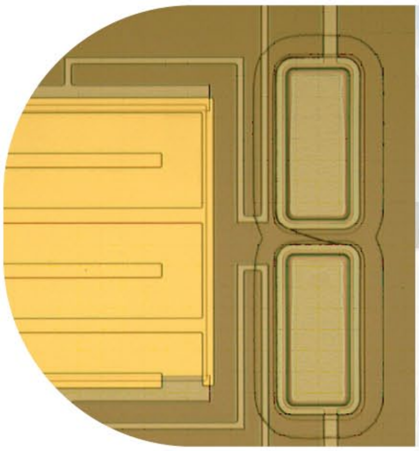
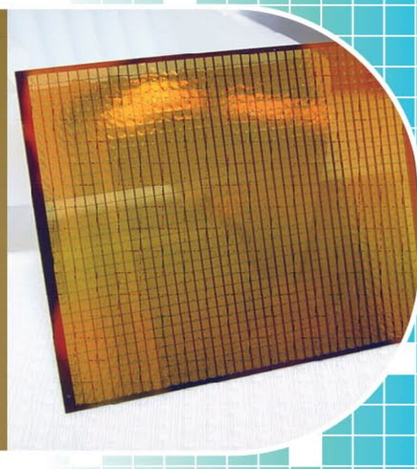
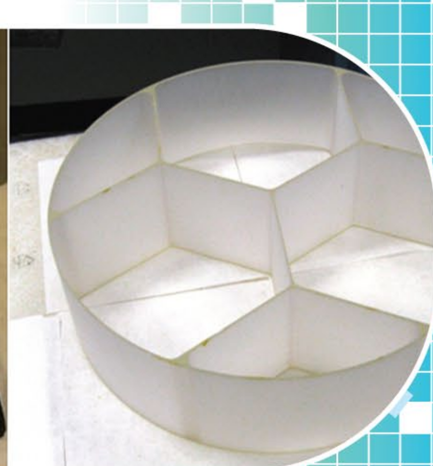
National Aeronautics and Space Administration

Cosmic Origins
Program Annual Technology Report





Cosmic Origins
Program Office
November 2012



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Executive Summary

Welcome to the second Program Annual Technology Report (PATR) for the Cosmic Origins (COR) Program of the NASA Astrophysics Division. This report is the annual summary of the technology development activities of the COR Program for the fiscal year (FY) 2012. This document serves two purposes. First, it summarizes the program technology needs identified by the science community and the results of this year's prioritization of the technology needs by the Program Technology Management Board (TMB). Second, it provides a summary of the current status of all the technologies that were supported by the COR Supporting Research and Technology (SR&T) funding in FY12, including progress over the past year and planned development activities for this coming year. The COR Program Office resides at the NASA Goddard Space Flight Center (GSFC) and serves as the implementation arm for the Astrophysics Division at Headquarters (HQ) for COR Program related matters. Responsibility for generating this PATR rests with the Advanced Concepts and Technology Office (ACTO), within the COR Program Office (PO).

The COR PO seeks to shepherd critical technologies for NASA toward the goal of incorporation into project technology development plans. These technologies can then serve as the foundation for robust mission concepts so that the community can focus on the scientific relevance of the proposed missions in subsequent strategic planning. The available COR SR&T FY12 funding is being used efficiently, as is evidenced by the noteworthy progress of development activities described in Section 2. The technology development status reports captured in Section 2 cover a number of efforts continued from earlier fiscal years as well as new efforts initiated in 2012. The new efforts were selected competitively through the Strategic Astrophysics Technology (SAT) solicitation.

The technology needs prioritization process described in Sections 3 and 4 was essentially unchanged from last year. It again provided a rigorous, transparent ranking of technology needs based on the Program's goals, community scientific rankings of the relevant missions, the state of available technologies, and the external programmatic environment. The goals for the COR Program are driven by the National Academy of Sciences National Research Council's (NAS/NRC) "New Worlds, New Horizons in Astronomy and Astrophysics" (NWNH) Decadal Survey report, released in 2010. The relevant recommendations, among other priorities, include augmentation of Explorers, the definition of a future ultraviolet-visible space capability, and a NASA participation in the Japanese Aerospace Exploration Agency/ Institute of Space and Astronautical Science (JAXA/ISAS) Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission. Broadly, the definition of a future UV-visible space capability includes both mission trade studies for potential means of satisfying the NWNH goals of imaging and spectroscopy at UV wavelengths to study topics ranging from the hot gas between galaxies through stars and the interstellar medium to exoplanets, and the support of technology development benefitting such future UV telescopes. We note that while WFIRST is formally part of the Exoplanet portfolio, relevant IR detector technologies also drive the COR Program due to the strong overlap in science goals.

Section 3 of this report summarizes the technology needs collected with the support of the COR Program Analysis Group (COPAG) during FY11–12. For this year, the program technology needs list includes submissions received last year and a few new ones. The list includes technology needs related to UV, visible, and IR missions, and consists of technology needs in detector, mirror, UV coating, telescope, interferometry, spectrometry, and cryocooler technologies.

The results of the TMB technology needs prioritization are included in Section 4. The prioritization process is a rigorous ranking of the program technology needs in 11 weighted criteria. The technology needs are categorized into three priority groups. These groups describe the relative importance of the technologies to the COR science objectives and the urgency of the need. The TMB determined the following technology areas to be Priority 1, representing the highest interest to the Cosmic Origins Program at this time. The TMB recommends that they **should** be invested in first, when funding is available. The Priority 1 technology areas are:

- High quantum efficiency, large-format UV detectors
- Photon counting, large-format UV detectors
- High reflectivity UV coatings
- Ultra-low-noise far-IR direct detectors

The Board categorized the rest of the technology needs into Priorities 2 and 3. Priority 2 contains technology activities that the Board feels are worthy of pursuit and **would** be invested in, if additional funding allows. Priority 3 technologies are deemed to be supportive of COR objectives, but for various reasons they do not warrant investment at the present time. However, they **could** be invested in, if significant additional funding is available.

The prioritization results will be referenced by the Program over the upcoming year as the calls for technology development proposals are drafted and investment decisions are made. The Board is cognizant that investment decisions will be made within a broader context and that other factors at the time of selection may affect these decisions. As with last year, this technology needs prioritization will be forwarded to other NASA programs (e.g., Small Business Innovation Research, or SBIR) and other Office of the Chief Technologist (OCT) technology development planning groups as requested.

During the implementation of the technology development process, the Program Office strives to: 1) improve the transparency of the prioritization and selection process by maintaining an open forum for community input, and providing the information in this PATR; 2) ensure the development of the most relevant technologies; 3) inform the community of current technology development investments and their progress; 4) inform the community of the process by which the PO technology development needs are identified and prioritized; 5) ensure that the community has opportunities to provide input to and receive feedback about the prioritization process; 6) inform the community of what the PO considers its highest technology needs; 7) leverage the technology investments of external organizations by defining technology needs and a customer in order to encourage non-NASA technology investments that will benefit COR science.

A key objective of the technology development process is to formulate and articulate the needs of COR future missions. Through a process of careful evaluation of the technologies proposed for development, the PO determines which technologies will meet its needs and then prioritizes them in order of its merit-based ranking for further development consideration. The PO then provides its recommendation to NASA HQ, in the form of this PATR, in an effort to aid decision makers in the process that ultimately results in the funding of selected technologies.

1 Program Overview

The goal of the COR Program is to understand the origin and evolution of the universe from the Big Bang to the present day. On the largest scale, COR's broad-reaching science question is to determine how the expanding universe grew into a grand cosmic web of dark matter enmeshed with galaxies and pristine gas, forming, merging, and evolving over time. COR also seeks to understand how stars and planets form from clouds in these galaxies to create the heavy elements that are essential to life—carbon, oxygen, nitrogen, and others—starting with the first generation of stars to seed the universe with trace amounts of these materials, so common on Earth today, and continuing up through the birth and death of stars even now. Much of the familiar study of astronomy during the past century falls within the purview of Cosmic Origins.

The Science Mission Directorate of NASA acknowledged the continued importance of this scientific field by establishing the Cosmic Origins Program Office in 2009 within the Astrophysics Division. In August 2011, the Agency Program Management Council confirmed the COR Program to proceed into the implementation phase. This is the second Program Annual Technology Report (PATR) following the beginning of the Program.

The COR Program Office, while acting as the Program implementation arm of HQ, is located at NASA's Goddard Space Flight Center. A primary function of the Program Office is to develop and administer an aggressive technology maturation program. In order to achieve this end, and along with the Physics of the Cosmos (PCOS) Program, an Advanced Concepts and Technology Office (ACTO) has been chartered to facilitate, manage, and promote the technology policies of both the COR Program and the PCOS Program. The ACTO coordinates the infusion of technologies into COR and PCOS missions, including the crucial phase of transitioning a wide range of nascent technologies into targeted project mission technology development plans when a project is formulated.

The ACTO oversees technology developments applicable to COR missions, funding for which is supported by the COR Supporting Research and Technology (SR&T) budget. The PATR is the annual comprehensive summary detailing the technologies currently being pursued and supported by COR SR&T. It also outlines a view, as of late 2012, of the COR prioritization for future technology needs.

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1.1 Background

The COR Program encompasses a diverse set of science missions aimed at meeting Program objectives, wherein each mission has unique science capability. The Program was established to integrate space, suborbital, and ground activities into a cohesive effort that enables each project within the Program to build upon the technological and scientific legacy of both its contemporaries and predecessors. The following current and future projects are shepherded commonly in support of the Cosmic Origins science goals. Each project operates independently to achieve its unique set of mission objectives, which contribute to the overall Program objectives. In 2012, the operating missions in the COR Program Office portfolio are:

- *Hubble Space Telescope* (HST)
  The launch of HST in 1990 began one of NASA's most successful and long-lasting science missions. It has beamed over a million observations back to Earth, shedding light on many of the great mysteries of astronomy. Its gaze has helped determine the age of the universe, peer into the hearts of quasars, study galaxies in all stages of evolution, find protoplanetary disks where gas and dust around young stars are birthing grounds for new planets, and provide key evidence for the existence of dark energy.

- *Spitzer Space Telescope*
  The final mission in NASA's Great Observatories Program, Spitzer's launch in 2003 has provided sensitive infrared instruments that allow scientists to peer into cosmic regions that are hidden from optical telescopes, such as dusty stellar nurseries, the centers of galaxies, and newly forming planetary systems. Many of its observations have focused on objects that emit very little visible light, including brown dwarf stars, extrasolar planets, and giant molecular clouds.

- The U.S. component of the European Space Agency's (ESA) *Herschel Space Observatory*
  Herschel is an ESA-led mission with a large cryogenic space telescope that is studying the light of the Universe in the far-infrared and submillimeter portions of the spectrum. It is revealing new information about the earliest, most distant stars and galaxies, as well as those forming and evolving closer to home. NASA contributed significant portions of the instrumentation for Herschel and contributes to the data and science analyses, which largely support COR science goals.

- *Galaxy Evolution Explorer* (GALEX)
  The GALEX mission has since 2003 been conducting a wide imaging survey in two ultraviolet bands, intended to trace the history of star formation 80 percent of the way back to the Big Bang. In May 2012 operations of GALEX were transferred to the California Institute of Technology in a novel agreement to lend this unique resource for a private, nonprofit science application.

In 2012, the COR Program Office development portfolio includes:

- COR Supporting Research and Technology (SR&T)
  The COR PO manages the investment of SR&T funds in a variety of avenues to advance COR technology needs. Section 2 of this PATR details the recent progress of those that were funded during the 2012 fiscal year.

- Future Mission Concept Development
  The COR PO conducts mission concept studies to assist in scoping future activities including technology development priorities and plans. During the 2012 fiscal year, progress was made on several studies related to COR missions. These include a study for a HST disposal mission planned for then 2020s, a study of potential NASA contributions to the JAXA SPICA mission, and several activities related to a future UV/visible mission to bring new capabilities to the astronomical community in a post-HST and post-GALEX era.

The following missions, currently under development, satisfy important COR science objectives although they are not managed within the COR Program:

- *Stratospheric Observatory For Infrared Astronomy* (SOFIA)
  A partnership between NASA and the German Aerospace Center (DLR), SOFIA is the world's largest airborne observatory, performing imaging and spectroscopy across the infrared spectrum. The SOFIA Program Office and aircraft are based at NASA's Dryden Flight Research Center (DFRC), with Science and Mission Operations based at NASA's Ames Research Center (ARC). SOFIA represents an important platform for development of COR technologies that may be applicable to future space missions, and therefore SOFIA science objectives are considered in relation to the applicable criteria described in Section 4 of this PATR.

- *James Webb Space Telescope* (JWST)—Science upon operations
  A partnership between NASA and ESA, JWST is the largest mission under development in the Science Mission Directorate. Among other purposes, it will provide near- and mid-infrared investigations of the earliest observable objects in the universe. JWST operations will be managed under the COR Program upon transition to Phase E after JWST's launch in 2018.

In support of the COR Program objectives, the Program Office is responsible for ensuring that NASA is positioned technologically to continue mission developments into the future to advance the broad scope of COR science goals. Accordingly, the Program is charged with overseeing the science of missions in formulation, implementation, and operations, as well as the maturation of technologies in development for these missions.

During the time since authorization to formulate the Program was granted in 2009, fiscal constraints have become more restrictive than anticipated, and priorities were redefined when the NRC released its Decadal Study for Astronomy and Astrophysics. The NRC's NWNH report has resulted in the COR Program shifting its focus to ardent technology development and mission concept studies which support the scientific priorities identified in NWNH.

In its NWNH report, the NRC placed a high value on the COR science missions relating to Cosmic Dawn (the science theme closely identifiable with COR). With JWST still in development, the NRC-prioritized recommendations did not include a specific named NASA-led mission that fit solely within the COR Program; however, it did include a conspicuous NASA contribution to the JAXA SPICA. The NRC also stridently recommended an augmentation to the Explorer Program that supports Astrophysics with rapid, targeted, competed investigations. This recommendation provides an additional robust vehicle to accomplish COR science (four of the six MIDEX/SMEX missions launched in the past 15 years primarily support COR objectives). The COR Program is committed to managing the available funds strategically and establishing partnerships, when possible, to maximize the benefits of its investments and to ensure that the Program will foster missions that continue to accomplish Program objectives. Key to this effort is tactically advancing enabling technologies to conduct COR science.

With the conclusion of the Space Shuttle Program in 2011, the safe re-entry or disposal of HST is a requirement for NASA (and a necessary use of Program resources to conclude the life-cycle of this great observatory). Accordingly, the COR Program Office has led the effort to study the options and develop plans for accomplishing this feat. The COR Program Office anticipates the resulting technology advancements can be designed into future missions for low-cost, end-of-life solutions. Additionally, the COR Program Office has investigated the possibility of carrying out the HST Disposal mission in conjunction with the deployment of new space assets to fulfill other Agency scientific or technical objectives.

The COR Program Office is leading a study to prepare for the next UV/visible astrophysics mission. The NWNH report recommends the development of a large ultraviolet and visible mission to continue and extend the science done with *Hubble*, conceived of as a 4m-class mission covering wavelengths shorter than *Hubble's* key range. The COR Program Office has undertaken to study a broader range of possible future endeavors, beginning with a recent Request for Information (RFI) for science objectives and requirements for any UV/visible astrophysics requiring future capabilities. A set of 34 responses from this RFI is available for information at the COR website (http://cor.gsfc.nasa.gov/). A very well attended community workshop was held in September 2012 to begin the process of developing a consensus set of science objectives and requirements. The overall goal is to assimilate multiple COR science investigations with closely related telescope or instrument performance needs and likely implementation choices. In the near term, the requirements will help guide the prioritization of COR SR&T technology development needs. A variety of mission concepts will likely be developed that trace back to these science objectives. These may include both large and modest concepts. The modest concepts are likely to focus on sensitive multi-object UV spectroscopy, but including broader UV/visible imaging capability, thereby being suitable for general astrophysics at UV and visible wavelengths.

During the past year, the COR Program Office has conducted an additional study to determine the feasibility of participation with Japan on an instrument contribution to the SPICA mission, currently slated for launch in 2022. In accordance with the NWNH recommendation that a SPICA contribution be undertaken only if affordable, near-term budget limitations have been a key factor in constraining NASA's ability to participate. The COR Program Office has considered approaches for a budget-constrained straw-man NASA contribution to SPICA. Additionally, a technology management board was convened under COR auspices to review the readiness level (and implicitly the development risk) of proposed SPICA instruments for NASA to provide, finding them requiring additional time and funding to reach sufficient readiness to begin a flight build. A decision on NASA's use of the instrument allocation has been requested by JAXA in early 2013, which requires a decision to be made soon on the presence and scope of a NASA contribution. Given budgetary pressures, the only mechanism for this contribution must come through the near-term Mission of Opportunity funding option. In the event that a NASA contribution to SPICA does not materialize through this independent competitive selection, the COR Program Office intends to coordinate with the far-infrared community in seeking alternate ways of meeting the science goals outlined for a NASA SPICA contribution.

The SOFIA mission, currently entering Science Cycle 1, provides a platform for observations across the infrared spectrum. The recently selected upgrade to SOFIA's High-resolution

Airborne Wide-bandwidth Camera (HAWC) includes the installation of new far-infrared detectors, providing one example of how COR technology development (and the associated funding) can be handed off to a flight project once the appropriate technology readiness level (TRL) is reached.

1.2 COR Program Technology Development

The COR SR&T funds support a variety of technology developments that are determined to be necessary for the advancement of COR science missions. Strategically, the COR Program Office inherits the mantle of the NWNH via its adoption of the prioritized complement of missions and activities to advance the set of COR science priorities. This strategic vision comes principally from NWNH, but also secondarily from the related NRC documents such as the "Report on the Panel on Implementing Recommendations from New Worlds, New Horizons Decadal Survey," "Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics," "Space Studies Board Annual Report 2010," and "An Enabling Foundation for NASA's Space and Earth Science Missions." The COR Program PATR is intended to be an open and available source for the public, academia, industry, and the government to learn about the status of the enabling technologies required to fulfill the COR Program science goals.

The COR technology management plan details the process that strategically identifies COR technology needs, enables the maturation of those technologies in a prioritized fashion, and inserts them into new missions responsively. The process diagram (Fig. 1.2–1) illustrates the annual cycle by which this is achieved. Starting at the left, science needs and requisite technologies are derived from the current astronomy community environment, and are intromitted (by means of many public fora, but in particular the COPAG workshops) into the NASA advisory chain. The COR Program Office is aware of these science needs independent of the COPAG, as all such presentations and deliberations are public.

The COPAG provides analyses through the NASA Advisory Council process. Meanwhile, the COR Program Office convenes its Technology Management Board (TMB), which prioritizes the technologies and publishes them annually in this PATR. The TMB recommends these priorities to NASA HQ, which solicits proposals for technology development. Principally, this is embodied by the Strategic Astrophysics Technology (SAT) portion of the astrophysics grant opportunity portfolio, which explicitly inherits the priorities enunciated in the COR PATR. Grants are awarded to technology developers, who submit annual progress reports that are reviewed by the TMB and become a portion of this PATR. Technological progress also changes the landscape of the requirements for the science needs, and so this process is repeated annually to ensure continued currency of the priorities.

Public outreach and science advocacy activities are conducted regularly by the COR Program Office to ensure that both the general public and the broad astronomy community is informed of these developments. It is expected that new starts for missions will lead technologies out of this management process and into project-specific technology development efforts.

The external scientific and technology communities are key stakeholders for the Program technology development activities. The community participates in the Program technology process in multiple ways, including through the COPAG workshops held by the Program in conjunction with specific studies and as developers through responses to solicitations. These workshops provide a mechanism for including community input into the Program technology process.

Technology Process Diagram

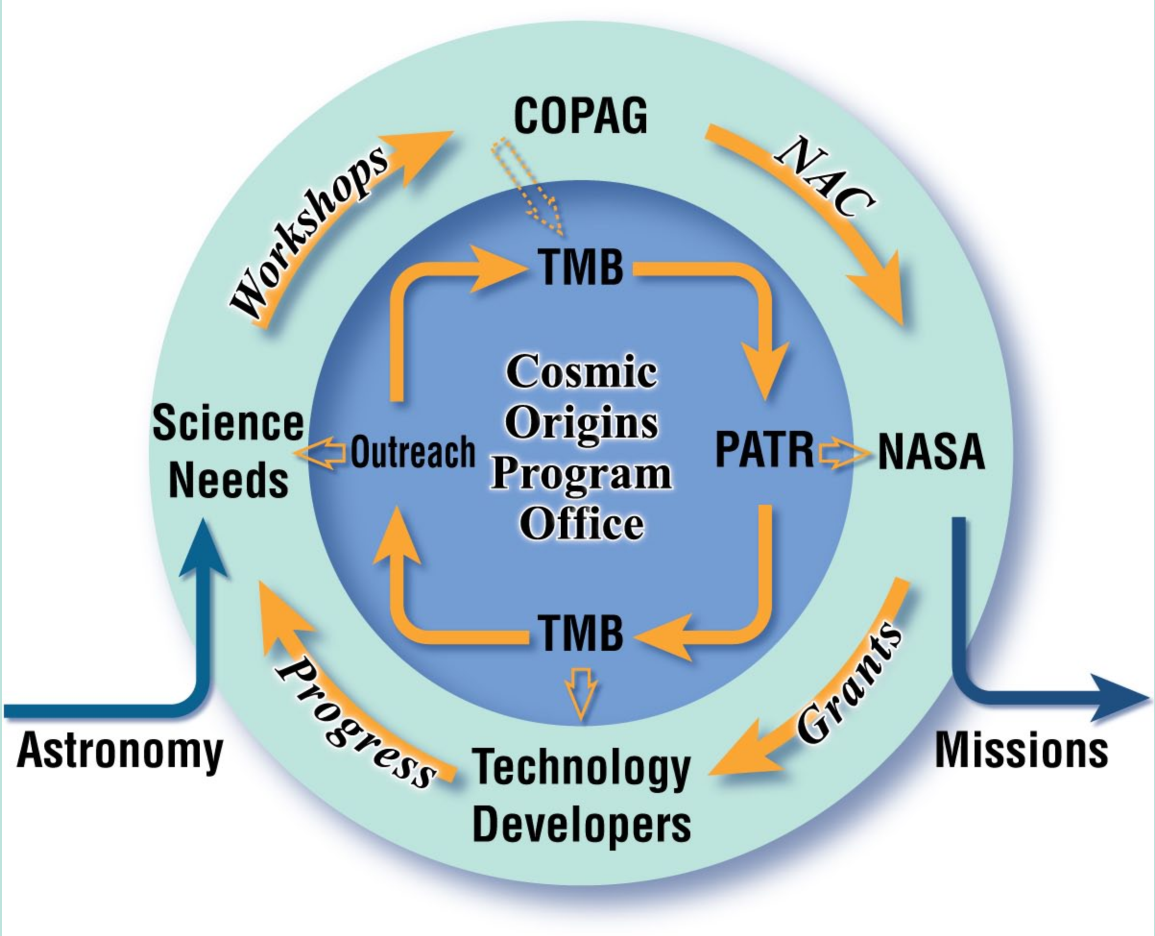

Figure 1.2–1. *This diagram illustrates the COR annual technology management process.*

2 Technology Status: Strategic Instrument Technology Development

FY12 Program Strategic Technology Development

This section describes the current technology development status, progress over the past year, and planned development activities for all the technologies that were supported by COR SR&T funding in FY12. These include detector, UV coatings, and mirror technologies that may enable or significantly enhance a COR science mission. This section provides technology overviews and is not intended to provide technical detail for flight implementation. Additional information can be obtained by contacting the Principal Investigator (PI) directly. The specific technology readiness levels (TRL) for each technology have been omitted by design, because the TRLs for each technology have yet to be vetted by the COR Program Technology Management Board (TMB). Table 2–1 lists the technologies that received Program funding for development work in FY12. Table 2–1 also shows the respective PI leading the technology development, their work institution, and the section in this report where their work is described.

