National Aeronautics and Space Administration

ExEP
Exoplanet Exploration

PCOS COR
Physics of the Cosmos Cosmic Origins

Astrophysics Division
Science Mission Directorate

Astrophysics Biennial Technology Report 2019

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About the Cover

This Astrophysics Biennial Technology Report (ABTR) is the first report of its kind, introducing joint technology reporting from the three Astrophysics Program Offices – Physics of the Cosmos (PCOS), Cosmic Origins (COR), and Exoplanet Exploration Program (ExEP). Reflecting this, the front and back cover combines visual elements from the three Programs. Opening the cover fully, we see in the lower part one large hexagon with portions of three smaller ones. The image in the central, larger, hexagon depicts a part of the sky that could be of interest for studies related to all Astrophysics science Programs. The partial hexagon at the bottom left (on the back cover) shows artists' impressions of a black hole and an active galactic nucleus, both of interest for the PCOS Program. The partial hexagon at the bottom middle shows a spiral galaxy, a result of the most recent stage of the development of the cosmos, a COR interest. The partial hexagon at the bottom right shows an artist's impression of an exoplanet orbiting a distant sun. The background spread of blue hexagonal outlines refers to the type of large segmented telescopes that will be needed to make future general astrophysics observations in the UV, optical, and IR. This background is distorted by a notional gravitational wave across much of the upper half of the cover, emitted by a pair of colliding black holes shown near the top right of the back cover. A faint set of vectors can be seen at the left middle of the back cover, referencing the search for B-mode polarization in the cosmic microwave background, a possible signal of an Inflationary phase during the first instants after the Big Bang.

Message from Astrophysics Division Director, Dr. Paul Hertz

In 2018, I directed the astrophysics technology management offices at Goddard Space Flight Center and Jet Propulsion Lab to produce a joint biennial technology report starting in 2019, instead of the three individual annual technology reports. From 2011 to 2017, the astrophysics technology management offices for Physics of the Cosmos (PCOS), Cosmic Origins (COR), and Exoplanet Exploration (ExEP) issued annual technology reports.

The most recent of these annual technology reports, produced in 2017, were supplemented with the inclusion of technology development needs identified by the Science and Technology Definition Teams for the Habitable Exoplanet Observatory (formerly the Habitable Exoplanet Imaging Mission), the Large UV/Optical/IR (LUVOIR) Surveyor, the Lynx X-ray Observatory (formerly the X-Ray Surveyor), and the Origins Space Telescope (formerly the Far-IR Surveyor). These studies were conducted to inform the 2020 Astronomy and Astrophysics Decadal Survey[1].

Producing a single technology report for astrophysics demands integration and coordination in order to assess technology gaps across the themes and to consolidate their priorities. With the collaboration of the science community through the Astrophysics Program Analysis Groups, this coordination and integration has been achieved, and I am pleased to present this inaugural Astrophysics Biennial Technology Report. This document is a streamlined and consolidated compilation of technology gaps across the astrophysics science themes, which continues to be driven by the requirements of future large missions and by the needs of the astrophysics community.

NASA missions rely on cutting-edge technologies to realize the next-generation capabilities required to address the highest-priority, most compelling science questions, and it is a core function of NASA's astrophysics program to develop the unique technologies needed to enable the trail-blazing space-based science missions of the future. NASA has a critical need to mature the technologies that will be infused into future flight programs beyond the proof-of-concept stage to the demonstration stage needed before a technology can be implemented in a space mission. Following a recommendation from the 2010 Decadal Survey, NASA strengthened the Strategic Astrophysics Technology program to mature those technologies required for future strategic astrophysics missions. These technology development efforts included both competed and directed projects, but they are all managed by the astrophysics technology management offices. The selection of technologies to include in the Strategic Astrophysics Technology program were previously informed by the priorities published in the annual technology reports, and will be informed by this 2019 Astrophysics Biennial Technology Report in the near future.

The next issue of the Astrophysics Biennial Technology Report, to be published in 2021, will be informed by the priorities and recommendations of the 2020 Decadal Survey.

I am confident that this new consolidated technology report will be of great benefit to the community in developing and maturing the innovative, next-generation technologies that are required to eliminate the technology gaps identified and enable NASA's future astrophysics missions.

Paul Hertz
Director, Astrophysics Division
Science Mission Directorate

[1] The final reports of the four large mission Science and Technology Definition Teams are available at *https://science.nasa.gov/astrophysics/2020-decadal-survey-planning*.

About NASA Astrophysics Science Programs

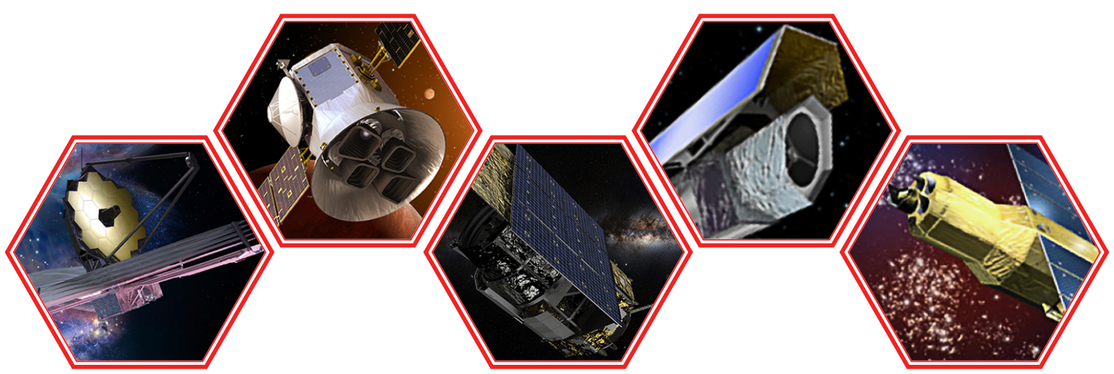
NASA's Astrophysics Division (APD) undertakes spaceflight missions such as the ones shown below to explore the nature of the universe at its largest scales, its earliest moments, and its most extreme conditions; missions that study how galaxies and stars formed and evolved to shape the universe we see 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 Strategic Astrophysics Technology (SAT) program to mature key technologies to enable these future missions, from demonstrated feasibility (i.e., TRL 3), to the point where they can be incorporated into NASA flight missions (i.e., TRL 6).

APD set up three science Programs, Physics of the Cosmos (PCOS), Cosmic Origins (COR), and Exoplanets Exploration Program (ExEP), to address three fundamental questions: "How does the universe work?" (PCOS), "How did we get here?" (COR), and "Are we alone?" (ExEP). The PCOS, COR, and ExEP Program Offices each supports its respective Program, 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 technologies, collecting inputs from the community and technology activities.
- Manage projects that mature technologies for strategic missions from initial Technology Readiness Levels (TRLs) of 3, 4, or 5.
- Promote infusion of technologies into missions and projects.
- Conduct mission studies and develop mission concepts to enable future scientific discoveries.
- Communicate progress to and coordinate with the scientific community.
- Inform the general public about progress achieved by the Programs (see searchable database of Astrophysics technology development projects at www.astrostrategictech.us).

