National Aeronautics and Space Administration

Astrophysics Biennial Technology Report

2022

Astrophysics Division

SCIENCE MISSION DIRECTORATE

NP-2022-5-768-GSFC

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About the Cover

This Astrophysics Biennial Technology Report (ABTR) follows the release of the Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020), which will help guide the Astrophysics Division's work for the coming decade. 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 (PCOS). Reflecting this, the front and back covers combine visual elements, including artist impressions, referencing science interests across Astrophysics. Viewing the front and back covers together, we see an imagined view of the sky from inside an icy cave on a planet orbiting some far away star – an exoplanet with two moons. Colliding black holes generating gravitational waves (top center) dominate the sky. Another exoplanet orbits its star near the right edge of the visible sky, while an active galactic nucleus appears to hover over the icy horizon (lower left). Faint vectors overlaying the warm red nebular gas (near right edge of the cave) reference the search for B-mode polarization in the cosmic microwave background (CMB), a possible signal of an inflationary phase during the first instants after the Big Bang. The blue web (top left) references the so-called "cosmic web" along with many gaseous nebulae – stellar nurseries where new stars are born. Overall, the cover references the breadth and majesty of the universe studied by astronomy and astrophysics, enabled by NASA Astrophysics technology development investments.

Message from Astrophysics Division Director, Dr. Paul Hertz

I am pleased to present this 2022 ABTR to the community. This is the second NASA Astrophysics technology report to cover all areas of NASA Astrophysics. Prior to 2019, separate technology reports were issued for COR, ExEP, and PCOS.

This ABTR has been updated to incorporate the priorities of the National Academies' 2020 Decadal Survey in Astronomy and Astrophysics, *Pathways in Astronomy and Astrophysics for the 2020s*[1]. The Decadal Survey provides NASA with science priorities for the coming decade, as well as recommended programmatic activities to realize those priorities. As a first step in implementing the recommendations, NASA solicited input from the astrophysics community regarding the technology challenges, gaps, and priorities that need to be addressed to realize Decadal Survey priorities; and convened Technology Analysis Groups to help prioritize the candidate technologies. This ABTR incorporates that work of the community.

The positive impact of NASA's investments in astrophysics technology is clear to see. The James Webb Space Telescope (JWST) required the maturation of 10 technologies to enable its development. Webb was launched on December 25, 2021, and its commissioning is ongoing as of this writing. Webb science results later this year will validate the investments in those 10 technologies.

All Astrophysics missions in our future portfolio benefited from our technology program. NASA matured multiple technologies to enable the Nancy Grace Roman Space Telescope, NASA's next great observatory after Webb, including the technologies in the Coronagraph Instrument technology demonstration. NASA's upcoming GUSTO, SPHEREx, and COSI Explorer missions are all enabled by technologies matured in NASA's suborbital program. Many NASA contributions to missions led by other space agencies, e.g., planned contributions to the Japan Aerospace Exploration Agency's XRISM and the European Space Agency's Euclid, Ariel, ATHENA, and LISA, are payload components (sensors, detectors, optics, etc.) developed through NASA's Astrophysics Research and Analysis (APRA) and Strategic Astrophysics Technology (SAT) programs.

The Aerospace Corporation recently conducted a study[2] of the effectiveness of NASA's astrophysics technology development programs over the past decade. One significant finding demonstrated that effectiveness – 62% of projects led to technology infusions into sub-orbital payloads and/or space missions.

With the 2020 Decadal Survey in hand, NASA will develop the precursor science and technologies necessary to enable the prioritized Astrophysics Probes and Future Great Observatories. We will use our entire suite of astrophysics technology development tools, including competed technology investigations, Center-based directed technology projects, and industry studies. The Decadal Survey provided an ambitious and inspiring program for us to follow over the next decade, and investments in enabling technologies is the first step.

This will be my last introduction for the ABTR. After more than 10 years as Director of Astrophysics, I will be stepping down later this year to take up a new position within the Science Mission Directorate. I have learned that the success of NASA's astrophysics missions depends on early and robust investments in astrophysics technologies. This ABTR is an important tool for the astrophysics community and for the next Director of Astrophysics.

Paul Hertz
Director, Astrophysics Division
Science Mission Directorate

[1] https://science.nasa.gov/astrophysics/2020-decadal-survey-planning
[2] https://science.nasa.gov/science-pink/s3fs-public/atoms/files/Hayhurst-Aerospace%20APAC%20Presentation-final.pdf

Astrophysics Science Programs and Technology Development

About NASA Astrophysics Science Programs

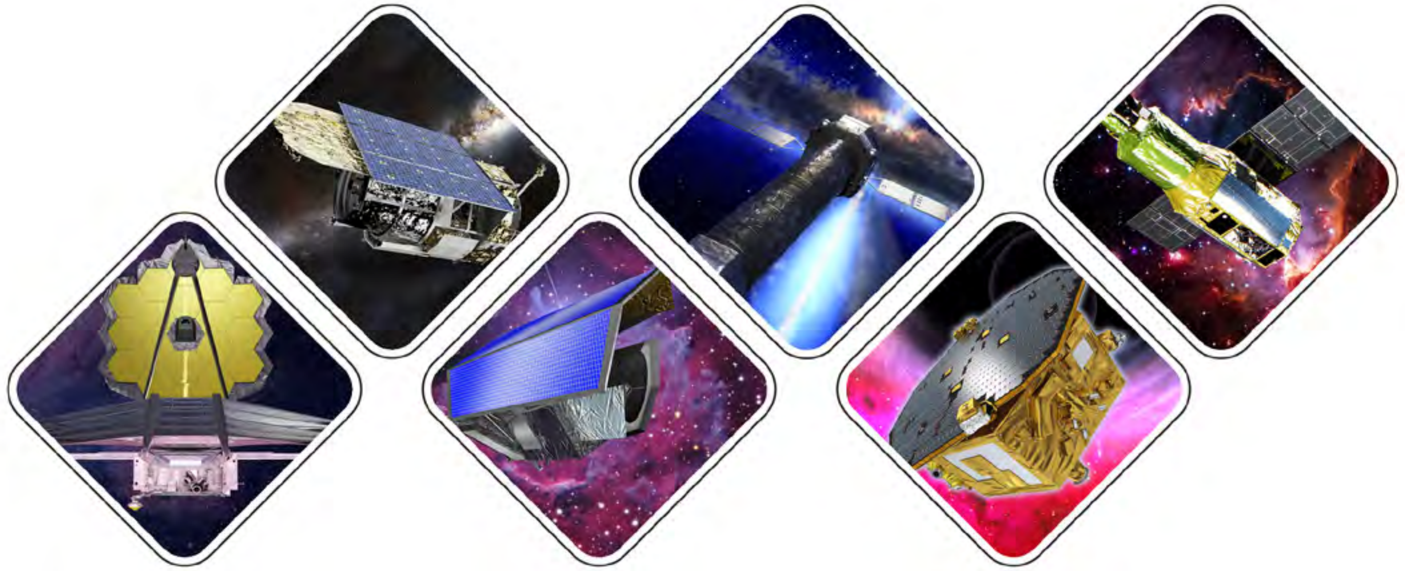
NASA Astrophysics undertakes space missions to explore the nature of the universe at its largest scales, its earliest moments, and its most extreme conditions; missions that study how galaxies and stars formed and evolved to shape the universe we see today; and missions that seek out and characterize planets and planetary systems orbiting other stars. Since such ambitious missions require technologies that exceed today's state of the art, NASA established the SAT program to mature key technologies that 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 6).

NASA set up three science-themed Programs, COR, ExEP, and PCOS, to address three fundamental questions: "How did we get here?" (COR), "Are we alone?" (ExEP), and "How does the universe work?" (PCOS). The COR, ExEP, and PCOS 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 functions 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, 4, 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 community.
- Inform the general public about progress achieved by the Programs (see searchable database of Astrophysics technology development projects at *www.astrostrategictech.us).*



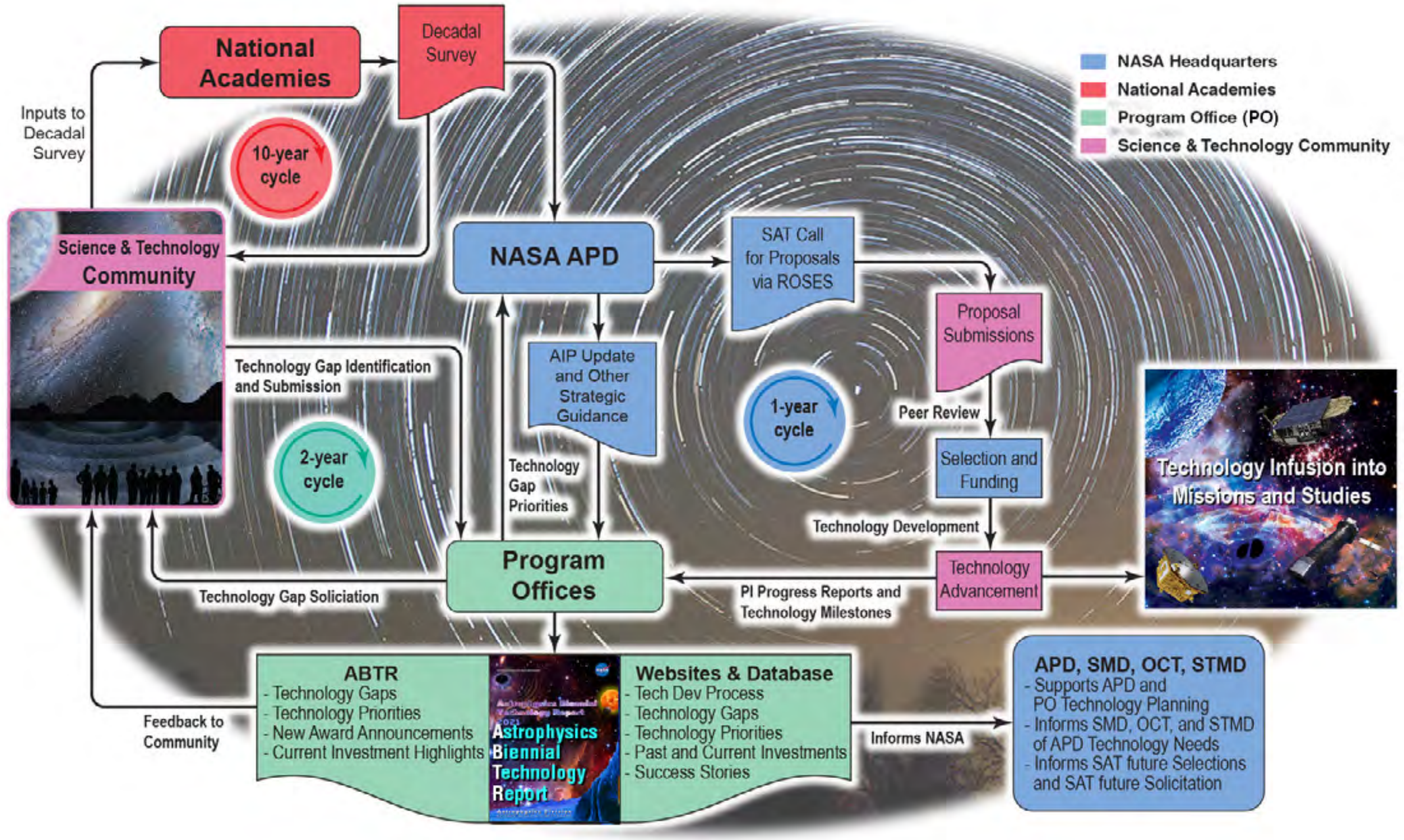
Major astrophysics missions currently in development or being deployed (from left to right: JWST, Roman, Euclid, ATHENA, LISA, and XRISM).

