National Aeronautics and Space Administration

Cosmic Origins
Program Annual Technology Report

Cosmic Origins Program Office
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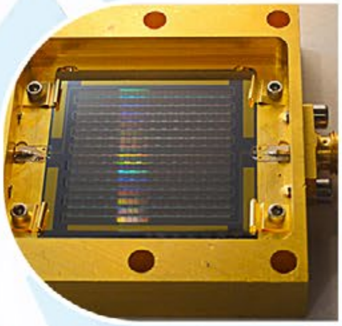

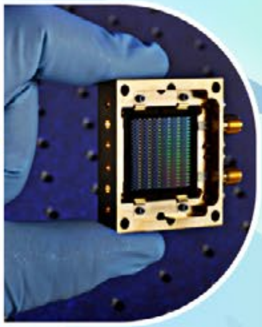

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Executive Summary

Welcome to the third *Program Annual Technology Report* (PATR) for the Cosmic Origins (COR) Program of the NASA Astrophysics Division. It has been an active year for technology development in the COR Program. The Program is currently investing in eight strategic technology development projects with Principal Investigators (PIs) from academia, industry, and multiple NASA centers. For fiscal year (FY) 2014, that portfolio will expand with two new projects. The projects span technology areas from mirrors, telescopes and optical coatings to detectors and electronics with applicability to the highest-ranked potential future COR missions. Within the Program Office (PO), the processes for prioritizing technology needs continue to mature and evolve to ensure that the calls for proposals and investment decisions are aligned with Program needs.

This is the third year in which the COR PO has implemented the Program technology needs prioritization process. This process serves to inform the calls for proposals for SAT funding and the selection of grant recipients. This year, as in previous years, the majority of technology needs that were input to this process were compiled by the Cosmic Origins Program Analysis Group (COPAG). The vast majority of technology needs were carried over from previous years. The prioritization process was streamlined this year by reducing and simplifying the prioritization criteria. Significant guidance for the prioritization process came from the *Astrophysics Implementation Plan* (AIP), which articulates the NASA Astrophysics Division's near-term plans for achieving the Decadal Survey's recommendations within current budget constraints.

The ongoing technology development projects are each summarized in a single-page quad chart format in Appendix A. Each project is also described in the PI reports collected in Appendix B. The current portfolio includes critical technology developments funded through the COR Strategic Astrophysics Technology (SAT) grants. Projects include those targeted at missions of interest to the astrophysics community covering a wide range of wavelengths from far-ultraviolet (FUV) to far-infrared (Far-IR). Each PI report summarizes that project's progress over the past year and plans for the next. Over the past year, each project team made excellent progress with respect to their critical milestones. It is notable that the recently selected upgrade to the *Stratospheric Observatory for Infrared Astronomy* (SOFIA) High-resolution Airborne Wide-bandwidth Camera (HAWC) includes the installation of new Far-IR detectors that were matured using COR funding in past years.

The COR Program is pleased to announce the new recipients of technology funding for FY 2014 start. These projects are "Advanced Mirror Technology Development Phase 2," with Principal Investigator P. Stahl at MSFC, and "A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping," with Principal Investigator I. Mehdi at JPL.

The results of this year's prioritization are presented in this PATR. The highest-ranked technology needs include ultraviolet (UV) detectors (high-quantum efficiency, or QE, and photon-counting), high-reflectivity UV coatings, UV monolithic and deployable precision mirrors, and UV spectrometers. These results are provided to aid decision makers at NASA Headquarters (HQ) in processes such as the SAT process that ultimately result in the funding of selected technologies.

Introduction

This PATR is the annual summary of the technology development activities of the COR Program for the FY 2013. This document serves three purposes. First, it summarizes the Program technology needs identified by the scientific community. Second, it presents the results of this year's prioritization of the technology needs by the COR Program Technology Management Board (TMB). Third, it summarizes the current status of all the technologies that were supported by the COR Supporting Research and Technology (SR&T) funding in FY13, including progress during the past year and planned development activities for this coming year. The COR PO resides at the NASA Goddard Space Flight Center (GSFC) and serves as the implementation arm for the Astrophysics Division at HQ for COR Program-related matters.

The COR Program 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 FY13 funding is being used efficiently, as is evidenced by the significant progress of development activities provided in Appendix B. These technology development status reports cover four developments continued from previous years as well as five developments that were newly awarded last year.[1]

The technology needs prioritization process described in Sections 3 and 4 was unchanged from last year, except that the number of prioritization criteria was reduced to streamline the process. It again provided a rigorous, transparent ranking of technology needs based on the Program's goals, community scientific rankings of the relevant missions, and the external programmatic environment. This year, we have the benefit of having the NASA AIP, which was released in December 2012, for guidance. The AIP articulates the Astrophysics Division's near-term (2013–2017) plans for achieving the National Research Council (NRC) 2010 *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) Decadal Survey science and priorities within current budget constraints.

Section 3 of this report summarizes the technology needs collected with the support of the COPAG. 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 four weighted criteria, reduced from last year's eleven. The technology needs are categorized into three priority groups. These groups are based on the relative importance of the technologies to the COR science objectives and the urgency of the need.

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 TMB 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. The technology needs prioritization will be forwarded to other NASA programs–e.g., Small Business Innovation Research (SBIR) and other Space Technology Mission Directorate (STMD)–or Office of the Chief Technologist (OCT) technology development planning groups as requested. As part of NASA's recognition of the critical role that space technology and innovation will play in enabling both future space missions and enhancing life here on Earth, STMD was created in February of this year. The STMD will develop the cross-cutting, advanced, and pioneering new technologies needed for NASA's current and future missions. The OCT serves as principal advisor and advocates on matters concerning agency-wide technology policy and programs. The OCT also leads

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[1] Subsequent to last year's SAT awards, principal investigators S. Anglin and B. Rauscher combined their efforts into a single project, with the approval of the Program, in order to enable a more rapid maturation of their near-infrared detector technology. Therefore, eight projects are under way that resulted from nine awards.

NASA's technology transfer and commercialization efforts to integrate, track, and coordinate all of NASA's technology investments across the agency.

During the implementation of the technology development process, the PO strives to:

- be transparent by informing the community of the technology needs collection and prioritization process, along with the resulting prioritization for the year, while maintaining an open forum for community input into the process;

- communicate to the community its technology development investments and their progress through this report;

- ensure the development of the most relevant technologies by following the guidance of the HQ Astrophysics Division; and

- leverage our technology investments by defining its technology needs in order to encourage external technology investments that will benefit COR science.

A key objective of the technology development process is to formulate and articulate the needs of the Program. Through a process of careful evaluation of the technology needs, the PO determines which technology needs will meet its objectives and then prioritizes them in order of a 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 Cosmic Origins (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–starting with the first generation of stars to seed the universe, and continuing up through the birth and death of stars even now. The majority of the field known as astronomy, from antiquity to the relatively recent present, falls within the purview of Cosmic Origins.

The Science Mission Directorate (SMD) of NASA acknowledged the continued importance of this scientific field by establishing the COR Program Office (PO) in 2009 within the Astrophysics Division. The COR PO, while acting as the Program implementation arm of Headquarters (HQ), is located at NASA's Goddard Space Flight Center (GSFC). A primary function of the PO is to develop and administer an aggressive technology maturation program. To do this, the PO is charged with coordinating the infusion of technologies into COR 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.

In 2013, the technology developments applicable to COR missions are funded by the Technology Development for the Cosmic Origins Program (TCOP), the COR portion of the Strategic Astrophysics Technology (SAT) proposal call. This merit-based selection process disburses 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 FY2013, of the COR prioritization for future technology needs.

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 all contribute to Cosmic Origins science goals. Each project operates independently to achieve its unique set of mission objectives, which contribute to the overall Program objectives. In 2013, the operating missions in the COR PO 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 relayed over a million observations back to Earth, shedding light on many of the great mysteries of astronomy. It 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

Spitzer, which recently celebrated the tenth anniversary of its launch, provided sensitive infrared (IR) observations 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 investigations have focused on objects that emit very little visible light, including brown dwarf stars, extrasolar planets, and giant molecular clouds. Although the primary phase of *Spitzer's* mission ended in 2009 with the exhaustion of its onboard cryogen, the *Spitzer* "warm" mission continues valuable work on COR science goals.

Three additional missions have completed operations but are still in their data analysis phase prior to a final release of their scientific data products. These include:

Herschel Space Observatory

The U.S. component of the European Space Agency (ESA) *Herschel Space Observatory* 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. Herschel was decommissioned in June 2013; data refinement and analysis will continue until 2017.

Galaxy Evolution Explorer (GALEX)

GALEX has conducted a wide imaging survey in two ultraviolet (UV) bands, intended to trace the history of star formation 80 percent of the way back to the Big Bang. In June 2013, GALEX was decommissioned; the final (privately obtained) data will become public in 2014.

Wide-field Infrared Survey Explorer (WISE)

WISE produced a sensitive all-sky, mid-infrared (mid-IR) imaging survey in four bands. This provides a new window for COR science, discovering rare new objects such as the coolest stars ever found and finding hot dusty galaxies halfway across the universe. WISE was decommissioned in February 2011, and the release of its full reprocessed data is scheduled for late 2013.

In 2013, the COR PO development portfolio includes:

COR SR&T

The COR PO manages the investment of SR&T funds in a variety of avenues to advance COR technology needs. Appendix A of this PATR details the recent progress of those projects that were supported during the 2013 fiscal year (FY).

Future Mission Concept Development

The COR PO conducts mission concept studies to assist in scoping future activities including technology development priorities and plans. During FY 2013, progress was made on several studies related to COR missions. These include concluding a study for a HST disposal mission planned for the 2020s, and 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 IR spectrum. The SOFIA Program Office and aircraft are based at NASA's Dryden Flight Research Center (DFRC), with science mission operations based at NASA's Ames Research Center (ARC). Because SOFIA science is well aligned with COR science, and SOFIA represents an important platform for the maturation of COR technologies that may be applicable to future space missions, the SOFIA science objectives are considered in relation to the applicable criteria described in Section 4 of this PATR.

James Webb Space Telescope (JWST)

A partnership between NASA and ESA, JWST is the largest science mission under development. Among other purposes, it will provide near- and mid-IR investigations of the earliest observable objects in the universe. JWST operations will be managed under the COR Program when JWST transitions to Phase E, after launch and commissioning in 2018.

In support of the COR Program objectives, the PO 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.

U.S. astrophysics priorities were redefined in 2010 when the National Research Council (NRC) released its Decadal Study for Astronomy and Astrophysics. The *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) report caused the COR Program to shift its focus to ardent technology development and mission concept studies which support the scientific priorities identified in NWNH. In this 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, several of its recommendations are directly relevant to the COR Program:

- The NWNH report's first priority space recommendation–the *Wide Field Infrared Survey Telescope* (WFIRST)–will address many key COR science goals, such as the formation and evolution of structure and galaxy growth.

- The report gave high priority to technology development in support of a future 4-m UV/Visible-band space telescope.

- The recommendations include a NASA instrument contribution to the Japanese Aerospace Exploration Agency (JAXA) *Space Infrared Telescope for Cosmology and Astrophysics* (SPICA) mission, if affordable.

- The report also strongly 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 Medium-Class Explorers (MIDEX)/Small Explorers (SMEX) missions launched in the past 15 years primarily support COR objectives.

During the time since the COR Program was formulated in 2009, and the NWNH report was released in 2010, fiscal constraints have become significantly more restrictive than anticipated then. The COR Program is committed to managing the available funds strategically to ensure that the Program will foster missions that continue to accomplish Program objectives. It is key to this effort for the Program to be strategic in advancing technologies that will enable COR science.

The COR PO is committed to preparing for the next UV/Visible astrophysics mission. The NWNH report recommends the development of technology for a large UV/Visible mission to continue and extend the science done with *Hubble*. In NWNH, this is discussed as a 4m-class mission covering wavelengths shorter than Hubble's key range. However, the COR PO 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 mission requiring future capabilities. A set of 34 responses from this RFI is available at the COR website. A 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, these 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, including both large and modest concepts. Many of the modest concepts are expected to focus on sensitive multi-object UV spectroscopy, or on broader-wavelength-coverage UV/Visible imaging capability, thereby being suitable for general astrophysics at UV and visible wavelengths. Two other independent groups are currently exploring science cases for future very large UV/Visible/Near-infrared (Near-IR) observatories. The COR Program expects to make use of findings from these studies to help guide technology needs. It is expected that most technology development in support of future UV/Visible missions will benefit the Explorer Program as well.

In 2012, the COR PO studied the feasibility of participation with Japan on an instrument contribution to the SPICA mission, currently slated for launch in 2022. Near-term budget limitations constrain NASA's ability to participate at the desired level, so the COR PO has considered approaches for a budget-constrained NASA contribution to SPICA. A TMB was convened under COR auspices to review the readiness level and development risk of possible NASA-provided SPICA instruments; the Board found that the possible instrument contributions all required additional time and funding, and so could not meet required JAXA schedule constraints. The COR PO is now working with the Far-IR community to identify alternate ways of addressing the SPICA science goals that were identified in the NWNH report.

The SOFIA mission, currently entering Science Cycle 2, provides a platform for observations across the IR spectrum. The recently selected upgrade to SOFIA's High-resolution Airborne Wide-bandwidth Camera (HAWC) includes the installation of polarimetric optics and new Far-IR detectors. These detectors were matured using COR funding in prior years and provide an example of how the COR technology development investment can be handed off to a flight project once the appropriate technology readiness level (TRL) is reached.

The activity given first priority in NWNH for a large space mission, WFIRST, is not formally within the COR Program's suite of future missions, as it is managed within the Exoplanet Exploration Program (ExEP) at the Jet Propulsion Laboratory (JPL). One possible external WFIRST implementation, using a 2.4-m repurposed telescope termed the Astrophysics Focused Telescope Assets (AFTA), received permission in June 2013 to continue mission concept studies in support of a possible new start in 2017. The COR Program, in conjunction with the Cosmic Origins Program Analysis Group (COPAG), is examining how the AFTA mission concept capabilities can serve to address COR science goals. In support of this high-priority mission activity, the COR Program is providing funding to support detector development suitable for WFIRST/AFTA through the SAT Program (described in Appendix B, page B–46).

Finally, the release in December 2012 of the Astrophysics Implementation Plan (AIP) provides guidance for the Astrophysics Division's overall strategy. The decision for NASA not to participate in the current version of the JAXA-led SPICA mission, and the planning work for future UV-Visible wavelength missions both fit into the larger picture described in the AIP, and the overall strategy provided additional guidance to the TMB for determining mission rankings and thus technology development priorities.

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 PO 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 of 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 vision presented in the NWNH report has been moderated somewhat by the 2012 NASA AIP, which reflects the realities of the current constrained budget outlook. This more recent document lays out the present view of activities being pursued by the Astrophysics Division in order to fulfill the vision of the NWNH as comprehensively as is feasible.

The COR 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 strategic process that 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. 1–1) 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 introduced into the NASA advisory chain (by means of public meetings, in particular COPAG workshops). The COR PO also solicits input directly from the science community.

The COPAG provides analyses through the NASA Advisory Council (NAC) process. Meanwhile, the COR PO convenes its 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 SAT portion of the astrophysics grant opportunity portfolio, which explicitly inherits the priorities enunciated in the COR PATR. Grants are awarded to selected technology developers, who submit annual progress reports that are reviewed by the TMB and become a portion of future PATRs. 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 PO to ensure that both the public and the broad astronomy community are informed of these developments. It is expected that new starts for missions will transition technologies out of the PATR 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 COPAG workshops held by the Program in conjunction with specific studies. Members of the community also participate as technology developers, through responses to technology needs and SAT proposal solicitations. Studies, workshops, and solicitation responses all provide community input to the Program's technology process.

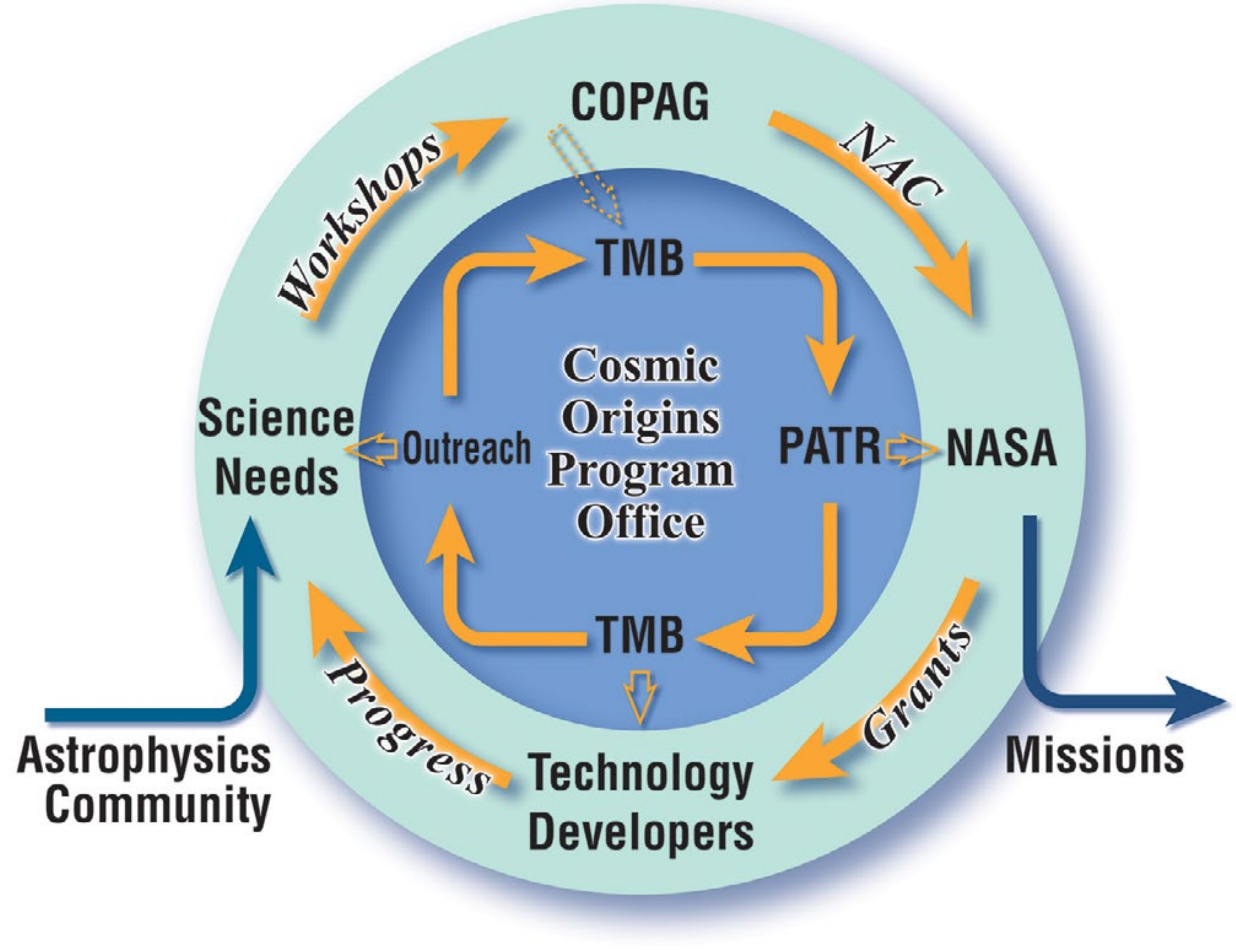


Figure 1-1: This diagram illustrates the COR annual technology management process.

2. Program Strategic Technology Development Portfolio

This section provides the current strategic technology development portfolio for the Program. This portfolio includes technology funded for development in FY13 and newly selected SAT funded for start of development in FY14. A top level summary for each project is provided in a single-page quad chart format in Appendix A. Each project is also described and statused in more detail in the PI reports collected in Appendix B. Development status, progress over the past year, and planned development activities for the technologies funded in FY13 are provided in Appendix B. This information provides technology overviews and statuses, and is not intended to provide technical detail for flight implementation. Additional information can be obtained by contacting the PO or the PI directly. Contact information for PIs appears at the end of their respective subsection of Appendix B. TRL above the approved entry level for each technology is not official until the Program TMB has vetted and concurred with the development team's TRL assessment. Vetting by the TMB occurs when the technologists feel they have accomplished their milestones to the point of TRL advancement and request a review to present their case for TRL reassignment. A TMB consisting of PO and HQ senior staff and subject matter experts is convened to assess the request and, when warranted, provides concurrence for TRL reassignment. The typical forum for such a request is during the technologists' end-of-year presentation to the PO, but it can be made at any time. Some of the PIs in our portfolio are planning to go through this TRL vetting process this coming year to elevate their TRL assignment. Table 2–1 lists the technologies that received Program funding for development work in FY13. Table 2–1 also shows the respective PI leading the technology development, their work institution, the fiscal year in which they started their development within the Program and the funded duration, the approved TRL of the technology, and the locations in Appendices A and B for their quad chart and status report.

Technology Development	PI	Institution	Start Year and Duration	Approved TRL	See Appx. A for Quad Chart and Appx. B for Status
Heterodyne Technology Development for SOFIA	P. Goldsmith	JPL	FY10 3 years	3	A-2, B-2
Enhanced MgF_2 and LiF Over-coated Al Mirrors for Far-Ultraviolet Space Astronomy	M. Quijada	GSFC	FY12 3 years	4	A-3, B-8
Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes	P. Stahl	MSFC	FY12 3 years	Varies from 3 to 5 for multiple technologies	A-4, B-18
Cross Strip Microchannel Plate Detector Systems for Spaceflight	J. Vallerga	UC Berkeley	FY12 3 years	4	A-5, B-25
Ultraviolet Coatings, Materials, and Processes for Advanced Telescope Optics	K. Balasubramanian	JPL	FY13 3 years	3	A-6, B-33
Kinetic Inductance Detector Arrays for Far-Infrared Astrophysics	J. Zmuidzinas	Caltech	FY13 2 years	3	A-7, B-39
H4RG Near-IR Detector Array with 10 micron Pixels for WFIRST and Space Astrophysics	S. Anglin and B. Rauscher	Teledyne and GSFC	FY13 3 years for Rauscher and 1 year for Anglin	4	A-8, B-46
High Efficiency Detectors in Photon-Counting and Large Focal Plane Arrays for Astrophysics Missions	S. Nikzad	JPL	FY13 3 years	4	A-9, B-52

Table 2–1. COR Strategic Technology Developments Funded in FY13.

Strategic Astrophysics Technology Selections for FY14 Start

The latest selection of proposals for funding under the COR SAT solicitation was announced in September, 2013. 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 this year. Their progress in the first year will appear in the 2014 PATR. Table 2–2 lists the technologies, along with their respective PIs and their institutions, start year, duration of investigation, and location of the abstract in Appendix B.

Proposal Title	PI	Institution	Start Year and Duration	See Appendix B for Abstract
Advanced Mirror Technology Development Phase 2	P. Stahl	MSFC	FY14 3 years	B–60
A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping	I. Mehdi	JPL	FY14 3 years	B–61

Table 2-2. COR SAT Awards for Start in FY 2014.

The COR Program funds SAT selections in order to further its ultimate goals for both COR missions and COR science. The two recent selections for new starts in FY14 serve to enable the kind of cutting-edge science that will push the boundaries of knowledge of our cosmic origins. Each of these new projects aims to achieve a TRL of at least 5, which is sufficient for space flight projects at Phase A.

One of the newly selected SAT projects, "Advanced Mirror Technology Development Phase 2," is designed to continue on an earlier SAT-funded effort to produce prototype mirrors suitable for future large (4m-class) UV/visible space telescopes. The first phase of this project produced full-depth 50 cm-scale mirrors; the second phase will fabricate a 1.5m-scale mirror, thereby demonstrating actual scaling to larger diameters, and will validate characterization on meter-scale optics at temperature down to 250 K. This proposal is in direct response to the need expressed by the COR Program in the SAT call that a "premium is placed on the ability to develop scalable manufacturing techniques … up to at least ~4 meters in diameter." Strategically, this investigation 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

The other SAT project selected, "A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping," will develop and demonstrate a 16-pixel array of heterodyne receivers operating at a frequency of ~2 THz (150 μm). Such an array could increase the spectral imaging efficiency of the present single-pixel instrument on SOFIA by a factor of 16, and such arrays could be tiled to bring to bear even greater focal planes. SOFIA science is COR science, and advances in a technology that is strongly enabling for SOFIA can also apply to other suborbital or orbital experiments. The COR Program solicited such a technological advance with the SAT language stating that "heterodyne Far-IR receiver arrays could provide significant enhancement to a variety of COR programs, including SOFIA."

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 PO invites the community to provide a listing of what they identify as technology needs of future missions within the Program's science portfolio. Input from the community comes through the COPAG, and through an outreach program that targets both meeting venues and potential providers of specific technologies. The COPAG, whose chairperson is a member of the NASA Astrophysics Subcommittee, provides this support as part of their community coordination and analysis of scientific and technological issues impacting NASA's COR Program.

A technology need can be identified by anyone and provided to the PO for prioritization in two ways. The first is to work with the COPAG to include it in the consolidated listing in response to the solicitation by the PO. The second is to submit it directly to the PO through the COR Program website. 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. The process is for the PO to pass on all inputs received via the website to the COPAG for integration prior to delivering the list to the PO for subsequent TMB prioritization.

After collection, consolidation, and tabulation, the inputs are then used by the Program's TMB to evaluate and prioritize all the needs according to a set of prioritization criteria. These criteria are described in detail in Section 4 of this report.

For this FY13's prioritization, the TMB assessed the COPAG's updated version of the 15 technology needs submitted last year along with newly received inputs. After consolidation, the list consists of 17 technology needs, as shown in Tables 3–1, 3–2, and 3–3.

The PO encourages that inputs include as much of the information requested as possible because insufficient submissions are challenging to prioritize highly. It is crucial that the technology need is submitted as a capability that is required and not submitted as a specific implementation process or methodology. The technology's goals and objectives should be clear and quantified. For example, stating that "a better cryocooler is needed" is lacking in detail. A complete description of the needed capability with specific performance goals based on mission needs would be very valuable. This would allow: 1) the TMB to best assess the need, 2) NASA HQ to develop precise technology development proposal calls, and 3) the research community to be clearly informed in order to best match candidate technologies to 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. The more relevant and compelling the case, the more likely it is to 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 (as a capability that is needed) 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 less informative.

- **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 may receive higher prioritization than those without quantified objectives.

- **TRL:** specifies the current TRL(s) of the technology per NASA Procedural Requirements (NPR) 7123.1B Appendix E with clear justification.

- **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 capability:** 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 (e.g., better science output), engineering (e.g., lower mass), or programmatic (e.g., 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, especially those in accordance with the Decadal Survey and the AIP.

- **Non-NASA but aerospace needs:** details specific needs and performance requirements for applications outside of NASA mission concepts and within the aerospace sector, such as space communications and national security.

- **Non-aerospace needs:** describes specific needs and performance requirements for all other needs (not covered in the previous two categories), such as medical or security applications.

- **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. Also, describe any known technical dependencies. For example, very large format detectors will not be feasible without very fast readout electronics.

- **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 PO technology needs input form also requests the following information:

- **Current state of the art:** describes the current state of the art for the most current technology development effort.

- **Technology is enabling or enhancing:** 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.

- **Potential relevant missions:** identifies future NASA or other agency missions or other applications for which the technology need is relevant and discusses how the need applies. Technology needs with broad cross-cutting 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

Table 3-1: Technology Needs for Future COR Missions Identified by the Astrophysics Community of Scientists and Technologists.

Name of technology	**High QE, large format UV detectors**	**Photon counting large-format UV detectors**	**High Reflectivity UV coatings**	**Large, low-cost, light-weight precision monolithic mirrors for Ultra-Stable Large Aperture UV/Visible/Near-IR Telescopes**	**Deployable light-weight precision mirrors for future Very Large Aperture UV/Visible/Near-IR Telescope**	**Very large format, low noise Visible/IR detector arrays**
Brief description	Future NASA UV missions, require high quantum efficiency (>70%), large-format (>2k × 2k) detectors for operation at 90–350nm or broader. Red leak (longer wavelength) suppression is highly desirable for some applications.	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 90–350nm or broader. Red leak (longer wavelength) suppression is highly desirable for some applications.	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/Near-IR telescopes will require increasingly large apertures to answer the questions raised by HST, JWST, Planck and Hershel, and to complement the ≥ 30-m ground-based telescopes that will be coming online in the next decade. For diffraction limited performance, the pointing budget gets tighter as aperture grows and wavelengths shrink, requiring $\theta \sim 0.1\ \lambda/D$ pointing accuracy. Technologies are therefore required that provide a high degree of thermal and dynamic stability, and wave front sensing and control. (e.g., very stable materials, actuators with very small step sizes (~1 nm), systems for rigidizing backplane structure, etc…)	Future UV/Visible/Near-IR telescopes will require increasingly large apertures to answer the questions raised by HST, JWST, Planck and Hershel, and to complement the ≥ 30-m 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 $\theta \sim 0.1\ \lambda/D$ pointing accuracy. Technologies are therefore required that provide a high degree of thermal and dynamic stability, and wave front sensing and control (e.g., very stable materials, actuators with very small step sizes (~1 nm), systems for rigidizing backplane structure, etc…)	Future NASA Visible/near-IR missions require large format detector arrays mosaicable in formats of ~Gpix, covering wavelengths from the visible to 1.7μm
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 for imaging and spectroscopy of the UV sky. Further enhancement would be to achieve energy-resolving capability.	Development of UV coatings with high reflectivity (>90–95%), high uniformity (<1–0.1%), and wide bandpasses (~100 nm to 300–2000 nm). Coating with good UV efficiency and good-enough IR efficiency could greatly increase the scientific range of a mission. New coating technologies such as Atomic Layer Deposition are particularly promising. Some will be required for large optics (0.5–4m+), and for smaller instrument optical elements.	Develop lightweight UV, visible and near-IR mirrors with real density <20kg/m^2 (preferably 5–10 kg/m2), 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 TRL 4–5. Other technologies (MCP, APD, CMOS) are TRL 2–4.	Silicon-CCD detectors are TRL4–5. Other technologies (MCP, APD, EBBCD with GaN Photocathodes) are TRL 2-4.	Depending on the coating and approach these range from TRL 3–5.	Lightweight 1.3-m Be and SiC mirrors are TRL 6. Borosilicate glass mirrors are TRL 5. Larger mirrors are TRL 2–3.	Lightweight 1.3-m Be and SiC mirrors are TRL 6. Borosilicate glass mirrors are TRL 5. Technologies for advanced deployment, wavefront sensing, and actuation are mid-TRL.	CCDs and HgCdTe arrays in megapixel formats are TRL >6.
Tipping point	TRL 6 with Si-CCD detectors can be achieved in ≈2 years with modest funding investment; in APDs later.	TRL 6 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.

Table 3-1 (continued)

Name of technology	High QE, large format UV detectors	Photon counting large-format UV detectors	High Reflectivity UV coatings	Large, low-cost, light-weight precision monolithic mirrors for Ultra-Stable Large Aperture UV/Visible/Near-IR Telescopes	Deployable light-weight precision mirrors for future Very Large Aperture UV/Visible/Near-IR Telescope	Very large format, low noise Visible/IR detector arrays
NASA capability	NASA is partnering with industry and academia to produce these detectors.	NASA is partnering with industry and academia 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/Near-IR mirror technologies in partnership with industry.	NASA has the necessary capabilities at GSFC, MSFC and JPL to develop these UV/Visible/Near-IR 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, depending on areal coverage and QE.	High performance detectors can increase the science impact of missions by 10–1000, depending on areal coverage and QE.	High coating reflectivity in UV make possible high-performance optical systems that can be highly-multiplexed, significantly increasing the potential impact of future missions Wideband coating could enable a combined UV to IR mission that would have a very broad scientific potential.	Low-cost, light-weight optics are required to enable the development of large aperture UV/Visible/Near-IR telescopes. Large aperture telescopes are required to provide the spatial resolution and sensitivity needed to open new discovery space	Low-cost, ultra-light-weight optics are required to enable the development of very large aperture UV/Visible/Near-IR telescopes. Large aperture telescopes are required to provide the spatial resolution and sensitivity needed to open new discovery space	Future missions with large area imaging or multiobject spectroscopic drivers operate ~100 times faster than present.
NASA Needs	Previously flown MCP-based UV detectors obtain ~5–20% QE (wavelength dependent), 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 Decadal Survey noted importance of technology development for a future 4-m class UV/visible mission for spectroscopy and imaging. Benefits will also accrue to Planetary, Heliospheric, and Earth missions in the UV band.	Previously flown UV detectors obtain ~5–20% QE (wavelength dependent), 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 survey noted importance of technology development for a future 4-m class UV/visible mission for spectroscopy and imaging. Benefits will also accrue to Planetary, Heliospheric, and Earth missions in the UV band.	2010 Decadal Survey noted importance of technology development for a future ≥4-m 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/Near-IR mission.	This technology is a key enabling technology for a far future very large UV/Visible/Near-IR mission.	This technology is a key technology of benefit for NASA's next large UV/Visible/Near-IR mission.