Report Title	PI	Institution	See Section
Heterodyne Technology Development for SOFIA	P. Goldsmith	JPL	2.1
SOFIA Technology Development: Far-Infrared Large Format Array Detectors	H. Moseley	GSFC	2.2
Enhanced MgF_2 and LiF Overcoated Al Mirrors for FUV Space Astronomy	M. Quijada	GSFC	2.3
Cross Strip Microchannel Plate Detector Systems for Spaceflight	J. Vallerga	UC Berkeley	2.4
Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes	P. Stahl	MSFC	2.5

Table 2–1. *COR Strategic Technology Developments Funded in FY12.*

Strategic Astrophysics Technology Selections for FY13 Start

The latest selection of proposals for funding under the COR Strategic Astrophysics Technology (SAT) solicitation was announced in August 2012. This selection was based on the following factors: 1) the overall scientific and technical merit of the proposal; 2) the programmatic relevance of the proposed work; and 3) the cost reasonableness of the proposed work. These technologies have recently been selected for funding and have not yet begun work, and hence each project's status is not presented here. Their progress in the first year will appear in this section in the 2013 PATR. Table 2–2 lists the technologies, along with their respective PIs and their institutions, approved to start development in FY13 under the COR SAT award.

Proposal Title	PI	Institution	Area
Ultraviolet Coatings, Materials and Processes for Advanced Telescope Optics	K. Balasubramanian	JPL	UV Coatings
Kinetic Inductance Detector Imaging Arrays for Far-Infrared Astrophysics	J. Zmuidzinas	Caltech	Far-IR Detectors
Improvement of the Performance of Near-Infrared Detectors for NASA Astrophysics Missions: Reducing the Sub-1% Detector Effects	S. Anglin	Teledyne	UVOIR Detectors
H4RG Near-IR Detector Array with 10 Micron Pixels for the Wide-Field Infrared Survey Telescope (WFIRST)	B. Rauscher	GSFC	UVOIR Detectors
High Efficiency Detectors in Photon Counting and Large Focal Plane Arrays for Astrophysics Missions	S. Nikzad	JPL	UVOIR Detectors

Table 2–2. *COR Strategic Astrophysics Technology Selections for FY13 Start.*

The COR Program funds SAT selections in order to further its ultimate goals, both COR missions and COR science. The recent selections for a new start in FY13 serve to enable the kind of cutting-edge science that will push the boundaries of knowledge of our cosmic origins. The project "Ultraviolet Coatings, Materials and Processes for Advanced Telescope Optics" is designed to improve the reflectivity of mirrors, which directly supports the NWNH recommendation to advance technologies for a future large UV and visible mission, but also—because of the inherent scalability of coating technologies—aligns well with advancing technology applicable to future Explorer missions. SOFIA science is COR science, and funding "Kinetic Inductance Detector Imaging Arrays for Far-Infrared Astrophysics" will advance a technology that is strongly enabling for SOFIA but also can apply to other suborbital or orbital experiments. The NWNH states that "understanding the dramatic evolution of galaxies over cosmic time through observations is a key part of the committee's recommended science program," and indeed is a key part of COR science. While WFIRST is programmatically an Exoplanet mission, its major surveys of galaxies will contribute significantly to the understanding of galaxy evolution, and so this top-ranked mission is of great interest and importance to the COR Program. Investigations into "Improvement of the Performance of Near-Infrared Detectors for NASA Astrophysics Missions: Reducing the Sub-1% Detector Effects" and "H4RG Near-IR Detector Array with 10 Micron Pixels for the Wide Field Infrared Survey Telescope (WFIRST)" will therefore support the maturation of technologies to enable the science promise of this valuable mission. High-performance detectors for ultraviolet wavelengths remains an area where significant improvements can dramatically increase scientific yield, and "High Efficiency Detectors in Photon Counting and Large Focal Plane Arrays for Astrophysics Missions" promises to bring about a new approach to improving the characteristics of ultraviolet detectors for space flight purposes.

For projects initiated in FY13, the SAT proposal call permitted a maximum project duration of 3 years. Three of the proposals indeed chose to use the full 3 years, while one project proposed to use 2 years, and a single focused project elected to complete its technology development work in only 1 year. The maximum term is expected to be left at 3 years in the near future, where technology maturation is expected to be somewhat exploratory. Toward the end of the decade, a natural focusing of efforts in support of missions being promoted for prominent inclusion in the review of the coming Decadal Survey is anticipated. Varied technological approaches will be downselected into a tighter group of critical enabling technologies. As this happens, more stringently defined technology performance criteria are expected and, hence, a narrowing of the project's scope should result. An accompanying reduction in the maximum term will likely be seen, in order to accommodate this narrower scope and the increased temporal pressure on achieving results in time to make an impact on future mission recommendations.

2.1 Heterodyne Technology Development for SOFIA

Prepared by: Paul Goldsmith (JPL) and Imran Mehdi (JPL)

Summary

Understanding the structure and properties of the interstellar medium (ISM) and its role in star formation is a key NASA strategic goal that can be achieved only with high-resolution spectroscopy. Stratospheric Observatory for Infrared Astronomy (SOFIA), with its robust instrumentation plan and high-altitude flight path, provides an ideal platform for conducting these investigations for galactic as well as extra-galactic sources. The proposed task focuses on developing and demonstrating heterodyne technology that can be infused into future instruments for SOFIA or other NASA missions, including long-duration balloon missions. The goal is to deploy advanced multi-pixel array receivers in the 1–5 THz range. The technology development is focused on bands that include astrophysically important atoms and molecules such as ionized carbon (C+), atomic oxygen (O), and deuterated hydrogen (HD). Such instruments will allow the science community to pursue high-resolution spectroscopy beyond the Heterodyne Instrument for the Far Infrared (HIFI) instrument on the *Herschel Space Observatory*.

Overview and Background

The far-infrared/submillimeter wavelength region of the spectrum (60–1000 microns/0.3 5 THz) in astrophysics is dominated by the continuum emission from warm dust with numerous spectral emission and absorption lines of atomic and molecular gas superimposed. Separation of components of the ISM requires velocity-resolved atomic, ionic, and molecular line profiles. The 2010 NWNH report has highlighted questions that will require heterodyne technology to resolve: How do stars form? How do circumstellar disks evolve and form planetary systems? What are the flows of matter and energy in the circumgalactic medium? And finally, what controls the mass-energy-chemical cycles within galaxies?

Resolution of these questions will require large-scale heterodyne mapping of the ISM. Two obvious targets are the brightest lines in the spectrum: C+, which traces gas in nearly all of the phases, and; OI, which effectively traces the densest regions where stars are forming. Other species, including singly ionized nitrogen (NII) and methylidyne radical (CH) provide a direct connection to the total gas column and a means to separate the atomic and molecular gas. The ideal way to study the complex structures is a two-dimensional image with a spectrum at every point—a data cube. But the current state-of-the-art for a deployed heterodyne receiver array, such as Herschel HIFI and SOFIA GREAT, are single-pixel receivers. The urgent need for sensitive velocity-resolved images of regions spanning a wide range of spatial scales requires a heterodyne array for more rapid mapping. This task develops the technology for practical heterodyne array receivers. Such arrays deployed on SOFIA and other platforms will be preeminent tools to answer the science questions above.

Objectives

Heterodyne spectroscopic instruments are the only technical possibility for obtaining velocity-resolved spectral resolution in the far infrared. Building on the HIFI and Stratospheric Terahertz Observatory (STO) hardware developed by the Jet Propulsion Laboratory (JPL), the focus of the proposed effort will be to increase the frequency coverage, the Local Oscillator (LO) output power, and the Technology Readiness Level (TRL) of the next generation of Receiver Front Ends (RFE) to enable the implementation of imaging array receivers at frequencies between 1.9 and 5 THz. A schematic of a simple heterodyne receiver system that is based on a superconducting mixer is shown in Fig. 2.1–1. In our case, the mixer is a superconducting Hot Electron Bolometer (HEB) detector that is cooled to 4K. A first-stage Intermediate Frequency (IF) amplifier is also cooled to cryogenic temperatures to obtain the best noise performance. The LO subsystem provides the monochromatic signal that is coupled to the input signal in the mixer. The function of the mixer is to produce a down-converted signal, which is amplified by the first-stage microwave amplifier and fed to room-temperature electronics for processing.

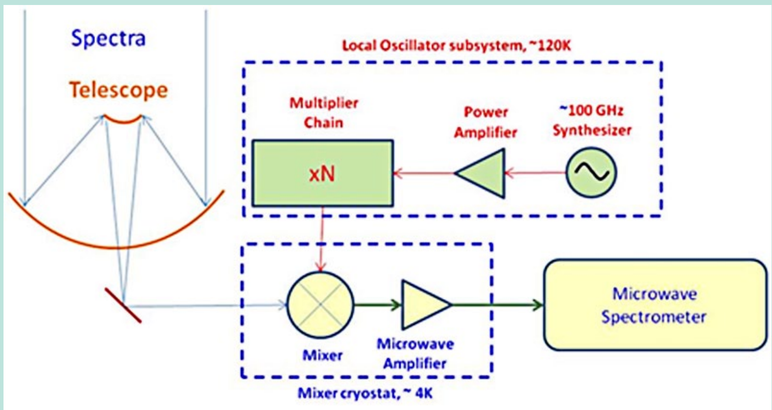

Figure 2.1–1. *Heterodyne detectors convert incoming photons to lower frequency by "mixing" them with a local oscillator signal. The down-converted signals are easy to amplify and analyze using standard microwave techniques, enabling spectral resolution of $\lambda/\Delta\lambda \approx 10{,}000{,}000$. Heterodyne spectrometers are tuned by adjusting the frequency of the local oscillator.*

This task is focused on developing ultra-sensitive heterodyne array receivers for frequencies at 1.9 THz (the upper limit of HIFI) and beyond. To produce an array such as we describe will require that we meet the following challenges: reliably make identical copies of sub-micron features in waveguide circuits; develop an architecture where we can efficiently distribute the LO power to an individual mixer without detrimentally affecting the system performance, and; reliably yield a number of mixers with the required large-IF bandwidths. These challenges are addressed by the key innovations developed in this task, including: hybridizing ultra-fine machining techniques—developed in recent years with micro-machined structures—to produce identical copies of the precise waveguide circuits that are required for an array receiver; improvement in the efficiency of JPL-produced diodes and obtain a better understanding of what multiplication scheme/topology will enable a practical array to be constructed. Finally, we have a partnership with a provider of superconducting films to study the factors affecting mixer quality.

Accomplishments

Higher IF-bandwidth HEB devices

Moscow State Pedagogical University (MSPU) has reported on some niobium nitride (NbN) HEB mixers that have competitive sensitivities along with higher IF bandwidth. JPL has procured two of these devices, and we are actively trying to measure their performance.

Device #3 is a 0.38 μm × 4 μm device that was fabricated from a standard thin NbN film (~5 nm), along with a spiral antenna on high-resistivity intrinsic silicon (Si) substrate, by the MSPU team and delivered to JPL (Fig. 2.1–2). The device chip is mounted on the back of a 10 mm-diameter Si lens. The device was delivered, along with a MSPU-made mixer block fitting to our test system.

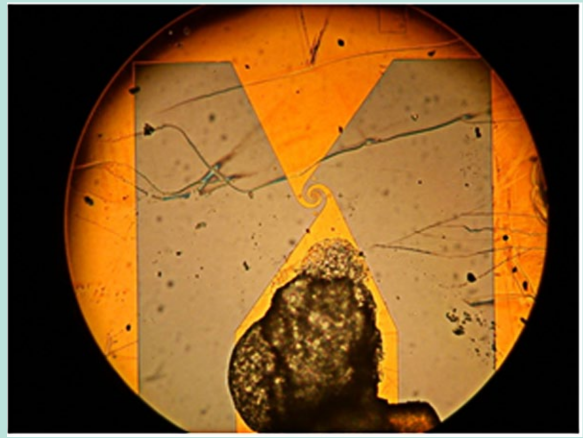

Figure 2.1–2. *Device #3, including the spiral antenna.*

We have tested this device at JPL rather thoroughly at 600 GHz and also obtained some preliminary T_M data at 2.5 THz. At 600 GHz, the minimum noise temperature is 1100K with a 4 GHz noise bandwidth. At a different bias (larger LO, and smoother IV) the noise temperature is 1500K with a 5.5 GHz noise bandwidth. These figures are in line with the previous data for the NbN devices in which the diffusion cooling was not enhanced. This device is very different from what we observed with MSPU diffusion-cooled (shorter) devices #1 and #2, for which IVs were very flat and the noise temperature was very high at 600 GHz. This means that the antenna, even though it is somewhat smallish, still works fine at this frequency for these types of lab measurements. It may be a combination of the bow-tie leads and the spiral that helps. The polarization was kept linear along the current flow direction to utilize the bow-tie part of the antenna. In the next couple of months, we intend to investigate the two devices that have been delivered and try to understand why we are not measuring performance similar to what was measured by our MSPU colleagues.

THz waveguide HEB array mixers

A second goal of this task is to demonstrate JPL-developed HEB devices in working mixers. We have utilized waveguide-based blocks for these mixers, which sets us apart from most other HEB developers who tend to utilize open quasi-optical feed structures. We believe that by utilizing waveguide-based structures we can provide a more controlled matching environment for the device, thus reducing out-of-band noise. Moreover, the waveguide approach allows us to implement more sophisticated circuit topologies, such as balanced mixers, and provides a straight-forward path toward arrays.

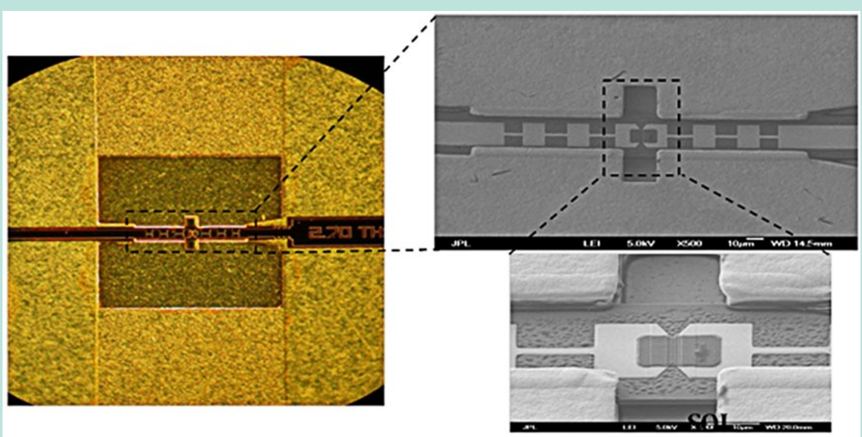

Figure 2.1–3. *Left: A microplated waveguide backpiece populated with a superconducting mixer produced by the silicon-on-insulator (SOI) process. The mixer chip is manually inserted into the channel and self-aligns with waveguide circuit. This circuit is butted to a horn section.*

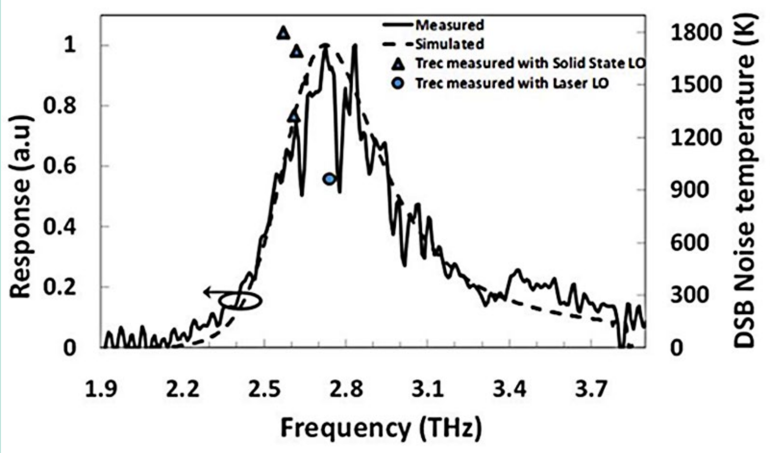

Figure 2.1–4. *Measured mixer noise temperature and frequency response.*

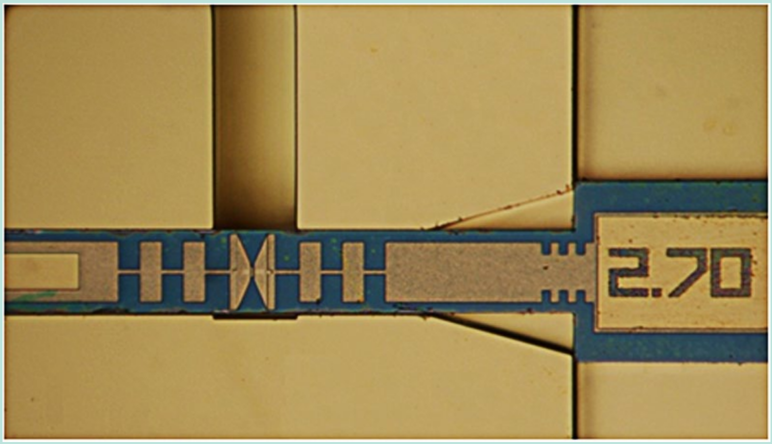

Figure 2.1–5. *SEM pictures of waveguide and channel structures defined into two square silicon substrates of 2×2×0.5 mm by photolithography and Deep Reactive Ion Etching (DRIE) techniques.*

A 2.7 THz single-ended mixer has been developed and characterized. Because the waveguide block requires features of very small size (<25 microns), a novel approach of putting the waveguide blocks together has been developed and is outlined in Fig. 2.1–3. The mixer has been characterized with the hot/cold method, and the measurement is shown in Fig. 2.1–4.

In a second and alternative approach being investigated, the waveguide embedding circuit is formed by silicon micro-machining. An example is shown in Fig. 2.1–5, and optimized devices for this scheme are currently being fabricated.

Next generation local oscillator sources
A third goal of this task is to develop the next generation of LO sources in the 1–5 THz range, especially for array receivers.

One of the goals is to develop a LO scheme that can successfully pump a 16-pixel receiver. The proposed architecture for the LO chain is shown in Fig 2.1–6, along with a picture of the completed hardware development. We have demonstrated a new 1.9 THz chain able to provide 30–60 μW at room-temperature when pumped with 100–200 mW at around

105–115 GHz. This represents an improvement of a factor of 20 relative to the 1.9 THz LO chain onboard HIFI. It is important to remark again that this multiplied chain is a direct evolution of the HIFI/Herschel chain—with optimized single-chip frequency multiplier stages and utilizing no power-combining of any kind.

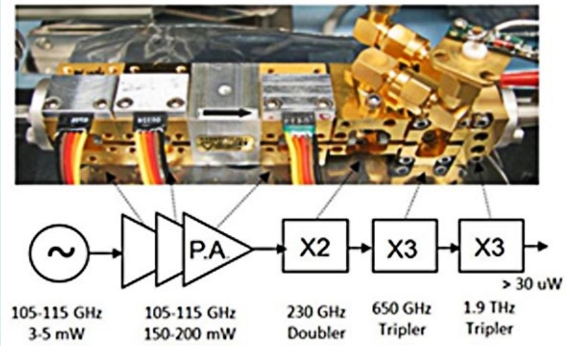

Figure 2.1–6. *Next generation 1.9 THz LO source schematic and completed hardware.*

The performance as a function of frequency of this 1.9 THz LO chain is shown in Fig. 2.1–7. Assuming that 2–5 μW are required to adequately pump a single-pixel HEB receiver, this power level is already sufficient to pump an array of HEB mixers (at least 4 pixels with a healthy margin to account for waveguide and coupling losses in the 1900 GHz.) The single horn output of the LO could be multiplexed using a phase grating to form multiple beams.

While these results from a single output are very impressive, this approach has some limitations. Chief among them is the inability to tune the power level for each individual mixer element. This is a serious concern and can lead to system instabilities. To address this we are developing a linear 1×4 array of sources at 1.9 THz.

The goal is for such a source to put out more than 10 microwatts at room temperature from 1900 to 2060 GHz per pixel. This will be sufficient to pump a 4-pixel linear mixer array. Four of these can then be stacked to complete the 16-pixel receiver. A proposed schematic for the LO chain is shown in Fig 2.1–8. This is similar to the LO chain described previously with one main difference: the output power from the second-stage tripler will be split, and two 1.9 THz tripler chips will be used. The output from each of the 1.9 THz triplers will be divided via a simple Y-junction. Thus, a total of four output beams will be generated from this configuration.

