NASA Strategic Astrophysics Technology investments: informed by and supporting Decadal Survey recommendations

Opher Ganel,*[a] Brendan Crill,[b] Jason Derleth,[a] Jay Falker,[a] Mario R. Perez,[c] Rachel Rivera,[a] Nicholas Siegler,[b]
[a] Physics of the Cosmos and Cosmic Origins Program Office, NASA Goddard Space Flight Center, 8800 Greenbelt Rd., Greenbelt, MD 20771, USA
[b] Exoplanet Exploration Program Office, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, USA
[c] Astrophysics Division, NASA Headquarters, 300 Hidden Figures Way SW, Washington DC 20546, USA

Abstract. Over the decades, the National Aeronautics and Space Administration (NASA) Astrophysics Division (APD) launched a series of strategic missions that produced incomparable science results. With each mission breaking new ground and facing greater challenges, APD needs to mature ever-more-advanced technologies to Technology Readiness Levels[1] (TRLs) sufficient for mission infusion. The so-called "mid-TRL" gap, from 3 to 6, has historically been a great challenge, especially given funding constraints. However, advancing past this gap is crucial to developing indispensable components for strategic missions. Recognizing this, APD established in 2009 the Strategic Astrophysics Technology (SAT) program. This program, along with others, funds technology maturation needed to close the strategic technology gaps identified and prioritized based on Decadal Surveys and other strategic documents. Since 2009, over 160 strategic technology projects have been funded on 98 technology topics, with dozens achieving TRL maturation and 46 percent leading to 106 technology infusions into astrophysics missions, other NASA missions, and missions and projects beyond NASA. We present the current investment portfolio by technology types; analyze TRL advances, technology infusions, and other benefits; and present APD's strategic investment priorities following the release of the Decadal Survey, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s"[2] (Astro2020).

Keywords: NASA, astrophysics, technology development, Decadal Survey, telescope, SAT

* Opher Ganel, E-mail: opher.ganel@nasa.gov

1 Introduction

NASA participates in space exploration and the quest to discover the origin of the universe and expand our understanding of how it works and our place within it. Within NASA's Science Mission Directorate, APD is responsible for carrying out the observations and measurements required to address such questions. Each Astrophysics mission's observations push forward our understanding of these topics and raise new questions that motivate more challenging measurements and inspire new missions. Each more advanced mission can only launch once all enabling technologies are sufficiently mature for infusion. The required measurements are often photon-starved, and often suffer high background levels. Delivering such measurements demands exquisite performance from all systems and subsystems that support the observations. This makes astrophysics technology development extraordinarily challenging, yet also compelling. Three thematic Program Offices, Cosmic Origins (COR), Exoplanet Exploration (ExEP), and Physics of the Cosmos (PhysCOS), were established by APD to cover the three most fundamental questions related to astrophysics: "How did we get here?" (COR), "Are we alone?" (ExEP), and "How does the universe work?" (PhysCOS).

1.1 Strategic Astrophysics Missions

Strategic Astrophysics missions are agency-led missions or concepts that APD is developing, participating in, or interested in, to respond to high-priority science questions. This includes the Nancy Grace Roman Space Telescope[3] (RST, formerly the Wide Field InfraRed Survey Telescope, WFIRST), the European Space Agency's (ESA) Euclid mission,[4] the Japan Aerospace Exploration Agency's (JAXA) X-Ray Imaging and Spectroscopy Mission[5] (XRISM), and ESA's Advanced Telescope for High-ENergy Astrophysics[6] (ATHENA) and Laser Interferometer Space Antenna (LISA).[7]

The recently released Decadal Survey, Astro2020, laid out a compelling and ambitious plan, recommending NASA launch three Great Observatories (GOs) and three Probe missions in the next few decades:

- A 6m-class Infrared (IR)/Optical/Ultraviolet (UV) GO, later named the Habitable Worlds Observatory (HWO), to be launched in the first half of the 2040s to observe ~25 exo-Earths and carry out general astrophysics measurements.
- A far-IR GO, to be launched at least a decade after HWO.
- An X-ray GO, also to be launched at least a decade after HWO.
- A far-IR Probe, one of two candidates for a Probe launch in the early 2030s.
- An X-ray Probe, also a candidate for launch in the early 2030s.
- An Early Universe Cosmology and Fundamental Physics Probe (or Cosmic Microwave Background, CMB, Probe), to compete for a 2040s launch with whichever of the above two Probes does not launch in the 2030s.

1.2 Astrophysics Technology Development

Recognizing that advancing our ability to address the above-mentioned enduring questions requires a wide range of relevant technologies, APD established several programs that fund technology development and maturation, including Astrophysics Research and Analysis (APRA), SAT, and Roman Technology Fellowship (RTF), all solicited through NASA's omnibus Research Opportunities in Earth and Space Science[8] (ROSES) announcement of opportunity.

APRA funds a wide array of investigations not limited to technology development. Its technology development focus spans the full TRL range, from 1 to 9. These development efforts may support any Astrophysics technology, not solely those supporting strategic missions. The SAT program addresses the so-called "mid-TRL gap" between TRL 3 and 6 for technologies that enable or enhance future strategic Astrophysics missions. RTF, established in 2011, funds early-career researchers, helping them develop the skills needed to lead astrophysics technology projects and future Astrophysics missions, and pursue long-term positions.

In 2018, APD kicked off the Segmented Mirror Technology Program (SMTP), an openly competed program funding industry to develop architectures and technologies enabling large, ultra-stable, segmented space telescopes. This program's two phases continued until the end of fiscal year 2023. A new program, "D.19 Critical Technologies for Large Telescopes" is expected to build on the work of SMTP and include enhanced telescope stability.

In parallel, APD also direct-funds technology development projects through study offices dedicated to specific missions, such as ATHENA and LISA. The United States' participation in these is considered strategic by APD. Additionally, the Internal Scientist Funding Model (ISFM) funds several technology development efforts involving NASA scientists.

In addition to a series of missions, Astro2020 recommended NASA initiate a program to manage architecture maturation for GOs. In response, APD established the Great Observatories Maturation Program (GOMAP) to manage architecture and technology development prior to the formulation of each GO mission. The existing competed and directed technology development programs provide models for future GOMAP investment platforms.

1.3 Strategic Astrophysics Technology Gaps

The three Program Offices, COR, ExEP, and PhysCOS, closely collaborate and coordinate technology development management efforts, including identifying and prioritizing strategic technology gaps. The three offices use a unified gap solicitation form and a unified gap-prioritization process, including prioritization criteria and metrics. Technologists from the three offices participate in three Program-specific prioritization processes. The uniform process, criteria, and metrics allow the three prioritized lists to then be merged into a single prioritized Astrophysics technology-gap list. The most recent prioritization cycle, in 2022, was informed by the Astro2020 recommendations. The resulting prioritized list is presented in Section 4.

2 Current Strategic Technology Development Portfolio

The current portfolio of strategic Astrophysics technology maturation investments includes 53 active projects managed by the three Programs.

COR focuses primarily on 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 can observe, 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. To accomplish this, it pursues technologies for measuring UV, visible light, and IR. The 18 technology development projects in the current COR Program portfolio are shown in Table 1.

Table 1. The current COR portfolio comprises 18 technology maturation awards (Acronyms: PI, Principal Investigator; KID, Kinetic Inductance Detector; NIST, National Institute of Standards and Technology; JPL, Jet Propulsion Lab; CMOS, Complementary Metal-Oxide Semiconductor; RIT, Rochester Institute of Technology; Caltech, California Institute of Technology; ALD, Atomic Layer Deposition; GSFC, Goddard Spaceflight Center; PSU, The Penn State University; LiF, Lithium Fluoride; TES, Transition-Edge Sensor; JHU, Johns Hopkins University; MSFC, Marshall Spaceflight Center; MCP, Multi-Channel Plate; UCB, University of California Berkeley).

