Best Paper Award

Technological challenges on the path to discovery in astrophysics

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ABSTRACT

Over the next decade, NASA's Astrophysics Division expects to undertake robotic or unmanned space flight missions that will explore the nature of the universe at its largest scales, its earliest moments, and its most extreme conditions. Current innovative and maturation technology programs are being conducted by NASA's Astrophysics Division to fill the technology gaps identified by the community. One of these efforts was to establish the Strategic Astrophysics Technology (SAT) program to support the maturation of key technologies. In this paper, these technology programs are described; in particular the SAT program will be presented describing the process to establish priorities, the technology management components, and the efforts to move these technologies into mission concepts and flight missions. The technology roadmap for a large mission concept such as ATLAST is presented as an example of the technology gaps derived and identified from these analyses, which could focus future efforts and investment priorities. Finally, the NASA preparation for the next decade, which will study and mature four large mission concepts, is briefly outlined.

Keywords: Space technology, technology innovation and maturation, strategic astrophysics technologies

1. INTRODUCTION

Current scientific advancements such as the recent discovery of gravitational waves produced by the merger of a binary black hole[1] is a great example of the promise and energy that these discoveries can inject into the national and international dialogue and emerging priorities. This was a fitting tribute to the 100-year celebration of General Relativity, celebrated during 2015. Also, last year, astrophysics and planetary science celebrated 20 years since the discovery of planets outside our solar system that orbit main sequence stars. This was an appropriate moment to anticipate and explore the next 20 years of discovery in the search for planets that may harbor the conditions to host life. In particular, this scientific driver is motivating technology advancements in the area of bio-signature characterization.[2]

Astrophysics, for being a photon-starved discipline, unlike other space sciences, faces demanding challenges in the observational areas of detection and characterization of cosmic features and celestial objects. Many of these challenges are unique to astrophysics such as achieving high-contrast imaging, attaining ultra stability in optical systems, eliminating persistency in detectors, and producing large format collecting mirrors and detectors.

Despite the obstacles that these challenges might present, the journey of discovery continues to unfold in unpredictable and surprising ways and many new discoveries could be enabled with the proper alignment of policies, investments, technologies, trained individuals and competent teams.

2. SCIENCE CHALLENGES TURN INTO TECHNOLOGY CHALLENGES

The science challenges across many disciplines are perceived as opportunities for research, modeling and experimentation. However, a more detailed analysis of the current obstacles to advance experimental science leads to one major roadblock: technology readiness of vital components. Only an integrated view of the expected outcomes of scientific discovery will be sensible to the need for parallel and frontier technology advancements to successfully implement these scientific challenges that will drive the need for exploration and discovery. The next level of detection in experimental astrophysics will be achieved only when the proper technologies and higher quality components are available, mature and ready to be used in real experimental settings and flight missions.

Due to prior preparations and strategic planning, astrophysics has many published guidelines, documents, roadmaps, and studies that can assist in finding priorities, missions, and scientific drivers of interest.[3,4,5] Additional mission concept

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studies of large missions sponsored by the scientific community, such as the High Definition Space Telescope (HDST) and the Advanced Technology Large-Aperture Space Telescope (ATLAST), have provided technology gaps, conceptual maturity and scientific applications to these capable space missions.[6,7]

3. TECHNOLOGY INCEPTION, MATURATION AND MANAGEMENT

During the rest of this decade, the astronomical community expects to study and mature ambitious flight mission concepts to continue exploring and probing the universe. These demanding and complex space missions will certainly require technology advances that will assure they are executable and successful. These advances will demand investments proportional to the complexity and scope of these space missions that will tackle astronomy's most difficult questions and mysteries on the nature and constitution of the universe. Several technology innovation programs (e.g., Astrophysics Research and Analysis – APRA) are the appropriate places to start the life cycle development by which these concepts could show promise and can be continued along this maturation path. In this context, properly funded space technology maturation programs will be critical to advancing these components or mission concepts. In the absence of these global technology maturation programs, mission concepts or flight programs in Phase A could directly fund the necessary development of components, which is a model that has been used for prior and current large missions (e.g. Hubble, Spitzer, Chandra, JWST, WFIRST).