Table 3-1 (continued)

Name of technology	High QE, large format UV detectors	Photon counting large-format UV detectors	High Reflectivity UV coatings	Large, low-cost, light-weight precision monolithic mirrors for Ultra-Stable Large Aperture UV/Visible/ Near-IR Telescopes	Deployable light-weight precision mirrors for future Very Large Aperture UV/Visible/Near-IR Telescope	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. This technology supports very low light level imaging, for nighttime Earth sensing.	UV sensors require high-performance optical 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 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 biological and medical imaging.	High performance UV detectors may have applications in biological and medical imaging, microscopy and photonics research.	Unknown.	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology	Unknown.	High performance visible/IR detectors may have applications in biological 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-moderate. Facilities and techniques exist for small optical 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. In order to support an Explorer AO in the second half of the 2010-2020 decade, a focal-plane technology development + flight testing project should be started in the 2014 – 2015 timeframe (i.e., immediately). This would allow time for a suborbital mission to fly in the 2017 – 2020 timeframe	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. In order to support an Explorer AO in the second half of the 2010-2020 decade, a focal-plane technology development + flight testing project should be started in the 2014 – 2015 timeframe (i.e., immediately). This would allow time for a suborbital mission to fly in the 2017 – 2020 timeframe	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. In order to support an Explorer AO in the second half of the 2010-2020 decade, an advanced coating development project should be started in the 2014 – 2015 timeframe (i.e., immediately). This would allow time for a suborbital mission to fly in the 2017 – 2020 timeframe.	Should come as early as possible since technology is applicable to small, medium and large missions. By 2020 for the next large UV/Visible/Near-IR astrophysics mission.	Must follow developments for near-term lightweight mirror segments. By 2030 for the far future large UV/Visible/Near-IR 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. In order to support an Explorer AO in the second half of the 2010-2020 decade, a focal-plane technology development + flight testing project should be started in the 2014 – 2015 timeframe (i.e., immediately). This would allow time for a suborbital mission to fly in the 2017 – 2020 timeframe.
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.

COR Technology Needs – Table 2 of 3

Table 3-2: Technology Needs For Future COR Missions Identified by the Astrophysics Community of Scientists and Technologists.

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	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 50m^2 are needed.	Interferometry in the Far-IR provides sensitive integral field spectroscopy with sub-arcsecond angular resolution and R ~ 3000 spectral resolution. It could resolve protoplanetary and debris disks and measure the spectra of individual high-z galaxies, probing beyond the confusion limits of single-aperture Far-IR telescopes. A structurally-connected interferometer would have these capabilities. Eventually, the formation-flying interferometer would provide Hubble-class angular resolution. Telescopes need to be operated at temperatures as low as 4K.	Optics and detectors for Far-IR, millimeter, and certain X-ray missions require very low temperatures of operation, typically in the tens of milli-K. Compact, low-power, lightweight coolers suitable for space flight are needed to provide this cooling. Both evolutionary improvements in conventional cooling technologies (adiabatic demagnetization and dilution refrigerators) and novel cooling architectures are desirable. Novel cooling approaches include optical, microwave, and solid-state techniques
Goals and Objectives	Develop high QE photon counting detectors for wavelengths of around 400nm–1.7µm. Further enhancement would be to achieve energy-resolving capability.	Detector format of at least 16×16 with high filling factor and with sensitivities (noise equivalent powers) of 10^{-19} W/√Hz are needed for photometry. Fast detector time constant (~200 µsec) is needed for Fourier-transform spectroscopy.	Detector sensitivities with noise equivalent powers of $\approx 3\times10^{-21}$ 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 ~1µm RMS.	The goal is to develop a feasible and affordable (Probe-class) approach to produce a 40m-class interferometer capable of launch and operation, in which a single science instrument provides both dense coverage of the u-v plane for high-quality, sub-arcsecond imaging and Fourier Transform Spectroscopy over the entire spectral range 25–400 microns in an instantaneous field of view >1 arc minute.	A cryocooler operating from a base temperature of ~4K and cooling to 30 mK with a continuous heat lift of 5 µW at 50 mK and 1 µW at 30 mK 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. Sensitive, fast detectors (TES bolometers and MKIDs in small arrays) are at TRL 3 for application in an interferometric mission.	Single detectors are at ~TRL3.	JWST Be mirror segments may meet requirements now, so TRL5 with an extremely expensive technology; TRL3 exists for other materials.	Wide field-of-view spatio-spectral interferometry has been demonstrated in the lab at visible wavelengths with a testbed that is functionally and operationally equivalent to a space-based Far-IR interferometer. Current TRL is 5 for a 40 m Probe-class Far-IR interferometer.	Existing magnetic refrigeration demonstrations and solid-state cooling approach based on quantum tunneling through normal-insulator-superconductor (NIS) junctions are both at TRL 3-4.

Table 3-2 (continued)

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
Tipping point	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. TRL 6 can be attained in 4 years for interferometric mission application.	TRL5 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.	TRL6 can be achieved at moderate cost in 2 years .	Modest investments based on existing technology to reach tipping point. Continuous ADR developed for IXO can be matured to TRL 6 for Far-IR focal plane cooling to tens of mK in 2 years. NIS junction cooling over the range 300 mK to 50 mK can be demonstrated within 3 years given moderate investment. Cooling over large temperature ranges and using different physical principles is less mature and will require lower level of effort over a longer time period to assess.
NASA capability	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 developed lab testbed and associated modeling and algorithm development capability at GSFC.	NASA has cryogenic refrigerator fabrication and testing capabilities at GSFC and JPL.
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 10×–100×. Overall mapping speed can increase by factors of thousands. Sensitivity enables measurement of low surface brightness debris disks and protogalaxies with an interferometer.	Sensitivity reduces observing times from many hours to a few minutes (≈100× improvement). Overall observing speed can increase by factors of thousands.	Low-cost, light-weight 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.	40 m class interferometric baselines are required to provide the spatial resolution needed to follow up on discoveries made with the Spitzer and Herschel space telescopes, and to provide information complementary to that attainable with ALMA and JWST.	Sub-Kelvin cryocoolers are required to achieve astrophysical photon background-limited sensitivity in the Far-IR and high resolution sensitive X-ray microcalorimetry. Techniques to lower cooling costs and improve reliability will aid the emergence of powerful scientific missions in the Far-IR and X-ray.
NASA Needs	This technology is a key technology of benefit for NASA's next large UV/Visible/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. This 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. This 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.	Wide-field spatio-spectral interferometry is a key enabling technology for a NASA Far-IR Astrophysics mission consistently given high priority by the Far-IR astrophysics community. Potential applications also exist in NASA's Planetary and Earth Science programs.	This technology is a key enabling technology for any future NASA-built Far-IR mission. Sensors operating near 100 mK are envisioned for future missions for X-ray astrophysics, measurements of the cosmic microwave background, and far-infrared imaging and spectroscopy. It is applicable to missions of all classes (balloons, Explorers, probes, and flagship observatories).

Table 3-2 (continued)

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
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.	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.	Similar technologies find application in airport screening devices for DHS.	Unknown.	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology	Unknown.	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 for individual detectors is low, as the approach is relatively mature. TES bolometers and MKIDs are promising alternative technologies. 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 low, as the technique is currently at TRL 5. Future work will yield insight into the practical limitations of the technique, but its potential viability for a future Far-IR interferometer has already been demonstrated.	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. In order to support an Explorer AO in the second half of the 2010–2020 decade, a focal-plane technology development + flight testing project should be started in the 2014–2015 timeframe. This would allow time for a suborbital mission to fly in the 2017–2020 timeframe.	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. Needed by 2020 for the next large Far-IR astrophysics mission.	Continuation of prototype efforts expected to yield mature technique in time for 2015 balloon flight. To enable credible discussion of a Far-IR interferometer, recognized as a critical investment in the future, must reach TRL 6 well in advance of 2020 Decadal Survey (e.g., by ~2018).	Beneficial to undertake soon, to take advantage of existing development momentum, to allow time for system integration and cryo-thermal system performance verification, and to enable balloon and Explorer applications in advance of the 2020 Decadal Survey. In order to support an Explorer AO in the second half of the 2010–2020 decade, a focal-plane technology development + flight testing project should be started in the 2014–2015 timeframe. This would allow time for a suborbital mission to fly in the 2017–2020 timeframe.
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.	NASA internal development with academic and international participation in the balloon experiment. 2 years to mature to TRL 6 for Far-IR applications on balloon and in space.	3-year effort at NASA.

COR Technology Needs – Table 3 of 3

Table 3-3: Technology Needs for Future COR Missions Identified by the Astrophysics Community of Scientists and Technologists.

Name of technology	Heterodyne Far-IR Detector Arrays	High Efficiency Cryocoolers	High Efficiency UV Multi-Object Spectrometers	Low Frequency, Wide Bandwidth Receiving Systems	Mirror Cleaning Technologies
Brief description	NASA's SOFIA observatory as well as suborbital and space missions could achieve a significant observational capability increase by upgrading its single-pixel coherent (heterodyne) spectrometers to arrays. Heterodyne focal plane arrays are necessary for high-sensitivity spectrally-resolved mapping of interstellar clouds, star-forming regions, and solar system objects including comets. These arrays require mixers with low noise temperature and wide IF bandwidth, local oscillators that are tunable but which can be phase locked, and accompanying system technology including optics and low-cost and low-power digital spectrometers	Optics and refrigerators for Far-IR, millimeter, and certain X-ray missions require very low temperatures of operation, typically roughly 4 K. Compact, low-power, lightweight, low vibration coolers suitable for space flight are needed to provide this cooling. 4 K cryocoolers additionally provide the heat sink for sub-Kelvin coolers.	Future NASA UV missions devoted to spectroscopy, require high throughput (>50%), multi-object spectrometer (>100 sources; R~3000 or greater) architectures and components for operation at 100–400nm or broader band (e.g., digital micro-mirror device (DMD), advanced diffraction gratings, microshutter arrays, fiber-fed spectrographs, and integral field specrometers)	Receiving systems (antenna and associated electronics) capable of making measurements sufficient to detect the highly redshifted neutral hydrogen 21 cm line from Cosmic Dawn, at redshifts z > 6. The desired signals of interest have amplitudes of milliKelvin to potentially a few hundred milliKelvin at frequencies of 10 to 120 MHz.	Safe, effective, and reliable last-minute or in-flight mirror cleaning technologies would be of great benefit to future space missions.

Table 3-3 (continued)

Name of technology	**Heterodyne Far-IR Detector Arrays**	**High Efficiency Cryocoolers**	**High Efficiency UV Multi-Object Spectrometers**	**Low Frequency, Wide Bandwidth Receiving Systems**	**Mirror Cleaning Technologies**
Goals and Objectives	Develop broad tunable bandwidth array receivers for operation at frequencies of 1THz–5THz. Arrays of 10 to 100 pixels are required to build on the discoveries of Herschel and exploit the submillimeter/FIR region for astronomy. Should include optics and accompanying system components.	Extend JWST cryocooler capability to enable cooling from a base temperature of ~300K and cooling to ~4 K with a continuous heat lift of 180mW at 18 K and 72 mW at 4 K, with <200W of input power, as required for several mission concepts. More stringent requirements may pertain to a large single-aperture Far-IR telescope if a cryocooler is used to cool the primary mirror.	Produce large-format, high QE, moderate resolution systems, routinely, that can be employed in a variety of Explorer, medium, and strategic missions. Key performance criteria for customization, maturation, and characterization of object selection components (such as DMDs, microshutters, or reconfigurable fibers) for UV/Vis/NIR space astronomy include: (1) Sensitivity over the spectral interval, 0.20 to 1.7 microns, (0.9–1.8 nm for DMDs) (2) Effective blockage of the sky background, e.g., zodiacal light, (3) low instrumental background (optical scattering, thermal background). Low-scatter echelle gratings are required for high-resolution far-UV (λ = 90–180 nm) spectroscopy. Performance goals for gratings in clued: scattered light control comparable to the best first-order diffraction grating currently flying (HST-COS), ~10^{-5} of the peak intensity at $\Delta\lambda$ = 10 Å from fiducial wavelength λo. In the short term (2014–2016), scattering < 10^{-3} would enable deeper, high-resolution UV spectroscopy than currently available with HST, in an Explorer-class mission.	Produce a receiving system for which the spectral response (i) has no feature for which the amplitude exceeds 1 mK over the required frequency range, and (ii) can be described by a set of functions that are smooth (e.g., polynomials) over the required frequency range (10 to 120 MHz) and which require no more than 10 parameters to model.	Last-minute cleaning technology on the ground or in-flight cleaning technology would reduce the high cost of keeping equipment clean for a decade in clean rooms. Existing approaches, such as CO2 snow, and electrostatic wands with AC excitation, do not clean off molecular contamination. Promising methods, using e.g., electron or ion beams could clean off molecular layers as well as dust.
TRL	For SOFIA, only single pixel receivers have been developed for flight; arrays of 16 pixels are approaching TRL~4.	Existing pulse tube, Stirling, and Joule-Thomson coolers with worse performance are at high TRL. The TRL is 4 for Far-IR interferometric mission application.	DMD is at TRL 5, based on European studies for Euclid, and particle-radiation tests at LBL. Microshutters for longer wavelengths (> 0.6microns) are at TRL 6. Low scatter echelle gratings are currently at TRL 2.	The TRL is around 3.	The fully capable technologies for ground use are at modest TRL; in-flight cleaning is at a very low TRL.
Tipping point	TRL4–5 could be achieved within a few years, and would enable near-term flight opportunities on SOFIA.	Modest investments based on existing demonstration to reach tipping point. Substitution of ^{3}He for working fluid in JWST cooler, may permit reaching TRL 6 for a Far-IR interferometer within 3 years.	TRL6 for object selection devices could be achieved within 2 years with modest investments using existing techniques.	TRL4–5 could be achieved within a few years.	The time to advance is not clear.
NASA capability	NASA has laboratory fabrication facilities at JPL currently working at a low level on these technologies.	Industry is well-suited for this work.	Industrial capability and work at GSFC, JPL apply to various elements listed above.	JPL is a potential provider of this enabling technology, also universities and NRL/NRAO.	

Table 3-3 (continued)

Name of technology	Heterodyne Far-IR Detector Arrays	High Efficiency Cryocoolers	High Efficiency UV Multi-Object Spectrometers	Low Frequency, Wide Bandwidth Receiving Systems	Mirror Cleaning Technologies
Benefit	Development of such systems and associated technology will be of significant benefit to laboratory spectroscopy and biomedical imaging. Observations would be significantly (>10×) faster in imaging applications.	Space qualified 4 K cryocoolers will replace expendable cryogens, which are huge consumers of volume and mass, drive mission cost, and limit mission lifetime. Large-capacity cryocoolers are required to achieve astrophysical photon background-limited sensitivity in the Far-IR and meet sensitivity requirements to achieve the science goals for future Far-IR telescopes or interferometers.	High performance spectrometers can increase the science impact of missions by orders of magnitude. Space telescopes today can obtain slit spectra of a single object or slitless spectra of a field, but not slit spectra of multiple objects in a field. A UV/visible slit selector (DMD, micro-shutter array, or multifiber) would eliminate confusion and block unwanted background (e.g., zodiacal light). Better gratings improve contrast and thereby sensitivity. For small, wide-field telescopes appropriate for an Explorer mission, these are enabling technologies.	This technology enables "Cosmic Dawn," studie, one of the three science objectives for this decade as identified by the New Worlds, New Horizons Decadal Survey. Studies of the highly redshifted neutral hydrogen 21 cm line will probe the Epoch of Reionization (EoR), and will address the science frontier question "What were the first objects to light up the Universe and when did they do it?	This technology could reduce schedule (thus cost) and simplify mirror processing before launch. Post-launch cleaning can improve on-orbit performance and extend mission life.
NASA Needs	Needed for future submm/FIR suborbital missions (instruments for SOFIA and balloons) and for potential small-satellite and Explorer missions that will go beyond Herschel. Solar system studies of planetary atmospheres will directly benefit. For Earth observing, focal plane arrays will improve coverage speed and will provide small spot sizes with reasonably-sized antennas.	This technology is a key enabling technology for any future NASA-built Far-IR mission. It is applicable to missions of all classes (balloons, Explorers, probes, and flagship observatories).	UV-visible-IR slit selectors are needed for astrophysics, heliospheric, and Earth-science missions.	The technology would enable new Astrophysics missions, and may allow for new Heliophysics missions. Other potential relevant missions include lunar orbiter missions to detect Cosmic Dawn and lunar farside surface radio array.	All future missions with optics would benefit from this technology
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.	Unknown	Unknown	Future missions with optics would benefit from this technology.
Non-aerospace needs	Remote sensing applications for pollutants. imaging of chemical reactions, and biomedicine. A variety of security applications would be dramatically enhanced (faster scanning and/or higher time resolution) by the availability of arrays	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology; other laboratory needs could be fulfilled with commercialization.	Unknown.	Ionospheric studies.	Future missions with optics would benefit from this technology.
Technical risk	Technical risk is moderate, as basic technology has significant prior investment.	Technical risk is low, as development leverages previous investments at NASA.	Technical risk is low, as development leverages previous investments at NASA.	Key risk is that a sufficiently simple spectral response cannot be obtained, with the result the redshifted 21 cm line is more difficult to identify and study given the instrumental characteristics.	None yet identified.

Table 3-3 (continued)

Name of technology	Heterodyne Far-IR Detector Arrays	High Efficiency Cryocoolers	High Efficiency UV Multi-Object Spectrometers	Low Frequency, Wide Bandwidth Receiving Systems	Mirror Cleaning Technologies
Sequencing/timing	2-THz arrays with 16–32 pixels needed by late in this decade; similar arrays at 4.7 THz by early in next decade. These should be accompanied by development of required local oscillator systems and optic. In parallel, development of low-power broadband amplifiers should be supported, to mitigate thermal complexity for large-N arrays. Digital spectrometers with minimum of 8 GHz bandwidth and 2000 spectral channels will be needed, and must be evaluated in terms of astronomical performance.	Beneficial to undertake soon to take advantage of existing development momentum, to allow time for system integration and cryo-thermal system performance verification, and because the technology is applicable to small, medium and large missions. Well before the 2020 Decadal Survey to enable consideration of the next large Far-IR astrophysics mission.	Should come as early as possible since mission definition and capabilities are built around instrument performance. Development for space astronomy is needed in time to respond to an expected announcement of opportunity for an Explorer-class mission in 2015–2016.	No known technical dependences. Receiving systems at these frequency ranges have been produced. Timing is for missions in the latter half of this decade and next decade.	As early as possible–would be immediately useful.
Time and effort	A modest effort spread over 5 years with appropriate technical and equipment support.	3-year effort in industry, plus one additional year for system integration and thermal performance verification.	3-year collaboration between NASA, university groups, and industry.	Readiness for flight may require a ~7-year SAT-level program.	Unknown

4. Program Technology Priorities and Recommendations

Background

Section 3, Program Technology Needs, discusses how the community technology needs are collected by the PO. As part of the annual technology needs prioritization process, after the needs list was compiled, the COR TMB scored these needs according to a set of evaluation criteria. The results of this process are included in this section.

Membership of this TMB includes senior members of the Astrophysics Division at NASA HQ, the COR PO, the SOFIA Program, Exoplanet Exploration Program. For 2013, the Board used a prioritization approach similar to previous years; however, as discussed in the background information at the end of this section, the number of selection criteria was reduced from 11 to 4. These criteria address the strategic alignment, benefits and impacts, timeliness, and applicability of each technology need. The four prioritization criteria are:

- **Strategic Alignment:** How well does the technology align with scientific and/or programmatic priorities as determined by the AIP (December, 2012) (which responded to the 2010 Decadal Survey recommendations within the current budgetary constraints) or current programmatic assessment? A technology related to a mission ranked highly by a major directive or review process should receive a higher score.

- **Benefits and Impacts:** What positive impact does the technology have on the science return or the ability to implement a notional mission? To what extent does the technology enable/enhance a mission, or to what degree is the technology unique? If a technology is a key element of a mission concept, then its score should be higher than for a technology that is of only minor importance.

- **Scope of Applicability:** How many mission concepts can benefit from this technology? How cross-cutting is it? If a technology is generally useful to many missions, then it is scored higher.

- **Time to Anticipated Need:** How much time is available before the technology is needed to be at TRL5/6 or before the decision to invest is necessary? If a mission is not planned for implementation for a long time and/or there is ample time to develop the technology for it, then the technology should receive a lower score than the more immediate needs.

For each criterion, a weighting factor was assigned that was intended to reflect the importance that the COR Program places on that criterion. Each criterion for each technology need received a score of 0 to 4 in the evaluation. That score was multiplied by the established weighting factor for the criterion, and this product was summed across all criteria for each technology. Descriptions of the criteria, their weighting factors, and scoring guidelines used by the TMB are shown in Table 4-1.

#	Criterion	Weight	Max Score	Weighted Score	General Description/ Questions	4	3	2	1	0
1	**Strategic Alignment**	10	4	40	Does the technology enable or enhance a mission concept that is prioritized by the Astrophysics Implementation Plan or a current programmatic assessment?	Applicable mission concept receives highest AIP ranking	Applicable mission concept receives medium AIP ranking	Applicable mission concept receives low AIP ranking	Applicable mission concept was not ranked by the AIP but was positively addressed in the 2010 Decadal Survey	Not ranked by the AIP or the 2010 Decadal Survey
2	**Benefits and Impacts**	9	4	36	What is the impact of the technology on a notional mission concept? What is the degree of unique or enabling/ enhancing capability the technology provides toward the science objective and the implementation of the mission?	Critical and key enabling technology - required to meet mission concept objective(s)	Highly desirable technology - significantly enhances science objectives(s) and/or reduces need for critical resources	Desirable - offers significant science or implementation benefits but not required for mission success	Minor science impact or implementation improvements	No science impact or implementation improvement
3	**Scope of Applicability**	3	4	12	How cross-cutting is the technology? How many mission concepts could benefit from this technology?	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	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 a decision point or implementation?	Decision point is now, or overdue, and implementation is needed within 7 years (this decade)	Decision point is now, or overdue, and implementation is needed in 8 to 10 years (early to mid 2020s)	Decision point is less than 5 years away, or implementation is needed in 13 to 17 years (late 2020s)	Decision point is 5 to 10 years away, or implementation is needed in 18 years or later (early 2030s)	No anticipated need

Table 4-1. Technology Needs Prioritization Criteria

In 2012, the TMB ranked 15 technology needs for COR. All of these technology needs ranked in 2012 were carried over. Note that for 2013 the Board specifically interpreted that technology needs expressed at a systems level would also encompass subordinate component-level needs. Thus, for example, the system-level technology need for telescopes is defined as including telescope structures, actuators, etc.

Results

After all technology needs were scored and reviewed by the TMB, they were binned into three priority groups. The divisions were based on a number of factors assessed by the TMB, including primarily a natural grouping of the technology needs based on their overall scores. The technology needs and bins are described below:

Priority 1: Contains technology activities that the Board has determined to be of the highest interest to the COR Program and recommends that they ***should*** be invested in first, when funding is available. These technology needs are enabling for the highest priority potential COR missions.

- **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 90–350 nm or broader.
- **High-reflectivity UV coatings:** Development of UV coatings with high reflectivity, high uniformity, and wide bandpass, ideally operating from the visible to wavelengths below 100 nm.
- **Large, low-cost, lightweight precision monolithic mirrors for ultra-stable large-aperture UV/Optical/Near-IR telescopes:** For 2013, this technology need received a higher score for strategic alignment and impact. As a result, it jumped from Priority 2 to Priority 1. Note that for 2013 the wavelength range was extended to include near-IR.
- **Deployable, lightweight, precision mirrors for future very-large-aperture UV/Optical/Near-IR telescopes:** This technology need was included in Priority 3 in 2012. However, based in part on guidance from the AIP and reassessment of the technology needs impact, it moved into Priority 1 for 2013.
- **High-efficiency UV multi-object spectrometers:** In 2012, this technology need received a Priority 3 ranking, primarily because it was interpreted as a high system-level need that did not define the specific individual technology needs to be addressed. With the 2013 interpretation of needs defined as system-level, this technology need received higher scores and jumped from Priority 3 to Priority 1.

Priority 2: Contains technology activities that the Board feels are worthy of pursuit and ***would*** be invested in, if funding allows. Priority 2 technology needs include those that are of somewhat less impact to the candidate missions. These technology needs may be enhancing, as opposed to enabling. Priority 2 includes the following, which were also Priority 2 in 2012, except as noted:

- **Large-format, low-noise Far-IR direct detectors**
- **Heterodyne Far-IR receiver arrays**
- **High performance sub-Kelvin coolers:** This technology need had slipped to Priority 3 last year. For 2013, it received the same scoring as high-efficiency cryocoolers.
- **High-efficiency cryocoolers**
- **Photon-counting Optical/IR detector arrays**

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 includes the following, which were also Priority 3 in 2012, except as noted:

- **Very-large-format, low-noise, Optical/IR detector arrays**
- **Mirror cleaning technologies:** This technology need is new for 2013. It was considered by the Board to have high strategic alignment and applicability, but overall impact to potential missions would be lower than technology needs in Priorities 1 and 2.
- **Ultra-low-noise Far-IR direct detectors:** This technology need was in the Priority 1 bin in 2013, based on its strategic alignment with a potential U.S. contribution to the JAXA-led SPICA mission. As discussed in the AIP, funding limitations do not permit NASA participation in SPICA. Thus, the strategic alignment score for this technology need was much lower in 2013, dropping the need to Priority 3.
- **Low-frequency, wide-bandwidth receiving systems:** This technology need is new for 2013. Given that it is not applicable to missions ranked in the AIP, its strategic alignment score was low, resulting in a Priority 3 ranking.
- **Interferometry for Far-IR telescopes**
- **Large cryogenic Far-IR telescopes**

Background Information on 2013 Evaluation Criteria Changes

Following the prioritization exercises for 2011 and 2012, a scoring analysis was performed to understand the correlation of scores for the technology needs for the 11 criteria used in those years. From this analysis, it was determined that several criteria could be combined and others eliminated without significantly changing the final rankings. That is, the process could be simplified without changing the final results. Thus, for 2013, the number of evaluation criteria was reduced from 11 to 4, as described in Table 4-2. The criteria weighting factors were adjusted to reflect the relative importance of the criteria to the COR Program.

2011–2012 Criteria	2013 Criteria	Comments
1. Scientific ranking of applicable mission concept	Strategic Alignment	This criterion remained the same from 2012 to 2013.
2. Overall relevance to applicable mission concept 5. Scientific impact 6. Implementation impact 7. Schedule impact 8. Risk reduction	Benefits and Impacts	In previous years, there were five criteria that captured the importance or impact of potential technology solutions to candidate mission concepts. Overall relevance, scientific impact, and implementation impact criteria tended to overlap. Schedule and risk impacts provided little differentiation. Thus, in the correlation analysis, the combination of Criteria 5–8 was essentially the same as Criterion 2. Based on this, these criteria have all been combined for 2013 and called Benefits and Impacts.
3. Scope of applicability	Scope of Applicability	This criterion remained the same from 2012 to 2013.
4. Time to anticipated need	Time to Anticipated Need	This criterion remained the same from 2012 to 2013.
9. Definition of required technology 10. Other sources of funding 11. Availability of providers	These three criteria were eliminated for 2013.	These criteria were weighted low and generally the spread of their scores was small. Thus, they had very little impact on overall rankings. Also, knowledge about funding and availability of providers was inconsistent across the technology needs, which could lead to skewing of the results.

Table 4-2. Summary of Evaluation Criteria Changes for 2013.

5. Closing Remarks

This COR PATR serves as the current snapshot of the dynamic state of technology development managed by the COR PO and provides future directions for technology maturation. This document serves to:

1. summarize the current needs for technology development as identified by the astrophysics community;

2. document the results of this year's prioritization of those technology needs as established by the COR TMB; and

3. provide up-to-date summaries of the status of all of the technologies in our COR Program strategic technology development portfolio.

This year's priorities will serve as recommendations from the COR PO to NASA HQ for future technology investment decisions to further the goals of the COR Program.

This report is produced annually in order to best reflect the continuing changes in the landscape of astrophysics scientific needs–and their requisite technologies–incorporating novel developments to respond to the always dynamic nature of our field.

The yearly activities of the COR PO that lead to the publication of the PATR provide a continuity of overall visions and processes for strategic purposes, while simultaneously retaining the flexibility to adapt tactically to new opportunities. This report is significant because it annually tracks the status of all of the technologies in the Program portfolio that are being matured to serve overall Program goals. This PATR also identifies the next generations of technologies that need to be developed.

The PO will continue to interact with the broad scientific community–through the COPAG, through various workshops, at public scientific conferences, and via public outreach activities. These activities identify and incorporate the astrophysics community's ideas about new science, current technology progress, and new needs for technology in an open and reliable process. Each year, we make improvements to this process and ameliorate any shortcomings from prior activities.

We would like to thank the COR scientific community, the PIs and their teams, and the COPAG for all of their efforts and inputs that make this annual report current and meaningful.

The COR PO welcomes continued feedback and inputs from the astrophysics community in developing next year's COR PATR. For more information about the COR Program and its activities–and to provide your greatly appreciated feedback and inputs–please visit us at: http://COR.gsfc.nasa.gov

Appendix A
Program Technology Development Quad Charts

Heterodyne Technology for SOFIA

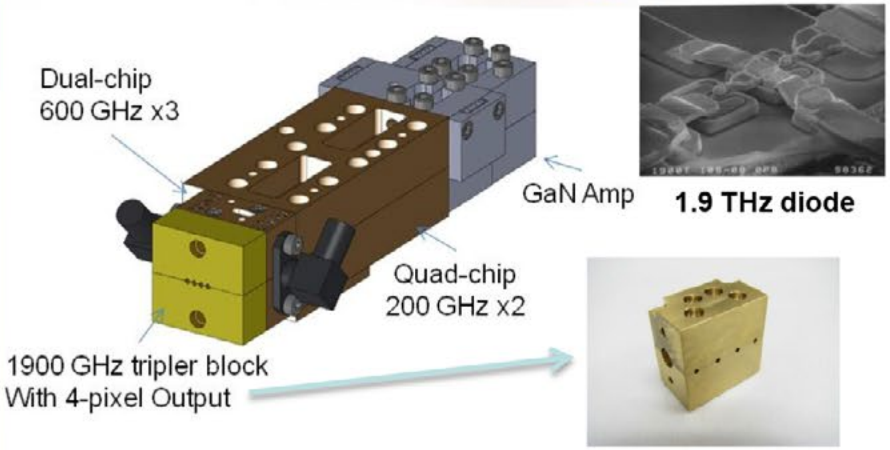
PI: Dr. Paul Goldsmith/JPL

Description and Objectives:

- Heterodyne technology is necessary to answer fundamental questions including - 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 what controls the mass-energy-chemical cycles within galaxies?
- We will develop local oscillator (LO) and receiver subsystems that will allow for the implementation of multi-pixel high spectral resolution imaging in the all important 1.9-2.06 THz range.

Key Challenge/Innovation:

- Lack of solid-state sources in the THz range is perhaps the single most important challenge towards implementing array receivers
- Lack of broad IF band Hot Electron Mixers is issue at higher freqs.