PROJECT TITLE	PI	PI ORG	TECH TYPE
Low-Noise, Large-Format, Direct-Absorption Far-IR KID Arrays	Austermann, J	NIST	Detector
Four-Megapixel Sensor for Ultra-Low-Background Shortwave IR Astronomy	Bottom, M	U Hawaii	Detector
Ultrasensitive Far-IR KID Arrays: Maturation for Flight	Bradford, CM	JPL	Detector
Characterizing Single-Photon Sensing CMOS Image Sensors for NASA Missions	Figer, D	RIT	Detector
Ultrasensitive Far-IR KID Arrays for Space	Hailey-Dunsheath, S	Caltech	Detector

PROJECT TITLE	PI	PI ORG	TECH TYPE
High Performance, Stable, and Scalable UV Al Mirror Coatings Using ALD	Hennessy, J	JPL	Coating
High-Performance Far-UV, Near-UV, and UV/Optical CMOS Imagers	Hoenk, M	JPL	Detector
High-Efficiency Continuous Cooling for Cryogenic Instruments and sub-Kelvin Detectors	Kimball, M	GSFC	Cooling Sys.
UV Spectroscopy for the Next Decade Through Nanofabrication Techniques	McEntaffer, R	PSU	Optics
High-Performance UV Photon-Counting Detector for Strategic Astrophysics Missions	Nikzad, S	JPL	Detector
Large-Format, High-Efficiency, UV/Optical/Near-IR Photon-Counting Detectors	Nikzad, S	JPL	Detector
Advanced Aluminum Mirrors with Passivated LiF for Environmentally Stable Meter-Class UV Space Telescopes	Quijada, M	GSFC	Coating
Advancing Readout of Large-Format Far-IR TES Arrays	Rostem, K	GSFC	Electronics
Scalable Microshutter Systems for Multi-Object Spectroscopy	Scowen, P	GSFC	Optics
Large Low-Noise Transition Edge Sensor Arrays for Future Far-IR Space Missions	Staguhn, J	JHU	Detector
Ultra-Stable Structures Development and Characterization Using Spatial Dynamic Metrology	Saif, B	GSFC	Metrology/ Structure
UV/Optical to Far-IR Mirror and Telescope Technology Development	Stahl, HP	MSFC	Optics
Large-Format, High-Dynamic-Range UV Detector Using MCPs and Timepix4 Readouts	Vallerga, J	UCB	Detector

ExEP focuses primarily on detection and characterization of planets around nearby stars, especially Earth-like planets in the habitable zones of their stars; and searching for signatures of life. ExEP's current technology needs include ultra-stable space-telescopes, starshades, coronagraphs, detectors enabling direct imaging and characterization of exo-Earths, and extreme precision radial velocity (EPRV) measurements. The 21 technology development investigations in the current ExEP portfolio are shown in Table 2.

Table 2. The current ExEP portfolio comprises 21 technology maturation awards (Acronyms: ARC, Ames Research Center; WFC, Wavefront Control; DST, Decadal Survey Testbed; MIT, Massachusetts Institute of Technology; µ-propulsion, micro-propulsion; STScI, Space Telescope Science Institute).

PROJECT TITLE	PI	PI ORG	TECH TYPE
Development of a Method for Exoplanet Imaging in Multi-Star Systems	Belikov, R	ARC	Coronagraph
Laboratory Demonstration of High Contrast Using Phase-Induced Amplitude Apodization Complex Mask Coronagraph on a Segmented Aperture	Belikov, R	ARC	Coronagraph
Laboratory Demonstration of Multi-Star WFC in Vacuum	Belikov, R	ARC	Coronagraph
Starshade Large-Structure Precision Deployment and Stability	Aaron, K	JPL	Starshade
Starshade Starlight Suppression	Aaron, K	JPL	Starshade
Adaptive High-Order WFC Algorithms for High-Contrast Imaging on the DST	Cahoy, K	MIT	Coronagraph
Segmented Coronagraph Design and Analysis study	Chen, P	JPL	Coronagraph
Linear WFC for High-Contrast Imaging	Guyon, O	U Arizona	Coronagraph

PROJECT TITLE	PI	PI ORG	TECH TYPE
Robust Deep-Contrast Imaging with Self-Calibrating Coronagraph Systems	Guyon, O	U Arizona	Coronagraph
Colloid Thruster Life Testing and Modeling	Marrese-Reading, C	JPL	µ-propulsion
Optimal Spectrograph and WFC Architectures for High-Contrast Exoplanet Characterization	Mawet, D	Caltech	Coronagraph
Radiation-Tolerant, Photon-Counting, Vis/Near-IR Detectors for Coronagraphs and Starshades	Rauscher, B	GSFC	Detector
Laboratory Demonstrations of High Contrast with Black Silicon Coronagraph Masks	Riggs, AJ	JPL	Coronagraph
Vortex Coronagraph High-Contrast Demonstrations	Serabyn, E	JPL	Coronagraph
System-level Demonstration of High Contrast for Segmented Space Telescopes	Soummer, R	STScI	Coronagraph
Ultra-Stable Mid-IR Detector Array for Space-Based Exoplanet Transit Spectroscopy	Staguhn, J	JHU	Detector
Demonstration of Advanced WFC for Segmented Aperture Telescopes	Tesch, J	JPL	Coronagraph
Super Lyot Exo-Earth Coronagraph	Trauger, J	JPL	Coronagraph
Low-Order Hardware Implementation for Sensing and Control in Exoplanet Imaging	Trauger, J	JPL	Coronagraph
A Novel Optical Etalon for Precision Radial Velocity Measurements	Vasisht, G	JPL	EPRV
Dual-Purpose Coronagraph Masks for Enabling High-Contrast Imaging with an IR/Optical/UV Flagship Mission	Wallace, K	JPL	Coronagraph

PhysCOS focuses primarily on understanding some of science's most profound phenomena. This includes 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. This requires technologies enabling measurement of gravitational waves, microwaves, and X rays. The 14 technology development investigations in the current PhysCOS portfolio are shown in Table 3.

Table 3. The current PhysCOS portfolio comprises 14 technology maturation awards (Acronyms: SQUID, Superconducting QUantum Interference Device; SAO, Smithsonian Astrophysical Observatory; LL, Lincoln Laboratory).

PROJECT TITLE	PI	PI ORG	TECH TYPE
Magnetically Coupled Calorimeters	Bandler, S	GSFC	Detector
Extremely Low-noise, High Frame-rate X-ray Image Sensors	Bautz, M	MIT	Detector
Microwave SQUID Readout Technology to Enable Lynx & Other GOs	Bennett, D	NIST	Electronics
Mounting and Alignment of Full-Shell X-ray Mirrors	Bongiorno, S	MSFC	Optics
Metrology Development for Full-Shell X-ray Mirrors	Davis, J	MSFC	Metrology/ Structure
Rapid Electron-Beam Lithography Patterning for Customized Reflection Gratings	DeRoo, C	U Iowa	Optics
Thin-Film Coatings for Full-Shell X-ray Mirrors	Gurgew, D	MSFC	Coating
Advanced Pixelated Si Sensors for Next Generation X-ray Observatories	Kenter, A.	SAO	Detector
Polishing Mandrels and Optics for Full-Shell X-ray Mirrors	Kolodziejczak, J	MSFC	Optics
Optimized Soft X-ray Sensors for Strategic X-ray Astrophysics Missions	Leitz, C	MIT/LL	Detector
High-Sensitivity and High-Resolving-Power X-ray Spectrometer	Schattenburg, M	MIT	Optics

PROJECT TITLE	PI	PI ORG	TECH TYPE
Replication Studies for Full-Shell X-ray Mirrors	Singam, P	MSFC	Optics
Advanced X-Ray Microcalorimeters	Smith, S	GSFC	Detector
Next-Generation X-ray Optics: High Resolution, Light Weight, and Low Cost	Zhang, W	GSFC	Optics

Information on these and other technology investigations is available via a searchable Astrophysics database[9] or through NASA's Technology Portfolio Management System[10] (TechPort).

3 Technology Investment Metrics and Results to Date

The following analyses cover the SAT Program's first 15 years, from 2009 to 2023, during which APD funded 166 strategic technology investigations.

3.1 Technology Investigations and Projects

Follow-on cycles (with the same PI or another) were merged with the initial investigation as parts of the same project. All told, 98 projects comprised one to five funded investigations each (Fig. 1), averaging just under two funding cycles per project. As a result, project durations ranged from a single year to 13 years (Fig. 2), with an average of 5.2 years.

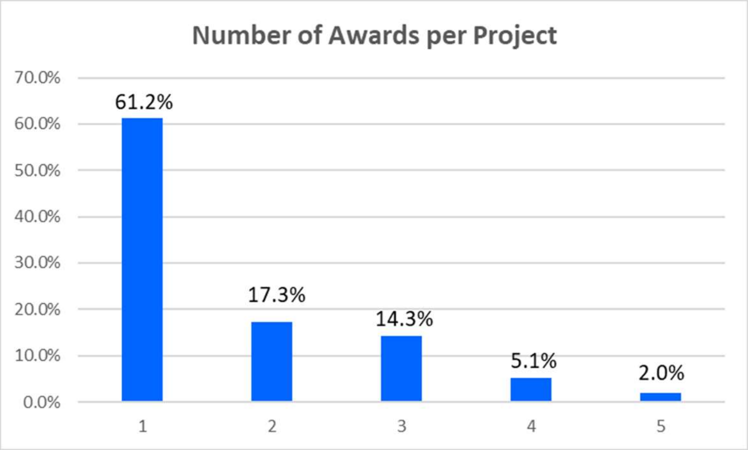

Fig. 1. Distribution of projects by number of funding cycles, with 98 projects comprising up to five funding cycles.

