Linking strategic astrophysics missions, technology gaps, and technology maturation investments

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ABSTRACT

The National Aeronautics and Space Administration's (NASA) Astrophysics Division (APD) funds the development of cutting-edge technologies through multiple programs to enable its strategic missions to achieve ambitious and groundbreaking science goals. These technology development efforts are managed by the Cosmic Origins (COR), Exoplanet Exploration (ExE), and Physics of the Cosmos (PhysCOS) programs. The 2020 Astronomy and Astrophysics Decadal Survey, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s" [1] (Astro2020), recommended a pan-chromatic set of missions, including three Great Observatories (GOs) and three Probe-class missions that could collect unprecedented data over the coming decades. We show the correlation between these strategic missions and the current astrophysics technology gaps, as well as recent and current technology maturation projects funded to help close these technology gaps. We also cover how these investments advanced their Technology Readiness Levels (TRLs) [2] and where they have been infused into missions and projects.

Keywords: NASA, astrophysics, technology development, optics, telescope, detector, PhysCOS/COR, ExEP

1. INTRODUCTION

NASA's Science Mission Directorate seeks to expand our knowledge and understanding of our planet, sun, solar system, and the universe we live in. NASA's APD is responsible for enabling and carrying out observations and measurements, focusing on the universe. Through three thematic programs, COR, ExEP, and PhysCOS, APD seeks to answer three fundamental questions: "How did we get here?" (COR), "Are we alone?" (ExEP), and "How does the universe work?" (PhysCOS). Each decade, APD's priorities are informed by a new Astronomy and Astrophysics Decadal Survey from the National Academies of Sciences, Engineering, and Medicine. The latest Decadal Survey, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," recommended three GOs – an Infrared (IR)/Optical/Ultraviolet (UV) mission to identify and characterize habitable exoplanets dubbed the Habitable Worlds Observatory (HWO), a far-IR GO, and an X-ray GO; and three Probe missions – a far-IR Probe, an X-ray Probe, and an Early Universe Cosmology and Fundamental Physics Probe to study the Cosmic Microwave Background (CMB). The Survey also recommended making Time Domain and Multi-Messenger (TDAMM) astrophysics the top sustaining astrophysics activities priority. Supported by the science and technology community, APD identifies and prioritizes biennially the technology gaps between the current state of the art and what is needed to fly these ever-more-challenging strategic missions. In the following, we show how the 2022 technology gaps correlate to the Astro2020 priorities and the APD-funded maturation efforts (Section 2), the current portfolios of projects maturing strategic technologies (Section 3), project stats and TRL advances resulting from these investments (Section 4), and infusions of APD-funded technologies into missions and projects (Section 5).

2. TECHNOLOGY GAPS, STRATEGIC PRIORITIES, AND INVESTMENTS

1.1 Strategic astrophysics missions

Strategic astrophysics missions are agency-led missions or concepts that APD is developing, participating in, or interested in, which are intended to respond to high-priority science questions. Astro2020 recommended launching an ambitious set

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of panchromatic missions – three GOs and three Probes – over the coming decades. These include HWO, to be launched in the early 2040s to observe ~25 exo-Earths and carry out general astrophysics measurements; a far-IR GO and an X-ray GO, to be launched at least a decade after HWO; a far-IR Probe and an X-ray Probe, one of which should launch early next decade; and a CMB Probe, to compete for a 2040s launch slot with the remaining Probe that did not launch in the 2030s.

1.2 Strategic astrophysics technology gaps

The COR, ExE, and PhysCOS Program Offices manage for APD strategic technology development efforts within their respective Programs. The three Offices collaborate and coordinate the technology gap prioritization process, including soliciting community inputs, updating the unified prioritization process as needed, prioritizing gaps (done separately but with technologists from the three Offices participating in all three efforts), and reporting the prioritized strategic astrophysics technology gaps to APD and the community. The 2022 prioritization cycle, informed by the Astro2020 recommendations, resulted in a prioritized list of 57 gaps in five priority tiers (Table 1). Gaps in Tiers 1-4 are automatically included in the ongoing 2024 prioritization. Tier 5 gaps, deemed non-strategic, are excluded from the current cycle.

Table 1. 2022 Technology gaps (COR/ExEP/PhysCOS) alphabetized within priority each tier Affected missions and activities are denoted by "×." Gaps with recent and/or ongoing investment denoted by shaded mission/activity area.