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, NASA Astrophysics, and the Program Offices, as shown in the flowchart below. This process comprises three interlinked cyclic processes:

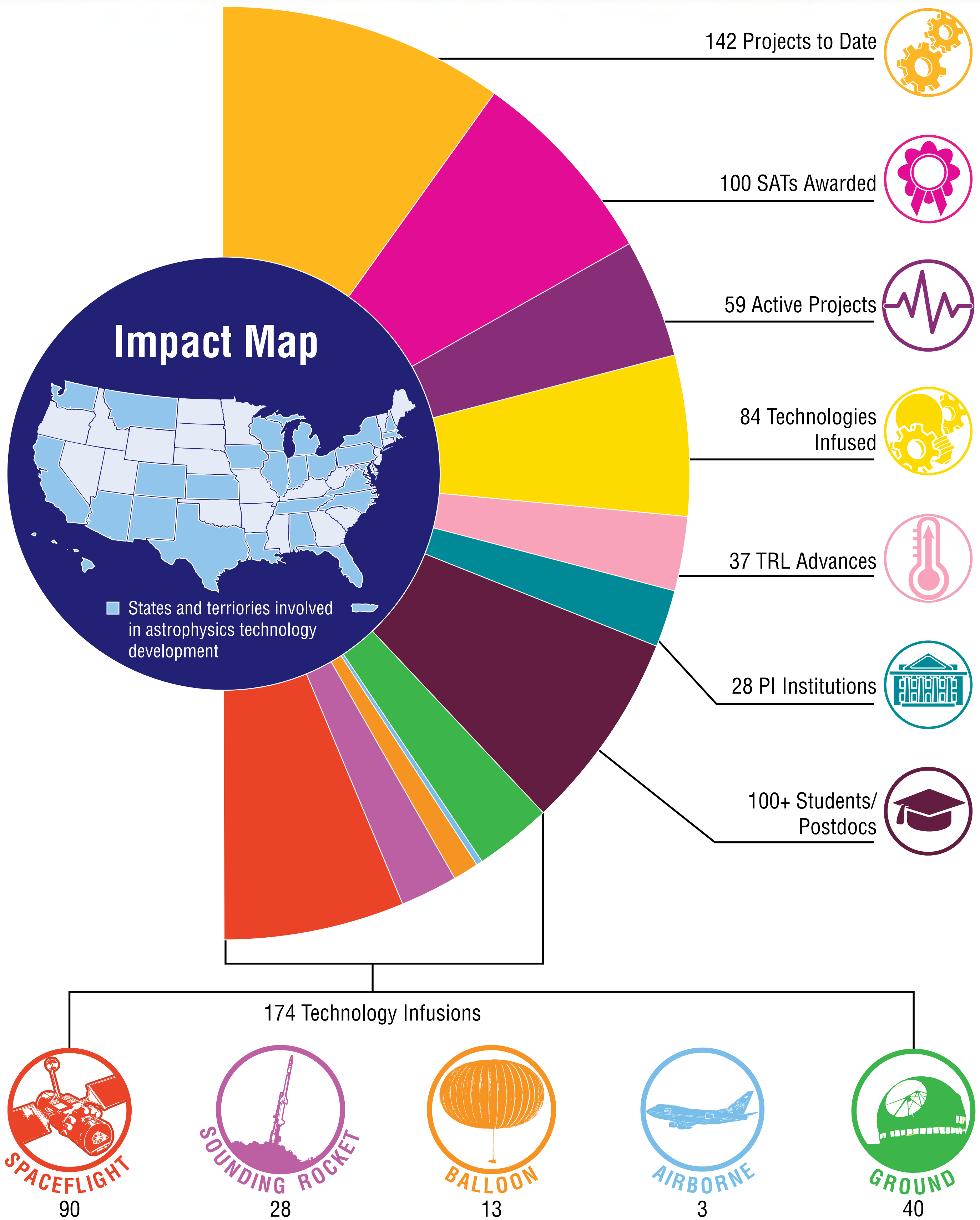
- A 10-year cycle through which the Decadal Survey panels collect and consider input from the community, and recommend to NASA the highest-priority missions and activities for the coming decade, such as the 2020 Decadal Survey of Astronomy and Astrophysics;
- A biennial cycle through which the Program Offices collect input from the community and prioritize technology gaps based on NASA Astrophysics and Decadal Survey strategic guidance (this ABTR is 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 are provided in the NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES).



The Astrophysics strategic technology development process starts with the National Academies' Decadal Survey recommendations, and NASA's current Astrophysics Implementation Plan (AIP). Based on these and other programmatic guidance, the process matures and enables infusion of key technologies into Astrophysics missions and beyond.

The Big Picture – Astrophysics Technology Development

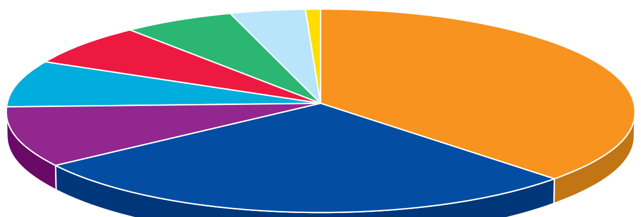


Technology Investment to Date

- 142 technology projects awarded to date to 28 PI institutions (59 projects currently active, including 32 SATs).
- 100 SAT projects competitively awarded from 2009 program inception to date, with a 29% proposal win rate.
- Work spread across 28 states and territories.
- 37 technologies advanced their TRL at least one level to date.
- 84 technologies were infused a total of 174 times into missions or projects (40 technologies 90 times into space missions, 27 technologies 44 times into suborbital missions, and 15 technologies 40 times into ground observatories).
- Over 100 students and postdocs participated in Astrophysics technology projects. Many were then accepted into graduate programs, graduated with a PhD, and/or obtained full-time research positions. One started a nanofabrication business. Many post-docs proceeded to 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.

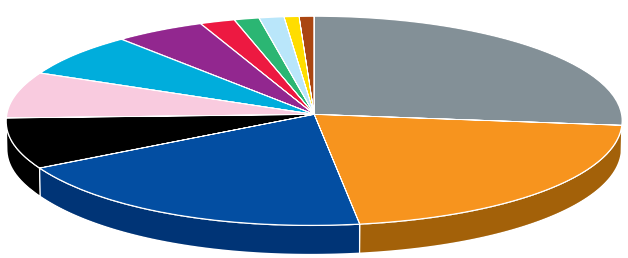
Signal types addressed include electromagnetic waves across the spectrum from X rays to sub-mm, as well as gravitational waves (GWs). Since future exoplanet observatories will observe across the UVOIR spectrum, coronagraph and starshade projects are deemed here to address that broad band. Several projects target more than one signal type and were thus double- or triple-counted here.

Projects by Signal Type



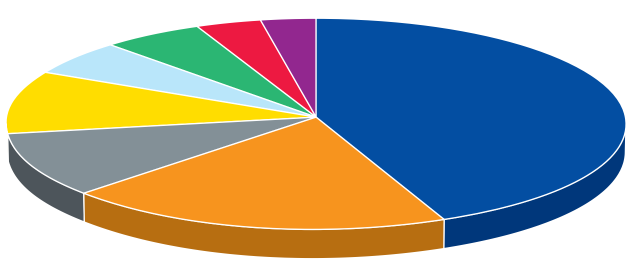
Technology areas funded by NASA include detectors, optics, coronagraphs, electronics, telescopes, starshades, optical coatings, and five others. Detectors, optics, and coronagraphs account for 66% of these projects.

Projects by Technology Area



Each of the 142 projects supports at least one strategic mission or concept*, and many support more than one. Thus, the number of technology applications is 165 (SOFIA, Stratospheric Observatory for Infrared Astronomy; LISA, Laser Interferometer Space Antenna; ATHENA, Advanced Telescope for High-ENergy Astrophysics)."

Projects by Missions Supported



* Strategic astrophysics missions are usually large, multi-purpose observatories that NASA Astrophysics 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.

Astrophysics Biennial Technology Report 2022

Astrophysics Technology Heritage Study

NASA engaged The Aerospace Corporation to conduct an independent, comprehensive Astrophysics Technology Heritage Study*, to assess the overall impact of competed grants and contracts on advancement of astrophysics technology. The study was organized in three major areas: Grants Database – compilation and analysis of astrophysics technology grants 2009-2020; Missions Database – space and suborbital missions 2010-Future; and PI Survey – survey of 300+ 2009-2020 PIs about technology status and non-technology benefits (68% responded).

Key Findings

1. Astrophysics grants and contracts fund a healthy portfolio of technologies that resulted in a 62% infusion rate, as suborbital missions provide ample science and technology maturation and transition opportunities. Since the development lifecycle for astrophysics technologies is often longer than 10 years, this percentage would likely be even higher if the prior decade's grants were also considered.
2. Beyond their primary purpose, grants enable development of students/staff, lab/infrastructure, and more.
3. PIs cited limited space-mission opportunities as the top reason why technologies are not infused, as SMEX/MIDEX missions are few and Flagships are even rarer.
4. A total of 120 unique organizations received grants, with most receiving only one. Nineteen received 58% of all grants, with the top two (JPL and GSFC) receiving 19% of all grants. The grant award process should be reviewed further to ensure the distribution is equitable.

Grants Database Overview

The grants database included competed grants for the following programs for ROSES years 2009-2020 including technology programs: APRA, SAT, Roman Technology Fellowships (RTF), NASA Earth and Space Science and Technology/Future Investigators in NASA Earth and Space Science and Technology (NESSF/FINESST), and Segmented Mirror Technology Program (SMTP). These programs contain both technology and non-technology development efforts. Some general statistics and analyses were examined for the entire database of all grant types, but non-technology grants were excluded for specific analyses, such as infusion rate calculation.

Program	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
APRA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	N/A	✓
NESSF/FINNEST	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	N/A
RTF	N/A	✓	✓	✓	N/A	✓	✓	N/A	N/A	✓	✓	✓
SAT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	N/A	N/A
SMTP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	✓	N/A

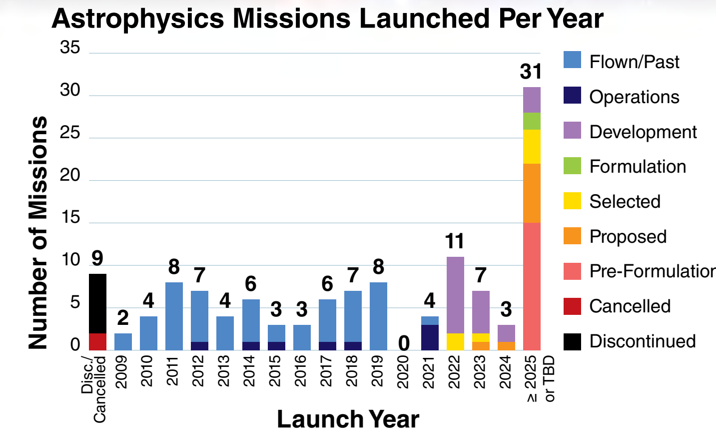
Mission Database Overview

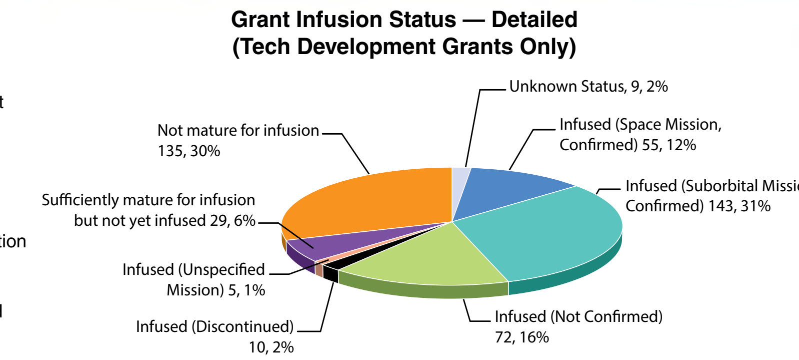
The Missions and Experiments database includes all NASA Astrophysics missions and instruments flown since 2010, or still planned. Suborbital missions flown multiple times were counted once unless a later flight features a significant change. Non-US missions with US-contributed instruments were counted. Launched in 2009 at the boundary of the study, Kepler and WISE were also included. The database contained 123 missions (62 past of operational, 28 in development or selected, 24 proposed or pre-formulation, and nine cancelled or discontinued).

Grant Infusion Status

A majority (62%) of grants/contracts resulted in technology infusions. Of these, 43% were infused into missions that were selected, in formulation/development, flying, or completed. Another 16% are in pre-formulation or proposed, and 3% were discontinued or unspecified. Another 30% of technologies were not matured enough for infusion. Only 6% resulted in a mature technology that was never infused.

