NASA Strategic Astrophysics Technology Investments: A Decade of Benefits, Outlook Informed by the 2020 Decadal Survey

Opher Ganel[1a], Rachel Rivera[a], Jay Falker[a], Nicholas Siegler[b], Brendan Crill[b], Mario R. Perez[c]
[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, Washington DC 20546, USA

ABSTRACT

NASA has launched a long and storied series of ambitious strategic astrophysics missions, such as the Hubble Space Telescope, Compton Gamma Ray Observatory, Chandra X-ray Observatory, and Spitzer Space Telescope, with the recently launched James Webb Space Telescope set to join their ranks in producing incomparable science results. Continuing such a record of success requires ever-more-advanced technologies, as the science requirements of each new mission are more challenging than those of its predecessors. Maturing technologies across the mid-range of Technology Readiness Levels (TRLs), from 3 to 6, the so-called "Mid-TRL gap," is crucial to developing indispensable components for such missions, a fact that was historically not appreciated. Recognizing this gap, in 2009, NASA's Astrophysics Division established the Strategic Astrophysics Technology (SAT) Program. In the decade plus since, the SAT program, along with direct funding of certain technology-development efforts, has provided a wide array of benefits including significant milestones, such as TRL maturation, infusion of technologies into projects and missions, training the astrophysics workforce, and many more. The technology development and maturation projects funded by NASA Astrophysics are managed by the Cosmic Origins, Exoplanet Exploration, and Physics of the Cosmos Programs (COR, ExEP, and PCOS, respectively). Since 2009, over 140 projects have been funded on over 80 technology topics, with dozens advancing their TRL, and over 2/3 leading to technology infusions. We present the portfolio distribution in terms of specific technology areas addressed including optics, detectors, coatings, coronagraphs, starshade, lasers, electronics, cooling, etc. We show an analysis of the rate of TRL advances, infusion, and other benefits. Finally, we present Astrophysics Division's strategic technology investment priorities following the recent release of the Decadal Survey, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s" (Astro2020).

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

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 (SMD), the Astrophysics Division 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, giving rise to new questions, that motivate new, more challenging measurements. These new measurement challenges inspire new missions. Each more advanced mission can only launch once all enabling technologies are sufficiently mature for infusion. Often, the required measurements are photon-starved, often with 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, COR, ExEP, and PCOS, were established by the Astrophysics Division 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?*" (PCOS).

1.1 Strategic Astrophysics Missions

Strategic Astrophysics missions are agency-led missions or concepts that the Astrophysics Division is developing, participating in, or interested in, to respond to high-priority science questions. This includes the Roman Space Telescope (formerly the Wide Field InfraRed Survey Telescope, WFIRST) [1], the European Space Agency (ESA) Euclid mission

[1] Opher.Ganel@nasa.gov; phone: +1-410-440-8029

[2], the Japan Aerospace Exploration Agency (JAXA) X-Ray Imaging and Spectroscopy Mission (XRISM) [3], and ESA's Advanced Telescope for High-ENergy Astrophysics (ATHENA) [4] and Laser Interferometer Space Antenna (LISA) [5].

The recently released Decadal Survey, Astro2020 [6], laid out a compelling and ambitious plan, recommending NASA launch three Great Observatories and three Probe missions in the next three or four decades:

- A 6m-class IR/Optical/UV (IROUV) Great Observatory, to be launched in the first half of the 2040s, intended to observe ~25 exo-Earths and carry out general astrophysics measurements.
- A far-IR Great Observatory, to be launched at least a decade after the IROUV Great Observatory.
- An X-ray Great Observatory, also to be launched at least a decade after the IROUV Great Observatory.
- 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

The Astrophysics Division, recognizing that advancing our ability to address these enduring questions requires advancing a wide range of relevant technologies, established several programs that fund technology development and maturation, including Astrophysics Research and Analysis (APRA), SAT, and Roman Technology Fellowship (RTF). All three are openly solicited through NASA's omnibus Research Opportunities in Earth and Space Science (ROSES) announcement of opportunity [7].

APRA funds a wide array of investigations, not limited to technology development. Its technology development focus spans the full TRL spectrum, from 1 to 9. These development efforts may support any Astrophysics technology, not solely those supporting strategic missions. The SAT program, established in 2009, 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 development projects and future Astrophysics missions, and pursue long-term positions.

In 2018, the Astrophysics Division kicked off the System-Level Segmented-Telescope Design (SLSTD) program, an openly competed program funding industry to develop architectures and technologies enabling large, ultra-stable, segmented space telescopes. This program is expected to continue at least to the end of FY 2023.

The Astrophysics Division also direct-funds technology development projects through, e.g., study offices dedicated to specific missions, such as ATHENA and LISA. US participation in these is considered strategic by the Astrophysics Division. Additionally, the Internal Scientist Funding Model (ISFM) funds several technology development efforts involving NASA scientists.

