-mosaic, visible-blind, near-UV focal planes with large-format (8k×8k), low noise (< 2.5 e^-), small pixels (5-10 µm), and broadband UVOIR response (>50% QE from 200 nm to 400 nm). This includes performance and radiation testing using JPL's UV detector characterization laboratory and Precision Projector Laboratory. Advanced CMOS designs from industry (Teledyne-e2v CIS120 and SRI Mk×Nk detectors) are subjected to JPL's molecular-beam-epitaxy delta-doping process and ALD of integrated multilayer anti-reflection (AR) coatings and out-of-band rejection filters. The team recently built and tested two cameras for performance, radiation, and on-sky testing of delta-doped CIS120 CMOS image sensors. SRI 1k×1k and 2k×4k detectors were then tested for technology infusion into NASA's Medium Explorer (MIDEX) Ultraviolet Explorer (UVEX) mission.

Large-Format, High-Efficiency, UV/Optical/Near-IR Photon-Counting Detectors (S. Nikzad, JPL)



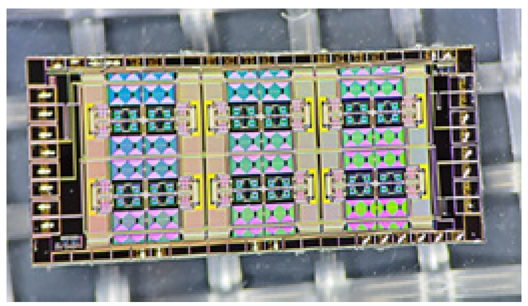
Scalable, high-efficiency, highly stable, photon-counting, solid-state UV/Optical and UV detectors with tailored response can be enabling for HWO. The project works with industry partners (e.g., Teledyne-e2v, or Te2v) to demonstrate and qualify UV/Optical and UV detectors based on 2D-doped Electron Multiplying CCDs (EMCCDs), though the techniques developed can be extended to other Si detectors. The team performs end-to-end post-fabrication processing of bonding, thinning, 2D doping, and (for a subset of devices) applying detector-integrated metal-dielectric filters. The detectors then undergo visible testing at Te2v, UV characterization at JPL, and environmental testing in partnership with Te2v. The team recently processed pathfinder wafers, optimized processes based on the results, verified with bare delta-doped and coated delta-doped devices, and demonstrated block coatings on delta-doped EMCCDs.

Linear Dark Field Control (O. Guyon, U of Arizona)



Space coronagraphs have the challenge of achieving contrast performance for directly imaging exo-Earths and maintaining that contrast long enough for spectroscopy of very faint planets, in the presence of mechanical and thermal disturbances. New wavefront-control techniques can leverage the brighter error signal separated either spatially or spectrally from the location of the planet and using that to feed back to DMs in a way that maintains the zone of deep contrast. Recently, the project demonstrated this novel wavefront-control technique can obtain more than 10× improvement in raw contrast stability at better than 7×10^{-9} raw contrast at the HCIT in a science band centered at 540 nm, while using a 630-nm band for control. In addition, a post-processing contrast improvement of 10-100× was demonstrated using the bright pixel values to calibrate and subtract the point-spread function of the star. The eventual goal of this technique is to loosen stability requirements on a future space observatory's telescope/coronagraph system.

Microwave SQUID Readout Technology Development for Future X-ray Astrophysics Missions (D. Bennett, NIST)