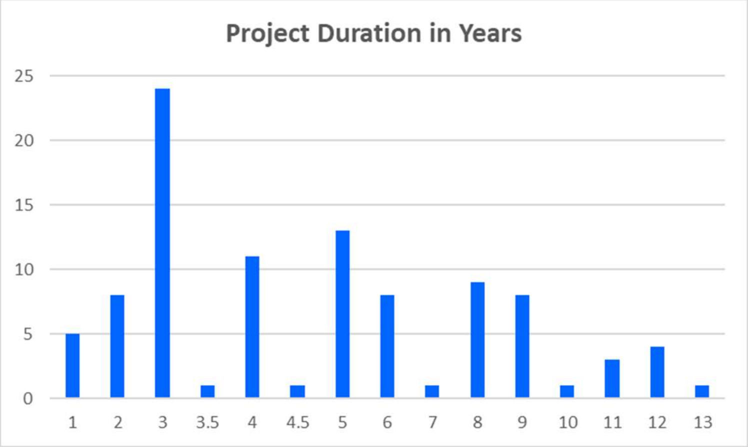

Fig. 2. Distribution of projects by total duration in years, including any follow-on cycles.

3.2 Distribution of Projects by Program, Organization Type, Technology Area, Signal Type, and Strategic Mission

The distribution of awards between the three programs over the first 15 years of the SAT program is shown in Fig. 3 (left), with 34 in COR (16 starting between 2019 and 2023), 27 in ExEP (six starting during the same five years), and 37 in PhysCOS (22 starting during those five years). The total investment to date was $322 million (33 percent funded between 2019 and 2023). Of that $322 million total investment, $119 million (37 percent) was in COR, $69 million (22 percent) in ExEP, and $133 million (41 percent) in PhysCOS (Fig. 3, right), with an average investment of $3.3 million per project ($3.5 million COR, $2.6 million ExEP, and $3.6 million PhysCOS).

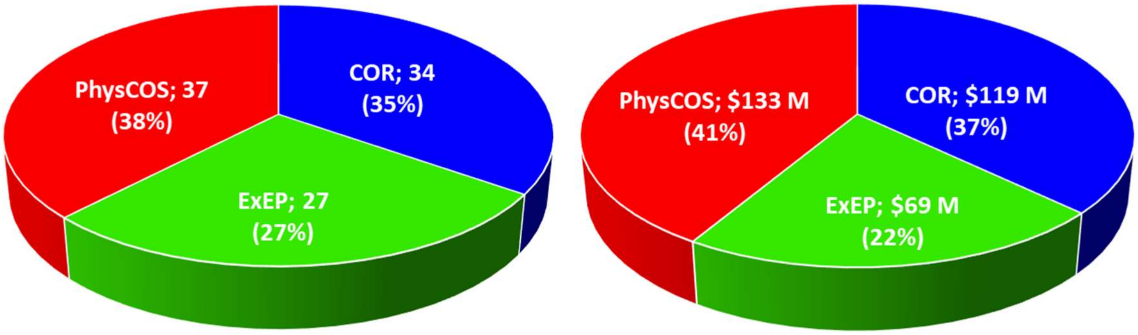

Fig. 3. Strategic technology development by Program from 2009 to 2023: number of distinct projects (left) and total investment (right). Note that this excludes certain direct-funded projects such as ExEP's S5 Starshade effort.

The distribution of projects by the type of organization receiving the awards is shown in Fig. 4. Government labs include Federally Funded Research and Development Centers (FFRDCs) such as JPL and non-NASA agencies such as NIST.

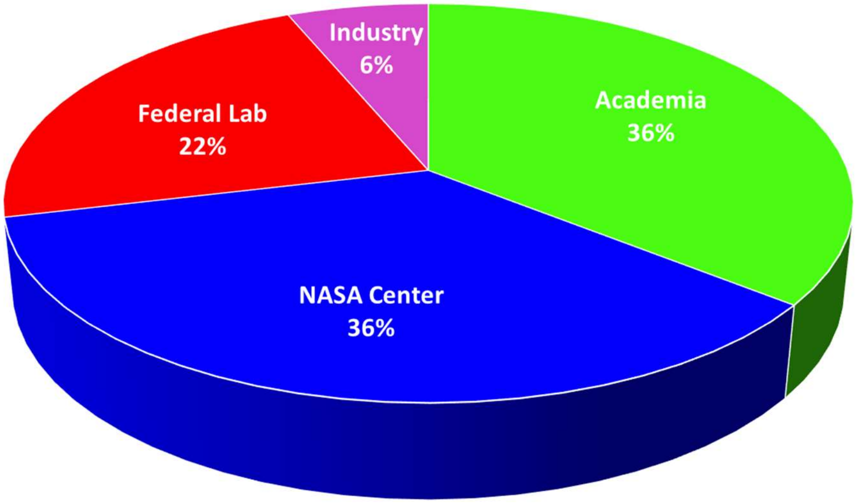

Fig. 4. Distribution of strategic technology development projects by institutional types receiving the awards.

Strategic astrophysics technology projects address detectors, optics, coronagraphs, optical coatings, electronics, starshades, telescopes, lasers, picometer-level metrology/structures, micro-propulsion, cooling systems, and EPRV (Fig. 5). Given their important roles in astrophysics missions, detectors, coronagraphs, and optics dominate with a combined 68 percent.

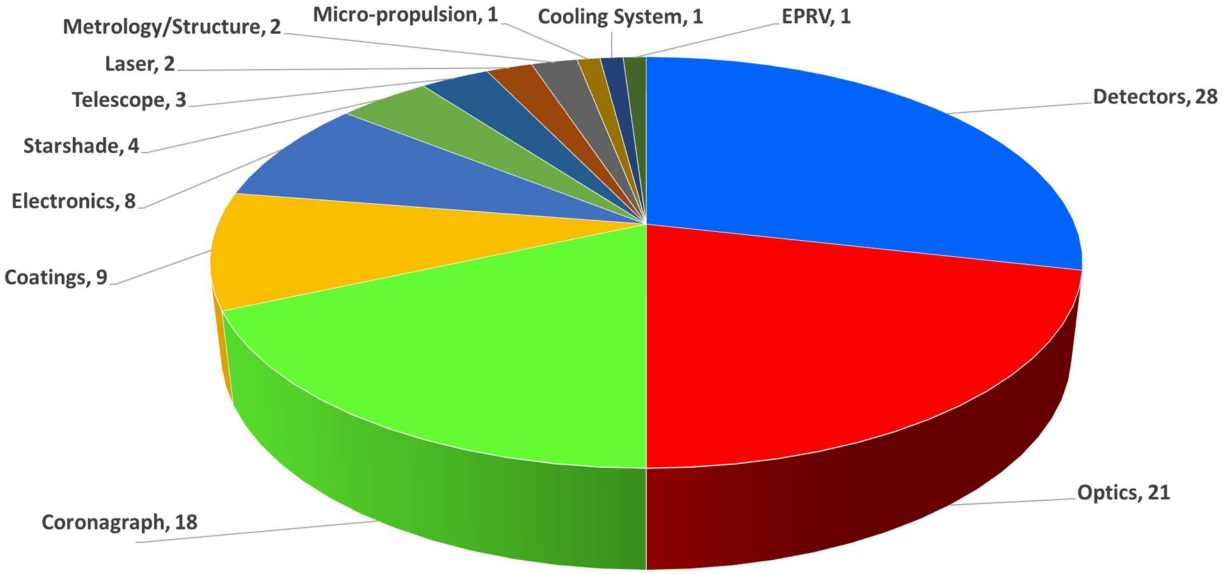

Fig. 5. Distribution of the 98 projects in the strategic technology portfolio by topic since SAT inception.

As Fig. 6 demonstrates, the 98 projects cover technologies addressing a broad range of the electromagnetic spectrum, as well as gravitational waves (GW).