In addition to a series of missions, Astro2020 recommended that a Great Observatories Maturation Program (GOMaP) carry out technology development prior to formulation of each Great Observatory 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 PCOS, 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 process. Owing to the uniform process, criteria, and metrics, the three prioritized lists can be merged into a single prioritized Astrophysics technology-gap list. The most recent prioritization cycle, concluded last month, was informed by the Astro2020 recommendations. The new prioritized list is presented in Section 4.

2. CURRENT STRATEGIC TECHNOLOGY DEVELOPMENT PORTFOLIO

The current portfolio of strategic Astrophysics technology maturation investments includes 58 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 17 projects in the current COR Program portfolio are shown in Table 1.

Table 1. Current COR strategic technology portfolio (PI, Principal Investigator; LmAPD, Linear-mode Avalanche PhotoDiode; JPL, Jet Propulsion Laboratory; RIT, Rochester Institute of Technology; GSFC, Goddard Space Flight Center; ALD, Atomic Layer Deposition; UC Berkeley, University of California, Berkeley; JHU, Johns Hopkins University; MCP, Micro-Channel Plate).

Title	PI	PI Org	Tech Type
Photon Counting NIR LmAPD Arrays for Ultra-low Background Space Observations	Bottom, Michael	U Hawaii	Detector
Ultrasensitive Bolometers for Far-IR Spectroscopy at the Background Limit	Bradford, Charles	JPL	Detector
Ultra-Stable Telescope Research and Analysis -Technology Maturation (ULTRA-TM)	Coyle, Laura	Ball Aerospace	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: High-Efficiency and Low-Scatter in the Vacuum UV	Fleming, Brian	U Colorado	Optics
Scalable micro-shutter systems for UV, visible, and IR spectroscopy	Greenhouse, Matthew	GSFC	Optics
High Performance, Stable, Scalable UV Aluminum Mirror Coatings Using ALD	Hennessy, John	JPL	Optical Coating
Development of High-Resolution Far-IR Array Receivers	Mehdi, Imran	JPL	Detector
Development of Digital Micromirror Devices (DMD) for Far-UV Applications	Ninkov, Zoran	RIT	Optics
Technology Maturation for Astrophysics Space Telescopes (TechMAST)	Nordt, Alison	Lockheed Martin	Telescope
Electron-beam Generated Plasma to Enhance Performance of Protected Aluminum Mirrors for Large Space Telescopes	Quijada, Manuel	GSFC	Optical Coating
Ultra-Stable Structures Development and Characterization Using Spatial Dynamic Metrology	Saif, Babak	GSFC	Metrology/ Structure
High Performance Sealed Tube Cross Strip Photon Counting Sensors for UV-Vis	Siegmund, Oswald	UC Berkeley	Detector
Development of a Robust, Efficient 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 System
Large Format, High Dynamic Range UV Detector Using MCPs and Timepix4 Readouts	Vallerga, John	UC Berkeley	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 include extreme precision radial velocity (EPRV) measurements. The 16 investigations in the current ExEP portfolio are shown in Table 2.

Table2. Current ExEP strategic technology portfolio (ARC, Ames Research Center; MEMS, Micro Electro-Mechanical Systems; BMC, Boston Micromachines Corporation; Caltech, California Institute of Technology; STSci, Space Telescope Science Institute).

Title	PI	PI Org	Tech Type
Development of a Method for Exoplanet Imaging in Multi-Star Systems	Belikov, Ruslan	ARC	Coronagraph
Laboratory Demonstration of High Contrast Using Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC) on a Segmented Aperture	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	U Arizona	Coronagraph

Optimal Spectrograph and Wavefront Control Architectures for High-Contrast Exoplanet Characterization	Mawet, Dimitri	Caltech	Coronagraph
Environmental Testing of MEMS Deformable Mirrors	Mejia Prada, Camilo	JPL	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
System-level Demonstration of High-Contrast for Future Segmented Space Telescopes	Soummer, Rémi	STSci	Coronagraph
Ultra-Stable Mid-IR 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 Starlight Suppression	Willems, Phil	JPL	Starshade
Starshade Large-Structure Precision Deployment and Stability	Willems, Phil	JPL	Starshade

PCOS 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 25 investigations in the current PCOS portfolio are shown in Table 3.

Table 3. Current PCOS Program strategic technology portfolio (MIT, Massachusetts Institute of Technology; SQUID, Superconducting QUantum Interference Device; NIST, National Institute of Standards and Technology; MSFC, Marshall Space Flight Center; SLAC, Stanford Linear Accelerator Laboratory; TES, Transition-Edge Sensor; X-IFU, X-ray Integral Field Unit; FPGA, Field-Programmable Gate Array; ASU, Arizona State University; PICO, Probe of Inflation and Cosmic Origins; SAO, Smithsonian Astrophysical Observatory).