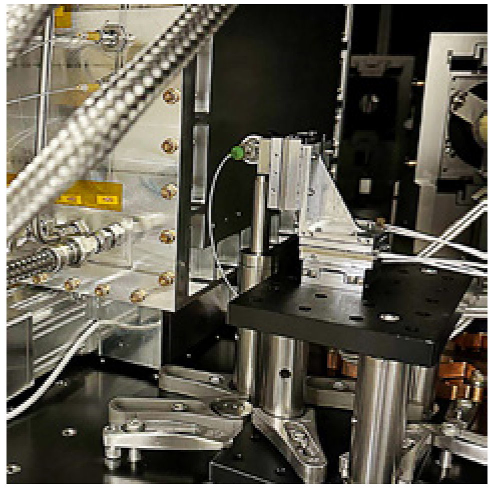


Robust and scalable integration of microwave SQUID multiplexing with large arrays of X-ray microcalorimeters enables large-format X-ray focal plane arrays needed for a future X-ray Great Observatory and X-ray Probe, such as the Line Emission Mapper (LEM). The team recently designed, fabricated, and delivered TDM chips targeting LEM's baseline parameters. They also designed small-footprint TDMs for the LEM compact focal plane option.

Next-Generation X-ray Optics: High Angular Resolution, High Throughput, and Low Cost (W. Zhang, GSFC)

Imaging astrophysical X-ray sources is crucial to studying the high-energy processes in the universe. Since X-rays can only be reflected at very shallow angles, X-ray telescopes use grazing-incidence reflections to focus photons on detectors several meters away. The project developed a process that carves sub-mm-thickness slices from commercial blocks of single-crystal silicon, then etches, polishes, trims, and coats them to make 10×10 cm^2 segments. Expecting this technology to reach its target resolution, the Lynx reference design baselined it, with nearly 40,000 segments to be assembled into a 3-m-diameter barrel, offering 30× larger collection area than Chandra at an expected cost that would fit within a flagship-mission-level budget. The project recently achieved 2.8"-half-power-diameter images and perfected a new method of polishing mirrors, scalable for mass production, reducing time and cost.

Optimal Spectrograph and Wavefront Control Architectures for High-Contrast Exoplanet Characterization (D. Mawet, Caltech)



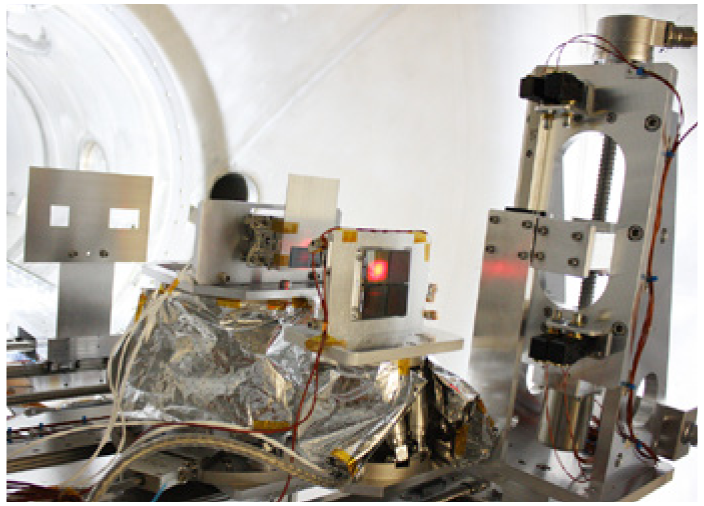
The spectral characterization of Earth-like exoplanets using a coronagraph requires a challenging combination of both deep starlight suppression and wide bandwidth. This project investigated coronagraph architectures and wavefront-control techniques that prioritize wide spectral bandwidth over wide angular coverage. In 2024, the team achieved a new high-contrast bandwidth record using an optical fiber in the image plane (fiber injection unit shown in the photo), reaching a contrast level of 2×10^{-9} at 25% bandwidth.

Parabolic Deformable Mirror (T. Groff, GSFC)

A coronagraph for directly imaging and characterizing Earth-like exoplanets could benefit from integrating DM functionality into an off-axis powered optic. It reduces the overall complexity and physical size of the coronagraph, reduces the necessary actuator count of the DM, and introduces new wavefront-control possibilities not offered by traditional flat deformable mirrors that could improve the bandwidth. A first-generation device was characterized in a coronagraph testbed, demonstrating the basic functionality of this concept, and a second-generation device is being fabricated that incorporate lessons from the first.