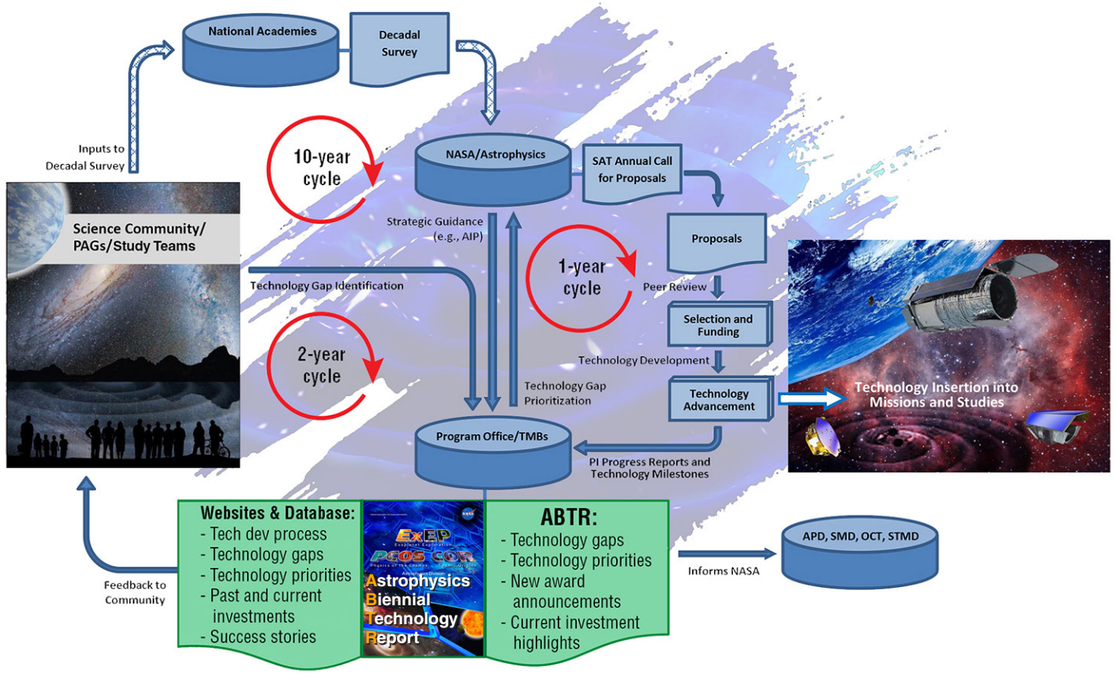


Astrophysics Program Office Technology Maturation

Identifying, soliciting, and funding strategic technologies requires collaboration and cooperation of many bodies and organizations, including the science/technology community, the National Academies' Decadal Survey panels, APD, and the Program Offices, as shown in the process flowchart below. This process is comprised of 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;
- 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 is the main reporting step of that cycle); and
- An annual process of soliciting, reviewing, and funding SAT proposals.

Recently, APD changed the proposal and NOI due dates for the SAT and other solicitations to enhance responsiveness and enable prompter proposal evaluations and selection decisions. These due dates were shifted from January NOI deadlines and March proposal deadlines by about nine months, to October and December, respectively. As a result, these solicitations will come out next in ROSES-2020 early next year, and placeholders in ROSES-2019 were removed.

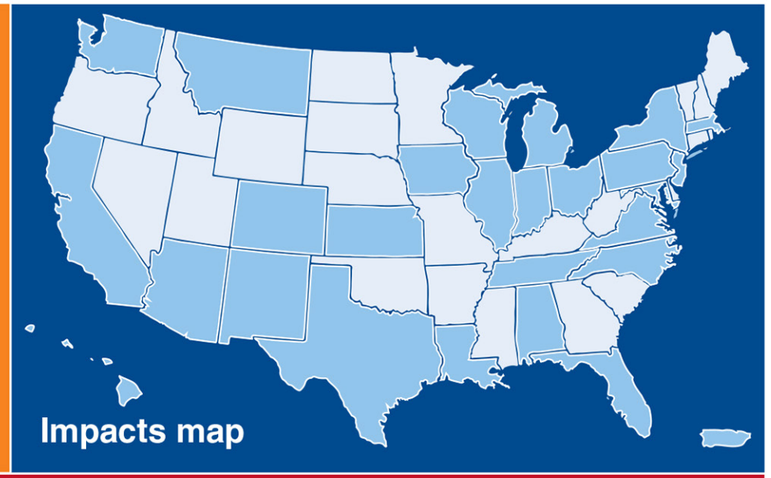


The Astrophysics Strategic Technology Development Process Matures and Enables Infusion of Key Technologies into Astrophysics Missions and Beyond

The Big Picture – Astrophysics Technology Development

136
Projects to date

81
Technologies



49 Active projects

3 Students/postdocs per project

100 SATs awarded
29% Proposal win rate

27% Advanced TRL

28 PI institutions

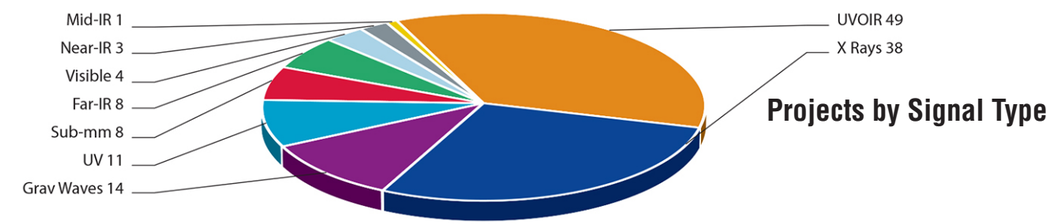
28 | 8 | 6 | 2 | 8

52 Technology infusions

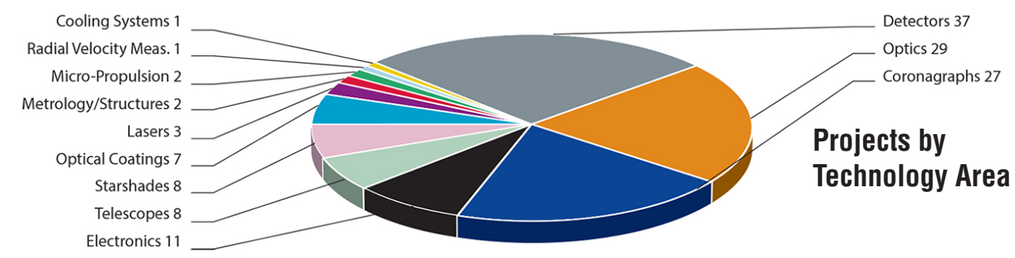
Technology Investment to Date

- 136 technology projects awarded to date to 28 PI institutions (49 projects, including 32 SATs, are currently active).
- 100 SAT projects competitively awarded from 2009 program inception to date.
- 29% SAT proposal win rate to date.
- Work spread across 28 states and territories.
- 20 technologies advanced their TRL at least one level to date (27% of technologies funded to date).
- 52 technologies were infused (28 flown or baselined for space, 16 suborbital, 8 in ground arrays).
- According to a recent survey, 69% of SAT projects hired an average of 3 students and/or postdocs each, training our future astrophysics technology workforce for decades to come.

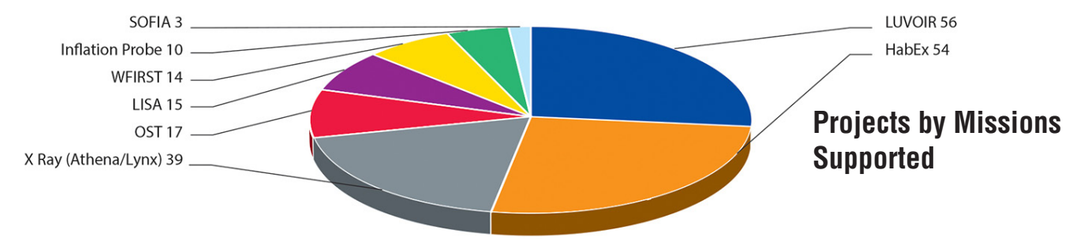
Signal types addressed include electromagnetic waves across the spectrum from X rays to sub-mm, as well as gravitational waves.



Technology areas include detectors, optics, coronagraphs, starshades, electronics, telescopes, optical coatings, and others, with 49% of projects pursuing detectors and optics.

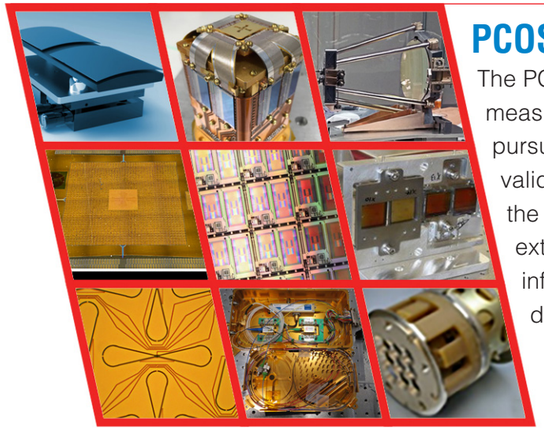


Each of the 136 projects supports at least one strategic mission or mission concept*, and many supported more than one (counting Athena and Lynx together). Applying those to each of the missions they support, the number of technology applications increases from 136 to 208.



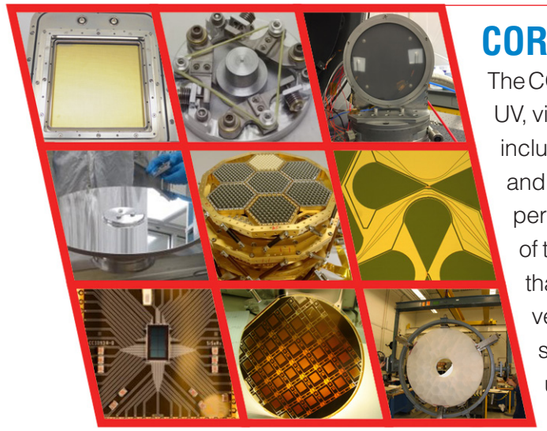
* Strategic astrophysics missions are medium- to large-class non-competed missions that the Astrophysics Division is developing, participating in, or interested in, to respond to high-priority science questions or mandates.