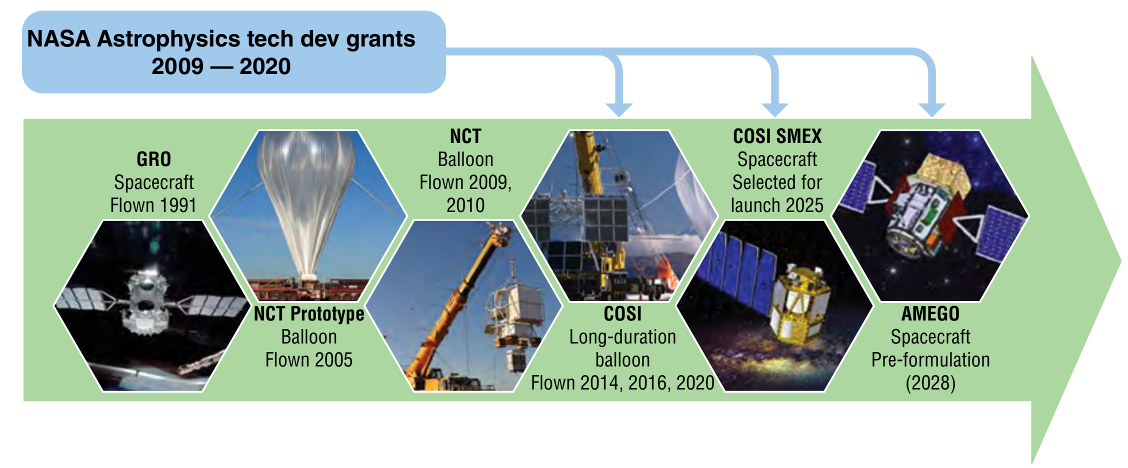
* For details, contact Marc Hayhurst (*marc.r.hayhurst@aero.org*), Kimberlee Sakai Alvarez (*kimberlee.sakaialvarez@aero.org*), Antonella Pinola (*antonella.s.pinola@aero.org*), or Uma Bruegman (*uma.bruegman@aero.org*).





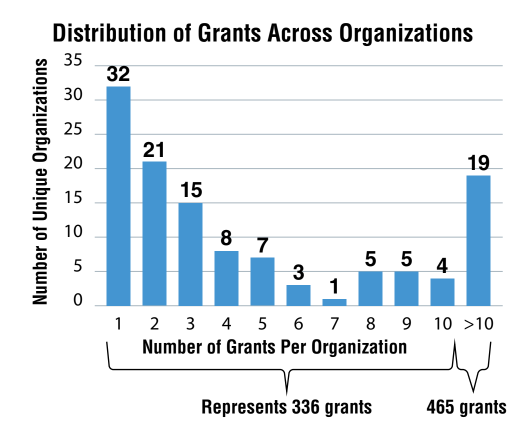
Heritage Example: COSI

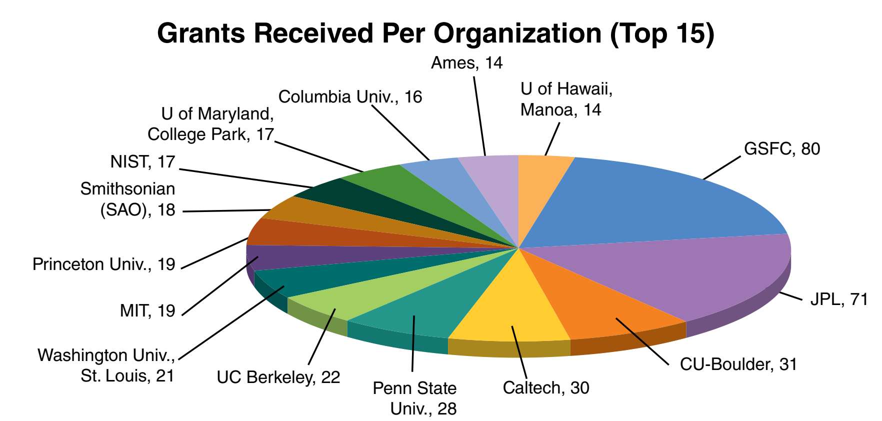
Astrophysics grants support technology maturation opportunities as well as infusions and transitions by supporting a significant suborbital program that can lead to an eventual space mission. For example, at least 13 Astrophysics grants supported development of miniaturized COMPTEL technologies as well as multiple balloon flights, an upcoming COSI SMEX spacecraft mission, and proposed future mission AMEGO.



Organizational Analysis

A total of 120 unique PI organizations were identified. Most received only one grant. However, 19 received 58% of all grants, with GSFC and JPL topping the list at 80 and 71 grants, respectively, followed by CU-Boulder with 31. Minority-serving institutions received 6% of grants.



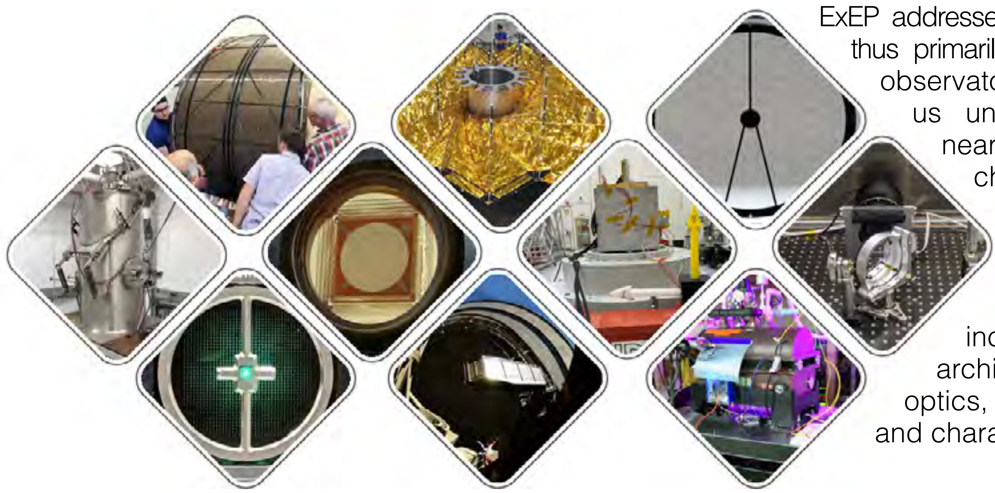


COR, ExEP, and PCOS Technologies

COR-Related Technologies

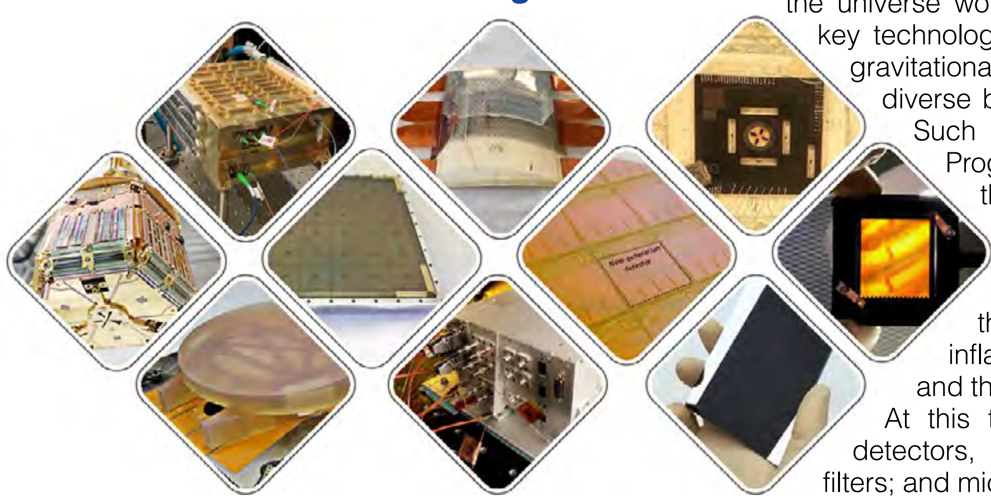
The COR Program addresses the question, "How did we get here?" and is thus primarily interested in technologies enabling observatories operating across much of the electromagnetic spectrum, from UV through the visible and into the IR, in pursuit of Program science objectives that include studying stellar 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. At this time, technology needs include detectors and spectrometers, multi-object selection, advanced mirror coatings and optical filters, large cryogenic optics, and advanced cooling.

ExEP-Related Technologies



ExEP addresses the question, "Are we alone?" and is thus primarily interested in technologies that enable observatories that can discover and help us understand planetary systems around nearby stars. This includes detecting and characterizing planets around our stellar neighbors, and especially Earth-like planets in their stars' habitable zones, 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.

PCOS-Related Technologies



The PCOS Program addresses the question, "How does the universe work?" and is thus primarily interested in key technologies for observatories that will measure gravitational waves and electromagnetic radiation in diverse bands such as microwaves and X rays. Such observatories will enable pursuit of Program science objectives 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. At this time, technology needs include X-ray detectors, gratings, optics, and optical-blocking filters; and microwave detectors and optical elements.

Current COR Portfolio

COR Technology Development Title	PI Name	Institution	Technology Area
Photon-Counting NIR LmAPD Arrays for Ultra-Low-Background Space Observations	Bottom, Michael	UH	Detector
Ultrasensitive Bolometers for Far-IR Spectroscopy at the Background Limit	Bradford, Charles	JPL	Detector
Ultrastable Large Telescope Research & Analysis – Technology Maturation (ULTRA-TM)	Coyle, Laura	Ball	Telescope
A Single-Photon-Sensing and Photon-Number-Resolving Detector for NASA Missions	Figer, Donald	RIT	Detector
Electron Beam Lithography Ruled Gratings for Future UV/Optical Missions	Fleming, Brian	CU Boulder	Optics
Scalable Micro-Shutter Systems for UV, Visible, and Infrared Spectroscopy	Greenhouse, Matthew	GSFC	Optics
High-Performance, Stable, and Scalable UV Aluminum Mirror Coatings Using ALD	Hennessy, John	JPL	Opt. Coating
Development of High-Resolution Far-Infrared Array Receivers	Mehdi, Imran	JPL	Detector
Development of Digital Micromirror Devices for Far-UV Applications	Ninkov, Zoran	RIT	Optics
Technology Maturation for Astrophysics Space Telescopes (TechMAST)	Nordt, Alison	LM	Telescope
Electron-Beam Generated Plasma to Enhance Performance of Protected Aluminum Mirrors	Quijada, Manuel	GSFC	Opt. Coating
Ultra-Stable Structures Development and Characterization Using Spatial Dynamic Metrology	Saif, Babak	GSFC	Metr./ Struct.
High Performance Sealed Tube Cross Strip Photon Counting Sensors for UV-Vis	Siegmund, Oswald	UCB	Detector
Process to Produce Scalable, Superconducting Kilopixel Far-IR Detector Arrays	Staguhn, Johannes	JHU	Detector
Precision Thermal Control (PTC) Performance Tests	Stahl, H. Philip	MSFC	Optics
High-Efficiency Continuous Cooling for Cryogenic Instruments and Sub-Kelvin Detectors	Tuttle, James	GSFC	Cooling Sys.
Large-Format, High-Dynamic-Range UV Detector Using MCPs and Timepix4 Readouts	Vallerga, John	UCB	Detector

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
Laboratory Demonstration of High Contrast Using PIAACMC on a Segmented Aperture	Belikov, Ruslan	ARC	Coronagraph
Laboratory Demonstration of Multi-Star Wavefront Control in Vacuum	Belikov, Ruslan	ARC	Coronagraph
MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection	Bierden, Paul	BMC	Coronagraph
Segmented Coronagraph Design and Analysis Study	Chen, Pin	JPL	Coronagraph
Linear Wavefront Control for High-Contrast Imaging	Guyon, Olivier	Arizona	Coronagraph
Optimal Spectrograph and Wavefront Control Arch. for High-contrast Exoplanet Characterization	Mawet, Dimitri	Caltech	Coronagraph
Radiation-Tolerant, Photon-Counting, Vis. & Near-IR Detectors for Coronagraphs and Starshades	Rauscher, Bernard	GSFC	Detector
Broadband Light Rejection with the Optical Vortex Coronagraph	Serabyn, Eugene	JPL	Coronagraph
Vortex Coronagraph High-Contrast Demonstrations	Serabyn, Eugene	JPL	Coronagraph
First System-level Demonstration of High Contrast for Future Segmented Space Telescopes	Soummer, Rémi	STScI	Coronagraph
Ultra-Stable Mid-Infrared Detector Array for Space-Based Exoplanet Transit Spectroscopy	Staguhn, Johannes	JHU	Detector
Super Lyot ExoEarth Coronagraph	Trauger, John	JPL	Coronagraph
A Novel Optical Etalon for Precision Radial Velocity Measurements	Vasisht, Gautam	JPL	EPRV
Starshade Large-Structure Precision Deployment and Stability	Willems, Phil	JPL	Starshade
Starshade Starlight Suppression	Willems, Phil	JPL	Starshade

