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

June 10, 2018

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The Strategic Astrophysics Technology (SAT) Program

- **Technologies need to be matured when the need is first recognized, not when a project is already burning through its schedule and budget –**

  "…in the mid-1980s, NASA's budget office found that during the first 30 years of the civil space program, no project enjoyed less than a 40% cost overrun unless it was preceded by an investment in studies and technology of at least 5 to 10% of the actual project budget that eventually occurred." [1]

- **Technology maturation involves technical, cost, and schedule risks better addressed in an R&D program; thus NASA Astrophysics Division (APD) started the SAT Program in 2009, divided into three Programs:**
  - Physics of the Cosmos (PCOS) seeks to answer "*How does our universe work?*"
  - Cosmic Origins (TCOR) seeks to answer "*How did we get here?*"
  - Exoplanet Exploration Program (ExEP) seeks to answer "*Are we alone?*"

[1] John C. Mankins, "The critical role of advanced technology investments in preventing spaceflight program cost overrun", The Space Review, December 1, 2008. Available at www.thespacereview.com/article/1262/1

The Strategic Astrophysics Technology (SAT) Program

- **APD solicits SAT proposals through the ROSES AO, in three elements:**
  - Technology development for Physics of the Cosmos (TPCOS)
  - Technology development for Cosmic Origins (TCOR)
  - Technology Development for Exoplanet Missions (TDEM)
- **The proposals are reviewed, with the best ones selected for funding**
- **The role of the SAT Program is to increase technology readiness levels (TRL) of technologies that enable or enhance strategic astrophysics missions across the so-called "mid-TRL gap" of 3-6**

SAT Management, Prioritization, and Selection Rate

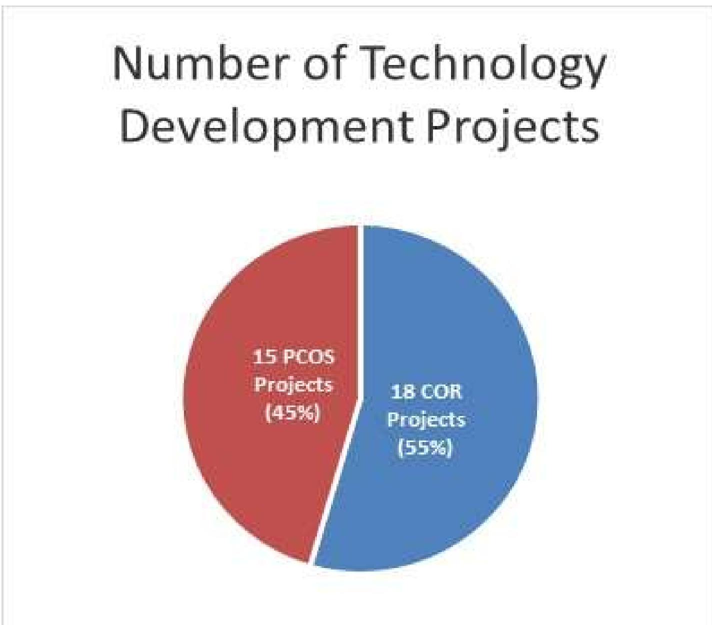
- We only report here on PCOS and COR technology development, not those managed by the Exoplanet Exploration Program (ExEP) Office; whenever we discuss SATs we refer only to TPCOS and TCOR
- TPCOS SATs are managed by the PCOS Program Office (POs) and TCOR SATs are manages by the COR PO, with the two POs operated by the same staff
- In parallel, several tasks have also been directed to fill technology requirement gaps in alignment with the PCOS and COR science goals
- Technology task selection depends on prioritization of technology gaps, which has been done annually until 2017, and will henceforth be biennial
- Since 2009, 33% of TPCOS proposals and 23% of TCOR proposals have been selected, for a 27% total SAT selection rate