PCOS, COR, and ExEP Technologies



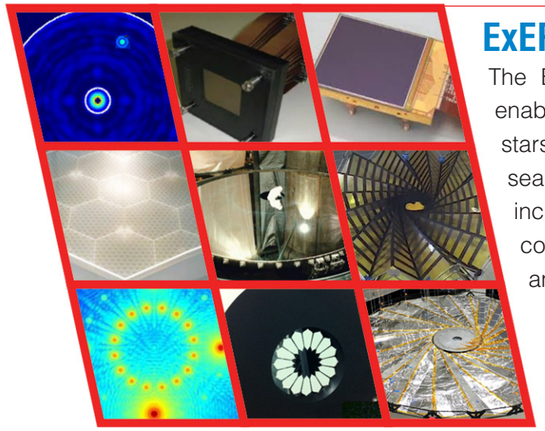
PCOS-Related Technologies

The PCOS Program is primarily interested in technologies enabling measurement of gravitational waves, microwaves, and X rays, in pursuit of Program science objectives that include testing the validity of Einstein's General Theory of Relativity and understanding the nature of spacetime, 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.



COR-Related Technologies

The COR Program is primarily interested in technologies for measuring UV, visible light, and IR, in pursuit of Program science objectives that include understanding when the first stars in the universe formed, and how they influenced the environments around them; how the pervasive and mysterious dark matter clumped up early in the life of the universe, pulling gas along with it into dense concentrations that eventually became galaxies; how galaxies evolved from the very first systems to the types we observe "in the here and now," such as our Milky Way; and understanding when in the early universe supermassive black holes first formed and how they have affected the galaxies in which they reside.



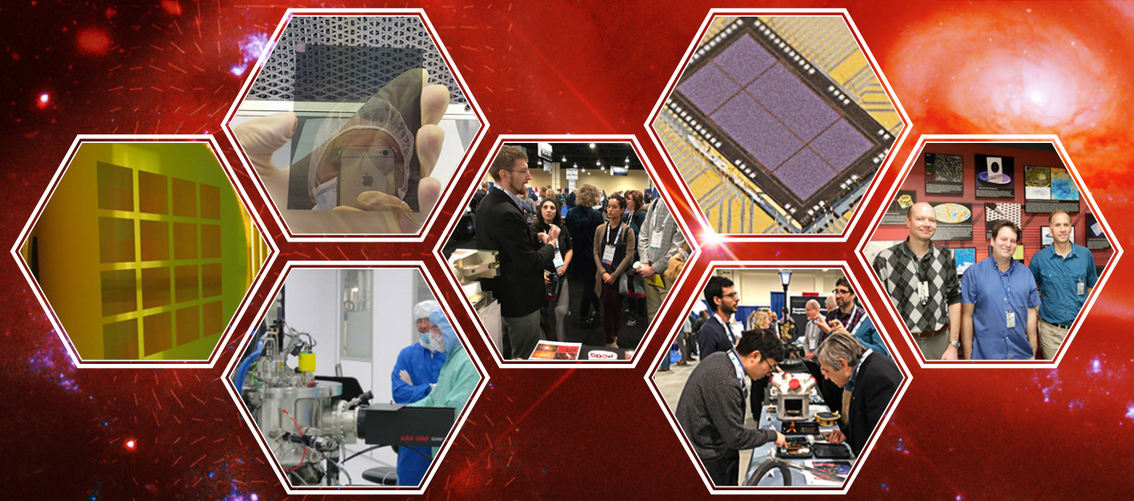
ExEP-Related Technologies

The ExEP Program is primarily interested in technologies that enable the detection and characterization of planets around nearby stars, especially Earth-like planets in the habitable zone and searching for signatures of life there. At this time, technology needs include ultra-stable space-telescope architectures, starshades, coronagraphs, optics, and detectors enabling direct imaging and characterization of exo-Earths.

Current PCOS Portfolio

PCOS Technology Development Title	PI Name	Institution	Technology Area
High-Speed, Low-Noise, Rad-Tolerant CCD Image Sensors for Strategic High-Energy Missions	Bautz, Mark	MIT	Detector
Superconducting Antenna-Coupled Detectors for CMB Polarimetry with the Inflation Probe	Bock, James	JPL	Detector
Development of Adjustable X-Ray Optics with 0.5 Arcsec Resolution for the Lynx Mission Concept	Reid, Paul	SAO	Optics
Microwave SQUID Readout Technology to Enable Lynx and Other Future Great Observatories	Bennett, Douglas	NIST	Electronics
High-Resolution and High-Efficiency X-Ray Transmission Grating Spectrometer	Schattenburg, Mark	MIT	Optics
Space-Based Gravitational-Wave Laser Technology Development Project for LISA	Yu, Anthony	GSFC	Laser
Telescopes for Space-Based Gravitational-Wave Observatories	Livas, Jeffrey	GSFC	Telescope
Phase-Measurement System Development for Interferometric Gravitational-Wave Detectors	Klipstein, William	JPL	Electronics
LISA Colloid Microthruster Technology Development	Ziemer, John	JPL	Micropropulsion
UV LED-Based Charge Management System	Conklin, John	U of FL	Electronics
Advancing the Focal Plane TRL for LiteBIRD and Other Next-Generation CMB Space Missions	Lee, Adrian	UCB	Detector
Next-Generation X-Ray Optics	Zhang, William	GSFC	Optics
Differential Deposition for Figure Correction in X-Ray Optics	Kilaru, Kiran	MSFC	Optics
Direct Fabrication of Full-Shell X-Ray Optics	Bongiorno, Stephen	MSFC	Optics
Computer-Controlled Polishing of High-Quality X-Ray Optics Mandrels	Davis, Jacqueline	MSFC	Optics
Low-Stress Mirror Coatings for X-Ray Optics	Broadway, David	MSFC	Coatings
X-Ray Testing and Calibration	Ramsey, Brian	MSFC	Optics
Hybrid X-Ray Optics by Additive Manufacturing	Broadway, David	MSFC	Optics
Advanced TES Microcalorimeters	Kilbourne, Caroline	GSFC	Detector
Laboratory Spectroscopy for Space Atomic Physics	Porter, Scott	GSFC	Detector
Magnetically Coupled Calorimeters	Bandler, Simon	GSFC	Detector
Providing Enabling and Enhancing Technologies for a Demonstration Model of the Athena X-IFU	Kilbourne, Caroline	GSFC	Detector
US Contribution to the Athena Wide Field Imager	Burrows, David	PSU	Electronics

For more information see *www.astrostrategictech.us*



Current COR Portfolio

COR Technology Development Title	PI Name	Institution	Technology Area
Raising the Technology Readiness Level of 4.7-THz Local Oscillators	Hu, Qing	MIT	Detector
Development of Large-Area (100 mm x 100 mm) Photon-Counting UV Detectors	Vallerga, John	UCB	Detector
Improving UV Coatings and Filters using Innovative Materials Deposited by ALD	Scowen, Paul	ASU	Optical Coating
Advanced FUVUV/Visible Photon-Counting and Ultralow-Noise Detectors	Nikzad, Shouleh	JPL	Detector
High-Efficiency Continuous Cooling for Cryogenic Instruments and Sub-Kelvin Detectors	Tuttle, James	GSFC	Cooling System
Ultrasensitive Bolometers for Far-IR Spectroscopy at the Background Limit	Bradford, Charles	JPL	Detector
High-Performance Sealed-Tube Cross-Strip Photon-Counting Sensors for UV-Vis Astrophysics Instruments	Siegmund, Oswald	UCB	Detector
Development of Digital Micromirror Devices for Far-UV Applications	Ninkov, Zoran	RIT	Optics
Development of a Robust, Efficient Process to Produce Scalable, Superconducting Kilopixel Far-IR Detector Arrays	Staguhn, Johannes	JHU	Detector
Ultra-Stable Structures Development and Characterization Using Spatial Dynamic Metrology	Saif, Babak	GSFC	Metrology/ Structure
Electron Beam Lithography Ruled Gratings for Future UV/Optical Missions: High-Efficiency and Low-Scatter in the Vacuum UV	Fleming, Brian	CU Boulder	Optics
Scalable Micro-Shutter Systems for UV, Visible, and Infrared Spectroscopy	Greenhouse, Matthew	GSFC	Optics
Electron-Beam-Generated Plasma to Enhance Performance of Protected Aluminum Mirrors for Large Space Telescopes	Quijada, Manuel	GSFC	Optical Coating
Development of High-Resolution Far-Infrared Array Receivers	Mehdi, Imran	JPL	Detector
Predictive Thermal Control (PTC) Performance Tests	Stahl, H. Philip	MSFC	Optics