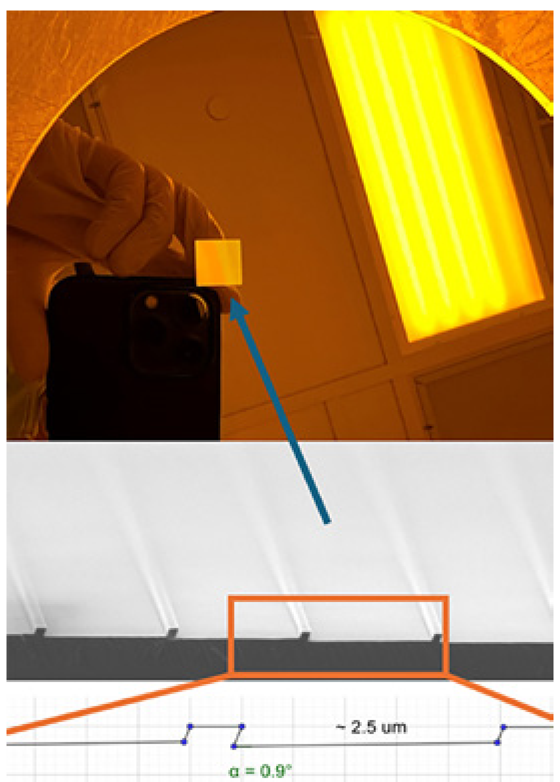
Starshade Mechanical Deployment and Stability (K. Aaron, JPL)

A starshade is a starlight-suppression technology that brings faint terrestrial exoplanets into view by blocking light from a star with an external occulter outside of a space telescope. This is done with a deployable structure, tens of meters in diameter once deployed, that directs diffracted starlight away from the telescope while flying in formation with the telescope thousands of kilometers away. NASA's starshade technology activity has advanced this technology since 2018. Most recently the team successfully achieved milestones in demonstrating deployment accuracy of a 10-m inner disk at the 1-mm level and maintaining shape stability of the optical edges to better than 100 microns, both needed to successfully suppress starlight to the needed level.



Technology Maturation for a High-Sensitivity and High-Resolving-Power X-ray Spectrometer (M. Schattenburg, MIT)

An improved Critical-Angle X-ray Transmission Grating Spectrometer with higher diffraction efficiency and resolving power in combination with grazing-incidence X-ray mirrors and CCD detectors, promise an order-of-magnitude improvement in both efficiency and resolving power over existing spectrographs, enabling absorption- and emission-line spectroscopy needed to study the large-scale structure of the universe, cosmic feedback, the interstellar and intergalactic media, and stellar activity across all stellar types and lifecycles. In collaboration with MIT/LL and Smithsonian Astrophysical Observatory (SAO), the team fabricated multiple 4- and 6-µm-deep flight-like CAT grating facets from 200-mm Silicon-on-Insulator (SOI) wafers using volume production tools; confirmed resolving power of 8,000-13,000 for individual and co-aligned grating facets; patterned new enhanced-SOI wafers with 10× better thickness control; and demonstrated increased diffraction efficiency from chemically thinned grating bars.