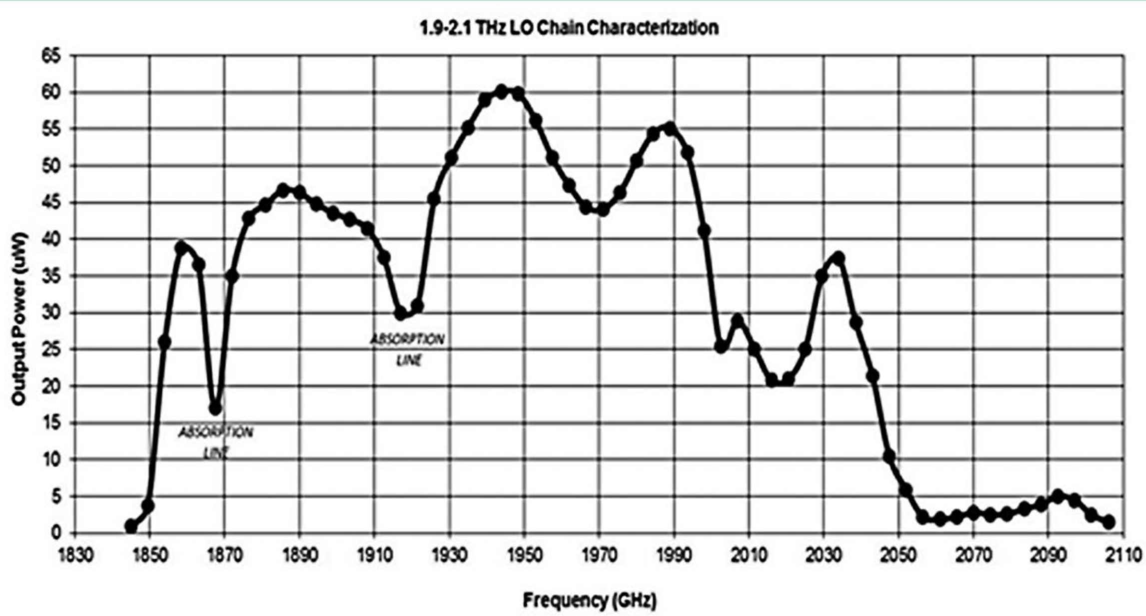

Figure 2.1–7. *Measured performance of the 1.9 THz LO source.*

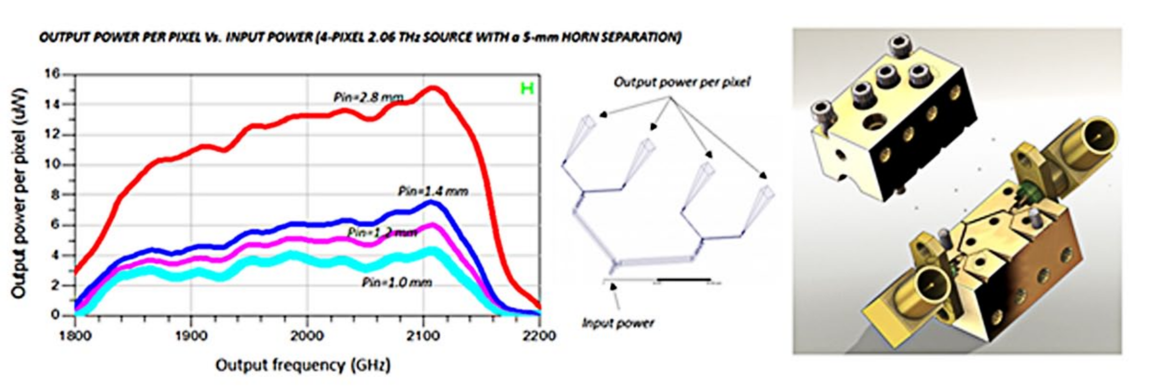

Figure 2.1–8. *Left: The expected performance from a 4-pixel LO sub-system as a function of the input drive power is shown. Right: The block schematic is shown. Two 1.9THz tripler chips will be used to generate four output beams.*

Milestones and Schedule

Task	Comments
HEB with IF>5 GHz	Two devices received from Moscow. Currently being evaluated. JPL devices under fabrication.
LO at 1.9 THz	Completed. World-record power output achieved.
4-pixel LO at 1.9 THz	Design has been completed. Block is currently under production in the machine shop.
4-pixel RFE at 1.9 THz	Mixer block has already been fabricated. Devices for 1.9 THz are under fabrication
16-pixel LO at 1.9 THz	To be addressed in FY13
16-pixel RFE at 1.9 THz	To be addressed in FY13

Table 2.1–2. *This table summarizes the current status of the development work.*

Technology Milestones

Task	FY12												FY13											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Validation of mixers with low noise and high IF												▲												
Optimization of single pixel mixer									▲															
1.9 THz LO Source						▲																		
Demonstration of a 4-pixel 1.9 THz RFE												▲												
Development of a LO for 16 pixels																▲								
Extension to a 16-pixel 1.9 THz RFE																					▲			

Future Plans/Next Steps

1. Optimize a 1.9 THz HEB mixer with wide IF bandwidth. The design will be based on the results obtained in FY12 from the MSPU-provided devices, but the devices will be fabricated at JPL. Following the MSPU recipe, the device material structure will be optimized to provide optimum sensitivity along with maximum IF bandwidth. The device will be incorporated into a single-pixel waveguide block and then tested for performance.

2. Demonstrate a 4-pixel LO source at 1.9 THz. The block is currently being machined, and when completed will be populated with two 1.9 THz multiplier diodes.

3. Characterize a 1900 GHz receiver front-end module with 4 pixels. The mixer block is complete, and the LO block (Item 2) is expected to be completed in September 2012. Characterizing this receiver will be important in order to understand and develop a calibration technique, and evaluate the cross-talk and optical properties of the array receivers.

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2.2 SOFIA Technology Development: Far-Infrared Large Format Array Detectors

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Johannes G. Staguhn (Johns Hopkins University)

Summary

The goal of this Cosmic Origins technology development project is to demonstrate the key component technologies required to produce space-worthy, far-infrared (far-IR) to submillimeter, high-sensitivity bolometer arrays on a large scale of 1,280 pixels. This objective is in direct support of one of the three Astrophysics Science Area Objectives in the 2011 NASA Strategic Plan:

"...improve understanding of the many phenomena and processes associated with galaxy, stellar, and planetary system formation and evolution from the earliest epochs to today."

Existing mission concept plans and community priorities convey the need for large-format, far-IR arrays containing thousands of pixels as an enabling technology required for future NASA missions. However, for wavelengths longer than 40 μm, there is no existing detector that can meet this requirement. This project builds on the results of previous APRA-funded research and leverages related Goddard-funded process improvements to prepare large-format, far-IR detector arrays for a suborbital demonstration in 2013. In October 2012, our group submitted a proposal to upgrade the detectors on the Stratospheric Observatory for Infrared Astronomy (SOFIA) High-resolution Airborne Wideband Camera (HAWC) far-infrared camera and to make it polarimetric with four 1,280-pixel arrays. This proposal has

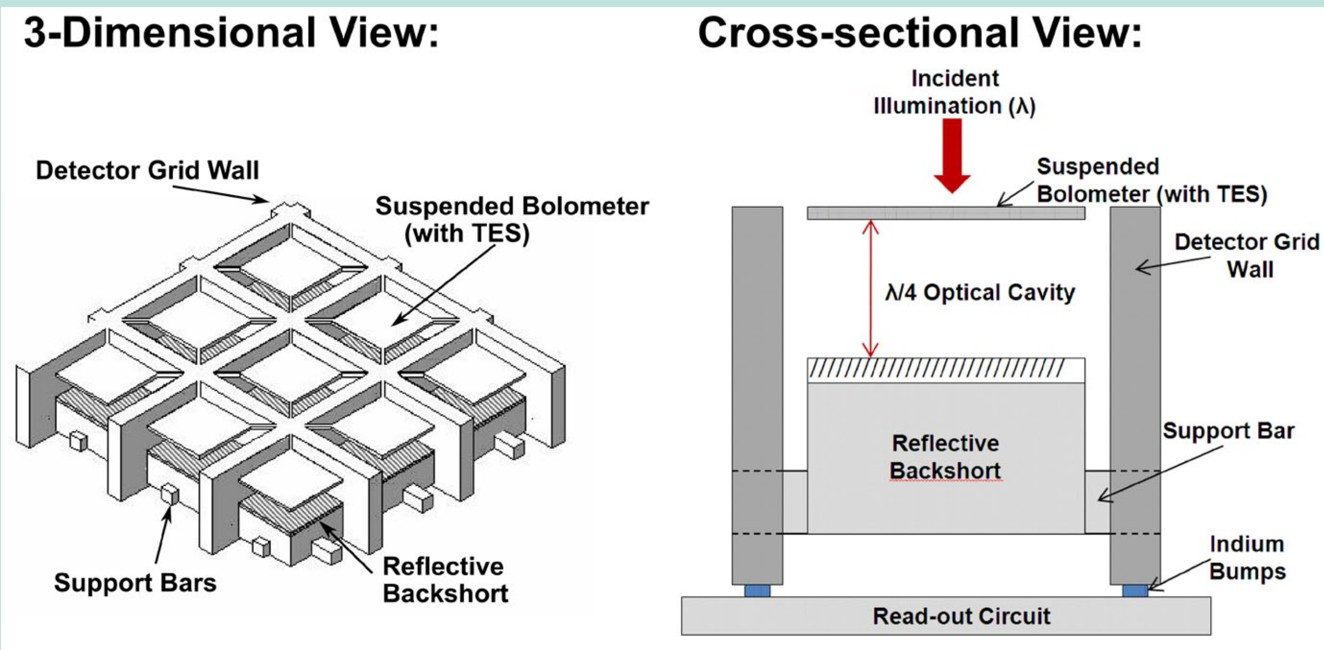

Figure 2.2–1. *A conceptual drawing of the BUG array architecture.*

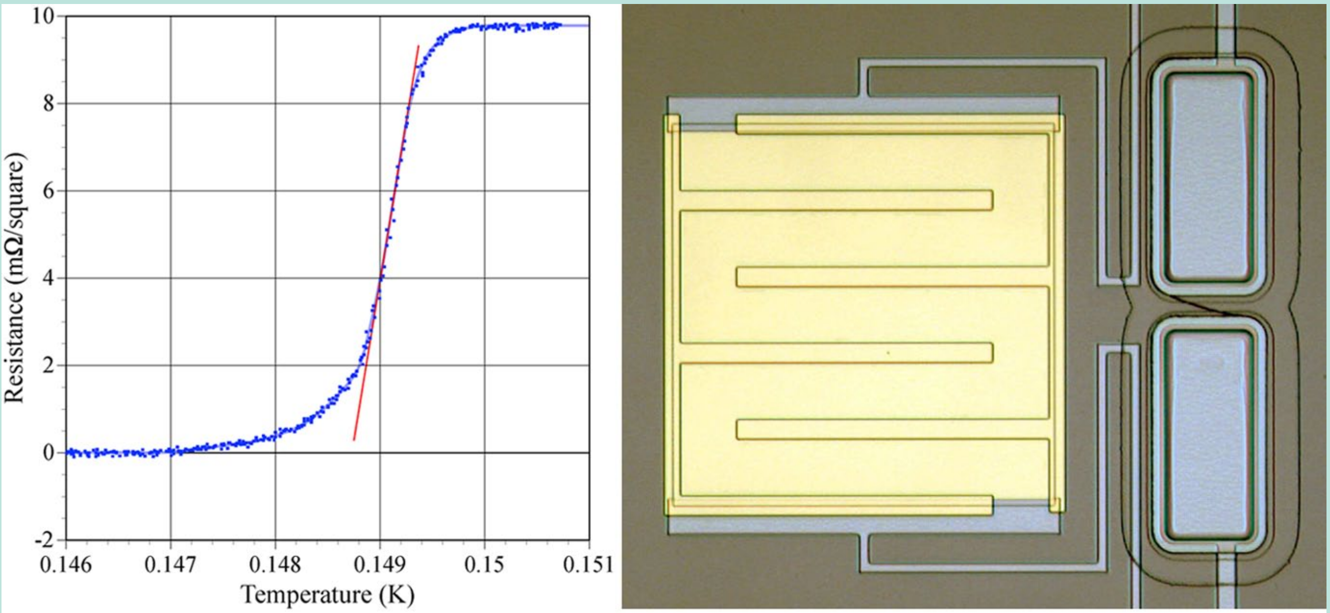

Figure 2.2–2*. Left: The superconducting transition temperature of a molybdenum (Mo) film is suppressed to the desired value by producing an molybdenum-gold (Mo:Au) proximity effect bilayer. Right: Shown is a microscope image of a small MoAu bilayer TES with normal metal bars, demonstrated to reduce noise. This TES has a normal-state resistance of ≈10 mΩ, which is ideal for the new NIST multiplexers.*

been accepted and will tentatively begin in FY13 for completion in 2015. It is due to the COR funding of this detector technology that the HAWC+ instrument will offer such enhanced capabilities to the astronomical community.

Overview and Background

Goddard has developed a far-infrared bolometer device architecture named the Backshort Under Grid (BUG) array, depicted in Fig 2.2–1. A BUG array having 16 × 8 pixels was first demonstrated in a Goddard-built ground-based instrument for the Institut de Radioastronomie Millimetrique (IRAM) 30m telescope, called GISMO (Goddard IRAM Superconducting 2-Millimeter Observer) (PI: Johannes Staguhn, GSFC/JHU). GISMO accomplishments will be described further in the text that follows.

The current evolution of this technology has been scaled up to include four separate 1280-pixel arrays for the balloon-borne instrument known as PIPER (Primordial Inflation Polarization Explorer, PI: Alan Kogut, GSFC). These kilopixel arrays will be described in the text that follows. Additionally, small-format BUG arrays have been slated to fly on the balloon instrument, BETTII (Balloon Experimental Twin Telescope for Infrared Interferometry, PI: Stephen Rinehart, GSFC). Also, as previously mentioned, kilopixel BUG arrays have been selected for an upgrade of the HAWC/SOFIA instrument (HAWC upgrade PI: Darren Dowell, JPL).

The BUG array architecture's inherent versatility and extensibility can fulfill a wide variety of detector instrument needs, including space applications. The BUG array is a three-component detector system: 1) superconducting Transition Edge Sensor (TES) bolometer pixels designed for background-limited sensitivity; 2) a tuned-cavity backshort (or terminator, depending upon the application) under each pixel, and; 3) a hybridized 2-D Superconducting Quantum Interference Device (SQUID) multiplexer to read out signals from the pixels. Fig. 2.2–1 shows a conceptual drawing of a portion of a BUG array, and a cross-section showing the optical cavity formed by insertion of the backshort grid. The detector array, designed as a grid of suspended, 1 µm-thick-silicon bolometers with superconducting TES thermistors, is bump-bonded directly to the SQUID multiplexer. The backshort is a separately fabricated, wafer-scale component that forms an optical cavity under each pixel. A key advantage of our BUG architecture is the versatility to tune its performance for specific wavelengths of operation by changing the dimensions of the optical cavity. The spacing of the backshort is adjustable from ~30–300 µm, by independently adjusting the depths of two silicon deep-etch processes needed to produce the grid. Additionally, this element can act as a reflective backshort or as a terminating load, depending on the needs of the optical design.

Accomplishments

A unique combination of three technical capabilities enable this bolometer architecture: the development of low noise superconducting transition-edge sensors; pixel lead routing to enable scaling; and hybridization to mate TES with the SQUID multiplexers.

Transition Edge Sensor Bolometer

The TES is made of a proximity effect bilayer, a superconducting thin film having its transition temperature (T_c) suppressed by virtue of close proximity to a normal metal film. GSFC uses a Mo:Au bilayer system. By selecting the appropriate thickness of the Mo and Au thin films, we can tune the T_c for operation in the milliKelvin regime (Fig. 2.2–2). This phenomenon is well understood and repeatable (Martinis et al., 2000). The bilayer sensors thus produced are operated within the transition from the normal to superconducting state. Highly sensitive SQUID circuits are needed to operate these devices. The GSFC detector team and National Institute of Standards and Technology (NIST) have worked together to produce a SQUID multiplexer design that is greatly improved over earlier models. The current design features

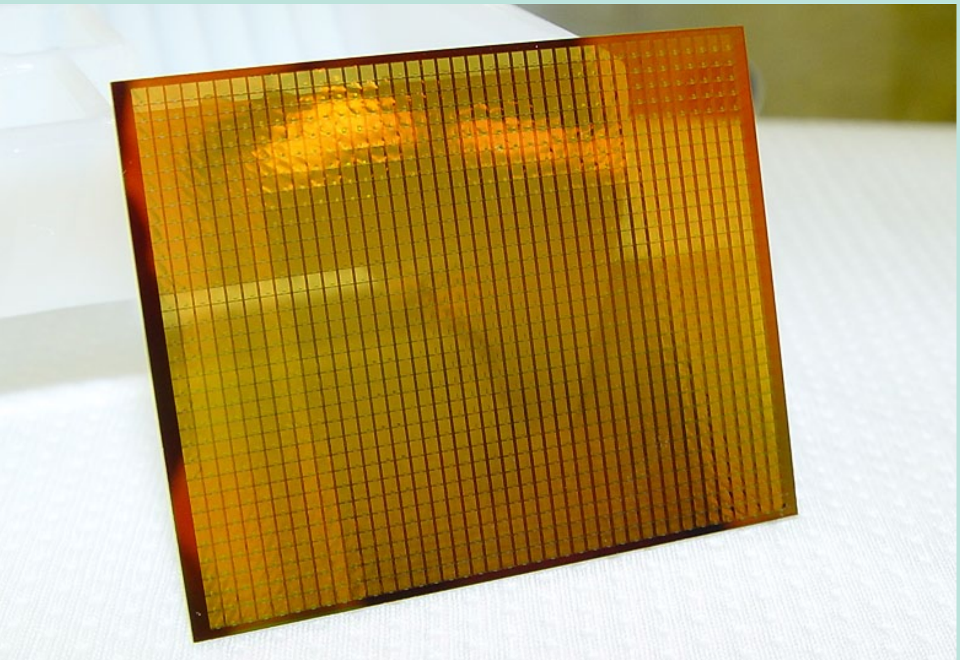

Figure 2.2–3. *This photo of a nearly completed kilopixel array was taken in the fabrication lab after the array—a 32 × 40 pixel array for calibration—was backetched. It is shown here leaning against the leg of a piece of labware, which can be seen through the thin membranes of the pixels.*

more than two orders of magnitude less magnetic field susceptibility (In fact, the first-stage SQUIDs now have an immeasurably low pickup.) and an order of magnitude reduction in unaddressable pixels. This generation of time domain multiplexer has inductors that have roughly half the value of the 475 nH of the original design (Irwin et al., 2004) and a significant reduction of the 300 mΩ TES normal state resistance (R_n). We have optimized the R_n of our TES design to 5–20 mOhm, appropriate for the current generation SQUIDs. One of our TES designs (Fig. 2.2–2, Right) has been tuned to operate in the range of 100–450 mK. We have shown that normal metal bars running perpendicular to the current flow suppress out-of-band noise in operation (Staguhn 2004).

TES to SQUID Interface—the Through-Wafer Via

In order to scale up the number of pixels we can place on a detector array, we must route the TES leads for each pixel to the SQUID read out in the most efficient manner possible. We invented two methods to do this: the Wrap-Around Via (WAV) and the Through-Wafer Via (TWV). Routing superconducting wires that demonstrate high critical current and are three-dimensional rather than planar is a significant technical challenge that we have overcome this year.

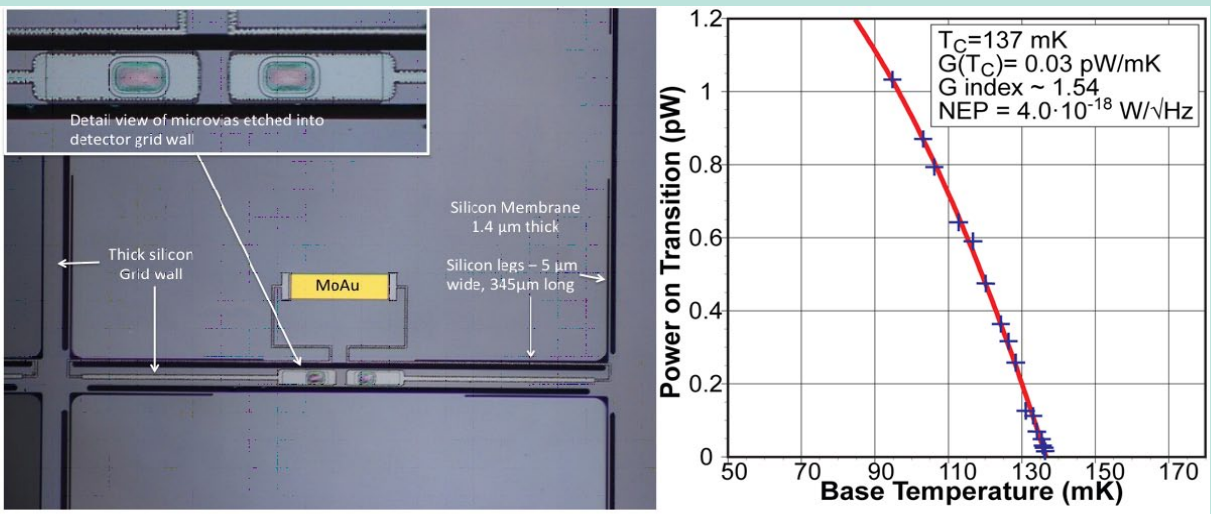

Figure 2.2–4. *Left: The MoAu sensor, used to apply heat to the pixel in this experiment, can be seen at the upper right of this image. This photo was taken at the point of intersection of 2 pixels with the thick silicon frame. This device has eight support legs (seen by the very narrow black lines) 5 µm wide and 345 µm in length. The photo inset shows a detail of the TWVs, discussed earlier, passing through the grid wall. Right: A plot of the applied power versus bath temperature for a 1 mm-square BUG pixel having leg geometry that is shown in the microscope image at left. From the measured G, a NEP of 4×10^{-18} W/$\sqrt{}$Hz is calculated at the T_C of 137 mK.*

We have aggressively matured a novel routing method for the TWV. We etch high-aspect-ratio micro-vias (measuring 10 × 20 µm) through thick wafers, as shown in Fig. 2.2–4. After drilling, the vias are conformally coated with superconducting titanium nitride using Atomic Layer Deposition (ALD). Pads around via openings are then patterned; the vias are plugged with SU-8 polymer to provide wafer planarity for the remaining detector processing. The TWV is now being carried as a primary path for TES to SQUID interconnect, for PIPER and all future kilopixel array programs. We have observed significant improvements in ease of fabrication and pixel yield with the TWV method of interconnection versus our earlier WAV technology. Cryogenic testing of TWV connections proves that the circuit paths are superconducting and have current-carrying capacity of more than 1 mA, suitable for TES operation. Fig. 2.2–3 is a photograph of a calibration run TWV array, taken after the array was released from a support wafer following deep etching of silicon behind the pixel membranes. If one looks closely, one can see the labware behind the array through the thin membranes. This array was subsequently front-etched, to delineate the detector legs, and hybridized to a dummy readout for cryogenic testing. We are now in the process of etching vias in a large batch of wafers (15 wafers) for ALD coating in preparation to begin the first full-up fabrication run of PIPER detectors.