TIER	TECHNOLOGY GAP	HWO	X-RAY GO/PROBE	FAR-IR GO/ PROBE	CMB PROBE	TDAMM
	Advanced Cryocoolers		×	×		
	Coronagraph Contrast and Efficiency	×				
	Coronagraph Stability	×				
	Cryogenic Readouts for Large-Format Far-IR Detectors			×	×	
	Heterodyne Far-IR Detector Systems			×		
	High-Throughput Large-Format Object Selection Tech for Multi-Object and Integral Field Spectroscopy	×				
	High-Performance, Sub-Kelvin Coolers		×	×	×	
	High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings	×				
	High-Resolution, Large-Area, Lightweight X-ray Optics		×			
1	High-Throughput Bandpass Selection for UV/Visible	×				
	Large Cryogenic Optics for the Mid IR to Far IR			×		
	Large-Format, High-Resolution Focal Plane Arrays	×				
	Large-Format, Low-Darkrate, High Eff., Photon-Counting, Solar-Blind, Far-UV and Near-UV Detectors	×				
	Large-Format, Low-Noise, and Ultralow-Noise Far-IR Direct Detectors			×		
	Low-Stress, High-Stability, X-ray Reflective Coatings		×			
	Mirror Technologies for High Angular Resolution in the UV/Visible/Near-IR	×				
	Optical Blocking Filters for X-ray Instruments		×			
	Stellar Reflex Motion Sensitivity: Extreme Precision Radial Velocity (EPRV)	×				
	Stellar Reflex Motion Sensitivity: Astrometry	×				
	Visible/Near-IR Detection Sensitivity	×				
	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			×		
2	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 Above 100 GHz			×		

TIER	TECHNOLOGY GAP	HWO	X-RAY GO/PROBE	FAR-IR GO/ PROBE	CMB PROBE	TDAMM
	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	×				
3	Advancement of X-ray Polarimeter Sensitivity		×			
3	Detection Stability in the Mid-IR			×		
3	Far-UV Imaging Bandpass Filters	×				
3	High-Efficiency Far-UV Mirror	×				
3	High-Efficiency Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blaze-Angle UV Gratings	×				
3	High-Quantum-Efficiency, Solar-Blind, Broadband Near-UV Detector	×				
3	Photon-Counting, Large-Format UV Detectors	×				
3	Short-Wave UV Coatings	×				
3	Warm Readout Electronics for Large-Format Far-IR Detectors			×		
4	Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry				×	
4	Improving Photometric/Spectrophotometric Precision of Time-Domain and Time-Series Measurements					×
4	UV/Optical/Near-IR Tunable Narrow-Band Imaging Capability	×				
4	Very-Wide-Field Focusing Instrument for Time-Domain X-ray Astronomy		×			×
5	Complex Ultra-Stable Structures for Future Gravitational-Wave (GW) Missions	None				
5	Disturbance Reduction for GW Missions					
5	Gravitational Reference Sensor					
5	High-Performance Spectral Dispersion Component/Device					
5	High-Power, High-Stability Laser for GW Missions					
5	Laser Phase Measurement Chain for a Decihertz GW Mission					
5	Micro-Newton Thrusters for GW Missions					
5	Stable Telescopes for GW Missions					

As shown in the table, recent and ongoing strategic technology development investments have been made to address 16 of the 20 Tier-1 gaps (80 percent), nine of the 16 Tier-2 gaps (56 percent), seven of the nine Tier-3 gaps (78 percent), and one of the four Tier-4 gaps (25 percent), for an overall 33 of 49 gaps (67 percent) with investments.

3. CURRENT TECHNOLOGY INVESTMENTS

The current portfolio of strategic astrophysics technology maturation investments comprises 53 active awards.

COR focuses primarily on understanding when the first stars 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. This requires mostly technologies for collecting and measuring photons in the UV, visible, and IR. The current COR portfolio comprises 18 active awards (Table 2).

Table 2. The current COR strategic technology portfolio comprises 18 awards (Acronyms: PI, Principal Investigator;; 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; JHU, Johns Hopkins University; Metr./Struct., Metrology/Structure; 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 Kinetic Inductance Detector (KID) Arrays	Austermann, J	NIST	Detector
Four-Megapixel Sensor for Ultra-Low-Background Shortwave IR Astronomy	Bottom, M	U Hawaii	Detector
Ultrasensitive Far-IR KID Arrays: Maturation for Flight	Bradford, CM	JPL	Detector
Characterizing Single-Photon Sensing CMOS Image Sensors for NASA Missions	Figer, D	RIT	Detector
Ultrasensitive Far-IR KID Arrays for Space	Hailey-Dunsheath, S	Caltech	Detector
High Performance, Stable, and Scalable UV Al Mirror Coatings Using ALD	Hennessy, J	JPL	Coating
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 Transition-Edge Sensor (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	Metr./Struct.
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 on the detection and characterization of planets around nearby stars, especially Earth-like planets in the habitable zones of their respective 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 EPRV measurements. There are 21 active awards currently pursuing these (Table 3).