Title	PI	PI Org	Tech Type
Magnetically Coupled Calorimeters	Bandler, Simon	GSFC	Detector
Toward Fast, Low-Noise, Radiation-Tolerant X-ray Imaging Arrays for Lynx: Raising Technology Readiness Further	Bautz, Mark	MIT	Detector
Microwave SQUID Readout Technology to Enable Lynx and Other Future Great Observatories	Bennett, Douglas	NIST	Electronics
Direct Fabrication of X-Ray Mirror Full Shells	Bongiorno, Stephen	MSFC	Optics
Low Stress X-Ray Mirror Coatings	Broadway, David	MSFC	Optical Coating
Hybrid X-ray Optics by Additive Manufacturing	Broadway, David	MSFC	Optics
UV LED-Based Charge Management System	Conklin, John	U Florida	Electronics
Computer-Controlled Polishing of High-Quality X-Ray Mirror Mandrels	Davis, Jacqueline	MSFC	Optics
Microwave Multiplexing Readout Development	Frisch, Josef	SLAC	Electronics
Differential Deposition for Figure Correction in X-ray Optics	Kilaru, Kiran	MSFC	Optics
Advanced TES Microcalorimeters	Kilbourne, Caroline	GSFC	Detector
Providing Enabling and Enhancing Technologies for a Demonstration Model of the ATHENA X-IFU	Kilbourne, Caroline	GSFC	Detector
Advancing the Focal Plane TRL for LiteBIRD and Other Next Generation CMB Space Missions	Lee, Adrian	UC Berkeley	Detector
Telescopes for Space-Based Gravitational-Wave Observatories	Livas, Jeffrey	GSFC	Telescope
Development of Low Power FPGA-based Readout Electronics for Superconducting Detector Arrays	Mauskopf, Philip	ASU	Electronics
Superconducting Antenna-Coupled Detectors and Readouts for CMB Polarimetry	O'Brient, Roger	JPL	Detector
Laboratory 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 for the Lynx Mission Concept	Reid, Paul	SAO	Optics
High Resolution and High Efficiency X-ray Transmission Grating Spectrometer	Schattenburg, Mark	MIT	Optics
Readying X-ray Gratings and Optics for Space Applications; Manufacturability and Alignment	Smith, Randall	SAO	Optics
Phase Measurement System for Interferometric Gravitational Wave Detectors	Ware, Brent	JPL	Electronics
Space-based Gravitational Wave Laser Technology Development Project for the LISA Mission	Yu, Anthony	GSFC	Laser
Next Generation X-ray Optics	Zhang, William	GSFC	Optics
LISA Colloid Microthruster Technology	Ziemer, John	JPL	Micro-propulsion

Information on technology investigations is available via a searchable Astrophysics database [8] or NASA's TechPort [9].

3. TECHNOLOGY INVESTMENT METRICS AND RESULTS TO DATE

The following analyses cover the SAT Program's 13-year span to date, during which the Astrophysics Division funded 132 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, 30 projects comprised between two to five funded investigations (Fig. 1). As a result, project durations ranged from a single year to 11 years (Fig. 2), with an average of 5.1 years.

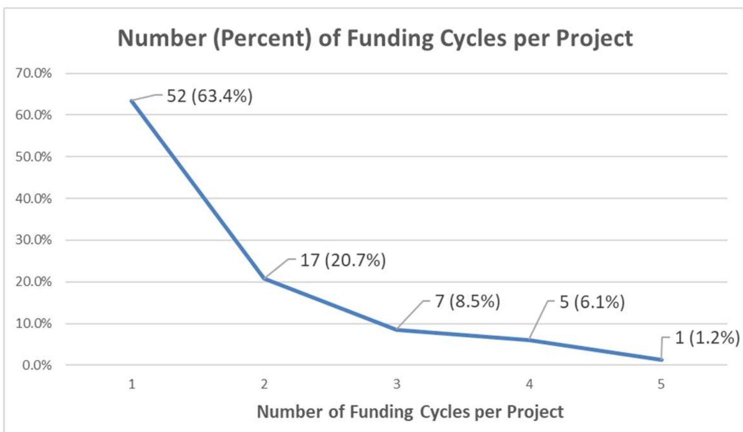

Fig. 1. Distribution of projects by number of funding cycles, with 30 projects comprising up to five funding cycles.

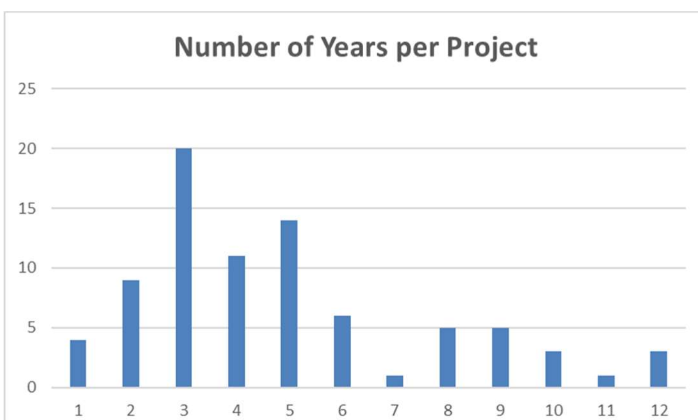

Fig. 2. Distribution of projects by total length in years, including any follow-on cycles.