Hybridizing Detector Arrays to Multiplexers

GSFC has established an indium bump bonding capability with broad applications for detector integration. This process allows us to add more functionality per unit area and allows us to optimize two components (the bolometer array and the SQUID) separately.

A large portion of this year was devoted to optimizing the hybridization process for superconducting sensors. Early on, we discovered that hybridized detector arrays were found to have unacceptable resistance in the junction between the indium bumps on the readout substrate and the contact metal on the back of the detector array. Our standard indium bump process, which serves us well for hybridizing high-impedance detectors—such as Quantum Well Infrared Photodetectors (QWIP) for the Thermal InfraRed Sensor (TIRS) used on Landsat satellites—is unsuitable for superconducting sensors ≤20 mOhm. Because of this,

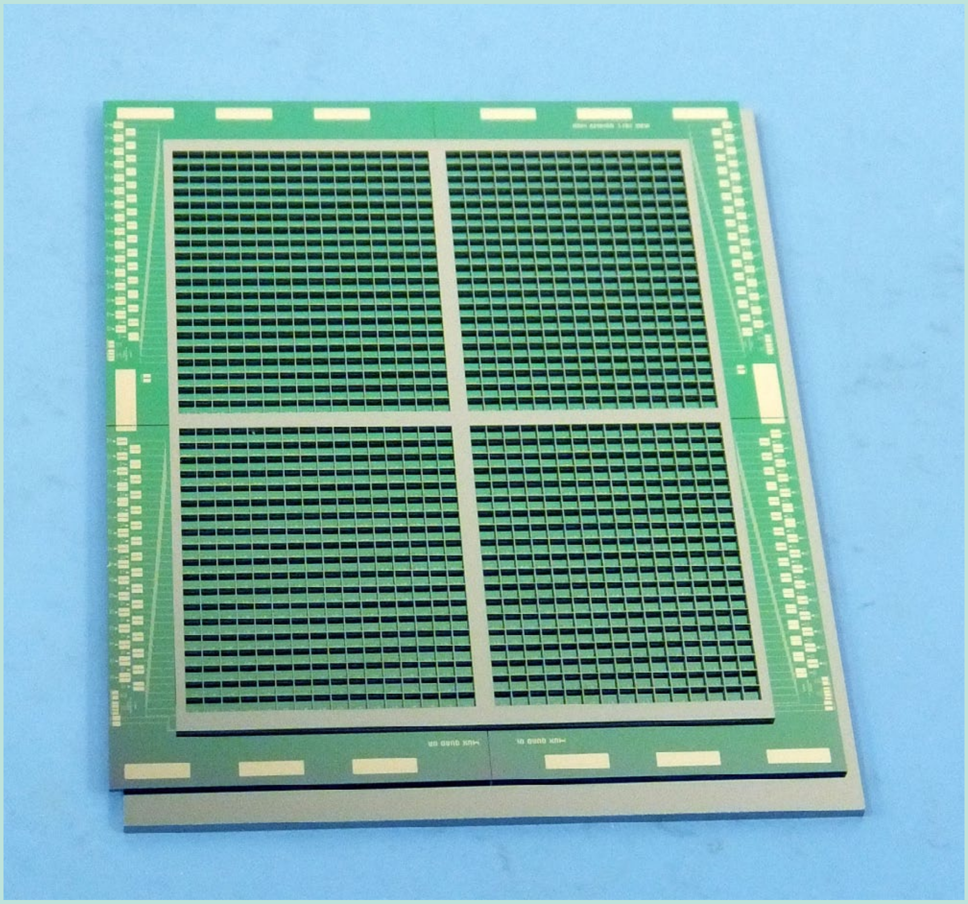

Figure 2.2–5. *This photograph shows a mechanical model of a detector array grid, bump bonded to a dummy readout circuit. This model was cryogenically tested and proved to have superconducting connection with high critical current (>1 mA).*

we needed to develop a zero-resistance connection. Ultimately, we eliminated the contact resistance by being considerably more aggressive in the indium bump cleaning process and by the addition of a post-hybridization heat treatment step. Fig. 2.2–5 shows an image of a detector mechanical model that was hybridized using the modified bump cleaning process and heat treatment. Cryogenic testing of this array proved that the indium connections were superconducting and had a current-carrying capacity of more than 1 mA, well above the requirement for projected TES operation; an estimated 200 μA at most.

Performance

An important figure of merit for a bolometric detector is the Noise Equivalent Power (NEP). The simplified calculation of this parameter for a thermodynamically limited bolometer depends on the thermal conductance, *G*. This can be expressed as:

$$NEP = \sqrt{2kT^2G},$$

where T is the temperature of the heat sink, and k is Boltzmann's constant. The thermal conductance represents the amount of heat energy that escapes through the detector's supporting legs and is dumped into the heat sink. The BUG detector is designed with a thick silicon frame, acting as a heat sink and surrounding each suspended pixel. The design of the suspension system determines G. Fig. 2.2–4 (right) shows a measurement of thermal conductance of a 1 mm BUG pixel having eight legs, each 5 μm in width and 345 μm in length, pictured to the left of the data. The photograph and inset show details of the pixel design, including the two TWVs that connect the MoAu sensor to the back-side of the array through the grid wall.

Astronomical Demonstration of BUG Arrays

To ensure a suitable opportunity to mature the BUG bolometer arrays by operating them for ground-breaking astronomy, we decided to build a novel astronomical instrument, the 2 mm camera GISMO for the IRAM 30m telescope. GISMO was built to highlight our first prototype BUG arrays, using high-temperature TES detectors (T_c 450 mK). GISMO enables a variety of scientific projects, ranging from observations of cold dust in the local universe to observations of the earliest starburst galaxies in the universe. Figure 2.2–6 demonstrates one such advance, with a wide image around the galactic center featuring a dynamic range

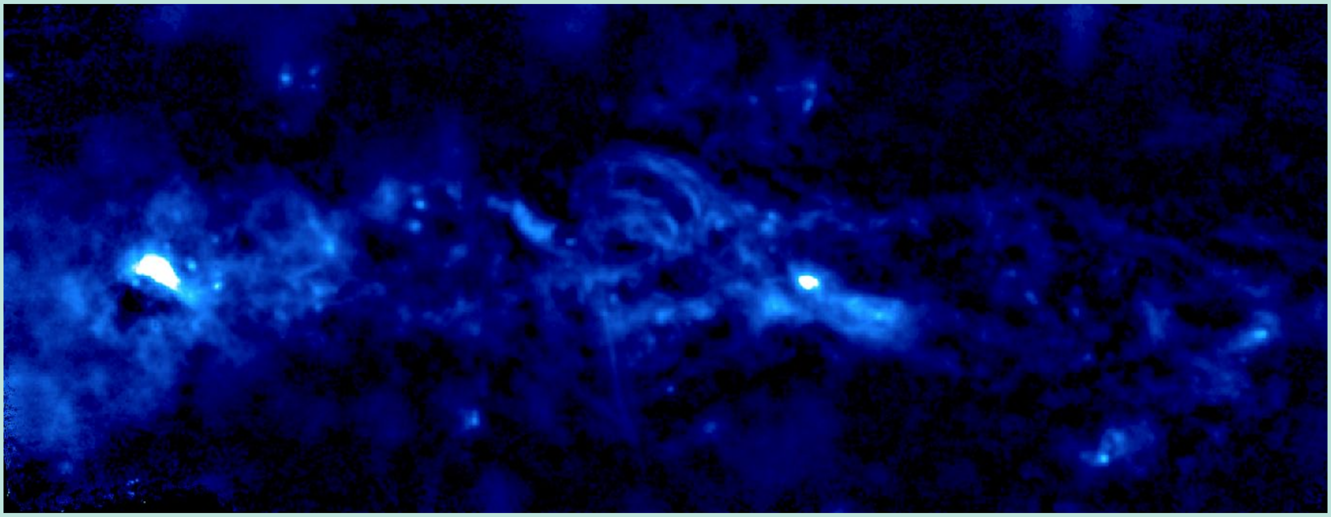

Figure 2.2–6. *This image shows the galactic center at wavelengths of 2 mm taken with the GISMO detector array.*

of over 1000:1. The structures seen in this field arise from combinations of thermal (dust) emission and nonthermal (radio) emission; thus, this provides astronomers with a valuable new insight into the physical properties operating in this complex region. Figure 2.2–7 shows a deep integration on faint galaxies; in this case, to flux limits never before achieved at this band, owing to the revolutionary sensitivity of the GISMO instrument and its BUG detector array, shown in Figure 2.2–8.

Status and Future Plans

We have demonstrated a very promising Through-Wafer Via technology mentioned in earlier in this report. In the remainder of this project, we will hybridize a calibration detector array having TWV interconnects. We have observed a significant improvement in the yield of pixels using the new technology, although at present we do not have cryogenic test data to quantify our results. Our latest array, as yet not hybridized, has a fabrication yield of 98% good pixels. We will be pushing this technology very rapidly to replace the Wrap-Around Via technology. (WAV fabrication yield demonstrated to date is 95%—acceptable, but lower than desired.)

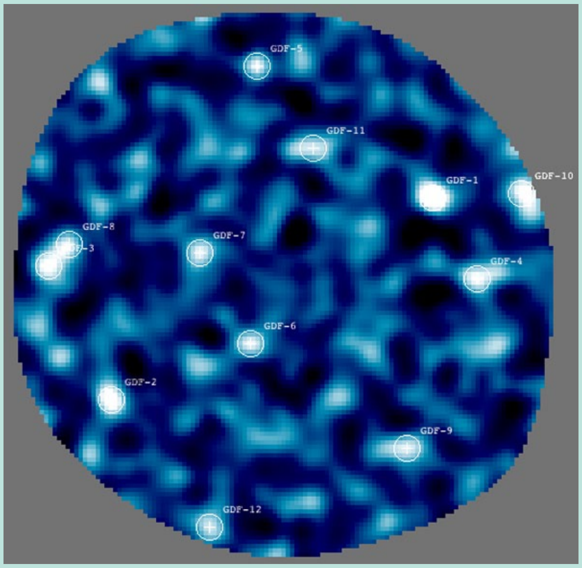

Figure 2.2–7. *This deep-field image was taken with the GISMO detector array.*

The COR-funded technology maturation effort has been integrated into a cohesive approach to delivering detector arrays for multiple suborbital projects that flow from the results of the work described here. Taken as a whole, this includes near-term major goals:

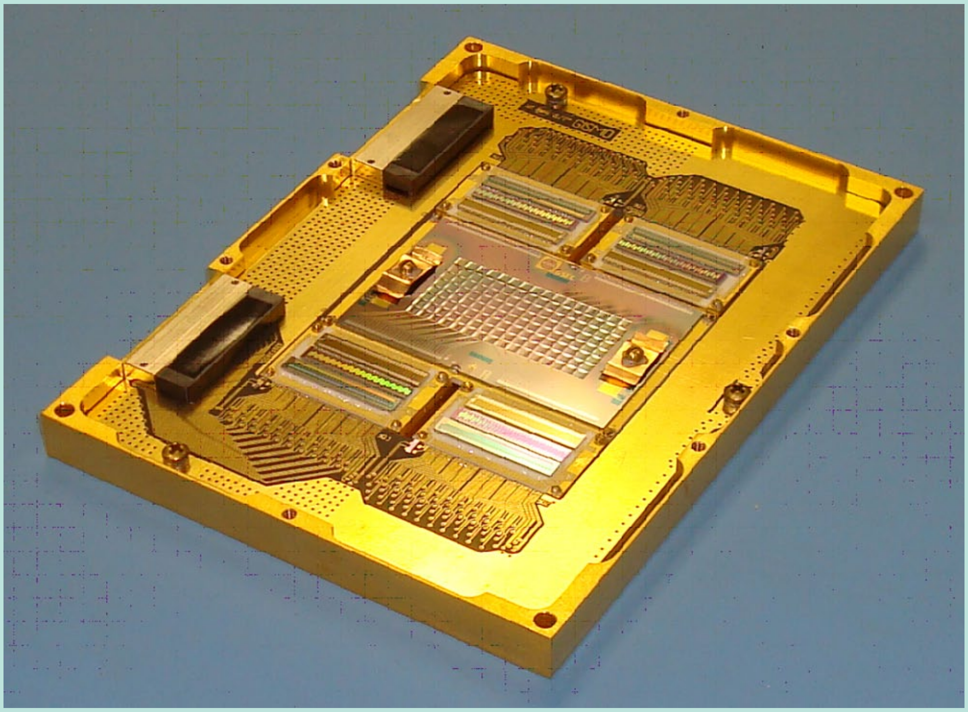

Figure 2.2–8. *This photograph shows a GISMO detector array. This is an array of 8 × 16, 2 mm TES pixels with SQUID multiplexed readout.*

1. Address the immediate needs by completing a flight-like prototype of a 32 × 40 detector array for suborbital requirements; FY12 (Under this funding).
2. Address the maturity for future missions/instruments by deploying large-format arrays in balloon-borne instruments—the first will be deployed in the Primordial Inflation Polarization Explorer (PIPER); FY13 (Separately funded project).
3. Produce additional arrays to demonstrate their operation under very different conditions (which may increase the TRL by broadening the scope of its relevant application)—specifically, for demonstration on the Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII), GISMO-2, and HAWC+; FY13-15 (Separately funded projects).

Task	FY11												FY12											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Deliver and test kilopixel "Calibration" detector arrays	▲																							
Mature TWV technology to replace WAV																				▲				
Annual Report																								▲

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2.3 Enhanced MgF_2 and LiF Overcoated Al Mirrors for FUV Space Astronomy

Prepared by: Manuel A. Quijada (NASA/GSFC), Steve Rice (NASA/GSFC), John Lehan (SGT Inc.), and Felix Threat (NASA/GSFC)

Summary

We have demonstrated considerable gains in Far Ultraviolet (FUV) reflectivity of aluminum/magnesium fluoride (Al/MgF_2) and aluminum/lithium fluoride (Al/LiF) mirrors by employing a three-step process during Physical Vapor Deposition (PVD) coating deposition of these materials. Part of the future plan is to transfer the process we have developed to an existing 2m chamber, which will allow coating optics much larger than the ones we are able to do currently in a smaller chamber. This will require retrofitting the larger coating facility with the necessary heating elements to achieve the required deposition temperature to enhance the FUV reflectance of these materials. We also plan to extend this to Al/LiF coatings, because observations show that similar gains could be realized with this type of coating, allowing enhanced reflectance down to the lower cut-off wavelength for LiF below 1000 Å.

We have also performed optical analysis to determine FUV optical properties—refractive index (n) and extinction coefficient (k) values—of the lanthanide trifluoride materials gadolinium fluoride (GdF_3) and lutetium trifluoride (LuF_3). These materials are considered as a high-index option that, when paired with a low-index material such as magnesium fluoride (MgF_2), could be used to enhance the reflectance of overcoated aluminum mirrors to operate at a particular design wavelength in the 1100 to 2500 Å spectral range or to produce all-dielectric reflectors to operate in the same spectral range.

Overview and Background

The FUV spectral region (900 to 1500 Å) is relevant to many aspects of NASA's Cosmic Origins Program, particularly the Astrophysics Science Area Objective 2: "Understand the many phenomena and processes associated with galaxy, stellar, and planetary system formation and evolution from the earliest epochs to today." Many of the resonance lines for both low-ionization and high-ionization states of common atoms are found only, or largely, in this region. Some lines are found on the high side of 1200 Å, but often their interpretation requires transitions with different oscillator strengths or different ionization states that are found in the FUV. Furthermore, the electronic ground state transitions of hydrogen (H_2) are found only on the low side of 1150 Å. Hydrogen gas is the most abundant molecule in the universe, and is the fundamental building block for star and planet formation. The absorption lines of deuterium (D) and the molecule hydrogen deuteride (HD) are also found only in the FUV region. The abundance of D is an important test of Big Bang cosmology and of chemical evolution over cosmic time.

The region from 900 to 1150 Å has been explored by only a handful of NASA astronomy missions: Copernicus, or Orbiting Astronomical Observatory 3 (OAO-3), launched in 1972; Hopkins Ultraviolet Telescope (HUT), which flew as space shuttle payloads in 1990 (Astro-1) and 1995 (Astro-2); and the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrograph (ORFEUS), which also flew as a shuttle payload in 1993 and 1996; and the Far Ultraviolet Spectroscopic Explorer (FUSE), which launched in 1999 and operated until 2007.

The FUSE observing program was the most extensive by far, but it was limited by a modest effective area (20 cm^2 below 1000 Å to 55 cm^2 above 1020 Å) and, for some programs, modest spectral resolution (R~20,000). Moreover, FUSE made significant strides in mapping variations in (deuterium/hydrogen) in the Galaxy, but lacked the sensitivity to study D/H in the intergalactic medium (IGM). This lack of sensitivity was due to low reflectance of the available coatings. The reflectivity of the Al/LiF coatings was ~50% at launch, while that of the silicon carbide (SiC) coatings was ~30 %. Improved reflectivity in itself would bring enormous gains in throughput, and the benefits of more capable optical designs enabled by higher reflectivity would address the shortcomings noted above and thus bring further gains in sensitivity.

Objectives

The motivation behind the efforts spelled out in this technology development program is to improve reflective coatings, particularly in the FUV part of the spectrum. These efforts will result in dramatically more sensitive instruments and permit more instrumental design freedom. Increasing system throughput is a very cost-effective way to achieve more science and often is less costly than simply using a larger primary mirror.

Moreover, the Technology Development section for the Cosmic Origins Program (TCOP) of NASA's Strategic Astrophysics Technology (SAT) program solicitation (ROSES, Appendix D.11) seeks to investigate the formation and history of planets, stars, galaxies, and cosmic structure, and how the elements of life in the universe arose. The mission-enabling technology development in this proposal specifically addresses Section 2 under the TCOP call that is titled "Ultraviolet Coatings." In particular, this technology development deals with improved deposition processes for known FUV reflective coatings (e.g., MgF_2 and LiF), investigations of new coating materials with promising UV performance, and examination of handling processes, contamination control, and safety procedures related to depositing coatings, storing coated optics, and integrating coated optics into flight hardware.

The technology development we propose here has one main objective: to transfer the process of enhancing the FUV reflectance of aluminum mirrors protected with MgF_2 and LiF layers to a larger, 2m PVD chamber. This process, which consists of reducing the absorption in these layers at FUV wavelengths, was originally implemented in a smaller PVD coating chamber that only allowed coating optics no larger than a couple of inches in diameter.

A second objective of this technology development is to begin with limited material studies, via the PVD process, of the best materials identified in the 1990 thesis work of Dr. Linda J. Lingg (University of Arizona). Dr. Lingg's work examined a series of lanthanide trifluorides and found some potential candidate materials beyond lanthanum fluoride (LaF_3) that would serve as high-index materials that could be paired with a low-index layer (such as MgF_2) to make all-dielectric reflectors and even interference filters to operate in the FUV spectral range. However, the films from Dr. Lingg's study suffered from sub-stoichiometry and alloying with the evaporation canoes, which limited their performance. Nonetheless, this work and others point to a fruitful area of investigation for a high-index material for FUV application.

This technology development will study those lanthanide trifluoride materials that have sufficiently low absorption at the Lyman-Alpha wavelength (1216 Å) to be usable near this spectral range. The efforts in this study will result in the identification and characterization of two of the best candidates (GdF_3 and LuF_3), as identified by Dr. Lingg, that have an index of refraction higher than that of MgF_2. A second task will be to design and produce an enhanced reflector by overcoating an Al layer with a dielectric stack of a high-low repetition on top to produce a reflector to operate near 1216 Å wavelength. The importance of this can hardly be overstated as low-absorption, all-dielectric coatings would allow the demonstration of enhanced reflectors or even interference filters for application in the FUV spectral region.

A third objective under this technology development is to pursue on almost parallel tracks developing low-absorption, thin-film coatings using an Ion Beam Sputtering (IBS) system, which is known to produce the nearest to ideal morphology optical thin film coatings. However, the energies involved in the IBS process make maintaining stoichiometry for certain materials difficult. This results in unacceptably large absorption losses in the UV, particularly for lithographic systems and the deep UV where oxides no longer transmit and fluorides become the materials of choice. We plan to address these shortcomings by flowing Freon or other fluorine containing gases during the deposition to compensate for the stoichiometry deficiency. We propose to combine the knowledge gained from previous studies to attack the problem of low scatter, low loss, UV dielectric coatings.

We explore MgF_2 and LiF because these two materials are the most commonly used to protect from oxidation the aluminum layers that affect the performance of this commonly used metal coating, particularly in the FUV. Successful production of low-absorption films of either material would allow overcoating them at ambient temperatures, which would reduce the oxidation of the aluminum that can occur in a hot process. The result should be a higher reflectance and greater specularity, reducing stray light from the coatings.

Accomplishments

Our accomplishments during FY12 include the following. First, we report on progress using a 3-step "enhanced" coating process that was originally developed in a previous technology effort to reduce absorption in the MgF_2 layer of Al+MgF_2 mirrors.

The coating depositions were done in a small (1m) high-vacuum chamber capable of doing PVD. The procedure was such that aluminum layer was applied first with the substrate at ambient temperature. An initial 50 Å layer of MgF_2 was then applied on top of the aluminum. A series of heaters installed inside the PVD chamber were turned on to raise the substrate temperature up to 240°C to finish the last part of the MgF_2 deposition.