An important framework in the advancements of technologies or technology maturation is intrinsically tied to the Technology Readiness Level (TRL) categorization. Since 18 April 2013, NASA has updated the definition of TRL. The official document that contains this description is the systems engineering process NASA Procedural Requirements (NPR) 7123.1B, Appendix E2.

The demand for technology maturation programs is imposed by the entrance requirement for proposing flight missions, which demands TRL 5 for most, if not all, the critical components so they can be integrated in a timely and cost-efficient manner into a flight prototype. The achievement of technology maturity of instruments and space components can directly reduce the cost and risk of space missions. The US Government Accountability Office (GAO) concluded after assessing 21 large NASA projects with a combined life-cycle cost in excess of $43 billion that most of the projects "did not meet technology maturity and design stability best practices criteria, which, if followed, can lessen cost and schedule risks faced by the project."[8]

Since technology maturation requires advancing hardware and software components toward higher TRL stages, which include validation, demonstration, and testing in laboratory and relevant environments, these activities become expensive, specialized, and laborious. The dearth of dedicated funding programs for technology maturation can be explained by recognizing that these programs are often seen as easy and obvious reductions from operating budgets because they are often not immediately associated with a critical or approved flight program.

An important lesson learned in our technology maturation program has been the need of explicit technology management across the spectrum of activities generated by selected investigations within these programs. This involves formal reporting and reviews to verify progress, advancements, and the completion of milestones. Certainly, this is time consuming and requires specialized, trained personnel that can follow through and track these investigations to enable proper use of the resources available to these investigators. In these exchanges with the technology teams, it is possible to provide external views and assistance that these teams can use to maximize their achievements and find synergies with other working groups across the country. These synergies are often used to further collaborate and subsequently create larger and more competent technology teams.

This technology management process includes the annual analysis of the appropriate technology gaps for each astrophysics theme as submitted by the community for consideration by a Technology Management Board (TMB), which, after many deliberations, produces a ranked list of technology recommendations, which are captured by the Program Annual Technology Report (PATR)[9]. Some of the activities are graphically depicted in Figure 1.

4. TECHNOLOGY MATURATION IN ASTROPHYSICS

In 2009, the Astrophysics Division pioneered a program for technology maturation known as the Strategic Astrophysics Technology (SAT).[10] This technology solicitation has three components associated with each of the themes, in which the Astrophysics Division is divided, namely, Physics of the Cosmos (PCOS), Cosmic Origins (COR) and Exoplanet Exploration (EXEP). This program supports the maturation of technologies of mid-range TRL already developed and tested in the laboratory (TRL ≤ 3) to a point where they can be incorporated into a flight mission with an acceptable level of risk (TRL 5 or 6).

