

NASA funding opportunities for optical fabrication and testing technology development

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ABSTRACT

NASA requires technologies to fabricate and test optical components to accomplish its highest priority science missions. The NRC ASTRO2010 Decadal Survey states that an advanced large-aperture UVOIR telescope is required to enable the next generation of compelling astrophysics and exo-planet science; and, that present technology is not mature enough to affordably build and launch any potential UVOIR mission concept. The NRC 2012 NASA Space Technology Roadmaps and Priorities Report states that the highest priority technology in which NASA should invest to ‘Expand our understanding of Earth and the universe’ is next generation X-ray and UVOIR telescopes. Each of the Astrophysics division Program Office Annual Technology Reports (PATR) identifies specific technology needs. NASA has a variety of programs to fund enabling technology development: SBIR (Small Business Innovative Research); the ROSES APRA and SAT programs (Research Opportunities in Space and Earth Science; Astrophysics Research and Analysis program; Strategic Astrophysics Technology program); and several Office of the Chief Technologist (OCT) programs.

Keywords: Technology Development

1. INTRODUCTION

Since its inception, NASA has depended on technology innovation to enable its highest priority goals. Per the 2012 NASA Strategic Space Technology Investment Plan¹, in Fiscal Year 2012 NASA invested nearly \$1 billion in pioneering and crosscutting technology development to accomplish the Goals defined in the 2011 NASA Strategic Plan². Of that amount, as shown in Figure 1, approximately 8% or \$80 million was invested in optics and photonics related technologies: 8.1.1 Detectors and Focal Planes; 8.1.3 Optical Systems (Instruments and Sensors); and 8.2.4 High Contrast Imaging and Spectroscopy Technologies.

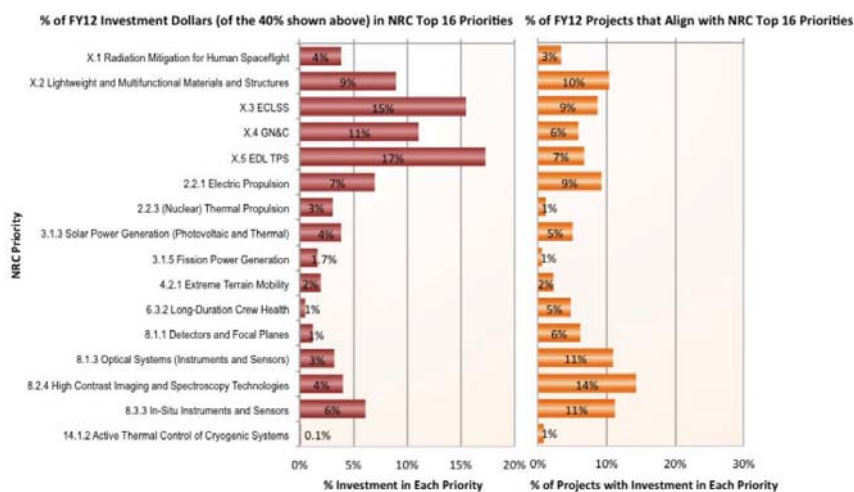


Figure 1: Distribution of FY12 technology investment across the NRC top 16 priorities for NASA.

These 3 technologies were defined in NASA’s Technology Assessment (TA08) on Science Instruments, Observatories and Sensor Systems³⁻⁵, then redefined by the NRC report on NASA’s Technology Roadmaps and Priorities and identified as being 3 of the most important 16 technologies in which NASA should invest over the next 5 years⁶.

NASA uses many different funding mechanisms for investing in technology (Figure 2), but most optics and photonics related investments are made by either the Science Mission Directorate of the Office of the Chief Technologist.

Science Mission Directorate	Office of the Chief Technologist
Astrophysics Research and Analysis	Centennial Challenges
Discovery Program (502A)	Center Innovation Fund
ESTO	Flight Opportunities
Exoplanet Exploration	Franklin Small Satellite Subsystems Technologies
HELIOS	Game Changing Development
Mars Exploration (269B)	NASA Innovative Advanced Concepts
NASA Earth Sciences	SBIR
Physics of the Cosmos (PCOS)	Small Spacecraft Technology Program
Planetary Science Research (515A)	Space Technology Research Grants, Space Technology Research Fellowships
Technology Program (051A)	STTR
Human Exploration and Operations Mission Directorate (HEOMD)	Technology Demonstration Missions
Advanced Exploration Systems	Office of Safety and Mission Assurance (OSMA)
SCaN	NASA Electronic Parts and Packaging Program
Robotic Servicing	Nondestructive Evaluation Program
Center Internal Research and Development (IRAD)	OSMA Software Assurance Research Program (SARP)
GSFC IRAD	Range Safety
JSC IRAD	Office of the Chief Information Officer (OCIO)
KSC IRAD	Chief Information Officer

Figure 2: FY2012 Space Technology Programs by Mission Directorate and Office

The most important programs for optics and photonics technology are SBIR/STTR; SMD's Research Opportunities in Space and Earth Science (ROSES) which includes APRA (Astrophysics Research and Analysis), SAT (Strategic Astrophysics Technology), ESTO (Earth Science Technology Office); and OCT's NASA Innovative Advanced Concepts (NIAC) and Space Technology Research Opportunities (STRO).

2. GUIDANCE DOCUMENTS

2.1 Decadal Studies

In the area of Science, NASA does not define its own priorities. Rather, NASA implements (within the constraints of its Congressionally authorized budget) the priorities define by the National Research Council decadal studies in Astrophysics, Heliophysics, Earth Science and Planetary Science⁷⁻¹⁰. These studies produce a prioritized list of the most compelling science questions to be answered over the next 10 years and make recommendations to NASA for potential missions to answer these questions. Additionally, the NRC Decadal Reports make recommendations to NASA regarding technology investments needed to enable these missions.