Table 3. The current ExEP strategic technology portfolio comprises 21 technology maturation awards (Acronyms: ARC, Ames Research Center; 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 Wavefront Control (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, Visible/Near-IR Detectors for Coronagraphs & 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 ExoEarth 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 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. The relevant technologies include those needed to measure GWs, microwaves, and X rays. The current PhysCOS portfolio comprises 14 technology maturation awards (Table 4).

Table 4. The current PhysCOS strategic technology 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 and 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	Metr./Struct.
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 the Next Generation of 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
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 technology investigations is available via a searchable database [3] or NASA's TechPort [4].

4. PROJECT STATS AND TECHNOLOGY READINESS LEVEL ADVANCEMENTS

One of the main measures of return on technology investment is the maturation of technologies to higher TRL. To assess that return, we analyze the 166 current and past Strategic Astrophysics Technology (SAT) and Internal Scientist Funding Model (ISFM) awards funded by APD for technology maturation (excluding eight grants awarded less than a year ago).

4.1 Technology maturation grants and projects

Since many grants are follow-on awards for maturing the same technology, usually but not always awarded to the same PI, we merge such follow-on awards, leaving us with 98 unique projects with at least one full year of work completed. These projects began between 2009 and 2023. Figure 1 shows the distribution of number of awards per project, with 61.2 percent having just one award, 17.3 percent with two, 14.3 percent with three, 5.1 percent with four, and 2.0 percent with five, resulting in an average of 1.7 per project. Since these awards may be as short as one year and up to four or five years, Figure 2 shows the distribution of project length in years. The most common duration is three years (typical SAT duration), while the longest project's duration was 13 years, with an average of 5.2 years. Note that APD also invests in technology-related facilities, software, and TDAMM-related activities through ISFM awards and Roman Technology Fellowships (RTFs). Since these are not direct technology-maturation investments they are not included in the analyses reported here.

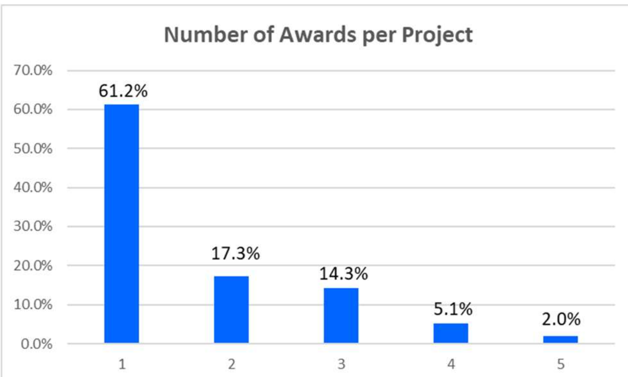

Figure 1. Distribution of projects by number of awards.

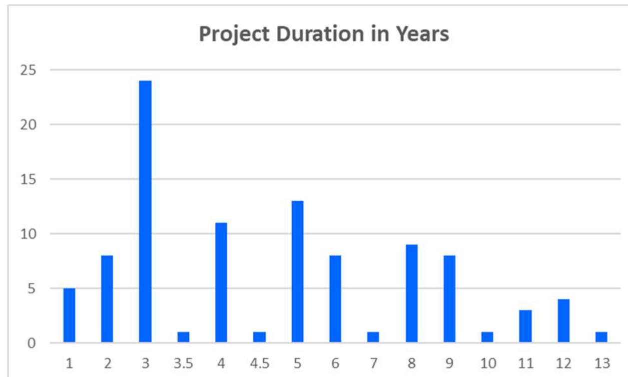

Figure 2. Distribution of project duration in years.

4.2 Technology maturation projects by technology type

Figure 3 shows the distribution of technology maturation projects by the type of technology they address. Given their important roles in astrophysics missions, the five most common categories – detectors, optics, coronagraphs, coatings, and electronics – account for 84 of the 98 projects (86 percent).