For more information see *www.astrostrategictech.us*

Current ExEP Portfolio

ExEP Technology Development Title	PI Name	Institution	Technology Area
Development of a Method for Exoplanet Imaging in Multi-Star Systems	Belikov, Ruslan	ARC	Coronagraph
MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection	Bierden, Paul	BMC	Coronagraph
Broadband Light Rejection with the Optical Vortex Coronagraph	Serabyn, Eugene	JPL	Coronagraph
Threshold Raw Retrieved Contrast in Coronagraphs Is Limited by Internal Polarization	Breckinridge, James	U of AZ	Coronagraph
Super-Lyot ExoEarth Coronagraph	Trauger, John	JPL	Coronagraph
Laboratory Demonstration of High Contrast Using PIAACMC on a Segmented Aperture	Belikov, Ruslan	ARC	Coronagraph
First System-Level Demonstration of High Contrast for Future Segmented Space Telescopes	Soummer, Rémi	STScI	Coronagraph
Segmented Coronagraph Design and Analysis Study	PO-Managed	JPL	Coronagraph
Starshade Technology Development Activity (S5)	PO-Managed	JPL	Starshade
Vortex Coronagraph High-Contrast Demonstrations	Serabyn, Eugene	JPL	Coronagraph
Linear Wavefront Control for High-Contrast Imaging	Guyon, Olivier	U of AZ	Coronagraph

For more information see *www.astrostrategictech.us*

Strategic Astrophysics Technology Gap Prioritization

In 2018, APD Director Paul Hertz directed the three Program Offices to modify their technology gap prioritization process. The main changes were to reduce the prioritization cadence from annual to biennial, to better match the process to the typical rate of changes in the context of technology development; and to coordinate the process among the Program Offices. The main changes in this regard were:

- The three Programs follow the same schedule for soliciting, prioritizing, and publishing technology gaps.
- Technologists and scientists from the three Program Offices divide the gaps between the Programs based on which Program's science goals would be most strongly affected by closing each gap. No gap is to be prioritized by more than one Program, but if and when appropriate, different versions of the same gap can be prioritized by different Programs under different names and with different requirements.
- Modify the prioritization criteria and implement them uniformly across the three Programs with identical guidance and weighting:
  - Strategic Alignment (as previously used by all three Programs, but addressing all Astrophysics missions and mission concepts)
  - Benefits and Impacts (as previously used by all three Programs, but addressing all Astrophysics science needs and goals)
  - Urgency (addressing both the need-by date and an estimated time needed to close the gap)
  - Scope of Applicability (addressing the number and strategic priority, if any, of Astrophysics missions and concepts that could benefit from closing the gap).
- Each Program still prioritizes its assigned gaps individually, but with the involvement of technologists and scientists from all three Programs.
- Once all three Programs complete their individual processes, the three lists are merged into a single Astrophysics technology gaps list, which is then submitted to APD and published in the ABTR.

The 2019 Technology Gap Prioritization

This cycle, the Program Offices assessed a total of 78 technology gaps. These gaps received from the general community (whether this cycle or carried over from 2017) were reviewed and edited by the relevant Program Analysis Groups (PAGs) if and as needed. The resulting lists were then consolidated with the gap lists submitted by the four large-mission-concept Science and Technology Definition Teams (STDTs). Next, technologists and scientists from the three Program Offices allocated each gap to the Program whose science would be most impacted by closing that gap.

The three Program Offices each prioritized their gaps using a uniform set of criteria, weightings, and guidelines. During this process, some gaps with similar goals were merged, as appropriate. Technologists from the three Program Offices participated in each of the three prioritizations, to provide the most comprehensive knowledge base possible and to ensure uniformity in how gaps were treated across the three Programs. Finally, the three lists were merged into the final joint Astrophysics Technology Gap Priority list of 48 gaps shown on the next page.

Technology Gap Priorities

Following a three-month prioritization process involving managers, technologists, scientists, and subject-matter experts from APD and the Program Offices, as well as independent reviewers, the following is the joint Astrophysics Technology Gap Priority List. 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. Tiers are in descending priority order. The gaps within any given tier are to be considered as equally prioritized (which is why the gaps are arranged alphabetically within each tier).

Tier 1 Technology Gaps
Angular Resolution (UV/Vis/NIR)
Coronagraph Contrast
Coronagraph Contrast Stability
Cryogenic Readouts for Large-Format Far-IR Detectors
Fast, Low-Noise, Megapixel X-Ray Imaging Arrays with Moderate Spectral Resolution
High-Efficiency X-Ray Grating Arrays for High-Resolution Spectroscopy
High-Resolution, Large-Area, Lightweight X-Ray Optics
Large-Format, High-Resolution, UV/Vis Focal Plane Arrays
Large-Format, High-Spectral-Resolution, Small-Pixel X-Ray Focal-Plane Arrays
Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
Large-Format, Low-Noise, High-QE Far-UV Detectors
Next-Generation, Large-Format, Object Selection Technology for Multi-Object Spectrometers for LUVOIR
Vis/NIR Detection Sensitivity

Tier 2 Technology Gaps
Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
Detection Stability in Mid-IR
Heterodyne FIR Detector Arrays and Related Technologies
High-Efficiency Object Selection Technology for UV Multi-Object Spectrometers
High-Performance Spectral Dispersion Component/Device
High-Reflectivity Broadband FUV-to-NIR Mirror Coatings
High-Throughput Bandpass Selection for UV/Vis
Large-Format Object Selection Technology for Multi-Object Spectrometers for HabEx
Starshade Deployment and Shape Stability
Starshade Starlight Suppression and Model Validation
Stellar Reflex Motion Sensitivity – Astrometry
Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity

Tier 3 Technology Gaps
Advanced Cryocoolers
High-Performance, Sub-Kelvin Coolers
Large Cryogenic Optics for the Mid-IR to Far-IR
Long-Wavelength-Blocking Filters for X-Ray Micro-Calorimeters
Low-Noise, High-QE UV Detectors
Low-Stress, Highly Stable X-Ray Reflective Coatings
Photon-Counting, Large-Format UV Detectors
Polarization-Preserving Millimeter-Wave Optical Elements
UV Coatings
UV Detection Sensitivity
UV/Vis/NIR Tunable Narrow-Band Imaging Capability
Warm Readout Electronics for Large-Format Far-IR Detectors

Tier 4 Technology Gaps
Compact, Integrated Spectrometers for 100 to 1000 μm
Optical-Blocking Filters
Rapid Readout Electronics for X-Ray Detectors
Short-Wave UV Coatings

Tier 5 Technology Gaps
Advancement of X-Ray Polarimeter Sensitivity
Far-IR Spatio-Spectral Interferometry
High-Precision Low-Frequency Radio Spectrometers and Interferometers
Mid-IR Coronagraph Contrast
Ultra-High-Resolution Focusing X-Ray Observatory Telescope
Very-Wide-Field Focusing Instrument for Time-Domain X-Ray Astronomy
Wide-Bandwidth, High-Spectral-Dynamic-Range Receiving System for Low-Radio-Frequency Observations on the Lunar Far Side

For full information on these technology gaps, visit the PCOS/COR or ExEP Program Office website (see page 26).

Technology Infusion Timeline

Current Investments Enable Missions Decades into the Future

Infused* Technologies 2010s

*Directly deposited optical blocking filters flying on **OSIRIS-REx** • Phasemeter flying on **GRACE Follow-On** • UV coatings flying on **GOLD** and will fly on **ICON** • Advanced CCD detectors baselined by **SPARCS** CubeSat*

*4.7 THz local oscillator flew on **STO-2** • Advanced CCD detectors flew on **FIREBall 2** • Antenna-coupled detectors flew on **Spider** • Heterodyne detectors flew on **STO** • TiN KIDs were integrated into **BLAST-TNG** balloon mission*

*X-ray reflection grating flew on **WRXR** • Superlattice-doped detector planned to fly on **SHIELDS***

*HIRMES is planned to fly on **SOFIA** • TES Bolometers for the HAWC+ flew on **SOFIA***

*Antenna-coupled detectors were deployed on **BICEP2 & BICEP3/Keck** • DMDs were deployed on the 4.1-m **SOAR** telescope • Feedhorn-coupled detectors will be deployed on **CLASS***

Planned Technology Infusions 2020s

*CMB detectors are planned for **LiteBIRD** • H4RG IR detectors and coronagraph baselined for **WFIRST** • MCP detectors to fly on **SPRITE CubeSat** • Micro-calorimeters are baselined for **Athena***