1.9 THz all solid-state LO source for pumping a 4-pixel heterodyne receiver

Approach:

- Utilize JPL developed membrane diode process to construct compact tunable sources in the 1.9-2.06 range
- Utilize novel waveguide based active device power combining schemes to enhance power at these frequencies
- Work with collaborators in Russia to demonstrate wide IF band Hot Electron Mixers
- Build and test multi-pixel receivers to investigate stability and demonstrate performance

Key Collaborators:

- Imran Mehdi, Jon Kawamura, Jeff Stern, Boris Karasik, Jose Siles, Choonsup Lee, Robert Lin (all JPL)

Development Period:

- Oct 2010 – Sept 2013 (no cost extension intended)

Accomplishments and Next Milestones:

- Demonstrated solid-state LO source at 1.904 THz that puts out 50 microwatts of power
- Demonstrated a biasable 1.9 THz LO source
- Demonstrated a 2.7 THz receiver with SOA performance
- Demonstration of 4-pixel LO chain (FY13)
- Development of waveguide based 4-pixel HEB mixer array (FY13)
- Demonstration of 4-pixel array receiver (FY14)
- Final design of 16-pixel array receiver (FY14)

Application:

- Array receivers for SOFIA
- Heterodyne array receivers for future suborbital and space missions
- Array receivers for CCAT

TRLin = ***3*** *TRLcurrent est. by PI =* ***3*** *TRLtarget =* ***4***

Enhanced MgF_2 and LiF Over-coated Al Mirrors for FUV Space Astronomy

PI: Manuel A. Quijada/GSFC

Description and Objectives:

- To develop on a large scale (up to 1 meter diameter) coating of mirrors using a Al+MgF_2 coating process to enhance performance in the Far-Ultraviolet spectral range
- Study other dielectric fluoride coatings and other deposition technologies such as Ion Beam Sputtering (IBS) that is known to produce the nearest to ideal morphology optical thin film coatings and thus low scatter

Key Challenge/Innovation:

- Improved reflective coatings for large optics, particularly in the ultraviolet part of the spectrum, could yield dramatically more sensitive instruments and permit more instrument design freedom

Approach:

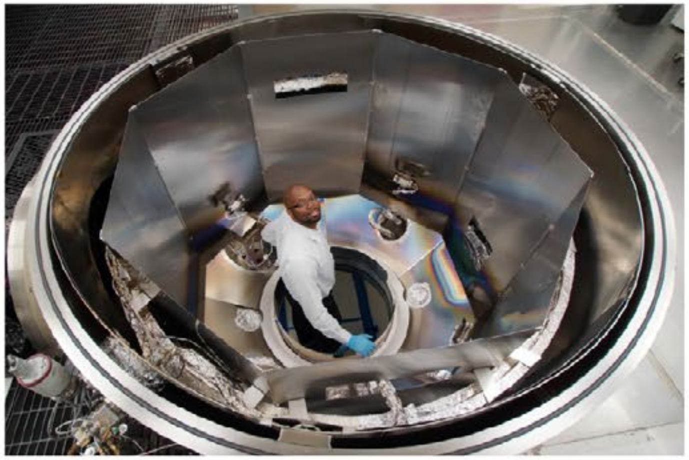
- Retrofit a 2 meter coating chamber with heaters/thermal shroud to perform coating iterations at a high deposition temperatures (200-300° C) to further improve performance of protected Al mirrors with either MgF_2 or LiF overcoats
- Optimize deposition process of lanthanide trifluorides as high-index materials that when paired with either MgF_2 or LiF will enhance reflectance of Al mirrors at Lyman-alpha
- Establish the IBS coating process to optimize deposition of MgF_2 and LiF with extremely low absorptions at FUV wavelengths

Key Collaborators:

- Steve Rice and Felix Threat (551)
- John Lehan (SGT)
- Jeff Kruk and Charles Bowers (665)

Development Period:

- FY12 – FY14



Inside 2-meter coating chamber after installation of thermal shroud and halogen-quartz heater lamps.

Accomplishments and Next Milestones:

- Established the short wavelength transmission cutoff of GdF3 and LuF3 films grown by physical vapor deposition method.
- Systematic study of MgF_2 films grown with the IBS process as function of growth temperature and other coating parameters.
- Re-optimized the growth process of Al+MgF_{2+} to realize additional reflectance gains below 1200 A.
- Initial coating run of Al+MgF_2 slide distribution in 2 meter chamber: August 2013
- Design and fabricate a narrow-wavelength reflector using a dielectric stack in the 1200-1500A range: November 2013

Application:

- This technology will enable FUV missions to investigate the formation and history of planets, stars, galaxies and cosmic structure, and how the elements of life in the universe arose

TRLin = **4** *TRLcurrent est. by PI* = **4** *TRLtarget* = **5**

Advanced Mirror Technology Development

PI: Phil Stahl/MSFC

Description and Objectives:

- Mature the TRL of 6 key technology challenges for the primary mirror of future large-aperture Cosmic Origin UVOIR space telescopes
- Include monolithic and segmented optics design paths
- Conduct prototype development, testing and modeling
- Trace metrics to science mission error budget

Key Challenge/Innovation:

- Deep core concept design traceable to 4m mirror
- 4m to 8m mirror and support structure point design that would meet launch vehicle and science requirements

Subscale Deep Core Mirror Testing at MSFC XRCF

Subscale Deep Core Mirror Static Load Testing at Exelis

Approach:

- Provide guidance for science community architecture down select in 2015.
- Advance key technology required to enable 4 different implementation paths.
- Develop science and engineering requirements for traceable mirror systems and determine their associated mass. Then select a launch system or down-size the mirror systems and science requirements.

Key Collaborators:

- Dr. Scott Smith, Ron Eng and Mike Effinger/ NASA MSFC
- Bill Arnold/Defense Acquisition Inc., Gary Mosier/GSFC
- Dr. Marc Postman/STScI, Laura Abplanalp, Keith Havey, Roger Dahl, Steve Maffett/ITT Excelis

Development Period:

- Sept 2011 – Sept 2014

Accomplishments and Next Milestones:

- Modeled and validated by test at MSFC the deep core mirror's thermal performance
- Modeled and validated by test at Exelis the deep core mirror's static load performance
- Updated mirror & spacecraft modelers and generated point design
- Submit nine papers to the SPIE Optics & Photonics conference/August 2013
- Test AMSD type mirror/Dec 2013

Application:

- Flagship optical missions
- Explorer type optical missions
- Department of Defense and commercial observations

TRLin = ***varies from TRL3 to TRL5.5 pending technology***

TRLcurrent est. by PI = ***varies from TRL3 to 5.5 pending technology***

TRLtarget = ***half step increase***

Cross Strip MCP Detector Systems for Spaceflight

PI: John Vallerga/ U.C. Berkeley

Description and Objectives:

- Cross strip (XS) MCP photon counting UV detectors have achieved high spatial resolution (12µm) at low gain (500k) and high input flux (MHz) using laboratory electronics and decades old ASICs. We plan to develop a new ASIC ("GRAPH") that improves this performance, which includes amps and ADCs in a small volume, mass and power package crucial for spaceflight and demonstrates its performance to TRL 6.

Key Challenge/Innovation:

- A new ASIC with amplifiers a factor of 5 faster yet with similar noise characteristics as existing amplifier ASIC
- GHz analog sampling and a low power ADC per channel
- FPGA control of ASIC chip

Approach:

- We will develop the ASIC in stages, by designing the four major subsystems (amplifier, GHz analog sampler, ADC and output multiplexor) using sophisticated simulation tools for CMOS processes. Small test runs of the more intricate and untested designs can be performed through shared access of CMOS foundry services to mitigate risk. We plan 2 runs of the full up GRAPH design (GRAPH1 and GRAPH2). In parallel, we will design and construct an FPGA readout circuit for the ASIC as well as a 50mm XS MCP detector that can be qualified for flight use.

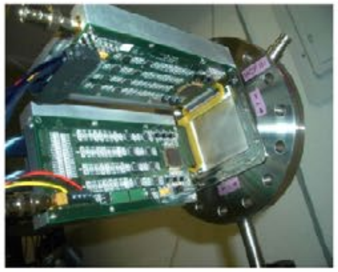
Key Collaborators:

- Prof. Gary Varner, U. Hawaii
- Dr. Oswald Siegmund, U.C. Berkeley

Development Period:

- May 1, 2012 – Apr 30, 2015

Existing 19" rack mounted XS electronics



Two small, low mass, low power ASIC and FPGA boards qualified for flight

Accomplishments and Next Milestones:

- 50 mm detector design and fabrication complete
- Commissioned detector with PXS electronics
- Designed and fabricated ASIC amplifiers
- Design and fabrication of FPGA board (Nov 2013)
- Design and fab of half-GRAPH1 ASIC (Nov 2013)
- Design and fab of GRAPH2 ASIC (Nov 2014)

Applications:

- High performance UV(1-300nm) detector for astrophysics, planetary, solar, heliospheric, or aeronomy missions
- Particle or time of flight detector for space physics missions
- Fluorescense lifetime imaging (FLIM) for biology
- Neutron radiography/tomography for material science

TRLin = ***4*** *TRLcurrent est. by PI =* ***4*** *TRLtarget =* ***6***

Ultraviolet Coatings, Materials and Processes for Advanced Telescope Optics

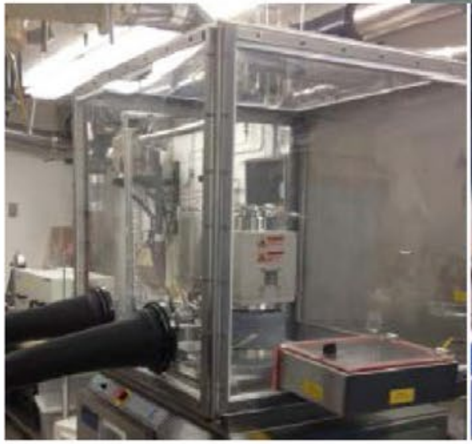
PI: K. Balasubramanian/JPL

Description and Objectives:

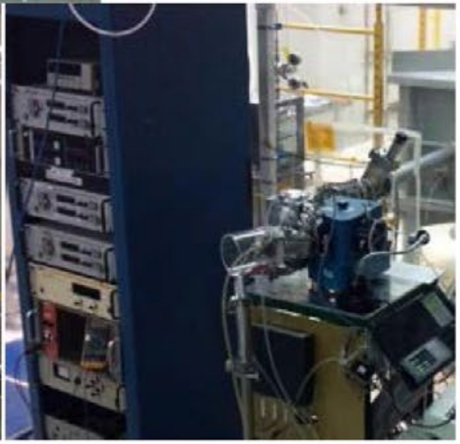
- "Development of UV coatings with high reflectivity (>90-95%), high uniformity (<1-0.1%), and wide bandpasses (~100 nm to 300-1000 nm)" is a major technical challenge as much as it is a key requirement for cosmic origins program and for exoplanet exploration program. This project aims to address this key challenge and develop feasible technical solutions.

Key Challenge/Innovation:

- Materials and process technology are the main challenges. Improvements in existing technology base and significant innovations in coating technology such as Atomic Layer Deposition will be developed.



ALD chamber at JPL



Deep UV Test station at U of Colorado

Approach:

- A set of experimental data will now be developed with MgF_2, AlF_3 and LiF protected Al mirrors in the wavelength range 100 to 1000 nm for a comprehensive base of measured data to enable full scale developments with chosen materials and processes.
- Enhanced coating processes including Atomic Layer Deposition (ALD) will be studied; Characterization and measurement techniques will be improved.

Key Collaborators:

- Stuart Shaklan (JPL), Nasrat Raouf (JPL), Shouleh Nikzad (JPL), Frank Greer (JPL), Paul Scowen (ASU), James Green (Univ of Colo)

Development Period:

- Jan 2013 – Dec 2015

Accomplishments and Next Milestones:

- A coating chamber has been upgraded with sources, temperature controllers and other monitors to produce coatings of various fluorides; measurement tools are also established now at JPL and U of Colo.
- Preliminary coatings with various fluorides will be produced and characterized during Aug-Dec 2013.
- Enhancements to conventional coating techniques will be developed; ALD coating process tools and process will be established at JPL (2014)
- ALD and other enhanced coating processes for protected and enhanced aluminum mirror coatings will be developed and improved (2015)
- Test mirror coupons representing a meter-class mirror to be produced and characterized (2015)

Application:

- The technology developed through this project will enable future astrophysics and exoplanet missions that aim to capture key spectral features from far UV to near infrared.

TRLin = ***3*** *TRLcurrent est. by PI =* ***3*** *TRLtarget =* ***5***

Kinetic Inductance Detector Arrays for Far-IR Astrophysics

PI: Jonas Zmuidzinas/Caltech

Description and Objectives:

- Half of the electromagnetic energy emitted since the big bang lies in the far-infrared. Large-format far-infrared imaging arrays are needed for studying galaxy formation and evolution, and star formation in our galaxy and nearby galaxies. Polarization-sensitive arrays can provide critical information on the role of magnetic fields.
- We will develop and demonstrate far-IR arrays for these applications.

Key Challenge/Innovation:

- Far-infrared arrays are in high demand but are difficult to fabricate, and therefore expensive and in short supply. Our solution is to use titanium nitride (TiN) absorber-coupled, frequency-multiplexed kinetic inductance detectors.

Approach:

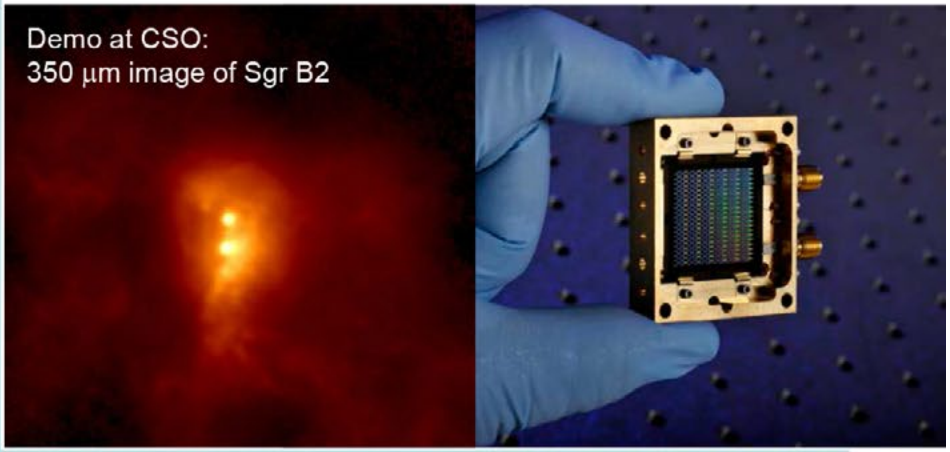
- The goal is to raise the TRL of these detectors so that investigators may confidently propose them for a variety of instruments:
    - Ground telescope demo, 350 mm, 3×10^{-16} W Hz$^{-1/2}$
    - Lab demo for SOFIA, 90 mm, 1.7×10^{-16} W Hz$^{-1/2}$
    - Lab demo for balloon, 350 mm, 7×10^{-17} W Hz$^{-1/2}$
    - Lab demo for space, 90 mm, 5×10^{-19} W Hz$^{-1/2}$

Key Collaborators:

- G. Chattopadhyay, JPL
- Peter Day, JPL
- Darren Dowell, JPL
- Matt Holllister, Caltech
- Rick Leduc, JPL
- Chris McKenney, Caltech

Development Period:

- Jan 2013 – Dec 2014



Demo at CSO:
350 μm image of Sgr B2

Accomplishments and Next Milestones:

- Fall 2012: Lab demonstration at 350 μm
- Spring 2013: Successful 350 μm telescope demo at the Caltech Submillimeter Observatory (CSO) (see image above)
- Summer 2013: Lab tests of 350 μm lens-coupled arrays
- Fall 2013: First lab tests of high-sensitivity arrays

Application:

- SOFIA instruments
- Balloon payloads
- Future space mission, e.g., SAFIR/CALISTO
- Ground-based telescopes
- Applicable to both cameras and spectrometers (low NEP lab demo)
- Potential impact on mm-wave CMB instrumentation

*TRLin = **3*** *TRLcurrent est. by PI = **3*** *TRLtarget = **4-6***

H4RG Near-IR Detector Array with 10 micron pixels for WFIRST and Space Astrophysics

PI: Bernard J. Rauscher/GSFC

Co-PI: Selmer Anglin/Teledyne Imaging Sensors

Description and Objectives:

- Develop the 16 megapixel H4RG-10 near-IR detector array to TRL-6 for WFIRST in time for the Astrophysics Mid-Decadal Review
- WFIRST Science Definition Team identified the H4RG-10 as the critical enabling technology that is needed for achieving the aims of the Astrophysics Decadal Survey *New Worlds, New Horizons*
- Mature this technology to minimize risk, cost, and schedule
- Reduce the persistence and noise of large format high resolution infrared array detectors

Key Challenge/Innovation:

- Hybridization improvements to meet WFIRST pixel operability requirements in 4K x 4K, 10 µm/pixel format
- Pixel design improvements to meet WFIRST read noise requirements and reduce persistence

Approach:

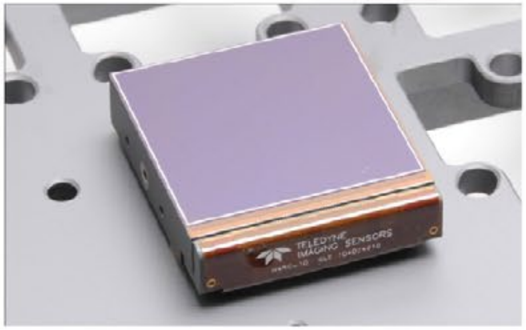
- Teledyne study to improve pixel interconnect yield
- Teledyne study to optimize process and improve read noise
- Fabricate lot splits of H4RG-10s at Teledyne
- Characterize H4RG-10s vs. WFIRST requirements in Goddard Detector Characterization Laboratory (DCL) and Teledyne
- Characterize H4RG-10s for WFIRST weak lensing and persistence at JPL/CalTech
- Environmental testing for TRL-6

Key Collaborators:

- Jason Rhodes (JPL: Institutional PI)
- Donald N.B. Hall (University of Hawaii)
- Bryan Dorland (U.S. Naval Observatory)
- Ed Cheng (WFIRST)
- Roger Smith (CalTech)

Development Period:

- FY13 – FY15



This H4RG-10 is identical to one that was tested in the Goddard DCL in 2011. It consists of a 4K x 4K pixel array of HgCdTe pixels mated to a silicon readout. It met all WFIRST performance requirements except: (1) pixel operability and (2) read noise

Accomplishments and Next Milestones:

- Demonstrate pixel interconnect operability yield >98%: Sept 2013
- Demonstrate an H4RG-10 that meets WFIRST performance requirements: Dec 2013
- Demonstrate an H4RG-10 that meets WFIRST environmental requirements: Dec 2014
- Complete TRL-6 demonstration: End of performance period

Application:

- WFIRST
- Explorer class near-IR missions
- Ground and space based astrophysics programs
- This is a broadly enabling technology for astrophysics

TRLin = ***4*** *TRLcurrent est. by PI =* ***4*** *TRLtarget =* ***6***

High Efficiency Detectors in Photon Counting and Large FPAs

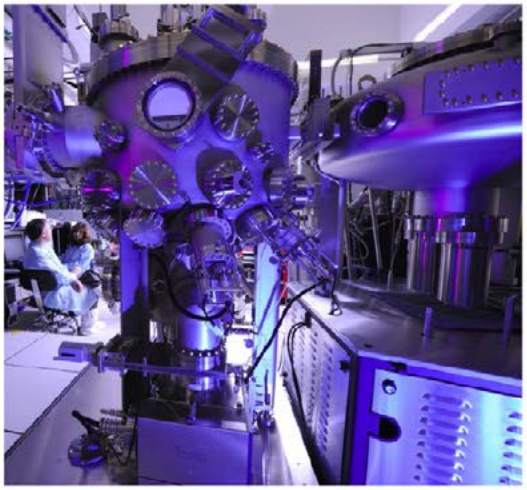
PI: Shouleh Nikzad/JPL

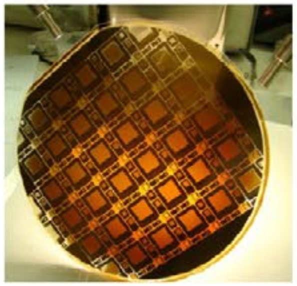
Description and Objectives:

- High efficiency, high stability imaging arrays that are affordable and stable are an efficient and cost effective way to populate UV/Optical focal planes for spectroscopic missions and 4m+ UV/Optical telescope as stated in the NWNH 2010

Key Challenge/Innovation:

- Atomic-level control of back illuminated detector surface and detector/AR coating interface produces high efficiency detectors with stable response and unique performance advantages even in the challenging UV and FUV spectral range





Approach:

- Develop and produce 2 megapixel AR-coated, delta doped electron multiplied CCDs (EMCCDs) using JPL's 8-inch capacity silicon molecular beam epitaxy (MBE) for delta doping and atomic layer deposition (ALD) for AR coating. Perform relevant environment testing, perform system-level evaluation on sky to validate performance over a wide range of signal level.

Key Collaborators:

- Chris Martin, Caltech, David Schiminovich, Columbia University, Paul Scowen, Arizona State University, Michael Hoenk, JPL

Development Period:

- Jan 2013 – Dec 2015

Accomplishments and Next Milestones:

- Wafers of 2Kx1K devices have been received and back -illumination process is underway. Wafers have been bonded to handle wafer. One wafer has been thinned to 8-10 micron. Wafer is ready for delta doping and next process steps. Complete first wafer in FY13Q4
- Characterize & validate the performance. (iterative, first in FY14Q1)
- Evaluate environmental performance. (FY14Q2 - FY15Q4)
- Evaluate performance in astrophysics-relevant and mission-relevant environments. (FY15Q3 – Q4)

Application:

- Large aperture UV/Optical Telescope, Explorers, Spectroscopy missions, UV/Optical imaging

TRLin = ***4*** *TRLcurrent est. by PI* = ***4*** *TRLtarget* = ***5-6***

Appendix B
Technology Development Status

New COR SATs for 2014:

Heterodyne Technology Development for SOFIA

Prepared by: Imran Mehdi and Paul Goldsmith (JPL)

Summary

Determining the structure and properties of the Interstellar Medium (ISM) is a key NASA strategic goal that can only be accomplished with high-resolution spectroscopy. The *Stratospheric Observatory for Infrared Astronomy* (SOFIA), with its large (2.5 m) telescope and high-altitude flight path, provides an ideal platform for conducting the necessary observations for Galactic as well as extragalactic sources. The present task, initiated in 2011 for a period of 2 years, focuses on developing and demonstrating heterodyne technology that can be infused into future instruments for SOFIA or other NASA missions including long-duration and ultra long-duration balloons. The goal is to deploy 1–5 THz multi-pixel heterodyne array receivers. Frequency-multiplied local oscillator sources will be developed and used to pump hot electron mixers coupled to low-noise, broadband Intermediate Frequency (IF) amplifiers, yielding systems with very high sensitivities. An optimized receiver architecture has been developed that allows mapping large portions of the sky with multi-pixel receivers. During the past year, a broadband local oscillator source that covers the scientifically important 1.9 to 2.06 THz range–includes the cosmologically important singly ionized carbon (C+) and neutral oxygen (OI) fine structure lines–has been demonstrated. A 4-pixel receiver within this frequency band has been designed and fabricated, and has also been partially demonstrated.

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. A number of large spatial surveys using the *Herschel* Photodetector Array Camera and Spectrometer (PACS) and Spectral and Photometric Imaging Receiver (SPIRE) photometers have determined that the dust emission is filamentary in nature at all scales that have been observed. In spite of the universality of the dust structures, large differences in the rates of star formation are observed. The physical processes that give rise to this structure and facilitate the onset of star formation remain the subject of a contentious debate between the effects of turbulence and magnetic fields. Another open question is the details of transition between the atomic and molecular phases of the diffuse ISM and their spatial and chemical relationship to the observed denser material and their influence on the star formation rate. The velocity structure of atomic and ionized gas associated with dense regions remains largely unknown and can only be obtained through spectroscopy. Separation of components of the ISM requires velocity-resolved atomic, ionic, and molecular line profiles. The recent Decadal Survey has highlighted questions that will require heterodyne technology to resolve (i.e., how do stars form? How do circumstellar disks evolve and form planetary systems? What are the flows of matter and energy between a Galactic disk and its circumgalactic medium? And what controls the mass-energy-chemical cycles within galaxies?).

Resolution of these questions will require heterodyne studies of statistically significant areas of the ISM. The obvious targets are the brightest lines in the spectrum: CII and OI; which trace the interfaces between low- and high-extinction regions. 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 observational output with which to study these complex structures is a two-dimensional image with spectrum at every point–a data cube. But current state-of-the-art is only a single pixel single-line detector. The urgent need for sensitive velocity-resolved images of regions spanning a wide range of spatial scales requires a broadband, tunable heterodyne array for more rapid and comprehensive mapping.

Heterodyne spectroscopic instruments are the only technical possibility for obtaining velocity resolved spectral resolution in the far infrared. Building on the Heterodyne Instrument for the Far-Infrared (HIFI) hardware developed by NASA's Jet Propulsion Laboratory (JPL), the focus of the proposed effort will be to increase frequency coverage and local oscillator (LO) output power, and develop an array architecture for the next generation of receiver front ends (RFE) to enable the implementation of imaging array receivers at frequencies between 1 to 5 THz. The hot electron bolometer (HEB) mixer and the first IF amplifier are cooled to 4K. The LO subsystem provides the LO signal that is mixed with the radio frequency (RF) signal from the spectra. The current focus is on the CII line at 1.9 THz.

This task is focused on developing super-sensitive heterodyne array receivers in the 1.9 THz frequency and above range. Receiver systems on HIFI can go up to 1.9 THz with a single pixel and T_{sys}=2400 (system and switchboard, or SSB). But the IF bandwidth on HIFI is less than 2 GHz for these receiver systems providing only a velocity span of 300 km/s at 1.9 THz. Moreover, the complicated optical path and poor thermal stabilization of the LO sources has resulted in the HIFI system having stability and calibration issues. The technology that will be developed and demonstrated under this task will correct for these shortcomings and show the feasibility of deploying heterodyne array receivers for future instruments.

Objectives and Milestones

The objective of this task is to demonstrate a robust architecture for array receivers in the 1–5 THz range. Table 1 identifies the main milestones and their current status.

Milestone	Status	Date completed
Validation of mixers with low noise and high IF	A number of devices from MSPU were imported and tested. We were unable to verify increased IF bandwidth. More testing is warranted but given limited resources we are now focused on the in-house built devices.	September 2012
Optimization of single-pixel mixer	Single mixer with SOA sensitivity demonstrated	June 2012
1.9-THz LO Source	Single output chain with enhanced output power has been demonstrated	March 2012
Demonstration of a 4-pixel 1.9 THz RFE	Ongoing	(expected Aug 2013)
Development of a LO for 16 pixels	Ongoing	(expected Aug 2013)
Extension to a 16-pixel 1.9 THz RFE	Ongoing	(expected Sep 2013)

Table 1

Progress and Accomplishments

The focus of this task during the last 12 months has been to demonstrate a 1×4 array receiver at 1.9 THz with a tunable solid state LO chain. The current state of the art (SOA) is a single pixel at this frequency.

1.1 JPL Developed Waveguide HEB Mixers

HEB mixers provide one of the most sensitive detectors in the frequency range of interest. We have been working on designing, fabricating, and characterizing HEB-based mixers in waveguide blocks. We have baselined waveguide 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 relatively straight-forward path toward arrays.

Since the waveguide block requires features of very small size (<25 microns), a novel approach of putting the waveguide blocks has been developed. Two different approaches have been demonstrated. In the first approach, while the majority of the waveguide block is machined via conventional metal machining the channel where the mixer device is mounted is machined from silicon using Deep Reactive-Ion Etching (DRIE). Moreover, a micro-plating process has been developed that results in providing a ‘lip’ allowing the mixer circuit to be slid in. The mixer has been characterized with the standard hot/cold method and the measurements have been reported previously. In a second and alternative approach, the channel for the mixer chip is formed directly via silicon micro-machining. This eliminates the micro-plating step and results in fairly robust waveguide structures. In Year 1 this approach was validated by building a 2.7-THz HEB mixer that provided SOA results.

During the last 12 months, we have focused on the 1.9 to 2.06 THz frequency band. Two mixer designs were completed. These are shown in Figure 1. The first design uses a bowtie antenna to couple the signal and sits perpendicular to the input signal waveguide. The second design utilizes a probe antenna and sits face-on in the input signal waveguide. Both designs show satisfactory simulated results but allow us to optimize the device/block assembly task, which is very critical due to the short wavelength.

Devices for these two designs have now been fabricated. In the first batch of devices, Fourier Transform Spectroscopy (FTS) measurements showed that they were detuned from the design center frequency of

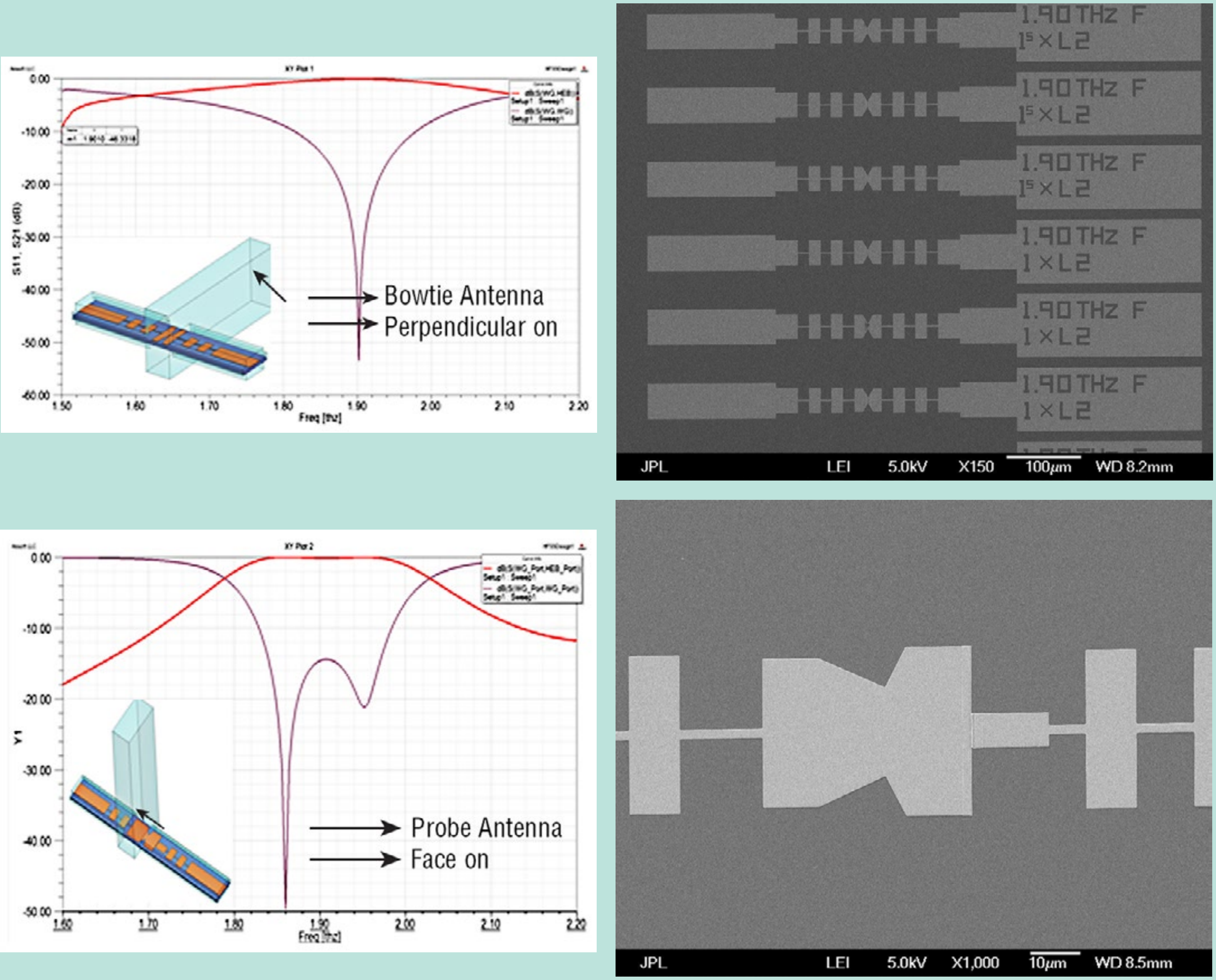


Figure 1: *Two HEB designs have been completed for the 1.9 THz receivers. The devices have been fabricated and have resulted in SOA sensitivities.*

1.9 THz, the rest frequency of C+. Electromagnetic modeling shows that this shift was caused by a thin layer of fused silicon (SiO_2) applied to the mixer devices for purposes of passivation and protection. This has now been corrected and a new set of devices has been fabricated.

Preliminary measurements of a single pixel block have resulted in a measured noise temperature of 700K double-sideband (DSB) at 1.9 THz.