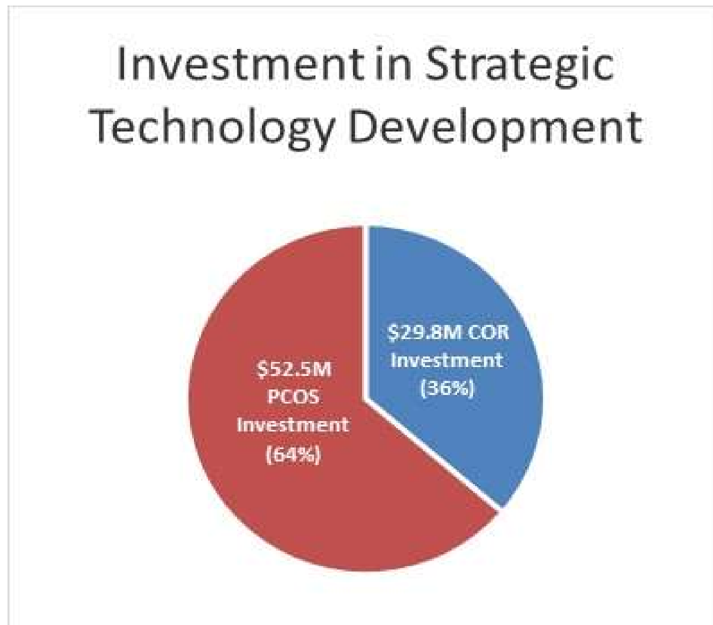
Technology Development Data Description

- **Including three legacy tasks, PCOS and COR POs manage(d) 78 technology development tasks (47 PCOS and 31 COR)**
- **For the analysis reported here, we removed 14 of the 78 tasks, as follows:**
  - Mission development rather than technology development (4 tasks)
  - Tasks started less than a year ago, not continuing a previous task (9 tasks, including 4 SATs)
  - Small, brief projects combines into a single task that the PO was asked to manage (1 task)
- **This leaves 64 tasks (40 PCOS and 24 COR):**
  - SATs: 46
  - Astrophysics Research and Analysis (APRA): 1
  - Direct funded: 17
- **Maturing strategic technologies is challenging, not typically expected to be completed within the schedule and budget of a single SAT, but most PIs won continued funding (and/or received direct funding); where the technology objective is the same, we combined tasks for the purpose of analysis**
- **This leaves 33 projects (15 PCOS and 18 COR) to be analyzed, with the results shown in the following slides**

Tech Development Project Investment and Duration

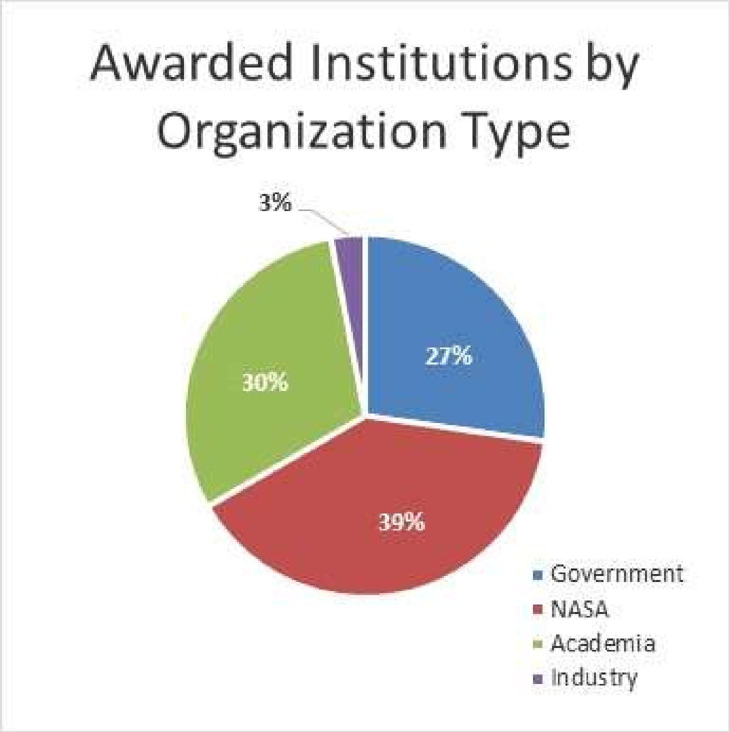
- **PCOS investment in their 15 projects was $52.5M ($3.5M average)**
- **COR investment in their 18 projects was $29.8M ($1.7M average)**
- **Average project duration was 3.6 years (4.3 years PCOS and 3.0 years COR)**
- **Note that many projects are still ongoing, these numbers may increase somewhat by the time they are completed**