For example, the 2010 Astrophysics Decadal Study recommended the following optics related technology investments:

- achieving a telescope with sufficient image quality over the focal plane necessary for a weak lensing study;
- manufacturing a low-mass large-aperture x-ray mirror which achieves an angular resolution of 5 arcseconds for the International X-Ray Observatory (IXO). Estimated to cost about \$200 million;
- starlight suppression techniques (e.g. coronagraphy, interferometry or star shades) for direct detection of exoplanets. A budget of \$4M per year is recommended for the first several years of the decade;
- manufacturing, testing and coating of a 4-meter or larger wide-field-of-view high-efficiency UV/Optical (Hubble replacement) telescope and detectors. A notional budget of \$40M is recommended for the decade.

2.2 Technology Taxonomy

The three optics related technologies discussed in NASA Strategic Space Technology Investment Plan (8.1.1 Detectors and Focal Planes, 8.1.3 Optical Systems, and 8.2.4 High Contrast Imaging and Spectroscopy Technologies) were defined in NASA's Technology Assessment (TA08) on Science Instruments, Observatories and Sensor Systems, then redefined by the NRC report on NASA's Technology Roadmaps and Priorities.

2.2.1 Technology Assessment Roadmap

In 2010, NASA's Office of the Chief Technologist published 14 Technology Assessments: TA01 Launch Propulsion Systems; TA02 In-Space Propulsion Technologies; TA03 Space Power and Energy Storage; TA04 Robotics, TeleRobotics and Autonomous Systems; TA05 Communications and Navigation; TA06 Human Health, Life Support and Habitation Systems; TA07 Human Exploration Destination Systems; TA08 Science Instruments, Observatories and Sensor Systems; TA09 Entry, Descent and Landing Systems; TA10 Nanotechnology; TA11 Modeling, Simulation, Information Technology and Processing; TA12 Materials, Structures, Mechanical Systems and Manufacturing; TA13 Ground and Launch Systems Processing; and TA14 Thermal Management Systems.

Each assessment defined its own technology taxonomy. The Science Instruments, Observatories and Sensors Systems (SIOSS) report was Technology Assessment 08 (TA08)³⁻⁵. Figure 3 shows the TA08 Technology Area Breakdown Structure (TABS). In general, only TABS 8.1.3 Optical Components and TABS 8.2.1 Large Mirror Systems require the development of optical manufacturing the testing technology.

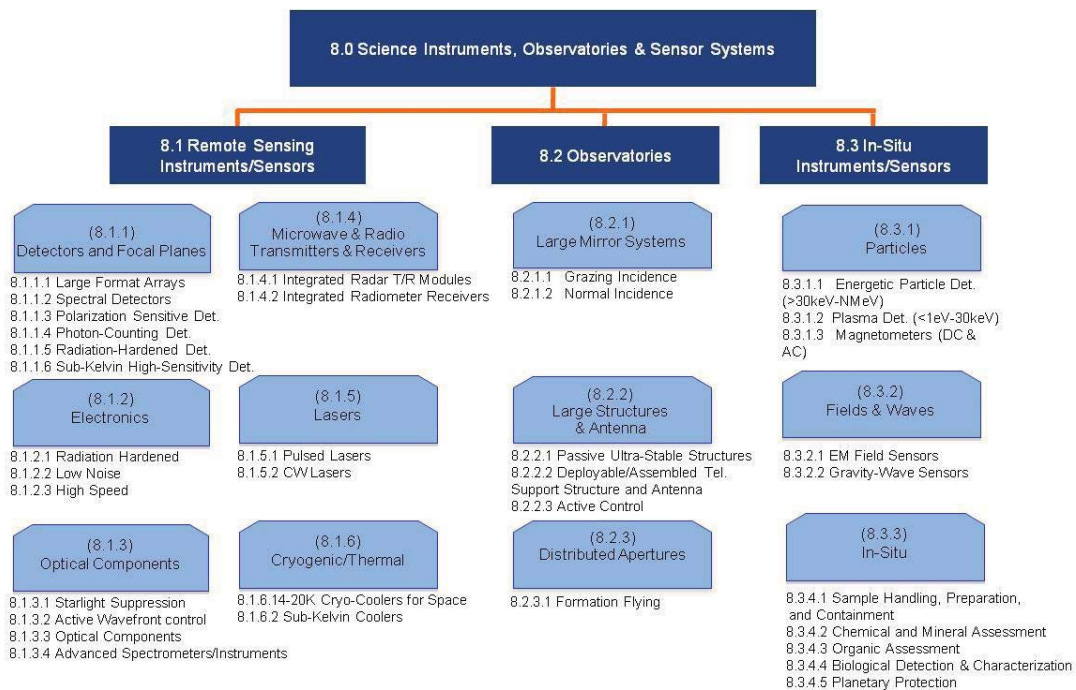


Figure 3: Technology Area 08 (TA08) Breakdown Structure

Science Instruments (TABS 8.1) require both incremental improvements and breakthrough technologies to enable entirely new instrument or observatory architectures. Optical component technology (TABS 8.1.3) challenges include: starlight suppression; active wavefront control; and advanced spectrometers/instruments. Specific technology needs include: Broadband and spectral optical coatings for uniform high throughput; Ability to fabricate aspheric optical components for novel optical systems with large fields of view; Highly stable optical support structures; High spectral resolution dispersive elements; and Precision Wavefront Sensing and Control. TABS 8.1.3 is specifically intended to cover 'small' beam space (i.e. < 0.5 meter diameter) optical components and only the manufacture of non-conventional aspheric optics because the manufacture of small and conventionally aspheric optics is a proven technology.