1.2 Next generation of Local Oscillator Sources

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

During the first year of the task, we demonstrated a new 1.9 THz chain able to provide up to 60 µW at room temperature when pumped with 100–200 mW at 105–115 GHz. This represented an improvement of a factor of 20 with regard to the 1.9-THz LO chain onboard HIFI. It is important to remark that this multiplied chain is a direct evolution of the HIFI/*Herschel* chain with optimized single-chip frequency multiplier stages with no power-combining of any kind. The second-stage tripler in this chain puts out around 1.8 mW of output power at 633 GHz. As a first step, we wanted to use this chain to demonstrate a 1×4 LO chain at 1.9 THz. The final-stage 1.9-THz tripler block has two chips, and the output from each chip is divided by two to obtain four outputs. We have completed this design. However, we could only measure less than 1 µW of output power at each pixel. Preliminary measurements of the 4-pixel 1.9-THz block indicated that we are not pumping the block with enough input power. The waveguide losses at 1.9 THz are significant and result in substantial losses (the waveguides had to be made long

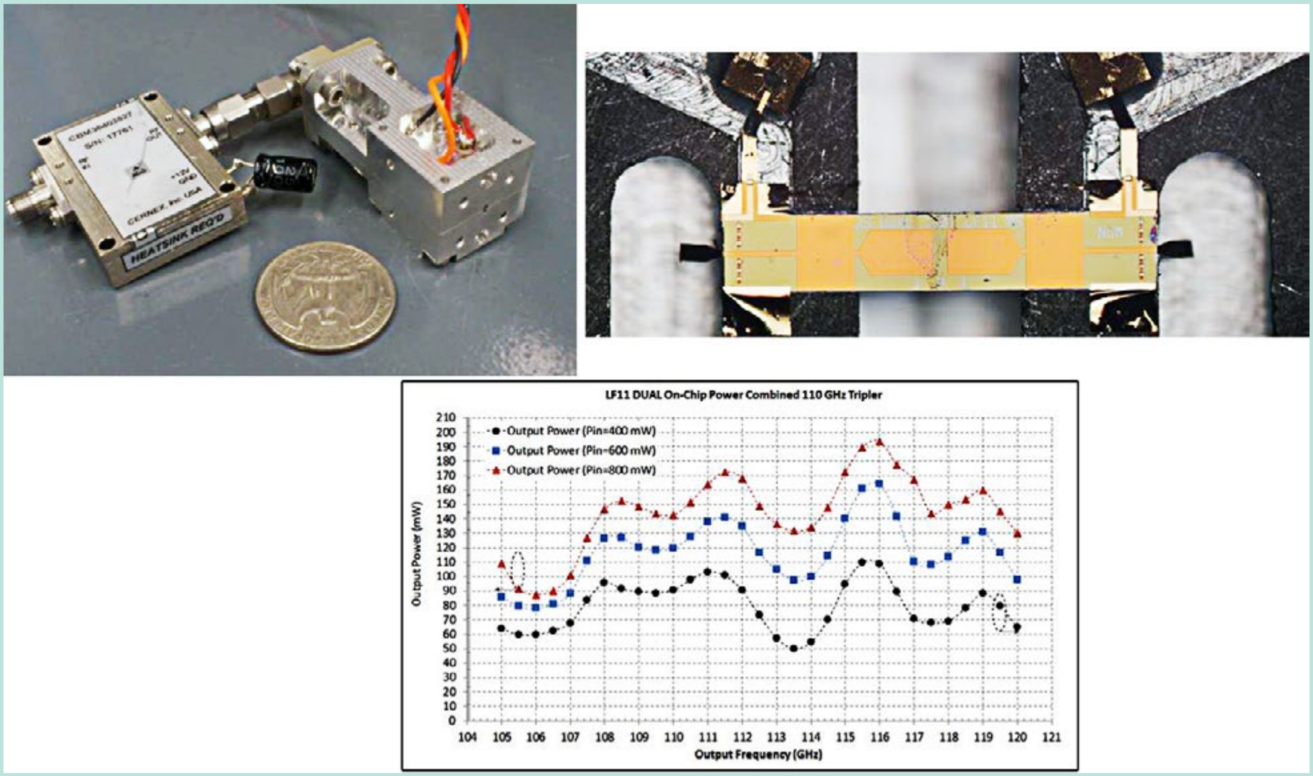


Figure 2: *Excellent performance has been achieved from recently fabricated W-band triplers. The tripler block is pumped by a commercially available Ka-band amplifier (top left). The dual-chip on-wafer power combining chip is shown at the top right. Measured performance at room temperature is shown in the bottom plot.*

due to the 10 mm inter-pixel spacing). Though this might be enough in an ideal setup (and cooling will certainly help), we are now building a more powerful source to drive the 1.9-THz 4-pixel block. This will be done by increasing the power handling capability at W-band and implementing a two-chip 630–650 GHz tripler.

To obtain more power at W-band, we have designed and implemented tripler chips that go from 106 to 114 GHz. Tripler chips at these frequencies would mean that we no longer require W-band power amplifiers. This will be a very great advantage for reducing cost, complexity, and power for future missions. The completed W-band source is shown in Figure 2. Measurements made at room temperature are also shown. To drive the 630 GHz tripler with sufficient power, we will power combine two of these blocks and thus achieve around 350 mW of input power at W-band. These are the largest multiplier chips made to date at JPL. Due to the large size and thick substrate the yield has been low, but we have been able to mount and characterize several of these blocks. The dual-chip 630–650 GHz tripler block has also been fabricated and assembled; it is shown in Figure 3. Detailed testing of this circuit is ongoing.

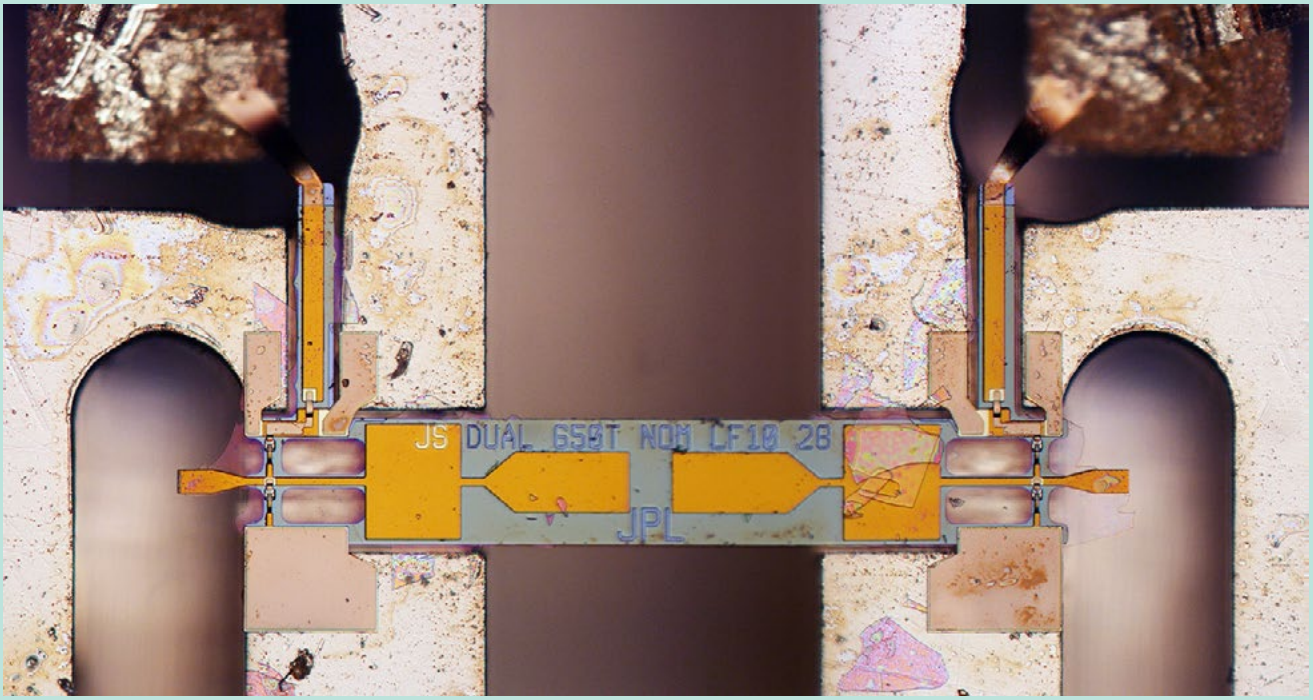


Figure 3: *The dual-chip 650-GHz tripler chip, while mounted in a block, is shown. Complete characterization of this chip is currently ongoing.*

1.3 Characterization of Array Receivers

A test setup that will allow the characterization of a 4-pixel array receiver has already been completed. The 4-pixel mixer and LO block are shown in Figure 4. The LO signal will be coupled to the mixer via a diplexer. The mixer block will be situated inside a 4K cryostat, while the LO chain will be operated at room temperature and be placed outside the cryostat. Receiver performance as a function of frequency will be measured once the hardware is assembled into the receiver cryostat (expected in September 2013).

Path Forward

The present focus is to demonstrate a working 4-pixel receiver at 1.9 THz and to show how this technology can be implemented for a 16-pixel array receiver. For the remainder of the task period the following activities have been planned:

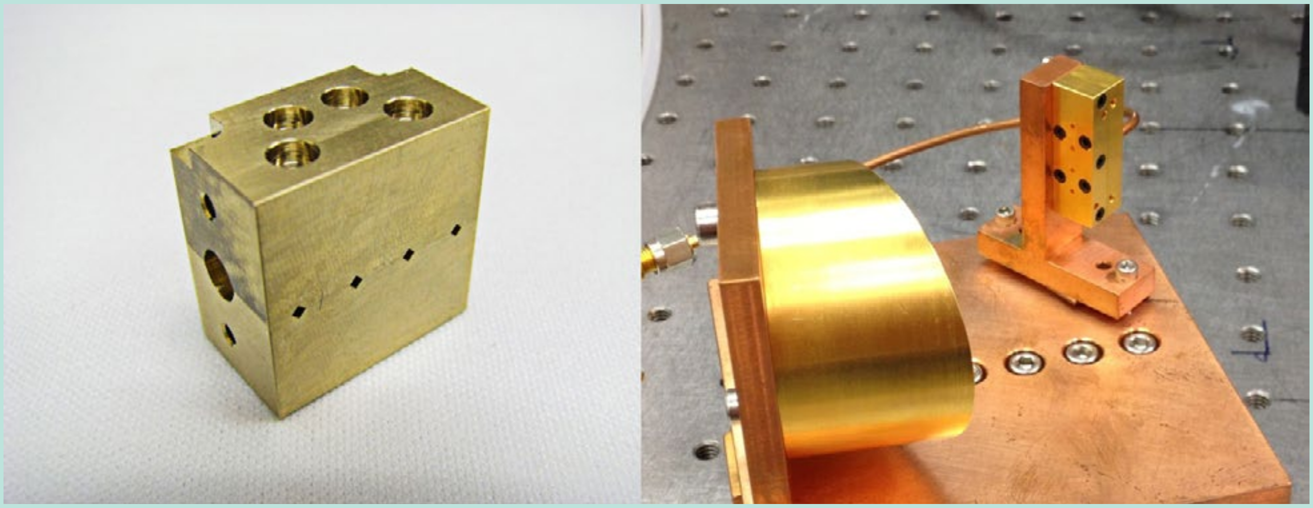


Figure 4: *The 4-pixel 1.9-THz tripler block (left) and the 4-pixel mixer block (right) have been designed and fabricated. Receiver testing is ongoing.*

1. Detailed characterization of the dual-chip 650-GHz tripler. Measure output power as a function of frequency and drive power (expected to be completed by end of July)
2. Assembly of the LO drive chain for the 4-pixel 1.9-THz tripler. This will include the Ka-band amp, the W-band tripler and the 650-GHz tripler (expected middle of August)
3. Complete the assembly of the 4-pixel mixer block. Two pixels have already been completed (expected end of July)
4. Complete assembly of the LO chain with 4 pixels (expected end of August)
5. Receiver test setup and array receiver testing (end of September)
6. Design for a 16-pixel array receiver (end of September)

Contact:
paul.f.goldsmith@jpl.nasa.gov

Enhanced MgF_2 and LiF Over-coated Al Mirrors for FUV Space Astronomy

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

Summary

The first task in this project is to demonstrate the viability for coating medium to moderately large mirrors to realize recent gains in Far Ultraviolet (FUV) reflectivity of aluminum/magnesium fluoride (Al+MgF_2) and aluminum/lithium fluoride (Al+LiF) coatings. These gains have been obtained by employing a three-step Physical Vapor Deposition (PVD) process that has been demonstrated in a smaller coating chamber on substrates of up to 5 cm in diameter. Application of these high-reflecting coatings on mirrors used in FUV astronomical telescopes will enhance throughput and hence add more flexibility to a system design that is certain to improve overall performance. A second task is to determine optical properties (n and k values) of the lanthanide trifluoride materials gadolinium fluoride (GdF_3) and lutetium fluoride (LuF_3). These materials are considered as a high-index option that when paired with a low index material such as MgF_2 could be used to enhance the reflectance of over-coated Al mirrors to operate at a particular design wavelength in the 1100 to 2500 Å range. A third task is to improve the quality of MgF_2 film depositions by using a two-gas system in a small Ion Beam Sputtering (IBS) coating system to produce more dense films with low scatter. This project started at the beginning of FY12, and it had a 2-year duration through the end of FY13. However, the NASA Headquarters (HQ) Program Office granted a no-cost extension for a third year until the end of FY14. This extension will give us sufficient time to complete the task of retrofitting our existing 2-m coating chamber to demonstrate the enhanced-reflectance coating process on mirror substrates of up to 1 m in diameter.

Among the achievements over the past year, we have continued tweaking the three-step PVD process in the small chambers and we have obtained the highest ever reported reflectivity values of Al+MgF_2 coatings–at 1216 Å. We finally completed the heat-shield panels and finished installation of the halogen-quartz heater system that will enable development of the three-step PVD process for making MgF_2 and LiF over-protected Al coatings in the large 2-m chamber. We performed a series of GdF3 and LuF_3 film depositions on MgF_2 substrates to determine the optical properties and absorption cutoff for these films at FUV wavelengths. Finally, we conducted a series of MgF_2 films on fused silica (FS) substrates using the IBS chamber to determine the feasibility of producing low-absorption MgF_2 films.

Background

The FUV spectral region (900 to 1500 Å) is relevant to many aspects of NASA's Cosmic Origins (COR) 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 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 deuterated hydrogen (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–the Copernicus satellite, also known as the *Orbiting Astronomical Observatory 3* (OAO-3), in the 1970s; the *Hopkins Ultraviolet Telescope* (HUT) and the *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrograph* (ORFEUS) shuttle payloads in the 1990s; and the *Far Ultraviolet Spectroscopic Explorer* (FUSE) in the 2000s. The FUSE observing program was the most extensive by far, but it was limited by modest effective areas (20 cm 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 D/H in the Galaxy, but lacked the sensitivity to study D/H in the inter-galactic 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 and Milestones

The overall objective in this program is to develop improved 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.

This mission-enabling technology specifically addresses the Technology for the Cosmic Origins Program (TCOP) development under the Section 2 that is titled “Ultraviolet Coatings.” In particular, we deal 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 number one objective is to demonstrate or to transfer to a larger 2-m PVD chamber the process of enhancing the FUV reflectance of Al mirrors protected with MgF_2 and LiF layers. This process, which consists of reducing the absorption in these layers at FUV wavelengths, was originally implemented in a smaller PVD coating chamber which allowed only the coating of optics not larger than a couple of inches in diameter.

Secondly, we are performing a limited material studies, via the PVD process, of the best materials identified in an earlier study[1]. This work examined a series of lanthanide trifluorides and found some potential candidate materials beyond 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. Our study will concentrate on studying the optical properties of GdF3 and LuF_3.

Thirdly, we are pursuing the development of low-absorption MgF_2 thin-film coatings using an IBS system that 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 shortcoming is being addressed through the flow of a fluorine-containing gas (such as Freon®) during the deposition process to compensate for the stoichiometry deficiency. The objective of this first-phase study is to see if stoichiometric deposits of select candidate material (MgF_2) can be successfully deposited by IBS. A second objective is to identify a method for making these deposits, and a third objective is to make low-loss fluoride layers.

Here is the detailed list of main project milestones submitted in last year's Program Annual Technology Report (PATR) report:

1) Performed additional optimization of MgF_2 and LiF in small coating chamber (Sept. 2012)
2) Perform initial Al+MgF_2 coatings with 2-m chamber (Nov. 2012)
3) Perform distribution study of Al+MgF_2 coatings with 2-m chamber (Dec. 2012)
4) Perform initial Al+LiF coatings with 2-m chamber (Jan. 2013)
5) Perform distribution study of Al+LiF coatings with 2-m chamber (May 2013)
6) Characterize lanthanide trifluoride for FUV application (Nov. 2012)
7) Design and fabrication of Lyman-Alpha reflector (April 2013)
8) Optimization and characterization of MgF_2 films using the IBS process (Nov. 2012)
9) Optimization and characterization of LiF films using the IBS process (March 2013)

Milestone 2 has a notable deviation of when it was scheduled (Nov 2012) versus when it was actually completed (May 2013). This had a ripple effect on the completion dates for milestones 3 through 5, and this was caused by a 5-month delay in the completion of the thermal shield inside the 2-m chambers and procurement of key hardware (power supply and halogen quartz heater system). It is important to note that these dates were based on the assumption of a 2-year program that was due to conclude at the end of FY13. However, and given the fact that we were granted a no-cost third year extension by the Program Office at NASA HQ, we are anticipating a successful completion of the unfinished business by no later than the end of FY14.

Progress and Accomplishments

First, we report on progress using the three-step coating process of Al+MgF_2 that produces enhanced reflectance at FUV wavelengths. This was originally developed in a previous technology effort to reduce absorption in the MgF_2 layer of Al+MgF_2 mirrors.[2] The coating depositions were done in a small high-vacuum chamber capable of doing PVD. The procedure was such that the Al 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 Al. The remaining MgF_2 deposition was done at an elevated temperature of 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 reaching success in producing coatings with a much reduced absorption in the MgF_2 layer. As an example, we show in Fig. 1 the comparison of calculated FUV reflectance of bare Al and Al+MgF_2 coatings. This figure also includes measured data from a sample prepared using the "enhanced" PVD process described previously. We also show a second sample that was prepared using the standard method, where all depositions were done at ambient temperature. These data show the "enhanced" sample shows substantial gains in reflectance, particularly for wavelengths shorter than 1300 Å. This is due to the fact that when the MgF_2 deposition is done at elevated temperatures its optical absorption approaches that of the bulk crystalline sample. This reduced absorption permits, for the first time, the reflectance of these MgF_2 overprotected samples to approach the values for non-oxidized bare Al.

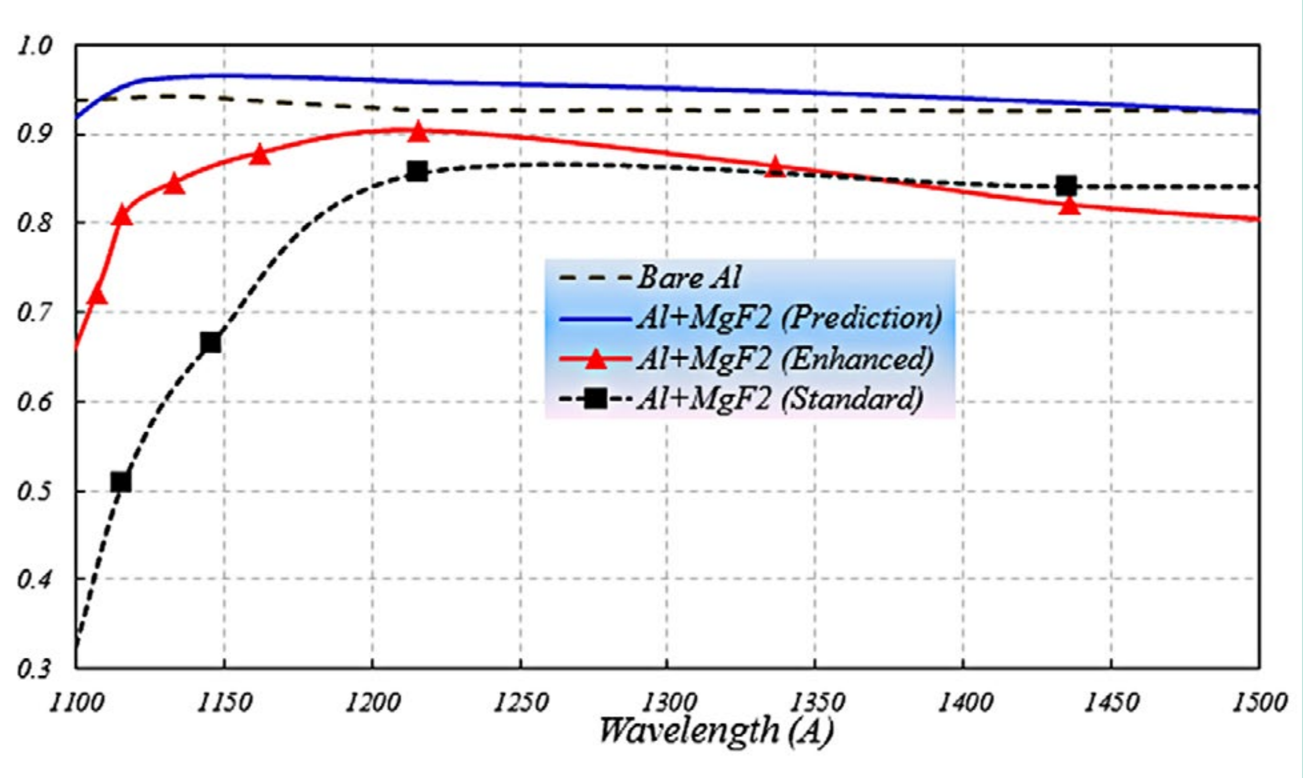


Figure 1. *The predicted and measured reflectance of bare Al and Al+MgF$_2$ films prepared with a standard and "enhanced" coating process.*

Large Chamber Preparation

The first objective in this technology development is to upscale the process described previously by using an existing 2-m coating chamber that will enable the coating of larger (up to a 1-m) diameter optics. The task of upgrading this chamber required the following steps:

- Design and fabrication of heat-shield panels to fit inside 2-m chamber.
- Acquisition of a 6-kW power supply system to operate halogen quartz lamps to provide heating element in chamber.
- Internal wiring of power supply and heating elements inside vacuum chamber.

These tasks were nearly completed at the end of FY12. However, final assembly of the heat-shield panels inside the chamber took several iterations of fit-checking that required multiple mechanical modifications until the assembly was deemed satisfactory. There was also delay in the acquisition and installation of the 6-kW power supply. These delays pushed final completion of this task to the end of April 2013. In this chamber, we performed the initial coating run of a standard "1216" coating in May 2013. The results confirmed the data of the curve labeled "standard" in Fig. 1. However, there was not enough time to perform additional coating runs that could be included in this report. Figure 2 shows the fully assembled heat-shield panels. These will be needed to concentrate the heat produced by the lamps mostly inside the chamber during hot MgF$_2$ deposition processes.

Figure 3 shows a view of the coating chamber dome from the bottom with the fully assembled heat shield cover. Finally, we recently finished installation of thermocouple sensors as we prepare to test the system thermal behavior and the maximum temperature that could be achieved for a substrate placed at the top by the rails shown in Fig. 3.

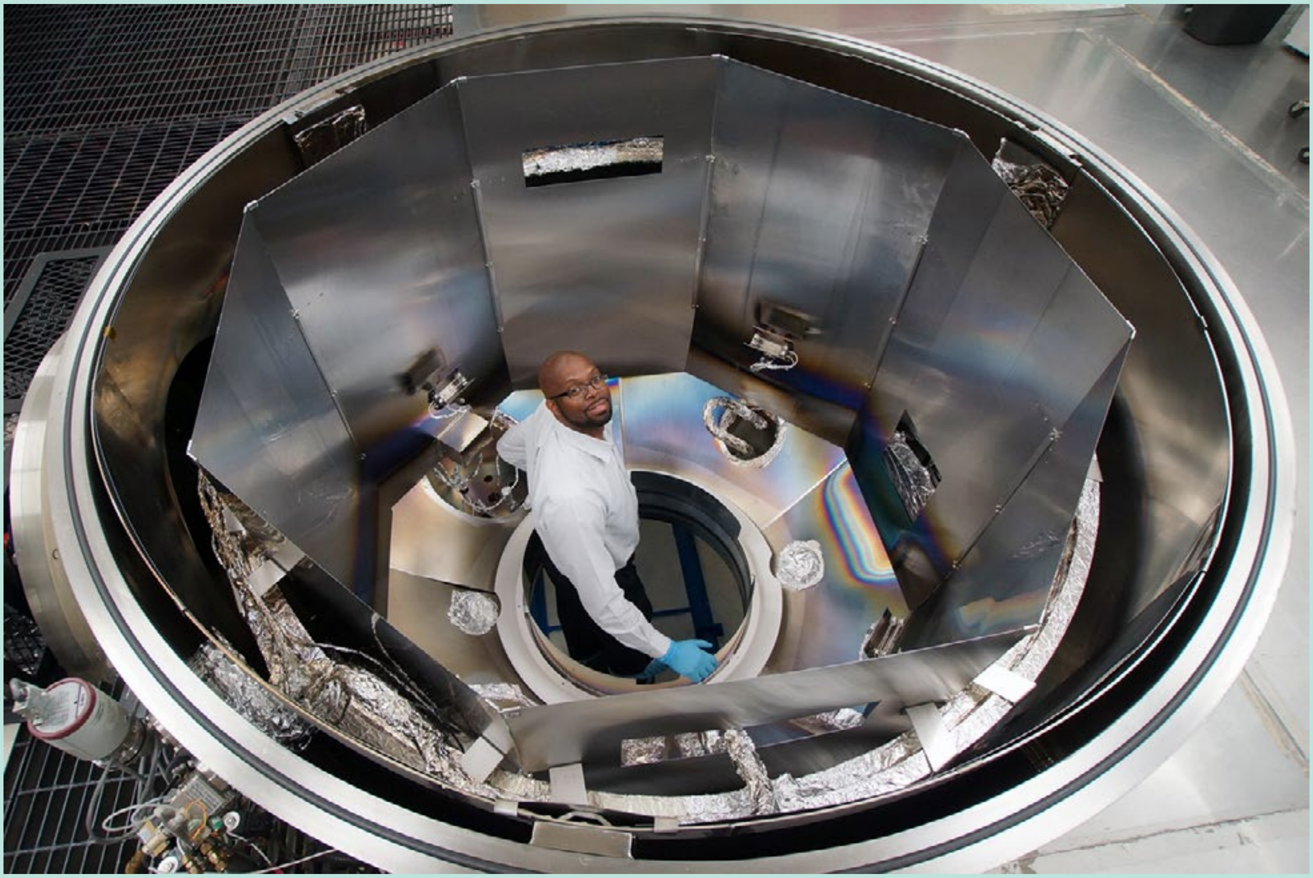


Figure 2: *Top view of the 2-m coating chamber with a person standing inside to give a sense of scale. The picture shows the 8-segment heat-shield panels and three of the four halogen-quartz lamps.*

Lanthanide Trifluoride Characterization:

In regard to the characterization of PVD produced films of GdF_3 and LuF_3, we have grown a number of samples with varying thicknesses with the purpose of determining the optical properties (n and k) as a function of wavelengths. These materials could be viable alternatives to be used as high-index layers that, when paired with low-index films such as MgF_2, will enable the fabrication of dielectric reflectors to operate at wavelengths as short as 1300 Å. Progress in the characterization has been delayed due to a calibration issue recently encountered with the Acton spectrophotometer used to measure the transmission and reflection data on these samples. This issue was recently resolved, but not in time to include a complete and a thorough analysis of the optical constants of the two materials studied in this program.

Ion Beam Sputtered Fluoride Layers for the Vacuum Ultraviolet Spectral Region:

The third objective of this work was to explore the feasibility of using an IBS process for depositing fluoride layers for use in the Vacuum Ultraviolet (VUV) region of the electromagnetic spectrum. The impetus for this is that IBS has shown that it can produce layers that are very dense (and thus mechanically and environmentally stable) and with very smooth interfaces (and thus with low optical scatter). These are very large advantages that have not been realized in the VUV. The reason for this is that most of the effort on IBS has concentrated on oxide materials which have band gaps in the near ultraviolet, with the exception of aluminum oxide (Al_2O_3) and silicon dioxide (SiO_2). For the VUV region of the spectrum, no oxides are transparent and only fluorides have adequately low absorption to be used for interference filters.

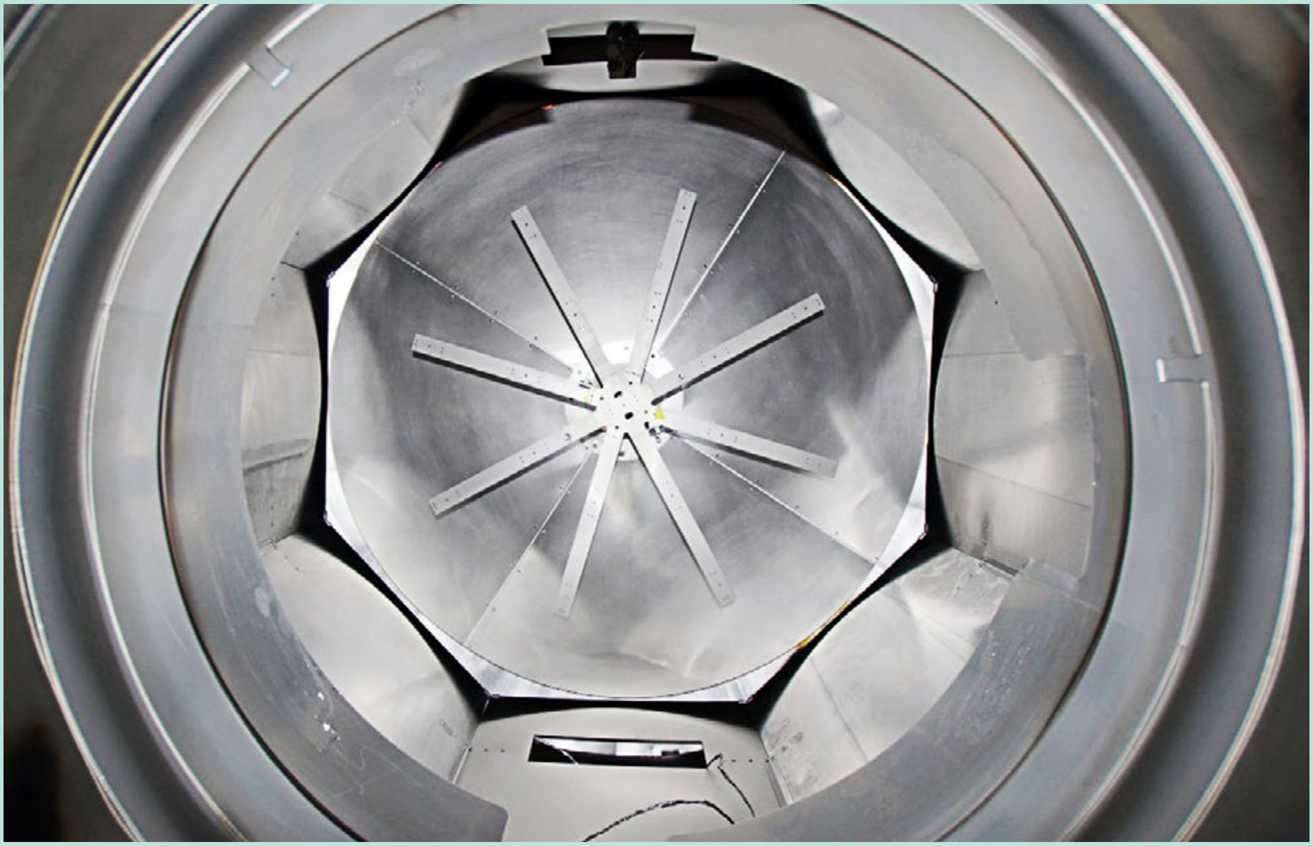


Figure 3: *The top cover heat-shield dome as viewed from the bottom of 2-m chamber.*

Ion Beam Sputtering is a physical vapor process in which an ion beam (typically of noble gas ions) is generated remotely and directed at a material target. The details of how IBS works have been described elsewhere[1]. The typical IBS process produces a coating that is chemically reduced on the substrate. This reduced deposit, in the case of fluorides, is fluorine deficient, and this deficiency results in interband absorption and poor transparency. Thus, some gas needs to be added into the deposition chamber to make up this deficiency.