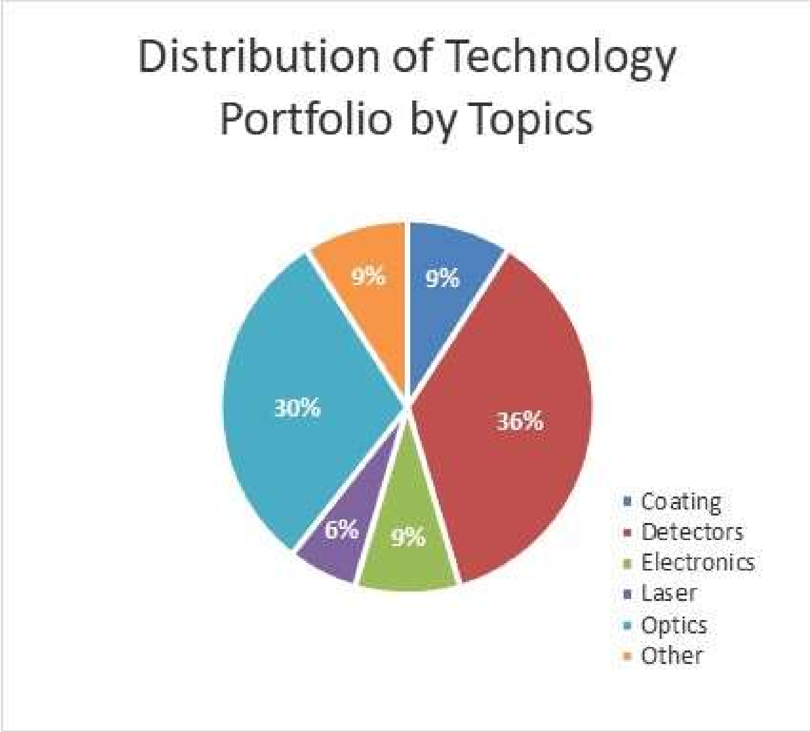
Principal Investigator (PI) Institution Type

- **13 projects were awarded to NASA PIs (GSFC and MSFC)**
- **10 projects were awarded to PIs at academic institutions**
- **9 projects were awarded to PIs at government labs (Federally Funded Research and Development Centers, FFRDCs, such as JPL and NIST)**
- **1 project was awarded to an industry PI**



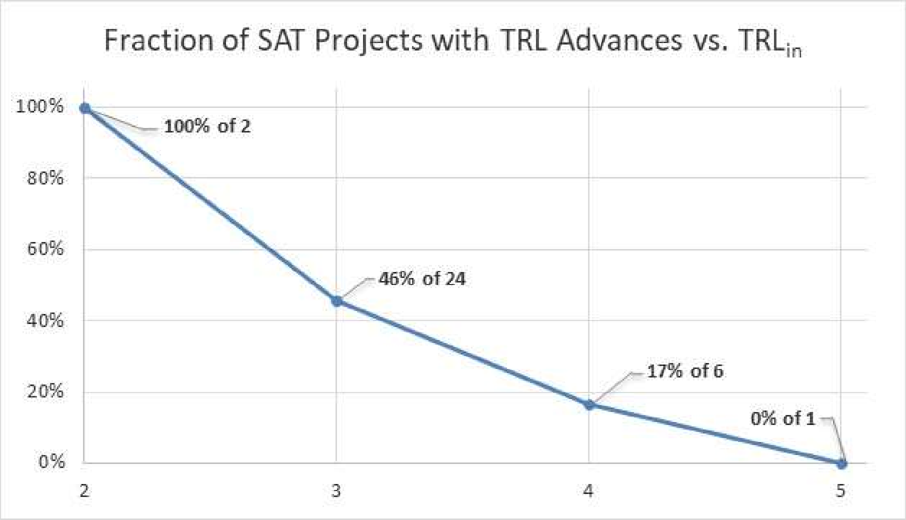
Investment Distribution by Technology Topic

- **12 projects worked on detector technologies**
- **10 projects worked on optics technologies**
- **3 projects each worked on technologies relating to coatings and electronics**
- **2 projects worked on laser technologies**
- **3 projects worked on other technologies (e.g., sub-Kelvin cooling, etc.)**



Challenges of TRL Advances

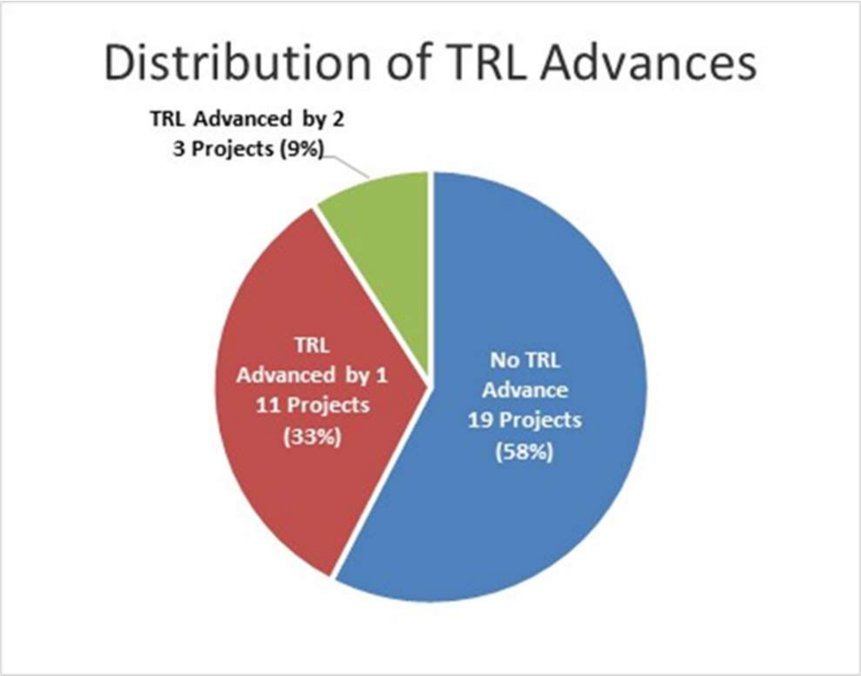
- **While TRL advances are our goal, they are not the sole measure of success**
- **The greatest challenges to achieving TRL advances include:**
  - Maturing technologies required for strategic missions is by definition very challenging
  - Many projects work on systems, where TRL is determined by the least-mature subsystem
  - POs impose rigorous standards, including establishment of credible path for achieving full on-orbit performance requirements; if any requirement is not completed, TRL doesn't advance
  - Incoming TRL assessed by PI; may be optimistic so actual TRL advance may not be recognized
  - Sometimes requirements become a moving target (e.g., project initially works on 5" X-ray mirrors for IXO, superseded by 5" for Athena, superseded by <1" for Lynx)
  - Advancing TRL is more challenging when initial TRL is higher (see below)
  - Budget and schedule may be insufficient for larger challenges; requiring follow-on funding



