A Summary and Analysis of NASA's Strategic Astrophysics Technology PCOS/COR Investments since Program Inception

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ABSTRACT

The NASA Strategic Astrophysics Technology (SAT) Program was established in 2009 as a new technology maturation program to fill the gap in the Technology Readiness Level (TRL) range from 3 to 6. Since the inception of the program, 47 tasks have been awarded under the auspices of the NASA Physics of the Cosmos (PCOS) Program in the areas of optics and detectors as well as lasers, electronics, and micro-thruster subsystems. In addition, 31 tasks have been awarded under the auspices of the NASA Cosmic Origins (COR) Program to develop optics, coatings, cooling subsystems, and detectors from the Far-IR to the Far-UV. We present the PCOS/COR portfolio distribution in terms of specific technology areas addressed and show an analysis of the rate and cost of TRL advancements. We present highlights of the infusion success stories that have emerged from the SAT maturation program as it relates to enabling future NASA astrophysics strategic missions. Finally, we present an outlook for future technology priorities for investment by the SAT Program.

Keywords: NASA, astrophysics, technology development, optics, telescope, detector, laser, SAT, PCOS, COR

1. INTRODUCTION

In 2009, NASA's Astrophysics Division established a new competitive funding line called Strategic Astrophysics Technology [1] as part of the NASA Research Opportunities in Space and Earth Sciences (ROSES) announcements of opportunity (AO). This technology maturation program fills the gap for TRL between 3 and 6.

Since then, the PCOS and COR Program Offices have been actively managing the technology-development efforts for the PCOS- and COR-funded tasks in the SAT Program as well as directed-funding tasks. The average selection rate for PCOS proposals to date is 33% while that for COR is 23%, with a joint average selection rate of 27%. A few tasks have also been directed to fill technology requirement gaps in alignment with the PCOS and COR science goals.

The selection of technology tasks depends on the prioritization of technology gaps at regular intervals. This process is discussed in the PCOS and COR Program Annual Technology Reports (PATR) [2], [3]. It is worth noting that currently the PCOS Program has more strategic flight projects planned and therefore, has greater technology development needs.

In this paper, we discuss the funded technology development projects managed by the PCOS and COR Program Offices, but not those managed by the Exoplanet Exploration Program (ExEP) Office. Thus, whenever the SAT Program is mentioned, this refers to the PCOS and COR elements of the SAT Program, and not the ExEP element. We present an analysis of average project duration and investment level, TRL advances achieved, other measures of success, distribution of Principal Investigator (PI) organization types, technology types addressed, etc.

2. UNDERSTANDING THE DATA

Since the inception of the SAT Program, a total of 75 PCOS or COR tasks have been selected and funded. Along with three legacy tasks, a total of 78 tasks have been or continue to be managed by the PCOS (47 tasks) and COR (31 tasks) Program Offices. Since this paper analyzes strategic technology development investments, and is concerned with investment outcomes, we removed 14 tasks before carrying out our analysis, as follows.

- Mission development rather than technology development tasks (four tasks removed)
- Tasks starting less than a year ago that are not a continuation of a prior task (nine removed, including four SATs)
- Small, short-duration projects that were combined into a single task that the Program Office was asked to manage through its technology development management process (one task removed)

Of the remaining 64 tasks (40 PCOS and 24 COR), 46 were funded by the SAT Program (27 PCOS and 19 COR), one by the Astrophysics Research and Analysis (APRA) Program, and the remaining 17 tasks were direct-funded.

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Since maturing strategic technologies is a very challenging undertaking that is not typically expected to be completed within the schedule and/or budget of a single SAT award, many PIs proposed for and won continued funding, and/or received direct funding where the Astrophysics Division deemed it necessary for programmatic reasons such as meeting Division objectives (e.g., enabling NASA contributions to ESA's Athena and LISA missions). Indeed, most of our PIs ended up receiving such follow-on funding to continue their technology maturation progress. Since the original and follow-on tasks have the same technology objective, we combined them for the purpose of analysis, reducing the sample size from 64 tasks to 33 projects (15 PCOS and 18 COR).

3. AVERAGE PROJECT DURATION, INVESTMENT, AND ORGANIZATION

Figure 1 shows the distribution of projects between the two Programs. The total investment to date in the 33 analyzed projects was \$82.3M, of which \$52.5M (64%) for PCOS and \$29.8M (36%) for COR. Considering each multi-task project as a single project, the average project duration to date has been 3.6 years overall (4.3 years for PCOS and 3.0 years for COR), with an average investment of \$2.5M (\$3.5M for PCOS and \$1.7M for COR).