Observatory (TABS 8.2) are necessary to design, manufacture, test, and operate space telescopes which collect, concentrate and/or transmit photons. Observatory technologies enable or enhance large-aperture monolithic and/or segmented single apertures as well as structurally connected and/or free-flying sparse and interferometric apertures. Applications span the electromagnetic spectrum, from X-ray to UVOIR to radio-wave. Planned and potential future NASA missions require specific enabling observatory technologies: Large Grazing and Normal Incidence Mirror Systems (TABS 8.2.1); Large Ultra-stable structures; Large-deployable/assembled structures; Control of Large

Structures; and Formation Flying. Deployment, assembly or formation flying technology is required to create extra-large apertures – where formation flying produces an actively controlled virtual structure. For all applications, regardless of whether the mirror system aperture is 0.5 m or 5 m or the angle of incidence is grazing or normal, the fundamental driving need is larger-collecting aperture with better performance at a lower cost per square meter. TABS 8.2.1 technologies achieve this performance capability: ability to manufacture and test large-mirror systems (normal and grazing incidence); ability to deposit large-aperture, uniform (amplitude and polarization), broadband high reflectance coatings; and ability to structurally hold the mirror system in a stable, strain-free state under the influence of anticipated dynamic and thermal stimuli. TABS 8.2.1 was specifically defined as covering the technologies need to make large mirror systems because the technologies needed to make such systems are entirely different from the technologies needed to make small optical systems.

2.2.2 NRC Report on NASA's Technology Roadmaps and Priorities

In 2012, each of the 14 Technology Assessment reports were reviewed by a committee of the National Research Council which published its findings in “NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space”⁶. The primary result of this report was the definition of 16 key technologies in which NASA should invest over the next 5 years to meet the Top Technical Challenges necessary to accomplish three primary Objectives: Objective A, Extend and sustain human activities beyond low Earth orbit; Objective B, Explore the evolution of the solar system and the potential for life elsewhere; Objective C, Expand our understanding of Earth and the universe in which we live. While optics and photonics technology can help enable all of these Objectives, the most relevant is Objective C. The committee determined that the second most important Top Technical Challenge to accomplish Objective C (after improved access to space) is “developing a new generation of larger-aperture lower-cost Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects by developing high-contrast imaging and spectroscopic technologies to provide unprecedented sensitivity, field of view and spectroscopy of faint objects.”

The committee identified 3 optical Top Technologies in which NASA needs to invest over the next 5 years to meet the New Telescopes Top Technical Challenge: Optical Systems (8.1.3), High Contrast Imaging and Spectroscopy (8.2.4), and Detectors and Focal Planes (8.1.1). The committee created Optical Systems (8.1.2) by deciding to delete TA08 TABS 8.2.1 Large Mirror Systems and merge it with TABS 8.1.3 Optical Components because “the technologies are very similar and it would be most effective to develop these technologies together.” Then, the committee decided to create High Contrast Imaging and Spectroscopy (8.2.4) to fill the gap created by deleting TA08 TABS 8.2.1 because the “development of advanced approaches to high-dynamic-range imaging would be a game-changing technology to support exoplanet imaging, which is a priority initiative in the Astro2010 decadal survey for astronomy and astrophysics (NRC, 2010). This technology would provide unprecedented sensitivity, field of view, and spectroscopy of exoplanetary systems, with many subsidiary applications such as solar physics and the study of faint structures around bright objects”.

The committee identified two game-changing Optical System technologies that would enable direct imaging of stars and detailed imaging of energetic objects such as active galactic nuclei: active wavefront control and grazing-incidence optical systems. Active wavefront control technology was defined as modifying mirror figure and alignment in response to external disturbances, allowing automated on-orbit alignment of optical systems and the use of lightweight mirrors and telescopes. This technology closely aligns with NASA's need to develop the next generation of large-aperture astronomical telescopes, lightweight laser communication systems, and high-performance orbiting observatories for planetary missions. To enable future x-ray astronomy missions, grazing-incidence optical systems require improved spatial resolution by at least a factor of ten, without increasing mass per unit area. This will involve improvements in production systems for piezo adjustment of thin slumped glass and in mounting and testing the sets of optics. Applications are for x-ray and far ultraviolet (UV) (<500 Angstrom) astronomy, and may be extended into the soft gamma/hard x-ray region (to ~100 keV). The committee cited adjustable grazing incidence x-ray optics based on thin slumped glass as an example of a strong linkage between these technologies. A third game-changing technology identified by the committee is normal incidence mirrors with diameters of four meters and beyond that operate to wavelengths as low as 30 nm.

2.3 Program Office Annual Technology Report

Each of the three Astrophysics Division Program Offices (Exoplanet Exploration, Physics of the Cosmos and Cosmic Origins) publishes a Program Annual Technology Report (PATR).¹¹⁻¹³ These reports provide detailed information about the current technology needs and the prioritization of these needs for each Program Area.

3. NASA CORE TECHNOLOGY INVESTMENTS

As defined by the NASA Strategic Space Technology Investment Plan, core technologies are indispensable for NASA's present and planned future missions. Because of this importance, core technologies comprise approximately 70% of the Agency's technology investment over the next four years. NASA's core technologies are:

1. Launch and In-Space Propulsion
2. High Data Rate Communications
3. Lightweight Space Structures and Materials
4. Robotics and Autonomous Systems
5. Environmental Control and Life Support Systems
6. Space Radiation Mitigation
7. Scientific Instruments and Sensors

While optics and photonics technology are enabling for many of these core technologies, such as High Data Rate Communications and Robotic and Autonomous Systems, the primary core area is Scientific Instruments and Sensors.

For the next four years, NASA will invest in observatory technologies with improved performance and angular resolution, and reduced weight and cost. Specific emphasis will be on large mirror systems and structures. Potential large mirror investments include x-ray mirrors, lightweight mirrors, ultraviolet coatings and segmented mirrors. Potential structure investments include passive and active ultra-stable structures, and deployable telescopes and booms.