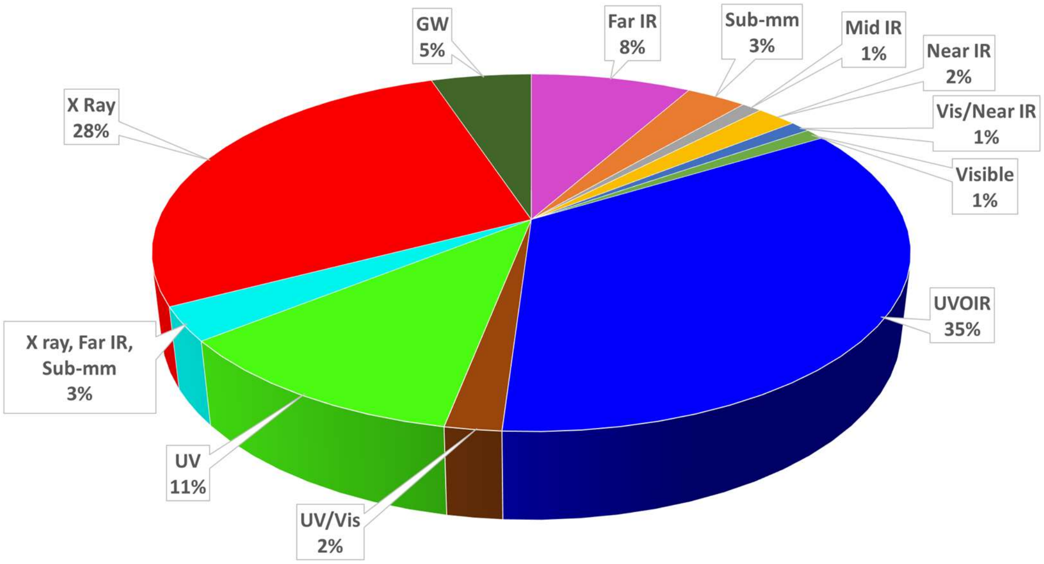

Fig. 6. Distribution of the projects in the strategic technology portfolio by signal type since SAT inception.

Each strategic technology matured by the maturation projects supports one or more future strategic missions, with some supporting more than one. Figure 7 shows the distribution of projects by the missions they support. Those supporting multiple missions are double-, triple-, and up to quintuple-counted, as appropriate. Note that RST, ATHENA, and LISA are now far enough along to fund their own technology maturation.

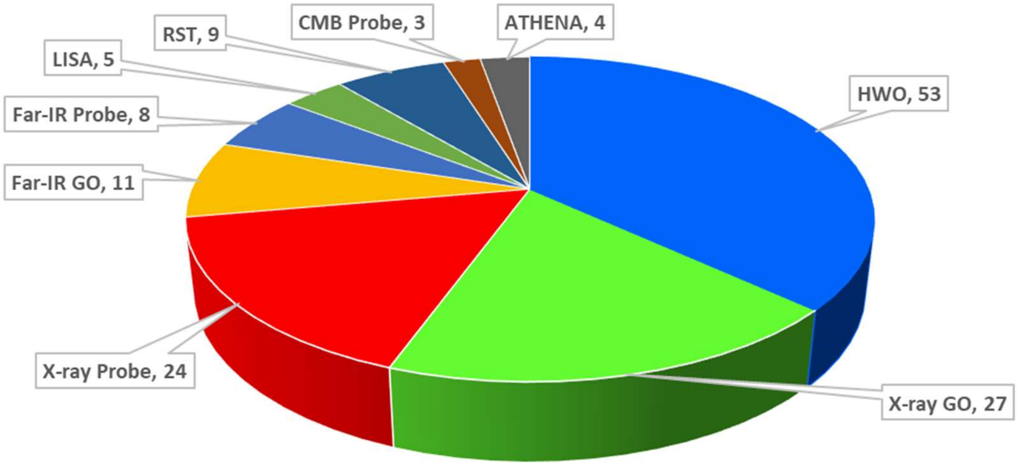

Fig. 7. Distribution of the 98 projects in the strategic technology portfolio by strategic mission(s) supported.

3.3 Assessing Technology Maturation

NASA's metric for assessing technology maturation is captured in TRLs, as defined in NASA Systems Engineering Processes and Requirements.[1] This metric proceeds as a step function, where a project may complete many of the criteria for attaining the next TRL, but if even one criterion has not yet been met, the TRL is not advanced. Given that strategic technology projects by their nature are required to move challenging technologies beyond the cutting edge of what is currently possible, many projects accomplish sub-TRL-step advances, which isn't captured by TRLs.

The NASA Office of Chief Technologist's Technology Readiness Assessment Best Practices Guide[11] provides a standard framework for assessing TRL, including the cases of TRL roll-up to higher levels of integration in systems and changing requirements as mission concepts advance.

Overall, 46 percent of strategic technology projects (45 of 98) advanced by at least one TRL, of which 12 percent (12) advanced by two (Fig. 8). Breaking this down by program, 18 of 34 PhysCOS projects (53 percent) advanced by at least one TRL; six of 27 ExEP projects (22 percent) made such advances; and 21 of 37 PhysCOS projects (57 percent) did so. The remaining 54 percent (53 of 98) made sub-TRL advances. The high-risk, high-reward nature of these projects makes these numbers especially impressive.

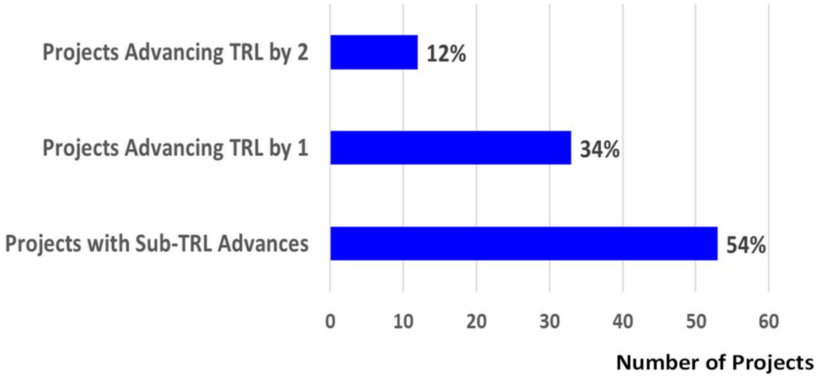

Fig. 8. Distribution of TRL advancement of strategic technologies. Some advances were during the relevant project's duration, and some continue advancing in TRL after project completion, especially those that were infused into spaceflight missions.

The majority of projects (74) began at TRL 3, with another 15 starting at TRL 4. Eight additional projects started at TRL 2 and only one came into the program at TRL 5. With these statistics, it is difficult to make a definitive assertion, but the data support the notion that the higher the entry TRL, the lower the likelihood of advancing TRL (Fig. 9).

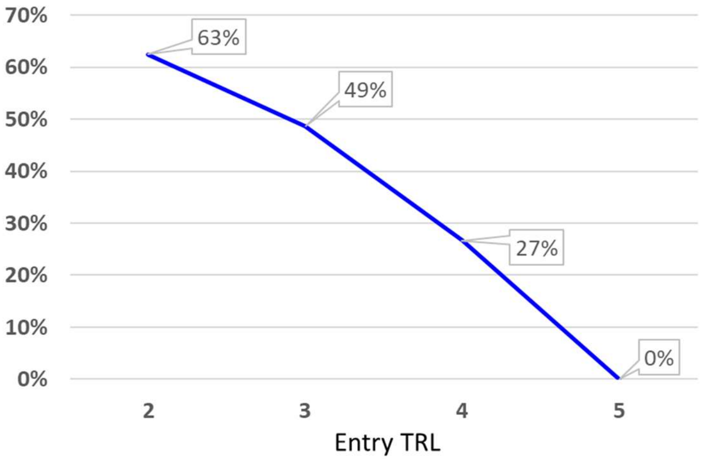

Fig. 9. Percentage of technology development projects achieving TRL advancement vs. entry TRL, e.g., 63 percent of projects entering at TRL 2 advanced, and 49 percent entering at TRL 3 advanced by at least one level. Note that 16 percent of projects entering with a TRL of 3 advanced their TRL by two levels to 5.