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

Figure 3, left, shows the distribution of projects between the three Programs, with 28 in COR, 26 in ExEP, and 28 in PCOS. The total investment to date was $233M, of which $76M (33%) in COR, $51M (22%) in ExEP, and $106M (46%) in PCOS (Fig. 3, right), with an average investment of $2.8M per project ($2.7M for COR, $2.0M for ExEP, and $3.8M for PCOS).

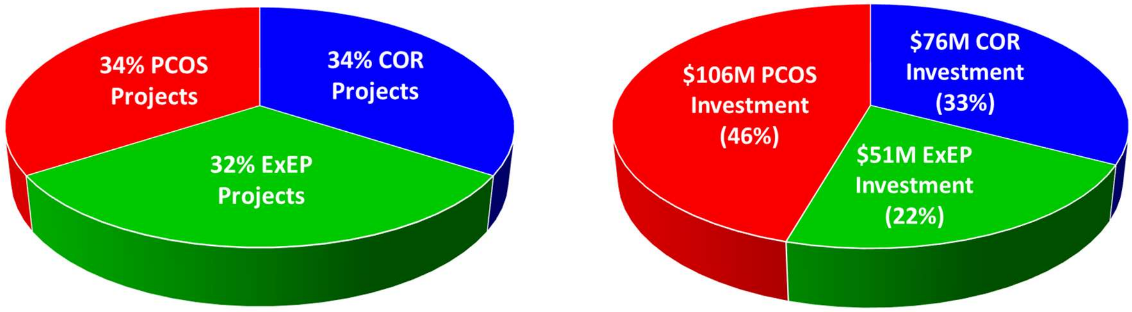

Fig. 3. Strategic technology development by Program since 2009: number of distinct projects (left) and total investment (right).

The distribution of organizational types receiving awards to date is shown in Fig. 4. Government labs include Federally Funded Research and Development Centers (FFRDCs) such as JPL and NIST.

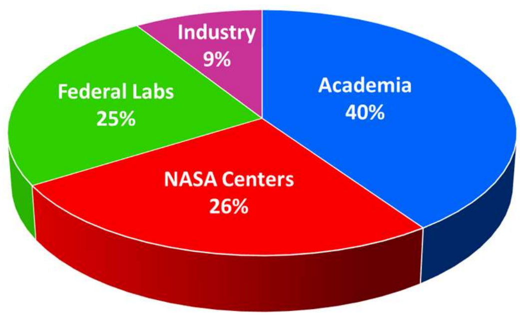

Fig. 4. Distribution institutional types receiving awards for strategic technology developments.

Strategic Astrophysics technology projects address multiple areas, including detectors, coronagraphs, optics, electronics, optical coatings, starshades, telescopes, lasers, micropropulsion, cooling systems, picometer-level metrology, and EPRV (Fig. 5). Given their important roles in Astrophysics missions, detectors, coronagraphs, and optics dominate at a combined 63%.

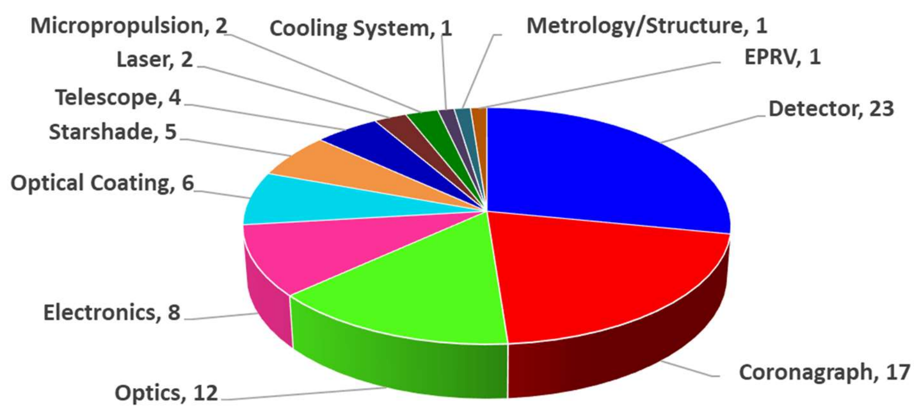

Fig. 5. Distribution of the 82 projects in the strategic technology portfolio by topic since SAT inception.

As Fig. 6 demonstrates, the 82 projects cover technologies addressing a broad range of the electromagnetic spectrum, as well as gravitational waves (GW).