Observatory technologies are necessary to design, manufacture, test and operate space telescopes that collect, concentrate and detect photons for astronomy missions. The capabilities of an observatory often dictate the limits of an astronomy mission. Relieving those limits and enabling new missions such as high-contrast exoplanet imaging, requires innovative observatory technologies, in some cases with an order of magnitude improvement. Low-mass grazing-incidence optical systems achieving an order of magnitude improvement in spatial resolution will enable advanced future x-ray astronomy missions. Other advances in observatory technologies such as integrated, adjustable, normal-incidence mirror systems can enable direct imaging of stars and detailed imaging of energetic objects such as active galactic nuclei. One potential exoplanet observatory concept involves the deployment and shape control of a large occulting starshade and formation flying of the starshade relative to the associated telescope. Other techniques for observing exoplanets include interferometry and coronagraphy. Innovations in materials for observatories may enable ultra-stable, large space structures. Regardless of the implementation architecture (segmented or monolithic, active or adjustable, etc.), all future space science missions can benefit from low-cost, low-risk, high-performance space optical systems.

4. SMALL BUSINESS INNOVATIVE RESEARCH (SBIR)

The Small Business Innovation Research (SBIR) program was established by Congress in 1982 (and reauthorized in 2000) to provide increased opportunities for small businesses to participate in R&D, to increase employment and to improve US competitiveness. The program's specific objectives are to stimulate US technological innovation, use small businesses to meet federal research and development needs, increase private-sector commercialization of innovations derived from federal R&D and foster and encourage participation by socially disadvantaged businesses. The Small Business Technology Transfer (STTR) program is a separately funded activity which awards contracts to small business concerns for cooperative research and development with a non-profit research institution such as a university. The SBIR/STTR programs are funded via a 'set-aside' of approximately 6% of each federal agencies 'extra-mural' R&D budget. The entire SBIR/STTR federal budget for FY11 was approximately \$2.6B of which approximately 10% or \$250M was invested by NASA. The DoD and Homeland Security percentage of the budget was ~70% while the DOE and NSF percentage was ~15%.

The SBIR/STTR program uses a two stage process. Proposals selected for Phase 1 funding receive \$125K and either 6 or 12 months (depending upon whether they are SBIR or STTR) to accomplish their objectives. If awarded a Phase II, they receive \$750K over 24 months. Starting in FY12, NASA created the SBIR Select program which awards \$200K for Phase I and \$1.5M for Phase II. Starting in FY13, NASA is adding to new programs: Phase II-Enhanced (II-E) and Phase II-eXpanded (II-X). Under the Phase II-E program, the NASA SBIR office will match 1:1 eligible 'external' investment of up to \$125K and provide up to 12 months of additional performance period. Under the Phase II-X program, the NASA SBIR office will match 2:1 eligible 'external' investments of up to \$250K and provide up to 12

months of additional performance period. For example, the NASA SBIR/STTR program will match up to \$500K a \$250K investment from a non-SBIR/STTR NASA Source. Additionally, once a company has a Phase 1 contract, they can receive a Phase III contract without going through a competitive bidding process.

SBIR/STTR proposals used to be solicited in the summer, but NASA is shifting the call for proposals to late fall to better align the program with the federal budget cycle. The 2013 call for proposals is expected to be released the first week of November 2013. In 2012, NASA's SBIR program solicited proposals in Topics in Aeronautics Research, Human Exploration and Operations and Science (Table 1)

Table 1: NASA 2012 SBIR Solicited Research Topics	
Aeronautics Research	A1 Aviation Safety
	A2 Air Traffic Management Research and Development (ATM R&D)
	A3 Air Vehicle Technologies
Human Exploration and Operations	H1 In-Situ Resource Utilization
	H2 Space Transportation
	H3 Life Support and Habitation Systems
	H4 Extra-Vehicular Activity Technology
	H5 Lightweight Spacecraft Materials and Structures
	H6 Autonomous and Robotic Systems
	H7 Entry, Descent and Landing Technology
	H8 High Efficiency Space Power Systems
	H9 Space Communications and Navigation
	H10 Ground Processing and ISS Utilization
	H12 Human Research and Health Maintenance
Science	S1 Sensors, Detectors and Instruments
	S2 Advanced Telescope Systems
	S3 Spacecraft and Platform Subsystems
	S4 Robotic Exploration Technologies
	S5 Information Technologies

While optic and photonic technology can be enabling for the Aeronautics and Exploration topics, most optic technology investment is made in support of Science. Table 2 lists the topics and subtopics which seek to develop technology to enable science missions. The two topics most relevant to optical fabrication and testing technology are S2.03 Advanced Optical Component Systems and S2.04 Optics Manufacturing and Metrology for Telescope Optical Surfaces.

4.1 S2.03 Advanced Optical Systems

Consistent with all guidance documents, S2.03 'Advanced Optical Systems' solicits proposals to mature technologies to manufacture, test, coat or operate complete mirror systems for potential x-ray or UV/Optical missions.

Future x-ray missions required x-ray imaging telescopes with < 1 arc-sec angular resolution and greater than 1 to 5 m² collecting area (0.3 to 2 meter diameter mirror shells or segments); improved metrology, performance prediction and testing techniques; active control of mirror shape; and new structures for holding and actively aligning of mirrors in a telescope assembly. For individual mirror shells, axial slope errors should be ~ 1 arc-sec rms (~100 nm rms figure error for 20 mm spatial frequencies) and surface finish should be < 0.5 nm rms. And, total mass for the total integrated mirror system (shells and structure) should be < 1000 kg. Finally, multilayer gradient coatings are needed for potential future hard x-ray mirrors (similar to NuSTAR) with high broadband reflectivity for 5 to 80 keV energy photons.