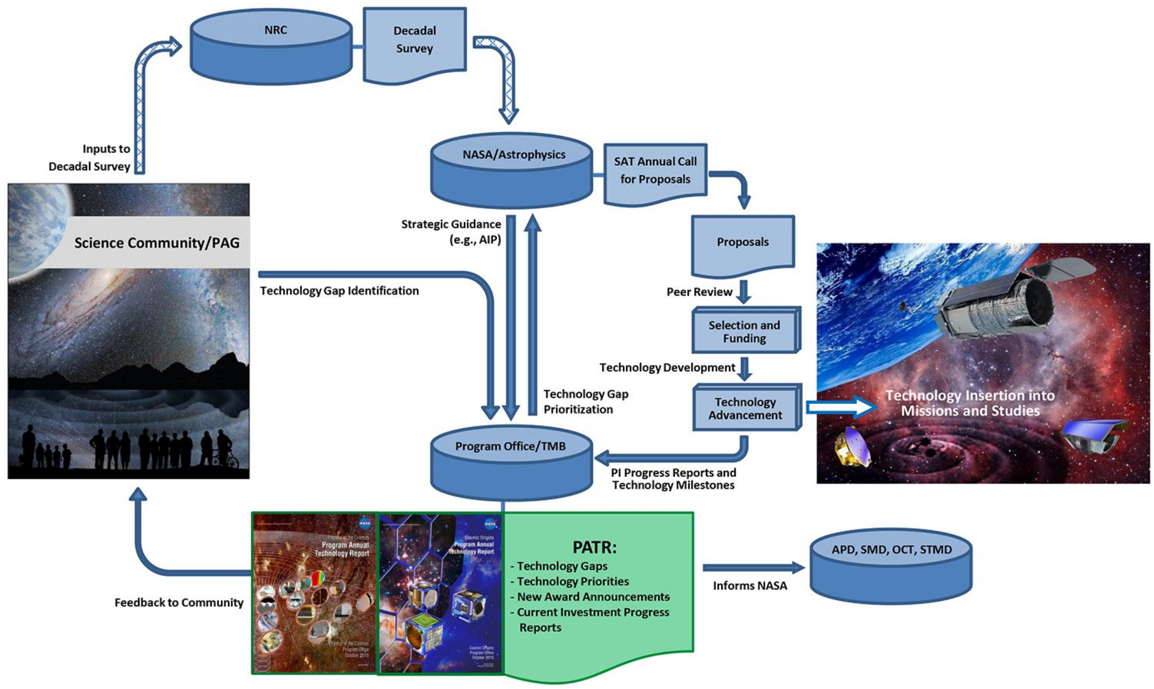

Figure 1. Annual technology management process for the Cosmic Origins and Physics of the Cosmos themes.

The SAT program is intended to fill the so-called "Mid-TRL Gap" of technologies that have potential but are not sufficiently mature, making them ill-suited to be part of flight programs or to be funded under basic research programs.

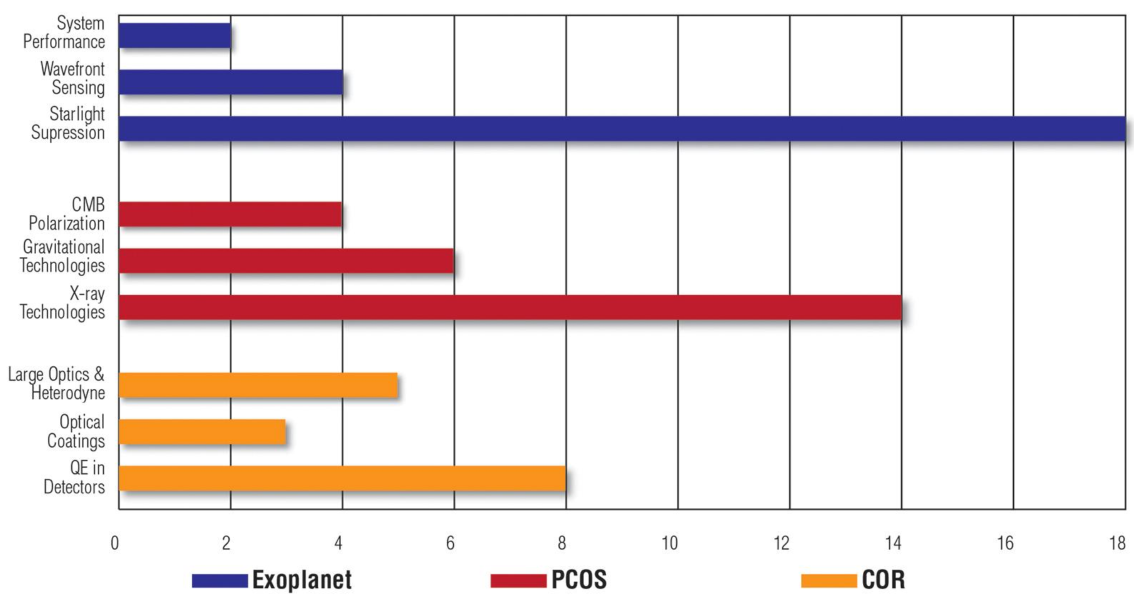

Figure 2. Number of successful SAT investigations for Fiscal Year from 2009-2015 for technology priorities within each theme.

The funded SAT proposals are not required or expected to complete the entire development process during the period of their grants. It is expected that the proposers are able to identify verifiable milestones and provide a realistic schedule to achieve these milestones. The technologies emphasized in the SAT program are basically enabling the achievement of science drivers, as opposed to enhancing aspects of further scientific interest.