Experimental Approach

We approached this first-phase work in a proof-of-principle manner. This meant a number of calculated risks were taken, and we discuss these here. The primary risk was using a Commonwealth Scientific uncooled, filamented, gridded ion source. This gun is optimized for argon (Ar) as a working gas and relatively low ion current since it relies on the expansion of the working gas for cooling. The cooling is a very inefficient process, as we discovered on a number of occasions. The heating of the ion gun has a number of undesirable consequences. Among these are: the reduction of the electron recycling magnet's field strength, misalignment of the grids, and outgassing of the gun and chamber walls. The last was probably the most problematic because it is a contamination source for the growing layer. Additionally, the ion current density was low and resulted in a low deposition rate. The manual indicates a 50 mA maximum current, but we never got more than 35 mA out of it and, more typically, 25–27 mA. It is not obvious why this is the case, but it is probably a combination of a number of factors related to both the chamber (gas flows and pressures) and power supply (old and possibly not delivering full performance anymore), and a variety of other gun issues.

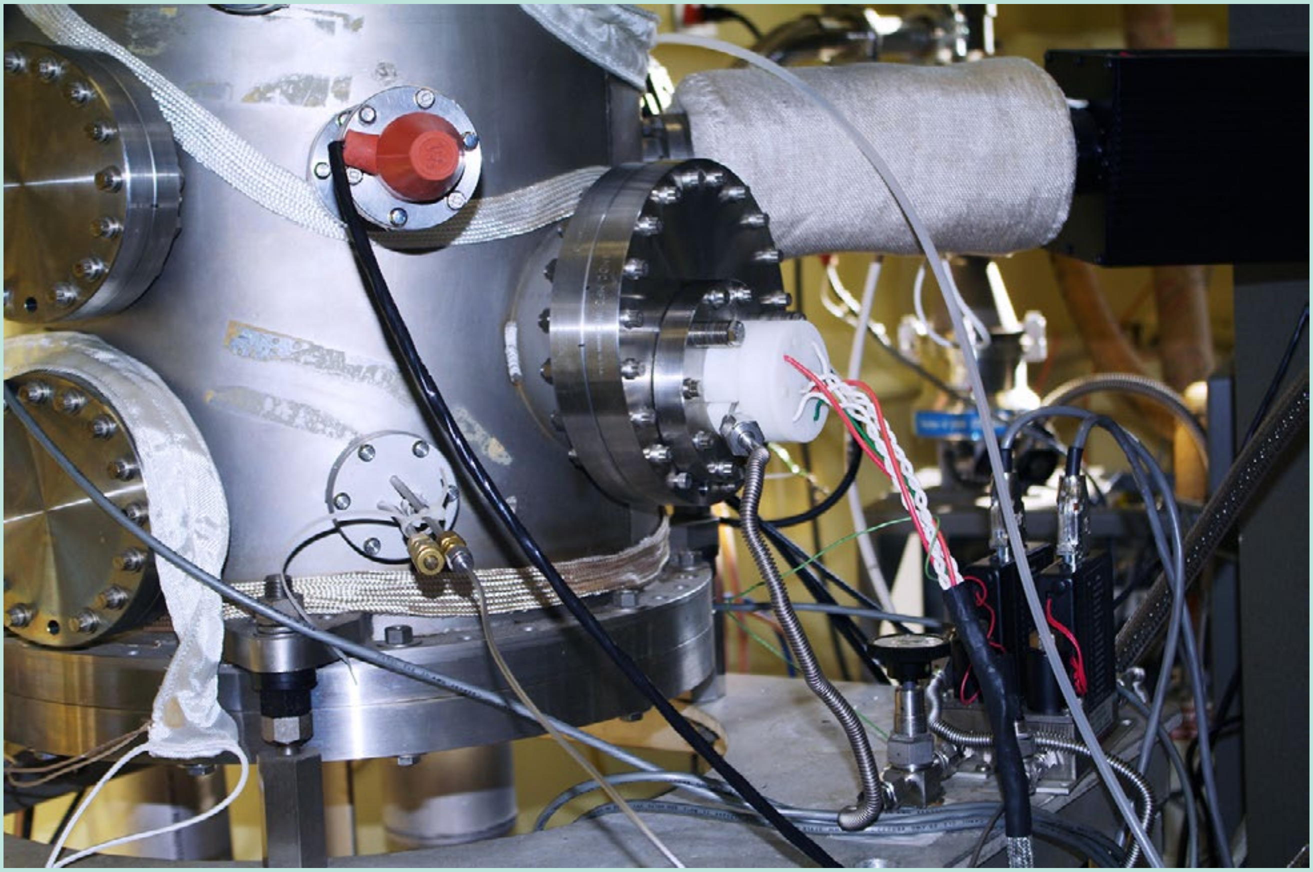


Figure 4: *Zoomed view of ion beam location on the research chamber coater. The working gas (Kr) is admitted through the gun, but the reactive gas is admitted nearby but external to the gun.*

We employed krypton (Kr) as our working gas. We wanted to use xenon (Xe), but this proved cost prohibitive. The use of a heavier, larger cross-section ion improves the sputter yield (energy per ion) and reduces the reduction of the target surface. We expected to see an improvement in the ion current density because of the lower ionization energy, but this was much more modest than we had hoped with only about a 33% improvement.

The ion-gun sputtering geometry was fixed at about a 60° ion incidence angle (as measured from the target normal). This was based on trends from sputtering theory of compounds to lower reduction of the fluoride and was not optimized empirically because we did not expect full stoichiometry, even under the best conditions. The target-substrate distance is about 25 cm. We also employed a reactive gas to replenish the target/deposit stoichiometry. This was, again, a strongly compromised choice. The best fluorine-containing gases for this work would have required significant cost to properly handle the bottle because they are hazardous. Instead, we chose to use Freon® (CF4) because this gas is very stable and nearly inert at room temperature and thus requires no special handling. This inertness, however, resulted in some surprises as we first admitted the gas near the substrate and it had almost no effect on the films. Admitting the gas nearer to the ion gun resulted in the expected reduction in film absorption losses. This is thought to be because the ions from the gun crack the CF4 molecules with the cracking products no longer being inert. This had a severely deleterious effect on the ion gun filaments. The cracking products attacked the tungsten (W) filaments and drastically reduced their lifetime. This was an expected result because this type of gun is not supposed to be used with reactive gases, but was another budgetary compromise and calculated risk in this proof-of-principle research. Follow-on research should use a filamentless ion source. The filament erosion is bad enough that the filaments have to be changed about every 1 to 2 hour of run time. This equates to every run. Lastly, we added heaters to our chamber. This was intended to improve the microcrystalline nature of the films, improving the transparency by reducing the Urbach absorption that results from disorder. It also has the added potential benefit of increasing the reaction rate at the growing film surface, but that is true for both the desired reactions (fluorine compounds) and the undesired reactions (water and other residual gas contaminants). The heat also drives off adsorbed contaminants from the chamber walls and tooling, but this was found to be only a local phenomenon because the heater-to-substrate distance was so small (~ 3 cm). We deposited films at both 100°C and 200°C.

The chamber configuration in the so-called "Research Chamber" was not ideal for this work. The chamber aspect ratio makes substrate loading difficult, the Conflat-flange-mounted ion gun proved tedious to use, especially because the filaments needed to be changed after every run. Conflat seals are not designed to be broken this frequently, and the sealing required the use of a new copper (Cu) gasket each time with the risk of a vacuum leak. Additionally, the system is cryo-pumped which is not appropriate for a high gas throughput process such as IBS. Fortunately, the pump was oversized for the coater so we did not overwhelm the pump. We were not, however, able to bake the entire chamber and heat it as we would have liked to drive off contaminants. This also drove the method we employed for installing the heaters, minimizing the heated volume. We would have been better served with a load-locked, turbo-pumped system, although this is secondary to a filamentless ion source.

Results: Ambient Temperature

The most runs were performed at ambient temperature and fell into two categories: non-reactive and reactive. Non-reactive was only run as a measure of comparison to see if the reactive ion-beam sputtering (RIBS) was accomplishing the desired result. A variety of beam voltages were employed to see if there was a strong difference in the resultant film properties. Beam voltage varied from 1500 to 500 V. There was not a dramatic variation in film properties, but there was a dramatic reduction in deposition rate at 500 V. Additionally, the 500-V run resulted in rather severe ion gun heating. To avoid permanent gun damage, we did not run at 500 V because the Curie point for the magnets is not known. Running at higher voltage did not seem to provide a notable ion gun operational advantage and previous studies (Allen, et al.[4]) indicate a lower beam voltage to have advantages for fluoride deposition. Thus we settled at 800 V.

We then added CF4 to the chamber. This was originally admitted above the substrate plane, not far from the cryogenic pump opening. This yielded essentially no discernible reduction in the extinction coefficient of the films. We postulated that the CF4 molecules were not reacting with the fluorine-deficient target and deposit surfaces and that the CF4 molecules needed to be cracked to increase their reactivity. The simplest way to do this was to admit the CF4 into the existing ion beam and let the two interact. This had the desired chemical activation but destabilized the ion gun operation. Some of the CF4 flows "upstream" into the ion gun and raises the average ionization voltage of the gas and attacks the W ion gun filaments, dramatically reducing their lifetime. We played with the no-reactive to reactive gas flows to try to stabilize the ion gun operation. The total flow is limited by the use of a cryopump so the total flow needed to be less than 20 standard cubic centimeters per minute (sccm). We finally settled on a 15:1 sccm ratio of Kr:CF4 flows that seemed to provide ~1.5 hours of filament life to get through a single coating run without filament breakage.

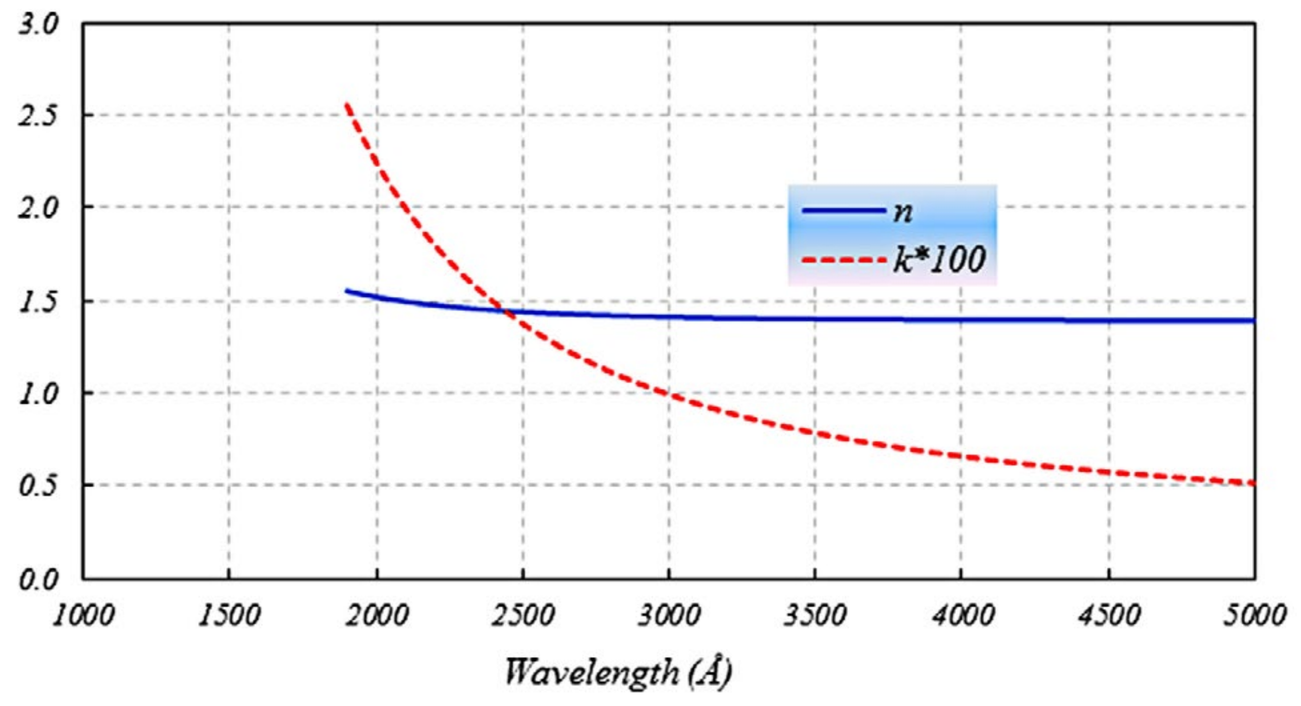


Figure 5: *This figure shows the optical constants obtained at ambient temperature with reactive ion beam sputtering (RIBS) with Kr and CF4.*

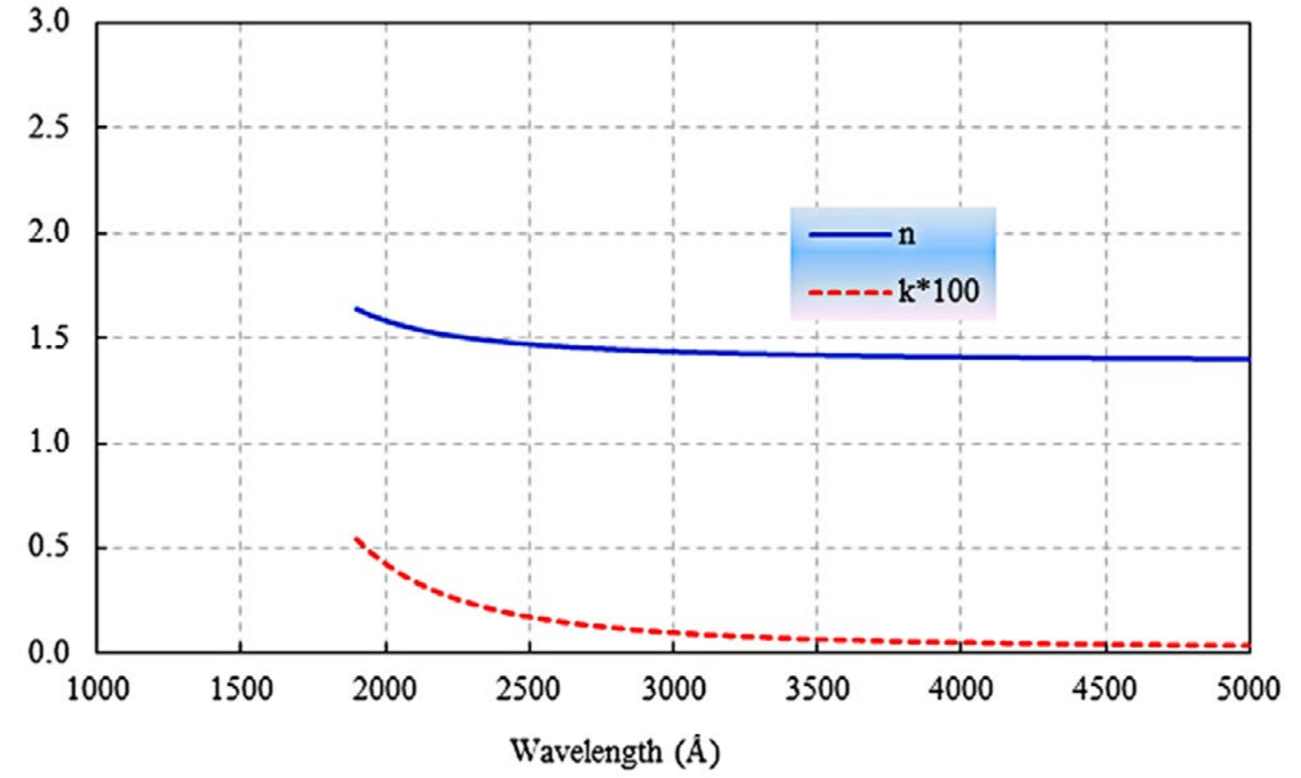


Figure 6: *Optical constants for MgF_2 deposited at 100°C onto SiO_2. Kr:CF4 flow ratio 15:1, beam voltage of 800 V. and ~ 25 mA beam current. Note that the k is smaller than that in Fig. 5 but still non-zero. It should be noted that k represents all losses, not just true extinction. For example, scatter losses and variations in substrate thickness or losses would show up as k here.*

One could get much fancier with the reactive gas admission and baffling to reduce the backstreaming into the ion gun, but we did not attempt this because the geometry of the research chamber would essentially require us to stand on our head to do the installation.

Elevated Temperature

We added a small ceramic heater just above the substrate plane. Using Epo-Tek® H77, a thermocouple was glued to a SiO_2 substrate to monitor the substrate temperature. We ran at both 100°C and 200°C. The 200°C temperature was chosen, based on work by Steve Rice with evaporation of MgF_2 films. Even higher temperatures might improve things further, but we were concerned about dumping the cryogenic vacuum pump. Optical constants are shown in Figures 5 and 6.

Path Forward

Now that the preparation of the large chamber has finally been completed, we will proceed to complete the unfinished milestones (3 through 5, listed previously) in the coming months. We plan to complete these tasks by the time this program concludes at the end of FY14. In fact, work on these tasks will accelerate in the coming months when a new coating engineer will join the program in September of this year.

Determination of the optical constants for the two lanthanide triufluorides materials that we have studied will proceed in the coming months. We will study the feasibility of designing and fabricating a dielectric reflector that will operate at the Lyman-Alpha wavelength (1216 Å).

In regard to the IBS process, this course of research shows significant promise but is not yet ready for scale-up. There were a number of issues that obfuscated the progress. The main one was substrate issues in the VUV, which is why we present an optical constant only down to 1900 Å. This issue was traced, in part, to contamination of the substrates during storage. This made optical constant determination highly uncertain and, given the high absorption of the contaminant, it completely obscured the most critical portion of the development–reducing the film absorption. Even for the SiO_2 substrates used for the results presented here, there was significant absorption that should not be in pure SiO_2 at these wavelengths. The most likely source of contamination is outgassing of the many plastics in the lab (e.g., see the FUSE Mission contamination control plan[5]). This problem needs to be solved in order for real progress to be made. A possible stop-gap measure is to perform reflectance measurements only on opaque substrates. The sensitivity to absorption would not be as high as in transmission, but contamination effects would also be reduced. One would need to find a substrate that is thermally stable and of relatively high reflectance in the VUV (> 10%). We attempted to test this with SiC but could not get samples in a reasonable timeframe at a reasonable cost. Another possibility would be a platinum-group metal film–platinum (Pt) or iridium (Ir)–with Ir being perhaps the best choice.

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Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes

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

Summary

The Advanced Mirror Technology Development (AMTD) project is a 3-year effort initiated in FY12 to mature by at least a half Technology Readiness Level (TRL) step six critical technologies required to enable 4- to 8-meter ultraviolet/optical/infrared (UVOIR) space telescope primary mirror assemblies for both general astrophysics and ultra-high-contrast observations of exoplanets. Thus far, AMTD has achieved all of its goals and accomplished all of its milestones. We did this by assembling an outstanding team from academia, industry, and government with extensive expertise in astrophysics and exoplanet characterization, and in the design/manufacture of monolithic and segmented space telescopes; by deriving engineering specifications for advanced normal-incidence mirror systems needed to make the required science measurements; and by defining and prioritizing the most important technical problems to be solved. Our results have been presented to the Cosmic Origins Program Analysis Group (COPAG) and Mirror Tech Days 2012; and will be published in eight papers at the 2013 SPIE Optics & Photonics Symposia.

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's (NRC) ASTRO2010 Decadal Survey, an advanced large-aperture UVOIR telescope is required to enable the next generation of compelling astrophysics and exoplanet science. The Decadal also noted that present technology is not mature enough to affordably build and launch any potential UVOIR mission concept. According to the NRC 2012 *NASA Space Technology Roadmaps and Priorities* 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 *NASA Office of Chief Technologist Science Instruments, Observatory and Sensor Systems Roadmap* (SIOSS) technology assessment, technology to enable a future UVOIR or high-contrast exoplanet mission needs to be at a TRL-6 by 2018 so that a viable flight mission can be proposed to the 2020 Decadal Review.

Objectives and Milestones

Our long-term objective is to mature technologies to enable large UVOIR space telescope mirrors to TRL6 by 2018. The current effort has assembled an integrated team of scientists, systems engineers, and technologists; derived engineering specifications, which flow from science requirements; and is advancing by at least a half TRL step six key technologies required to make an integrated primary mirror assembly (PMA) for a large-aperture UVOIR space telescope.

- *Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates*
- *Support System*
- *Mid/High-Spatial Frequency Figure Error*
- *Segment Edges*
- *Segment-to-Segment Gap Phasing*
- *Integrated Model Validation*

Progress and Accomplishments

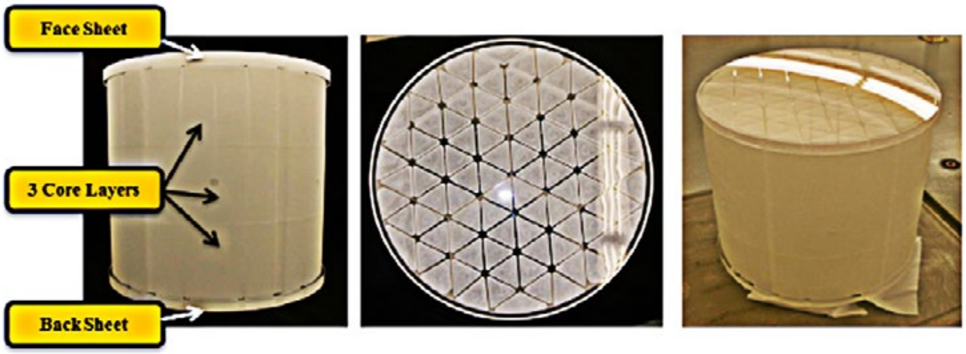
During FY12/13, each of our six critical technologies has had activity, and TRL has been advanced in at least five of the six critical technologies.

Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates:

Need: To achieve the ultra-stable mechanical and thermal performance required for high-contrast imaging, both (4- to 8-m) monolithic and (8- to 16-m) segmented primary mirrors require larger, thicker, and stiffer substrates.

Accomplishment: AMTD partner Exelis successfully demonstrated a new five-layer 'stack and fuse' process for fabricating deep-core mirror substrates. Using this new process, three structural core element layers were fused to front and back faceplates to form a 43-cm diameter 'cut-out' of a 4-m diameter, 40-cm thick, < 45 kg/m^2 mirror substrate. The facesheet and internal structural element dimensions are exactly what would be used to make a 4-m mirror. The core layers are water-jet cut with large cell diameters to reduce total mass. The new process offers significant cost and risk reduction over the incumbent process. It is difficult, and thus expensive, to cut a deep-core substrate to exacting rib thickness requirements. The current state-of-the-art (SOA) is ~300 mm on an expensive custom machine. But, cutting cores ~130 mm deep can be done on commercial machines. Testing indicates that the fusion bonds between core elements are stronger than the bonds between facesheets and core. Front and back facesheets are water-jet pocket milled to reduce mass and enhance stiffness. Pockets are sized to minimize mid-spatial quilting effects. This technology advance enables the manufacture of stiffer 2- to 4- to 8-m class mirror substrates at a lower cost and risk. Such substrates can be used for either monolithic or segmented mirrors.

In another first, this mirror was slumped twice. First it was slumped to a flight-traceable 5.0-m radius of curvature. Then it was slumped a second time to a 2.5-m radius to allow the mirror to fit inside NASA's



Post-Fusion Side View
3 Core Layers and Vent Hole Visible

Post-Fusion Top View
Pocket Milled Faceplate

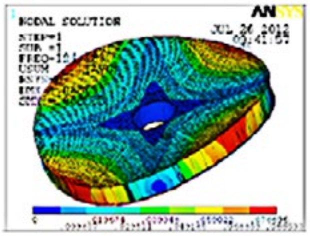
Post Slump:
2.5 meter Radius of Curvature

Marshall Space Flight Center (MSFC) thermal-vacuum chamber for environmental testing. Based on the success of this demonstration, it should be possible to make an inventory of substrates that can be slumped 'on-demand' to custom radii of curvatures.

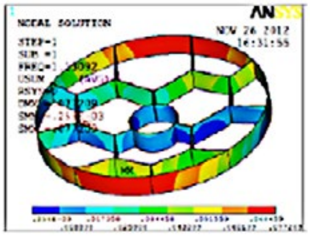
Support System:

Need: Large-aperture mirrors require large support systems to ensure that they survive launch and deploy on orbit in a stress-free and undistorted shape.

Accomplishment: We have developed a new modeler tool in Visual Basic for ANSYS Finite Element Model (FEM). This tool allows the rapid creation and analysis of detailed mirror designs. It can create a 400,000-element model in minutes. This tool facilitates the transfer of a high-resolution mesh to various mechanical and thermal analysis tools. We have used our new tool to compare pre-Phase-A point designs for 4-m and 8-m monolithic primary mirror substrates and supports. The 4-m substrate was constrained to ~700 kg such that it could be launched via a standard evolved expendable launch vehicle (EELV) rocket. The 8-m substrate was not mass constrained because it would be launched via the space launch system (SLS), but the optimum design was ~ 4000 kg. Dynamic and static analysis was performed on both substrate designs to determine stress on internal structural elements and at mount interfaces. Currently we are designing launch and on-orbit support systems for these substrates. For the duration of our effort we will continue to refine the tool and optimize designs. Also, we employed four undergraduate interns and one graduate student to support these efforts.



Free-Free 1st Mode: 4 m dia 40 cm thick substrate



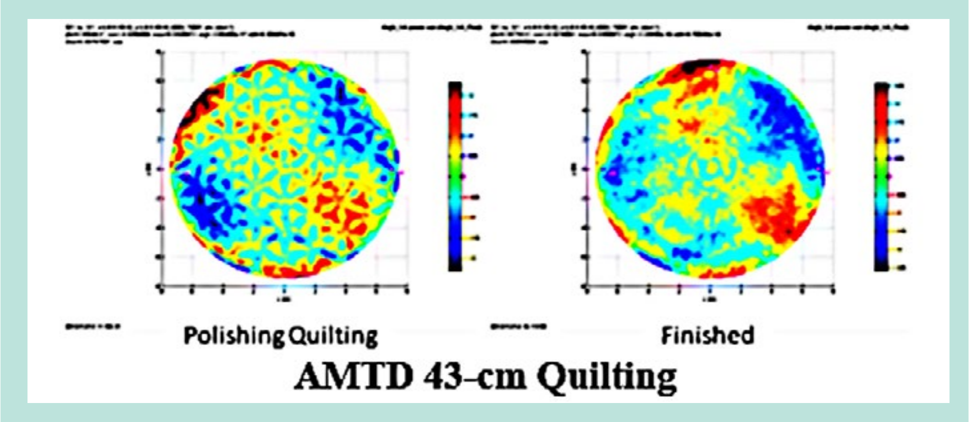
Internal Stress: 4 m dia with 6 support pads

Additionally, AMTD partner Exelis has investigated kinematic mirror mount launch support systems. For 4-m and larger mirrors, a three-point kinematic mirror mount may not provide sufficient support for launch, requiring the addition of multipoint bi-pod constraints that could passively and/or actively damp mirror flexible modes during launch and flight. Past mirror designs with positive launch margins of safety have had 1 g deflections of less than 50 micrometers. For an 8-m monolithic mirror, the 1 g deflection requires at least 12 additional supports. Optimization of the placement and stiffness of these additional supports and mount design will depend on the final mirror substrate design and actual load cases.

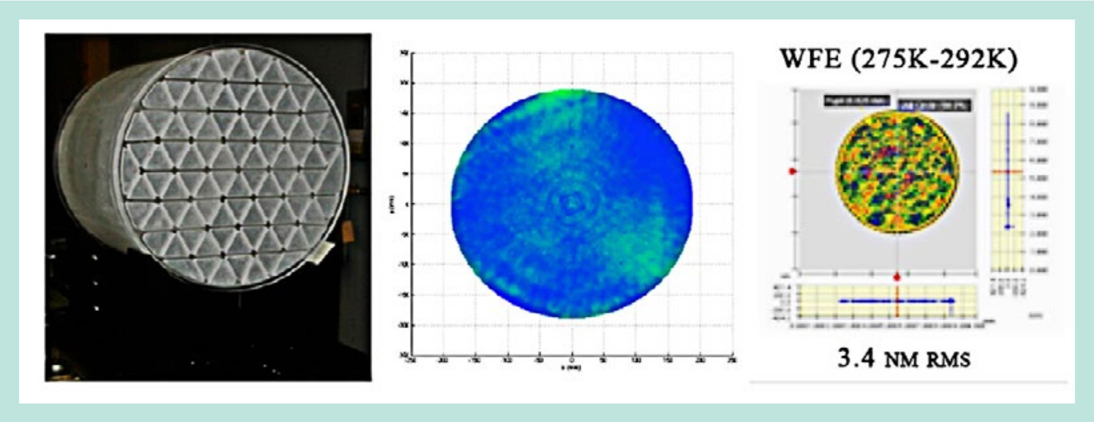
Mid/High-Spatial Frequency Figure Error:

Need: Per our engineering specification derived from science requirements, a very smooth mirror (~ 7-nm rms) 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. And, because the on-orbit operational temperature is different from the fabrication temperature, thermal stress–even for a low coefficient of thermal expansion (CTE) material such as Ultra-Low Expansion (ULE) glass–might cause deformation errors, which can impact UVOIR performance.

Accomplishment: AMTD partner Exelis specifically designed the 43-cm deep-core mirror's facesheet to minimize mid/high spatial frequency quilting error from polishing pressure and thermal stress. Exelis polished the 43-cm deep-core mirror to 5.4-nm rms finished surface, removing the systematic quilting structure that can degrade high-contrast imaging.



When tested from 250 to 300K in the MSFC 1-m thermal-vacuum chamber, the 43-cm deep-core mirror's gravity deformation was the expected trefoil and its thermal deformation was insignificant (smaller than our 4-nm rms measurement resolution).



Based on these results, we believe that the ability to design and fabricate a mirror substrate to minimize mid/high spatial frequency polishing and thermal deformation error has been proven. This ability needs to be certified at increasingly larger diameters, but there is no need to continue effort in this area with the 43-cm deep-core mirror.

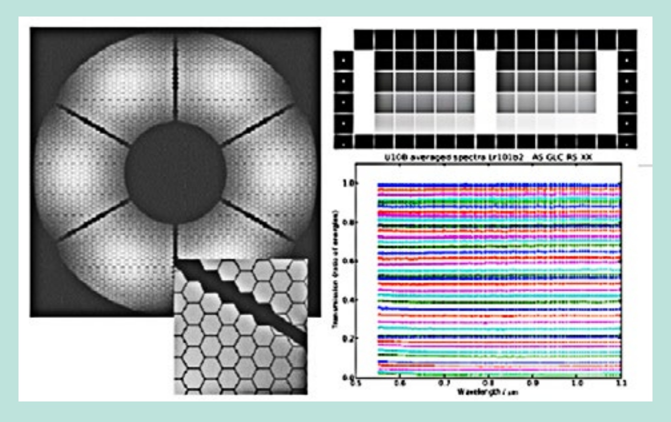
Segment Edges:

Need: For a segmented primary mirror, the quality of segment edges impacts PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture. Diffraction from secondary mirror obscuration and support structure also impacts performance.

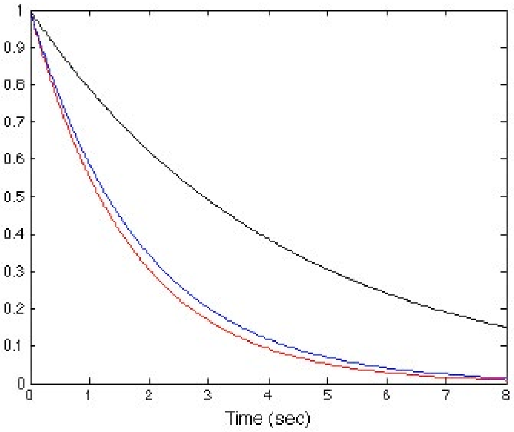
Accomplishment: AMTD Partner Space Telescope Science Institute (STScI) successfully demonstrated an achromatic apodization coating. The coating consists of metallic micro-dots which provide a variable attenuation with uniform performance over a broad spectral band. Such a coating deposited on a segmented mirror enables a high-contract imaging PSF by minimizing edge diffraction and stray light, and structure obscuration diffraction. This technology meets its current specification.