*Next-gen microshutter arrays to fly on **FORTIS** • MCP detectors to fly on **INFUSE** and **SISTINE** • X-ray reflection gratings to be flown on **OGRE** and **TREXS** • Single-crystal silicon X-ray mirrors to be flown on **OGRE***

*4.7 THz local oscillators are baselined for **GUSTO***

*Vortex coronagraph to be deployed to **Palomar**, **Keck**, and **Subaru** observatories • Antenna-coupled detectors to be deployed to **BICEP Array***

Planned Technology Infusions 2030s+

*Continuous ADR is baselined for **Lynx** as are single-crystal silicon X-ray mirrors and X-ray gratings • Continuous ADR is also baselined for **Origins** and **PICO** • Superconducting kilopixel far-IR detector architecture baselined for **Origins** • Directly deposited optical blocking filters baselined for **Lynx** • MCP detectors are baselined for **HabEx** and **LUVOIR** • Micro-Newton thrusters are baselined for **HabEx** fine pointing and jitter suppression • PTC is expected to serve as a pathfinder for zonal thermal control in **HabEx** • Next-gen microshutter arrays baselined for **HabEx**, **LUVOIR**, and **CETUS Probe** • Coronagraph technologies and MEMS deformable mirrors are baselined for **HabEx** and **LUVOIR***

* *Infusion here means that a technology was implemented in a mission/project, baselined by a mission, or incorporated into a strategic mission concept's reference design.*

Technologies developed for strategic astrophysics missions often find applications beyond strategic missions, including Probes, Explorers, sub-orbital rockets, balloon missions, and ground-based projects. Further, applications aren't limited to astrophysics, with technologies being infused into cross-cutting applications in Earth Science (GRACE-FO and GOLD), Planetary Science (OSIRIS-REx), and Heliophysics (ICON). Finally, since competed projects cannot usually fund their own technology development efforts, and must instead use state-of-the-art technologies available when they're funded, we expect strategic technologies being developed now to be infused into more and more competed missions as time goes by.

New Awards for FY 2020 Start

SAT Project Title	PI Name	Institution	Technology Area
Toward Fast, Low-Noise, Radiation-Tolerant X-Ray Imaging Arrays for Lynx: Raising Technology Readiness Levels Further	Bautz, Mark	MIT	Detectors
Laboratory Demonstration of Multi-Star Wavefront Control in Vacuum	Belikov, Ruslan	ARC	Coronagraph
A Single-Photon-Sensing and Photon-Number-Resolving Detector for NASA Missions	Figer, Donald	RIT	Detectors
Microwave Multiplexing Readout Development	Frisch, Josef	Stanford	Electronics
Photon-Counting NIR LmAPD Arrays for Ultra-Low-Background Space Observations	Hall, Don	U Hawaii	Detectors
High-Performance, Stable, and Scalable UV Aluminum Mirror Coatings Using ALD	Hennessy, John	JPL	Coatings
A Novel Optical Etalon for Precision Radial Velocity Measurements	Leifer, Stephanie	JPL	EPRV
Development of Low-Power FPGA-Based Readout Electronics for Superconducting Detector Arrays	Mauskopf, Philip	ASU	Electronics
Optimal Spectrograph and Wavefront Control Architectures for High-Contrast Exoplanet Characterization	Mawet, Dimitri	Caltech	Coronagraph
Superconducting Antenna-Coupled Detectors and Readouts for PICO CMB Polarimetry	O'Brient, Roger	JPL	Detectors
Development of an Ultra-Stable Mid-Infrared Detector Array for Space-Based Exoplanet Transit Spectroscopy	Staguhn, Johannes	JHU	Detectors
Large-Format, High-Dynamic-Range UV Detector Using MCPs and Timepix Readouts	Vallerga, John	UCB	Detectors

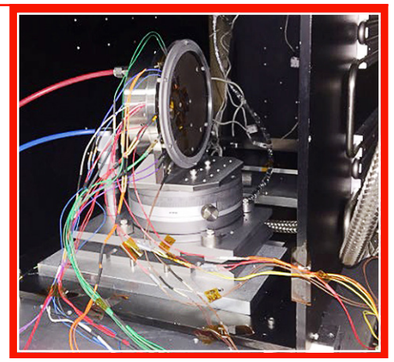
System-Level Segmented Telescope Design Project Title	PI Name	Institution	Technology Area
Ultra-Stable Telescope Research and Analysis – Technology Maturation	Coyle, Laura	Ball Aerospace	Telescopes
Technology Maturation for Astrophysics Space Telescopes	Nordt, Alison	Lockheed Martin	Telescopes

For more information see www.astrostrategictech.us

Project Highlights

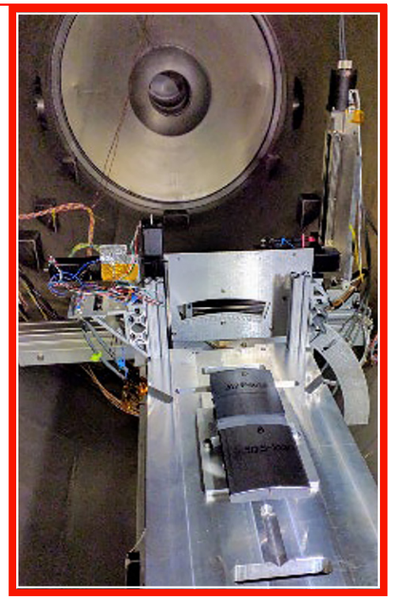
The following is a selection of current technology development projects addressing a wide range of challenges to enable the gamut of strategic Astrophysics missions. Each of the missions enabled is expected to provide breakthrough science measurements that will push forward the limits of human knowledge 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.

Ultra-Stable Structures: Development and Characterization Using Spatial Dynamic Metrology



Coronagraphic observations in direct imaging and characterization of habitable planets requires actively and passively correcting wave-front errors of telescopes up to 15 meters in diameter (larger than a volleyball court), and keeping them stable to 10 pm (1/5 the radius of a hydrogen atom) for the duration of the science observation. **The picometer-level metrology test-bed developed by this project enables the characterization of thermal and dynamic behavior of optical systems, crucial for missions such as the Large UV/Optical/IR (LUVOIR) Surveyor and Habitable Exoplanet Observatory (HabEx). The team successfully measured distance to a ULE® target at nm-level accuracy.**

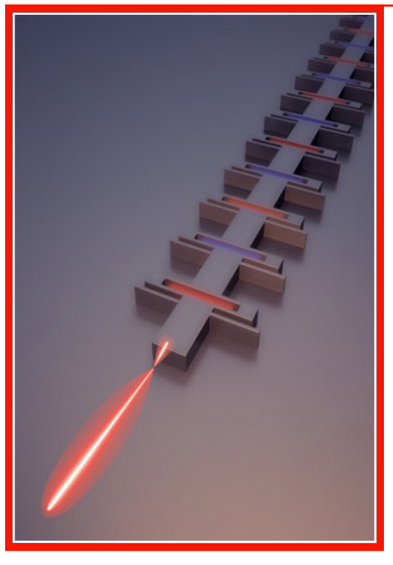
Next-Generation X-ray Optics: High Angular Resolution, High Throughput, and Low Cost



Accurately imaging astrophysical X-ray sources is crucial to studying the high-energy processes in the universe. X rays can only be reflected at very shallow angles, so X-ray telescopes use grazing-incidence reflections to focus X rays on detectors several meters away. **This project develops a process that carves out thin curved slices from commercial blocks of single-crystal silicon, then etches, polishes, trims, and coats them to make 0.5-mm-thin 10×10 cm² segments. This technology was baselined for the Lynx reference design. The team's mirror substrates have proven to be comparable to or better than Chandra's mirrors in figure quality. Their alignment and bonding approach was validated by aligning, bonding, and X-ray-testing a pair of silicon mirrors.** Once the project reaches its performance target, it will enable many future X-ray astronomical missions, including the Lynx mission, which requires nearly 40,000 segments assembled into a 3-m-diameter barrel, with 30× larger collection area than Chandra, at a cost that fits within a flagship-mission-level budget.