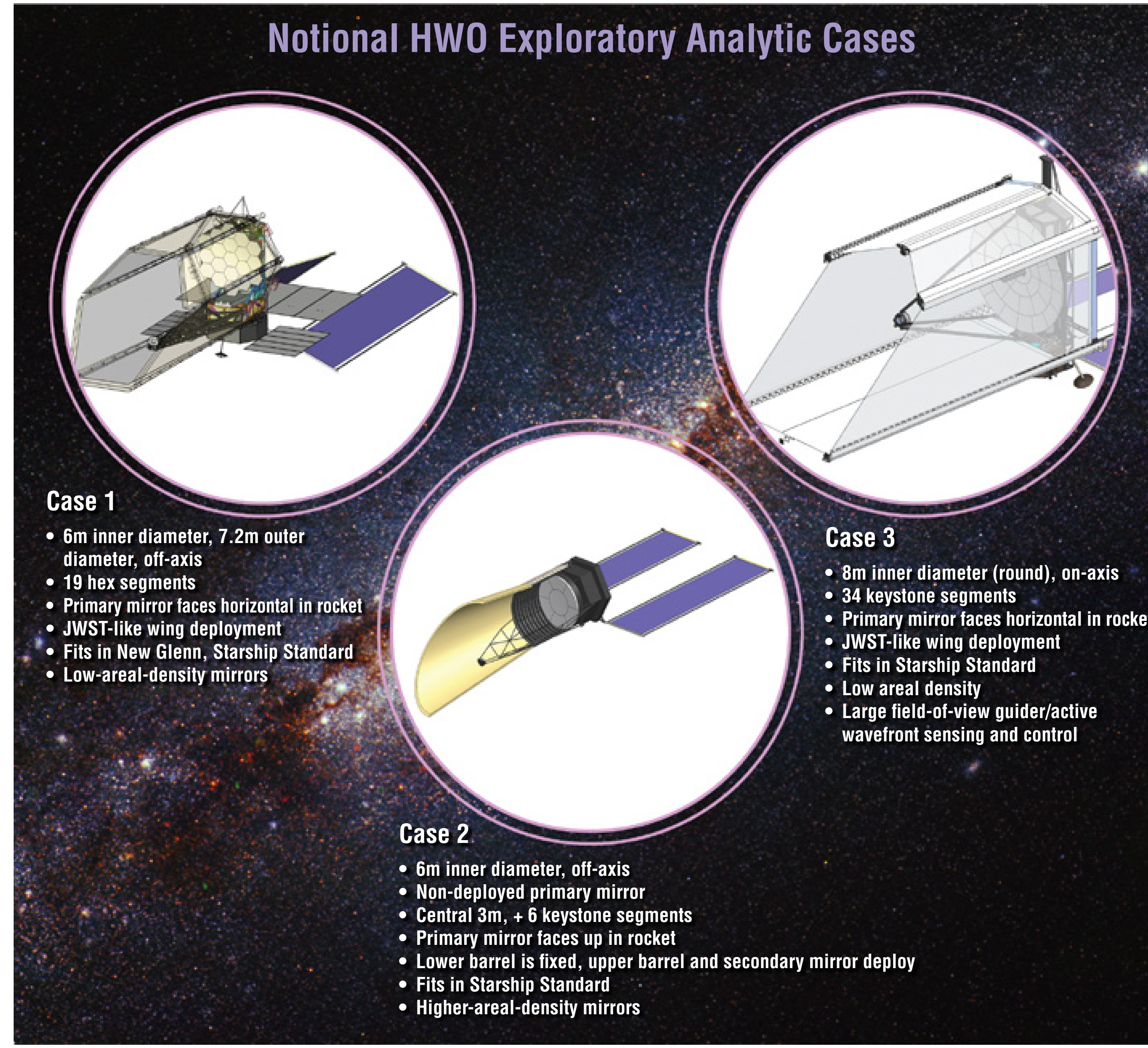
UV Spectroscopy for the Next Decade Enabled Through Nanofabrication Techniques (R. McEntaffer, PSU)

Fabricating flight-like, full-sized, high-efficiency, low-scatter UV echelle gratings with low blaze angles and curved grooves on curved substrates will enable spectroscopy for strategic missions such as HWO, and are also applicable to Explorers, Probes, and sounding-rocket missions. The project investigates a wide range of grating characteristics, including large/small periods, low/high blaze angle, parallel/curved effects, etc. using nanofabrication techniques. Additional project goals include improving UV-grating modeling software, measuring empirical performance, and using suborbital-rocket payloads to define prototypes. The team recently fabricated a 0.9° low-blaze-angle grating and procured and tested a new confocal microscope for substrate alignment with the electron-beam lithography tool.