Segment-to-Segment Gap Phasing:

Need: Segment phasing is critical for producing a high-quality and temporally stable PSF. According to our Science Advisory Team, dynamic segment-to-segment co-phasing error introduces speckle noise, which interferes with exoplanet observation. For internal coronagraphs, dynamic co-phasing error needs to be less than 10 pico-meters rms between active control measurements. Development is required for the alignment, phasing, sensing, and control segment phasing.



Accomplishment: We investigated the utility of correlated magnetic interfaces to reduce dynamic co-phasing error. While we found that such interfaces increase dampening by approximately 2×, they cannot achieve the required specification. Also, we found that, while the correlated magnetic interfaces acted over a shorter distance than conventional magnets, their dampening was not significantly different from that provided by a conventional magnet. Therefore, given the inability of correlated magnetic interfaces to reduce dynamic segment-to-segment co-phasing error below the required level, we plan no further investigation of this approach. However, we are continuing in FY 13/14 to mature the Exelis two-stage actuator for rigid body control, which will combine positioning and active damping functions. The Exelis actuator can be used for either segmented or monolithic aperture telescopes.

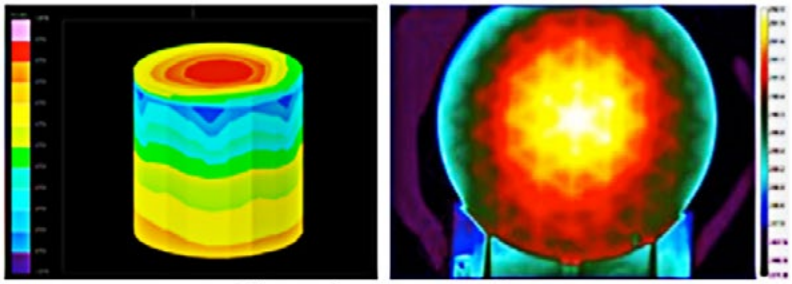


Integrated Model Validation:

Need: On-orbit performance is determined by mechanical and thermal stability. As future systems become larger, compliance cannot be 100% tested; performance verification will rely on results from a combination of sub-scale tests and high-fidelity models. It is necessary to generate and validate as-built models of representative prototype components to predict on-orbit performance for transmitted wavefront, point spread function, pointing stability, jitter, and thermal stability, as well as vibro-acoustics and launch loads.

Accomplishment: We used our new design tool to create models to predict gravity sag and 2°C thermal gradients for the 43-cm deep-core mirror. Because it can create a 400,000-element model in minutes, it facilitates the transfer of a high-resolution mesh to mechanical and thermal analysis tools. Then we validated these models with data from the 250 to 300K test performed at MSFC. The 43-cm deep-core mirror was tested in the MSFC 1-m diameter cryogenic-vacuum test facility. Its surface shape was monitored at center of curvature via a four-dimensional (4D) PhaseCam interferometer. The mirror was instrumented with 12 thermal diodes to characterize front to back and center to edge thermal gradients. Also, in a first for MSFC, the mirror was also imaged during the test with an indium antimonide (InSb) microbolometer to measure front surface temperature gradient to 0.05°C. The measured thermal gradients matched the predicted thermal gradients to ~ 5%. The measured figure change from 275K to ambient of 2.4-nm rms was smaller than the measurement uncertainty. Given the stiffness of the 43-cm mirror, it may be necessary to characterize the thermal performance of a larger mirror.

Test Setup

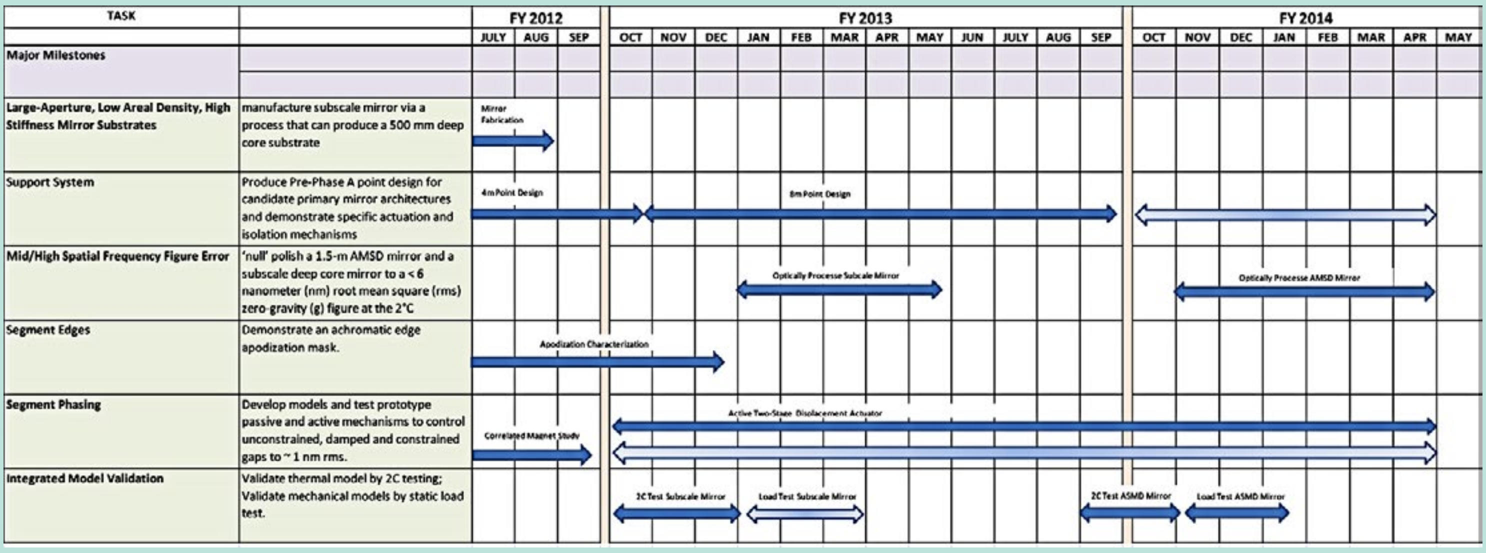


Predicted vs Actual

Additionally, AMTD partner NASA's Goddard Space Flight Center (GSFC) defined and partially implemented an optical systems design and analysis framework that combines simulation results from multiple independent engineering disciplines (e.g., static, dynamic, thermal, etc.). This can be used to generate high-fidelity PSF simulations and compute standard metrics associated with imaging systems–modulation transfer function (MTF), electrical engineering (EE), Zernike Coefficients, etc.–plus user-defined metrics. This represents an advance over the previous SOA, in which performance estimates from multiple independent sources were often combined via an error budget framework (e.g., via root-sum-squares of scalar quantities, where all terms are assumed to be independent whether or not this is actually the case).

Milestone Schedule and Future Plans

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 budget and schedule permit. All fiscal year (FY) 12/13 tasks were accomplished and all FY13/14 tasks are on schedule to be accomplished.



TASK	
Major Milestones	
Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates	manufacture subscale mirror via a process that can produce a 500 mm deep core substrate
Support System	Produce Pre-Phase A point design for candidate primary mirror architectures and demonstrate specific actuation and isolation mechanisms
Mid/High Spatial Frequency Figure Error	'null' polish a 1.5-m AMSD mirror and a subscale deep core mirror to a < 6 nanometer (nm) root mean square (rms) zero-gravity (g) figure at the 2°C
Segment Edges	Demonstrate an achromatic edge apodization mask.
Segment Phasing	Develop models and test prototype passive and active mechanisms to control unconstrained, damped and constrained gaps to ~ 1 nm rms.
Integrated Model Validation	Validate thermal model by 2C testing; Validate mechanical models by static load test.

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Cross Strip Microchannel Plate Detector Systems for Spaceflight

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Summary

Microchannel Plate (MCP) detectors have been an essential imaging technology in space-based NASA ultraviolet (UV) missions for decades and have been used in numerous orbital and interplanetary instruments. The Experimental Astrophysics group at the Space Sciences Laboratory, University of California, Berkeley, was awarded an Astrophysics Research and Analysis (APRA) grant in 2008 to develop massively parallel Cross Strip (XS) readout electronics. These laboratory XS electronics have demonstrated spatial resolutions of 12-µm full width at 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 and neutron imaging labs, but are presently too bulky and high-powered to be used for space applications (though a current version will be used in an upcoming rocket flight).

The goal of this Strategic Astrophysics Technology (SAT) program is to take this XS technology and raise its TRL by: (1) Developing new application-specific integrated circuits (ASIC) that combine optimized faster amplifiers and associated analog-to-digital converters (ADC) in the same chip(s); (2) Develop 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) Develop 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, satellite, and interplanetary UV instruments and could be easily adapted to different sizes and shapes to match various mission requirements. Having this detector flight design available will also reduce the cost and development risk for future Explorer-class missions.

Since the start of our 3-year project in April 2012, we have designed and constructed a 50-mm XS detector with a new low-noise anode, and are just commencing with its performance testing using our existing XS electronics. The digital part of our new ASIC is being prepared for submission to a foundry in early August, with delivery expected in late fall.

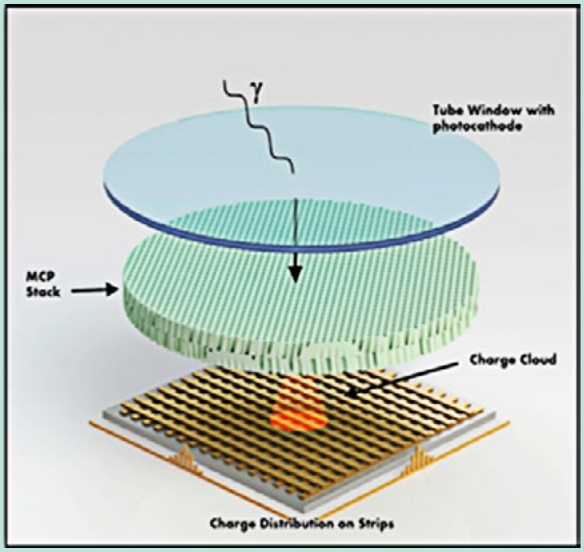

Figure 1. *Schematic of a Cross Strip readout behind an MCP stack*

Background

The National Academy of Sciences Astro2010 Decadal Survey, commenting on UV astronomy, noted that "…key advances could be made with a telescope with a 4-meter-diameter aperture with large field of view and fitted with high-efficiency UV and optical cameras/spectrographs." Further, it recommends to "…invest in essential technologies such as detectors, coatings, and optics, to prepare for a mission to be considered by the 2020 decadal survey." Many of the White Paper submissions to the decadal survey on UV astrophysics missions require large fields of view (detector formats >10 cm), high spatial and/or spectral resolution recorded with high efficiency over a large wavelength range [Scowen 2010, Sembach 2009].

Our laboratory XS electronics have demonstrated spatial resolutions of 12-µm 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 with formats ranging up to 100 mm. 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 ASIC(s) that combines optimized faster amplifiers and associated ADCs; (2) Developing an 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, satellite, and interplanetary UV instruments and could be easily adapted to different sizes and shapes to match various mission requirements. New technological developments in photocathodes (e.g., gallium nitride; 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. 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) whose individual outputs must all be digitized and analyzed. The advantage this technique has over existing and previous MCP read out 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 to be used presently in the field in many laboratory environments, producing quality scientific results (Michalet 2009; Berendse 2006), and is ready for the next step of development: preparing for an orbital or deep-space mission implementation.

Our current XS readout electronics, called the Parallel Cross Strip (PXS) electronics, consist 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 above. However, the PXS laboratory electronics are too bulky, massive and use relatively high power and therefore 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 or two low power, low mass chip(s). When a set of these chips are 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.

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 (JHU), University of Colorado–are currently utilizing MCP detectors with delay-line 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 easily scaled 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 and Milestones

1. Design and fabricate an ASIC to amplify and digitize cross strip signal charges

New ASICs 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 input ASICs that have the following features:

1. An optimized front-end charge-sensitive amplifier that is matched to the anode strip load capacitance with fast signal rise/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. 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. Charge impulses from anode strips of the MCP detector come in on the left side into an array of 10 charge-sensitive amplifiers (CSA) 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, and 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 (MUX) and low-voltage differential signaling (LVDS) lines to itself. An 80 × 80 strip anode in this case, using 20 ASICs, could have an output event rate of 64 MHz (one event gives a trigger in X and Y simultaneously).

2. FPGA system to read out GRAPH ASICs

Our proposed parallel cross-strip readout system is not simply comprised of the new ASICs. New board assemblies must be designed, laid out, and constructed to couple 10 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 has not only a new input interface, but also a new output interface to couple to the high-bandwidth computer interface required for our ultimate event rates.

3. 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 deposition (ALD)–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

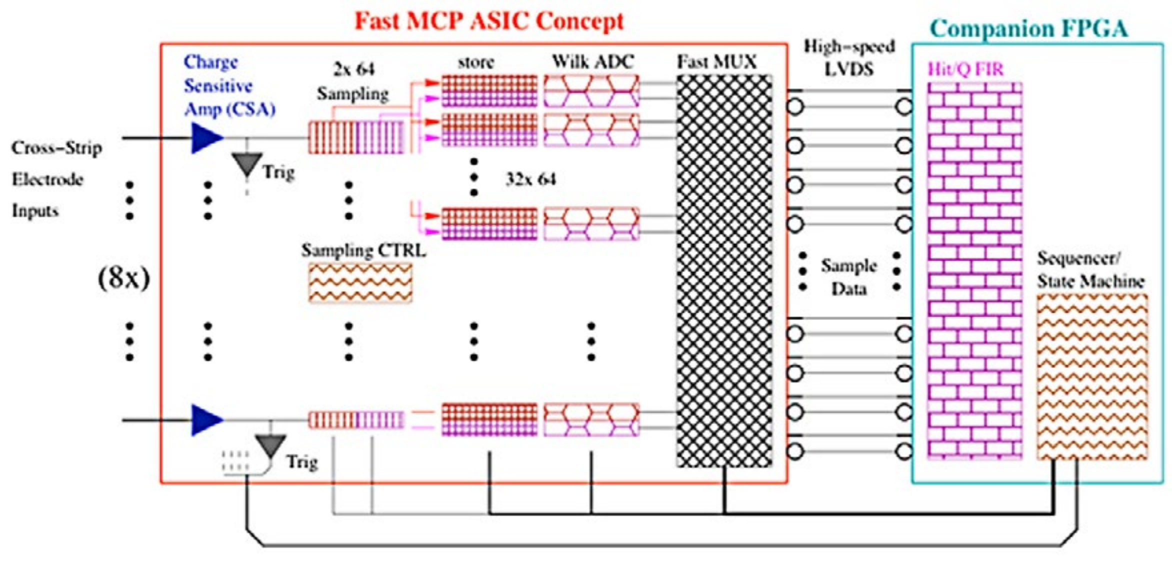

Figure 2. *Strawman ASIC design baseline schematic showing the major functional elements of the design, including the CSA, fast analog sampling and storage, Wilkinson analog-to-digital conversion, and fast multiplexer, all under the control of an external FPGA sequencer.*

are spatial resolution of ~20 µm, background rates <0.1 events cm^{-2} sec^{-1}, low fixed-pattern noise and long lifetime, ~50% quantum efficiency over much of the extreme ultraviolet-far ultraviolet (EUV-FUV) band, multi-megahertz rate capability with low dead-time and detector mass of a few hundred grams. 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-vacuum 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.

Progress and Accomplishments

Though the grant official start date is February 8, 2012, the contract was signed off on April 25, 2012, when work commenced. So this report covers the progress of the first 14 months. The proposal was also written as a 2-year effort, though after discussions with our technical officer we mutually agreed to a 3-year effort, with the bulk of the funding in the second year to match our ASIC development schedule.

There are three parallel efforts that are expected to come together in the final year of this program. The ASIC design and fabrication (called GRAPH) at the University of Hawaii, the FPGA control electronics at the University of California, Berkeley, and the 50-mm XS detector design, also at Berkeley. As explained in the original proposal, most of the initial effort is in design and procurement of the various sub-assemblies for an eventual test detector.

GRAPH ASIC Design

The proposed GRAPH chip was to have a fast charge-sensitive amplifier followed by a fast analog sampling circuit and a Wilkinson ADC that would provide a digitized stream of event amplitudes for a downstream FPGA to calculate event centroids and times. We started with the analog design of the

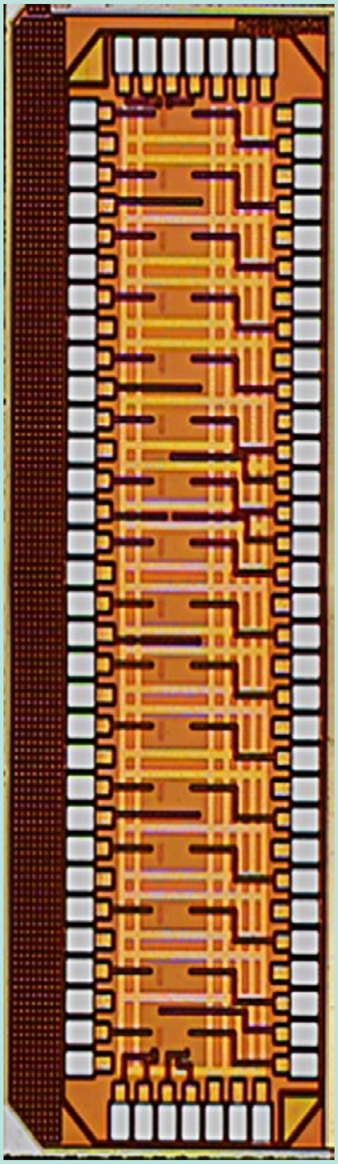

Figure 3. *CSAv2 bare die. Inputs pads on the left, outputs on the right.*

front-end amplifier and have produced two versions: CSAv1 and CSAv2. The downstream digital part of the GRAPH concept is now being designed in a 0.25-µm complementary metal-oxide semiconductor (CMOS) process and is now called the "Half GRAPH."

CSAv1:

The Charge Sensitive Amplifier, CSAv1, was designed to test a charge-sensitive amplifier design using a 130-nm CMOS manufacturing process from the International Business Machines (IBM) Corporation. The CSAv1 was received on February 27, 2012, with dimensions of 3100 µm by 1280 µm. The ASIC offers 16 channels of amplifiers, three channels of test amplifiers (various parameters altered), and test structures to verify simulation performance. The amplifiers have power rails of +/- 0.6 V due to the CMOS process being 1.2 V.

The CSAv1 was designed to drive a 3-pico Farad (pF) load with a 3-pF to 20-pF input capacitance. A basic charge-sensitive amplifier architecture was chosen for the CSAv1 (as well as CSAv2) with a preamp circuit driving a shaper circuit. A printed circuit board (PCB), the CSAv1 Evaluation Board (CEB1), was created to test the CSAv1. The CEB1 interfaces with a control board, providing power and digital control signals. The CEB1 contains digital-to-analog converters (DAC) to set the required bias voltages.

Noise on the CEB1 was problematic primarily due to high-speed digital logic contained on the control board, mounted directly below the CEB1. Parasitic structures on the CEB1 limited readout performance and gave guidance to the design of the CSAv2 as well as the corresponding new evaluation board.

The CSAv1 was useful as a demonstration of the 130-nm process successfully implementing a charge-sensitive amplifier. Lessons learned allow for a more optimized design for the CSAv2, along with improved readout equipment for the CSAv2.

CSAv2:

The CSAv2, with 16 channels of amplifiers, is expected to lower the noise of the CSAv1, with an expected noise value of 291 electrons (e^-). The CSAv2 uses the same architecture for the charge-sensitive amplifier, with the same analog components that were shown to work correctly on the CSAv1. Transistor sizing, capacitor values, and layout optimizations improve the expected noise value.

CSAv2 Evaluation Board:

The CSAv2 Evaluation Board (CEB2) has been designed and fabricated (Fig. 5). The CEB2 is designed to remain in a Faraday cage to reduce noise. Optocouplers will isolate the external (from the Faraday cage) digital control logic from the DACs on the CEB2 to set bias voltages. The DACs will be programmed once and held at the output level to disable data input and clock signals from creating interference. The input and output signal sub-miniature version A (SMA) connectors have additional grounding and shielding to improve noise performance relative to the CEB. Four SMA connectors will connect through low capacitance analog switches to the CSAv2 in order to minimize trace lengths, with four SMA connectors as output.

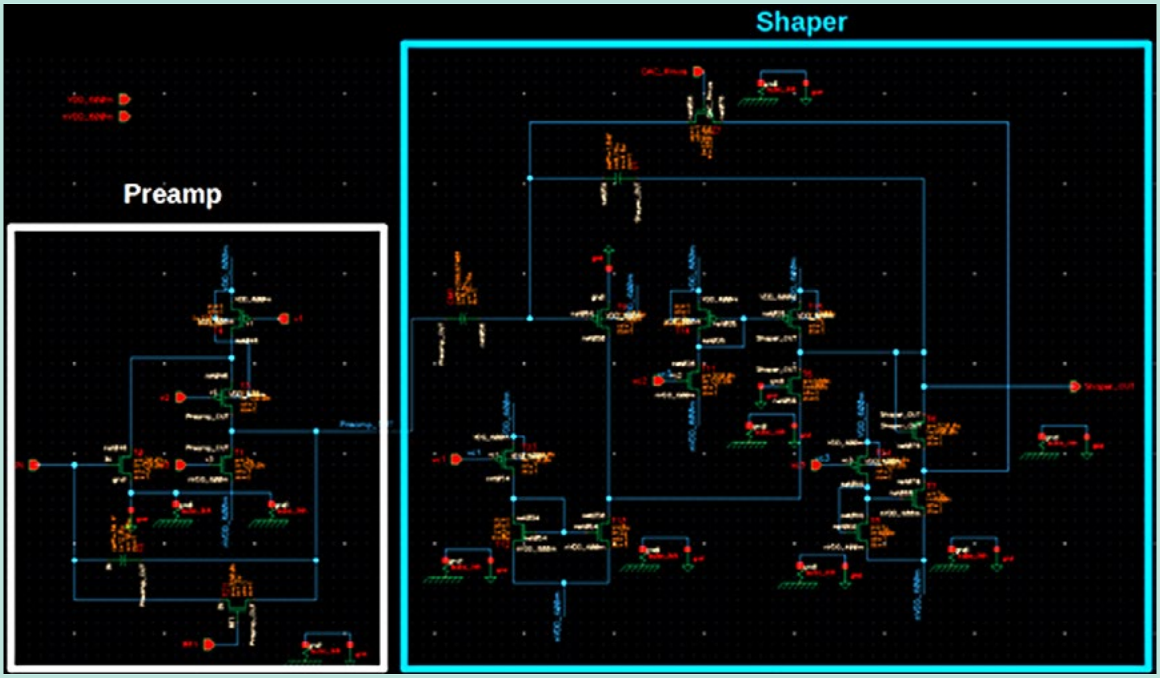

Figure 4. *Schematic of CSAv2 chip*

Current CSAv2 Status

The CSAv2 dies were delivered in January, and after mounting into the evaluation board, we discovered there was no ouput signal, consitent with an “open” somewhere in the circuit. Tests are still ongoing to determine the cause before a resubmittal of the ASIC design. We do not believe this setback is a fundamental problem, more likely a simple layout error.

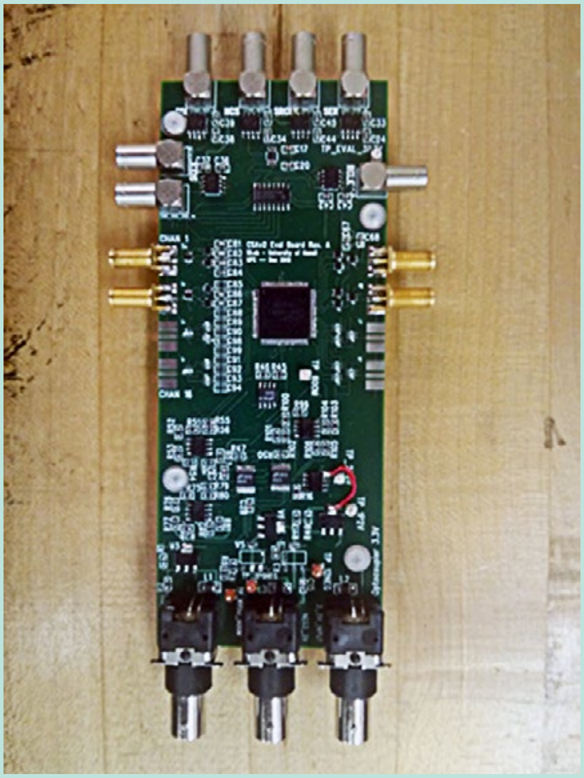

Figure 5. *CSAv2 Evaluation board*

Half-Graph

The digital sampling circuit and ADC are going through final design stages, getting ready for submission to the foundry in early August 2013. The CSAs were designed in 0.13-micron CMOS technology, but we have decided to pursue the digital part in 0.25-micron technology. It has better analog performance for much less cost and faster fabrication turnaround. We have dubbed our initial design the “Half-Graph” as it does not have the analog front end of our initial concept, but we will eventually couple the two, either on the same package or close together on a printed circuit board. This scheme has the advantage of keeping the large digital signal swings away from the sensitive front end. One possible disadvantage to using 0.25-micron process for the back end is the speed of the output LVDS lines.

FPGA controller

It is a bit premature to design the FPGA controller until the ASIC control circuits and output designs are more complete, but initial discussions of the required

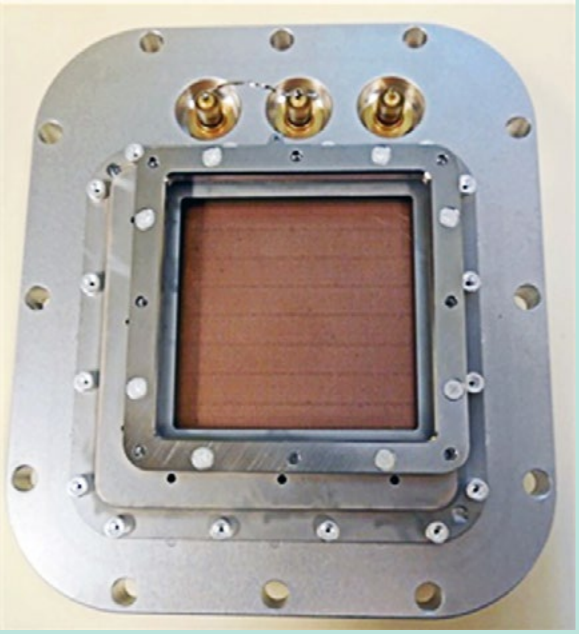

Figure 6. View of windowless 50-mm XS detector mounted on vacuum flange with three high-voltage feedthroughs showing the XS anode (MCPs removed).

Figure 7. External side of detector showing 80 contact feedthroughs (x2) with a 64-channel preamp board plugged into one axis.

resources have started. The Half-Graph will have up to four LVDS lines per channel to meet our throughput requirements, and if we are designing for 80 × 80 channels, that would mean 640 LVDS lines running at 250MHz. Our scheme to avoid this is to use a simple but fast FPGA (e.g., Spartan) to take these four LVDS lines as inputs and output a single GHz LVDS line into the downstream FPGA. These rates are not a problem for current generation of FPGAs, even those that are flight qualified.

1.1.1 50-mm XS detector

A key aspect of this SAT program is to design a flight-like 50 × 50 mm XS detector. We envisioned a brazed Kovar-ceramic body mounted over a XS anode, similar to the successful designs we have used on many missions–e.g., the Cosmic Origins Spectrograph (COS) on the *Hubble Space Telescope*. We chose 50-mm, as that is a standard MCP size available from commercial firms for a reasonable price.

There are two key aspects to our new design. The first is a photo-lithographic and laser-cut XS anode design made with polyimide. The polyimide has a factor of three less dielectric constant than alumina ceramic, so that the capacitance of the individual strips is less and therefore the amplifier noise. The top strip pattern is first etched in the copper, and then a laser cuts the material between the strips. This top layer is then bonded to the bottom strip pattern etched on a much thicker polyimide substrate. The input side of the anode is shown in Fig. 6 installed in the 50-mm XS detector, and the measured capacitances of the strips match our design model. Outputs from the 80 × 80 strips go through a hermetic seal consisting of 2 × 80 pin connectors sealed with vacuum epoxy (Fig. 7).

The other key aspect of our detector is using a Kovar and ceramic brazed body to mount the MCPs over the XS anode. This is a technique used in vacuum image tube construction to make a strong, robust, and clean detector that can survive launch stress. Fig. 6 shows the brazed body mounted over our XS anode onto a vacuum backplate with three high-voltage (HV) feedthroughs (the MCPs have been removed to show the anode in Fig. 6).

Path Forward

Next Year Plans

Early next year in our program, we will submit the first Half-Graph digital ASIC fabrication and determine the error in the CSAv2 analog circuit and prepare for a re-submittal. The first articles will be tested with our existing and new FPGA board designs and the results fed back to the ASIC design process. We will start the full performance testing of the 50-mm detector and anode using the existing parallel XS electronics and begin environmental testing. As useful ASICs appear, we will incorporate them into printed circuit board designs that will be coupled to the new 50-mm detector.

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Ultraviolet Coatings, Materials, and Processes for Advanced Telescope Optics

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Summary

The Technology Development for Cosmic Origins Program (TCOP) calls for "improved reflective coatings for optics, particularly in the ultraviolet [UV] part of the spectrum" for increased throughput," "Studies of improved deposition processes for known UV reflective coatings (e.g., MgF_2 [magnesium fluoride])," and "investigations of new coating materials with promising UV performance" are sought (Ref: NASA NRA NNH11ZDA001N, page D.8-10). Our primary objectives address these needs of new space missions that aim to capture the UV part of the spectrum for astrophysics investigations without sacrificing the performance in the visible-to-near-infrared (VNIR) spectral range needed for exoplanet imaging when both mission objectives are combined. Specific expected capabilities of such a combined mission include: "Imaging at the diffraction limit with large aperture UV/optical (4m to 8m) telescopes (100–1000 nm). High contrast imaging using an internal coronagraph (100–1000 nm)." [Cosmic Origins Program Analysis Group (COPAG) Technology Assessment 2011, page 2.] In essence, our comprehensive and ambitious goal is to arrive at a set of chosen materials and processes to produce the required mirror coatings. These should satisfy the throughput requirements of UV astrophysics instruments as well as meet the needs of exoplanet imaging systems with minimal negative impact on either, thus providing significant cost savings and risk reduction for missions that address both of these two important science objectives simultaneously.

This 3-year project was started in 2013 with a team of Jet Propulsion Laboratory (JPL) engineers. Professor James Green of University of Colorado and Professor Paul Scowen of Arizona State University collaborate on key measurements and advise on scientific goals, respectively. A subcontract has recently been established with ZeCoat Corporation for initial experiments on coating materials and processes, while an advanced Atomic Layer Deposition (ALD) technique is planned for development at JPL in the coming years. Preliminary results are expected from these experiments over the next 6 months. A judicious combination of materials and processes will be arrived at finally to meet the project goals. A new spectrophotometer and an ellipsometer have been set up and calibrated at JPL for characterization of coated samples. The University of Colorado has already made preliminary measurements on a couple of commercial samples with their far-UV measurement facility (Figures 1 and 2), thus establishing a reference baseline for future measurements. Professor Paul Scowen is now preparing a detailed draft of the science drivers for future missions addressing UV astrophysics.