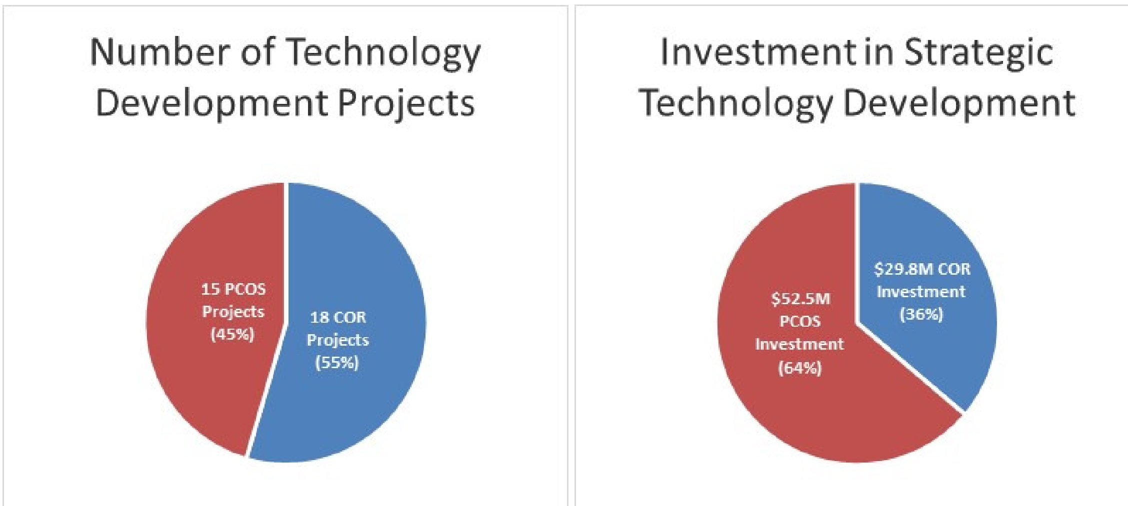

Figure 1. Strategic technology development by Program since SAT inception: number of projects (left) and total investment (right).

The distribution of awarded organizations to date is shown in Figure 2. Government labs include Federally Funded Research and Development Centers (FFRDCs) such as the Jet Propulsion Lab (JPL) and the National Institute of Standards and Technology (NIST).

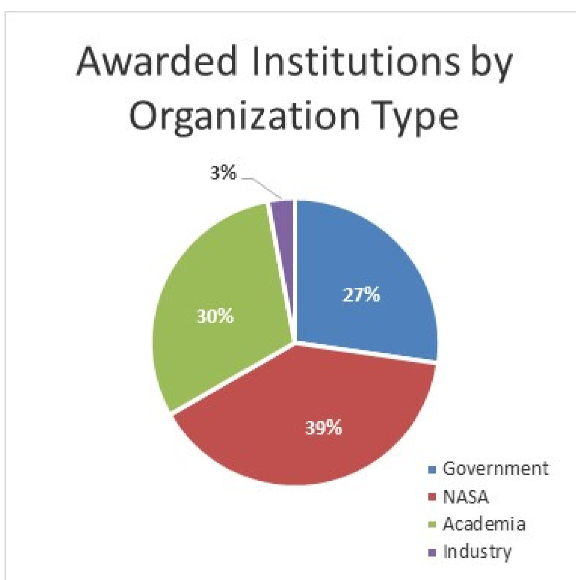

Figure 2. Distribution of awarded institutions since inception of the SAT Program.

4. THE STRATEGIC TECHNOLOGY DEVELOPMENT PORTFOLIO

The SAT Program investments are distributed among a variety of technology development areas, including optical coatings, detectors, electronics, lasers, optics, and several others (e.g., cooling, pm-level metrology, and micro-Newton thrusters). The distribution of the technology portfolio is summarized in Figure 3. Detectors and optics dominate the portfolio at a combined 66%, which should not be surprising given the important roles these technologies play in the portfolio of strategic missions addressing PCOS and COR science.