Looking to the Future

Astro2020 sets the nation's astronomy and astrophysics science priorities for the coming decade and beyond. Aligned with its recommendations, APD's large-mission development focus in the coming years will be on defining HWO science goals, technical requirements, architectures, and technologies (three notional exploratory analytic cases below). In addition, the first Probe mission will soon be selected and begin pre-implementation and then implementation.

These activities will guide the three Program Offices as we continue collaborating in pursuit of development and infusion of key strategic technologies to enable the missions recommended by Astro2020 and later decadal survey reports.



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Astrophysics Technology Database

Searchable database of Astrophysics technology development projects: *www.astrostrategictech.us*

Acronyms

A
ABS . . . Atacama B-mode Search
ABTR . . . Astrophysics Biennial Technology Report
ACT . . . Atacama Cosmology Telescope
ACTPol . . . Atacama Cosmology Telescope Polarization-sensitive detector arrays
ADR . . . Adiabatic Demagnetization Refrigerator
AI . . . Artificial Intelligence
ALD . . . Atomic Layer Deposition
ALI-CPT . . . Ali CMB Polarization Telescope
APD . . . Astrophysics Division
APRA . . . Astrophysics Research and Analysis
AR . . . Anti-Reflective
ARC . . . Ames Research Center
ART-XC . . . Astronomical Roentgen Telescope - X-ray Concentrator
ASIC . . . Application-Specific Integrated Circuit
ASTHROS . Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter wavelengths
Astro2020 . 2020 Decadal Survey on Astronomy and Astrophysics
ASU . . . Arizona State University
Athena . . . Advanced Telescope for High ENergy Astrophysics
ATU . . . Astrophysics Technology Update
AXIS . . . Advanced X-ray Imaging Satellite

B
BICEP . . . Background Imaging of Cosmic Extragalactic Polarization
BLAST-TNG . Balloon-borne Large-Aperture Sub-millimeter Telescope – The Next Generation
BNL . . . Brookhaven National Laboratory

C
C&DH . . . Command and Data Handling
CADR . . . Continuous Adiabatic Demagnetization Refrigerator
CASTOR . . Cosmological Advanced Survey Telescope for Optical and uv Research
CAT . . . Critical-Angle Transmission
CCAT . . . Cerro Chajnantor Atacama Telescope
CCD . . . Charge Coupled Device
CETUS . . . Cosmic Evolution Through UV Spectroscopy
CHESS . . . Colorado High-resolution Echelle Stellar Spectrograph
CI . . . Confidence Interval
CLASS . . . Cosmology Large Angular Scale Surveyor
CMB . . . Cosmic Microwave Background
CMOS . . . Complementary Metal-Oxide Semiconductor
COPAG . . . Cosmic Origins Program Analysis Group
COR . . . Cosmic Origins
Cube-X . . . CubeSat X-ray Telescope

D
DarkNESS . Dark matter as a sterile NEutrino Search Satellite
DAVINCI . . . Deep-Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging
DEUCE . . . Dual-channel Extreme Ultraviolet Continuum Spectrograph
DM . . . Deformable Mirror
DMD . . . Digital Micro-mirror Device
DR-TES . . . Dilution Refrigerator - Transition-Edge Sensor

E
EC . . . Executive Committee
eLiF . . . enhanced Lithium Fluoride
EMCCD . . . Electron-Multiplying CCD
ePIC . . . electron-Proton/Ion Collider
EPRV . . . Extreme-Precision Radial Velocity
ESCAPE . . . Extreme-ultraviolet Stellar Characterization for Atmospheric Physics and Evolution
EUNIS . . . Extreme Ultraviolet Normal Incidence Spectrograph
EXCLAIM . . EXperiment for Cryogenic Large-Aperture Intensity Mapping
ExEP . . . Exoplanet Exploration Program