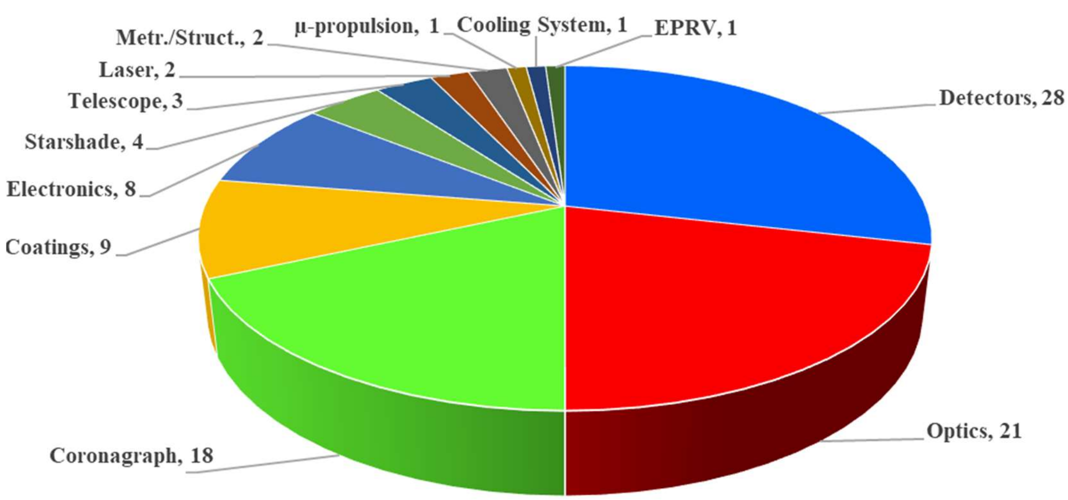

Figure 3. Distribution of technology maturation projects by technology type. The most common are detectors (28), optics (21), coronagraphs (18), coatings (9), and electronics (8).

4.3 Projects supporting strategic missions

Of course, there is a close connection between technology maturation projects, the gaps they address, and the strategic missions they can enable or enhance. Figure 4 shows the number of technology maturation projects that enable or enhance strategic missions. Note that since these projects began as far back as 2009, some of these are no longer in our current set of strategic missions. Some of the missions, e.g., the Roman Space Telescope (RST) [5], are nearing launch; some are already funded and expected to launch in the coming decade, e.g., the European Space Agency's Advanced Telescope for High-ENergy Astrophysics (ATHENA) [6] and Laser Interferometer Space Antenna (LISA) missions [7]. The remaining six are the set of strategic astrophysics missions recommended by Astro2020. As shown, the mission with the largest number of supporting projects is HWO (53 projects), unsurprising given its level of complexity and challenge.

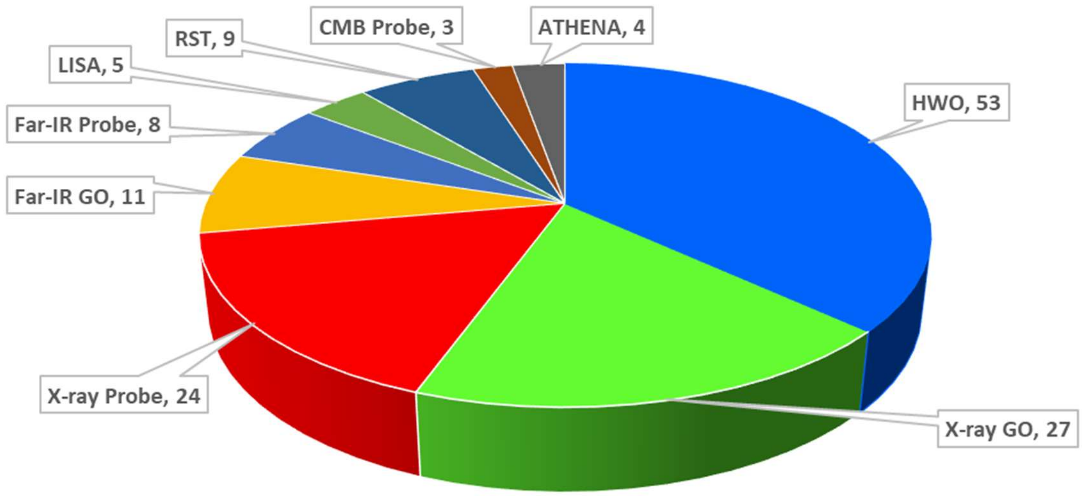

Figure 4. Distribution of technology maturation projects by strategic mission(s) affected. Note that the total, 144, is higher than the number of projects, 98, because some technologies affect more than one mission.

4.4 Projects advancing TRL

Table 5 shows that of 98 projects, 45 (46 percent) advanced by at least one TRL (12 of these, or 12 percent, advanced by two levels). The remaining 53 projects (54 percent) made significant progress but did not meet all the requirements for the next TRL. Unsurprisingly, the fraction of projects advancing their TRL was highest for the lowest entry TRL, 2, with the fraction of projects that advanced dropping as the entry TRL increased. The table also shows that the most common entry TRL by far was 3 (74 projects), followed by TRL 4 (15 projects).