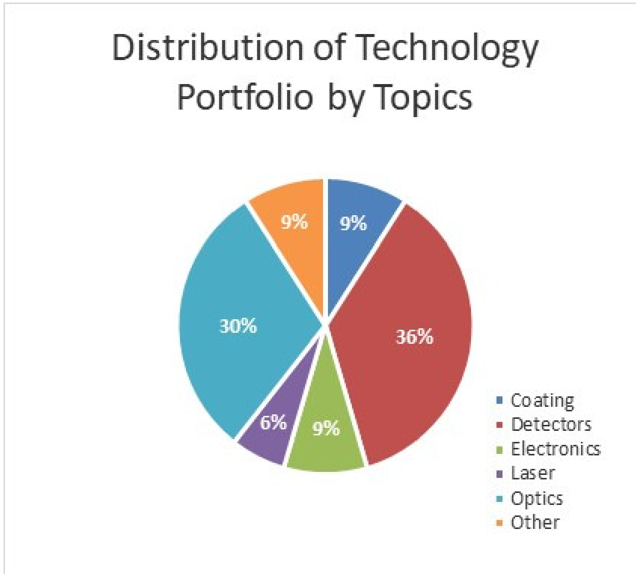

Figure 3. Distribution of the SAT technology portfolio since inception.

5. THE SAT PROGRAM AND TRL ADVANCES

For the following discussion, we reference NASA TRL definitions as explained in the NASA Systems Engineering Processes and Requirements [4].

NASA Astrophysics Division manages technology development and maturation through three Programs, each addressing one of three strategic themes that respond to three fundamental questions. The PCOS Program addresses the question "*How does our universe work?*" The COR Program works on the question "*How did we get here?*" Finally, ExEP seeks to answer the question "*Are we alone?*" The SAT Program is divided similarly, with one element for each of the three Programs, Technology Development for Physics of the Cosmos (TPCOS), Technology Development for Cosmic Origins (TCOR) and Technology Development for Exoplanet Missions (TDEM). These three elements solicit competitive proposals through the ROSES AO. The proposals are reviewed, leading to the selection and funding of the best proposals responding to the details of the solicitation.

The PIs of the funded SAT projects are not expected to necessarily mature their technologies all the way to TRL 6 during their grant's period of performance (PoP). Instead, they are expected to define verifiable milestones for maturing their technology, develop a realistic schedule toward achieving those milestones, and achieve as much progress toward those milestones as realistically possible given the breadth and level of challenge of the technology in question, the project budget, and the PoP duration. Thus, while TRL advances are certainly an important measure of progress, they are not and cannot be the sole measure of project success.

The following are some of the greatest challenges to achieving TRL advances:

- Maturing technologies required for strategic missions is almost by definition a very significant challenge;
- Many of the SAT projects take on system-level technologies, and then, even if one or more subsystems are advanced to a higher TRL, the overall system TRL is still determined by the least-mature subsystem;
- The PCOS and COR Program Offices impose rigorous standards, including the establishment of a credible path for achieving the full requirements of on-orbit performance;
- The incoming TRL is assessed by the project PIs which may be optimistic at times, such that a Program Office assessment might have been lower, leading to actual TRL advances not being recognized;

- The TRL scale is a set of step functions, so as long as any part of the requirements for the next TRL is not completed, the TRL remains at the initial level;
- As time progresses, the requirements for closing the technology gap can evolve, making them a moving target (e.g., if a project initially worked to mature X-ray mirror technology for the International X-ray Observatory, IXO, which was then superseded by the European Space Agency's, ESA, Advanced Telescope for High-ENergy Astrophysics, Athena, mission, and then moved on to addressing the requirements of the Lynx mission concept; this evolution led to an angular resolution requirement that started at 5" and tightened to under 1");
- While the challenge of maturing a technology from TRL 2 to TRL 3 is not always easy to overcome, maturing from TRL 3 to 4 is more difficult, and from TRL 4 to 5 even more challenging; and
- SAT projects have limited budget and time, possibly insufficient to address larger technological challenges, which is why most SATs end up being awarded further tasks, extending both the budget and the schedule.

Overall, 14 of 33 strategic technology projects (42%) advanced by at least one TRL, of which 3 (9%) advanced by two (Figure 4). The high-risk, high-reward nature of the SAT R&D portfolio makes this result very impressive. It is worth noting that half the projects recording TRL advancements were in the area of optics technology.

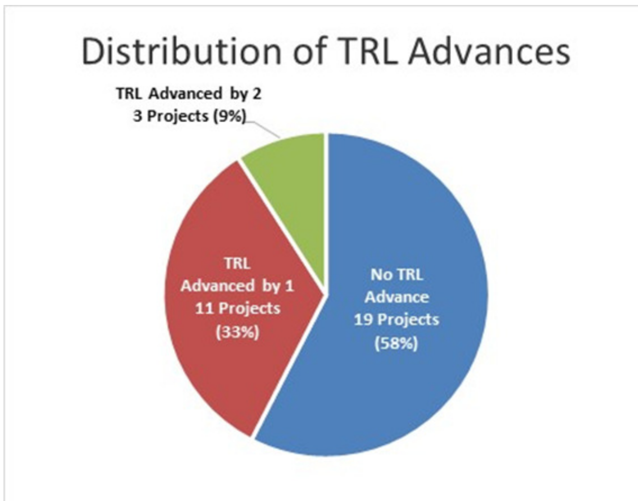

Figure 4. Distribution of TRL advancement for strategic technology development projects.