The main challenges to achieving TRL advances within technology-maturation projects include:

- Maturing strategic technologies is, almost by definition, highly challenging.
- The TRL scale is a set of step functions, so as long as any part of the requirements for the next TRL is not met, the TRL does not advance.
- Many SAT projects take on system-level technologies, and if the lowest-TRL subsystem does not advance, neither can the overall system.
- The Program Offices impose rigorous TRL standards, including requiring a credible path for achieving the full on-orbit performance requirements to attain TRL 4.
- The entry TRL asserted by the project PI may be optimistic relative to what the Program Offices may have assessed. In such cases, an actual TRL advance may not be recognized.
- As time progresses, the requirements for a technology often evolve, making them a moving target (e.g., a project may have initially worked to mature X-ray mirror technology to meet the IXO 5-arcsec angular resolution requirement for 0.3-7 keV X rays, which was superseded by ATHENA’s current 9-arcsec requirements at 1 keV, which may then have been superseded by the Lynx mission concept’s sub-arcsec requirement).
- The limited time and budget of SAT projects, even ones with one or two follow-on cycles, are often insufficient to address larger technological challenges. This notion is supported by the fact that the five projects receiving four awards and both projects receiving five awards have all advanced by at least one TRL.

3.4 Technology Infusions

While TRL advances are the primary metric for technology maturation, infusion into missions and projects is arguably just as important, as that is the ultimate goal of maturing technologies. Using this metric, APD’s technology investment is an even more spectacular success, with 91 already-implemented infusions, 65 upcoming infusions, and 62 instances of technologies baselined into concepts reference designs of funded studies, primarily flagship and Probe missions (Table 4). These infusions include space, sounding-rocket, and balloon missions, as well as airborne and ground-based instruments. In total, 106 missions/projects/studies benefitted, and while Astrophysics is naturally the main beneficiary with 84 of those, Earth-Science, Planetary, and Heliophysics missions also benefited, as did four non-astronomy/astrophysics applications (Table 5). The list of all infusions is provided below in Table 6 (implemented), Table 7 (upcoming), and Table 8 (concepts).

Table 4. Summary of technology infusions, already implemented, upcoming, conceptual, and infusion-ready by mission/project type.

Phase		Space	Rocket	Balloon	Airborne	Ground	Total
Infused	**Implemented**	19	15	11	3	43	**91**
	Upcoming	31	19	8	1	6	**65**
Potential	**Concepts**	62	-	-	-	-	**62**
	Infusion-Ready	3					**3**
Total		**115**	**34**	**19**	**4**	**49**	**221**

Table 5. Summary of technology infusions by discipline and mission/project type (excluding infusion-ready).

Discipline	Space	Rocket	Balloon	Airborne	Ground	Total
Astrophysics	95	26	19	3	45	**188**
Planetary	7	-	-	-	1	**8**
Heliophysics	3	8	-	-	-	**11**
Earth Science	**7**	**-**	**-**	**-**	**-**	**7**
Non-Space	-	-	-	1	3	**4**
Total	**112**	**34**	**19**	**4**	**49**	**218**

Table 6. Details of 91 already implemented technology infusions by mission/project (Acronyms: OSIRIS-REx, Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer; Si, silicon; HgTe, mercury telluride; microcal., microcalorimeter; GRACE-FO, Gravity Recovery and Climate Experiment – Follow-On; GOLD, Global-scale Observations of the Limb and Disk; ICON, Ionospheric Connection Explorer; SRG, Spectr-Roentgen-Gamma; ADR, Adiabatic Demagnetization Refrigerator; UVS, UV Spectrograph; JUICE, Jupiter Icy Moons Explorer; NuSTAR, Nuclear Spectroscopic Telescope Array; FORTIS, Far-UV Off Rowland circle Telescope for Imaging and Spectroscopy; XQC, X-ray Quantum Calorimeter; WRXR, Water Recovery X-ray Rocket; tREXS, the Rockets for Extended-Source X-ray Spectroscopy; SISTINE, Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet host stars; SHIELDS, Spatial Heterodyne Interferometric Emission Line Dynamics Spectrometer; MaGIXS, Marshall Grazing-Incidence X-ray Spectrometer; FIRE, Far-UV Imaging Rocket Experiment; SLICE, Sub-orbital Local Interstellar Cloud Experiment; EUNIS, Extreme-UV Normal-Incidence Spectrograph; VeSpR, Venus Spectral Rocket; CHESS, Colorado High-resolution Echelle Stellar Spectrograph; DEUCE, Dual-Channel Extreme-UV Continuum Spectrograph; Micro-X, high-resolution Microcalorimeter X-ray imaging rocket; STO-2, Stratospheric Terahertz Observatory II; GUSTO, Galactic/extragalactic Ultra-long-duration-balloon Spectroscopic Terahertz Observatory; ASIC, Application-Specific Integrated Circuit; CCD, Charge-Coupled Device; FireBALL 2, Faint Intergalactic medium Red-shifted Emission Balloon II; PICTURE-C, Planetary Imaging Concept Testbed Using a Recoverable Experiment – Coronagraph; PIPER, Primordial Inflation Polarization Explorer; TiN, Titanium nitride; BLAST-TNG, Balloon-borne Large-Aperture Sub-millimeter Telescope – The Next Generation; HAWC+, High-resolution Airborne Wideband Camera – Plus; SOFIA, Stratospheric Observatory For IR Astronomy; BICEP, Background Imaging of Cosmic Extragalactic Polarization; LmAPD, Linear-mode Avalanche Photodiode; UH, University of Hawaii; ULBCam, Ultra-low Background Camera; NIF, National Ignition Facility; RFSoC, Radio-Frequency System on Chip; LMT, Large Millimeter Telescope; WaSP, Wafer-Scale camera for Prime; ZTF, Zwicky Transient Facility; SOAR, Southern Astrophysical Research telescope; IRAM, Institut de Radioastronomie Millimétrique; GBT, Green Bank Telescope; MUSTANG2, Multiplexed SQUID TES Array at Ninety GHz II; ABS, Atacama B-mode Search; ACT, Atacama

Cosmology Telescope; ACTPol, ACT Polarization-sensitive observations; Ali-CPT, Ali CMB Polarization Telescope; SPTPol, South Pole Telescope Polarimeter; JCMT, James Clerk Maxwell Telescope; SCUBA2, Sub-millimeter Common-User Bolometer Array II; CLASS, Cosmology Large-Angular-Scale Surveyor).

Project Type	PI	Technology	Infused Into
Space Mission	Bautz, M	Directly deposited optical blocking filters	OSIRIS-REx
	Bongiorno, S	High-precision mirror shell alignment and mounting	Imaging X-ray Polarimetry Explorer (IXPE)
	Kilbourne, C	Si-thermistor/HgTe microcal. array	Hitomi
	Klipstein, W	Phasemeter	GRACE-FO
	Quijada, M	UV coatings	GOLD, ICON
	Ramsey, B	High-energy replicated optics	IXPE, SRG
	Shirron, P	ADR	Hitomi, XRISM
	Siegmund, O and Vallerga, J	MCPs	ICON, GOLD, Juno-UVS, JUICE, Solar Orbiter
	Thomas, N and Baumgartner, W	X-Ray test processes and techniques	IXPE, SRG
	Zhang, W	Slumped-glass X-ray mirrors	NuSTAR
Sounding Rocket	Greenhouse, M	Next-generation microshutter arrays	FORTIS
	Kilbourne, C	Si-thermistor/HgTe microcal. array	XQC
	McEntaffer, R	X-ray reflection grating	WRXR, tREXS
	Nikzad, S	ALD mirror coating	SISTINE
	Nikzad, S	Superlattice-doped detector	SHIELDS
	Schattenburg, M and Heilmann, R	Blazed soft X-ray reflection grating	MaGIXS
	Siegmund, O and Vallerga, J	MCPs	FIRE, SLICE, EUNIS, FORTIS, VeSpR, CHESS, SISTINE, DEUCE
	Ullom, J	TES microcalorimeters	Micro-X
	Ullom, J	Time-division SQUID multiplexers	Micro-X
Balloon	Bock, J	Antenna-coupled detectors	Spider
	Hu, Q	4.7 THz local oscillator	STO-2, GUSTO
	Mehdi, I	Heterodyne detectors	STO-2
	Mehdi, I	Heterodyne-detector-related command & data handling (C&DH) and ASIC	High-Altitude Student Platform (HASP)
	Nikzad, S	Advanced CCD detectors	FireBALL 2
	Serabyn, E	Broadband light rejection with optical vortex coronagraph	PICTURE-C
	Staguhn, J	Far-IR large-format detectors	PIPER
	Ullom, J	Time-division SQUID multiplexers	Spider, PIPER
	Zmuidzinas, J	TiN KIDs	BLAST-TNG
Airborne	Mosely, H	TES Bolometers	HAWC+ (SOFIA)
	Ullom, J	Time-division SQUID multiplexers	HAWC+ (SOFIA)