The selected SAT investigations for each of the prioritized areas for each of the themes are described in Figure 2. These activities have greatly advanced the state-of-the-art in some of the areas related to these technologies. Moreover, there are some early successes of activities that have graduated from SAT and have been adopted by flight mission programs for further development[10] (e.g., H4RG detectors and coronagraph technologies are now part of the WFIRST flight program development). The total cost invested in this program since its beginning until fiscal year 2015, is about $70 M in fixed year dollars. In Figure 3, some of the diverse technologies being funded by the Cosmic Origins SAT program are depicted.

Figure 3. Schematic sample of technology activities within the Cosmic Origins Development Program.

5. EXAMPLE OF A TECHNOLOGY ROADMAP

A concrete example of technology mission planning efforts sponsored and sustained by community activities for a future large mission that will follow HST, JWST and WFIRST, is the Advanced Technology Large-Aperture Space Telescope (ATLAST) mission concept. This mission represents an advance in ultraviolet, optical and infrared (UVOIR) astronomy from space. It was conceived to find earthlike habitable worlds and to understand star and galaxy formation and evolution. The design of this mission included a powerful general-purpose international space telescope capable of advancing general astrophysics and exoplanet science goals. The requirements described for the telescope in Table 1, are demanding and many of them have not yet been developed.

Table 1. ATLAST Telescope Design Parameters

Telescope Parameter	Requirement
Primary Mirror Aperture	≥ 8 meters
Primary Mirror Operating Temperature	~ 25 C
UV Coverage	90 nm – 300 nm, FOV= 1 – 2 arcmin
Vis/NIR Coverage	300 nm – 2500nm, FOV= 4 – 8 arcmin
Mid-IR Coverage	Sensitivity competitive with ground to 8 μm
Vis/NIR Image Quality	Diffraction-limited performance at 500 nm
UV Image Quality	Not worse than 0.10 arcsec at 150 nm
Wavefront Error Stability for General Astrophysics	35 nm rms 1.3 – 1.6 mas pointing stability
Wavefront Error Stability for Exoplanet Imaging	<10 ppm rms effective <10 min bandpass Active correction in an internal coronagraph

The ATLAST technology gap analysis indicates that the overall mission requirements are highly demanding when compared with the current state-of-the-art. For example, the wavefront error stability requirement of 10 ppm over 10 min, is about 1000 times better than for JWST, which is still on the ground and will be launched in late 2018. Similarly, a high contrast requirement for direct imaging of 10^{-11} is at least 100 higher than for WFIRST, which will be launched around 2025. The same is true for the telescope aperture of more than 8 meters, which is 4 times bigger than HST and 1.2 the size of JWST. Detectors, optics and stability requirements are far more stringent than for previous flight missions and will require serious investments in the current and upcoming decades. However, demanding and visionary mission concepts such as the Large UV/Optical/IR Surveyor (LUVOIR)[5], HDST[6] and ATLAST[7] have helped to focus the need on technology development and investments with the goal of moving these mission concepts toward future flight programs.

6. PLANNING FOR THE NEXT DECADE

In anticipation of the upcoming 2020 Decadal Survey in Astronomy and Astrophysics conducted by the National Research Council (NRC) on behalf of the National Academy Sciences, NASA is preparing to mature large mission concept studies (larger than $1B) and provide some conceptualization about mid-class missions or Probes (less than $1B).

NASA Astrophysics started a process of involving the community to form Science and Technology Definition Teams (STDT) for large missions that were recommended to the agency by the three existing community Program Analysis Groups: Exo-PAG, PhysPAG, and COPAG. These large missions are: Far-IR Surveyor, X-ray Surveyor, Large UV/Optical/IR Surveyor (LUVOIR), and the Habitable-Exoplanet Imaging Mission (HabEx). The goals of these efforts are to provide a compelling science case, a design reference mission (DRM) with strawman payload, technology development needs, and some cost requirement assessment. These STDTs will provide input to the 2010 Decadal Survey in the form of White Papers and other requested information. All of these four mission concepts are currently functioning and starting their work of producing the many deliverables leading to executable DRMs up to a Concept Maturity Level (CML)11 4 point design.

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