For more information see *www.astrostrategictech.us*

Current PCOS Portfolio

PCOS Technology Development Title	PI Name	Institution	Technology Area
Advanced X-ray Microcalorimeters: Magnetically Coupled Calorimeters	Bandler, Simon	GSFC	Detector
High-Speed, Low-Noise, Radiation-Tolerant CCD Image Sensors	Bautz, Mark	MIT	Detector
Microwave SQUID Readout to Enable Lynx and Other Future Observatories	Bennett, Douglas	NIST	Electronics
Direct Fabrication of Full-Shell X-ray Optics	Bongiorno, Stephen	MSFC	Optics
Hybrid X-ray Optics by Additive Manufacturing	Broadway, David	MSFC	Optics
Low-Stress Mirror Coatings for X-ray Optics	Broadway, David	MSFC	Opt. Coatings
UV-LED-Based Charge Management System	Conklin, John	UF	Electronics
Computer-Controlled Polishing of High-Quality X-ray Optics Mandrels	Davis, Jacqueline	MSFC	Optics
High-Density Readout Technology for Superconducting Sensor Arrays for Spaceflight	Frisch, Josef	SLAC	Electronics
Differential Deposition for Figure Correction in X-ray Optics	Kilaru, Kiran	MSFC	Optics
Advanced TES Microcalorimeters	Kilbourne, Caroline	GSFC	Detector
Enabling and Enhancing Technologies for ATHENA X-IFU Demonstration Model	Kilbourne, Caroline	GSFC	Detector
Advancing the Focal Plane TRL for LiteBIRD and Other Next-Generation CMB Missions	Lee, Adrian	UCB	Detector
Telescopes for Space-Based Gravitational-Wave Observatories	Livas, Jeffrey	GSFC	Telescope
Development of RFSoC-Based Readout Electronics	Mauskopf, Philip	ASU	Electronics
Superconducting Antenna-Coupled Detectors for CMB Polarimetry	O'Brient, Roger	JPL	Detector
Advanced X-ray Microcalorimeters: Lab Spectroscopy for Space Atomic Physics	Porter, Scott	GSFC	Detector
X-ray Testing and Calibration	Ramsey, Brian	MSFC	Optics
Development of Adjustable X-ray Optics with 0.5 Arcsecond Resolution	Reid, Paul	SAO	Optics
High Resolution High Efficiency X-ray Transmission Grating Spectrometer	Schattenburg, Mark	MIT	Optics
Manufacturability & Alignment of X-ray Gratings and Optics for Space Applications	Smith, Randall	SAO	Optics
Phase Measurement System for Interferometric Gravitational Wave Detectors	Ware, Brent	JPL	Electronics
Space-based Gravitational Wave Laser Technology Development for the LISA Mission	Yu, Anthony	GSFC	Laser
Next Generation X-ray Optics	Zhang, William	GSFC	Optics
LISA Colloid Microthruster Technology	Ziemer, John	JPL	Micropropulsion

For more information see *www.astrostrategictech.us*

Strategic Astrophysics Technology Gap Prioritization

Since 2019, the COR, ExEP, and PCOS Program Offices biennially generate a joint list of strategic Astrophysics technology gaps. The process is described in detail on our technology website (*https://apd440.gsfc.nasa.gov/tech_gap_priorities.html*). 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 recently released Astro2020 report. 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 search for, and imaging and characterization of exo-Earths.

Astro2020 recommends the following strategic space observatories:

- A 6m-class IR/Optical/UV observatory to be launched during the first half of the 2040s;
- A Far-IR Flagship to be launched later than the 2040s;
- An X-ray Flagship, also 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 coming 10 years; 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 the large IR/Optical/UV Flagship 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. If the first Probe launches within the coming 10 years, technologies enabling it will already need to be fairly mature, with some work possible if funded directly.

The 2022 Technology Gap Prioritization

This cycle, the Program Offices assessed 48 technology gaps from last cycle, plus 96 gaps submitted following the release of the Astro2020. Of these 144 entries, 24 were deemed not strategic technology gaps within NASA Astrophysics payload focus. The remaining 120 gaps were reviewed by the Executive Committees of the COR and PCOS Program Analysis Groups and the Exoplanet Technical Analysis Committee. After implementing their feedback, each of the three Program Offices prioritized its gaps with participation from the others. During this process, several new entries were added and numerous others were merged or removed. Following prioritization, the three lists (28 COR gaps, 19 PCOS gaps, and 10 ExEP gaps) were merged into the prioritized Astrophysics Technology Gap List of 57 gaps shown on the right.

Technology Gap Priorities

Following the recent release of Astro2020, a prioritization process was completed involving managers, technologists, scientists, and subject matter experts from NASA Headquarters and the Program Offices, as well as independent reviewers. The following is the joint Astrophysics Technology Gap Priority List resulting from that process. This list will inform NASA 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. Gaps within any given tier are considered as equally prioritized, and are thus arranged alphabetically.

Tier 1 Technology Gaps

Advanced Cryocoolers
Coronagraph Contrast and Efficiency
Coronagraph Stability
Cryogenic Readouts for Large-Format Far-IR Detectors
Heterodyne Far-IR Detector Systems
High-Performance, Sub-Kelvin Coolers
High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
High-Resolution, Large-Area, Lightweight X-ray Optics
High-Throughput Bandpass Selection for UV/VIS
High-Throughput, Large-Format Object Selection Technologies for Multi-Object and Integral Field Spectroscopy
Large Cryogenic Optics for the Mid IR to Far IR
Large-Format, High-Resolution Focal Plane Arrays
Large-Format, Low-Darkrate, High-Efficiency, Photon-Counting, Solar-blind, Far- and Near-UV Detectors
Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
Long-Wavelength-Blocking Filters for X-ray Micro-Calorimeters
Low-Stress, High-Stability, X-ray Reflective Coatings
Mirror Technologies for High Angular Resolution (UV/Vis/Near IR)
Stellar Reflex Motion Sensitivity – Astrometry
Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity
Vis/Near-IR Detection Sensitivity

Tier 2 Technology Gaps

Broadband X-ray Detectors
Compact, Integrated Spectrometers for 100 to 1000 μm
Far-IR Imaging Interferometer for High-Resolution Spectroscopy
Far-IR Spatio-Spectral Interferometry
Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths
Improving the Calibration of Far-IR Heterodyne Measurements
Large-Aperture Deployable Antennas for Far-IR/THz/sub-mm Astronomy for Frequencies over 100 GHz
Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays
Polarization-Preserving Millimeter-Wave Optical Elements
Precision Timing for Space-Based Astrophysics
Rapid Readout Electronics for X-ray Detectors
Starshade Deployment and Shape Stability
Starshade Starlight Suppression and Model Validation
UV Detection Sensitivity

Tier 3 Technology Gaps

Advancement of X-ray Polarimeter Sensitivity
Detection Stability in Mid-IR
Far-UV Imaging Bandpass Filters
High-Efficiency Far-UV Mirror
High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blazed-Angle UV Gratings
High-Quantum-Efficiency, Solar-Blind, Broadband Near-UV Detector
Photon-Counting, Large-Format UV Detectors
Short-Wave UV Coatings
Warm Readout Electronics for Large-Format Far-IR Detectors

Tier 4 Technology Gaps

Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
Improving the Photometric and Spectro-Photometric Precision of Time-Domain and Time-Series Measurements
UV/Opt/Near-IR Tunable Narrow-Band Imaging Capability
Very-Wide-Field Focusing Instrument for Time-Domain X-ray Astronomy

Tier 5 Technology Gaps

Complex Ultra-Stable Structures for Future Gravitational-Wave Missions
Disturbance Reduction for Gravitational-Wave Missions
Gravitational Reference Sensor
High-Performance Spectral Dispersion Component/Device
High-Power, High-Stability Laser for Gravitational-Wave Missions
Laser Phase Measurement Chain for a Decihertz Gravitational-Wave Mission
Micro-Newton Thrusters for Gravitational Wave-Missions
Stable Telescopes for Gravitational Wave-Missions

For full information on these technology gaps, visit the Program Office website: *https://apd440.gsfc.nasa.gov/tech_gap-descriptions.html*

Technology Infusion Timeline Current Investments Enable Missions Decades into the Future

Implemented

*Directly deposited optical blocking filters flying on **OSIRIS-REx** • MCP detectors flying on **Juno**, **GOLD,** and **ICON** • Phasemeter flying on **GRACE Follow-On** • Si-thermistor/HgTe microcalorimeters flew on **Hitomi** • UV coatings flying on **GOLD** and **ICON***

*ALD AlF_3 coating flew on **SISTINE** • Si-thermistor/HgTe microcalorimeter array flew on **XQC** • MCP detectors flew on **FIRE**, **SLICE**, **EUNIS**, **FORTIS**, **VeSpR**, **CHESS**, **SISTINE**, and **DEUCE** • Next-gen microshutter arrays flew on **FORTIS** • X-ray reflection grating flew on **WRXR** • TES microcalorimeters and time-division SQUID multiplexers flew on **Micro-X***

*4.7-THz local oscillator and heterodyne detectors flew on **STO-2** • Antenna-coupled detectors flew on **SPIDER** • Delta-doped and AR-coated EMCCD detectors flew on **FIREBall2** • Far-IR large-format detectors flew on **PIPER** • Time-division SQUID multiplexers flew on **SPIDER** and **PIPER** • TiN KIDs flew on **BLAST-TNG***

*TES bolometers and time-division SQUID multiplexers for the HAWC+ flew on **SOFIA***

*Antenna-coupled detectors deployed on **BICEP2** & **BICEP3/Keck** •Delta-doped CCDs deployed at **Palomar-WaSP** and **ZTF**•DMDs deployed on the 4.1-m **SOAR** telescope•Feedhorn-coupled detectors deployed on **CLASS**•Microwave SQUID multiplexers deployed on **MUSTANG2** and **Simons** observatory•OMT-coupled TES bolometers deployed on **ABS**, **ACTPol**, **AdvancedACT**, **ALI-CPT**, **MUSTANG2**, **SPTPol**, and **Simons** observatory•TES bolometers used at the **IRAM** 30-m telescope and deployed on **SCUBA2**•Time-division SQUID multiplexers deployed on **ABS**, **ACT**, **ACTPol**, **AdvancedACT**, **BICEP2**, **BICEP3/Keck**, and **SCUBA2**•Microwave SQUID multiplexer crosstalk avoidance implemented at **Simons** observatory*

Upcoming

*Advanced CCDs baselined by **SPARCS**•CMB detectors planned for **LiteBIRD**•End-to-end coronagraph models baselined for **Roman**•H4RG IR detectors and coronagraph baselined for **Roman**•Hybrid Lyot coronagraph baselined for **Roman**•MCP anti-coincidence shielding for UV to fly on **SPRITE**•MCP detectors to fly on **Aspera**, **ESCAPE**, **Europa Clipper**, **EUVST**, **GLIDE**, **JUICE**, **SPRITE**, and **Solar Orbiter**•Micro-calorimeters baselined for **ATHENA**•Multi-star wavefront sensing and control to fly on **Roman**•Protected-eLiF mirror coatings to fly on **SPRITE**•Si-thermistor/HgTe microcalorimeter array to fly on **XRISM**•TES microcalorimeters and time-domain multiplexing baselined for **ATHENA** X-IFU•Wavefront control with two deformable mirrors baselined for **Roman**•Timepix2 ASICs to fly on **PADRE***

*Blazed soft-X-ray reflection grating baselined for **MaGIXS** • Electron-beam-lithography-ruled gratings to be flown on **CHESS** and **DEUCE** • Image slicer to fly on **INFUSE** • MCP detectors to fly on **INFUSE**, **DICE**, and **HERSCHEL** • Single-crystal silicon X-ray mirrors to be flown on **OGRE** • Superlattice-doped detector with out-of-band rejection to fly on **SHIELDS** • X-ray reflection gratings to be flown on **OGRE** and **TREXS** • Tpx3 CdTe detector and electroformed X-ray mirror shells to fly on **FOXSI-4** • DMDs to fly on **INFUSE***