Table 5. Projects by entry TRL that achieved TRL advances.

ENTRY TRL	NUMBER OF PROJECTS	NUMBER ADVANCING	FRACTION ADVANCING
2	8	5	63 percent
3	74	36	49 percent
4	15	4	27 percent
5	1	0	0 percent
Total	**98**	**45**	**46 percent**

5. TECHNOLOGY INFUSIONS

Another important metric of return on technology investment is infusion into missions or projects. Here, we define infusion as a mission, project, or funded study concept that implemented or baselined the technology in question. These have resulted from APD funding from 2009 to 2023 through SATs, ISFMs, and Astrophysics Research and Analysis (APRA) grants received by SAT/ISFM PIs (we did not include APRA projects with PIs who have not also received SAT and/or ISFM funding as that information was not readily available).

We subdivide infusions into these categories:

- **Implemented** in a past or current flight mission or ground-based project (e.g., Hitomi; X-Ray Imaging and Spectroscopy Mission, XRISM; Ionospheric Connection Explorer, ICON; Solar Orbiter).
- **Upcoming** flight missions or ground projects (e.g., RST, LISA, ATHENA, Sprite CubeSat) baselined the technology.

- **Concept** or reference design of an APD-funded large-mission study (Large UV/Optical/IR Surveyor, LUVOIR; Habitable Exoplanet Observatory, HabEx; Lynx, or Origins); Probe (e.g., Probe of Inflation and Cosmic Origins, PICO; Galaxy Evolution Probe, GEP; Cosmic Evolution Through UV Surveys, CETUS); or other funded study (e.g., Survey and Time-domain Astrophysical Research Explorer, STAR-X) baselined the technology.
- **Infusion-ready** at TRL 5 but not yet included in any of the above categories, likely due to lack of opportunity.

We consider the first two of these categories as having been infused, the third as a concept infusion, and the last as ready for infusion but not yet infused.

Figure 5 summarizes the first two infusion categories divided by mission/project type. We see a total of 156 infusions (50 into spaceflight missions, 34 into sounding rocket missions, 19 into stratospheric balloon missions, four into airborne missions, and 49 into ground-based projects). Of these, 91 (58 percent) have already flown or been implemented. Figure 6 similarly summarizes potential infusions, with 62 technologies baselined by funded mission concepts/studies and three more technologies at TRL 5 that have not yet been infused or baselined.

		Space	Rocket	Balloon	Airborne	Ground	Total
Infused	Implemented	19	15	11	3	43	**91**
	Upcoming	31	19	8	1	6	**65**
Infused Subtotal		50	34	19	4	49	156

Figure 5. Distribution of 91 implemented and 65 upcoming infusions by mission/project type.

Potential	Concepts	62	-	-	-	-	**62**
	Ready	3	-	-	-	-	**3**
Potential Subtotal		65	-	-	-	-	65
Infused/Infusable Total		115	34	19	4	49	221

Figure 6. Distribution of 65 potential infusions by mission/project type.

An independent study conducted by the Aerospace Corporation [8] found that 62 percent of APD-funded technology development projects led to technology infusions, of which 12 percent were for spaceflight missions and 31 percent for suborbital ones. This study included all APRA technology development projects, explaining the somewhat higher infusion rate.

6. SUMMARY

We presented the 57 strategic astrophysics technology gaps prioritized in 2022 and the strategic missions/activities affected by each (the next prioritized list will be published later this year). We then listed the 53 current technology maturation investigations divided by managing Program Office (COR, ExEP, and PhysCOS). We analyzed 166 SAT, ISFM, and other technology maturation grants awarded by APD, merging them into 98 unique technology projects. For these, we showed the distribution of the number of awards and duration in years of each project, as well as their distribution by technology type and strategic missions affected. Finally, we demonstrated the impressive impact of APD's technology maturation investments. Of 98 projects, 45 (46 percent) achieved TRL advances (the remaining 53 advanced their technologies significantly but have not yet met all the requirements of their next TRL). In addition, 42 of these investments (43 percent) resulted in 156 technology infusions into past and upcoming missions/projects along with 65 potential infusions, 62 baselined by funded concept studies and three infusion-ready at TRL 5. Some technologies were infused into multiple missions/projects, and some projects resulted in multiple technologies being infused into one or more missions/projects. It's worth noting that in addition to direct investments in technology maturation projects, APD invests in technology-related facilities, software, and TDAMM-related activities through both ISFM awards and RTFs.

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