Advanced Packaging for Critical-Angle-X-ray Transmission Gratings

Critical-angle transmission (CAT) gratings, used in combination with grazing-incidence X-ray mirrors and CCD detectors, promise an order-of-magnitude improvement in efficiency and another order-of-magnitude improvement in resolving power over existing spectrographs, enabling absorption- and emission-line spectroscopy needed to study the large-scale structure of the universe, cosmic feedback, and the interstellar and intergalactic media. **After previously developing nano-fabrication techniques for making CAT gratings demonstrating single-grating resolution of >10,000 at TRL 4, the project now successfully fabricated larger (32 × 32 mm^2) gratings, frame-mounted, and aligned them to each other. The gratings were tested in an X-ray beam line, obtaining ray-trace-predicted performance. The team fabricated several Arcus-sized (25 × 26 mm^2) gratings, and used integrated laser-based alignment with frame bonding station to bond several Arcus grating facets.**



Raising the Technology Readiness Level of 4.7-THz Local Oscillators

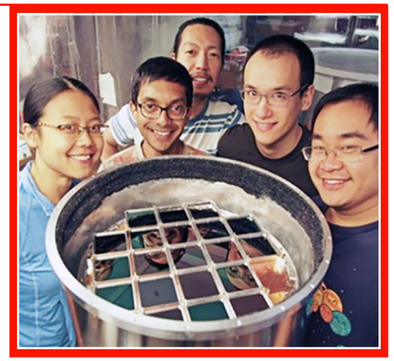
The 63-μm (4.744 THz) [OI] fine-structure line is the dominant cooling line of warm, dense, neutral atomic gas, crucial for astrophysics observations. Spectrally resolved observations of this line with a heterodyne receiver array will let users study the energy balance, physical conditions, morphology, and dynamics of these complex extended regions, providing new and unique insights into the interrelationship of stars and gas in a wide range of galactic and extragalactic environments. The project designed, fabricated, and tested antenna-coupled 3rd-order distributed-feedback structures; and developed a novel scheme of electrically tuning the frequency by ~10 GHz. The lasing frequency and 1.5 mW power level already meet the project's final goal. The maximum operating temperature, at ~30 K, is close to actual observatories' 40-K requirement. **The project developed unidirectional structures with forward output power levels doubled, and a novel π-coupled device with frequency electrically tunable over ~10 GHz. Several devices were shipped to SRON collaborators to test their beam splitters and hot-electron-bolometer mixers for the recently initiated Gal/Xgal U/LDB Spectroscopic/Stratospheric THz Observatory (GUSTO) project.**

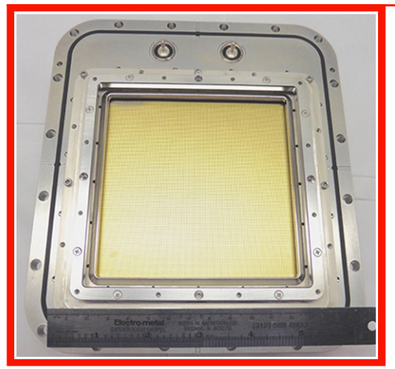
Advanced FUVUV/Visible Photon-Counting and Ultralow-Noise Detectors

This project develops high-performance UV and visible detectors and coating technologies essential for LUVOIR and HabEx, two large-mission concepts studied by NASA as potential astrophysics flagship missions. To address the need for far-UV science, the team uses super-lattice (SL) doping and ALD thin-film coatings to modify large-format, commercial electron-multiplying CCDs (EMCCD) and silicon CMOS active-pixel sensors, creating photon-counting, ultra-low-noise, solar-blind detectors with significantly enhanced UV response. **Beyond enabling large missions, the dramatic increases in detector efficiency enable flagship-class science with the smaller apertures possible for Probe- and Explorer-class missions. The team processed EMCCD wafers by low-temperature SL-doping, optimized visible-blind filters on these devices, and successfully deployed the detectors on the FIREBall-2 balloon mission.**

Superconducting Antenna-Coupled Detectors for CMB Polarimetry with the Inflation Probe

The Cosmic Microwave Background (CMB) is a background glow from the early universe. Finding a so-called B-mode polarization signature in the CMB would support the concept that the universe expanded exponentially in a tiny fraction of a second in an episode cosmologists call "Inflation." Unfortunately, polarized foreground emission from our galaxy makes measuring CMB B-mode polarization challenging. The project developed antenna-coupled detectors with the sensitivity, 30-300 GHz coverage, and systematic-error control needed for space-based CMB-polarization experiments. Deployed in the ground-based BICEP2, BICEP3, and Keck experiments, **these detectors were used to create the deepest CMB maps ever made, in a small section of the sky. Deployed on a future space-based Inflation Probe (IP), this capability would expand to map the entire sky. The team recently tested 40-GHz devices successfully, and fabricated dual-band 30-GHz/40-GHz devices.**





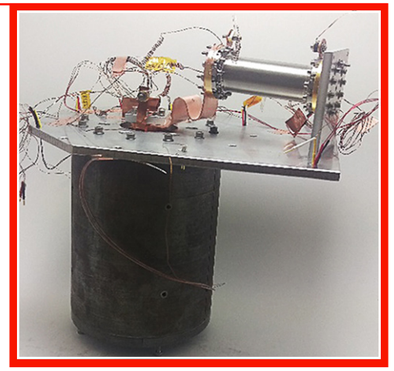
High-Performance Cross-Strip Photon-Counting Sensors for UV-Vis Astrophysics Instruments

Microchannel-plate (MCP) detectors have been the detector of choice for many UV astronomy missions and instruments over the last two decades. MCPs combine high spatial resolution and noiseless imaging in a robust, radiation-hard package, scalable to large formats (>10 × 10 cm^2 and >5k × 5k pixels), and even curved focal planes. **The project developed and tested such large-format detectors, with readout electronics designed to support their noiseless operation, and is in the process of developing higher-performance devices.** Demonstrating that cross-strip detectors with ALD MCPs can be implemented as robust, high-performance detectors addresses the needs of LUVOIR and HabEx, and should do the same for many future NASA missions.

Providing Enabling and Enhancing Technologies for a Demonstration Model of the Athena X-IFU

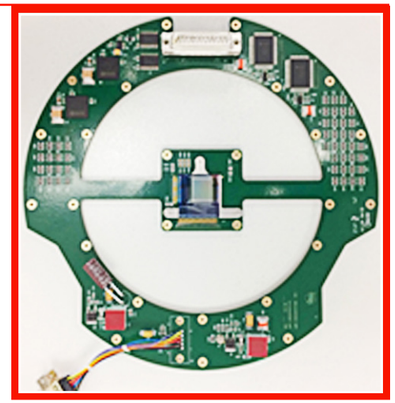
The Athena X-ray integral field unit (X-IFU) will enable high-resolution spectroscopy of X rays emitted from the hot and energetic universe, with high spatial resolution over a wide field of view. This will allow scientists to study the formation of large structures in the universe, the evolution of black holes, and many astrophysical targets of interest. To achieve this unprecedented capability, X-IFU will use transition-edge-sensor (TES) micro-calorimeter pixels developed by NASA, NIST, and Stanford University. **The detectors developed by this collaboration demonstrate improved reproducibility and uniformity of flight-scale (4096-pixel) detector arrays. The team developed alternate multiplexing techniques that improve performance compared to traditional ones, providing Athena with viable options to trade. They demonstrated X-IFU-level performance in 85 pixels of a kilo-pixel array, and integrated a flight-scale array into an experimental platform for testing.**

High-Efficiency Continuous Cooling for Cryogenic Instruments and Sub-Kelvin Detectors



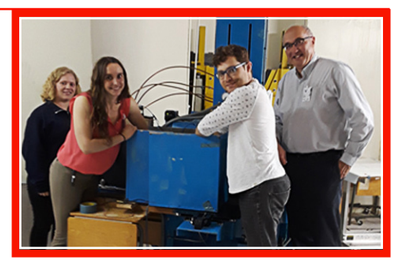
Future major astrophysics missions such as OST, Lynx, and IP will include large superconductor-based focal planes cooled to near absolute zero (below -459°F). These missions require greater cooling power at lower operating temperatures than any previous mission. Achieving this without liquid helium (which runs out, ending the mission) and without jitter that disturbs sensitive measurements is extremely challenging. **The project was able to fabricate and assemble a flight-like 10-to-4-K stage of a six-stage 10-to-0.5-K Continuous Adiabatic Demagnetization Refrigerator, and test it through a complete cooling cycle.** The above three mission concepts have all baselined the 4-to-0.05-K part of this technology into their reference designs, and are considering the 10-to-4-K part as well.