*4.7-THz local oscillators baselined for **GUSTO** • THz heterodyne arrays baselined for **ASTHROS** • RFSoC readout baselined for **EXCLAIM** and **TIM** • Microwave SQUID multiplexer firmware and parameters baselined for **SLEDGEHAMMER***

*IF board to be flown in **ONR KID** instrument*

*Antenna-coupled detectors to be deployed to **BICEP Array**• Linear wavefront control to be deployed to **Subaru** observatory•OMT-coupled TES bolometers to be deployed on **CMB-S4**•TiN KIDs to be deployed to **Toltec**•Vortex coronagraph to be deployed to **Palomar**, **Keck**, and **Subaru** observatories•GISMO to be deployed to **GLT**•RFSoC readout to be used at **LMT** and **CCATprime**•Mandrel used to form **NIF X-ray microscope optic**•Near-IR LMAPD implemented in **ULBCam** and **Subaru** observatory •Spectrograph and wavefront control architectures to be deployed on **Keck Planet Imager and Characterizer**•EPRV etalon will be deployed on **Keck Planet Finder***

Strategic Concepts

*Advanced CCDs baselined by **AXIS**•Antenna-coupled detectors baselined by **PICO**•Apodized pupil Lyot coronagraph baselined by **LUVOIR**•Avalanche photodiode HgCdTe NIR detectors baselined by **HabEx** and **LUVOIR**• Charge management device, laser technology, and telescope developed as NASA contributions for **LISA**•Continuous ADR baselined by **Lynx**, **Origins**, **PICO**, and **GEP**•Cross-strip MCP detector systems baselined for **HabEx**, **LUVOIR**, and **CETUS**•Delta-doped CCDs baselined by **Dorado**•Delta-doped CMOS arrays baselined by **LUVOIR**•Delta-doped EMCCD detectors baselined by **HabEx**•Directly deposited optical blocking filters baselined by **Lynx**•GdF_3 coatings baselined by **Dorado**•Linear wavefront control, predictive wavefront control, and sensor fusion baselined by **HabEx** and **LUVOIR**•Low-power FPGA-based readout electronics for superconducting detector arrays baselined by **PICO**, **Origins**, **GEP**, and **CDIM**•MCP anti-coincidence shielding baselined by **LUVOIR**•MCP detectors baselined by **CETUS**, **HabEx**, and **LUVOIR**•MEMS deformable mirrors baselined by **HabEx** and **LUVOIR**• Micro-Newton thrusters baselined by **HabEx**•Microwave SQUID multiplexers baselined by **Lynx** and **Origins**•Next-gen microshutter arrays baselined by **HabEx**, **LUVOIR**, and **CETUS**•PIAACMC coronagraph and multi-star wavefront sensing and control baselined by **HabEx** and **LUVOIR**•PTC expected to serve as pathfinder for **HabEx** zonal thermal control•Single-crystal silicon X-ray mirrors and stress compensation coatings baselined by **Lynx**, **AXIS**, and **TAP**•Starshade technologies baselined by **Starshade-Roman Rendezvous Probe**•Superconducting kilopixel far-IR detector architecture baselined by **Origins**•Time-division SQUID multiplexers baselined by **PICO**•Vortex coronagraph baselined by **HabEx** and **LUVOIR**•X-ray grating spectrometer baselined by **Lynx**•CMB detectors baselined for **PICO***

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.

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.

NASA Astrophysics technology development investments have advanced TRLs of dozens of technologies, and led to over 170 infusions into space, suborbital, and ground-based missions and projects.

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 these missions 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 technology development database at *www.astrostrategictech.us*. Additional, more detailed highlights can be found at *https://science.nasa.gov/technology/technology-highlights?topic=11*

Despite the challenges posed by the COVID-19 pandemic, our PIs and their teams persevered and continued pushing NASA technology development work forward, as can be seen above and in the following pages.

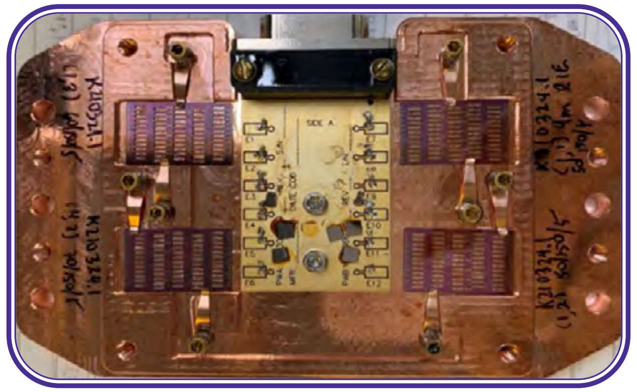
Toward Fast, Low-Noise, Radiation-Tolerant X-ray Imaging Arrays

Missions such as an X-ray Great Observatory and/or X-ray Probe, both recommended by Astro2020, as well as X-ray spectrometer-based Explorers could all benefit from advanced, radiation-tolerant, low-noise, wide-field, high-resolution, CCD X-ray image sensors. The project is building on an existing MIT Lincoln Laboratory digital CCD program developing low-noise, low-power, high-frame-rate CCDs. **The team recently validated CCD charge diffusion simulation with lab data and used them to explore noise requirements. 2.6 e- RMS noise was demonstrated for a modified pJFET CCD amplifier at 2.0 MHz, far better than Lynx/AXIS requirement of 4e- RMS. PI Mark Bautz, MIT**

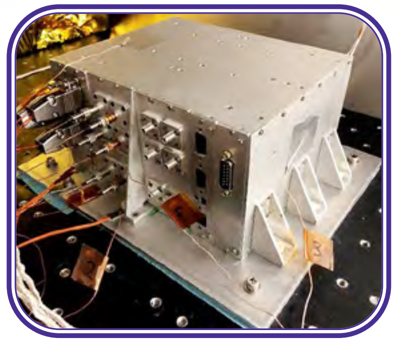
Exoplanet Imaging in Multi-Star Systems

A large fraction of stars in our galaxy, including 61% of sun-like stars within 10 parsecs, are in multi-star systems. These systems, including the nearest to our sun, the Alpha-Centauri system, are exo-Earth search candidates. A coronagraph studying one of these multi-star systems must suppress light from multiple stars simultaneously. A new technique, multi-star wavefront control, can solve this, enabling observation of many multi-star systems. Using a new wavefront control algorithm and modified coronagraph masks greatly expands the target list, and thus science yield, of future exoplanet direct-imaging missions. This project develops models and lab demonstrations to advance the technology. **The effort demonstrated performance in a 10% bandwidth coronagraph in vacuum at JPL's High Contrast Imaging Testbed lab. The technology will be included in a spare mask slot in Roman's Coronagraph Instrument (CGI), demonstrating it on-orbit in the mid-2020s when Roman launches. PI Ruslan Belikov, ARC**

Ultra-Sensitive Bolometers for Far-IR Space Spectroscopy at the Background Limit



This technology is applicable to future missions such as the Far-IR Great Observatory and/or Far-IR Probe, both recommended by Astro2020, as well as the Space Infrared Telescope for Cosmology and Astrophysics. **The team's Initial noise measurements indicate sensitivities < $1x10^{-19}$ W/sqrt(Hz), exceeding their requirement, possibly the world's most sensitive bolometer. Time-constant measurements indicate speed of response as low as 5 ms, exceeding requirement and goal. Their latest sub-arrays are coming out with perfect yield and are under test now. PI Matt Bradford, JPL**

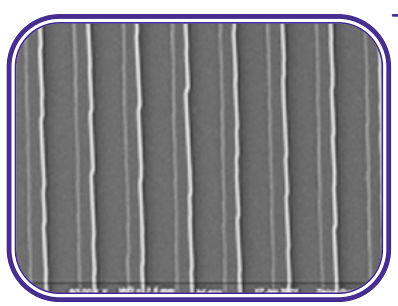


UV-LED-based Charge Management Device

Each of LISA's three spacecraft needs to fly in formation with free-falling test masses in enclosures inside the spacecraft. The extremely precise measurements require zero mechanical contact between the spacecraft and the enclosed test masses, and sufficiently low electrostatic force noise. This requires keeping test mass bulk potential below 70 mV. The project plans to reduce system size, mass, and power relative to the LISA Pathfinder mercury-lamp system by developing a new UV-LED-based Charge Management Device. These also provide wider spectrum selection, broader operating temperature range, higher dynamic range, and improved efficiency and robustness. **In 2020, the project delivered a TRL-4 replica unit to the European Space Agency for subsystem-level testing, and recently completed a TRL-6 Systems Requirements Review. Following environmental testing completion, they achieved TRL 5. PI John Conklin, U. of Florida**

Ultra-Stable Large Telescope Research and Analysis – Technology Maturation

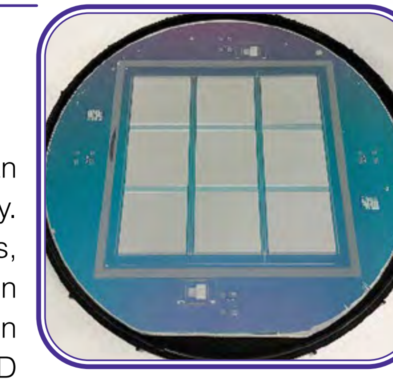
Coronagraphic observations in direct imaging and characterization of habitable planets requires keeping large telescopes stable to 10 pm for the duration of a science observation, nominally 10 minutes. The primary objective of this project is to mature the TRL of key components for ultra-stable architectures, with a focus on enabling low- to mid-TRL technology gaps identified in an earlier system study and to demonstrate component performance in the picometer regime. **The team has made significant progress in picometer metrology and actuators, thermal sensing and control, stability budgets, material property metrology, structural damping and stability, and developing low-distortion mirror mounting schemes. PI Laura Coyle, Ball Aerospace**



Electron-Beam-Lithography-Ruled Gratings for UV/ Optical Missions

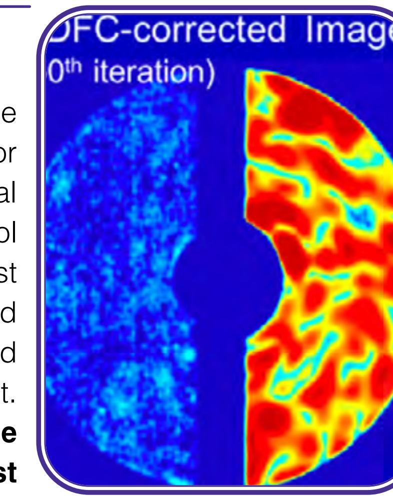
Advanced gratings, increasing sensitivity via high diffraction efficiency with low scatter, are crucial for UV spectroscopic missions such as LUVOIR, HabEx, CETUS, etc. Using e-beam lithography alleviates design restrictions suffered by conventional processes. This project leverages synergies with sounding rocket missions such as CHESS and DEUCE to demonstrate increased performance in relevant environments by producing prototype gratings that match flight grating parameters. **The team recently produced echelle-type gratings demonstrating nearly 70% relative diffraction efficiency at hydrogen Lyman alpha, 50% better than conventionally ruled options. Curved groove patterns were also successfully written on test substrates. PI Brian Fleming, U of Colorado**

Scalable Microshutter Systems for UV, Visible, and Infrared Spectroscopy



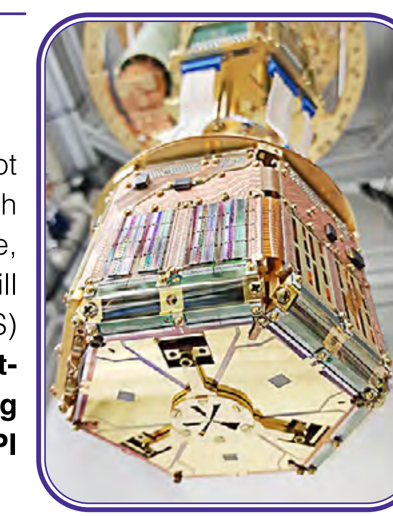
Strategic mission concepts such as HabEx, LUVOIR, and CETUS, require an advanced multi-object-selection technology for large field-of-view spectroscopy. Electrostatically actuated microshutter arrays enable such measurements, eliminating macro-mechanisms like those required by JWST's magnetic actuation technology. The large-format Next-Gen Microshutter Array (NGMSA) design developed by this project includes three-side-buttable packaging, incorporates 3D printing, and uses anti-stiction techniques to improve pixel operability. **The team developed a single-array module, including a 736×384 shutter array packaged to a ceramic substrate, fully populated with IC drivers and other passive electronic components for shutter operation. PI Matthew Greenhouse, GSFC**