While the statistical sample is small, especially for TRL_{in} of 2 and 5, the trend is clear and unsurprising. The higher a project's entry TRL, the more difficult it is to complete all requirements for advancing to the next TRL (Figure 5).

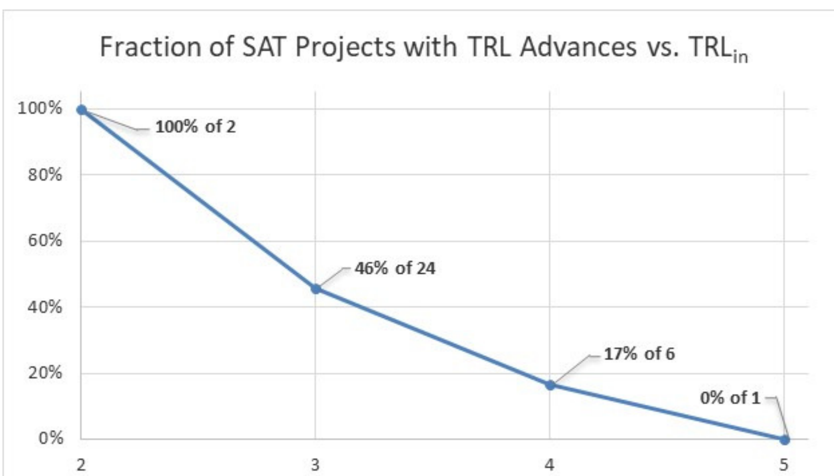

Figure 5. Fraction of strategic technology development projects achieving TRL advance of at least 1 vs. TRL_{in}. Note that three of 24 SAT projects entering with a TRL_{in} of 3 advanced their TRL by two levels to TRL 5.

Counting advances by two TRLs twice, the portfolio had a total of 17 TRL advances, for an average Program cost per TRL advance of $4.8M. Counting only the $38.5M cost of the advancing projects, that average drops to $2.3M.

6. OTHER MEASURES OF SAT PROJECT SUCCESS

The main benefit of the SAT Program is that it helps mature technologies needed for strategic astrophysics missions toward TRL 5 or 6, so they can be infused into strategic flight missions or enable NASA contributions to major international missions such as Athena, Laser Interferometer Space Antenna (LISA), etc. However, the 58% of projects that haven't advanced to the next TRL should not be assumed to have made no progress. Indeed, all such projects have achieved significant progress toward the next TRL.

Both the PCOS and COR Programs have had remarkable success stories. The technologies developed are suitable for a variety of astrophysics missions and beyond, and also enable current international collaborations on several projects. These technologies are available for infusion into Explorers, suborbital missions, and ground-based experiments. The following success stories highlight some of the impacts the SAT Program has had to date.