Several trials were required to optimize coating parameters, such as vacuum cleanliness and deposition rate, before successfully producing coatings with a much reduced absorption in the MgF_2 layer. As an example, we show in Figure 2.3–1 the comparison of calculated FUV reflectance of bare aluminum and Al+MgF_2 mirrors. This figure also includes measured data from a sample prepared using the "enhanced" PVD process described above. We also show in Figure 2.3–1 a second sample that was prepared using the standard method in which all depositions were done at ambient temperature. These data show that the "enhanced" sample is superior to that of the sample prepared using the standard method. But more importantly, this figure shows that, for the first time, the reflectance of the "enhanced" sample is approaching data for non-oxidized bare aluminum. Figure 2.3–2 displays the performance of Al+LiF mirrors at FUV wavelengths. Although, there is a larger gap between the predicted and measured performance, the results show higher values in reflectance for these coatings at 1050 Å.

The first objective in this technology development is to demonstrate this process using a coating chamber that will enable coating larger-diameter (up to a 1m) optics. We will do this by coating a distribution of slides to study uniformity over a radius. Some of the tasks we have completed during the FY12 performance period include:

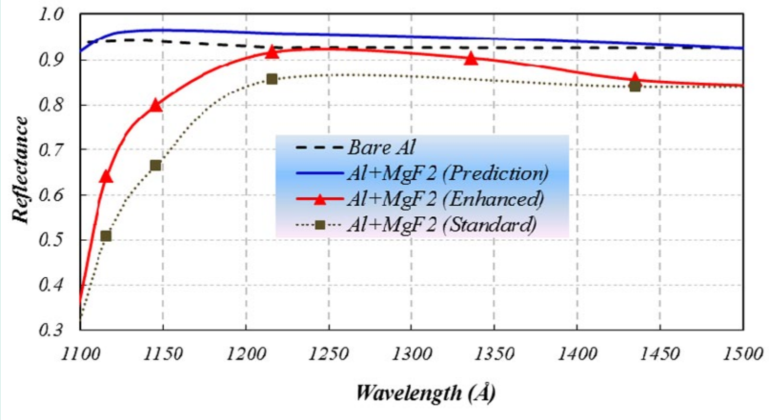

Figure 2.3–1. *Predicted reflectance of bare aluminum and Al+MgF_2 in comparison with measurements on two samples with standard and enhanced Al+MgF_2 coating.*

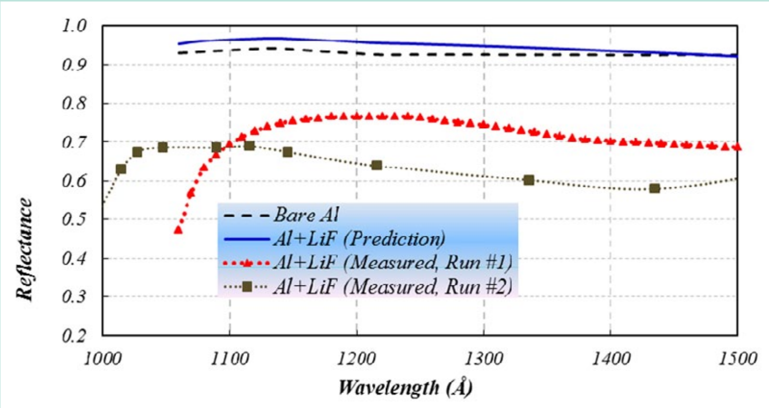

Figure 2.3–2. *Predicted reflectance of bare aluminum and Al+LiF in comparison with measurements on two different coating runs of enhanced Al+LiF.*

- Design and fabrication of heat-shield panels to fit inside a chamber;
- Acquisition of a 6000 W power supply system to operate halogen quartz lamps to provide a heating element in the chamber;
- Internal wiring of a power supply and heating elements inside the vacuum chamber.

The tasks above indicate that we are on the verge of starting coating depositions in the chamber. This schedule is in line with what we proposed during the first year of performance for this technology development effort.

With regard to the accomplishments related to the second objective of researching new high-index materials for use as dielectric reflectors in the FUV, we show in Figure 2.3–3 transmittance and reflectance data of a GdF_3 film (480 Å) grown on MgF_2. This film was recently produced using the PVD coating facility in the Optics Branch (Code 551) of the Applied Engineering and Technology Directorate at NASA GSFC.

Figure 2.3–2 shows an enhancement of the transmission (relative to MgF_2) near 1500 Å, on account of the etalon effect due to a combined effect of the film's thickness and index of refraction. We also observe from Figure 2.3–2 that the cutoff wavelength is below at least 1300 Å, which is not too far from that of the bare MgF_2 substrate below 1200 Å. These results point to a promising alternative of a high-index material that has its cutoff wavelength in the FUV spectral region.

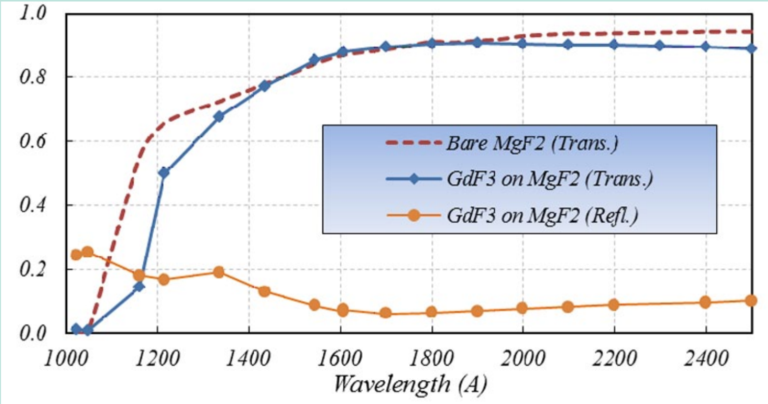

Figure 2.3–3. *Transmission and reflection of a 480 Å film of GdF_3 grown on MgF_2 substrate.*

With regard to the third task of refurbishing the IBS chamber for improving MgF_2 and LiF film quality by using a fluorine-containing gas during deposition, we cite the following accomplishments:

- Retrofitted the IBS chamber with a two-gas system that is need in the coating deposition process;
- Purchased two six-inch sintered disks of MgF_2 and LiF for use as source materials during depositions in the IBS chamber;
- Performed minor repairs of the ion gun system, such as replacing magnets and realignment of the graphite grids;
- Performed initial chamber break-in by performing test runs using the MgF_2 target.

These coating activities were carried out on fused-silica (SiO_2) substrate in order to study film absorption down to 1900 Å. Table 2.3–1 displays coating parameters with initial parameters and the results.

Gases	Beam voltage	Beam current	Rate	Performance near 1900 Å
Krypton	800	30 mA	~ 1A/s	Absorbing
Krypton /Tetrafluoromethane	800	25 mA	~ 1 A/s	Low absorption
Krypton /Tetrafluoromethane	650	22 mA	~ 0.7 A/s	Low absorption
Krypton /Tetrafluoromethane	500	22 mA	< 0.5 A/s	Low absorption

Table 2.3–1. *IBS coating results using a sintered MgF_2 target on SiO_2 substrate are shown.*

The future plan is to start coating films using the MgF_2 target on MgF_2 substrate in order to study absorption performance down to lower wavelengths than possible on SiO_2.

Milestones and Schedule

Here is the list of milestones as it was first proposed during the FY12 performance period:

1. Establish the optimum temperature for deposition of either MgF_2 or LiF overcoats in the smaller chamber.
2. Retrofit a PVD coating chamber with a heater, thermometers, and a refurbished thermal shroud.
3. Upgrade the IBS sputtering chamber for a multigas mixture and substrate rotation.
4. Establish IBS sputtering conditions and optimize the optical constants and morphology for each material.
5. Perform an initial test run and a characterization of the enhanced deposition process on a distribution of slides in the chamber.
6. Run screening and optimization experiments on selected lanthanide trifluorides; characterize and optimize the best performing material.

Task	FY13											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Major Milestones				▲		▲		▲		▲		▲
Perform initial Al+MgF_2 coatings with 2m chamber		▲										
Perform distribution study of Al+MgF_2 coatings with 2m chamber			▲									
Perform initial Al+LiF coatings with 2m chamber				▲								
Perform distribution study of Al+LiF coatings with 2m chamber					▲	—	—	▲				
Optimize Lanthanide Trifluoride for FUV application	▲											
Design and fabrication of Lyman-Alpha reflector							▲					
Optimization and characterization of Al+MgF_2 films using the IBS process		▲										
Optimization and characterization of LiF films using the IBS process						▲						
Final Report												▲

For the most part, we have accomplished nearly all the milestones listed above. Studies with the LiF material have been slowed due to its hygroscopic nature. The relatively quick reaction time of films made of this material has prevented the determination of its intrinsic absorption properties immediately after the deposition is done. For the future, we are working on a plan to have an operating procedure in place that will minimize the time between the film exposure to ambient conditions and optical testing. With regard to milestone No. 5, we are in the final stages of procuring a power supply/heater system that we hope will be available for operation within a 1- to 2-month timeframe.

The milestone list for FY13 includes:

1. Continue performing test coating runs for MgF_2- and LiF-enhanced coatings to optimize the process in the chamber and evaluate the coatings' durability by measuring samples at regular time intervals.

2. Carry out micro-roughness studies on coated slides.
3. Deposit and optimize protected mirrors with the best performing material by IBS and characterize the deposition plume.
4. Produce an aluminum-based reflector with enhanced operation based on the best low-index fluoride (MgF_2 or LiF) and high-index fluoride (lanthanide trifluoride, identified in year 1) centered at Lyman-Alpha.

In conclusion, we are on track to accomplish most, if not all, of the FY13 milestones listed above. As part of our future plans beyond FY13, we intend to submit a second proposal in response to the next ROSES-SAT call that is expected in the first quarter of 2013. The major task here will be to upgrade a larger coating chamber with an IBS capability for deposition of MgF_2 films on a larger scale. This will facilitate the fabrication of enhanced Al+MgF_2 reflectors using a combined thermal evaporation (for the aluminum film) and sputtering processes for the MgF_2 layer.

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2.4 Cross Strip Microchannel Plate Detector Systems for Spaceflight

Prepared by: Dr. John Vallerga (Space Sciences Laboratory, University of California, Berkeley)

Summary

Microchannel Plate (MCP) detectors have been an essential imaging technology in space-based NASA UV missions for decades and have been used in numerous orbital and interplanetary instruments. The reasons for this are many: they have high Quantum Efficiency (QE) in the extreme and far ultraviolet; they are photon counting with high spatial and temporal resolution in combination with a low dark count rate; they are available in various large, adaptable formats, even curved; readout electronics can be compact, low mass, and low power; they do not require cryogens; and they are quite radiation hard.

However, as with any detector technology, they have their limitations: lower QE in the near UV, MCPs with fixed pattern noise; and limited lifetime and dynamic range as a result of high-gain operation. The first of these limitations is being addressed by an Astronomy and Physics Research and Analysis (APRA) grant on gallium nitride (GaN) photocathodes, and the second has been largely ameliorated by new MCP fabrication techniques within the industry. We have addressed the remaining issues with our Cross Strip (XS) anode readout technology, and the goal of this Strategic Astrophysics Technology (SAT) effort is to transition from successful laboratory and early rocket demonstrations of XS readouts to an adaptable prototype detector qualified for flight-like environments.

Overview and Background

The Experimental Astrophysics group at the Space Sciences Laboratory, University of California, Berkeley, was awarded an APRA grant in 2008 to develop massively parallel XS readout electronics. These laboratory XS electronics demonstrated spatial resolutions of 12 µm at full-width half-maximum (FWHM), global output count rates of 2 MHz, and local count rates of 100 kHz, all at gains a factor of ~20 lower than existing delay-line readouts. They have even been deployed in biomedical imaging labs but are presently too bulky and high-powered to be used for space applications. Our SAT program plans to take this XS technology and raise it to TRL6 by: 1) developing a new Application Specific Integrated Circuit (ASIC) that combines optimized faster amplifiers and associated Analog-to-Digital-Converter (ADC)s in the same chip; 2) developing a field-programmable gate array (FPGA) circuit that will control and read out groups of these ASICs so that XS anodes of many different formats can be supported; and 3) developing a spaceflight compatible 50 mm XS detector that integrates with these electronics and can be tested as a system in flight-like environments. This detector design can be used directly in many rocket,

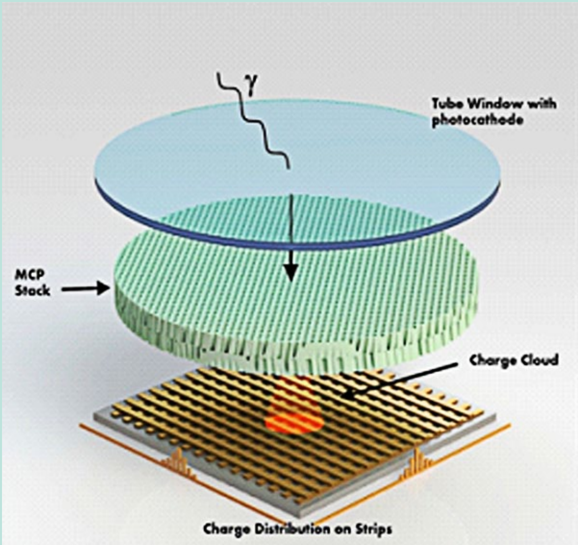


Figure 2.4–1. *Schematic of a Cross Strip readout behind an MCP stack.*

satellite, and interplanetary UV instruments and could easily be adapted to different sizes and shapes to match various mission requirements. New technological developments in photocathodes (e.g., GaN) or MCPs (e.g., low-background, surface-engineered borosilicate glass MCPs) would be able to be accommodated into this design as their TRL levels increase.

XS readouts collect the charge exiting from a stack of MCPs with two sets of coarsely spaced and electrically isolated orthogonal conducting strips (Fig. 2.4–1). When the charge collected on each strip is measured, a centroid calculation determines the incident location of the incoming event (photon or particle). This requires many identical amplifiers (e.g., 64, 128), the individual outputs of which all must be digitized and analyzed. The advantage this technique has over existing and previous MCP readout techniques (wedge and strip, delay-line, intensifiers) is that the anode capacitance per amplifier is lower, resulting in a higher signal-to-noise ratio (SNR). This allows lower MCP gain operation (factors of ~20) while still achieving better spatial resolution compared to the delay-line MCP readouts of current space missions (Vallerga 2010), thereby increasing the dynamic range of MCP detectors by up to two orders of magnitude. They can also be readily scaled to large (>100 × 100 mm) or other unique formats (e.g., circular for optical tubes, rectangular for spectrographs, even curved anodes to match curved MCP focal planes). The XS readout technology is mature enough at present to be used in the field in many laboratory environments to produce quality scientific results (Michalet 2009; Berendse 2006) and is ready for the next step of development: preparing for implementation in an orbital or deep-space mission.

Our current XS readout electronics, called the Parallel XS (PXS) electronics, consists of a preamplifier board placed near the MCP anode and a rack-mounted set of electronics containing ADCs and FPGAs. The existing PXS electronics performance presently meets or exceeds *all* of the specifications of the previous flight systems mentioned previously. However, the PXS laboratory electronics are too bulky, massive, and use relatively high power; and therefore, they are not currently suitable for a long-term space mission. One important goal of the present effort is to replace the PXS electronics with an ASIC that combines the functionality of the preamp board and the downstream ADCs into one low-power, low-mass chip. When a set of these chips is combined with a FPGA and XS anode, we expect the performance to exceed the higher-power PXS electronics due to the noise improvement expected for the smaller-scale components.

The ASIC we propose to develop is "application specific" to XS readouts in general, not just the specific scientific missions XS MCP detectors can support. The format and size of an eventual flight detector will only determine how many of these ASICs are to be used and the capabilities of the flight FPGA. We are experienced enough with flight mission developments to realize the actual chosen flight ASIC will probably be a modified version of this pathfinder XS ASIC. But it is much less risky and time consuming to modify an existing ASIC than develop one from scratch. We are raising the level of our XS system to TRL6 as a prototype demonstration in a relative environment (ground or space) and we firmly believe that having started the development of this ASIC now, there will be ample time for the end-product to be thoroughly tested in a wide range of applications (such as sounding rocket flights, biomedical imaging, etc.) prior to being implemented on a space science mission.

In addition to the space-flight appropriate ASIC development, we plan to construct a flight prototype 50 mm XS MCP detector with a XS readout using our new ASICs. The new ASICs and FPGA control electronics will be integrated into a compact package so that the whole detector system performance can be qualified in space-like environments (e.g., thermal vacuum tests). This standard detector design will become the baseline XS detector and could be used in many proposed rocket and satellite missions. We note that many of the current UV sounding rocket programs (e.g., Johns Hopkins University, University of Colorado) are currently utilizing MCP detectors with delayline readouts. In fact, we expect this detector to be the baseline of many Explorer-Class mission proposals in the future. This XS design can also be scaled easily to other useful formats required by specialized instruments. For example, doubling the length of one detector dimension entails adding more strips to the anode and more ASIC chips to read them out, not a redesign of the ASIC.

Objectives

Design and fabricate an ASIC to amplify and digitize cross strip signal charges
A new ASIC that can overcome the limitations on the front-end of our existing electronics is a major thrust of this proposal. We wish to design and fabricate an input ASIC that has the following features:

1. An optimized front-end charge-sensitive amplifier that is matched to the anode strip load capacitance with fast signal rise-and-fall-times to minimize event collision.
2. Fast (~GHz) analog sampling to fully characterize both the amplitude and arrival time of the intrinsically fast input charge pulse.
3. Digital conversion of the analog samples in the ASIC so that we can avoid complex, bulky, and high-powered discrete ADCs downstream.
4. Take advantage of ASIC self-triggering capabilities to select and transfer only event data across long cables to the FPGA, where the centroiding and timing calculations will take place.

We are collaborating with Prof. Gary Varner and the Instrumentation Development Laboratory at the University of Hawaii. Our initial scheme designated the Gigasample Recorder of Analog waveforms from a PHotodetector (GRAPH) is shown schematically in Fig 2.4–2. Charge impulses from anode strips of the MCP detector come in on the left side into an array of 8 Charge Sensitive Amplifiers (CSA)s on the ASIC input. Each CSA output is continuously sampled at an adjustable sampling frequency (nominally 1 Giga-sample/s), and these analog values are held in two 64-cell analog buffers, then transferred to a larger ring buffer of 2048 (32 × 64) cells. This large 2048 analog sample storage array (one per channel) is configured in a ring-buffer topology and will overwrite in ~2 microseconds. After the analog samples arrive in the storage register, they are digitized to 10 bits using a Wilkinson ADC technique, which is very linear and low power (though relatively slow). The digital conversion then uses a comparator and register for every storage cell, and a voltage ramp is applied to every comparator while the register counts the clock cycles. When the comparator triggers, the counting stops, and the digital value now represents the analog voltage. For a 10-bit ADC, this takes up to 1024 clock cycles or ~1 microsecond. Contemporaneously with the continuous data sampling, if a CSA signal output exceeds a level set in a comparator (1 per channel), a trigger signal is generated and sent to the downstream FPGA. The FPGA will analyze which channels are triggered, and algorithmically decide which data points are to be transferred downstream through the multiplexer and Low Voltage Differential Signal (LVDS) lines to itself. In this case, a 64 × 64 strip anode using 16 ASICs, could have an output event rate of 64 MHz (one event gives a trigger in X and Y simultaneously).

FPGA system to readout GRAPH ASICs
Our proposed parallel cross strip readout system (called the PXS2) is not simply comprised of

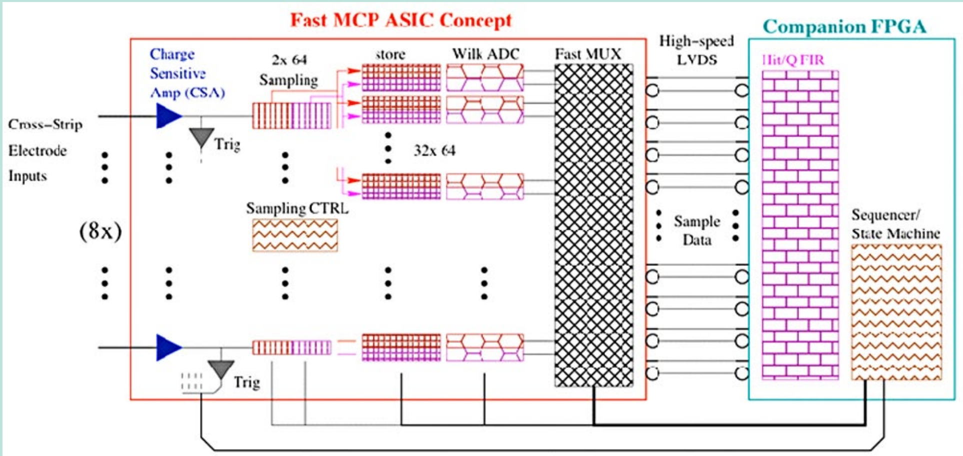


Figure 2.4–2. *Strawman ASIC design baseline schematic showing the major functional elements of the design, including the CSA, fast analog sampling and storage, Wilkinson analog to digital conversion, and fast multiplexer, all under the control of an external FPGA sequencer.*

the new ASICs. New board assemblies must be designed, laid out, and constructed to couple eight ASICs to our existing XS anodes, minimizing stray load capacitances and incorporating 64 LVDS pairs. These Digitizer ASIC boards must send their signals to a new FPGA board that not only has a new input interface, but also a new output interface to couple to the high-bandwidth computer interface required for our ultimate event rates.

Design of a 50 mm XS MCP detector incorporating new electronics
Migration of our laboratory detectors to a flight demonstrable scheme can be done in a well defined way, while allowing for the later incorporation of new developments such as high efficiency photocathodes (GaN) and novel MCPs (Borosilicate-Atomic Layer Deposits) that are currently in APRA development. Key issues for the XS MCP detector implementation include a low mass, robust construction scheme that accommodates the capability for a high vacuum sealed tube configuration. Without incurring excessive costs, a reasonable format to accomplish this is ~50 mm. Our expectations are spatial resolution of ~20 μm, background rates <0.1 events cm^2/s, low fixed pattern noise and long lifetime, ~50% quantum efficiency over much of the EUV-FUV band, multi-megahertz rate capability with low dead-time and detector mass of a few hundred grams. The design and construction of brazed-body assemblies provides for the best packaging and diversity of applications, so this is one of the core tasks. XS anodes will be baselined on the current fabrication scheme, but will also incorporate some of our recent APRA developments that reduce the anode capacitive load (and hence, noise). The overall configuration represents a device compatible for use in many current sounding rocket experiments, and can be qualified in vibration—thermal-vac cycling, etc.—in a straightforward manner. It also permits a clear path for use of GaN photocathodes and Borosilicate-ALD MCPs in the future, and is a good stepping stone for the implementation of much larger format devices for large optics/missions.