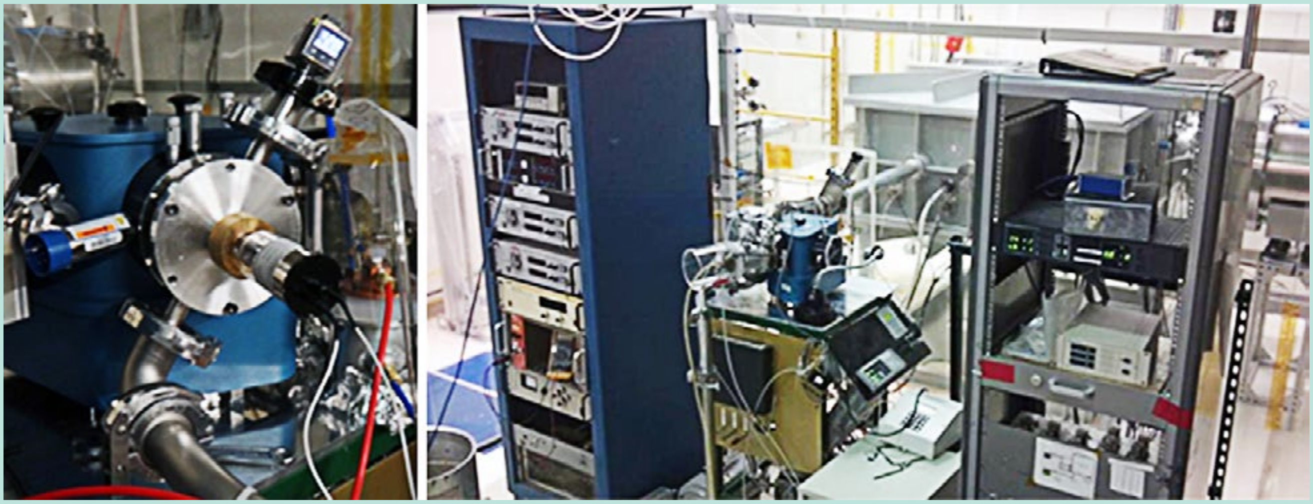


Figure 1: *FUV measurement system at University of Colorado (Courtesy: Prof. James Green). The light sources include sealed platinum neon (Pt-Ne) and deuterium discharge lamps, and windowless gas discharge systems. These can provide a host of emission lines from 400–2000 Å, and continuum emission >1608 Å. The monochromator is a normal incidence McPherson; its selectable bandwidth can be scanned over the full 400–2000 Å range. The vacuum tank is operated in a Class 2000 clean tent.*

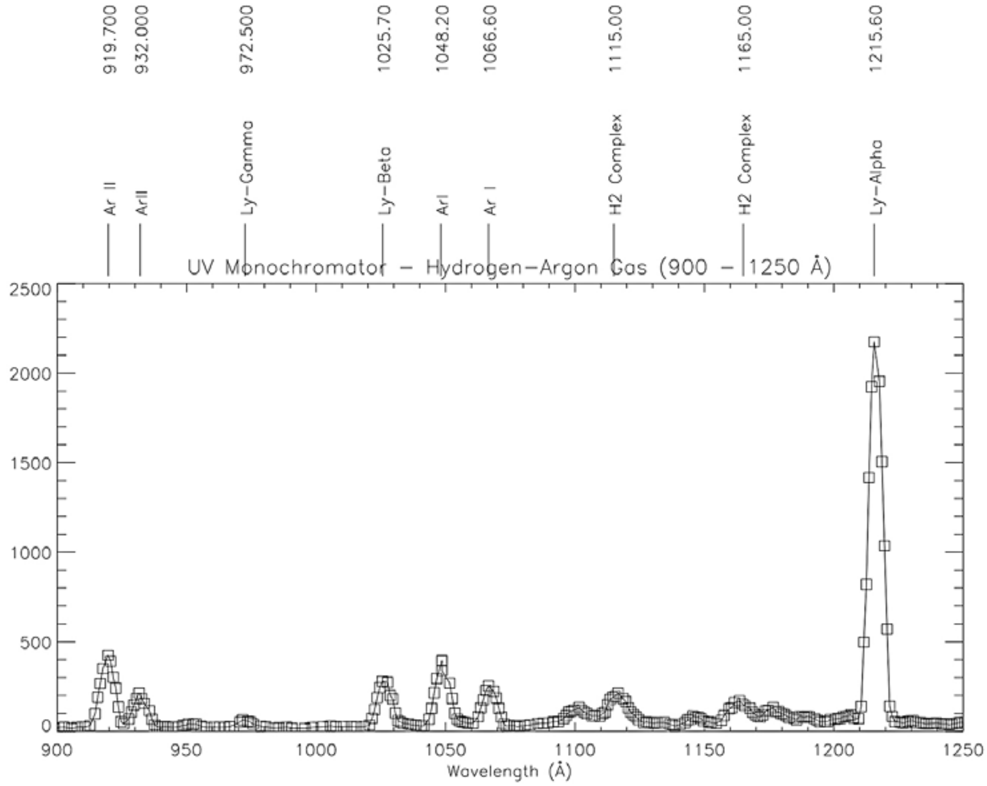


Figure 2. *Representative measurement results from University of Colorado FUV measurement system indicating its current functionality for further work.*

Background

It has been recognized that at mid- to far-UV wavelengths ($90 < \lambda < 300$ nm), it is possible to detect and measure important astrophysical processes, which can shed light into the physical conditions of many environments of interest. For example, in the local interstellar medium (LISM) all but two–singly ionized calcium (Ca II), hydrogen (H), and postassium (K) lines–of the key diagnostic of resonance lines are in the ultraviolet (Redfield 2006). In addition to the fruitful science areas that UV spectroscopy has contributed since the early 1970s, France et al. (2013) have emphasized the role of UV photons in the photodissociation and photochemistry of water (H_2O) and carbon dioxide (CO_2) in terrestrial planet atmospheres, which can influence their atmospheric chemistry, and subsequently the habitability of Earth-like planets. However, only limited spectroscopic data are available for extrasolar planets and their host stars, especially in the case of M-type stars. Similarly, new areas of scientific interest are the detection and characterization of the hot gas between galaxies and the role of the intergalactic medium (IGM) in galaxy evolution (Shull et al., 2012).

The Range of Galactic Science Drivers in the UV (derived from France et al 2012):

Future NASA missions are under consideration to offer a UV spectroscopic capability that would provide fundamentally new insight into how exoplanetary systems form and the physics that govern their atmospheres. A fundamental requirement for such a mission is the combination of high sensitivity and low background equivalent fluxes. Advances in component technology, such as high-reflectivity UV coatings (as represented by this SAT project; providing a factor of three improvement per optic at $\lambda < 1100$Å) and low-noise borosilicate glass photon-counting detectors (Siegmund et al., 2011; a factor of ~10 lower noise than *Hubble Space Telescope* (HST)-Cosmic Origins Spectrograph (COS) detectors) could provide many of the advantages of a much larger telescope but for a fraction of the cost. Thus our primary goals are adopted from a set of science objectives and technology requirements for future Cosmic Origins (COR) missions that have been defined by the COPAG, at its September 2011 workshop at the Space Telescope Science Institute.

Key Excerpts from the COPAG Technology Assessment 2011 Report relevant to this project:

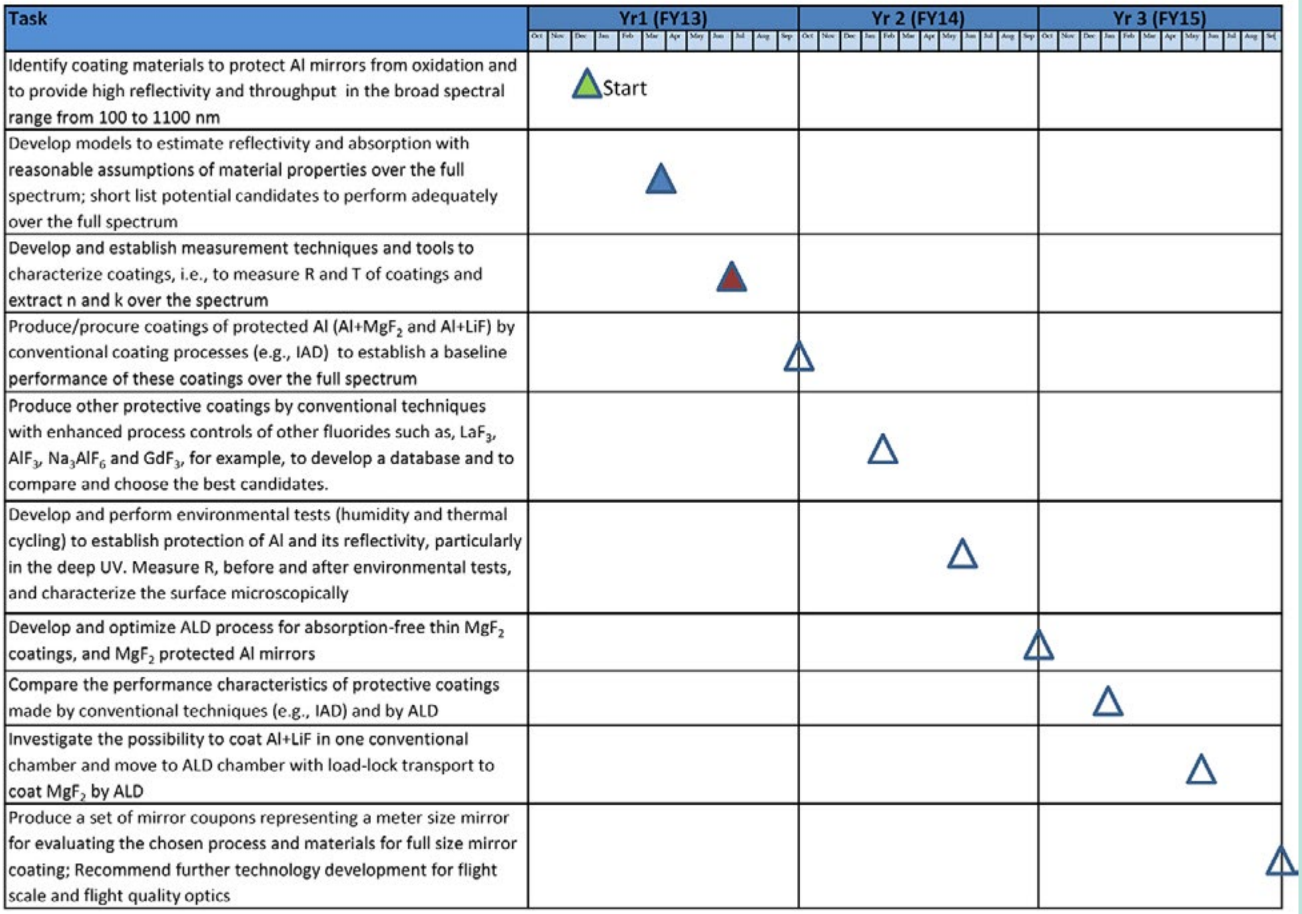
“The COPAG is considering a future large UVOIR [Ultraviolet/Optical/Infrared] mission for general astrophysics that would also perform exoplanet imaging and characterization. Some technologies may be specifically required to make these two missions compatible, for example telescope coatings”. [COPAG Technology Assessment 2011, page 5]

Specific requirements are: “Imaging at the diffraction limit with large aperture UV/optical (4m to 8m) telescopes (100–1000 nm). High contrast imaging using an internal coronagraph (100–1000 nm).” [COPAG Technology Assessment 2011, page 2]

The NASA COR Program Annual Technology Report (PATR) (COR Technology Needs, Table 7, Item 8.1.3., page 43, Oct 2011) defined the primary goal that we have adopted for this project: “Development of UV coatings with high reflectivity (>90–95%), high uniformity (<1–0.1%), and wide bandpasses (~100 nm to 300–1000 nm).” High-reflectivity coatings covering the 100–120 nm spectral region are considered important for studying IGM. The COPAG assessed the degree of difficulty to achieving this as very high. This is indeed very challenging, particularly in the 100–300 nm band. A successful pathway to achieve the objectives of this proposal, namely to develop durable mirror coatings that will provide high reflectance over the extended spectral band, requires the best choice of materials and processes after a careful experimental study of potential candidates. Void-free thin films of absorption-free materials are required to protect and maintain high reflectivity and durability of aluminum mirrors in laboratory and pre-launch environments. A precisely controllable and scalable deposition process is also required to produce such coatings on large telescope mirrors.

Objectives and Milestones

The major milestones listed in Table 1 are adopted from our original proposal and updated slightly. The project started about 3 months late into the first year–fiscal year (FY)13–in alignment with the late funding received from NASA. However, we compressed the tasks in the first year to focus on more challenging tasks early on.



Task	Yr1 (FY13)	Yr 2 (FY14)	Yr 3 (FY15)
Identify coating materials to protect Al mirrors from oxidation and to provide high reflectivity and throughput in the broad spectral range from 100 to 1100 nm	▲Start		
Develop models to estimate reflectivity and absorption with reasonable assumptions of material properties over the full spectrum; short list potential candidates to perform adequately over the full spectrum	▲		
Develop and establish measurement techniques and tools to characterize coatings, i.e., to measure R and T of coatings and extract n and k over the spectrum	▲		
Produce/procure coatings of protected Al (Al+MgF_2 and Al+LiF) by conventional coating processes (e.g., IAD) to establish a baseline performance of these coatings over the full spectrum	△		
Produce other protective coatings by conventional techniques with enhanced process controls of other fluorides such as, LaF_3, AlF_3, Na_3AlF_6 and GdF_3, for example, to develop a database and to compare and choose the best candidates.		△	
Develop and perform environmental tests (humidity and thermal cycling) to establish protection of Al and its reflectivity, particularly in the deep UV. Measure R, before and after environmental tests, and characterize the surface microscopically		△	
Develop and optimize ALD process for absorption-free thin MgF_2 coatings, and MgF_2 protected Al mirrors		△	
Compare the performance characteristics of protective coatings made by conventional techniques (e.g., IAD) and by ALD			△
Investigate the possibility to coat Al+LiF in one conventional chamber and move to ALD chamber with load-lock transport to coat MgF_2 by ALD			△
Produce a set of mirror coupons representing a meter size mirror for evaluating the chosen process and materials for full size mirror coating; Recommend further technology development for flight scale and flight quality optics			△

Table 1. *Development milestones.*

Progress and Accomplishments

Sub-contracts with University of Colorado, Arizona State University, and ZeCoat Corporation, a coating vendor, have been established now. A state-of-the-art spectrophotometer and an ellipsometer have been installed and calibrated at JPL. Initial tests and measurement methods have also been established at JPL and at the University of Colorado. Preliminary measurements were made on a commercial test sample and compared with measurements made on the same sample at NASA's Goddard Space Flight Center (GSFC). Excellent agreement was observed (Figure 3). This sample is also being tested now at the University of Colorado to establish a baseline for future measurements and comparisons. Based on published literature (e.g., Bridou et al., 2010, Keski-Kuha et al., 1999, Yang et al., 2005) and our thin-film models, a short list of candidate materials has been chosen for initial experiments. The first set of coating experiments with aluminum (Al), magnesium fluoride (MgF_2), lithium fluoride (LiF), aluminum fluoride (AlF_3), lanthanum fluoride (LaF_3), sodium hexafluoroaluminate (Na_3AlF_6), and gadolinium fluoride (GdF_3) with conventional methods are expected to begin in July 2013 with preliminary results expected by September 2013. We are also initiating work on the ALD process this year (originally planned for in the second and third years of the proposal) for early acceleration in the second year. John Hennesy, a California Institute of Technology

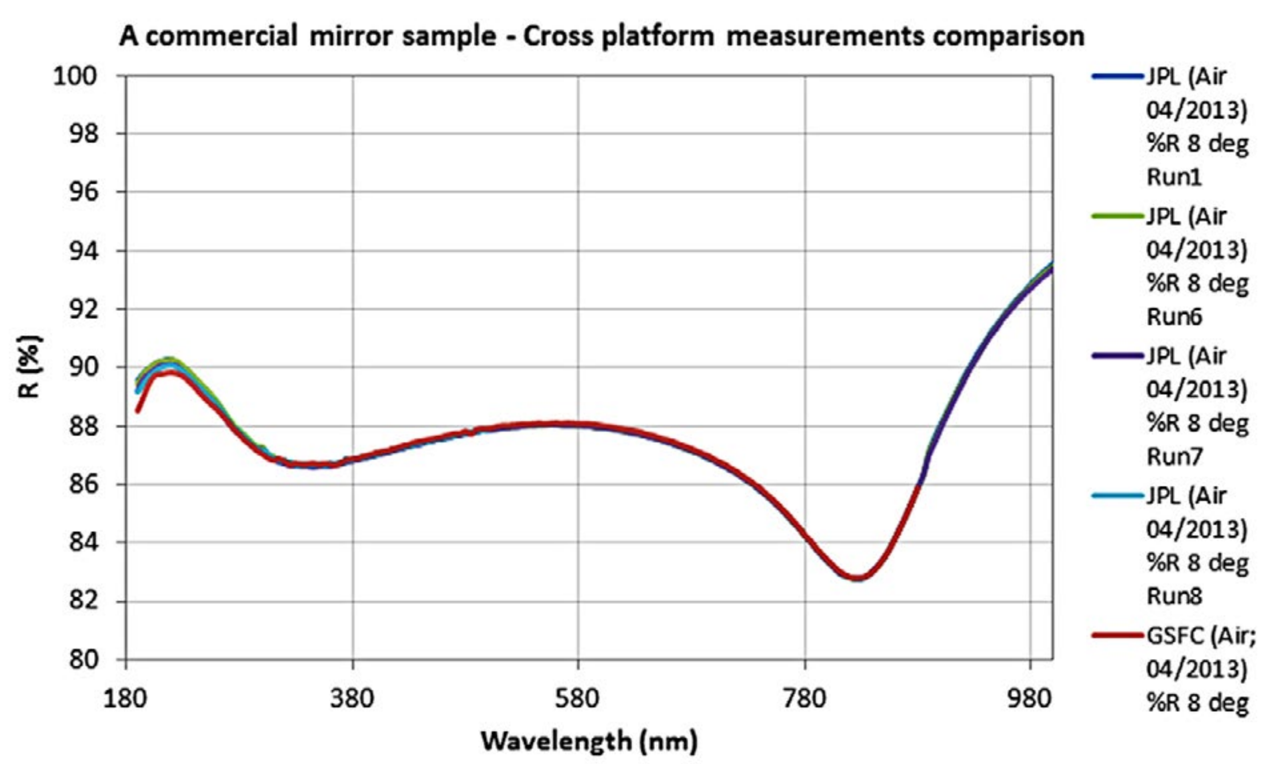


Figure 3. *A cross platform measurement of reflectance of a commercial mirror sample showing excellent agreement between measurements made with two different instruments.*

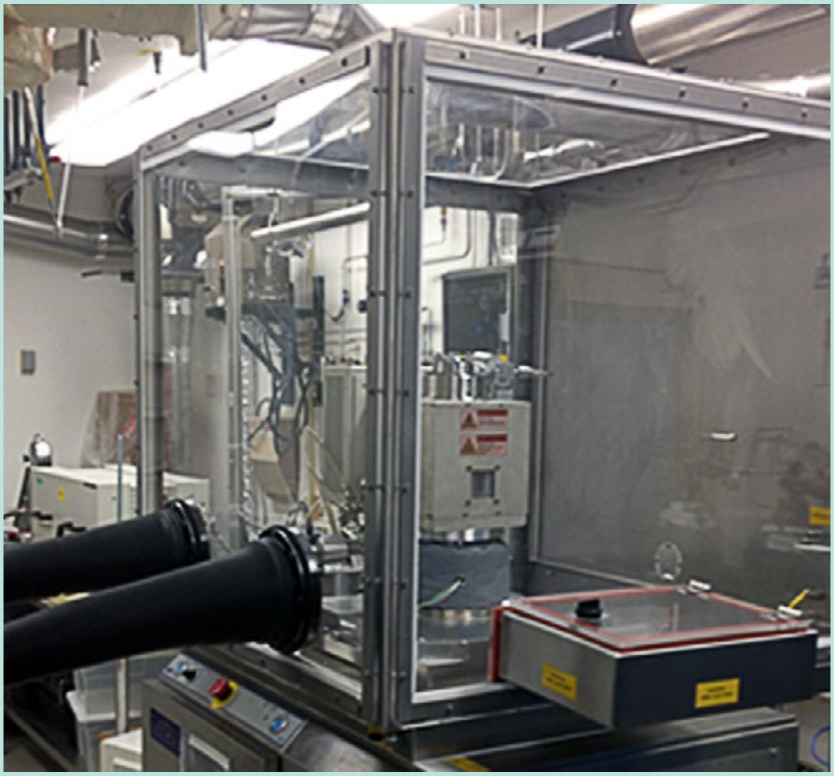


Figure 4. *ALD coating system at JPL*

(Caltech) postdoctoral researcher at JPL, is now included in the project to start coating experiments with ALD (Figure 4) at JPL's Micro Devices Lab (MDL). Our MDL team has successfully deposited MgF_2 film on Al for the first time with ALD. They are currently studying the interface between MgF_2 and Al to optimize the interface chemistry and consequently the far-UV (FUV) reflectivity.

Path Forward

Coating experiments in the first year and early part of the second year will guide the choice of specific materials and process details to follow later in the second year and third year of the project. The goal is to establish a viable scalable process to produce durable overcoats on Al that will preserve/enhance reflectivity of Al mirrors in the FUV spectral region while preserving their performance characteristics in the visible part of the spectrum. A combination of LiF and MgF_2 coating materials together with a combination of conventional process and ALD is expected to achieve the desired results. Although this is a challenging approach, successful implementation is expected to provide a significant payoff in science return as well as the cost effectiveness of future astrophysics missions. Our projected milestones are in line with the current level of progress and understanding. We are currently starting our coating experiments in a meter-class coating chamber fitted with all of the necessary diagnostic tools. Transferring the ALD process, when developed in a small chamber, to large conventional coating chamber would constitute the primary challenge in the third year.

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Kinetic Inductance Detector Arrays for Far-IR Astrophysics

Prepared by: Jonas Zmuidzinas (California Institute of Technology)

Summary

This is a 2-year project that was initiated in 2013. The collaboration includes team members Goutam Chattopadhyay, Peter Day, Darren Dowell, Rick LeDuc, and Loren Swenson at NASA's Jet Propulsion Laboratory (JPL) and Matt Hollister, Chris McKenney, and Jonas Zmuidzinas (Principal Investigator) at the California Institute of Technology. The project focuses on the development of sensitive detector arrays for far-infrared (Far-IR; $\lambda = 50$–500 µm) astrophysics, perhaps the most significant technology challenge for this band. The detectors must be exquisitely sensitive, capable of measuring a power of only 10^{-16} to 10^{-19} Watts (W) in a one-second (s) measurement (this value is known as the noise equivalent power, or NEP). Not surprisingly, the detectors operate at very low temperatures, typically in the range of 0.1–0.3 Kelvin (K). The evolution of Far-IR detector technology has been very rapid. In the early 1990s, Far-IR instruments typically contained only a few hand-built detectors. The Spectral and Photometric Imaging Receiver (SPIRE) instrument for the *Herschel Space Observatory*, developed in the early 2000s, has several hundred detectors. The largest ground-based instrument, the Submillimetre Common-User Bolometer Array-2 (SCUBA-2), now contains 10^4 pixels. However, Far-IR arrays remain very expensive, difficult to produce and to operate, and remain a significant impediment for the future development of the field.

The goal of our project is to develop and demonstrate Far-IR detector arrays using (microwave) kinetic inductance detectors (MKIDs or KIDs)[1]. The ultimate aim is to provide inexpensive, high-performance, large-format arrays suitable for use on a wide range of platforms including airborne, balloon-borne, and space-borne telescopes. Specific project goals include laboratory demonstrations of arrays targeting the sensitivity and optical power levels appropriate for several of these platforms, along with an end-to-end full system demonstration using a ground-based telescope. In fact, a ground-based demonstration was performed very recently, in April 2013, using the Caltech Submillimeter Observatory (CSO).

Background

The universe shines very brightly at far-infrared wavelengths–in fact, about half of the photon energy ever produced by stars and galaxies over the history of the universe falls in the Far-IR band. This remarkable fact was originally predicted by Frank Low and Wallace Tucker in 1968 on the basis of a handful of early Far-IR observations of galaxies, and was first demonstrated observationally in 1996 by Jean-Loup Puget and collaborators, working with data collected by the NASA *Cosmic Background Explorer* (COBE) satellite. To put it in another way–there is just as much light in the Far-IR as there is in the visible/near-IR band. This simple fact alone makes it imperative to study the universe in the Far-IR. Fortunately, the technology to image and survey the universe in the Far-IR is now becoming available.

Fundamentally, the large luminosity of the universe in the Far-IR is intimately tied to the process of star formation. Star formation occurs deep inside thick clouds of interstellar dust and gas. The dust provides a shield against radiation that would otherwise heat and ionize the gas, and allows the gas to form molecules, to cool to temperatures below 10 K, and to become quite dense. Gravitational collapse of these dense cores then leads to star formation, but the radiation produced by a newly formed star cannot escape its dusty cocoon. Instead, the stellar radiation is absorbed by the surrounding dust and gas, heating this material to temperatures around 50–100 K and causing it glow brightly in the Far-IR. The Far-IR radiation readily escapes these thick clouds, providing a view of sites of recent star formation, sites that are often entirely invisible in the optical/IR. Such Far-IR studies can be performed locally by imaging sites of star formation in the Milky Way Galaxy. In addition, the *Infrared Astronomical Satellite* (IRAS) survey showed that many galaxies are bright in the Far-IR. Indeed, galaxy-galaxy collisions are believed to be a key factor in the evolution of galaxies, and such collisions often trigger giant bursts of star formation that provide a large boost to the Far-IR luminosity. The *Herschel Space Observatory* provides a recent example of the importance of Far-IR observations for studying star formation both near and far, in our galaxy and across cosmic time. Indeed, many of the brightest Far-IR galaxies found by *Herschel* are undetectable by the *Hubble Space Telescope* (HST) or the largest ground-based optical telescopes.

The Decadal Survey reports by the National Academy of Sciences' National Research Council provide a long history of strong support for far-infrared astrophysics. In 1982, the Field report[2] recommended the construction of a 10–20 m space-borne Far-IR telescope, known as the Large Deployable Reflector (LDR). As with many Decadal recommendations, this project was never built due to budget issues, but the recommendation did stimulate NASA technology investments that ultimately led to NASA's participation in *Herschel*, which was launched by the European Space Agency (ESA) in 2009. The 1991 Bahcall report[3] recommended the Stratospheric Observatory for Infrared Astronomy (SOFIA) airborne observatory, a prime platform for Far-IR astronomy, and called out star/planet formation and galaxy formation as two of the four key science themes for the decade. Another large Far-IR space mission, the 10-m (cold) Single-Aperture Far-Infrared (SAFIR) telescope, was recommended in the 2001 McKee-Taylor report[4]. The recommendation was to focus on technology development, leading to a new start by the end of the decade (2010). The recommendations in the latest report, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH), made facing a difficult budget outlook, included a ground-based project that relies on similar array technology (the 25-m Cerro Chajnantor Atacama Telescope, or CCAT), hardware/science involvement in the Japanese Aerospace Exploration Agency's (JAXA) *Space Infrared Interferometric Telescope* (SPICA) Far-IR space mission, and increased support for NASA's balloon program–another prime platform for Far-IR astrophysics. In addition, the NWNH report emphasizes many of the science themes that are highly relevant for the Far-IR, including the origins of stars and galaxies as well as cosmic dawn. The technology being developed in our project thus connects strongly to a broad cross-section of Decadal recommendations, not only in the NWNH report but also reaching back over 30 years. In short, the fundamentals have not changed.

Far-IR detector arrays have evolved rapidly over the past two decades. In the early 1990s, Far-IR detectors were laboriously built, individually, by hand. By around 2000, several instruments were fielded using lithographically fabricated arrays with a few hundred detectors in which the detectors were read out with individual amplifiers and wiring. The development of superconducting detectors, coupled with the invention of multiplexed readout schemes, propelled the field to its present level of arrays with up to ~1000 pixels. A good example is the ground-based SCUBA-2 instrument, which contains eight array tiles, each with 1280 detectors, for a total of around 10^4 pixels. However, the transition edge sensor/superconducting quantum interference device (TES/SQUID) technology used for SCUBA-2, while being flexible and adaptable to broad range of requirements, is expensive and difficult to produce. Indeed, detectors now often constitute the largest single budget item for new Far-IR instruments and impose a bottleneck on future advances. The goal of our project is to show that the simpler, lower-cost KID technology[1] can meet the needs of a similarly broad range of applications, ranging from ground-based to space instruments. KID technology was proposed by our group in 1999, and with support from NASA has shown very rapid development over the past decade. However, instrument groups have often been hesitant to adopt the technology due to its lower level of maturity. Our project addresses this issue head-on through laboratory demonstrations covering a wide range of sensitivity levels, coupled with a full system, end-to-end demonstration on a ground-based telescope. The combination of laboratory and telescope testing will provide the confidence and technological maturity needed for adoption of these arrays by teams proposing new instruments or payloads.

Objectives and Milestones

Over the duration of the 2-year project, our goal is to perform laboratory demonstrations of kinetic inductance detector arrays suitable for airborne, balloon, and space platforms, and to perform and end-to-end, full system demonstration of an instrument on a ground-based telescope. The key performance specifications are shown in the table below. From a technical standpoint, the most difficult task is the ground-based demonstration, followed by the laboratory demonstration for space. Meeting the performance requirements is often an iterative process, requiring several cycles of array design, fabrication, and test. Our schedule for these tasks is as follows:

- Ground–telescope demonstration: April 2013 (already accomplished)
    - Option to perform a second demonstration will be investigated
- Space–laboratory demonstration
    - First iteration: second half 2013
        - Array design: summer 2013
        - Array fabrication: early fall 2013
        - First lab tests: late fall 2013
    - Second iteration: first half 2014
    - Third iteration: second half 2014
- Balloon–laboratory demonstration
    - First iteration: first half 2014
    - Second iteration (if needed): second half 2014
- SOFIA–laboratory demonstration
    - First iteration: first half 2014
    - Second iteration (if needed): second half 2014

Platform	Optical power	NEP_{phot} (W/rt Hz)	NEP_{goal} (W/rt Hz)	TRL goal
Space (90 µm)	0.12 fW	7.3×10^{-19}	5×10^{-19}	3→4
Balloon (350 µm)	18 pW	1.5×10^{-16}	7×10^{-17}	3→4
SOFIA (90 µm)	26 pW	3.4×10^{-16}	1.7×10^{-16}	3→4
Ground (350 µm)	100 pW	6.5×10^{-16}	3.3×10^{-16}	3→6

Progress and Accomplishments

With previous NASA support, we constructed a cryostat containing a 4K pulse-tube cooler and a self-contained helium-3 (^{3}He) sorption refrigerator system capable of reaching 220 mK. This instrument, known as MAKO, is shown in Fig. 1. MAKO is fitted with a 432-pixel kinetic inductance detector array (shown in Fig. 2) fabricated at JPL's Microdevices Laboratory (MDL). Each pixel in the array is designed to simultaneously be an efficient Far-IR absorber as well as a high-Q radio frequency (RF) resonator with a unique frequency in the 170–240 MHz band. The Far-IR radiation absorbed by a pixel causes its RF resonance frequency to shift in proportion to the Far-IR power; the frequency shifts for all pixels in the array are simultaneously measured by the room-temperature electronics using frequency multiplexing. The pixel design[5–7] is very simple: a single-layer metal film (titanium nitride, TiN[8]) is lithographically patterned into an interdigitated capacitor (*C*) and a meandered inductor (*L*). The inductor also serves as the Far-IR absorber.