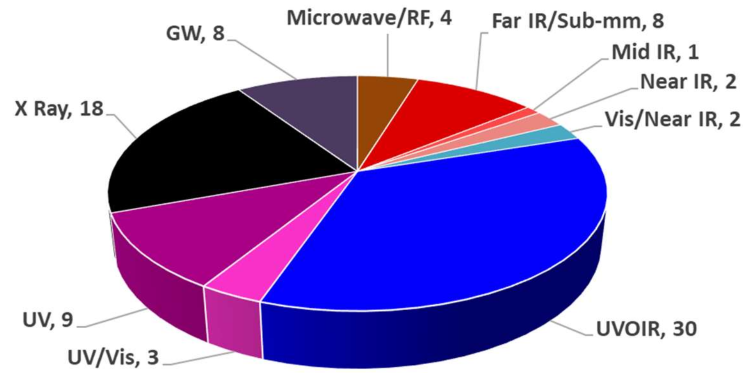

Fig. 6. Distribution of the 82 projects in the strategic technology portfolio by topic since SAT inception.

Each technology matured by the strategic portfolio supports one or more 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.)

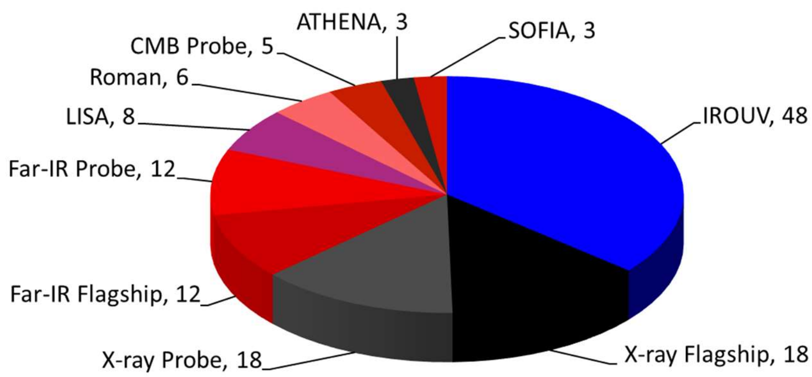

Fig. 7. Distribution of the 82 projects in the strategic technology portfolio by strategic mission(s) supported.

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 [10]. 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, despite significant progress. Where the TRL is assessed for a system, the least mature subsystem limits the system TRL. Further, if the mission requirements or performance goals change during a technology development project's period of performance, the TRL may well be downgraded for the new requirements. The evolution of X-ray mirror requirements over the past decade is a perfect example. As the target concept changed from the International X-ray Observatory to ATHENA, and then to the Lynx concept, the mirror angular resolution performance target tightened by an order of magnitude, from 5 arcsec to 0.5 arcsec. 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% of strategic technology projects (38 of 82) advanced by at least one TRL, of which 12% (10) advanced by two (Fig. 8). The remaining 54% (46 of 82) made sub-TRL advances. The high-risk, high-reward nature of these projects make this especially impressive.

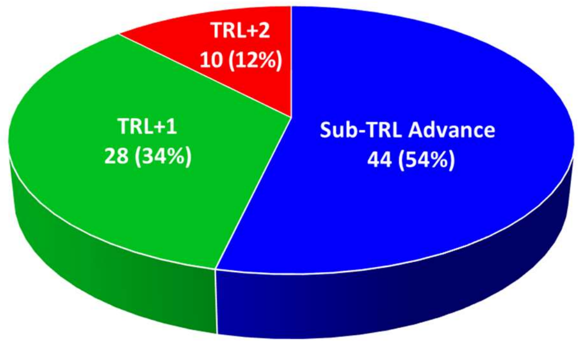

Fig. 8. Distribution of TRL advancement while in the program for strategic technology development projects. Some technologies continue advancing in TRL after project completion, especially those that are infused into spaceflight projects.

The majority of projects, 64, began at TRL 3, with another 12 starting at TRL 4. Five additional projects started at TRL 2, and only one came into the program at TRL 5. With these statistics, it's difficult to make a definitive assertion, but the data support the notion that the higher the entry TRL, the lower the likelihood of advancing by one or more levels (Fig. 9).