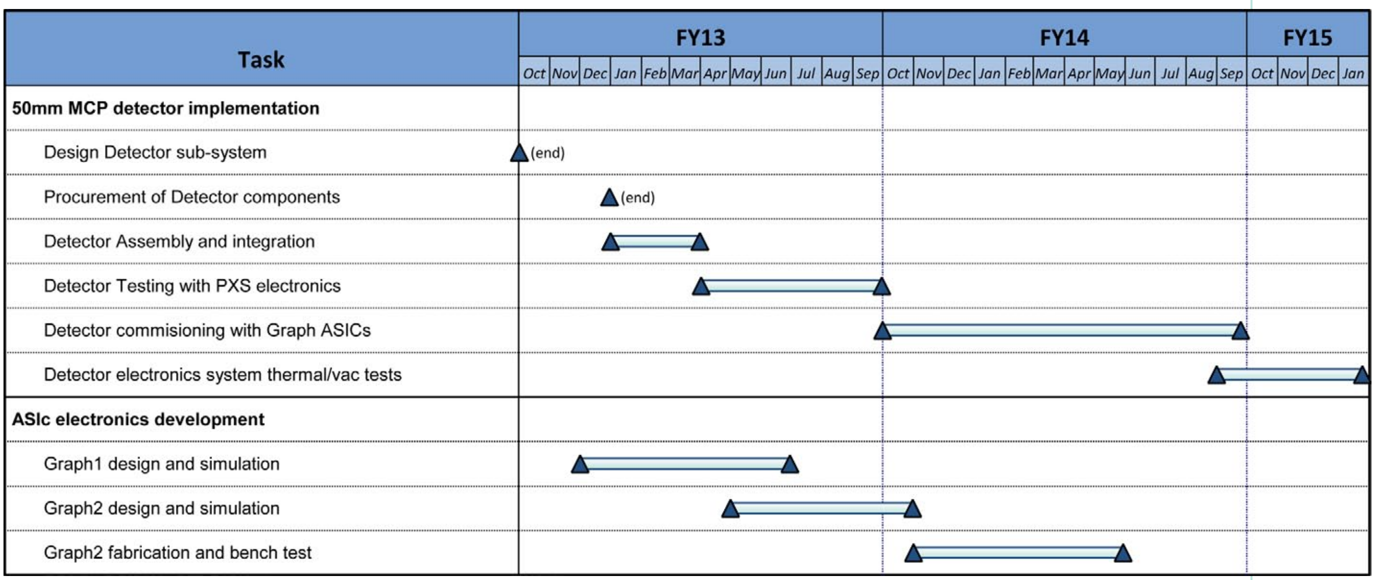
Accomplishments

Though originally proposed as a 2-year project, by mutual consent with the program office, we stretched the effort to 3 years with a resource ramp that fit better with our planned activities. Unfortunately, the contract did not get placed until May 1, 2012. However, we had previously subcontracted with the University of Hawaii on a previous project to develop an amplifier chip very similar to the front end of the new GRAPH ASIC. Testing that amplifier's (CSAv1) performance against its simulation in the first few months gave us confidence in the new front-end design, designated CSAv2, which was submitted to the Metal Oxide Semiconductor Implementation Service foundry on August 6. Multiple submissions of small subsystems of a final ASIC is a low-cost, risk minimizing strategy, and developing a low noise front-end amplifier is a key challenge of this program. The downstream fast sampling and digital conversion subsystems are less risky in that they are based on previous existing designs developed by the University of Hawaii group. We expect to receive the packaged CSAv2 dies back in early November 2012.

The GRAPH ASIC requires an FPGA sequencer/readout to produce photon events, and we have determined that our existing FPGA board can perform that function, though at limited count rates and formats. This is important because it provides a bridge to the next full performance version, and we can optimize algorithms and interfaces as inputs to the new FPGA board design.

We have initiated our 50 mm XS detector design by first reviewing a 50 mm polyimide anode design. Using polyimide as the dielectric significantly reduces the capacitance of the strips and, hence, the noise of the front end. This anode can be used on all UV detectors except sealed tube devices, which require the use of all metal/ceramic anodes for the high processing temperatures (>300°C).

Major Milestones



Future Plans/Next Steps

Now that the front-end amplifier design has been submitted for fabrication, the downstream analog sampler/digitizer designing and simulation can begin. This should be straightforward because it is based on existing sub-component designs in the library. Simulations will help us decide whether to proceed with the idea of combining this with the front end on single die or keeping them separate on two different die structures in a single package, which might have advantages in terms of noise and digital isolation. We believe we have budgeted sufficient resources for these multiple ASIC submissions.

The 50 mm detector design is also rather straightforward, in terms of mounting MCPs over anodes, where we have a long heritage of many flight-qualified designs. What is new is the 50 mm polyimide anode and figuring out the best way to interface the multiple ASICs to the strip outputs in an efficient, low capacitance package. We are also trying to be cognizant of the requirements of sealed-tube detectors in terms of electronic layouts, though we are not planning to build sealed-tube detectors because that would be cost prohibitive given the goals and resources of this program.

2.5 Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes

Prepared by: H. Philip Stahl (NASA/MSFC)

Summary

The Advanced Mirror Technology Development (AMTD) is a 3-year project initiated in FY12 to mature by at least a half-TRL step six critical technologies required to enable 4–8m ultraviolet, optical, and infrared (UVOIR) space telescope primary-mirror assemblies for both general astrophysics and ultra-high-contrast observations of exoplanets.

As part of our long-term plan, we have assembled an outstanding team of academic, industry, and government experts and organizations with extensive expertise in UVOIR astrophysics and exoplanet characterization, monolithic and segmented space telescopes, and optical manufacturing and testing. We have set up a science advisory team and integrated the team members with a systems engineering team to derive engineering specifications for advanced, normal-incidence mirrors that flow down from science measurement needs and flow up from implementation constraints. Finally, we have defined milestones to systematically mature the TRL of prioritized technical challenges using design tools to construct analytical models and prototypes/test beds to validate those models in relevant environments.

Overview and Background

Measurements at UVOIR wavelengths provide robust, often unique diagnostics for studying a variety of astronomical environments and objects. UVOIR observations are responsible for much of our current astrophysics knowledge and will produce as-yet unimagined paradigm-shifting discoveries. A new, larger UVOIR telescope is needed to help answer fundamental scientific questions, such as: Does life exist on nearby Earth-like exoplanets? How do galaxies assemble their stellar populations? How do galaxies and the intergalactic medium interact? And, how did planets and smaller bodies in our own solar system form and evolve?

According to the National Research Council (NRC) NWNH, an advanced large-aperture UVOIR telescope is required to enable the next generation of compelling astrophysics and exoplanet science. NWNH also noted that present technology is not mature enough to affordably build and launch any potential UVOIR mission concept. According to the NRC's 2012 NASA Space Technology Roadmaps and Priorities[1] report, the highest priority technology in which NASA should invest to enable "Objective C: Expand our understanding of Earth and the universe in which we live" is to develop a new generation of low-cost stable astronomical telescopes for high-contrast imaging and faint object spectroscopy to "enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects." Finally, according to the Science Instruments, Observatory and Sensor Systems (SIOSS) Technology Assessment Roadmap[2] issued by NASA's Office of the Chief Technologist, technology to enable a future UVOIR or high-contrast exoplanet mission needs to be at a TRL6 by 2018 so that a viable flight mission can be proposed to the NRC's 2020 Astronomy and Astrophysics Decadal Survey.

Objectives

Our long-term objective is to define and initiate a program to mature technologies to enable large UVOIR space telescope mirrors to TRL6 by 2018. The objectives of our current effort are to: 1) assemble an integrated team of scientists, systems engineers, and technologists; 2) derive engineering specifications that flow from science requirements; and 3) advance by at least a half-TRL six key technologies required to make an integrated primary mirror assembly (PMA) for a large-aperture UVOIR space telescope. The six critical technologies are:

- *Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:* Both (4–8m) monolithic and (8–16m) segmented primary mirrors require larger, thicker, and stiffer substrates.
- *Support System:* Large-aperture mirrors require large support systems to ensure that they survive launch and deploy on orbit in a stress-free and undistorted shape.
- *Mid/High Spatial Frequency Figure Error:* A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging applications. While a deformable mirror can correct low spatial errors, it cannot correct mid/high spatial errors.
- *Segment Edges:* The quality of segment edges impacts PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.
- *Segment-to-Segment Gap Phasing:* Segment phasing is critical for producing a high-quality and temporally stable PSF. Development is required for the alignment, phasing, sensing, and control of segment phasing.
- *Integrated Model Validation:* On-orbit performance is determined by mechanical and thermal stability. Compliance cannot be 100% tested, but relies on modeling. It is necessary to generate and validate as-built models of representative prototype components.

Accomplishments

The AMTD project was proposed as a 2-year effort starting in FY12, but was re-phased to a 3-year effort for budgetary reasons. As part of the re-phrasing, some tasks were deferred. Of our six critical technology areas, only four had activity in FY12 (Fig. 2.5–2). To date, all of our FY12 tasks have either been accomplished or are in process and anticipated to be completed on schedule.

While not a defined technology milestone metric, we did assemble an outstanding team of academic, industry, and government experts and organizations with extensive expertise in UVOIR astrophysics and exoplanet characterization, monolithic and segmented space telescopes, and optical manufacturing and testing. The Science Advisory Team met four times and, in collaboration with the Systems Engineering Team, has compiled a draft on-orbit performance document. This document derives from desired science requirements the on-orbit performance specifications for 4m and 8m monolithic aperture telescopes, including: system wavefront error, encircled energy, wavefront error stability, encircled energy stability, and pointing stability. Additionally, this document defines the requirements for the primary-mirror assembly, including surface error as a function of spatial frequency and surface error stability. In FY13, the Science Advisory and System Engineering teams will extend the document to include segmented mirror specifications including: segment size, segment edge requirements, segment gap stability, and segment phasing requirements.

The mirror substrate technology milestone is on-schedule, and we expect to complete all four of its required tasks in FY12. A trade study was performed that compared the advantages and disadvantages of two approaches for making 4m face and back sheets: plano/plano versus pocket milled. The pocket milled approach was selected because it is faster and lower risk.

With the plano/plano method, the front and back sheets start as thick sheets of glass, and then both sides are ground and polished to their final thickness. This is a slow and potentially risky process. In the pocket milled design, the face and back sheets are ground and polished to a much thicker dimension, saving considerable processing time. Pockets are then water-jet milled into the thick sheets until the final face and back sheet thicknesses are achieved. Again, this is a much faster and lower risk process. A second trade study was performed to evaluate the utility of adding a thin sheet of glass between the stacked core layers. This layer was proposed to aid in stacking the cores and to add potential stiffness. However, because this structural element is close to the center of system mass, it adds very little stiffness benefit at the expense of increased mass. Therefore, it was decided not to pursue an intermediate layer.

Because of these trade studies, it was decided to make only one subscale mirror instead of two (and keep the surplus glass in reserve in case of breakage). Originally, we proposed to make two 200 mm-deep (approximately 100 mm-diameter) deep-core substrates—one using plano/plano, and the other using pocket milled. After eliminating the plano/plano approach, we decided to make a single subscale deep-core substrate of approximately 400 mm in diameter and 400 mm thick. And, instead of using two stacked core elements, we decided to use three stacked core elements. We believe that this subscale substrate has better traceability to a potential 4m mirror. The 4-cm subscale substrate is currently being fabricated. Fig. 2.5–1 shows the front and back sheets along with two of the three core elements.

Figure 2.5–1. *Left:This image shows the top and bottom face plates. Right: This image shows two of the three deep-core subscale substrate elements.*

The key technology advance of this activity is to demonstrate the feasibility of making deep-core mirror substrates by stacking smaller, thinner core elements. Smaller, thinner core elements can be made quickly, in parallel, on conventional water-jet cutting machines. This reduces processing time and cost as well as mitigates the impact and expense of potential processing errors. And, while we did experience some small process anomalies during the fabrication of the subscale substrate, resulting in the loss of one pocket rib, we do not expect any performance degradation.

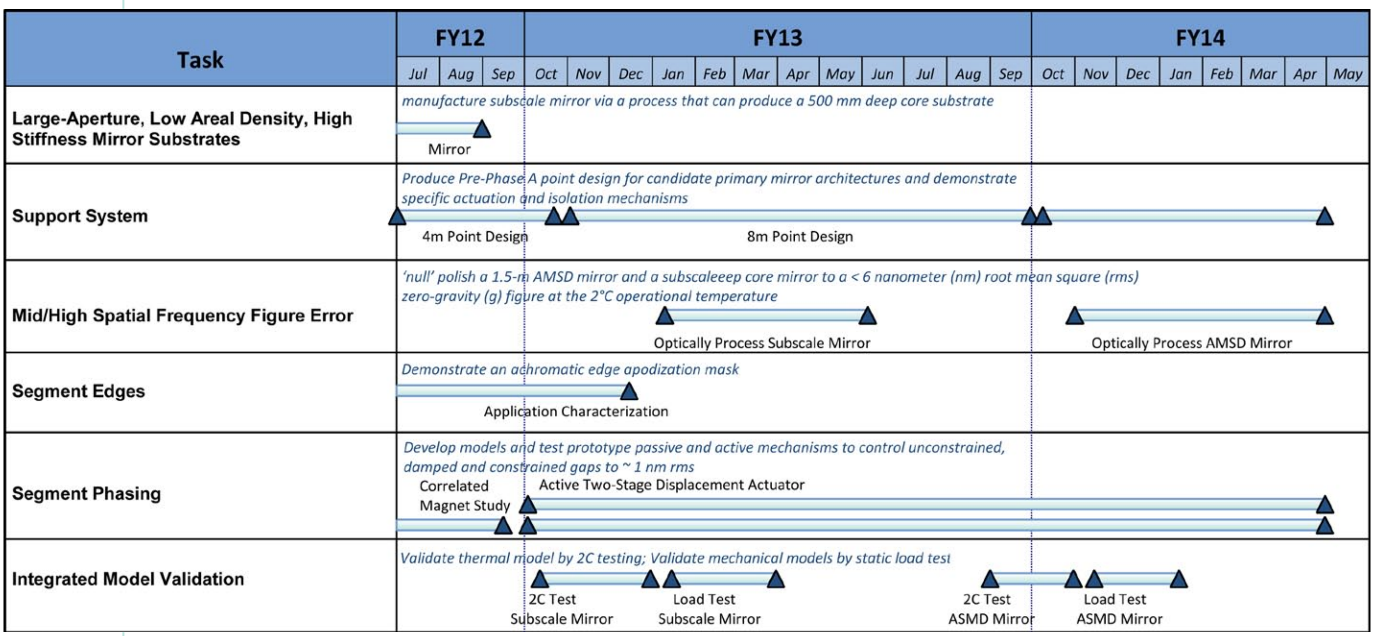
The support structure technology milestone is on-schedule, and we expect to complete a pre-Phase-A point design of a 4m primary-mirror assembly by the end of FY12. A new modeler tool has been developed in Visual Basic for an ANSYS® Finite Element Model (FEM). This tool allows the rapid creation and analysis of detailed mirror substrate designs. This tool is a recreation of a similar tool that was used to design the mirror substrate for NASA's Kepler satellite's primary mirror.

To achieve the segment edge control technology milestone, one task remains to be completed in FY12: to demonstrate a broadband achromatic-edge apodization mask to mitigate the effect of diffraction in advanced coronagraph designs. A chromium-on-glass grayscale prototype mask has been fabricated and, at the time of this report, is being tested at the Brookhaven National Laboratory beam line. When used at a high focal ratio, the synchrotron beam simulates collimated starlight. The purpose of the test is to use a Fourier Transform Spectrometer to measure the mask's transmission (to an accuracy of approximately 0.1%) from 500 nm to 1000 nm.

To achieve the segment phasing technology milestone, one task also remains to be completed in FY12: to evaluate the utility of correlated magnetic interfaces for segment phasing. To eliminate the effect of eddy-current dampening, a Delrin plastic pendulum test setup was constructed. At present, multiple correlated magnetic interfaces are undergoing testing. However, at the time of this report, analysis of the data is not complete.

Milestones, Schedule, and Future Plans

To achieve our objective, we have established quantifiable milestones for each of our key technologies. The solid lines are defined tasks. The gradient lines are tasks that we hope to do if the budget and schedule permit. Because the project was re-phased from 2 to 3 years, some tasks were delayed until FY14. Only four of our key technology developments had activity in FY12. Furthermore, none of our FY12 activities were scheduled to reach their completion milestones until after the time of this report.



FY12 Milestone Activities:

- **Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:** Manufacture a deep-core subscale mirror via a process that can produce 500 mm-deep mirrors.
- **Support System:** Produce a pre-Phase-A point design for a 4m candidate primary-mirror assembly.
- **Segment Edges:** Demonstrate an achromatic-edge apodization mask.
- **Segment-to-Segment Gap Phasing:** Study the utility of the Correlated Magnetic Interface.

FY13/14 Milestone Activities:

- **Support System:** Produce a pre-Phase-A point design for an 8m candidate primary-mirror assembly.
- **Mid/High Spatial Frequency Figure Error:** Demonstrate the ability to 'null' polish a 1.5m AMSD mirror and subscale mirror to a <6 nm rms at 2°C.
- **Segment Edges:** Finish the demonstration of an achromatic-edge apodization mask.
- **Segment-to-Segment Gap Phasing:** Demonstrate active two-stage actuation/vibration isolation mechanisms; if warranted, test prototype passive and active correlated magnetic interface mechanisms.
- **Integrated Model Validation:** Validate the thermal model by 2°C testing AMSD. Validate mechanical model by static load test AMSD.

References

[1]"NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space"; Steering Committee for NASA Technology Roadmaps; National Research Council of National Academies; 2012

[2]"Science Instruments, Observatories, and Sensor Systems Roadmap: Technology Area 08"; Richard D. Barney, Chair, Jill J. Bauman, Lee D. Feinberg, Daniel J. Mccleese, Upendra N. Singh, H. Philip Stahl; NASA Office of Chief Technologist; April 2012

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3 Program Technology Needs

The first step in prioritizing the Program's technology needs is to identify and gather all of the perceived needs from the astrophysics community of scientists and technologists. As input to the technology development process, the Program Office (PO) invites potential stakeholders to provide a listing of what they identify as technology needs that can enable or enhance current and future missions within the Program's science portfolio. Input from the community comes through the Cosmic Origins Program Analysis Group (COPAG), and through an outreach program that targets both meeting venues and potential providers of specific technologies. The COPAG, whose Chair is a member of the NASA Astrophysics Subcommittee, supports community coordination and analysis of scientific and technological issues impacting NASA's COR Program. A technology need can be derived by anyone and provided to the PO for prioritization in two ways. The first way is to work with the COPAG to include it in the consolidated listing in response to the solicitation by the PO. The second way is to download, fill out, and submit the "Program Technology Needs Input" form located on the COR Program website, http://cor.gsfc.nasa.gov/technology/. Although technology needs are solicited annually and collected at the end of June to begin the annual prioritization process, they can be submitted to the PO at any time. After collection, consolidation, and tabulation, the inputs are then used by the Program's Technology Management Board (TMB) to evaluate and prioritize all the needs according to a set of prioritization criteria. These criteria are shown and described in detail in Section 4 of this report.

For this year's prioritization, in collaboration with the COPAG, the TMB assessed the technology needs submitted last year because they are still relevant, along with three newly identified needs for a total of 15 technologies. The 2012 technology needs collected are shown in Tables 3–1, 3–2, and 3–3.

The science and research community is encouraged to continue to submit technology needs that enable current and future COR science objectives. The main conduit for collecting program technology needs is through the COPAG. However, direct submission to the PO via the COR website is also acceptable. Next year, both input formats will be coordinated so that the same information will be available in the COPAG submission and the direct Program Office submission.

The PO encourages inputs that include as much of the information requested as possible and, most importantly, the technology's goals and objectives should be clear and quantified. For example, stating that "a better cryocooler is needed" is a paucity of detail. A complete description with specific performance goals based on mission needs would be far more valuable. This best allows the TMB to assess the need, NASA HQ to develop proposal calls, and the research community to be informed and to match candidate technologies and mission needs. If specifying the technical parameters is not possible due to the competition sensitivity of the information, then the submitter should consider specifying the ranges or targets of the important technical parameters. When relevant, the submitter should quantitatively and qualitatively explain how the need exceeds the current state-of-the-art. Additionally, a clear description of potential relevant NASA missions or applications is needed for the prioritization process. It would be instructive to view these inputs as a mini-proposal. The more relevant and compelling the case, the more likely it will receive favorable prioritization and/or funding recommendations.

For each need shown in the technology needs tables, information was provided for the following categories:

- **Brief description:** summarizes the technology need and the associated key performance criteria for the technology. In general, technology needs that are well defined will tend to receive higher prioritization than those that are vague.
- **Goals and objectives:** details the goals and/or objectives for a candidate technology to fill the described need. For example, "The goal is to produce a detector with a sensitivity of *X* over a wavelength of *Y* to *Z* nm." Technology needs with objectives that are clearly quantified will receive higher prioritization than those without quantified objectives.
- **TRL:** specifies the current Technology Readiness Level(s) of the technology per NASA Procedural Requirements (NPR) 7120.8.
- **Tipping point:** provides a timeframe during which the technology's state-of-the-art, as assessed by the submitter, can be brought to a level where its eventual viability can be assessed. This can be when the technology reaches the mid TRL thresholds (4, 5, or 6).
- **NASA capabilities:** describes NASA's current capability to implement and/or access the technology.
- **Benefit:** describes the scientific, engineering and/or programmatic benefits of fulfilling the technology need. If the need is enabling, then describe how and/or why. If the need is enhancing, then describe, and if possible quantify, the impact. Benefits could be scientific (i.e., better science output), engineering (e.g., lower mass), or programmatic (i.e., reduced cost or schedule). For example, "Material *X* is 50% stronger than the current state of the art and will enable the optical subsystem for a 2m telescope to be *Y* kg lighter." Technology needs with greater potential mission benefits will receive higher prioritization.
- **NASA needs:** details specific needs and performance requirements for NASA mission concepts.
- **Non-NASA but aerospace needs:** details specific needs and performance requirements for applications outside of NASA mission concepts and within the aerospace sector.
- **Non-aerospace needs:** describes specific needs and performance requirements for all other needs (not covered in the previous two categories).
- **Technical risk:** describes the known technical risks in developing the technology.
- **Sequencing/timing:** describes when the technology will be needed to support anticipated mission needs. Technology needs with the shorter time windows relative to required development times will receive higher prioritization.
- **Time and effort:** estimates the duration and scope of the technology development effort.