F
Far-IR . . . Far Infrared
Far-UV . . . Far Ultraviolet
FIRE . . . Far-ultraviolet Imaging Rocket
FIREBall . . . Faint Intergalactic Redshifted Emission Balloon
FLUID . . . Far- and Lyman-Ultraviolet Imaging Demonstrator
FORTIS . . . Far-uv Off Rowland-circle Telescope for Imaging and Spectroscopy
FOXSI . . . Focusing Optics X-ray Solar Imager
FPGA . . . Field-Programmable Gate Array
FY . . . Fiscal Year

G
GBT . . . Green Bank Telescope
GEP . . . Galaxy Evolution Probe
GISMO . . . Goddard-Iram Superconducting 2-Millimeter Observer
GLIDE . . . Global Lyman-alpha Imager of the Dynamic Exosphere
GLT . . . Greenland Telescope
GOLD . . . Global-scale Observations of the Limb and Disk
GRACE . . . Gravity Recovery and Climate Experiment
GSFC . . . Goddard Space Flight Center
GUSTO . . . Galactic/extra-galactic ULDB Spectroscopic THz Observatory
GW . . . Gravitational Wave

H
HabEx . . . Habitable Exoplanet Observatory
HASP . . . High-Altitude Student Payload
HAWC . . . High-resolution Airborne Wideband Camera
HCIT . . . High Contrast Imaging Testbed
HiCAT . . . High-Contrast Imager for Complex Aperture Telescopes
HWO . . . Habitable Worlds Observatory

I
ICON . . . Ionospheric CONnection Explorer
IF . . . Intermediate Frequency
INFUSE . . . INtegral Field UV Spectroscopic Experiment
IR . . . Infrared
IRAM . . . Institut de Radioastronomie Millimetrique
ISFM . . . Internal Scientist Funding Model
IXPE . . . Imaging X-ray Polarimetry Explorer

J
JCMT . . . James Clerk Maxwell Telescope
JHU . . . Johns Hopkins University
JPL . . . Jet Propulsion Laboratory
JUICE . . . JUpiter ICy moons Explorer
JWST . . . James Webb Space Telescope

K
KID . . . Kinetic Inductance Detector

L
LASP . . . Laboratory for Atmospheric and Space Physics
LEM . . . Line Emission Mapper
LISA . . . Laser Interferometer Space Antenna
LiteBIRD . . Light satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection
LmAPD . . . Linear-mode Avalanche Photo Diode
LMT . . . Large Millimeter Telescope
LUVOIR . . . Large UV/Optical/IR Surveyor

M
m-Class . . . Meter-Class
MAGIC . . . Mass-change And Geosciences International Constellation
MaGIXS . . . Marshall Grazing Incidence X-ray Spectrometer
MANTIS . . . Mission and Agile Nanosatellite for Terrestrial Imagery Services
MCP . . . Micro-Channel Plate
MEMS . . . Micro-Electro-Mechanical Systems
Mid-IR . . . Mid Infrared
MIDEX . . . Medium Explorer
MIT . . . Massachusetts Institute of Technology
MIT/LL . . . MIT/Lincoln Labs
MiXo . . . Miniature X-ray optics
ML . . . Machine Learning
mm-Wave . Millimeter-Wave
MOBIUS . . Multi-Octave Bandpass Intergral-field Ultraviolet Spectrograph
MSFC . . . Marshall Space Flight Center
MUSTANG . Multiplexed SQUID TES Array for Ninety Gigahertz

N
N/A . . . Not Applicable
Near-IR . . . Near Infrared
NIRCAM . . Near-IR Camera
NIF . . . National Ignition Facility
NIST . . . National Institute of Standards and Technology
NuSTAR . . . Nuclear Spectroscopic Telescope Array

O
OAxFORTIS . Off-Axis FORTIS
OCT . . . Office of the Chief Technologist
OGRE . . . Off-Plane Grating Rocket Experiment
OMT . . . Orthomode Transducer
ONR . . . Office of Naval Research
OSIRIS-APEX . Origins, Spectral Interpretation, Resource Identification, and Security - Apophis Explorer
OSIRIS-REx . Origins, Spectral Interpretation, Resource Identification, and Security, Regolith Explorer