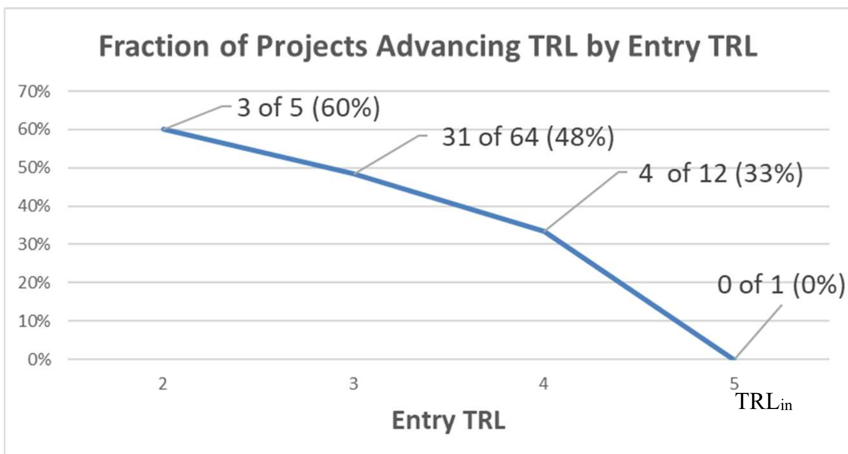

Fig. 9. Percentage of technology development projects achieving TRL advancement vs. TRL_{in} (e.g., 60% of five projects entering at TRL 2 advanced). Note that nine of 64 projects entering with a TRL_{in} of 3 advanced their TRL by two levels to 5.

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, the Astrophysics Division's technology investment is an even more spectacular success, with 57 implemented infusions, 56 upcoming infusions, and 61 technologies baselined into flagship and Probe mission concepts reference designs (Table 4). These infusions include space, sounding-rocket, and balloon missions, as well as airborne and ground-based instruments. In total, 88 missions/projects benefitted, and while Astrophysics is naturally the main beneficiary with 77 of those, Earth-Science, Planetary, and Heliophysics missions also benefited, as did two non-space 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, and conceptual by mission/project type.

	Space	Rocket	Balloon	Airborne	Ground	Total
Implemented	8	14	8	2	25	**57**
Upcoming	21	14	5	1	15	**56**
Concepts	61	-	-	-	-	**61**
Total	**90**	**28**	**13**	**3**	**40**	**174**

Table 5. Summary of technology infusions by discipline and mission/project type.

Discipline	Space	Rocket	Balloon	Airborne	Ground	Total
Astrophysics	22	15	10	1	23	**71**
Planetary	4	1	-	-	-	**5**
Heliophysics	4	3	-	-	-	**7**
Earth Science	**3**	**-**	**-**	**-**	**-**	**3**
Non-Space	-	-	-	1	1	**2**
Total	**33**	**19**	**10**	**2**	**24**	**88**

Table 6. Details of 57 already implemented technology infusions by mission/project.

Project Type	PI	Technology	Infused Into
Space Mission	Bautz, Mark	Directly deposited optical blocking filters	OSIRIS-REx
Space Mission	Kilbourne, Caroline	Si-thermistor/HgTe microcalorimeter array	Hitomi
Space Mission	Klipstein, William	Phasemeter	GRACE-FO
Space Mission	Quijada, Manuel	UV coatings	GOLD and ICON
Space Mission	Siegmund, Oswald	MCPs	ICON, GOLD, JUNO-UVS
Sounding Rocket	Greenhouse, Matthew	Next-gen microshutter arrays	FORTIS
Sounding Rocket	Kilbourne, Caroline	Si-thermistor/HgTe microcalorimeter array	XQC
Sounding Rocket	McEntaffer, Randall	X-ray reflection grating	WRXR
Sounding Rocket	Nikzad, Shouleh	ALD mirror coating	SISTINE
Sounding Rocket	Siegmund, Oswald and Vallerga, John	MCPs	FIRE, SLICE, EUNIS, FORTIS, VeSpR, CHESS, SISTINE, DEUCE
Sounding Rocket	Ullom, Joel	TES microcalorimeters	Micro-X
Sounding Rocket	Ullom, Joel	Time-division SQUID multiplexers	Micro-X
Balloon	Bock, James	Antenna-coupled detectors	Spider
Balloon	Hu, Qing	4.7 THz local oscillator	STO-2
Balloon	Mehdi, Imran	Heterodyne detectors	STO-2
Balloon	Nikzad, Shouleh	Advanced CCD detectors	FIREBall 2
Balloon	Staguhn, Johannes	Far-IR large-format detectors	PIPER
Balloon	Ullom, Joel	Time-division SQUID multiplexers	Spider, PIPER
Balloon	Zmuidzinas, Jonas	TiN Kinetic Inductance Detectors (KIDs)	BLAST-TNG
Airborne	Mosely, Harvey	TES Bolometers	HAWC+ (SOFIA)
Airborne	Ullom, Joel	Time-division SQUID multiplexers	HAWC+ (SOFIA)
Ground-Based	Bennett, Douglas	Microwave SQUID mux crosstalk avoidance	Simons Observatory
Ground-Based	Bock, James	Antenna-coupled detectors	BICEP2, BICEP3/Keck
Ground-Based	Nikzad, Shouleh	Delta-doped CCDs	Palomar-WaSP, ZTF
Ground-Based	Ninkov, Zoran	DMDs	4.1-m SOAR telescope
Ground-Based	Staguhn, Johannes	TES bolometers	Bolometer camera at IRAM 30m telescope
Ground-Based	Ullom, Joel	Microwave SQUID multiplexers	MUSTANG2, Simons Observatory
Ground-Based	Ullom, Joel	OMT-coupled TES bolometers	ABS, ACTPol, AdvancedACT, ALI-CPT, MUSTANG2, SPTPol, Simons Observatory
Ground-Based	Ullom, Joel	TES bolometers	SCUBA2

Ground-Based	Ullom, Joel	Time-division SQUID multiplexers	ABS, ACT, ACTPol, AdvancedACT, BICEP2, BICEP3/Keck, SCUBA2
Ground-Based	Wollack, Edward	Feedhorn-coupled detectors	CLASS

Table 7. Details of 56 upcoming technology infusions by mission/project.