In addition to the above categories and to further inform the TMB during prioritization, the Program Office technology needs input form also requested the following information:

- **<u>Technology is enabling or enhancing:</u>** describes whether fulfilling the technology need is required to meet the associated missions' objectives, which makes the technology enabling, or whether it is an enhancing technology, because fulfilling the need would have significant benefits but is not absolutely required.
- **<u>Potential relevant missions:</u>** identifies future NASA missions or applications for which the technology need is relevant and discusses how the need applies. Technology needs with

significant relevance to highly ranked missions or applications will be prioritized favorably.

- **Potential providers, capabilities, and known funding:** identifies any known potential providers of relevant technology. Describes the current capability as it relates to the technology need and any information regarding current funding sources for relevant technology development.

COR Technology Needs—Table 1 of 3

Name of technology	High QE, large format UV detectors	Photon counting UV large-format detectors	High Reflectivity UV coatings	Large, low-cost, lightweight precision mirrors for Ultra-Stable Large Aperture UV/visible Telescopes	Deployable lightweight precision mirrors for future Very Large Aperture UV/visible Telescopes	Very large format, low noise visible/IR detector arrays
Brief description (1024)	Future NASA UV missions, require high quantum efficiency (>70%), large-format (>2k × 2k) detectors for operation at 100–400nm or broader.	Future NASA UV missions, particularly those devoted to spectroscopy, require high quantum efficiency (>50%), low noise (<1e-7 ct/pixel/s), large-format (>2k × 2k) photon-counting detectors for operation at 100–400nm or broader.	High reflectivity, highly uniform UV coatings are required to support the next generation of UV missions, including explorers, medium missions, and a UV/visible large mission. High reflectivity coatings allow multiple reflections, extended bandpasses, and accommodate combined UV and high-contrast exoplanet imaging objectives.	Future UV/visible telescopes will require increasingly large apertures to answer the questions raised by HST, JWST, Planck and Hershel, and to complement the ≥ 30m ground-based telescopes that will be coming on line in the next decade. For diffraction limited performance, the pointing budget gets tighter as aperture grows and wavelengths shrink, requiring $\theta \sim 0.1$ λ/D pointing accuracy. Technologies are therefore required that provide a high degree of thermal and dynamic stability, and wave front sensing and control.	Future UV/visible telescopes will require increasingly large apertures to answer the questions raised by HST, JWST, Planck and Hershel, and to complement the ≥ 30m ground-based telescopes that will be coming on line in the next decade. For diffraction limited performance, the pointing budget gets tighter as aperture grows and wavelengths shrink, requiring $\theta \sim 0.1$ λ/D pointing accuracy. Technologies are therefore required that provide a high degree of thermal and dynamic stability, and wave front sensing and control.	Future NASA visible/near-IR missions require large format detector arrays mosaicable in formats of ~Gpix, covering wavelengths from the visible to 1.7 µm.
TABS category	8.1.1	8.1.1	8.1.3	8.1.3	8.1.3	8.1.1
Goals and Objectives	The goal is to produce large-format, high QE, low-noise UV-sensitive detectors routinely that can be employed in a variety of explorer, medium, and strategic missions.	The goal is to produce large-format, high QE, low-noise UV-sensitive detectors routinely that can be employed in a variety of explorer, medium, and strategic missions.	Development of UV coatings with high reflectivity (>90–95%), high uniformity (<1-0.1%), and wide bandpasses (~100 nm to 300–1000 nm). New coating technologies such as Atomic Layer Deposition are particularly promising. Some will be required for large optics (0.5–4m), many for smaller instrument visible elements.	Develop lightweight UV and visible mirrors with Areal density <20kg/m^2, surface roughness 5 to 10 nm rms, cost <\$2M/m^2, for telescopes with ~50 m^2 aperture,<1 mas pointing accuracy, and < 15 nm rms stability.	Develop deployable lightweight UV and visible mirror architectures with areal density <20kg/m^2, surface roughness 5 to 10 nm rms, for telescopes with > 100 m^2 aperture,<1 mas pointing accuracy, and < 15 nm rms stability.	Develop high QE, low noise visible/IR arrays that can produce focal planes of a gigapixel.
TRL	Silicon-CCD detectors are TRL4–5. Other technologies (MCP, APD) are TRL2–4.	Silicon-CCD detectors are TRL4–5. Other technologies (MCP, APD) are TRL2–4.	Depending on the coating and approach these range from TRL3–5.	Lightweight 1.3m Be and SiC mirrors are TRL6. Borosilicate glass mirrors are TRL5. Larger mirrors are TRL2–3	Lightweight 1.3m Be and SiC mirrors are TRL6. Borosilicate glass mirrors are TRL5. Larger mirrors are TRL 2–3	CCDs and HgCdTe arrays in megapixel formats are TRL >6.

Table 3–1. *Technology needs for future COR missions identified by the astrophysics community of scientists and technologists.*

Page 1 of 3

COR Technology Needs—Table 1 of 3

Name of technology	**High QE, large format UV detectors**	**Photon counting UV large-format detectors**	**High Reflectivity UV coatings**	**Large, low-cost, lightweight precision mirrors for Ultra-Stable Large Aperture UV/visible Telescopes**	**Deployable lightweight precision mirrors for future Very Large Aperture UV/visible Telescopes**	**Very large format, low noise visible/IR detector arrays**
Tipping point (100 words or less)	TRL6 with Si-CCD detectors can be achieved in ≈2 years with modest funding investment; in APDs later.	TRL6 with APDs detectors can be achieved in ≈3 years with moderate funding investment.	Relatively modest investment can determine the best approaches and scalability of various coatings and coating techniques.	One or more mirror technologies can be matured to meet requirements with reasonable investments in 3–5 years.	One or more mirror technologies can be matured to meet requirements with reasonable investments in 3–5 years.	Credible path to gigapixel imager can be achieved in ≈2 years with very modest funding investment with an industry partner.
NASA capability (100 words of less)	NASA is partnering with industry to produce these detectors.	NASA is partnering with industry to produce these detectors.	NASA has capabilities for UV coatings at GSFC and JPL to ~10 cm for ALD coating development. Large optics will require more significant investments. NASA-private industry partnerships are possible and likely particular for matured coating techniques.	NASA has the necessary capabilities at GSFC, MSFC, and JPL to develop these UV/visible mirror technologies in partnership with industry	NASA has the necessary capabilities at GSFC, MSFC, and JPL to develop these UV/visible mirror technologies in partnership with industry	NASA has partnered with industry to produce these detectors.
Benefit	High-performance detectors can increase the science impact of missions by 10–1000.	High-performance detectors can increase the science impact of missions by 10–1000.	High coating reflectivity in UV make possible high-performance visible systems that can be highly multiplexed, significantly increasing the potential impact of future missions High uniformity will allow a combined general UV/visible and exoplanet imaging mission, which could provide a natural follow-on to JWST.	Low-cost, lightweight optics are required to enable the development of large-aperture UV/visible telescopes in the 2020 decade. Large aperture telescopes are required to provide the spatial resolution and sensitivity needed to follow up on discoveries with the current generation of space telescopes.	Low-cost, ultra-lightweight optics are required to enable the development of very large-aperture UV/visible telescopes in the 2030+ decades. Large aperture telescopes are required to provide the spatial resolution and sensitivity needed to follow up on discoveries with the next generation of space telescopes.	Future missions with large area imaging or multiobject spectroscopic drivers operate ~100 times faster than present.
NASA Needs	Current MCP-based UV detectors obtain ~5–20% QE, require high voltage, and can be difficult to fabricate. The science impact of cost-constrained, aperture-constrained future missions is dramatically improved by reaching near-perfect detector performance. 2010 Astro Decadal survey noted importance of technology development for a future 4m-class UV/visible mission for spectroscopy and imaging. Benefits will also accrue to Planetary, Heliospheric, and Earth missions in the UV band.	Current UV detectors obtain ~5–20% QE, require high voltage, and can be difficult to fabricate. The science impact of cost-constrained, aperture-constrained future missions is dramatically improved by reaching near-perfect detector performance. 2010 Astro Decadal survey noted importance of technology development for a future 4m-class UV/visible mission for spectroscopy and imaging. Benefits will also accrue to Planetary, Heliospheric, and Earth missions in the UV band.	2010 Astro Decadal survey noted importance of technology development for a future 4m-class UV/visible mission for spectroscopy and imaging. Benefits will accrue to Planetary, Heliospheric, and Earth missions utilizing the UV band.	This technology is a key enabling technology for NASA's next large UV/visible mission.	This technology is a key enabling technology for a far future very large UV/visible mission.	This technology is a key technology of benefit for NASA's next large UV/visible mission.

Table 3–1. *Technology needs for future COR missions identified by the astrophysics community of scientists and technologists.*

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COR Technology Needs—Table 1 of 3

Name of technology	High QE, large format UV detectors	Photon counting UV large-format detectors	High Reflectivity UV coatings	Large, low-cost, lightweight precision mirrors for Ultra-Stable Large Aperture UV/visible Telescopes	Deployable lightweight precision mirrors for future Very Large Aperture UV/visible Telescopes	Very large format, low noise visible/IR detector arrays
Non-NASA but aerospace needs	High-performance UV detectors can have numerous aerospace applications, remote-sensing, situational awareness, etc.	High-performance UV detectors can have numerous aerospace applications, remote-sensing, situational awareness, etc.	UV sensors require high-performance visible systems that benefit greatly from UV coating improvements.	This technology is critically important for many remote sensing missions sponsored by other government agencies	This technology may connect with many remote sensing missions sponsored by other government agencies	High-performance visible/IR detector mosaics can have numerous aerospace applications, remote-sensing, situational awareness, etc.
Non-aerospace needs	High-performance UV detectors may have applications in bio and medical imaging.	High-performance UV detectors may have applications in bio and medical imaging.	Unknown but could be important.	Ground-based, airborne, balloon and sounding rocket telescopes could all benefit from this technology.	Unknown but could be important.	High-performance visible/IR detectors may have applications in bio and medical imaging.
Technical risk	Technical risk of Si-CCD detectors is low-moderate because of prior investments in Si detector and CCD processing.	Technical risk of Si-CCD detectors is low-moderate because of prior investments in Si detector and CCD processing.	Technical risk is low to moderate. Facilities and techniques exist for small visible elements. Moderate risk in scaling to large optics.	Technical risk is moderate because the development effort is an extension of activities currently planned or underway at several government, academic, and industrial facilities.	Technical risk is moderate because the development effort is an extension of activities currently planned or underway at several government, academic, and industrial facilities.	Technical risk is low, as basic technology is mature.
Sequencing/ timing	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since mission definition and capabilities are built around coating performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since technology is applicable to small, medium and large missions. By 2020 for the next large UV astrophysics mission.	Must follow developments for near-term lightweight mirror segments. By 2030 for the far future large UV astrophysics mission.	Should come early since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.
Time and effort	5-year collaboration between NASA, university groups, and industry.	5-year collaboration between NASA, university groups, and industry.	5-year collaboration between NASA, university groups, and industry.	5-year collaboration between NASA, university groups, and industry.	5-year collaboration between NASA, university groups, and industry.	3-year collaboration between NASA, industry, and other government agencies.

Table 3–1. *Technology needs for future COR missions identified by the astrophysics community of scientists and technologists.*

Page 3 of 3

COR Technology Needs—Table 2 of 3

Name of technology	**Photon counting visible/IR detector arrays**	**Large format, low noise Far-IR direct detectors**	**Ultralow-noise far-IR direct detectors**	**Large, cryogenic far-IR telescopes**	**Interferometry for far-IR telescopes**	**High-Performance Sub-Kelvin Coolers**
Brief description (1024)	Future NASA visible/near-IR missions require high QE, fast response time photon counting detector arrays to cover the visible and near-infrared.	Future NASA far-IR missions require large format detectors optimized for the very low photon backgrounds present in space. Arrays containing up to tens of thousands of pixels are needed to take full advantage of the focal plane available on a large, cryogenic telescope. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	Future NASA far-IR missions require detectors optimized for the very low photon backgrounds present in space for spectroscopy. Arrays containing up to thousands of pixels are needed to take full advantage of the spectral information content available. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	Large telescopes provide both light gathering power, to see the faintest targets, and spatial resolution, to see the most detail and reduce source confusion. To achieve the ultimate sensitivity, their emission must be minimized, which requires that these telescopes be operated at temperatures that, depending on the application, have to be as low as 4K. Collecting areas on the order of 10m are needed.	Interferometry in the far-IR provides spatial resolution to see the most detail and reduce source confusion. Structurally connected or free-flying Interferometric telescope systems are required for far-future missions in the far-IR. Telescopes are operated at temperatures that have to be as low as 4K.	Optics and detectors for far-IR and certain X-ray missions require very low temperatures of operation, typically well below 1K. Compact, low-power, lightweight coolers suitable for space flight are needed to provide this cooling.
TABS category	8.1.1	8.1.1	8.1.1	8.1.3	8.1.3	8.1.3
Goals and Objectives	Develop high QE photon counting detectors for wavelengths of around 400 nm–1.7 μm.	Detector format of at least 32 × 32 with high filling factor and with sensitivities (noise equivalent powers) of 10 19 W/√Hz are needed for photometry.	Detector sensitivities with noise equivalent powers of $\approx 3 \times 10^{-21}$ W/√Hz are needed for spectroscopy, arrayable in a close-packed configuration in at least one direction.	The goal is to develop a feasible and affordable approach to producing a 10m-class telescope with sufficiently high specific stiffness, strength, and low areal density to be launched, while maintaining compatibility with cryogenic cooling and far-IR surface quality/figure of ~1 μm RMS.	The goal is to develop a feasible and affordable approach to producing a 40m-class interferometer capable of launch and operation, while maintaining compatibility with cryogenic cooling and far-IR surface quality/figure of ~1 μm RMS.	A cryocooler operating from a base temperature of ~4K and cooling to <0.1K with a continuous heat lift of 10 μW is required for several mission concepts. Features such as compactness, low power, low vibration, intermediate cooling, and other impact-reducing design aspects are desired.
TRL	APDs for the near-IR are under development in industry, but are low TRL (~2).	Single detectors are at ~TRL5, but demonstrated array architectures are lagging at ~TRL3.	Single detectors are approaching TRL3.	JWST Be mirror segments may meet requirements now, so TRL5 with an extremely expensive technology; TRL3 exists for other materials.	Interferometry demonstrated at visible wavelengths in labs; far-IR interferometry on a balloon expected in ~4 years. TRL~3.	Existing magnetic refrigeration demonstrations have achieved TRL3–4.
Tipping point (100 words or less)	TRL6 will be achieved via substantial military investments, but optimization for low-background purposes could be a modest NASA effort.	TRL5 with transition edge sensors could be achieved within 3 years with moderate investment; with MKIDs within 4–5 years.	TRL4–5 with transition edge sensors could be achieved within 3 years with moderate investment; with MKIDs within 4–5 years.	TRL4 could be achieved within 3 years with modest investments using existing materials.	TRL5 could be achieved within 5 years with moderate investments building on existing efforts.	TRL5 could be achieved within 3 years with modest investments based on existing demonstration.
NASA capability (100 words or less)	NASA will likely have to partner with industry to produce these detectors.	NASA has laboratory fabrication facilities at GSFC and JPL currently working at a low level on these technologies.	NASA has laboratory fabrication facilities at GSFC and JPL currently working at a low level on these technologies.	NASA has cryogenic mirror testing capabilities at GSFC, MSFC, and JPL; mirror production would likely rely on industry partnerships.	NASA has performed cryogenic Interferometric testbed work.	NASA has cryogenic refrigerator fabrication and testing capabilities at GSFC, with some relevant experience at JPL.

Table 3–2. *Technology needs for future COR missions identified by the astrophysics community of scientists and technologists.*

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COR Technology Needs—Table 2 of 3

Name of technology	Photon counting visible/IR detector arrays	Large format, low noise far-IR direct detectors	Ultralow-noise far-IR direct detectors	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	High-Performance Sub-Kelvin Coolers
Benefit	Future missions with spectroscopic drivers operate ~100 times faster than present. Distant missions (beyond the Zodiacal dust cloud) will observe significantly (>10×) faster even in imaging applications.	Sensitivity reduces observing times from many hours to a few minutes (≈100× improvement), while array format increases areal coverage by a 10×–100×. Overall mapping speed can increase by factors of thousands.	Sensitivity reduces observing times from many hours to a few minutes (≈100× improvement). Overall observing speed can increase by factors of thousands.	Low-cost, lightweight cryogenic optics are required to enable the development of large-aperture far-IR telescopes in the 2020 decade. Large apertures are required to provide the spatial resolution and sensitivity needed to follow up on discoveries with the current generation of space telescopes.	Large baselines are required to provide the spatial resolution needed to follow up on discoveries with the next generation of space telescopes.	Sub-Kelvin cryocoolers are required to enable the use of far-IR telescopes in the next decade, and are similarly necessary for certain X-ray detectors.
NASA Needs	This technology is a key technology of benefit for NASA's next large UV/Optical/IR mission.	Far-IR detector technology is an enabling aspect of all future far-IR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. However, the development serves astrophysics almost exclusively (with some impact to Planetary and Earth studies).	Far-IR detector technology is an enabling aspect of all future far-IR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. However, the development serves astrophysics almost exclusively (with some impact to Planetary and Earth studies).	This technology is a key enabling technology for any future NASA-built far-IR mission.	This technology is a key enabling technology for a far future NASA-built far-IR mission.	This technology is a key enabling technology for any future NASA-built far-IR mission.
Non-NASA but aerospace needs	High-performance visible/IR photon counting detectors have numerous aerospace applications, remote-sensing, situational awareness, etc.	This technology is primarily needed and supported by NASA.	This technology is primarily needed and supported by NASA.	Lightweight telescopes are critically important for remote sensing applications.	Unknown but could be important.	This technology is primarily needed and supported by NASA.
Non-aerospace needs	High-performance visible/IR photon counting detectors may have applications in bio and medical imaging.	Large-format arrays are needed by suborbital astrophysics missions, and similar technologies find application in airport screening devices for DHS.	Unknown but could be important.	Ground-based, airborne, balloon and sounding rocket telescopes could all benefit from this technology.	Unknown but could be important.	Ground-based, airborne, balloon and sounding rocket telescopes could all benefit from this technology; other laboratory needs could be fulfilled with commercialization.

Table 3–2. *Technology needs for future COR missions identified by the astrophysics community of scientists and technologists.*

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COR Technology Needs—Table 2 of 3

Name of technology	Photon counting visible/IR detector arrays	Large-format, low-noise far-IR direct detectors	Ultralow-noise far-IR direct detectors	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	High-Performance Sub-Kelvin Coolers
Technical risk	Technical risk is moderate, as basic technology has significant prior investment.	Technical risk for individual detectors is low, as the approach is relatively mature. Large-format array technologies include integrated readout devices, which have moderate development risk.	Technical risk for individual detectors is low, as the approach is relatively mature. Large-format array technologies include integrated readout devices, which have moderate development risk.	Technical risk is low, as development of many other mirror materials leverages large existing investments in industry; NASA needs in the near term can be demonstrated by testing existing technologies.	Technical risk is moderate, as maturity is lacking.	Technical risk is low, as development leverages previous investments at NASA.
Sequencing/ timing	Should come early since mission definition and capabilities are built around detector performance.	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since technology is applicable to small, medium, and large missions. By 2020 for the next large far-IR astrophysics mission.	Must follow further results from prototype efforts. Underway by 2020 for the next large far-IR astrophysics mission.	Would be beneficial to undertake soon since technology is applicable to small, medium, and large missions. By 2020 for the next large far-IR astrophysics mission.
Time and effort	5-year collaboration between NASA, industry, and other government agencies.	3-year collaboration between NASA, university groups, and other government agencies.	3-year collaboration between NASA, university groups, and other government agencies.	3-year collaboration between NASA and industry.	5-year collaboration between NASA and industry.	3-year effort at NASA.