Linear Dark Field Control

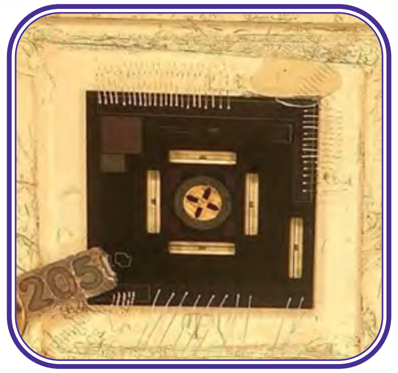


Space coronagraphs have the challenge of achieving contrast performance for directly imaging exo-Earths and maintaining that contrast long enough for spectroscopy of very faint planets. The smallest mechanical and/or thermal disturbances on a spacecraft can perturb the image. New wavefront-control techniques are being developed to improve the stability of very-deep-contrast coronagraphs. These are based on leveraging the brighter error signal separated either spatially or spectrally from the location of the planet and using that to feed back to deformable mirrors in a way that maintains the zone of deep contrast. **Recently, the project demonstrated that this novel wavefront control technique can obtain a 10× improvement in raw contrast stability at 10^{-5} raw contrast on an in-air testbed at ARC, with future milestones aiming to demonstrate the technique at a deeper contrast in vacuum at ExEP's High Contrast Imaging Testbed (HCIT), with the eventual goal of loosening stability requirements on telescope/coronagraph systems aiming for contrast of 10^{-10}. PI Olivier Guyon, U. of Arizona**

Providing Enabling and Enhancing Technologies for a Demonstration Model of the X-ray Integral Field Unit (X-IFU)

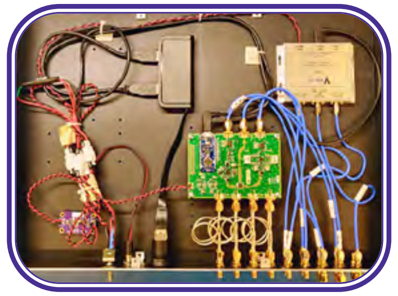


ATHENA's X-IFU instrument will enable high-resolution X-ray spectroscopy of the hot and energetic universe, with high spatial resolution over a wide field of view. Such measurements will allow the study of formation of large structures in the universe, the evolution of black holes, and other astrophysical targets of interest. X-IFU will be able to accomplish all this by using advanced transition-edge-sensor (TES) micro-calorimeter pixels. **Measurements on 962 pixels from a full-size flight-like array, a key milestone towards TRL 5, are ongoing. Design and planning work has started for a full testing program for the X-IFU engineering model. PI Caroline Kilbourne, GSFC**



Technology for LiteBIRD and Other CMB Missions

Studying the CMB, the background glow from the early universe, helps us understand the physics of the Big Bang. LiteBIRD is a Japan Aerospace Exploration Agency Main Mission, with US contribution through a Mission of Opportunity. Detectors and readout electronics meeting mission requirements are key technologies, which will be applicable to any space mission from far-IR to mm-wave bands. **Horn-coupled detectors were built at NIST in a space configuration with suitably low saturation power and tuned heat capacity for the required detector bandwidth. The pixels have bands centered at 220 and 340 GHz, toward the higher end required for space-based CMB observations. The project also designed and built a low-frequency array with LiteBIRD geometry and pixel design. PI Adrian Lee, UC Berkeley**



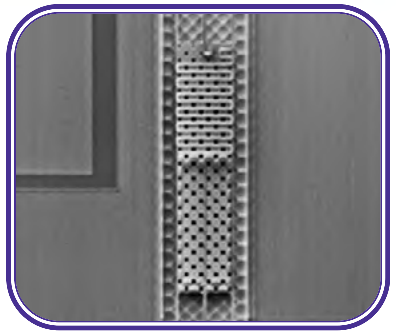
Development of RFSoC-Based Readout Electronics

New high-speed FPGAs can provide flexible solutions for balloon-borne and space-based readout electronics, replacing decade-old technology. Future X-ray, far-IR, and other observatories will field large arrays of superconducting detectors. Reading out such large arrays with sufficient speed, and low enough size, mass, and power will be enabled by the latest high-speed digital signal processing chips, Radio Frequency System on Chip (RFSoC). **The project programmed a Xilinx RFSoC evaluation board, generating arbitrary waveforms, and read them in. The team developed and implemented firmware for scalable "weighted overlap-add" polyphase filter bank on the RFSoC. A full BLAST-TNG-style Kinetic Inductance Detector (KID) readout chain was implemented on RFSoC, characterizing dynamic range, noise, and stability. Auxiliary interface boards were developed for reading out superconducting resonators with resonant frequencies at 0.1 – 8 GHz. This readout technology was baselined by the EXCLAIM and TIM balloon missions. PI Philip Mauskopf, ASU**

Technology Maturation for Astrophysics Space Telescope

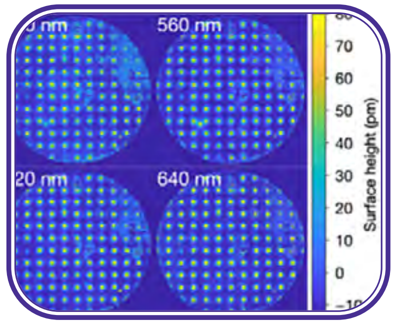
Coronagraphic observations in direct imaging and characterization of habitable planets requires keeping large telescopes stable to 10 pm for the duration of a science observation, nominally 10 minutes. The primary objectives of this project are to mature the TRL of key technology challenges for large ultra-stable space telescopes, develop a CubeSat flight demonstration of Disturbance Free Payload, improve dynamic performance predictions of large space telescope, and develop compact picometer-level metrology tools for use in a space environment. **The team has made substantial progress in integrated modeling, photonic integrated circuit metrology, CubeSat demonstrator design, and tracking frequency gauge metrology. PI Alison Nordt, Lockheed Martin**

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



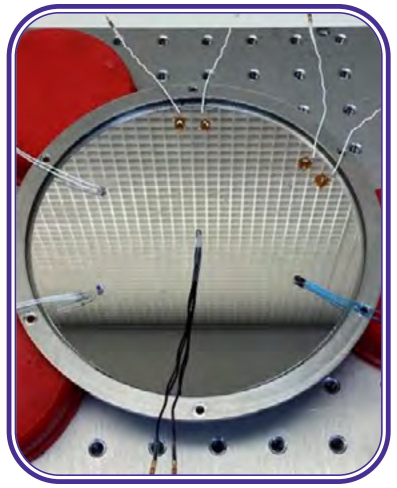
Finding a so-called B-mode polarization signature in the CMB would support "Inflation," an exponential expansion of the universe that may have occurred a fraction of a second after the Big Bang. Unfortunately, polarized foreground emission from our galaxy makes it challenging to identify and measure CMB B-mode polarization. The project developed antenna-coupled detectors with the sensitivity, broadband coverage, and systematic-error control needed for space-based CMB-polarization experiments. These were deployed in ground experiments including BICEP2, BICEP3, and Keck, providing unprecedented-depth CMB maps. While these cover limited sections of the sky, space-based missions such as PICO could expand that coverage and map the entire sky. **The team demonstrated strong electrothermal feedback that linearizes Thermal KID (TKID) response. This addresses concerns of TKID non-linearity compared to TESs, without compromising detector speed. PI Roger O'Brient, JPL**

Zernike Wavefront Sensor



High-contrast space coronagraphs use adaptive optics to measure and correct wavefront errors. To achieve 10^{-10} planet-to-star contrast, pm-scale corrections must be made over a wide range of spatial scales. As part of Decadal Survey Testbed (DST) Phase II upgrade in ExEP's HCIT, a state-of-the-art wavefront sensor was demonstrated to measure wavefront errors to < 1 pm. The device consists of a dimple etched on glass, and using Zernike's phase contrast method creates an image of the phase error in the pupil plane. Injecting a wavefront error with a deformable mirror provided wavefront sensing performance at the level needed for exoplanet direct-imaging missions. **Roman's CGI will use a spatially filtered version of this technique to provide a low-order wavefront sensor to correct tip/tilt aberrations on a fast timescale. In addition, a new Zernike Wavefront Sensor based on the DST design was selected for a CGI spare mask slot. This will allow monitoring dynamic wavefront errors in Roman's telescope and coronagraph system and collect valuable data for future exoplanet direct-imaging missions. PI Garreth Ruane, JPL**

Development and Characterization of Ultra-Stable Structures



Coronagraphic observations in direct imaging and characterization of habitable planets requires actively and passively correcting wave-front errors (WFEs) of large telescopes 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 6m-class IR/optical/UV Great Observatory recommended by Astro2020. **The team recently carried out metrology calibrations, and successfully controlled a ULE® test article to 0.3 millikelvin for 15 hours. PI Babak Saif, GSFC**

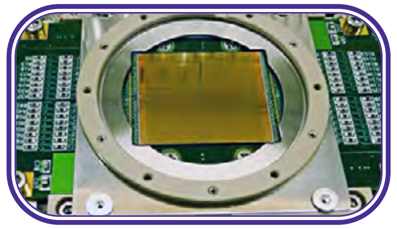
Packaging Critical-Angle-X-ray Transmission Gratings

Critical-angle transmission gratings, in combination with grazing-incidence X-ray mirrors and CCD detectors, promise an order-of-magnitude improvement in efficiency and an 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. **The project designed a new front-side photolithography mask that monolithically integrates and strengthens grating bars and support structures in the front side mask. The patterns are continuous across 200-mm wafers. The back-side L2 hexagons are patterned in alignment with front-side L2s. Grating size is independent of front-side pattern and determined through the back-side mask. The team recently demonstrated resolution R>12,000 with a pair of co-aligned gratings. PI Mark Schattenburg, MIT**

Broadband Light Rejection with the Optical Vortex Coronagraph

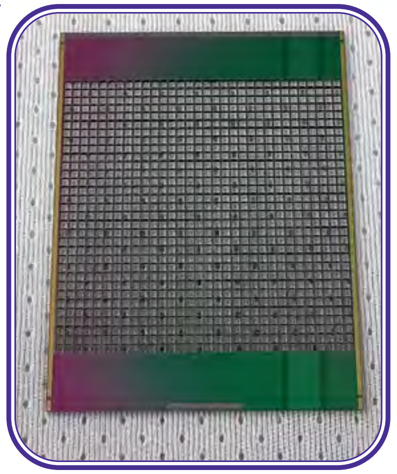
Coronagraphs suppress light from bright sources, such as stars, allowing observation of nearby faint objects such as planets orbiting them. This enables finding exo-Earths in the habitable zones of sun-like stars and characterizing their atmospheres. Using a vortex mask to block on-axis starlight offers high throughput and suppressed sensitivity to low-order wavefront aberrations, while obtaining the deep contrast needed to find dim planets. These advantages led to HabEx and LUVOIR-B baselining vortex coronagraphs. The project seeks to mature vortex coronagraph technology through lab demonstrations in JPL's HCIT lab. Key challenges involve manufacturing the mask to high enough quality and with enough layers for the necessary contrast performance at a wide bandwidth. **2021 HCIT demonstrations in vacuum achieved 5×10^{-10} monochromatic contrast and 4×10^{-9} at 10% bandwidth, a key step towards the 10^{-10} broadband contrast goal. PI Eugene Serabyn, JPL**

Large-Format, High-Dynamic-Range UV Multi-Channel Plate (MCP) Detectors with Timepix4 Readouts



MCPs have flown on many UV astronomy missions and instruments over the last two decades. These devices 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 confirmed retention of good gain, pulse-height distribution, and image uniformity of 54×54-mm^2 ALD 10-µm-pore MCPs, after processing into sealed tube Planacons. They fabricated and tested a Planacon with 10-µm ALD MCPs and 50-mm cross-strip anodes, demonstrating 30% quantum efficiency at 185 nm and 20-µm FWHM spatial resolution at MHz rates. High-speed 10 Gbps output was demonstrated with Timepix4, and the logic confirmed. PIs Oswald Siegmund and John Vallerga, UC Berkeley**

Robust, Efficient Process to Produce Scalable, Superconducting Kilopixel Far-IR Detector Arrays