Future UVOIR missions require 4 to 8 or 16 meter monolithic or segmented primary mirrors with < 10 nm rms surface figures. Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e. 15 kg/m² for a 5 m fairing EELV vs. 60 kg/m² for a 10 m fairing SLS). Future UVOIR missions also require coatings with broadband reflectivity > 60% and uniform polarization from 90 nm to 2500 nm which can be deposited onto a 2 to 4 to 8 meter mirror substrate. Additionally, the coatings need to have > 90% reflectivity from 450 nm to 2500 nm. Future EUV missions require coatings with reflectivity > 90% from 6 nm to 200 nm which can be deposited onto mirror substrates as large as 2.4 meters in diameter.

Table 2: NASA 2012 SBIR Science Topics and Sub-Topics

TOPIC S1 Sensors, Detectors and Instruments

- S1.01 Lidar Remote Sensing Technologies
- S1.02 Microwave Technologies for Remote Sensing
- S1.03 Sensor and Detector Technology for Visible, IR, Far IR and Submillimeter
- S1.04 Detector Technologies for UV, X-Ray, Gamma-Ray and Cosmic-Ray Instruments
- S1.05 Particles and Field Sensors and Instrument Enabling Technologies
- S1.06 Cryogenic Systems for Sensors and Detectors
- S1.07 In Situ Sensors and Sensor Systems for Lunar and Planetary Science
- S1.08 Airborne Measurement Systems
- S1.09 Surface & Sub-surface Measurement Systems

TOPIC S2 Advanced Telescope Systems

- S2.01 Proximity Glare Suppression for Astronomical Coronagraphy
- S2.02 Precision Deployable Optical Structures and Metrology
- S2.03 Advanced Optical Component Systems
- S2.04 Optics Manufacturing and Metrology for Telescope Optical Surfaces

TOPIC S3 Spacecraft and Platform Subsystems

- S3.01 Command, Data Handling, and Electronics
- S3.02 Power Generation and Conversion
- S3.03 Propulsion Systems
- S3.04 Power Electronics and Management, and Energy Storage
- S3.05 Unmanned Aircraft and Sounding Rocket Technologies

TOPIC S4 Robotic Exploration Technologies

- S4.01 Planetary Entry, Descent and Landing Technology
- S4.02 Robotic Mobility, Manipulation and Sampling
- S4.03 Spacecraft Technology for Sample Return Missions

TOPIC S5 Information Technologies

- S5.01 Technologies for Large-Scale Numerical Simulation
- S5.02 Earth Science Applied Research and Decision Support
- S5.03 Algorithms & Tools for Science Data Processing, Discovery & Analysis, in State-of-the-Art Data Environments
- S5.04 Integrated Science Mission Modeling
- S5.05 Fault Management Technologies

TOPIC E3 Select Science

- E3.01 Laser Transmitters and Receivers for Targeted Earth Science Measurements
- E3.02 Advanced Technology Telescope for Balloon Mission
- E3.03 Extreme Environments Technology

4.2 S2.04 Optics Manufacturing and Metrology for Telescope Optical Surfaces

This subtopic focuses primarily on manufacturing and metrology of optical surfaces, especially for very small or very large and/or thin optics. Optical systems of interest include extreme aspheric and/or anamorphic optics for pupil intensity amplitude apodization; segmented x-ray mirror systems spanning 60 degrees in azimuth, 200 mm axial length and cone angles from 0.1 to 1 degree.

Optical manufacturing technology is required to accurately figure and polish across six orders of magnitude in period. Technologies are sought that will enhance the figure quality of optics in any range as long as the process does not introduce artifacts in other ranges; low normal force figuring/polishing systems operating in the 1 mm to 50 mm period range with minimal impact at significantly smaller and larger period ranges; innovative methods of improving the figure of extremely lightweight and thin mirrors without polishing, such as using the coating stress.

Also, novel metrological solutions that can measure figure errors over a large fraction of the PSD range are desired, especially techniques and instrumentation that can perform measurements while the optic is mounted to the figuring/polishing machine. Interferometric nulling optics for very shallow conical optics used in x-ray telescopes. Also of interest is analytical software to process, fit, and model large optics surface metrology data with the goals to characterize surface morphology over spatial frequency bandwidths determined by the desired angular resolution performance; to provide stitched metrology capabilities obtained with different surface measuring instruments with

different fields of view and resolution; to provide a data analysis tool for defining the optical surface fabrication tolerances based on the desired x-ray optics angular resolution performance; to allow forecasting of the surface morphological properties of optics.

To make ultra-thin mirrors, innovative substrate materials or manufacturing methods that produce thin substrates that are stiffer and/or lighter than existing materials or methods are desired; large lightweight monolithic metallic aspheres manufactured using innovative mirror substrate materials that can be assembled and welded together from smaller segments; low stress metrology mounts that can hold optics without introducing mounting distortion; and innovative methods of bonding extremely lightweight (less than 1 kg/m² areal density) and thin (less than 1 mm) mirrors to a housing structure, preserving both alignment and figure.

4.3 Previous Optic Technology Investments

Since 2005, the two primary optic technology subtopics (S2.04 and S2.05) have funded a total of 65 Phase I contracts (from a total of 187 proposals for a 35% funding rate); and 22 Phase II contracts (from a total of 49 proposals for a 45% funding rate). Table 3 lists some of the Phase II optical fabrication related technology investments.