P
PADRE . . . PolArization and Directivity X-Ray Experiment
PhysCOS . . Physics of the Cosmos
PhysPAG . . Physics of the Cosmos Program Analysis Group
PI . . . Principal Investigator
PIAACMC . Phase-Induced Amplitude Apodization/Complex Mask Coronagraph
PICO . . . Probe of Inflation and Cosmic Origins
PICTURE-C . Planetary Imaging Concept Testbed Using a Recoverable Experiment - Coronagraph
PIPER . . . Primordial Inflation Polarization Explorer
PSU . . . Penn State University
PTC . . . Precision Thermal Control
PUEO . . . Payload for Ultrahigh-Energy Observations

Q
QE . . . Quantum Efficiency

R
REDSOX . . Rocket Experiment Demonstration of a Soft-X-ray polarimeter
RFSoC . . . Radio Frequency System-on-Chip
RIT . . . Rochester Institute of Technology
ROSES . . . Research Opportunities in Space and Earth Sciences
rPVD . . . reactive Physical Vapor Deposition
RST . . . (Nancy Grace) Roman Space Telescope
RTF . . . Roman Technology Fellowship

S
SAO . . . Smithsonian Astrophysical Observatory
SAT . . . Strategic Astrophysics Technology
SCUBA . . . Submillimetre Common-User Bolometer Array
SHIELDS . . Spatial Heterodyne Interferometric Emission Line Dynamics Spectrometer
SiSeRO . . . Single-electron-Sensitive ReadOut
SISTINE . . . Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet host stars
SLICE . . . Suborbital Local Interstellar Cloud Experiment
SMD . . . Science Mission Directorate
SOAR . . . SOuthern Astrophysical Research
SOFIA . . . Stratospheric Observatory For IR Astronomy
SOI . . . Silicon on Insulator
SPARCS . . . Star-Planet Activity Research CubeSat
SPHEREx . . Spectro-Photometer for the History of the Universe and Ices Explorer
SPIDER . . . Suborbital Polarimeter for Inflation Dust and Epoch of Reionization
SPRITE . . . Saturn PRobe Interior and aTmospheric Explorer
SPTPol . . . South Pole Telescope Polarization-sensitive receiver
SQUID . . . Superconducting QUantum Interference Device
SRG . . . Spectr-Roentgen-Gama
SRI . . . Stanford Research Institute
STAR-X . . . Survey and Time-domain Astrophysical Research eXplorer
START . . . Science, Technology, and Architecture Review Team
STMD . . . Space Technology Mission Directorate
STO . . . Stratospheric Terahertz Observatory
STScI . . . Space Telescope Science Institute
Sub-mm . . . Sub-millimeter

T
TAG . . . Technical Assessment Group
TAP . . . Transient Astrophysics Probe
TDM . . . Time-Domain Multiplexing
TE-TM . . . Transverse Electric - Transverse Magnetic
Te2v . . . Teledyne e2v
TES . . . Transition-Edge Sensor
TIM . . . Terahertz Intensity Mapper
TLS . . . Two-Level Switching
tREXS . . . The Rocket for Extended X-ray Spectroscopy
TRL . . . Technology Readiness Level

U
UCB . . . University of California, Berkeley
ULBCam . . Ultra Low Background Camera
UV . . . Ultraviolet
UVEX . . . Ultraviolet Explorer
UVOIR . . . UV/Optical/IR

V
VeSPR . . . Venus Spectral Rocket Experiment

W
WaSP . . . Wafer-Scale Imager for Prime
WFC . . . Wavefront Control
WRXR . . . Water Recovery X-ray Rocket

X
X-IFU . . . X-ray Integral Field Unit
XQC . . . X-ray Quantum Calorimeter
XRCF . . . X-ray & Cryogenic Facility
XRISM . . . X-Ray Imaging and Spectroscopy

Z
ZTF . . . Zwicky Transient Facility

*****
μ-propulsion . Micro-propulsion