Table 3–2. *Technology needs for future COR missions identified by the astrophysics community of scientists and technologists.*

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COR Technology Needs—Table 3 of 3

Name of technology	Coherent far-IR detector arrays	High-Efficiency Cryocoolers	High-Efficiency Spectrometers
Brief description (1024)	NASA's SOFIA mission could achieve a significant observational capability increase by upgrading its single-pixel coherent (heterodyne) spectrometers to arrays.	Optics and refrigerators for far-IR and certain X-ray missions require very low temperatures of operation, typically roughly 5K. Compact, low-power, lightweight coolers suitable for space flight are needed to provide this cooling.	Future NASA UV missions, devoted to spectroscopy, require high throughput (>50%), multi-object spectrometer (>100 sources; R~3000 or greater) architectures for operation at 100–400 nm or broader.
TABS category	8.1.1	8.1.3	8.1.1
Goals and Objectives	Develop broad tunable bandwidth array receivers for operation at frequencies of 1THz–5THz, Arrays of at least 16 pixels would be required to have significant impact. Could include local oscillator and backend technologies suited for r.	A cryocooler operating from a base temperature of ~300K and cooling to <5K with a continuous heat lift of 100 mW with <200 W of input power/s required for several mission concepts.	The goal is to produce large-format, high QE, moderate resolution routinely that can be employed in a variety of explorer, medium, and strategic missions.
TRL	For SOFIA, only single pixel receivers have been developed for flight; arrays of 16 pixels are approaching TRL4.	Existing Stirling and J-T coolers with worse performance are high TRL.	
Tipping point (100 words or less)	TRL4–5 could be achieved within a few years, and would enable flight opportunities on SOFIA	TRL5 could be achieved within 3 years with modest investments based on existing demonstration.	
NASA capability (100 words or less)	NASA has laboratory fabrication facilities at JPL currently working at a low level on these technologies.	Industry is best-placed for this work.	
Benefit	Observations would be significantly (>10×) faster even in imaging applications.	Large-capacity cryocoolers are required to enable the use of far-IR telescopes in the next decade, and are similarly necessary for certain X-ray detectors.	High-performance spectrometers can increase the science impact of missions by 100.
NASA Needs	This technology is a key technology of benefit for NASA's next SOFIA instruments (3rd Gen).	This technology is a key enabling technology for any future NASA-built far-IR mission.	
Non-NASA but aerospace needs	Such receivers have numerous aerospace applications, remote-sensing, situational awareness, etc.	This technology is primarily needed and supported by NASA.	
Non-aerospace needs	Similar technologies find application in airport screening devices for DHS.	Ground-based, airborne, balloon, and sounding rocket telescopes could all benefit from this technology; other laboratory needs could be fulfilled with commercialization.	
Technical risk	Technical risk is moderate, as basic technology has significant prior investment.	Technical risk is low, as development leverages previous investments at NASA.	
Sequencing/timing	Should come early since SOFIA 3rd Gen proposals are anticipated within a few years.	Would be beneficial to undertake soon since technology is applicable to small, medium and large missions. By 2020 for the next large far-IR astrophysics mission.	Should come as early as possible since mission definition and capabilities are built around instrument performance. There is a clear plan to achieve this technology. Users identified.
Time and effort	5-year collaboration between NASA, industry, and other government agencies.	3-year effort in industry.	3-year collaboration between NASA, university groups, and industry; suborbital?

Table 3–3. *Technology needs for future COR missions identified by the astrophysics community of scientists and technologists.*

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4 Program Technology Priorities, Recommendations, and Funding Results

Technology Priorities and Recommendations

Section 3 discusses how the community technology needs are collected by the Program Office. As discussed here in Section 4, as part of the annual technology needs prioritization process, after the needs list was compiled, the Technology Management Board (TMB) scored these needs according to an agreed-upon set of evaluation criteria. The results of this process are included herein.

Membership of the TMB includes senior members of the Astrophysics Division at NASA Headquarters and the COR Program Office. Subject matter experts, consultants, and internal/external personnel are included as needed. For 2012, the Board used a prioritization approach very similar to that used in 2011. The evaluation was based on 11 criteria. These criteria address the strategic alignment, benefits and impacts, timeliness, and effectiveness of investment of each technology need. These criteria are summarized in Table 4–1 and have been carried over from 2011 with minor changes to the score definitions to account for lessons learned. For each criterion, a weight is assigned that is intended to reflect the importance that the COR Program places on that criterion. These were unchanged from 2011. Each criterion for each technology received a score of 0 to 4 in the evaluation. The score was multiplied by the established weight for the criterion, and this product is summed across all criteria for each technology.

The criteria are described below:

1. **Scientific ranking of applicable mission concept:** The intent is that the technology needs associated with missions ranked highly by a major review process are scored higher than those associated with other missions. As with 2011, the NWNH report is the main source of the mission ranking for 2012.
2. **Overall relevance to applicable mission concept:** If a technology need is a key element of a mission concept, then it is scored higher than those that are less important. This criterion intentionally overlaps several more specific criteria below. The redundancy increases accuracy (by averaging scores over more targeted criteria) and captures any unanticipated aspects of mission applicability.
3. **Scope of applicability:** If a technology need is generally useful to multiple missions, it is scored higher. For example, optics or detector technologies generally span more than one mission, whereas an ultra-high-precision timekeeping technology may have more limited applicability.
4. **Time to anticipated need:** If a mission concept is not planned for implementation for a long time, its technology needs receive a lower score than more immediate needs.
5. **Scientific impact:** This criterion captures the value of a technology in terms of its impact on the science return of a mission. If a technology need must be filled for mission success, it is scored highest. If it improves the scientific return from a mission, then its score reflects the improvement.

6. **Implementation impact:** This criterion captures how important a technology need is to mission implementation. Primarily, it is a measure of the engineering impact. Technology needs that are required for a mission are scored highest. Those providing improvements in terms of major mission resources (cost, mass, power, etc.) are scored relative to the magnitude of the improvement.
7. **Schedule impact:** The intent of this criterion is to capture a technology need's likely impact on mission schedule. If a technology is likely to drive mission schedule, then it receives a higher score.
8. **Risk reduction:** The intent of this criterion is to help ensure that technology needs that provide important risk mitigation (i.e., secondary paths to mission implementation) are ranked appropriately. If a technology reduces mission risk compared to the baseline mission concept, then it is scored higher. If it is already in the mission concept baseline, then it has no additional risk reduction benefits and is scored low.
9. **Definition of required technology:** The intent of this criterion is to codify in this process the idea that well defined technology needs are better targets for development resources. If a technology need is well defined and described, then it is scored higher than those more vaguely defined.
10. **Other sources of funding:** This criterion captures the likely return on NASA development funding. If research related to a particular technology need is already well funded by U.S. agencies and commercial and foreign investments, then additional NASA resources are unlikely to have a large impact. Thus, its score is low. In contrast, if a technology is not funded through any other sources, then NASA investments are more likely to generate significant advancements.
11. **Availability of providers:** This criterion seeks to ensure that a viable supplier base to address the technology need is developed and maintained. If there are few providers or a single provider, then the score is higher.

In 2011, the TMB ranked 12 technology needs for COR. As discussed in Section 3, for 2012, the needs list included three new technology needs. All 15 technology needs were ranked by the TBM in 2012. Based on these rankings, the technology needs were grouped, by priority, into three categories. The divisions were based on a number of factors assessed by the TMB including, primarily, a natural clustering of the technology needs based on their overall scores.

Technology Needs Prioritization Criteria

#	Criterion	Weight	Score (0-4)	Weighted Score	General Description/Question	Score Meaning: 4	3	2	1	0
1	Scientific Ranking of Applicable Mission Concept	4	4	16	Scientific priority as determined by the Decadal Review, other community-based review, other peer review, or programmatic assessment. Captures the importance of the mission concept which will benefit from the technology.	Highest ranking	Medium rank	Low rank	Not ranked by the Decadal	No clear applicable mission concept
2	Overall Relevance to Applicable Mission Concept	4	4	16	Impact of the technology on the applicable mission concept. Captures the overall importance of the technology to the mission concept.	Critical key enabling technology—required to meet mission concept goals	Highly desirable technology—reduces need for critical resources and/or required to meet secondary mission concept goals	Desirable—offers significant benefits but not required for mission success	Minor implementation improvements	No implementation improvement
3	Scope of Applicability	3	4	12	How many mission concepts could benefit from this technology? The larger the number, the greater the reward from a successful development.	The technology applies to multiple mission concepts across multiple NASA programs and other agencies	The technology applies to multiple mission concepts across multiple NASA programs or other agencies	The technology applies to multiple mission concepts within a single NASA program	The technology applies to a single mission concept	No known applicable mission concept
4	Time To Anticipated Need	3	4	12	When does the technology need to be ready for implementation?	4 to 8 years (this decade)	9 to 14 years (early 2020s)	15 to 20 years (late 2020s)	Greater than 20 years (2030s)	No anticipated need
5	Scientific Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the scientific harvest of the applicable mission concept. How much does this technology affect the scientific harvest of the mission?	Needed for applicable mission concept	Major improvement (> ~2×) to primary scientific goals	Only enables secondary scientific goals	Minor scientific improvement	No scientific improvements
6	Implementation Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the implementation efficiency of the applicable mission concept. How much does this technology simplify the implementation or reduce the need for critical resources?	Needed for applicable mission concept	Enables major savings in critical resources (e.g., smaller launch vehicle, longer mission lifetime, smaller spacecraft bus, etc.) or reduces a major risk	Enables minor savings in critical resources or reduces a minor risk	Minor implementation improvement	No implementation improvements
7	Schedule Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the schedule of the applicable mission concept. How much does this technology simplify the implementation to bring in the schedule?	Technology is likely to drive the applicable mission schedule.	Technology is likely to drive the schedule for a major subsystem/component of the applicable mission concept	Technology is likely to drive the schedule for a minor applicable mission concept component	Technology is less likely to be a factor for the schedule of the applicable mission concept	Technology will not be a factor for the schedule of the applicable mission concept
8	Risk Reduction to Applicable Mission Concept	2	4	8	Ability of the technology to reduce risks by providing an alternate path for a high risk technology that is part of the applicable misssion concept.	Technology is a direct alternative to a key technology envisioned for the applicable mission concept. No other known alternate technologies	Technology is a direct alternative to a key technology envisioned for the applicable mission concept. At least one other known alternate technology	Technology is a direct alternative to a secondary technology envisioned. No other known alternate technologies	Technology is a direct alternative to a secondary technology envisioned. At least one other known alternate technology	No risk benefits or technology is already part of the applicable mission concept
9	Definition of Required Technology	1	4	4	How well defined is the required technology? Is there a clear description of what is sought?	Exquisitely defined	Well defined, but some vagueness	Well defined, but some conflicting goals not clarified	Not well defined, lacking in clarity	Poorly defined, not clear at all what is being described
10	Other Sources of Funding	1	4	4	Are there other sources of funding to mature this technology? If funding is expected to be available from other sources, this will lower the prioritization.	No, the Program is the only viable source of funding.	Interest from other sources can be developed during the development time of the technology	Interest from other sources is likely during the development time of the technology	Moderate investments (relative to the potential level for a NASA investment) in the technology are already being made by other programs, agencies, or countries.	Major investments (relative to the potential level for a NASA investment) in the technology are already being made by other programs, agencies, or countries.
11	Availability of Providers	1	4	4	Are there credible providers/developers of this technology? Where providers are scarce, there may be a compelling need to maintain continuity for the technology in the event there are no replacement technologies.	Potential providers/developers have insufficient capabilities to meet applicable mission concept needs.	Potential providers/developers have uncertain capability relative to applicable mission concept needs.	Single competent and credible provider/developer known	Two competent and credible providers/developers known	Multiple competent and credible providers/developers known

Table 4–1. *This table shows the evaluation criteria for technology prioritization.*

The COR Program Office establishes its 2012 technology needs and priority categories as follows:

Priority 1: Contains technology activities that the Board has determined to be of the highest interest to the Cosmic Origins program and recommends that they **should** be invested in first, when funding is available. This priority level consists of the technology needs described below. (They are identical to the highest ranked technology needs from last year.)

- High-QE, large-format UV detectors—Future NASA UV missions require high-QE (>70%), large-format (>2k × 2k) detectors for operation at 100–400 nm or broader. The goal is to produce large-format, high-QE, low-noise, UV-sensitive detectors routinely that can be employed in a variety of suborbital, Explorer, medium-class, and strategic missions.
- Photon-counting, large-format UV detectors—Future NASA UV missions, particularly those devoted to spectroscopy, require high-QE (>50%), low-noise ($<10^{-7}$ ct/pixel/s), large-format (>2k × 2k) photon-counting detectors for operation at 100–400 nm or broader.
- High reflectivity UV coatings—Development of UV coatings with high reflectivity, high uniformity, and wide bandpasses, ideally operating from the visible to wavelengths below 100 nm.
- Ultra-low-noise far-IR direct detectors—Future NASA far-IR missions require detectors optimized for the very low photon backgrounds present in space for spectroscopy at wavelengths between ~30 μm and ~300 μm. Highly sensitive (noise-equivalent powers of $\approx 3 \times 10^{-21}$ W/√Hz) detectors that are arrayable in a close-packed configuration in at least one direction are needed.

Priority 2: Contains technology activities that the Board feels are worthy of pursuit and **would** be invested in, if funding allows. Priority 2 technologies include:

- Very large format, low noise, visible/IR detector arrays.
- Large, low-cost, lightweight, precision mirrors for ultra-stable large-aperture UV/visible telescopes in ≈4m-class sizes
- Large-format, low-noise far-IR direct detectors
- Photon-counting visible/IR detector arrays.
- Heterodyne far-IR receiver arrays.
- High efficiency cryocoolers.

Priority 3: Contains technologies that are deemed to be supportive of COR objectives but, for various reasons, do not warrant investment at the present, although they **could** be invested in, if significant additional funding is available. Priority 3 technologies include:

- High-efficiency UV multi-object spectrometers.
- High-performance sub-Kelvin coolers.
- Large, cryogenic far-IR telescopes
- Interferometry for far-IR telescopes
- Deployable, lightweight, precision mirrors for future very-large-aperture UV/visible telescopes.

Funding Results from 2011 PATR

The process outlined in the above section is designed to enable a prospicient strategy for technology needs fulfillment. This will be realized only if the needs identified by the community become high priorities, both in the PATR and the concomitant SAT proposal call, and that then the resultant selections for funding align with those identified priorities and fulfill those requested needs. The past year has seen the first complete cycle of this strategic technology development activity, and so it is appropriate to consider whether the annual process appears to succeed in its objective.

Last year, the PATR recommended a similar suite of high priority technologies derived from a somewhat abbreviated version of the same technology needs list that appears in this PATR. At the same time, the COPAG deliberated over the technology needs list and came to the same conclusions as the TMB as to the broad band prioritization category of each (although, it must be noted, the COPAG used a somewhat different scale more consistent with two bands as opposed to the three represented in this report). The highest priority technology needs were then published in an amendment to the SAT proposal call, and in March of 2012 proposals were received. The affirmative selections, listed in Section 2 on page 15, are each traceable directly to a high priority technology need promulgated by last year's PATR.

This result indicates the promise of the annual technology development process, but demonstrating this for a single year is not in itself sufficient proof of the enduring value of the effort. With the continued attention of the COR Program Office to manage the progress of each technology effort, the highest priority technology needs should ultimately be fulfilled. These would then be at a sufficient state of maturity to be applied to flight projects, advancing Cosmic Origins science investigations, thereby leading to new avenues of research requiring further technological advances. That this be the ultimate result is the true test of the technology development process.

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5 Closing Remarks

This Cosmic Origins 2012 PATR serves as a snapshot of the state of technology development under the COR Program Office and future directions for technology maturation. The PATR captures the technology needs as identified by the astrophysics community. The Technology Management Board established rankings for the technology needs. The priorities are intended to serve as the recommendation from the COR Program Office to NASA HQ for future technology investments to serve Program goals optimally.

This report is produced annually and reflects the continuing changes in the landscape of scientific needs and their requisite technologies, incorporating novel developments to allow for the dynamic nature of the field. The COR Program Office annual activities, leading to the release of the PATR, provide a continuity of overall vision and process for strategic purposes, while retaining the flexibility to adapt tactically to new opportunities. This report tracks the status annually of all technologies being matured to serve Program goals and identifies the next generations of technologies to be developed.

The Program Office will continue to interact with the broad scientific community—through the COPAG, its workshops, at public conferences, and via public outreach activities—to identify and incorporate the community's ideas about new science and new technology needs in a sustained process. The Program Office welcomes continued feedback from the community in developing the 2013 Program Annual Technology Report.

For more information about the Cosmic Origins Program and to be informed of Program activities, or to provide feedback, please visit: http://cor.gsfc.nasa.gov/.

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6 ACRONYMS

ACT . . . . *Atacama Cosmology Telescope*
ACTO. . . . . . . Advanced Concepts and Technology Office
ADC. . . . . Analog-to-Digital Converter
ALD . . . . Atomic Layer Deposition
ALMA. . . . . . . *Atacama Large Millimeter/submillimeter Array*
AO . . . . Announcement of Opportunity
AMTD . . . . . . Advanced Mirror Technology Development
APRA . . . . Astronomy and Physics Research and Analysis
ARC . . . . Ames Research Center
ASIC . . . . Application Specific Integrated Circuit
BETTII . . . . . . *Balloon Experimental Twin Telescope for Infrared Interferometry*
BUG . . . . Backshort Under Grid
CALISTO . . . . *Cryogenic Aperture Large Infrared Space Telescope Observatory*
CCD. . . . . Charge-Coupled Device
COPAG . . . . . Cosmic Origins Program Analysis Group
COR. . . . . Cosmic Origins
CSA . . . . Charge Sensitive Amplifiers
DFRC. . . . . . . Dryden Flight Research Center
DLR . . . . German Aerospace Center
DRIE . . . . Deep Reactive Ion Etching
ESA . . . . European Space Agency
EUV. . . . . Extreme Ultraviolet
FACA . . . . . . Federal Advisory Committee Act
Far-IR. . . . . . . Far Infrared
FEM . . . . Finite Element Model
FPGA . . . . Field Programmable Gate Array
FUSE . . . . *Far Ultraviolet Spectroscopic Explorer*
FUV . . . . Far Ultraviolet
FWHM . . . . . . Full-Width Half-Maximum
FY . . . . Fiscal Year
GALEX. . . . . . *Galaxy Evolution Explorer*
GISMO. . . . . . *Goddard IRAM Superconducting 2-Millimeter Observer*
GRAPH . . . . . Gigasample Recorder of Analog Waveforms from a Photodetector
GSFC . . . . Goddard Space Flight Center
HAWC . . . . . . High-resolution Airborne Wide-bandwidth Camera
HEB. . . . . Hot Electron Bolometer
HIFI. . . . . Heterodyne Instrument for the Far Infrared
HQ . . . . Headquarters
HST . . . . *Hubble Space Telescope*
HUT. . . . . *Hopkins Ultraviolet Telescope*
IBS . . . . Ion Beam Sputtering
IF. . . . . Intermediate Frequency
IGM . . . . Inter-galactic Medium
IR . . . . Infrared
IRAM . . . . Institut de Radioastronomie Millimétrique
ISAS. . . . . Institute of Space and Astronautical Science
ISM . . . . Interstellar Medium

JAXA . . . . Japanese Aerospace Exploration Agency
JHU . . . . Johns Hopkins University
JPL. . . . . Jet Propulsion Laboratory
JWST . . . . *James Webb Space Telescope*
LO . . . . Local Oscillator
LVDS . . . . Low Voltage Differential Signal
MCP. . . . . Microchannel Plate
MIDEX. . . . . . Medium-Class Explorers
MSPU. . . . . . . Moscow State Pedagogical University
MUSTANG . . . Multiplexed SQUID TES Array at Ninety Gigahertz
NAC. . . . . NASA Advisory Council
NAS . . . . National Academy of Sciences
NASA. . . . . . . National Aeronautical and Space Administration
NEP . . . . Noise-Equivalent Power
NIST . . . . National Institute of Standards and Technology
NPR. . . . . NASA Procedural Requirements
NRC. . . . . National Research Council
NWNH . . . . . . New Worlds New Horizons
OAO-3 . . . . . . Orbiting Astronomical Observatory 3
OCT. . . . . Office of the Chief Technologist
ORFEUS . . . . . Orbiting Retrievable Far and Extreme Ultraviolet Spectrometer
PATR . . . . Program Annual Technology Report
PCOS . . . . Physics of the Cosmos
PI . . . . Principal Investigator
PIPER . . . . . . Primordial Inflation Polarization Explorer
PMA. . . . . Primary Mirror Assembly
PO . . . . Program Office
PSF . . . . Point Spread Function
PVD. . . . . Physical Vapor Deposition
PXS . . . . Parallel Cross Strip
QE . . . . Quantum Efficiency
QWIP. . . . . . . Quantum Well Infrared Photodetectors
RFE . . . . Receiver Front Ends
RFI . . . . Request for Information
ROSES . . . . . . Research Opportunities in Space and Earth Science
SAFIR. . . . . . . *Single Aperture Far Infrared Observatory*
SAT . . . . Strategic Astrophysics Technology
SBIR . . . . . . .Small Business Innovation Research
SEM . . . . Scanning Electron Microscope
SIOSS. . . . . . . Science Instruments, Observatory and Sensor Systems
SMEX. . . . . . . Small Explorer
SNR . . . . Signal-to-Noise Ratio
SOFIA . . . . . . *Stratospheric Observatory for Infrared Astronomy*
SPICA . . . . . . *Space Infrared Telescope for Cosmology and Astrophysics*
SPIRIT . . . . . . *Space Infrared Interferometric Telescope*
SQUID . . . . . . Superconducting Quantum Interference Device
SR&T . . . . Supporting Research and Technology
STO . . . . *Straospheric Terahertz Observatory*
TABS . . . . Technology Area Breakdown Structures
TCOP. . . . . . . Technology Development Section for the Cosmic Origins Program
TES . . . . Transition Edge Sensor

TIRS. . . . . Thermal InfraRed Sensor
TMB. . . . . Technology Management Board
TRL . . . . Technology Readiness Level
TWV . . . . Through-Wafer Via
UV . . . . Ultraviolet
UVOIR . . . . . . Ultraviolet/optical/infrared
WAV. . . . . Wrap-Around Via
WFIRST . . . . . *Wide Field Infrared Survey Telescope*
XS . . . . Cross Strip

Chemical Elements

Al/LiF. . . . . . . Aluminum/Lithium Fluoride
Al/MgF_2 . . . . . Aluminum/Magnesium Fluoride
CII . . . . Singly Ionized Carbon
CH . . . . Methylidyne Radical
D . . . . Deuterium
GaN . . . . Gallium Nitride
HD . . . . Deuterated Hydrogen
LaF_3 . . . . Lanthanum Fluoride
LiF . . . . Lithium Fluoride
LuF_3 . . . . Lutetium Trifluoride
MgF_2 . . . . Magnesium Fluoride
NII . . . . Singly Ionized Nitrogen
NbN . . . . Niobium Nitride
Si . . . . Silicon
SiC . . . . Silicon Carbide
SiO_2 . . . . Fused Silicon

Units

Å . . . . Angstroms
C . . . . Celsius
GHz . . . . Gigahertz
Hz . . . . Hertz
k . . . . Kilo, or Thousand
K . . . . Kelvin
keV . . . . Kiloelectronvolt
kHz . . . . Kilohertz
kV . . . . Kilovolt
λ . . . . Wavelength
mA. . . . . Milliamp
mm . . . . Millimeters
mOhm . . . . . . Milliohms
mW . . . . Milliwatts
nH . . . . Nanohenries
nm. . . . . Nanometers
µm. . . . . Micrometers, or Microns
s . . . . Seconds
THz . . . . Terahertz
W . . . . Watts

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