Table 3: 'sampling' of S2.04 and S2.05 Phase II Optical Manufacturing Technology Investments		
Year	Project	Company
2002	Ultra-Smooth Diamond Tooling for Machining Lightweight Mirrors	Diamond Materials
	Lightweight Active Nanolaminate Mirror	Xinetics
	Computer Controlled Optical Surfacing of Bare Beryllium Aspheric Optics	SSG Precision Optonics
2003	Integration of Full-Spectrum Metrology and Polishing for Rapid Production of Large Aspheres	Bauer Associates
	Large Segmented Optics Fabrication Using Magnetorheological Finishing	QED Technologies
	Highly Adaptive Primary Mirror Having Embedded Actuators, Sensors, and Neural Control	Xinetics
2004	Subaperture Stitching Interferometry for Large Convex Aspheric Surfaces	QED Technologies
	Rapid Damage-Free Shaping of Lightweight SiC Using Reactive Atom Plasma (RAP) Processing	RAPT Industries
2006	Nano-Enabled Low-Cost High-Performance UV Anti-Reflection Coatings	AGILTRON
2007	Affordable Pre-Finishing of Silicon Carbide for Optical Applications	Creare
2008	Low Cost Very Large Diamond Turned Metal Mirror	Dallas Optical Systems
	High Reflectivity, Broad-Band Silver Coating	Surface Optics Corp
	Low-Stress Iridium Coatings for Thin-Shell X-Ray Telescopes	Reflective X-ray Optics
	RAP Figuring Slumped Mirrors to Remove Mid-Spatial Frequency Errors	RAPT Industries
2009	Silicon Carbide Lightweight Optics With Hybrid Skins for Large Cryo Telescopes	Optical Physics Company
	Minimally Machined HoneySiC Mirrors for Low Areal Cost and Density	Trex
	Removing Mid-Spatial Frequency Errors with VIBE	Optimax Systems
2011	Optical Fabrication and Metrology of Aspheric and Freeform Mirrors	OptiPro Systems

5. RESEARCH OPPORTUNITIES IN SPACE AND EARTH SCIENCE (ROSES)

Research Opportunities in Space and Earth Sciences (ROSES) is how the NASA Science Mission Directorate (SMD) solicits basic and applied research in support of NASA's strategic goals:

- Advance Earth System Science to meet the challenges of climate and environmental change;
- Understand the Sun and its interactions with the Earth and the solar system;
- Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere; and
- Discover how the universe works, explore how it began and evolved, and search for Earth-like planets.

SMD pursues NASA's strategic outcomes using sub-orbital and space programs from Earth orbit to, or even beyond, objects in the solar system; and also through ground-based research activities. ROSES solicits proposals for ground-based supporting research and technology (SR&T) investigations that seek to understand naturally occurring space and Earth phenomena, human-induced changes in the Earth system, and Earth and space science-related technologies and to support the national goals for further robotic and human exploration of space. ROSES covers all aspects of basic and applied supporting research and technology in space and Earth sciences, including, but not limited to: theory, modeling, and analysis of SMD science data; aircraft, stratospheric balloon, suborbital rocket, International Space Station, and suborbital reusable launch vehicle investigations; development of experiment techniques suitable for future SMD space missions; development of concepts for future SMD space missions; development of advanced technologies relevant to SMD missions; Earth surface observations and field campaigns that support SMD science missions; etc.

SMD activities are organized into four Research Programs (aligned to NASA's strategic goals):

- The Earth Science Division sponsors research to explore interactions among major components of the Earth system, to distinguish natural from human-induced causes of change, and to understand and predict the consequences of change.
- The Heliophysics Division sponsors research to understand the Sun as a magnetic variable star and its effects on the Earth and other planets, and the dynamics of structures in the solar system.
- The Planetary Science Division sponsors research to explore the solar system to study its origins and evolution, including the origins of life within it.
- The Astrophysics Division sponsors research to explore the universe beyond, from the search for planets and life in other solar systems to the origin, evolution, structure, and destiny of the universe itself.

Each SMD Division (Astrophysics, Earth Science, Heliophysics and Planetary Science) solicits proposals for Advanced Component Technology and Instrument Development to enable their specific science measurement needs. Frequently, the advanced components needed to enable future instruments require optics and photonics technology (detectors, dispersion gratings, spectral filters, wavefront sensors, deformable mirrors, optical elements, optical coatings, etc.). For Astrophysics, most optics related technology development is funded via either the Astrophysics Research and Analysis (APRA) or Strategic Astrophysics Technology (SAT) programs. In general, APRA funds early-TRL (TRL 1-3) and SAT funds mid-TRL (TRL 4-6) technology development. Please note, all proposals must clearly explain why their technology is relevant to or will help enable a specific high-priority SMD science measurement need.

Awards range from under \$100K per year for focused, limited efforts (e.g., data analysis) to more than \$1M per year for extensive activities (e.g., development of science experiment hardware). The typical period of performance for an award is three to five years. In Fiscal Years 2012 (FY12), the APRA program spent about \$20M on detectors and supporting technology development, and about \$23.5M on suborbital flight payloads (including technology demonstrations); SAT spent \$10 to \$15M. Organizations of every type, domestic and foreign, Government and private, for profit and not-for-profit, may submit proposals without restriction on teaming arrangements. But, it is NASA policy that all investigations involving non-U.S. organizations must be conducted with no exchange of funds.

For more information about ROSES, go to <http://nspires.nasaprs.com/> and subscribe to the SMD notification system. And, for more information about NASA's strategic vision, go to <http://nasascience.nasa.gov/about-us/science-strategy>.