- Transition Edge Sensors (TES) micro-calorimeters are expected to be a major US contribution to the ESA Athena mission's X-ray Integral Field Unit (X-IFU);
- Continued development of time-division Superconducting QUantum Interference Device (SQUID) multiplexing is viewed as a backup to Athena X-IFU's baseline readout, which is currently at a lower TRL;
- Maturing a Field-Programmable-Gate-Array (FPGA) -based fast X-ray event recognition that NASA Astrophysics selected for work on a possible US contribution for Athena's Wide-Field Imager;
- Phasemeter technology, including phase locking and laser stabilization, was infused into the Laser-Ranging Interferometer (LRI) on the Gravity Recovery and Climate Experiment (GRACE) Follow-On mission. Advances from this LRI work were then leveraged by the PI back into his SAT project;
- Antenna-coupled TES bolometer technology was deployed in the BICEP2 experiment in Antarctica, helping search for B-mode polarization in the Cosmic Microwave Background (CMB) signal; this provided an order-of-magnitude increase in measurement speed compared to the Background Imaging of Cosmic Extragalactic Polarization 1 (BICEP1) experiment; detector-array technology was then incorporated into BICEP3 and Keck Array, and flown on the Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization (Spider) long-duration balloon mission during the 2014/15 Antarctic season, measuring CMB polarization at 90 and 150 GHz with excellent low-frequency stability and low cosmic-ray event rates;
- Directly deposited optical blocking filters were incorporated into flight CCDs of the REgolith X-ray Imaging Spectrometer (REXIS), an MIT student instrument on the Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer (OSIRIS-Rex) mission (launched September 8, 2016; expected to rendezvous with asteroid 10195 Bennu in late 2018; with the REXIS aperture door expected to open in early 2019); the instrument successfully completed initial calibrations; this filter technology meets the experiment's stringent performance requirements without straining its technical budgets; as a bonus, this provides the SAT project a nearly free opportunity to space-qualify its development, with environmental testing leading to the discovery and subsequent resolution of unexpected light leaks;
- High-efficiency 40-GHz feedhorn-coupled TES-based detector architecture was deployed in the Cosmology Large-Angular-Scale Surveyor (CLASS) telescope in the Atacama Desert;
- SAT team member R.S. Shiri filed on May 23, 2016 for a patent (GSC-17289-1, "Design and fabrication of partially transparent petaled mask or occulter using grayscale lithography"), which may one day be used for flight missions;
- The Arcus Medium-class Explorer (MIDEX) proposal, based on Critical-Angle-Transmission (CAT) -grating technology, was selected for a Phase A concept study;
- TES bolometer detectors were selected to support the Stratospheric Observatory for Infrared Astronomy (SOFIA) High-resolution Airborne Wide-bandwidth Camera (HAWC) instrument;
- Advanced high-efficiency, photon-counting CCD detectors were implemented into the Faint Intergalactic medium Redshifted Emission Balloon (FIREBall) long-duration balloon mission, the Guide and Focus CCDs for Wafer-Scale Imager for Prime instrument (WaSP) at Palomar, and for Caltech Optical Observatory's Zwiki Transient Facility;
- Advanced UV-reflective coatings were implemented on the Ionospheric Connection Explorer (ICON) and Global-scale Observations of the Limb and Disk (GOLD) missions;
- HIgh-Resolution Mid-InfrarEd Spectrometer (HIRMES) was selected as a third-generation facility for SOFIA;
- H4RG Near-IR detectors were adopted by the Wide Field InfraRed Survey Telescope (WFIRST) project;
- Heterodyne detector technology was incorporated into the Stratospheric Terahertz Observatory (STO) balloon experiment; and
- A 4.74-THz local oscillator was flown on the STO-2 balloon experiment. Unfortunately, due to sun damage to the control electronics, no data was obtained.

Other benefits of the SAT Program include infusion of technologies into ground-based, sub-orbital, and Explorer missions including in scientific areas beyond the Astrophysics Division (e.g., Earth science and planetary missions). More than half of SAT project PIs have successfully leveraged their SAT projects to bring in additional funding, including matching internal research and development funding (e.g., GSFC Internal Research and Development, IRAD); co-funding (e.g., from the Defense Advanced Research Projects Agency, DARPA; and the National Science Foundation); fellowships (e.g., Smithsonian Astrophysical Observatory, SAO, internal funding including two Leon Van Speybroeck Fellowships in X-ray Optics; a National Research Council, NRC, fellowship; a National Science Foundation post-doctoral fellowship; NASA Postdoctoral Program; and university funding for undergraduate research); and/or funded parallel efforts on related projects (e.g., APRA). Several PIs succeeded in setting up collaborations with researchers at other institutions on proposals and new programs, and/or generated industry interest in their technologies, and one PI was inducted as a fellow in the National Academy of Inventors (NAI).

Most PIs report having hired undergraduate and graduate students and/or post-doctoral fellows for their SAT projects (in 2017, PIs reported hiring on average two undergraduate students, two graduate students, and one post-doctoral fellow per project). In total, over 100 students and post-docs have contributed to SAT projects and learned through that experience. Students have received their PhDs, were accepted into graduate programs, and/or have gone on to full-time research positions at universities and government labs; and post-docs have proceeded to positions at other institutions or high-tech companies. All these prove that the SAT Program is helping train and shape the future astrophysics work force and impacts the wider technological work force in the US.

7. SUMMARY

We presented an analysis of the SAT program accomplishments during its first nine years. While funding since the Program's inception was modest, we believe the return on investment in terms of technology maturation for future astrophysics missions, the listed success stories, and development of the next generation of astrophysics technologists, has had a highly significant positive impact on the field.

Our goal for the next decade of strategic astrophysics technology development is to further improve the success rate of TRL advancements, and to proactively enable technology infusion into future missions at a faster rate. We recommend that PIs continue and aggressively involve undergraduate and graduate students, as well as postdoctoral fellows, in their SAT efforts, thereby sustaining the pipeline of technologists and PIs for the next generation. We are in the process of developing strategies to improve the metrics reported here, and will describe them in a later paper.

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