Scalable Microshutter Systems for UV, Visible, and Infrared Spectroscopy

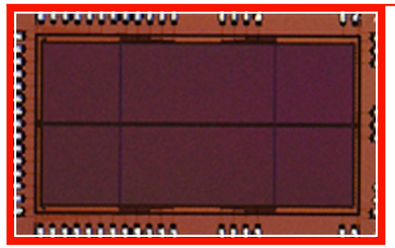


Multiple mission reference designs, including HabEx, LUVOIR, and CETUS, will be enabled by advanced, electrostatically actuated microshutter arrays for large-field-of-view multi-object spectroscopy. These eliminate the macro-mechanisms required by JWST's magnetic actuation technology. The large-format design includes three-side buttable packaging and incorporates 3D printing. Pixel operability is improved by incorporating anti-stiction techniques. **The project team fabricated and assembled a number of pilot arrays, and delivered suborbital flight assemblies to FORTIS sounding rocket mission.**

Development of Digital Micromirror Devices for Far-UV Applications



A technology allowing target selection in a field of view to be input to an imaging spectrometer will enable multi-object spectroscopy. One option for this technology is a modified digital micro-mirror device (DMD). **The team modifies commercial off-the-shelf DMDs, recoating their mirrors (e.g., with Al/AlF_3) and replacing their windows with UV-transparent ones, or operating in an open mode. The recoated devices were successfully tested and are functional**.



Fast, Low-Noise, Radiation-Tolerant CCD Image Sensors for High-Energy Astrophysics

Mission concepts such as Lynx, a Probe-class X-ray imaging mission, and X-ray spectrometer-based Explorers could all benefit from advanced, radiation-tolerant, low-noise, wide-field, high-resolution, CCD X-ray image sensors. The team is building on an existing MIT Lincoln Laboratory digital CCD program developing low-noise, low-power, high-frame-rate CCDs. **Improved 2nd-generation front-illuminated devices demonstrated 4.2 e- RMS noise at 2.5 MHz, within 5% of goal, and a first back-illuminated device was fabricated and packaged.**

Phase-Measurement System Development for Interferometric Gravitational-Wave Detectors

Keeping the LISA constellation aligned and its lasers phase-locked requires a phasemeter system to measure the precise phase evolution of laser beat signals. Technology challenges for the phasemeter include tracking the 100-picowatt, noisy LISA laser signals with micro-cycle precision and high dynamic range. The JPL team developed a flight phasemeter for the GRACE Follow-On Earth Science mission's Laser Ranging Interferometer (LRI). The LRI is a LISA-like inter-spacecraft laser interferometer with many requirements similar to LISA's. **The GRACE-FO LRI recently provided the first successful demonstration of inter-spacecraft laser interferometry, providing relevant flight experience and heritage for LISA.**

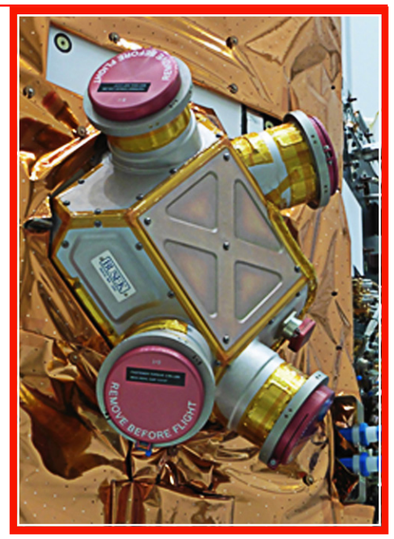
Space-Based Gravitational-Wave Laser Technology Development Project for LISA

Recent first-ever detections of gravitational waves opened a new window to observe some of the most extreme phenomena in the universe, such as mergers of supermassive black holes that occur when galaxies collide. LISA, planned to launch in the 2030s, will be the largest experiment ever constructed by humanity, with three spacecraft flying in a triangular formation over 1.5 million miles on a side. **The project recently demonstrated a prototype of an extremely stable, low-noise mNPRO laser that meets all of LISA's requirements, a first step needed to achieve the goal of measuring a change as small as 10 pm (for comparison, a hydrogen atom's size is about 50 pm) in the immense distance between spacecraft.**

UV-LED-Based Charge Management System

The three LISA spacecraft will fly in formation not only with each other, but each will also fly in formation with a free-falling test mass located in an enclosure inside the spacecraft. To make the extremely precise measurements needed for LISA to succeed requires not only no mechanical contact between each spacecraft and its enclosed test mass, but also sufficiently low electrostatic force noise. This requires keeping test mass bulk potential under 70 mV without physical contact between the spacecraft and the test mass. LISA Pathfinder used UV photons generated by mercury lamps. A new Charge Management System based on UV LEDs will reduce system size, mass, and power; while providing wider spectrum selection, broader operating temperature range, higher dynamic range, and improved efficiency and robustness of the discharging process. **The project recently completed a breadboard prototype, delivered a replica unit for testing by the LISA team in Italy, and began lifetime testing of 96 UV LED devices.**

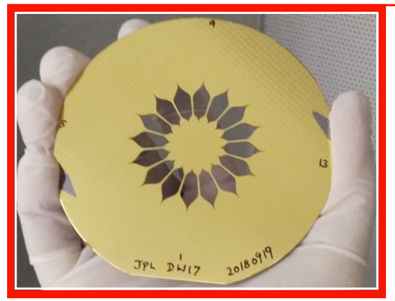
LISA Colloid Microthruster Technology Development



To measure gravitational waves, the LISA spacecraft must maneuver precisely to counteract external forces such as solar pressure, avoiding any contact with the test mass free-falling inside it. Colloid microthrusters' low-noise precise thrust enables drag-free spacecraft operation. The same system can also provide ultra-stable pointing for exoplanet characterization. Overall system mass is much lower than LISA's baseline cold-gas thruster system, enabling extended mission life up to six years. The superior platform-pointing (compared to reaction wheels) of colloid microthrusters, enabling detection and characterization of Earth-like exoplanets, led to the HabEx reference design baselining it. The key challenges for colloid microthrusters are maintaining performance demonstrated on ST7 while increasing thrust range, improving reliability, and qualifying the thrusters for up to a 4-year mission with 10 years of "expendables." **The team incorporated lessons from multiple missions and studies to derive LISA design guidelines and requirements. Accelerated life tests demonstrated "backspray" (uncontrolled spray from a saturated porous electrode to another) didn't occur until over 95% of the porous electrode capacity was full. Busek, JPL's industry partner, finished design and fabrication of breadboard-level emitters, thruster-head manifold, microvalves, volume compensator, and accumulator components.**

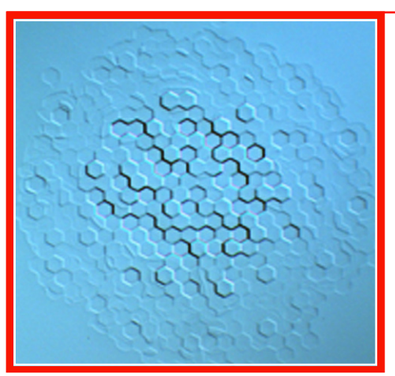
Broadband Light Rejection with the Optical Vortex Coronagraph

Coronagraphs suppress light from bright sources such as stars, enabling observation and characterization of exo-Earths in the habitable zones of Sun-like stars. Using a vortex mask to block on-axis starlight offers high throughput and suppressed sensitivity to low-order wavefront aberrations, while obtaining the deep contrast needed to find dim planets. These advantages led HabEx and LUVOIR-B to baseline vortex coronagraphs. Key challenges involve manufacturing the mask to high enough quality with enough layers to meet the contrast requirement at a wide bandwidth. **The team recently designed and built a mask demonstrating 5E-10 monochromatic contrast and 1E-8 at 10% bandwidth centered at 575 nm, a key step toward the 1E-10 broadband contrast goal.**



Starshade Technology Development Activity (S5)

A starshade flies in formation with a space telescope, occulting light from a star so that faint orbiting planets can be observed. This could enable, e.g., HabEx to discover and characterize exo-Earths in the habitable zones of their stars. The goal is to retire as much risk as possible before the 2020 Decadal Survey, and achieve TRL 5 by 2023. The work addresses formation sensing, starlight suppression, deployment accuracy, and shape stability. The team achieved the formation-sensing milestone in late 2018, showing a pupil-plane camera on a space telescope can measure starshade lateral position to < 10 cm at tens of thousands of km (exceeding the 30-cm requirement), and control an orbit-correction feedback loop. **In 2019, the team achieved two milestones using a subscale starshade in a flight-like configuration, demonstrating narrowband and 10%-broadband contrast exceeding the 1E-10 required for a scalar-diffraction-dominated configuration.**