5.1 Astrophysics Research and Analysis Program (APRA)

The Astrophysics Research and Analysis Program (APRA) program solicits basic (i.e. TRL 1-3) research proposals for investigations that are relevant to NASA's programs in astronomy and astrophysics and includes research over the entire range of photons, gravitational waves, and particles of cosmic origin. APRA seeks to support research that addresses the best possible (i) state-of-the-art detector technology development for instruments that may be proposed as candidate experiments for future space flight opportunities; (ii) science and/or technology investigations that can be carried out with instruments flown on suborbital sounding rockets, stratospheric balloons, or other platforms; and (iii) supporting technology, laboratory research, and/or (with restrictions) ground-based observations that are directly applicable to space astrophysics missions. While the solicitation of detector technology development is explicit, proposals for the development of optics, mirrors, coating or grating technology is specifically solicited in 'Supporting Technology'.

5.2 Strategic Astrophysics Technology Program (SAT)

The Strategic Astrophysics Technology (SAT) program supports focused development of key technologies needed to enable major missions in the three science themes of the Astrophysics Division (Exoplanet, Cosmic Origins or Physics of the Cosmos). The SAT program is designed to support the maturation of technologies whose feasibility has already been demonstrated (i.e., TRL 3), to the point where they can be incorporated into NASA flight missions (TRL 6-7). Sometimes referred to as the "mid-TRL gap," funding for such intermediate TRL development activities has historically been problematic because technologies in this regime are sufficiently mature that they are ill suited to funding under basic research programs. The problem of the mid-TRL gap was of sufficient concern that an enhancement in funding specifically targeted at mid-TRL development is included among the Small Project recommendations in Astro2010.

SAT solicits proposals in three science areas:

- Technology Development for Exoplanet Missions (TDEM)
- Technology Development for Physics of the Cosmos Program (TPCOS)
- Technology Development for the Cosmic Origins Program (TCOR)

Technology Development for Exoplanet Missions (TDEM) supports the maturation of key technologies to enable searching out and characterizing extrasolar planets and planetary systems. TDEM solicits investigations that will undertake focused development of starlight suppression techniques and wavefront sensing and control technologies to enable direct detection of exoplanets (coronagraphy, external occulters, interferometry). Detailed discussions of the current technology needs in the relevant areas can be found in the Exoplanet Exploration Program Technology Plan, which can be downloaded at <http://exep.jpl.nasa.gov/reportsAndDocuments>. Prospective SAT/TDEM proposers are strongly encouraged to review this document before preparing their proposal, as it reflects the programmatic considerations that will be taken into consideration in the review and selection of TDEM submissions.

Technology Development for Physics of the Cosmos Missions (TPCOS) supports technology needed to enable missions which seek to understand the origin and destiny of the Universe, phenomena near black holes and the nature of gravity (missions directed at advancing the fields of cosmology, high-energy astrophysics and fundamental physics). TPCOS solicits efforts to mature technologies for: (1) X-ray Astrophysics, including, but not limited to, high-resolution microcalorimeter arrays, lightweight replicated optics and precision structures, high-resolution gratings (both transmission and reflection); (2) Gravitational Wave Astrophysics, including, but not limited to dimensionally stable, optical telescopes, frequency-stabilized metrology lasers, high-resolution phasemeters, low-noise microthrusters, ultra-quiet inertial references, and long-distance laser metrology techniques; and (3) CMB Polarization Measurements, including, but not limited to, high-throughput cold mm-wave telescopes and large low-background multiplexed arrays of detectors. Detailed discussions of current PCOS technology needs can be found in the PCOS Program Annual Technology Report, which is available from the PCOS Program web site at <http://pcos.gsfc.nasa.gov/>. Prospective SAT/TPCOS proposers are urged to review this document before preparing their proposals.

Technology Development for the Cosmic Origins Program (TCOR) supports technology needed to investigate how planets, stars, galaxies, and cosmic structure come into being and when and how the elements of life in the Universe arose. Detailed discussions of current Cosmic Origin (COR) technology needs can be found in the COR Program Annual Technology Report (PATR) at: <http://cor.gsfc.nasa.gov>. First and second priorities for areas of long-lead and mission enabling technology development that are of particular interest to the Cosmic Origins Program include: (1) highly-sensitive large-array low-noise detectors from the extreme ultraviolet to the far-infrared; (2) improved broad-band reflective and anti-reflective ultraviolet optical coatings with particular emphasis on 90 to 130 nm; and (3) precision large optic, heterodyne receivers and cryocoolers.

COR missions rely heavily on their ability to collect enough light energy with appropriate angular resolution. Therefore, a premium is placed on the ability to develop scalable manufacturing techniques, including the testing and control optics of sizes up to at least ~4 meters in diameter. Keys to advancements in this arena are new techniques and technologies for reducing areal density of optics, production times, and cost; manufacturing ultra-precise, low-mass structures to reduce launch volume for large-aperture space telescopes and interferometers; operation at short wavelengths; and mechanisms and methods for improving control of the surface figure.

6. SPACE TECHNOLOGY RESEARCH OPPORTUNITIES

The Office of the Chief Technologist (OCT) Space Technology Research Opportunities (STRO) program fosters the development of innovative, low-TRL technologies that have the potential to lead to dramatic improvements at the system level – performance, weight, cost, reliability, operational simplicity or other figures of merit associated with space flight hardware or missions. The goal of this low-TRL endeavor is to accelerate the development of groundbreaking, high-risk/high-payoff space technologies, not necessarily directed at a specific mission, to support the future space science and exploration needs of NASA, other government agencies, and the commercial space sector. Such efforts complement the other NASA Mission Directorates' focused technology activities which typically begin at TRL 3 or higher. The TRL of the efforts to be funded as a result of this call will be TRL 1 or TRL 2 at the beginning of the selected effort and TRL 2 or TRL 3 at the end of the effort. Proposals are solicited from accredited US universities. Typical award amounts are \$250K per year for a maximum of two years.

In 2012, the STRO program solicited proposals for two optical technologies (in support of TABS 8.1.3): active wavefront control and grazing incidence optical systems.