Project Type	PI	Technology	Infused Into
Space Mission	Belikov, Ruslan	Multi-star Wavefront Sensing and Control	Roman Space Telescope
Space Mission	Fleming, Brian	Protected enhanced LiF mirror coatings	SPRITE CubeSat
Space Mission	Fleming, Brian	MCP anti-coincidence shielding	SPRITE CubeSat
Space Mission	Kasdin, Jeremy	Wavefront control with two deformable mirrors	Roman Space Telescope
Space Mission	Kilbourne, Caroline	Si-thermistor/HgTe microcalorimeter array	XRISM
Space Mission	Kilbourne, Caroline	TES Microcalorimeter arrays	ATHENA X-IFU
Space Mission	Kilbourne, Caroline	Time-Domain Multiplexing (TDM)	ATHENA X-IFU
Space Mission	Krist, John and Shaklan, Stuart	End-to-end Coronagraph models	Roman Space Telescope
Space Mission	Lee, Adrian	CMB detectors	LiteBIRD
Space Mission	Nikzad, Shouleh	Advanced CCD detectors	SPARCS CubeSat
Space Mission	Rauscher, Bernard	H4RG IR detectors	Roman Space Telescope
Space Mission	Siegmund, Oswald and Vallerga, John	MCPs	SPRITE, JUICE-UVS, EUROPA-UVS, EUVST, GLIDE, ESCAPE, Aspera, and Solar Orbiter
Space Mission	Vallerga, John	Timepix2 ASICs	PADRE CubeSat
Space Mission	Trauger, Jim	Hybrid Lyot Coronagraph	Roman Space Telescope
Sounding Rocket	Bongiorno, Stephen	Electroformed X-ray mirror shells	FOXSI 4
Sounding Rocket	Fleming, Brian	Electron-beam-lithography-ruled gratings	CHESS, DEUCE
Sounding Rocket	Fleming, Brian	Image Slicer	INFUSE
Sounding Rocket	McEntaffer, Randall	X-ray reflection gratings	OGRE, TREXS
Sounding Rocket	Nikzad, Shouleh	Superlattice-doped detector	SHIELDS
Sounding Rocket	Schattenburg, Mark and Heilman, Ralf	Blazed soft x-ray reflection grating	MaGIXS
Sounding Rocket	Siegmund, Oswald and Vallerga, John	MCPs	INFUSE, DICE, Herschel
Sounding Rocket	Vallerga, John	Tpx3 CdTe detector	FOXSI 4
Sounding Rocket	Vorobiev, Dmitry	DMDs	INFUSE
Sounding Rocket	Zhang, William	Single-crystal silicon X-ray mirrors	OGRE
Balloon	Bennett, Douglas	Microwave SQUID mux firmware and parameters	SLEDGEHAMMER
Balloon	Hu, Qing	4.7 THz local oscillators	GUSTO
Balloon	Mehdi, Imran	THz heterodyne arrays	ASTHROS
Balloon	Mauskopf, Philip	RFSoC readout	EXCLAIM, TIM
Airborne	Mauskopf, Philip	IF board	ONR airborne KID instrument
Ground-Based	Bock, James	Antenna-coupled detectors	BICEP Array
Ground-Based	Bongiorno, Stephen	Mandrel	NIF X-ray microscope
Ground-Based	Bottom, Michael	Near-IR LmAPD	ULBCam, Subaru observatory
Ground-Based	Guyon, Olivier	Linear Wavefront Control	Subaru observatory

Ground-Based	Mauskopf, Philip	RFSoC readout	LMT, CCATprime
Ground-Based	Mawet, Dimitri	Spectrograph and Wavefront Control Architectures	Keck Planet Imager and Characterizer
Ground-Based	Serabyn, Eugene	Vortex coronagraph	Palomar, Keck, Subaru observatories
Ground-Based	Staguhn, Johannes	GISMO	GLT
Ground-Based	Ullom, Joel	OMT-coupled TES bolometers	CMB-S4
Ground-Based	Ullom, Joel	TiN KIDs	Toltec
Ground-Based	Vasisht, Gautam	EPRV etalon	Keck Planet Finder

Table 8. Details of 61 technology infusions baselined by strategic mission design concepts.