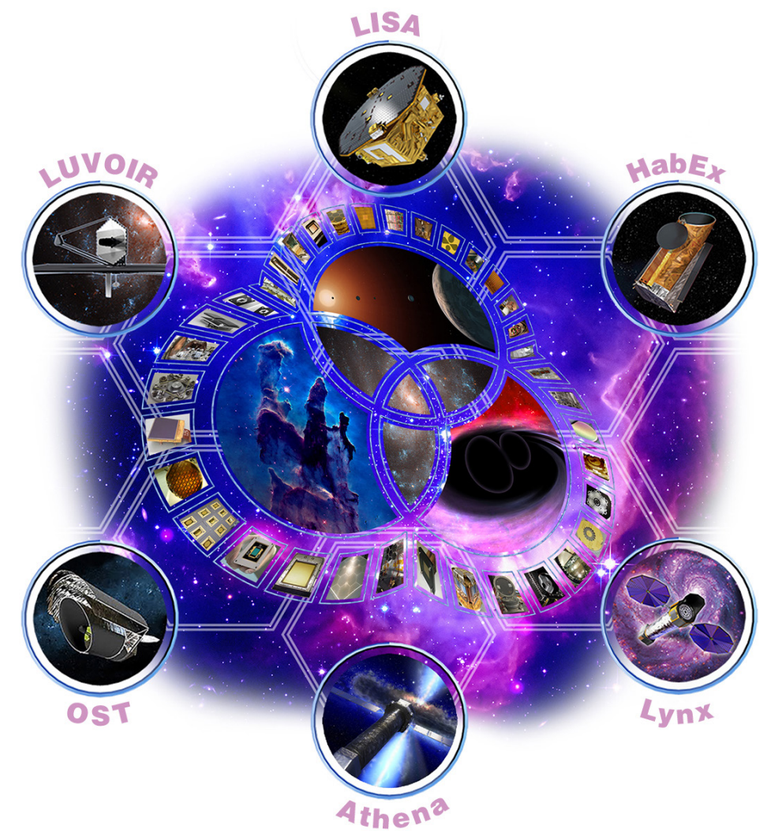
Laboratory Demonstration of High Contrast Using PIAACMC on a Segmented Aperture

Phase-Induced Amplitude Apodization/Complex Mask Coronagraph (PIAACMC) is known to enable observations at very small inner working angles (theoretically < 1 λ/D) with high throughput. Having shown promise as a solution for partially obscured telescopes, PIAACMC is a candidate for LUVOIR. **The coronagraph design was recently finalized, a PIAA optical bench was assembled, and the specialized PIAA optics are being fabricated. A complex phase mask was designed, built, and delivered, with demonstrations in the High Contrast Imaging Testbed to start in fall 2019.**

The 2020 Decadal Survey on Astronomy and Astrophysics by the National Academies of Science, Engineering, and Medicine is currently underway. Their report will set the nation's astronomy and astrophysics science priorities for the coming decade. In anticipation of this report, four APD-chartered, community-led, large-mission concept study teams, HabEx, LUVOIR, Lynx, and Origins, developed compelling science cases, design reference missions, and technology roadmaps that will inform the work of the Decadal Survey panels. These are detailed in their recently delivered final reports, available at *https://science.nasa.gov/astrophysics/2020-decadal-survey-planning*.

Meanwhile, APD continues to fund technology development projects in support of potential NASA contributions to two European Space Agency large astrophysics missions, the Athena X-ray mission, and the LISA gravitational-wave observatory.

Once the 2020 Decadal Survey report is available, APD will update its Astrophysics Implementation Plan (AIP) in response. The new Decadal Survey report and updated AIP will guide the three Program Offices as they continue collaborating in pursuit of development and infusion of technologies, enabling future missions. The updated strategic guidance will also inform the next cycle of technology gap prioritization, in 2021.



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Astrophysics Technology Database

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

Acronyms

A
ABTR . . . . . Astrophysics Biennial Technology Report
ADR . . . . . Adiabatic Demagnetization Refrigerator
AIP . . . . . Astrophysics Implementation Plan
ALD . . . . . Atomic Layer Deposition
APD . . . . . Astrophysics Division
ARC . . . . . Ames Research Center
ASU . . . . . Arizona State University
Athena . . . . . Advanced Telescope for High ENergy Astrophysics
B
BICEP . . . . . Background Imaging of Cosmic Extragalactic Polarization
BLAST-TNG . . Balloon-borne Large-Aperture Sub-millimeter Telescope – The Next Generation
C
CAT . . . . . Critical-Angle Transmission
CETUS . . . . . Cosmic Evolution Through UV Spectroscopy
CLASS . . . . . Cosmology Large Angular Scale Surveyor
CMB . . . . . Cosmic Microwave Background
COR . . . . . Cosmic Origins
CU . . . . . Colorado University
D
DMD . . . . . Digital Micro-mirror Device
E
EMCCD . . . . . Electron-Multiplying CCD
EPRV . . . . . Extreme Precision in Radial Velocity
ExEP . . . . . Exoplanet Exploration Program
F
Far-IR/FIR . . . Far Infrared
Far-UV/FUV . . Far Ultraviolet
FIREBall . . . . . Faint Intergalactic Redshifted Emission Balloon
FORTIS . . . . . Far-uv Off Rowland-circle Telescope for Imaging and Spectroscopy
FPGA . . . . . Field-Programmable Gate Array
FY . . . . . Fiscal Year
G
GOLD . . . . . Global-scale Observations of the Limb and Disk
GRACE . . . . . Gravity Recovery and Climate Experiment
GRACE-FO . . GRACE Follow-On
GSFC . . . . . Goddard Space Flight Center
GUSTO . . . . . Galactic/extra-galactic ULDB Spectroscopic Terahertz Observatory
H
HabEx . . . . . Habitable Exoplanet Observatory
HAWC . . . . . High-resolution Airborne Wideband Camera
HIRMES . . . . . HIgh-Resolution Mid-infrared Spectrometer
I
ICON . . . . . Ionospheric CONnection Explorer
INFUSE . . . . . INtegral Field UV Spectroscopic Experiment
IP . . . . . Inflation Probe
IR . . . . . Infrared
J
JHU . . . . . Johns Hopkins University
JPL . . . . . Jet Propulsion Laboratory
JWST . . . . . James Webb Space Telescope
K
KID . . . . . Kinetic Inductance Detector
L
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
LRI . . . . . Laser Ranging Interferometer
LUVOIR . . . . . Large UV/Optical/IR Surveyor
M
MCP . . . . . Micro-Channel Plate
MEMS . . . . . Micro-Electro-Mechanical Systems
Mid-IR . . . . . Mid Infrared
MIT . . . . . Massachusetts Institute of Technology
mNPRO . . . . . Micro Non-Planar Ring Oscillator
MSFC . . . . . Marshall Space Flight Center
N
NIR . . . . . Near Infrared
NIST . . . . . National Institute of Standards and Technology
NOI . . . . . Notice Of Intent
O
OCT . . . . . Office of the Chief Technologist
OGRE . . . . . Off-Plane Grating Rocket Experiment
OSIRIS-REx . . Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
OST . . . . . Origins Space Telescope
P
PAG . . . . . Program Analysis Group
PCOS . . . . . Physics of the Cosmos
PI . . . . . Principal Investigator
PIAACMC . . . Phase-Induced Amplitude Apodization / Complex Mask Coronagraph
PICO . . . . . Probe of Inflation and Cosmic Origins
PO . . . . . Program Office
PSU . . . . . Penn State University
PTC . . . . . Predictive Thermal Control
Q
QE . . . . . Quantum Efficiency
R
RIT . . . . . Rochester Institute of Technology
RMS . . . . . Root Mean Square
ROSES . . . . . Research Opportunities in Space and Earth Science
S
SAO . . . . . Smithsonian Astrophysical Observatory
SAT . . . . . Strategic Astrophysics Technology
SISTINE . . . . . Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet host stars
SL . . . . . Super Lattice
SMD . . . . . Science Mission Directorate
SOAR . . . . . SOuthern Astrophysical Research
SOFIA . . . . . Stratospheric Observatory For IR Astronomy
Spider . . . . . Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization
SPRITE . . . . . Saturn PRobe Interior and aTmospheric Explorer
SQUID . . . . . Superconducting QUantum Interference Device
SRON . . . . . Netherlands Institute for Space Research
ST7 . . . . . Space Technology 7
STDT . . . . . Science and Technology Definition Team
STMD . . . . . Space Technology Mission Directorate
STO . . . . . Stratospheric Terahertz Observatory
STScI . . . . . Space Telescope Science Institute
T
TES . . . . . Transition-Edge Sensor
TMB . . . . . Technology Management Board
TREXS . . . . . The Rocket for Extended X-ray Spectroscopy
TRL . . . . . Technology Readiness Level
U
UCB . . . . . University of California, Berkeley
ULE® . . . . . Ultra-Low Expansion (glass)
UV . . . . . Ultraviolet
V
Vis . . . . . Visible
W
WFIRST . . . . . Wide-Field InfraRed Survey Telescope
WRXR . . . . . Water Recovery X-ray Rocket
X
X-IFU . . . . . X-ray Integral Field Unit

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