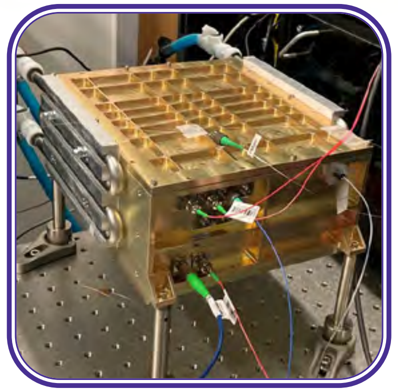
Major suborbital and space-based far-IR observatories, such as Origins, will require a robust and efficient process for producing large far-IR detector arrays. This requires reducing the complexity of individual components. The project seeks to demonstrate a versatile scheme to connect 2D superconducting detectors and cold readout electronics through a separate silicon structure with superconducting through-wafer vias. **The team recently finished designing, fabricating, and completing the detector package. The first detector was successfully hybridized directly to the fanout board, and initial laboratory tests indicate a significant number of detector pixels are performing as predicted. PI Johannes Staguhn, JHU**

PTC Technology to Enable Thermally Stable Telescopes

Direct observation and characterization of exo-Earths by future missions such as HabEx and LUVOIR require ultra-stable telescopes. One crucial part of achieving pm-scale stability is maintaining thermal stability beyond the capability of current technologies and techniques. This project seeks to demonstrate that a PTC system can achieve such performance. PTC uses models to predict thermal optical performance of real mirrors and structure based on their structural designs and constituent material properties, i.e. coefficient-of-thermal-expansion distribution, thermal conductivity, thermal mass, etc. **The team successfully demonstrated PTC on a 1.5-m ULE® mirror via tests in relevant environment. They characterized the ability to compensate for external changes in the mirror's thermal environment, and then imposed specific shapes into the mirror. PI H. Philip Stahl, MSFC**

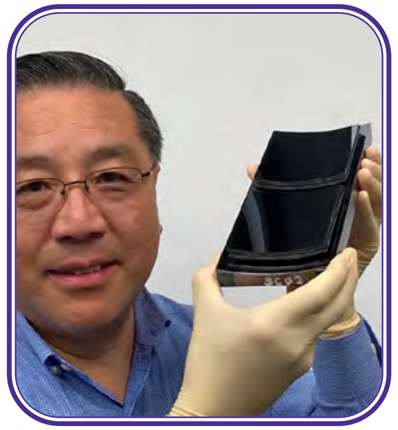
High-Efficiency Continuous Cooling for Cryogenic Instruments and Sub-Kelvin Detectors

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 10-to-0.05-K Continuous Adiabatic Demagnetization Refrigerator (CADR) technology to enable such missions. The above three mission concepts all baselined the 4-to-0.05-K part of this technology into their reference designs, and are considering adding the 10-to-4-K part as well. **The team recently grew a stage-1 chrome-potassium-alum salt pill, and assembled and tested stage 4, showing good performance. They verified the Kevlar-epoxy joints in the end fittings of salt-pill suspensions are sufficiently robust; fit-checked all CADR components; and installed thermometers, heaters, and wiring for upcoming tests. PI James Tuttle, GSFC**



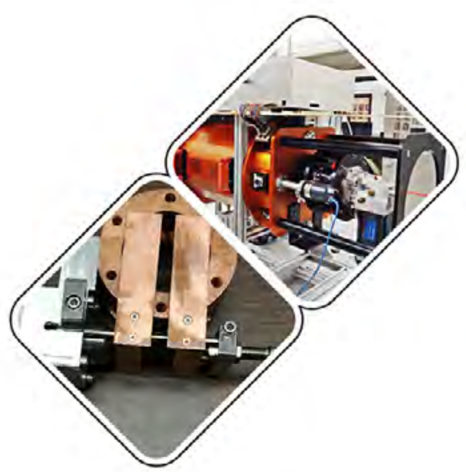
Space-based GW Laser Technology for LISA

When LIGO first measured GWs, it 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 2.5 million km on a side. **The project recently completed a TRL-4 Master Oscillator Power Amplifier laser meeting form-factor and functional requirements, and demonstrated free-running frequency noise performance well within LISA requirements in the 1-Hz-to-10-kHz band. The Power Amplifier module met LISA power-scaling and relative intensity noise requirements. A TRL-6 Master Oscillator is currently being fabricated. PI Anthony Yu, GSFC**



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. 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. It is also working on a process to assemble and align these segments into a large barrel mirror assembly. 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 fabricated X-ray mirrors with image quality better than 0.4" half-power diameter and demonstrated that ALD-coating with 30 nm platinum doesn't cause excessive distortion. They successfully fabricated, aligned, bonded, and X-ray-tested two mirror modules, each with five primary-secondary mirror pairs, achieving an image quality of 3". PI William Zhang, GSFC**



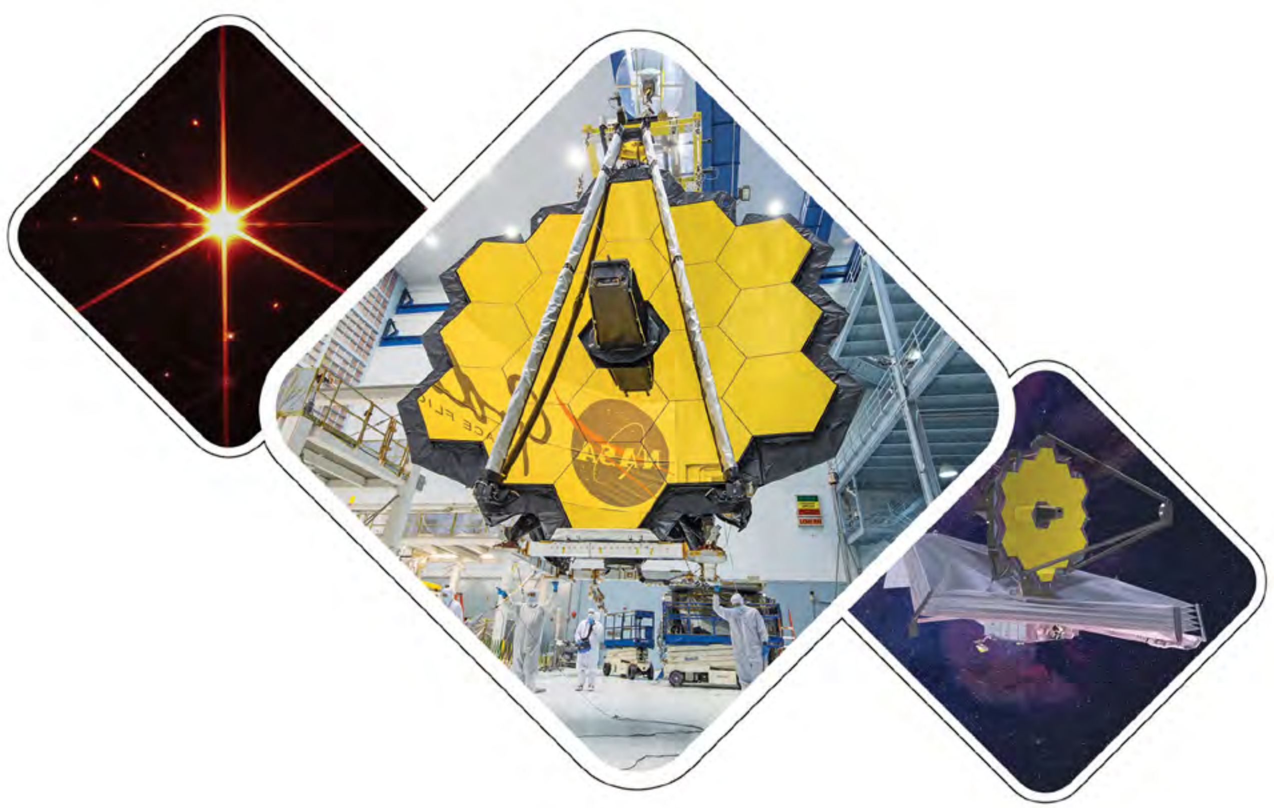
Looking to the Future

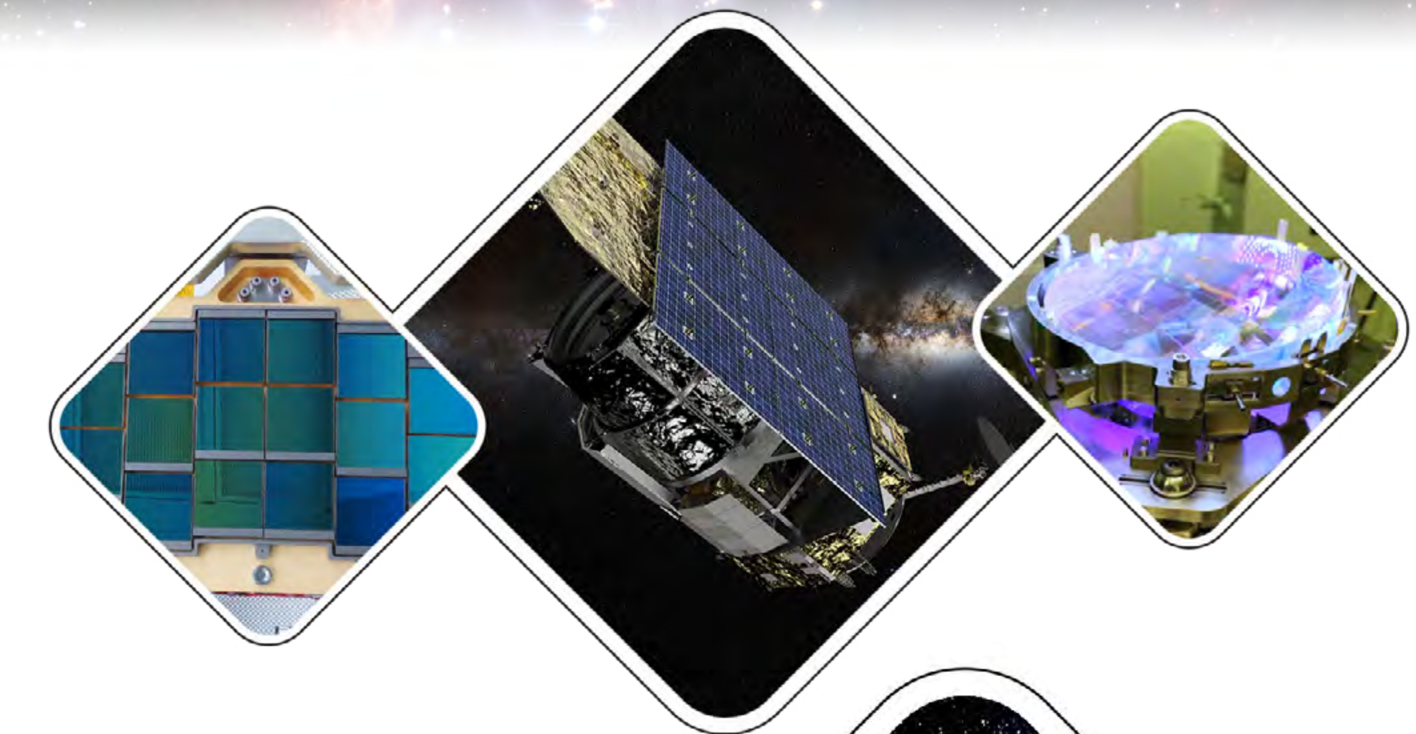
The 2020 Decadal Survey on Astronomy and Astrophysics was released by the National Academies of Science, Engineering, and Medicine. This report sets the nation's astronomy and astrophysics science priorities for the coming decade.