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

TRL Advances in PCOS and COR Programs

- **Overall, 14 of 33 technology development projects (42%) advanced by at least one TRL, of which 3 (9%) advanced by two; The high-risk, high-reward nature of this R&D portfolio makes the result especially impressive**
- **Counting double-TRL advances twice, the 17 TRL advances cost the Program an average of $4.8M each (counting only $38.5M cost of advancing projects drops the average to $2.3M)**



Successes Beyond TRL Advances

- **PCOS and COR Programs had remarkable technology development successes:**
  - TES micro-calorimeters expected to be major US contribution to Athena X-IFU
  - Time-division SQUID multiplexing is backup to Athena X-IFU baseline readout
  - FPGA-based fast X-ray event recognition may contribute to Athena WFI
  - Phasemeter technology infused into GRACE-FO’s LRI
  - Antenna-coupled detectors deployed in BICEP2, BICEP3 and Keck Array, and flown on Spider LDB mission (2014/15)
  - Optical blocking filters incorporated into REXIS instrument on OSIRIS-Rex
  - Feedhorn-coupled TES-based detector architecture deployed in CLASS telescope
  - Arcus MIDEX proposal based on CAT-grating selected for Phase A concept study
  - TES bolometer detectors selected to support HAWC instrument on SOFIA
  - Advanced CCD detectors implemented into FIREBall LDB mission, WaSP instrument at Palomar, and Caltech Optical Observatory’s Zwiki Transient Facility
  - Advanced UV-reflective coatings implemented on ICON and GOLD missions
  - HIRMES selected as third-generation facility for SOFIA
  - H4RG Near-IR detectors adopted by WFIRST project;
  - Heterodyne detector was incorporated into STO balloon experiment
  - 4.74-THz local oscillator flown on STO-2 balloon experiment

Successes Beyond TRL Advances (cont.)

- **Other benefits of the SAT Program include:**
  - Over half of SAT PIs successfully leveraged their SAT projects to gain additional funding
    - Matching internal research and development funding
    - Co-funding
    - Fellowships
    - Funded parallel efforts on related projects (e.g. via APRA)
  - Several PIs set up collaborations with researchers at other institutions on proposals and new programs, and/or generated industry interest in their technologies
  - One PI inducted as fellow in the National Academy of Inventors (NAI)
- **SAT Program helps train and shape the future astrophysics work force and impacts the wider technological work force in the US:**
  - In 2017, on average two undergrads, two grad students, and one post-doc contributed to each SAT project; total to date is over 100 students and post-docs
  - Students received PhDs, were accepted into graduate programs, and/or accepted full-time positions at universities, government labs, or industry

ASTROPHYSICS

Summary

- **APD's SAT Program and direct-funded investments in maturing strategic development over the past 9 years has been a great success story**
  - 42% of projects led to TRL advance of 1 or 2 levels
  - A wide range of projects, including many without a TRL advance, led to technology infusion into missions and projects
  - Over 100 students and post-docs participated in projects, helping train the future Astrophysics workforce and contributing to the wider US high-tech workforce
- **Average project duration to date is 3.6 years**
- **Average project investment to date is $2.5M (total $82.3M)**
- **Technology topics invested in most are detectors and optics (67%), with the balance in coatings, electronics, lasers, etc.**
- **Project PIs distributed almost uniformly between NASA centers, academia, and government labs**