The active wavefront control topic sought advanced technologies to enable a new generation of active space-based optical systems that sense and correct wavefront aberrations and mechanical misalignments caused by launch, deployment and the thermal space environment. Larger space telescopes are required for future advances in astrophysics where a large collecting area and high angular resolution are needed to study faint and distant sources. Optical telescopes with aperture sizes exceeding the dimensions of available launch vehicle fairings drive the need for deployable mirror systems with extremely precise alignment tolerances. Technologies are needed that will enable autonomous alignment and phasing of next-generation large telescopes after deployment in space. Technologies that simplify integration and reduce testing requirements during telescope development and that enable wavefront modulation, such as starlight suppression, are of interest.

The grazing incidence optical system topic sought advanced technology to enable the manufacture mirror systems for next generation x-ray astronomy missions which require an order of magnitude improvement in spatial resolution while maintaining system mass at suitable levels. Technologies that enable precision fabrication, alignment, spacing, and replication are sought. As an example, it is envisioned that future x-ray telescope systems will be comprised of thousands of mirror segments, driving the need for efficient, low-risk, cost-effective techniques for fabrication, mounting, and alignment of these systems. Advanced coatings, reflectors, and other technologies for directing and focusing high-energy particles are of interest. Because mechanical misalignments in the telescope will result from the launch environment, changing gravitational conditions of orbit vs. ground-based fabrication and testing, and on-orbit thermal variations, technologies that enable active alignment and figure control of grazing-incidence optical system elements to correct these misalignments are of particular interest.

In 2013, the STRO program solicited proposals for ‘Optical Coatings and Thin-film Physics’ to identify and develop novel optical coatings for high-reflection in the Lyman ultraviolet wavelengths which can be applied to >2 meter mirrors or for anti-reflections coatings at millimeter to far-infrared wavelengths which can be applied to >30 cm mirrors.

This topic sought to break new ground on advanced technologies (currently at TRL 1 or 2) for UV space-flight optical coatings. Specifically, coatings are desired which have ~80% reflectivity across the Lyman ultraviolet or >97% reflectivity at 120-300 nm. The next generation of high-quantum efficiency (QE) detectors used in large focal plane arrays demand accurate reflective and anti-reflective (AR) coatings capable of performing with minimal flux losses, free of scattering and polarization effects. Reflective coatings for visible and ultraviolet wavelengths have been in use for the last 40 years. However, these coatings (e.g., LiF, MgF₂, CaF₂, LaF₃), typically used with aluminum substrates, have demonstrated serious, potentially insurmountable limitations, especially around shorter wavelengths such as the Lyman- α region ($90\text{ nm} < \lambda < 125\text{ nm}$). The wealth of lines in the Lyman ultraviolet exceeds that in the rest of the UV and visible combined, and yet this is a very understudied portion of the spectrum due to the low coating throughput. Better coatings would make revolutionary discoveries in this wavelength range, including discovering the missing matter around galaxies and potentially characterizing the atmospheres of exoplanets.

Additionally, future Cosmic Microwave Background (CMB) missions utilizing polarization-sensitive sensors demand AR coatings that can operate at cryogenic temperatures with high performance at wavelengths from the far-infrared to millimeter. Coatings having low reflectance, low loss, and broad bandwidth, or with improved fabricability on high-index materials such as silicon and sapphire could improve optical designs for these missions.

The field of optical coatings demands disruptive solutions derived from first principles of thin-film physics. The current known coatings materials and deposition techniques will not produce the performance and quality desirable to match the next generation of high sensitivity detectors. The use of novel materials (for instance, using approaches such as plasmonic nanomaterials for the UV or metamaterials for the millimeter to far-infrared) can provide a radical advance to fill these needs. All SMD divisions require these solutions; however, Astrophysics is in more urgent need due to the faint signals that must be measured to achieve the compelling science goals at UV and far-IR through millimeter wavelengths. Advances in these technologies will lead to the understanding of the first moments of the universe, the characterization of galaxy evolution across cosmic time, and the characterization of newly found exoplanets.

7. CONCLUSIONS

Per the 2012 National Research Council “NASA Space Technology Roadmaps and Priorities: Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space”, Optical System technology is required to meet several of NASA’s Top Technical Challenges: next generation of large-aperture astronomical telescopes, lightweight laser communication systems, and high-performance orbiting observatories for planetary missions. And, two specific game-changing capabilities were identified which require optical fabrication and testing technology development: lightweight grazing-incidence optical systems for x-ray astronomy with spatial resolution < 0.1 arc-seconds; and normal-incidence mirrors with diameters of four meters and beyond that operate to wavelengths as low as 30 nm.

As defined in the “NASA Strategic Space Technology Investment Plan”, Scientific Instruments and Sensors technology is one of 7 Core Technologies indispensable for NASA’s present and planned future missions. Over the next four years, NASA will invest in observatory technologies with improved performance and angular resolution, and reduced weight and cost. Specific emphasis will be on large mirror systems and structures. Potential large mirror investments include x-ray mirrors, lightweight mirrors, ultraviolet coatings and segmented mirrors. Potential structure investments include passive and active ultra-stable structures, and deployable telescopes and booms.

NASA is actively investing in optic and photonic technologies through multiple programs including: SBIR/STTR; SMD’s Research Opportunities in Space and Earth Science (ROSES) which includes APRA (Astrophysics Research and Analysis), SAT (Strategic Astrophysics Technology), ESTO (Earth Science Technology Office); and the OCT’s NASA Innovative Advanced Concepts (NIAC) and Space Technology Research Opportunities (STRO).

Finally, for detailed information about the current technology needs and the prioritization of these needs for astrophysics, please see the three Astrophysics Division Program Offices (Exoplanet Exploration, Physics of the Cosmos and Cosmic Origins) Program Annual Technology Report (PATR).¹¹⁻¹³

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