Project Type	PI	Technology	Infused Into
	Wollack, E	Absorptive mixtures and glint reduction coatings	HAWC+ (SOFIA)
Ground-Based	Bennett, D	Microwave SQUID multiplexing crosstalk avoidance	Simons Observatory
	Bock, J	Antenna-coupled detectors	BICEP2, BICEP3/Keck, BICEP Array
	Bottom, M	Near-IR LmAPD	UH 2.2m telescope ULBCam
	Bradford, CM	Ultra-sensitive bolometers	Kitt's Peak Observatory
	Guyon, O	Linear WFC	Subaru observatory
	Kolodziejczak, J	X-ray optics mandrel	NIF X-ray microscope
	Mauskopf, P	RFSoC readout	Toltec camera at LMT
	Mawet, D	Spectrograph & WFC architectures	Keck Planet Imager and Characterizer
	Nikzad, S	Delta-doped CCDs	Palomar-WaSP, ZTF
	Ninkov, Z	Digital Micromirror Devices (DMDs)	4.1-m SOAR telescope
	Thomas, N and Ramsey, B	Electroformed X-ray mirror shell techniques	NIST Neutron Microscope
	Serabyn, E	Vortex coronagraph	Palomar, Keck, and Subaru observatories
	Staguhn, J	TES bolometers	Bolometer camera at IRAM 30m telescope
	Ullom, J	Microwave SQUID multiplexers	GBT MUSTANG2, Simons Observatory
	Ullom, J	Orthomode Transducer (OMT) - coupled TES bolometers	ABS, ACTPol, AdvancedACT, Ali-CPT, GBT MUSTANG2, SPTPol, Simons Obs.
	Ullom, J	TES bolometers	JCMT SCUBA2
	Ullom, J	Time-division SQUID multiplexers	ABS, ACT, ACTPol, AdvancedACT, BICEP2, BICEP3/Keck, JCMT SCUBA2
	Ullom, J	TiN KIDs	Toltec Camera at LMT
	Wollack, E	Feedhorn-coupled symmetric-OMT architectures	ABS, ACTpol, Advanced ACTpol, CLASS, Simons Observatory
	Wollack, E	Feedhorn-coupled symmetric-OMT focal planes	CLASS
	Wollack, E	Absorptive mixtures and glint reduction coatings	CLASS

Table 7. Details of 65 upcoming technology infusions by mission/project (Acronyms: ctrl., control; SPRITE, Supernova Remnant and Proxies for Reionization Testbed Experiment; Electr., electron; MANTIS, Monitoring Activity from Nearby Stars with UV Imaging and Spectroscopy; UVEX, UV Explorer; X-IFU, X-ray Integral Field Unit; LiteBIRD, Light satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection; DarkNESS, Dark matter as a sterile Neutrino Search Satellite; DAVINCI, Deep Atmosphere Investigation of Noble gases, Chemistry, and Imaging; GLIDE, Global Lyman-alpha Imagers of the Dynamic Exosphere; EUVST, Extreme UV high-throughput Spectroscopic Telescope; PADRE, PolArization and Directivity X-Ray Experiment; FOXSI, Focusing Optics X-ray Solar Imager; REDSoX, sounding Rocket Experiment Demonstration of a Soft X-ray polarimeter; OAx, Off-Axis; MOBIUS, Multi-Octave Bandpass Integral-field UV Spectrograph; INFUSE, INtegral-Field UV Spectroscopic Experiment; OGRE, Off-plane Grating Rocket Experiment; CdTe, cadmium telluride; ASTHROS, Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Sub-millimeter wavelengths; EXCLAIM, Experiment for Cryogenic Large-Aperture Intensity Mapping; PUEO, Payload for Ultrahigh Energy Observations; ONR, Office of Naval Research; CCAT-Prime, Cerro Chajnantor Atacama Telescope Prime; GISMO, Goddard IRAM 2 Millimeter Observer).

Project Type	PI	Technology	Infused Into
Space Mission	Belikov, R	Multi-star wavefront sensing and ctrl.	RST
	Conklin, J	Charge management device	LISA
	Fleming, B	Protected enhanced LiF mirror coatings	SPRITE
	Fleming, B	MCP anti-coincidence shielding	SPRITE
	Fleming, B	Electr.-beam-lithography-ruled gratings	MANTIS
	Hennessy, J	ALD UV coatings	SPRITE, Aspera, UVEX
	Hennessy, J	Multilayer aluminum dielectric filters for UV detectors	Star-Planet Activity Research CubeSat (SPARCS)
	Hoenk, M	CMOS image sensors	UVEX
	Kasdin, J	WFC with two deformable mirrors	RST
	Kilbourne, C	TES microcalorimeter arrays	ATHENA X-IFU
	Kilbourne, C	Time-domain multiplexing	ATHENA X-IFU
	Krist, J and Shaklan, S	End-to-end coronagraph models	RST
	Lee, A	CMB detectors	LiteBIRD
	Livas, J	Telescope	LISA
	Nikzad, S	Advanced CCD detectors	SPARCS
	Quijada, M	Physical vapor deposition	SPRITE, Aspera
	Rauscher, B	H4RG IR detectors	RST
	Rauscher, B	Radiation-tolerant, photon-counting, visible and near-IR detectors	DarkNESS, DAVINCI
	Siegmund, O and Vallerga, J	MCPs	SPRITE, Aspera, Europa Clipper, GLIDE, EUVST, MANTIS
	Trauger, J	Hybrid Lyot coronagraph	RST
	Vallerga, J	Timepix2 ASICs	PADRE
	Trauger, J	Hybrid Lyot coronagraph	RST
	Wollack, E	Feedhorn-coupled symmetric-OMT architectures	LiteBIRD
	Yu, A	Laser technology	LISA
Sounding Rocket	Baumgartner, W	Electroformed X-ray mirror shells	FOXSI-4
	Bongiorno, S	Electroformed X-ray mirror shells	FOXSI-4
	Bongiorno, S	Electroformed X-ray mirror shells	REDSoX
	Champey, P	Electroformed X-ray mirror shells	MaGIXS-2
	Fleming, B	Electr.-beam-lithography-ruled gratings	OAx-FORTIS, MOBIUS
	Fleming, B	Image slicer	INFUSE
	Gurgew, D	Single & multilayer coating techniques	FOXSI-4
	McEntaffer, R	X-ray reflection gratings	OGRE
	Quijada, M	Far-UV coatings	FORTIS
	Schattenburg, M and Heilmann, R	X-ray Critical-Angle Transmission (CAT) grating	REDSoX

Project Type	PI	Technology	Infused Into
	Siegmund, O and Vallerga, J	MCPs	INFUSE, MOBIUS, FORTIS
	Singam, P	Electroforming Process Modeling	FOXSI-4
	Thomas, N and Baumgartner, W	X-Ray test processes and techniques	FOXSI-4
	Vallerga, J	Timepix3 CdTe detector	FOXSI-4
	Vorobiev, D	DMDs	INFUSE
	Zhang, W	Single-crystal silicon X-ray mirrors	OGRE
Balloon	Bennett, D	Microwave SQUID multiplexing firmware and parameters	Dilution Refrigeration TES (DR-TES)
	Bradford, CM	Setup for ultra-sensitive bolometers	Terahertz Intensity Mapper (TIM)
	Mehdi, I	THz heterodyne arrays	ASTHROS
	Mauskopf, P	RFSoC readout	EXCLAIM, PUEO, TIM
	Wollack, E	Low-loss transmission lines and micromachined packaging	EXCLAIM
	Wollack, E	Absorptive mixtures and glint reduction coatings	EXCLAIM
Airborne	Mauskopf, P	Intermediate-Frequency (IF) board	ONR airborne KID instrument
Ground-Based	Bottom, M	Near-IR LmAPD	ULBCam, Subaru observatory
	Caputo, R	AstroPix CMOS Monolithic Active Pixel Sensors	Electron-Proton/Ion Collider (ePIC)
	Mauskopf, P	RFSoC readout	Toltec camera at CCATprime
	Staguhn, J	GISMO	Greenland Telescope (GLT)
	Ullom, J	OMT-coupled TES bolometers	CMB Stage IV (CMB-S4)
	Ullom, J	TiN KIDs	Toltec
	Vasisht, G	EPRV etalon	Keck Planet Finder

Table 8. Details of 62 technology infusions baselined by NASA-funded studies (Acronyms: AXIS, Advanced X-ray Imaging Satellite; STAR-X, Survey and Time-domain Astrophysical Research Explorer; HabEx, Habitable Exoplanet Observatory; LUVOIR, Large UV/Optical/IR Surveyor; PIAACMC, Phase-Induced Amplitude Apodization Complex Mask Coronagraph; MEMS, Micro Electro-Mechanical System; CETUS, Cosmic Evolution Through UV Surveys; HgCdTe, mercury cadmium telluride; CASTOR, Cosmological Advanced Survey Telescope for Optical and UV Research; FPGA, Field-Programmable-Gate-Array; GEP, Galaxy Evolution Probe; ESCAPE, Extreme-UV Stellar Characterization for Atmospheric Physics and Evolution; TAP, Transient Astrophysics Probe; MAGIC, Massive Star Asteroseismology Instrument Cubesat; MiXO, Miniature Wolter-I X-ray Optics; CubeX, CubeSat X-ray Telescope).