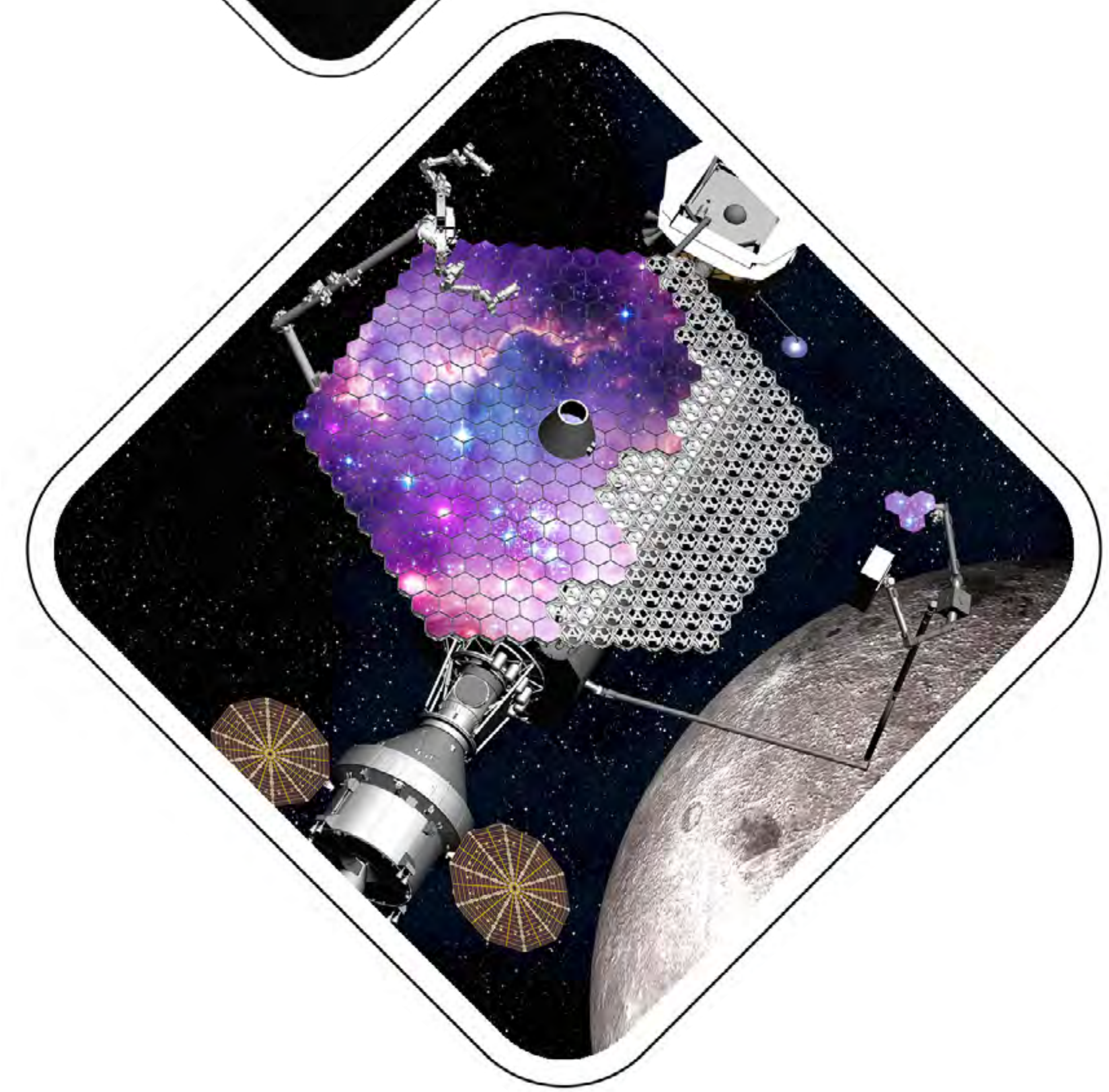
Aligned with Astro2020, NASA Astrophysics will focus in the coming 2–3 years on commissioning and collecting observations from JWST (JWST during assembly, below at center; an alignment verification sky image, below at left; and an artist's impression of the deployed observatory on orbit, below at right); and maintaining momentum in developing Roman (artist's impression of the observatory, opposite at top middle; an engineering test unit of the Roman focal plane, opposite at top left; and the Roman primary mirror, opposite at top right). A new Astrophysics Implementation Plan (AIP), scheduled for release by the end of 2022, will clarify NASA's plan for implementing Astro2020 recommendations, which include three Great Observatories – one observing across the IR/optical/UV, one in the far IR, and one in X rays; plus three Probe missions, one observing in the far IR, one in X rays, and one concentrating on the CMB. NASA Astrophysics will expand its investment in strategic technologies identified as relevant to those recommendations, as well as NASA's contributions to two European Space Agency large astrophysics missions, the ATHENA X-ray mission, and the LISA GW observatory.

The new Decadal Survey and the updated AIP will guide the three Program Offices as we continue collaborating in pursuit of development and infusion of key strategic technologies to enable future missions recommended by the 2020 Decadal Survey and beyond.

Ultimately, space telescopes will likely become too large to be launched fully assembled, even folded and stowed, at which time robotic in-space assembly may provide a solution (see artist's impression at right bottom).







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Astrophysics Technology Database

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

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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
AIP . . . . . . Astrophysics Implementation Plan
ALD . . . . . Atomic Layer Deposition
ALI-CPT . . . Ali CMB Polarization Telescope
AMEGO . . . All-sky Medium Energy Gamma-ray Observatory
APRA . . . . . Astrophysics Research and Analysis
AR . . . . Anti-Reflective
ARC . . . . . . Ames Research Center
ASU . . . . . . Arizona State University
ASTHROS . Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter wavelengths
Astro2020 . 2020 Decadal Survey on Astronomy and Astrophysics
ATHENA. . . Advanced Telescope for High ENergy Astrophysics
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
BMC . . . . . Boston Micromachines Corporation

C
CADR . . . . Continuous Adiabatic Demagnetization Refrigerator
CCAT . . . . . Cerro Chajnantor Atacama Telescope
CCD. . . . . . Charge Coupled Device
CDIM . . . . . Cosmic Dawn Intensity Mapper
CETUS. . . . Cosmic Evolution Through UV Spectroscopy
CGI . . . . . . Coronagraph Instrument
CHESS. . . . Colorado High-resolution Echelle Stellar Spectrograph
CLASS. . . . Cosmology Large Angular Scale Surveyor
CMB . . . . . Cosmic Microwave Background
CMD . . . . . Charge Management Device
COMPTEL . Compton Telescope
COR. . . . . . Cosmic Origins
COSI . . . . . Compton Spectrometer and Imager
CU . . . . Colorado University

D
DEUCE . . . Dual-channel Extreme Ultraviolet Continuum Spectrograph
DICE . . . . . Diffuse Interstellar Cloud Experiment
DMD . . . . . Digital Micro-mirror Device
DST . . . . . . Decadal Survey Testbed

E
EMCCD . . . Electron-Multiplying CCD
EPRV . . . . . Extreme Precision in Radial Velocity
ESCAPE. . . Extreme-ultraviolet Stellar Characterization for Atmospheric Physics and Evolution
EUNIS . . . . Extreme Ultraviolet Normal Incidence Spectrograph
EUVST . . . . Extreme UV High-Throughput Spectroscopic Telescope
EXCLAIM . . EXperiment for Cryogenic Large-Aperture Intensity Mapping
ExEP . . . . . Exoplanet Exploration Program

F
Far-IR. . . . . Far Infrared
Far-UV . . . . Far Ultraviolet
FINESST . . Future Investigators in NASA Earth and Space Science and Technology
FIRE. . . . . . Far-ultraviolet Imaging Rocket
FIREBall. . . Faint Intergalactic Redshifted Emission Balloon
FORTIS . . . Far-uv Off Rowland-circle Telescope for Imaging and Spectroscopy
FOXSI . . . . Focusing Optics X-ray Solar Imager
FPGA . . . . . Field-Programmable Gate Array
FWHM . . . . Full Width at Half Maximum

G
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
GRO . . . . . Gamma Ray Observatory
GRACE . . . Gravity Recovery and Climate Experiment
GRACE-FO . GRACE Follow-On
GSFC. . . . . Goddard Space Flight Center
GUSTO . . . Galactic/extra-galactic ULDB Spectroscopic THz Observatory
GW . . . . . . Gravitational Wave

H
HabEx . . . . Habitable Exoplanet Observatory
HAWC . . . . High-resolution Airborne Wideband Camera
HCIT . . . . . High Contrast Imaging Testbed
HERSCHEL . HElium Resonance Scatter in the Corona and HEliosphere

I
IC. . . . . Integrated Circuit
ICON . . . . . Ionospheric CONnection Explorer
IF . . . . Intermediate Frequency
INFUSE . . . INtegral Field UV Spectroscopic Experiment
IR. . . . . Infrared
IRAM . . . . . Institut de Radioastronomie Millimetrique

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

K
KID . . . . . . Kinetic Inductance Detector

L
LED . . . . . . Light-Emitting Diode
LIGO . . . . . Laser Interferometer Gravitational-Wave Observatory
LISA. . . . . . Laser Interferometer Space Antenna
LiteBIRD . . Light satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection
LM . . . . Lockheed Martin
LmAPD . . . . Linear-mode Avalanche Photo Diode
LMT . . . . . . Large Millimeter Telescope
LUVOIR . . . Large UV/Optical/IR Surveyor

M
MaGIXS . . . Marshall Grazing Incidence X-ray Spectrometer
MCP. . . . . . Micro-Channel Plate
Metr.. . . . . . Metrology
MEMS . . . . Micro-Electro-Mechanical Systems
Mid-IR . . . . Mid Infrared
MIDEX . . . . Medium Explorer
MIT . . . . . . Massachusetts Institute of Technology
MSFC. . . . . Marshall Space Flight Center

N
NCT . . . . . . Nuclear Compton Telescope
Near-IR/NIR . Near Infrared
NESSF . . . . NASA Earth and Space Science Fellowship
NGMSA . . . Next-Generation Micro-Shutter Array
NIF. . . . . . . National Ignition Facility
NIST. . . . . . National Institute of Standards and Technology
NSPIRES . . NASA Solicitation and Proposal Integrated Review and Evaluation System

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

P
PADRE . . . . PolArization and Directivity X-Ray Experiment
PCOS. . . . . Physics of the Cosmos
PI . . . . Principal Investigator
PIAACMC . Phase-Induced Amplitude Apodization/Complex Mask Coronagraph
PICO . . . . . Probe of Inflation and Cosmic Origins
PIPER . . . . Primordial Inflation Polarization Explorer
pJFET . . . . p-type Junction gate Field-Effect Transistors
PO . . . . Program Office
PTC . . . . . . Predictive Thermal Control

R
RFSoC . . . . Radio Frequency System-on-Chip
RIT. . . . . . . Rochester Institute of Technology
RMS. . . . . . Root Mean Square
ROSES. . . . Research Opportunities in Space and Earth Sciences
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
SISTINE . . . Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet host stars
SLAC . . . . . Stanford Linear Accelerator Center
SLICE . . . . Suborbital Local Interstellar Cloud Experiment
SMD. . . . . . Science Mission Directorate
SMEX . . . . . Small Explorer
SMTP . . . . . Segmented Mirror Technology Program
SOAR. . . . . SOuthern Astrophysical Research
SOFIA . . . . Stratospheric Observatory For IR Astronomy
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
STMD. . . . . Space Technology Mission Directorate
STO . . . . . . Stratospheric Terahertz Observatory
STScI . . . . . Space Telescope Science Institute

T
TAP . . . . . . Transient Astrophysics Probe
TBD . . . . . . To Be Determined
TechMAST. . Technology Maturation for Astrophysics Space Telescopes
TES . . . . . . Transition-Edge Sensor
TIM . . . . . . Terahertz Intensity Mapper
TKID . . . . . Thermal Kinetic Inductance Detector
TMB . . . . . . Technology Management Board
TREXS . . . . The Rocket for Extended X-ray Spectroscopy
TRL . . . . . . Technology Readiness Level

U
UCB. . . . . . University of California, Berkeley
UF . . . . University of Florida
UH . . . . University of Hawaii
ULBCam . . Ultra Low Background Camera
ULE® . . . . . Ultra-Low Expansion (glass)
ULTRA-TM. . Ultra-Stable Large Telescope Research and Analysis - Technology Maturation
UV . . . . Ultraviolet
UVOIR . . . . UV/Optical/IR

V
VeSPR . . . . Venus Spectral Rocket Experiment

W
WaSP. . . . . Wafer-Scale Imager for Prime
WFE. . . . . . Wavefront Error
WISE . . . . . Wide-field Infrared Survey Explorer
WRXR . . . . Water Recovery X-ray Rocket

X
X-IFU . . . . . X-ray Integral Field Unit
XQC. . . . . . X-ray Quantum Calorimeter
XRISM . . . . X-Ray Imaging and Spectroscopy Mission

Z
ZTF . . . . . . Zwicky Transient Facility