Project Type	PI	Technology	Infused Into
Space Mission	Bautz, Mark	Directly deposited optical blocking filters	Lynx
Space Mission	Bautz, Mark	Advanced CCD detector	AXIS Probe
Space Mission	Belikov, Ruslan	Multi-star Wavefront Sensing and Control	HabEx, LUVOIR, Roman Space Telescope
Space Mission	Belikov, Ruslan	PIAACMC	HabEx, LUVOIR
Space Mission	Bierden, Paul	MEMS deformable mirrors	HabEx, LUVOIR
Space Mission	Bock, James and O'Brient, Roger	CMB detectors	PICO
Space Mission	Bock, James and O'Brient, Roger	Antenna-coupled detectors	PICO
Space Mission	Conklin, John	Charge Management System (CMS)	US contribution to LISA
Space Mission	Hall, Don and Bottom, Michael	APD HgCdTe Near-IR detectors	HabEx, LUVOIR
Space Mission	Fleming, Brian	MCP Anti-coincidence shielding	LUVOIR
Space Mission	Greenhouse, Matthew	Next-gen microshutter arrays	HabEx, LUVOIR, CETUS Probe
Space Mission	Guyon, Olivier	Linear wavefront control	HabEx, LUVOIR
Space Mission	Guyon, Olivier	Predictive wavefront control	HabEx, LUVOIR
Space Mission	Guyon, Olivier	Sensor fusion	HabEx, LUVOIR
Space Mission	Kasdin, Jeremy; Casement, Susan; Glassman, Tiffany; and Cash, Webster	Starshade technologies	Starshade-Roman Rendezvous Probe
Space Mission	Lee, Adrian	CMB detectors	PICO
Space Mission	Livas, Jeffrey	Telescope	US contribution to LISA
Space Mission	Mauskopf, Philip	Low-power FPGA-based readout electronics for superconducting detector arrays	PICO, Origins, GEP, CDIM Probe
Space Mission	Nikzad, Shouleh	Delta-doped CCDs	Dorado (formerly GUCI)
Space Mission	Nikzad, Shouleh	Delta-doped Electron-Multiplying CCDs	HabEx
Space Mission	Nikzad, Shouleh	Delta-doped CMOS detector arrays	LUVOIR
Space Mission	Quijada, Manuel	GdF_3 coatings	Dorado
Space Mission	Schattenburg, Mark	Critical-Angle-Transmission X-ray gratings	Lynx
Space Mission	Schattenburg, Mark	Thermal oxide coating-stress compensation	Lynx, AXIS Probe, TAP
Space Mission	Serabyn, Eugene	Vortex Coronagraph	HabEx, LUVOIR
Space Mission	Siegmund, Oswald and Vallerga, John	MCPs	HabEx, LUVOIR, CETUS

Space Mission	Siegmund, Oswald and Vallerga, John	Cross-strip MCP detector systems	HabEx, LUVOIR, CETUS
Space Mission	Soummer, Rémi	Apodized Pupil Lyot Coronagraph	LUVOIR
Space Mission	Staguhn, Johannes	Superconducting kilo-pixel far-IR detectors	Origins
Space Mission	Stahl, H. Philip	Precision Thermal Control	Pathfinder for HabEx zonal thermal control
Space Mission	Tuttle, James	Continuous Adiabatic Demagnetization Refrigerator (CADR)	Lynx, Origins, PICO, GEP
Space Mission	Ullom, Joel	Microwave SQUID multiplexers	Lynx, Origins
Space Mission	Ullom, Joel	Time-division SQUID multiplexers	PICO
Space Mission	Yu, Anthony	Laser technology	US contribution to LISA
Space Mission	Zhang, William	Single-crystal-silicon X-ray mirrors	Lynx, AXIS, TAP
Space Mission	Ziemer, John	Micro-Newton thrusters	HabEx fine pointing and jitter suppression

3.5 Other Benefits of Astrophysics Division Technology Investments

Beyond technology maturation and TRL advances, the technology investments generated multiple other benefits. A majority of PIs were able to leverage 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 graduate 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 PCOS; reviewed, edited as needed, and consolidated as deemed appropriate. Beyond community inputs as to new gaps, 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 PCOS. 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 this 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 priority rank it received. 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 published in 2022 Astrophysics Biennial Technology Report (ABTR) [12]. The detailed text for each of the gaps, including a description of the gap, 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. 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 PCOS. We analyzed a total of 132 investigations grouped into 82 projects. The projects were broken down by managing Program Office, PI organization type, technology area (63% focused on the critical topics of detectors, coronagraphs, and optics), signal type, strategic mission supported, and TRL advances (46% of projects advanced by at least one TRL). We listed 174 technology infusions arising from this program, breaking them down by implementation timeline (implemented, upcoming, concept), and by the discipline of the mission/project that benefited (over 19% were beyond astrophysics). These and other listed benefits demonstrate an impressive return on the $233 million invested in these 82 projects. Finally, we presented the 2022 prioritized list of 57 Astrophysics technology gaps.

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