Project Type	PI	Technology	Infused Into
Space Mission	Bautz, M	Directly deposited optical blocking filters	Lynx
	Bautz, M	Advanced CCD detector	AXIS Probe, STAR-X
	Belikov, R	Multi-star wavefront sensing and ctrl	HabEx, LUVOIR
	Belikov, R	PIAACMC	HabEx, LUVOIR
	Bierden, P	MEMS deformable mirrors	HabEx, LUVOIR

Project Type	PI	Technology	Infused Into
	Bock, J and O’Brient, R	CMB detectors	Probe of Inflation and Cosmic Origins (PICO)
	Bock, J and O’Brient, R	Antenna-coupled detectors	PICO
	Fleming, B	MCP Anti-coincidence shielding	LUVOIR
	Greenhouse, M	Next generation microshutter arrays	HabEx, LUVOIR, CETUS Probe
	Guyon, O	Linear WFC	HabEx, LUVOIR
	Guyon, O	Predictive WFC	HabEx, LUVOIR
	Guyon, O	Sensor fusion	HabEx, LUVOIR
	Hall, D and Bottom, M	APD HgCdTe Near-IR detectors	HabEx, LUVOIR
	Hoenk, M	CMOS image sensors	CASTOR
	Kasdin, J; Casement, S; Glassman, T; and Cash, W	Starshade technologies	Starshade-RST Rendezvous Probe
	Lee, A	CMB detectors	PICO
	Mauskopf, P	Low-power FPGA-based readout electronics for superconducting arrays	PICO, Origins, GEP, Cosmic Dawn
	McEntaffer, R	Low-blaze-angle grating	ESCAPE
	Nikzad, S	Delta-doped electr.-multiplying CCDs	HabEx
	Nikzad, S	Delta-doped CMOS detector arrays	LUVOIR
	Schattenburg, M	CAT X-ray gratings	Lynx
	Schattenburg, M	Thermal oxide coating stress compensation	Lynx, AXIS, TAP
	Serabyn, E	Vortex coronagraph	HabEx, LUVOIR
	Siegmund, O and Vallerga, J	Cross-strip MCP detector systems	HabEx, LUVOIR, CETUS
	Siegmund, O and Vallerga, J	MCPs	HabEx, LUVOIR, CETUS, ESCAPE, MAGIC
	Singam, P	Electroforming Process Modeling	MiXO for CubeX
	Soummer, R	Apodized Pupil Lyot Coronagraph	LUVOIR
	Staguhn, J	Superconducting kilo-pixel far-IR detectors	Origins
	Stahl, HP	Precision thermal control	HabEx zonal thermal control pathfinder
	Thomas, N and Baumgartner, W	X-Ray test processes and techniques	MiXO for CubeX
	Tuttle, J	Continuous ADR (CADR)	Lynx, Origins, PICO, GEP
	Ullom, J	Microwave SQUID multiplexers	Lynx, Origins
	Ullom, J	Time-division SQUID multiplexers	PICO
	Zhang, W	Single-crystal-silicon X-ray mirrors	Lynx, AXIS, TAP, STAR-X
	Ziemer, J	Micro-Newton thrusters	HabEx fine pointing and jitter suppression

3.5 Other Benefits of APD Technology Investments

Beyond technology maturation and TRL advances, the technology investments generated multiple other benefits. A majority of PIs leveraged their initial projects and received additional funding, generated collaborations, were inducted into the National Academy of Inventors, and/or raised industry interest in their technologies. Over 100 students and post-docs were hired by PIs, helping train our future astrophysics and technological workforce. One student, after receiving his PhD, started a small business providing nano-fabrication services for the lab from which he graduated.

4. Outcome of the 2022 Technology Gap Prioritization

Inspired and informed by Astro2020, the community submitted dozens of new technology gap entries. These were added to the 48 gaps from the previous (2019) cycle; filtered to remove entries that were not technology gaps and/or not addressing the instrument-centric purview of the SAT program; split between COR, ExEP, and PhysCOS; reviewed, edited, and consolidated as deemed appropriate. Beyond new gaps submitted by the community inputs, the three Program Analysis Groups (PAGs) supported the preparation of gap entries for prioritization.

Each Program Office then conducted a prioritization exercise of its final list of gaps: 28 for COR, 10 for ExEP, and 19 for PhysCOS. Each gap was assessed using the same four criteria below, with the same weights and guidelines for all three Programs.

1 Strategic Alignment: How well does closing the gap align with Astrophysics science and programmatic priorities?
2 Benefits and Impacts: How big an impact would closing the gap have on applicable strategic Astrophysics mission(s)? To what degree would this enable and/or enhance achievable science objectives, reduce cost, and/or reduce mission risks?
3 Urgency: How large a schedule margin do we have for closing the gap before the technologies need to be at TRL 6?
4 Scope of Applicability: How crosscutting would the impact of closing the gap be? How many Astrophysics programs and/or mission concepts could it benefit, with an emphasis on strategic missions?

Where a gap was deemed relevant for more than one mission, it was ranked separately for each such mission, and assigned the highest of these parallel priority ranks. Finally, the three prioritized Program lists were merged into a unified, prioritized Astrophysics technology gap list of 57 gaps. This list is shown in Table 9 below and was published in the 2022 Astrophysics Biennial Technology Report (ABTR).[12] The detailed text for each of the gaps, including a detailed description, the current state-of-the-art and performance goals and objectives, benefits of closing the gap, and urgency to close the gap can be found on the Astrophysics Strategic Technology Gaps website.[13]

Table 9. The 2022 Astrophysics technology gap list, broken into five tiers of descending priority. Each gap within the same tier is considered as having the same priority as all other gaps in that tier (hence their alphabetical order). Tier 5 gaps are considered non-strategic.

Tier 1

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

Tier 2

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

Tier 3

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

Tier 4

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

Tier 5

1. Complex Ultra-Stable Structures for Future Gravitational-Wave Missions
2. Disturbance Reduction for Gravitational-Wave Missions
3. Gravitational Reference Sensor
4. High-Performance Spectral Dispersion Component/Device
5. High-Power, High-Stability Laser for Gravitational-Wave Missions
6. Laser Phase Measurement Chain for a Decihertz Gravitational-Wave Mission
7. Micro-Newton Thrusters for Gravitational Wave-Missions
8. Stable Telescopes for Gravitational Wave-Missions

5. Summary

We presented the current Astrophysics strategic technology development portfolio for COR, ExEP, and PhysCOS. We analyzed a total of 166 investigations grouped into 98 projects, broken down by the managing Program Office, PI organization type, technology area (68 percent focused on the critical topics of detectors, optics, and coronagraphs), signal type, strategic mission supported, and TRL advances (46 percent of projects advanced by at least one TRL). We listed 218 infusions of 99 technologies arising from technology maturation projects funded by APD into 106 missions, projects, and funded studies; we broke these down by implementation timeline (implemented, upcoming, concept), and by the discipline of the mission/project that benefited (nearly 14 percent were beyond Astrophysics). These and other listed benefits demonstrate an impressive return on the $322 million invested in these 98 projects. Finally, we presented the 2022 prioritized list of 57 Astrophysics technology gaps.

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Opher Ganel is a technologist in NASA APD’s PhysCOS and COR Program Office. He received his BSc in mathematics and physics from the Hebrew University in Jerusalem, and his MSc in theoretical high-energy physics and PhD in experimental high-energy physics from the Weizmann Institute of Science in 1986, 1989, and 1994, respectively. He is co-author of more than 35 journal papers to which he made significant contributions.

Biographies and photographs for the other authors are not available.

Caption List

Table 1. The current COR portfolio comprises 18 technology maturation awards (Acronyms: PI, Principal Investigator; KID, Kinetic Inductance Detector; NIST, National Institute of Standards and Technology; JPL, Jet Propulsion Lab; CMOS, Complementary Metal-Oxide Semiconductor; RIT, Rochester Institute of Technology; Caltech, California Institute of Technology; ALD, Atomic Layer Deposition; GSFC, Goddard Spaceflight Center; PSU, The Penn State University; LiF, Lithium Fluoride; TES, Transition-Edge Sensor; JHU, Johns Hopkins University; MSFC, Marshall Spaceflight Center; MCP, Multi-Channel Plate; UCB, University of California Berkeley).

Table 2. The current ExEP portfolio comprises 21 technology maturation awards (Acronyms: ARC, Ames Research Center; WFC, Wavefront Control; DST, Decadal Survey Testbed; MIT, Massachusetts Institute of Technology; µ-propulsion, micro-propulsion; STScI, Space Telescope Science Institute).

Table 3. The current PhysCOS portfolio comprises 14 technology maturation awards (Acronyms: SQUID, Super-conducting QUantum Interference Device; SAO, Smithsonian Astrophysical Observatory; LL, Lincoln Laboratory).

Fig. 1. Distribution of projects by number of funding cycles, with 98 projects comprising up to five funding cycles.

Fig. 2. Distribution of projects by total duration in years, including any follow-on cycles.

Fig. 3. Strategic technology development by Program from 2009 to 2023: number of distinct projects (left) and total investment (right). Note that this excludes certain direct-funded projects such as ExEP’s S5 Starshade effort.

Fig. 4. Distribution of strategic technology development projects by institutional types receiving the awards.

Fig. 5. Distribution of the 98 projects in the strategic technology portfolio by topic since SAT inception.

Fig. 6. Distribution of the projects in the strategic technology portfolio by signal type since SAT inception.

Fig. 7. Distribution of the 98 projects in the strategic technology portfolio by strategic mission(s) supported.

Fig. 8. Distribution of TRL advancement of strategic technologies. Some advances were during the relevant project's duration, and some continue advancing in TRL after project completion, especially those that were infused into spaceflight missions.

Fig. 9. Percentage of technology development projects achieving TRL advancement vs. entry TRL, e.g., 63 percent of projects entering at TRL 2 advanced, and 49 percent entering at TRL 3 advanced by at least one level. Note that 16 percent of projects entering with a TRL of 3 advanced their TRL by two levels to 5.

Table 4. Summary of technology infusions, already implemented, upcoming, conceptual, and infusion-ready by mission/project type.

Table 5. Summary of technology infusions by discipline and mission/project type (excluding infusion-ready).

Table 6. Details of 91 already implemented technology infusions by mission/project (Acronyms: OSIRIS-REx, Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer; Si, silicon; HgTe, mercury telluride; microcal., microcalorimeter; GRACE-FO, Gravity Recovery and Climate Experiment – Follow-On; GOLD, Global-scale Observations of the Limb and Disk; ICON, Ionospheric Connection Explorer; SRG, Spectr-Roentgen-Gamma; ADR, Adiabatic Demagnetization Refrigerator; UVS, UV Spectrograph; JUICE, Jupiter Icy Moons Explorer; NuSTAR, Nuclear Spectroscopic Telescope Array; FORTIS, Far-UV Off Rowland circle Telescope for Imaging and Spectroscopy; XQC, X-ray Quantum Calorimeter; WRXR, Water Recovery X-ray Rocket; tREXS, the Rockets for Extended-Source X-ray Spectroscopy; SISTINE, Suborbital Imaging Spectrograph for Transition region Irradiance from Nearby Exoplanet host stars; SHIELDS, Spatial Heterodyne Interferometric Emission Line Dynamics Spectrometer; MaGIXS, Marshall Grazing-Incidence X-ray Spectrometer; FIRE, Far-UV Imaging Rocket Experiment; SLICE, Sub-orbital Local Interstellar Cloud Experiment; EUNIS, Extreme-UV Normal-Incidence Spectrograph; VeSpR, Venus Spectral Rocket; CHESS, Colorado High-resolution Echelle Stellar Spectrograph; DEUCE, Dual-Channel Extreme-UV Continuum Spectrograph; Micro-X, high-resolution Microcalorimeter X-ray imaging rocket; STO-2, Stratospheric Terahertz Observatory II; GUSTO, Galactic/extragalactic Ultra-long-duration-balloon Spectroscopic Terahertz Observatory; ASIC, Application-Specific Integrated Circuit; CCD, Charge-Coupled Device; FireBALL 2, Faint Intergalactic medium Red-shifted Emission Balloon II; PICTURE-C, Planetary Imaging Concept Testbed Using a Recoverable Experiment – Coronagraph; PIPER, Primordial Inflation Polarization Explorer; TiN, Titanium nitride; BLAST-TNG, Balloon-borne Large-Aperture Sub-millimeter Telescope – The Next Generation; HAWC+, High-resolution Airborne Wideband Camera – Plus; SOFIA, Stratospheric Observatory For IR Astronomy; BICEP, Background Imaging of Cosmic

Extragalactic Polarization; LmAPD, Linear-mode Avalanche Photodiode; UH, University of Hawaii; ULBCam, Ultra-low Background Camera; NIF, National Ignition Facility; RFSoC, Radio-Frequency System on Chip; LMT, Large Millimeter Telescope; WaSP, Wafer-Scale camera for Prime; ZTF, Zwicky Transient Facility; SOAR, Southern Astrophysical Research telescope; IRAM, Institut de Radioastronomie Millimétrique; GBT, Green Bank Telescope; MUSTANG2, Multiplexed SQUID TES Array at Ninety GHz II; ABS, Atacama B-mode Search; ACT, Atacama Cosmology Telescope; ACTPol, ACT Polarization-sensitive observations; Ali-CPT, Ali CMB Polarization Telescope; SPTPol, South Pole Telescope Polarimeter; JCMT, James Clerk Maxwell Telescope; SCUBA2, Sub-millimeter Common-User Bolometer Array II; CLASS, Cosmology Large-Angular-Scale Surveyor).

Table 7. Details of 65 upcoming technology infusions by mission/project (Acronyms: ctrl., control; SPRITE, Supernova Remnant and Proxies for Reionization Testbed Experiment; Electr., electron; MANTIS, Monitoring Activity from Nearby Stars with UV Imaging and Spectroscopy; UVEX, UV Explorer; X-IFU, X-ray Integral Field Unit; LiteBIRD, Light satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection; DarkNESS, Dark matter as a sterile Neutrino Search Satellite; DAVINCI, Deep Atmosphere Investigation of Noble gases, Chemistry, and Imaging; GLIDE, Global Lyman-alpha Imagers of the Dynamic Exosphere; EUVST, Extreme UV high-throughput Spectroscopic Telescope; PADRE, PolArization and Directivity X-Ray Experiment; FOXSI, Focusing Optics X-ray Solar Imager; REDSoX, sounding Rocket Experiment Demonstration of a Soft X-ray polarimeter; OAx, Off-Axis; MOBIUS, Multi-Octave Bandpass Integral-field UV Spectrograph; INFUSE, INtegral-Field UV Spectroscopic Experiment; OGRE, Off-plane Grating Rocket Experiment; CdTe, cadmium telluride; ASTHROS, Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Sub-millimeter wavelengths; EXCLAIM, Experiment for Cryogenic Large-Aperture Intensity Mapping; PUEO, Payload for Ultrahigh Energy Observations; ONR, Office of Naval Research; CCAT-Prime, Cerro Chajnantor Atacama Telescope Prime; GISMO, Goddard IRAM 2 Millimeter Observer).

Table 8. Details of 62 technology infusions baselined by NASA-funded studies (Acronyms: AXIS, Advanced X-ray Imaging Satellite; STAR-X, Survey and Time-domain Astrophysical Research Explorer; HabEx, Habitable Exoplanet Observatory; LUVOIR, Large UV/Optical/IR Surveyor; PIAACMC, Phase-Induced Amplitude Apodization Complex Mask Coronagraph; MEMS, Micro Electro-Mechanical System; CETUS, Cosmic Evolution Through UV Surveys; HgCdTe, mercury cadmium telluride; CASTOR, Cosmological Advanced Survey Telescope for Optical and UV Research; FPGA, Field-Programmable-Gate-Array; GEP, Galaxy Evolution Probe; ESCAPE, Extreme-UV Stellar Characterization for Atmospheric Physics and Evolution; TAP, Transient Astrophysics Probe; MAGIC, Massive Star Asteroseismology Instrument Cubesat; MiXO, Miniature Wolter-I X-ray Optics; CubeX, CubeSat X-ray Telescope).

Table 9. The 2022 Astrophysics technology gap list, broken into five tiers of descending priority. Each gap within the same tier is considered as having the same priority as all other gaps in that tier (hence their alphabetical order). Tier 5 gaps are considered non-strategic.