The interdigitated capacitors are not photosensitive but occupy ~30% of the array real estate in the first-generation design. Thus, 30% of the Far-IR photons collected by the instrument optics and delivered to

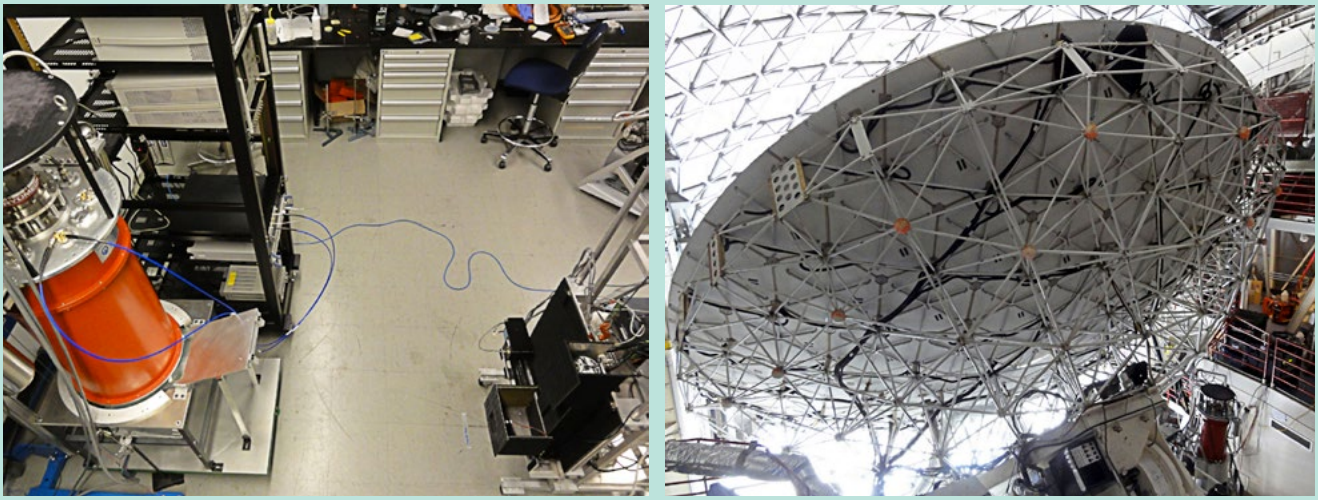

Figure 1. *LEFT: The MAKO instrument undergoing laboratory tests at Caltech. The entire 432-pixel array is read out using a pair of RF coaxial cables, colored blue, visible against the cryostat. RIGHT: MAKO at the Caltech Submillimeter Observatory on Mauna Kea, HI. MAKO is visible in the lower right corner.*

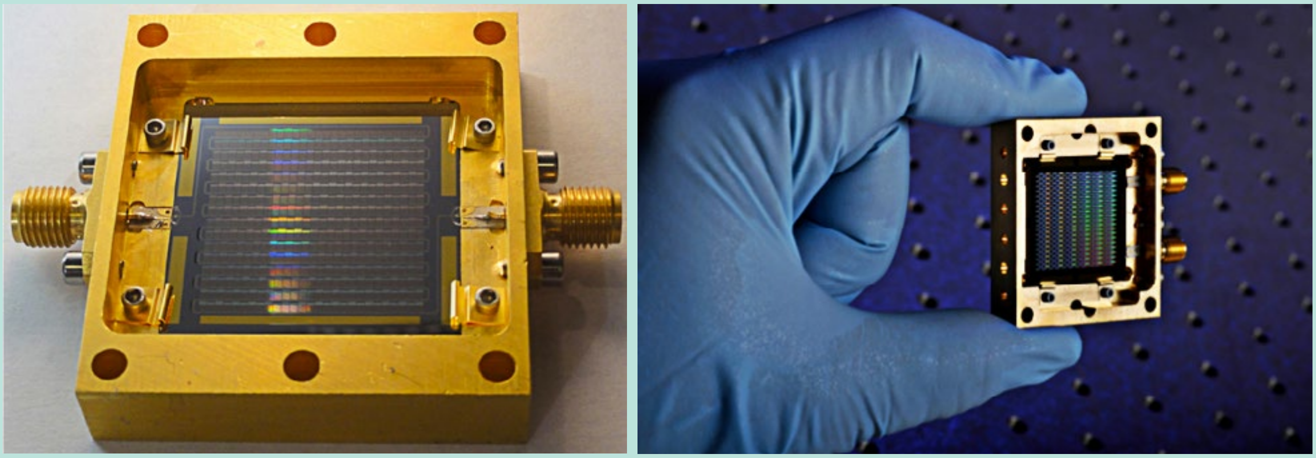

Figure 2. *LEFT: The first-generation, 432-pixel TiN KID array used for the MAKO demonstration at the Caltech Submillimeter Observatory (CSO). RIGHT: A second-generation 484-pixel array, designed for use with a microlens array.*

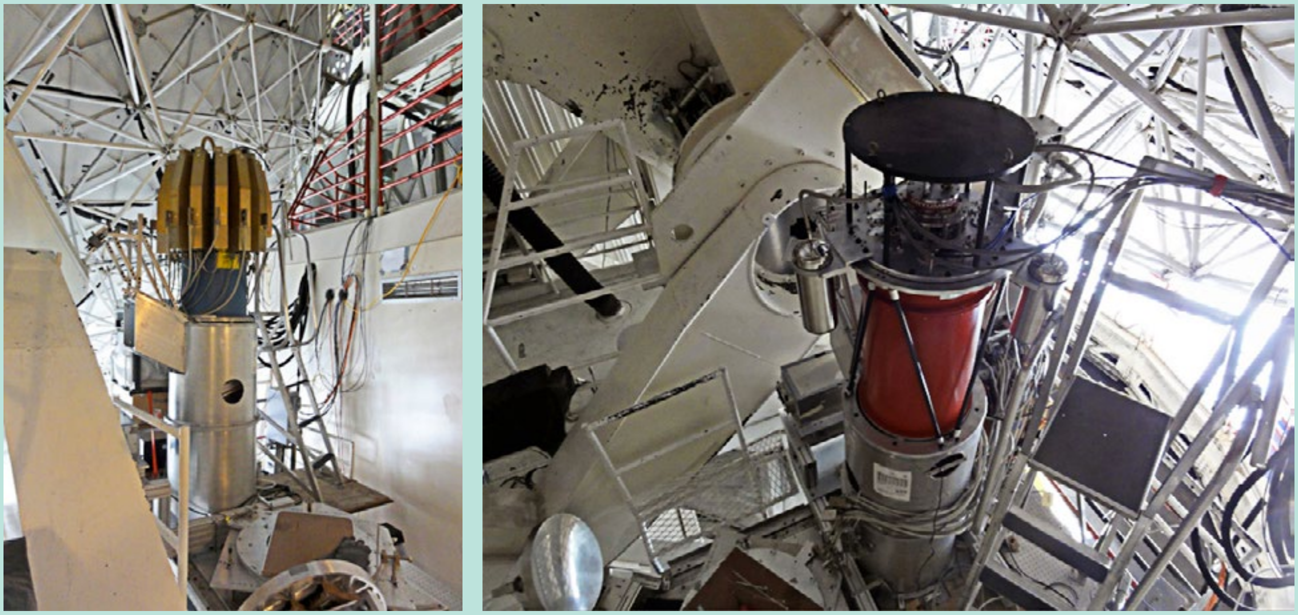

Figure 3. *LEFT: The CSO's Submillimeter High Angular Resolution Camera 2 (SHARC-2) 350 µm camera, which contains a (non-multiplexed) 384-pixel micromachined silicon "pop-up" bolometer array. The massive array of preamps and wiring needed for detector array readout is visible on top of the liquid helium cryostat (blue). RIGHT: MAKO, mounted at the SHARC-2 position at the CSO.*

the array are not detected. This is being improved in the second-generation array design (Fig. 2, right) that will use microlens arrays to focus the Far-IR radiation on the inductor only. We have successfully prototyped microlens arrays with spherical lens shapes using photolithography and reactive ion etching (MDL) and also UV laser machining (commercial vendor), and are experimenting with planar gradient-index lenses made using silicon-on-insulator wafers and reactive ion etching (MDL). Microlens arrays offer the opportunity of concentrating the radiation onto smaller-area, smaller-volume inductors, which results in more sensitive detectors (lower NEP). This technique is one of the strategies we plan to use to achieve the NEP goals specified in Table 1.

In April 2013, MAKO was shipped to the CSO on Mauna Kea, HI, in order to perform a full system demonstration on a telescope. Fig. 3 (right) shows an image of MAKO installed at the CSO. The optics for MAKO were designed to be identical to those used SHARC-2, the CSO's facility 350 µm camera. SHARC-2 uses a 384-pixel silicon micromachined bolometer array developed and fabricated by NASA's Goddard Space Flight Center (GSFC) over a decade ago as a prototype for the University of Chicago's High-resolution Airborne Wide-bandwidth Camera (HAWC) Far-IR camera for SOFIA. The SHARC-2 detectors are not multiplexed; each bolometer requires separate wires, a separate low-noise junction gate field effect transistor (JFET) amplifier and electronics chain, which adds greatly to the complexity and expense of the instrument. In comparison, MAKO is read out using only two RF cables. However, SHARC-2 is a high-performance, well-understood instrument that serves as an excellent benchmark.

As Fig. 4 illustrates, the CSO demonstration of MAKO was very successful. The instrument team was successful in getting the full system up and running on the telescope, performing the necessary calibrations, and obtaining high-quality astronomical images. These results clearly demonstrate the feasibility of using TiN kinetic-inductance detector arrays for Far-IR astronomy. The detailed performance of MAKO on the CSO is now being carefully evaluated. Preliminary results indicate that MAKO is a factor of several less sensitive than SHARC-2; part of the discrepancy is due to a smaller absorber area and single-polarization operation for MAKO. However, it currently appears likely that the detector noise

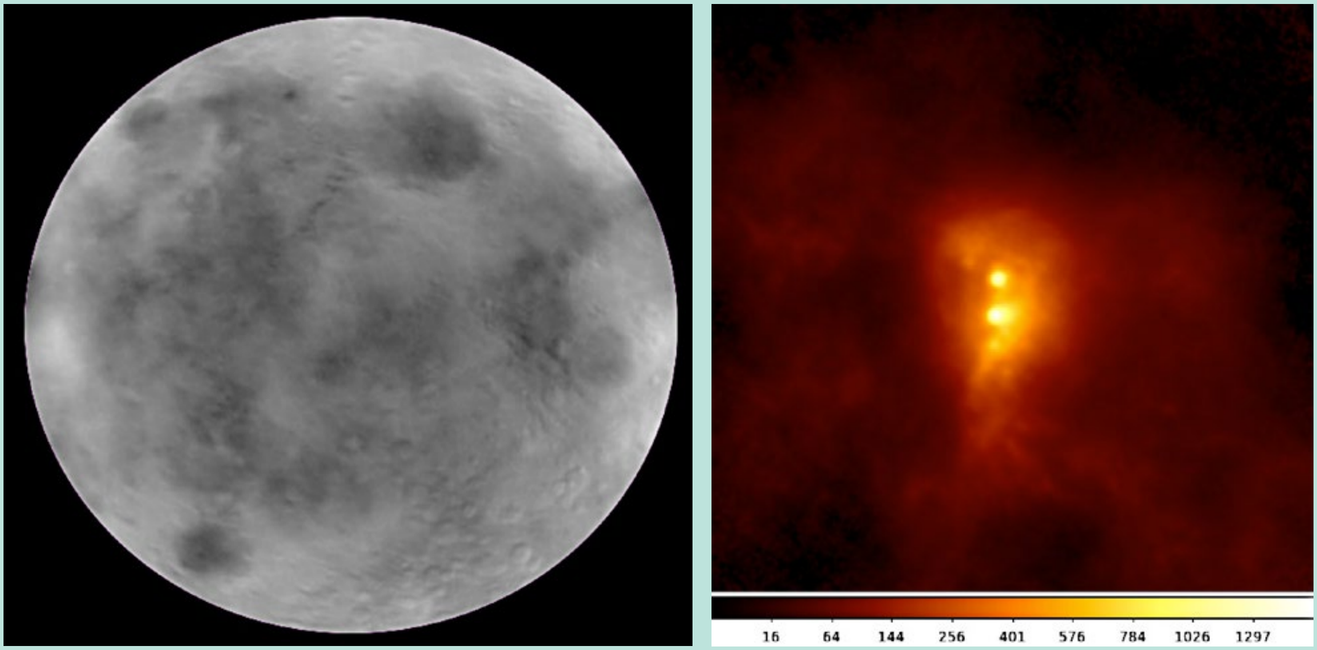

Figure 4. *LEFT: Image of the moon, obtained using MAKO at the CSO. RIGHT: MAKO image of Sagittarius (Sgr) B2, a region of massive star formation located ~200 parsecs (pc) from the galactic center. The three well-known bright cores–Sgr B2(N), Sgr B2(M), and Sgr B2(S)–are visible at the center of the image and correspond to dense concentrations of interstellar dust heated by the newly formed stars. Fainter extended emission from the larger molecular cloud region is also visible. The MAKO Sgr B2 image corresponds quite well with an image of the same region obtained using SHARC-2.*

will need to be reduced by a modest factor in order for MAKO to solidly reach the photon noise limit at the CSO. The necessary noise reduction should be readily achievable through use of microlens array coupling and/or through an increased electrode separation in the interdigitated capacitor design; both are currently being investigated.

Path Forward

There are no technical or programmatic impediments at the present time. The next steps are clear:

1. Make adjustments to the array design to place the MAKO detectors solidly in the photon noise limit. This will involve relatively minor adjustments to the resonator design and/or use of microlens arrays for optical coupling. A substantial noise reduction should be possible by increasing the separation of the capacitor electrodes.

2. Begin noise measurements of small arrays of resonators, with the space application as the target. The large reduction in NEP required relative to the MAKO arrays requires a significant boost in detector responsivity, which implies a corresponding reduction in inductor volume. This can be accomplished by using small-area inductors illuminated with low focal ratio (F/#) microlenses, and/or the use of aluminum (with a much lower area fill factor as dictated by its lower resistivity) in place of TiN. These measurements will be performed using a dilution refrigerator system at JPL.
3. Prepare for array tests using the MAKO cryostat at the lower optical powers relevant for airborne and balloon platforms. This will involve construction of a cryogenic blackbody, acquisition of neutral-density filters, and acquisition of the relevant bandpass filters.

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H4RG Near-IR Detector Array with 10 micron pixels for WFIRST and Space Astrophysics

Prepared by: Bernard J. Rauscher (NASA/GSFC) and Selmer Anglin (Teledyne Imaging Sensors)

Summary

The aim of this 3-year project is to mature a new generation of very large format, 16-megapixel near-infrared (NIR) array detectors to TRL-6 for the *Wide-Field InfraRed Survey Telescope* (WFIRST) and other astrophysics missions (Fig. 1). The new Teledyne H4RG-10 advances the state of the art by: (1) approximately quadrupling the pixel count per unit focal plane area and (2) improving the performance of individual pixels. The higher pixel density, which reduces system cost per pixel, is critical to achieving WFIRST's scientific objectives most cost effectively. Year-1 funding was received at NASA Goddard Space Flight Center (GSFC) in November 2012, and production of the first prototype H4RG-10s is now underway at Teledyne.

The GSFC and Teledyne co-led team includes the Jet Propulsion Laboratory (JPL), the U.S. Naval Observatory (USNO), and the University of Hawaii. NASA/GSFC leads testing. Teledyne is designing and fabricating the H4RG-10s. JPL leads characterization for weak lensing and will participate in testing. The USNO is providing readout integrated circuits (ROIC) and will participate in evaluating the H4RG-10s for astrophysics. The University of Hawaii is a liaison to the nearly identical H4RG-15 (a 16-megapixel detector with 15-micron pixels) that the National Science Foundation (NSF) began developing a few years ago. They are providing insight into lessons learned from the H4RG-15. This

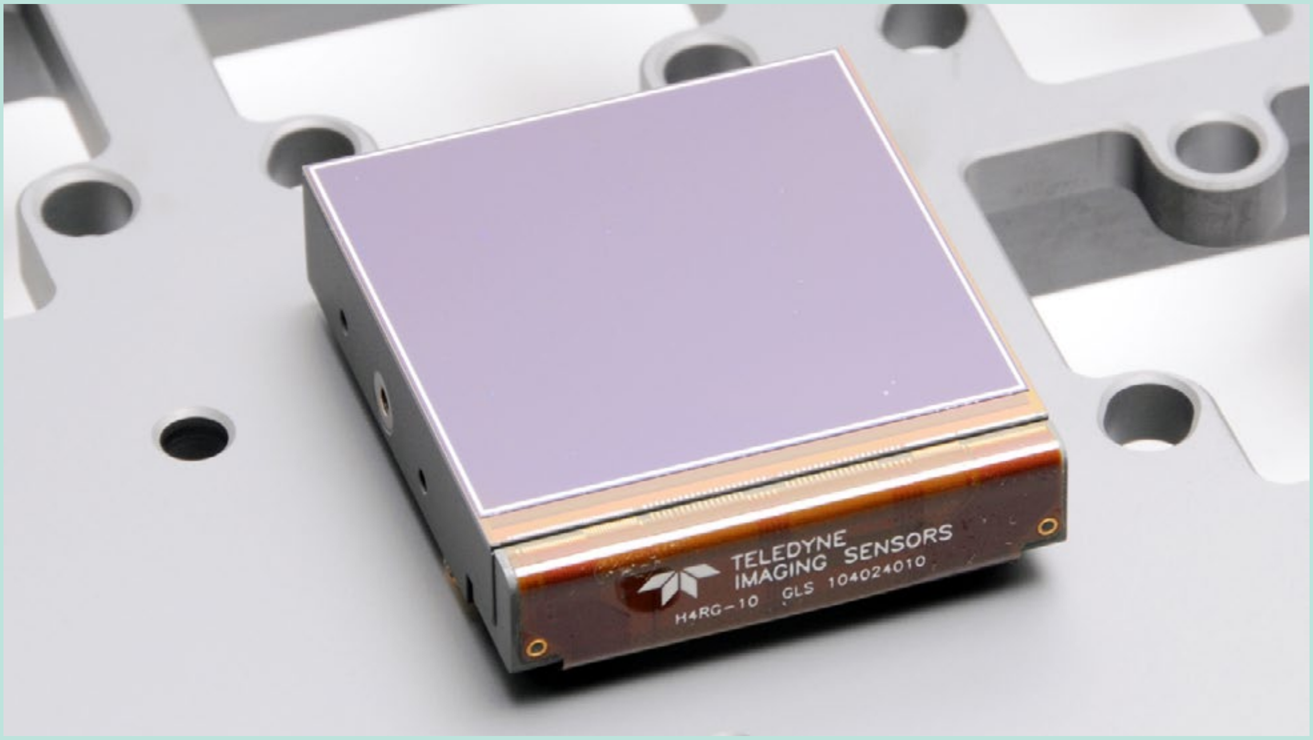
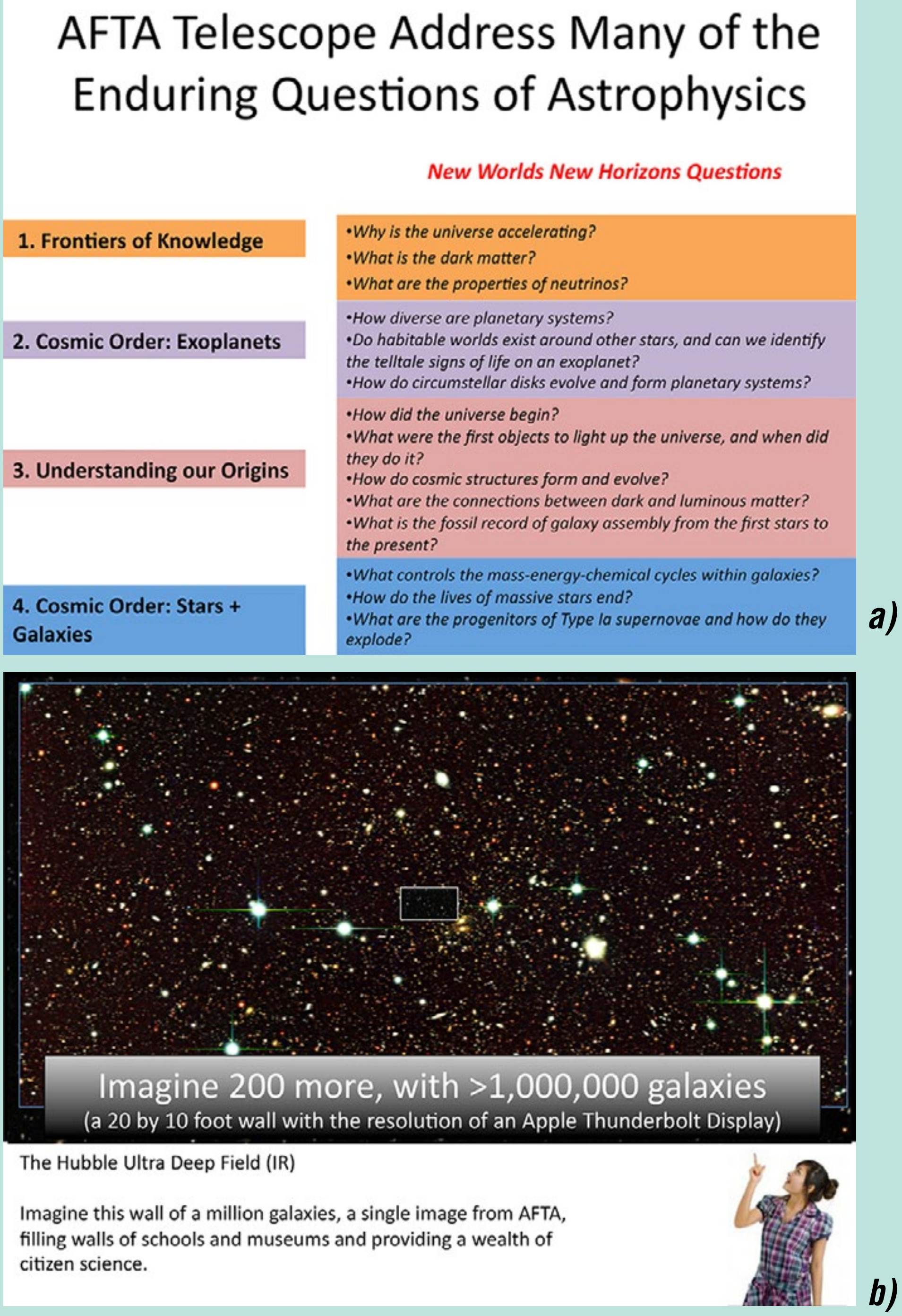


Figure 1. *The H4RG-10 is a 16-megapixel near-infrared detector array. Although it is about the same physical size as one of James Webb Space Telescope's (JWST) H2RGs, each H4RG-10 packs four times as many pixels into about the same focal plane area, resulting in significant cost savings when viewed as part of a system.*

H4RG-10 development is intimately coupled to the requirements of the WFIRST mission. The principal investigator (PI) and JPL Institutional PI are both members of the WFIRST/Astrophysics Focused Telescope Assets (AFTA) Science Definition Team (SDT). Our project manager is the WFIRST deputy project manager and co-investigator Jeff Kruk is a scientist in the project office.



AFTA Telescope Address Many of the Enduring Questions of Astrophysics

New Worlds New Horizons Questions

1. Frontiers of Knowledge	•*Why is the universe accelerating?* •*What is the dark matter?* •*What are the properties of neutrinos?*
2. Cosmic Order: Exoplanets	•*How diverse are planetary systems?* •*Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?* •*How do circumstellar disks evolve and form planetary systems?*
3. Understanding our Origins	•*How did the universe begin?* •*What were the first objects to light up the universe, and when did they do it?* •*How do cosmic structures form and evolve?* •*What are the connections between dark and luminous matter?* •*What is the fossil record of galaxy assembly from the first stars to the present?*
4. Cosmic Order: Stars + Galaxies	•*What controls the mass-energy-chemical cycles within galaxies?* •*How do the lives of massive stars end?* •*What are the progenitors of Type Ia supernovae and how do they explode?*

Imagine 200 more, with >1,000,000 galaxies

(a 20 by 10 foot wall with the resolution of an Apple Thunderbolt Display)

The Hubble Ultra Deep Field (IR)

Imagine this wall of a million galaxies, a single image from AFTA, filling walls of schools and museums and providing a wealth of citizen science.

Figure 2. *a) WFIRST/AFTA uses the H4RG-10 to address some of the most enduring questions in astrophysics (Spergel 2013). b) Like Hubble before it, WFIRST's beautiful, ultra wide-field, high resolution images will inspire legions of young people to pursue science, technology, engineering, and math (STEM) careers. Realizing these dreams requires flying the unprecedentedly large number of NIR pixels that the H4RG-10 makes possible.*

Background

After the diameter of the primary mirror, no component affects the performance of a space observatory more than its detectors. This is particularly true for WFIRST, which was the highest ranked large new space mission in the Nnational Research Council (NRC) *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) Decadal Survey of Astronomy and Astrophysics. The WFIRST SDT left no doubt, singling out the H4RG-10 as the one technology development that holds the most promise for realizing the scientific objectives of New Worlds, New Horizons (Green et al. 2012) in a constrained cost environment. More generally, the H4RG-10 is a broadly enabling new technology for space astrophysics. "Very large format, low noise Optical/IR detector arrays," such as the H4RG-10, are specifically called for in the Cosmic Origins (COR) Program Annual Technology Reports (PATR) for 2011 and 2012.

WFIRST asks big questions. What is dark energy? Is our solar system special? Are the planets around nearby stars like those of our own solar system? How do galaxies form and evolve? These are just a few of the scientific questions that the WFIRST/AFTA chose to highlight (Fig. 2a). WFIRST/AFTA's societal impact will be profound (Fig. 2b). *Hubble* inspired legions of young people to study science, technology, engineering, and math (STEM). For every young student who went on to become a professional astronomer, there are many more working in private industry and government. The H4RG-10 is key to realizing WFIRST's potential.

The H4RG-10 aims to advance the state of the art by significantly reducing the system cost per pixel. For flight hardware, cost-to-orbit scales roughly with mass and volume. To a crude approximation, the size of an astronomical instrument scales with the physical size of the detector. Because an H4RG-10 packs 4 times as many pixels into a package that is only 10% larger than today's state of the art H2RG, pixel-for-pixel an instrument that is built from H4RG-10s costs significantly less than a physically larger and heavier instrument built from H2RGs. At mission level, this translates into significantly more science per dollar.

The H4RG-10 aims to provide better pixels too. Since the H2RG was first introduced to astronomy over 10 years ago, technology has advanced. Today's molecular beam epitaxy mercury cadmium telluride (HgCdTe) growth is better than it was then. We now know how to achieve better passivation for lower residual images, and the H4RG-10 incorporates reference pixel advances that have been gleaned from the James Webb Space Telescope (JWST) program.

The development plan maximizes the synergy between two Strategic Astrophysics Technology (SAT) awards for NIR detector development and directed WFIRST project funding. The focus in year-1 is on building "banded" H4RG-10 prototypes at Teledyne. Already, we have completed growth of all planned HgCdTe layers (Fig. 3). The 16 layers should provide sufficient material to make three to four good H4RG-10s plus a few engineering grade devices that may still be useful for environmental testing. The first eight layers used a JWST-heritage passivation technique and explored HgCdTe doping variations aimed at reducing the read noise. The second batch of eight layers included doping and passivation variations aimed at improving the read noise, persistent charge, and dark current properties of the detector arrays. In year-2, Goddard will begin testing and JPL will begin evaluation for weak lensing using their astronomical scene projector. Some data sets, for example, darks and conversion gain, will be common to both labs, so there will be ample opportunities to cross check results. The focus in year-3 will shift to the environmental testing that is needed for TRL-6; e.g., thermal cycling, vibration, radiation testing, and accelerated life testing.

Objectives and Milestones

Summary Level Description of Objectives

Our objectives are to build several banded H4RG-10s at Teledyne and test these against WFIRST requirements at GSFC and for weak lensing at JPL. The results of these tests will inform a TRL-5 review with the COR Program Office during year 2. If TRL-5 is achieved during year-2, we will make additional flight-representative H4RG-10s with all pixels having the same design. These will be used for more testing at Goddard and JPL. After TRL-5, testing will include the environmental testing that is needed for TRL-6. Prior to completion of a fully successful program, we will coordinate a TRL-6 review with the COR Program Office.

To enable testing many design variations within the cost and schedule constraints of the SAT program, we are using “banded arrays” for the initial demonstration. In a banded array, Teledyne divides the Sensor Chip Assembly (SCA) area up into “bands” (e.g., eight 512 × 4096 pixel bands) to characterize several design variations in each SCA. Each band serves much the same function as a lot split. Although most astronomers will be more familiar with traditional SCAs, in which all pixels use the same design, banded arrays have a lot of heritage for detector development.

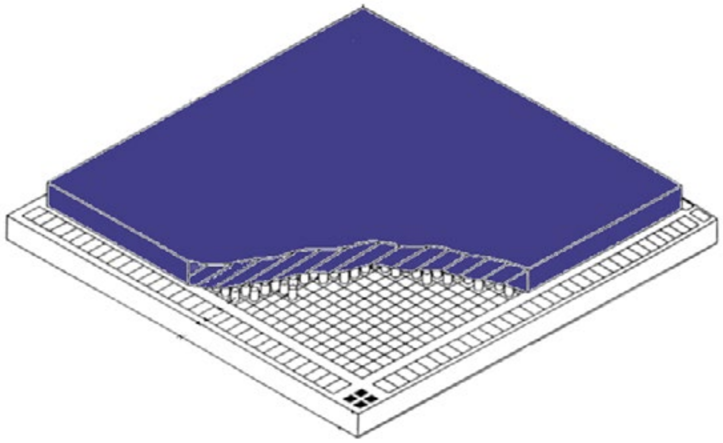


Figure 3. *In a NIR hybrid detector array, the detector layer (top) is attached to the silicon readout (bottom) by small indium interconnects. There is one indium interconnect per pixel.*

Key Milestones

The Year-1 funding is known for both SATs and the WFIRST project. In years 2 and 3, we will coordinate with the WFIRST project to work within the WFIRST funding profile and two SATs.

Year 1 Milestones:

- Feb 2013 Teledyne contract mod in place
- March 2013 H4RG-10 HgCdTe growth starts
- April 2013 H4RG-10 HgCdTe growth complete
- Sept 2013 First banded H4RG-10s to be delivered to Goddard

Year 2 Milestones: (Dates are to be determined and are contingent upon WFIRST project funding)

- Testing begins at Goddard
- Weak lensing emulation testing begins at JPL
- Deliver TBD additional banded H4RG-10s to GSFC
- Demonstrate pixel interconnect operability requirement met for a full H4RG-10
- By end of calendar year, demonstrate by test that a 1-megapixel band meets WFIRST performance requirements

Year 3 Milestones: (Dates are TBD and contingent upon WFIRST project funding)

- TRL-5 review with COR Program Office
- Deliver first non-banded H4RG-10 to Goddard
- TRL-6 testing begins at Goddard
- Weak Lensing characterization document delivered by JPL
- By end of calendar year, demonstrate TRL-6

Changes Since Project Kickoff

There have been several important changes since kickoff. Most importantly, the COR Program Office asked us to coordinate the two SAT awards for WFIRST detectors with the WFIRST Project Office. The resulting synergy allows us to aim for TRL-6 rather than TRL-5 as was originally proposed. The combined project addresses all of the aims of both the GSFC and Teledyne SAT awards.

Progress and Accomplishments

We started the 3-year project in November 2012. Our first accomplishment was to re-phase the work plan to make more H4RG-10 detectors (incorporating the design optimizations that Teledyne proposed in their SAT), and to do so as early in the project as possible. The re-phasing shifted most year-1 funding to Teledyne for detector production, and most year-2 funding to Goddard and JPL for testing. Building an NIR array detector is a multi-step process. In June 2013, we completed the first major step, which is the growth of 16 HgCdTe detector layers. This is the photosensitive material that converts light into voltages that can be sensed electronically. Based on prior NASA experience working with Teledyne, this should be sufficient to yield three or four good detectors for testing versus WFIRST requirements. To meet our year 2 milestones, we need to produce an H4RG-10 pixel design that meets WFIRST performance requirements in a large, contiguous area. To advance from TRL-5 to TRL-6, we need to show by test that a fully functional H4RG-10 design meets WFIRST environmental requirements.

Parameter	WFIRST Requirement
Bandpass (µm)	0.6 - 2.1
Dark current (e^-/s/pixel)	< 0.05
Interconnect operability	> 98%
Read noise per CDS (e^- rms)	<15
Quantum efficiency2	> 70%, $\lambda < 1.5$ µm > 85%, $\lambda > 1.5$ µm
Charge persistence	< 0.1%
Crosstalk	< 1%

Path Forward

The path forward is to deliver banded H4RG-10s to Goddard starting in September 2013. These will enter performance testing at Goddard versus WFIRST requirements for read noise, dark current, quantum efficiency, linearity, and persistence, etc. The table above lists some of the driving requirements. This table is taken from our original SAT proposal. In parallel, JPL will begin evaluating the banded H4RG-10s for weak lensing using an astronomical scene projector. This will naturally generate some additional data sets that will overlap with those taken at Goddard, creating valuable opportunities to crosscheck results.

If we produce one or more bands that meet WFIRST requirements, we will begin to prepare for a TRL-5 review with the COR Program Office. Assuming that TRL-5 is achieved, Teledyne will make additional non-banded H4RG-10s. These will be tested versus WFIRST performance requirements as full SCAs. Low performing detectors, which are deemed engineering grade, will be used for the environmental testing that is needed for TRL6. If testing shows that the H4RG-10s meet both performance and environmental requirements, we will coordinate a TRL-6 review with the COR Program Office.

If TRL-5 is not achieved in the first lot of detectors, we will continue making banded arrays until TRL-5 is achieved. In this case, Teledyne's models would inform the new detectors along with the detector physics knowledge of the team. This process would be informed every step of the way by careful testing at GSFC and JPL.

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High Efficiency Detectors in Photon-Counting and Large Focal Plane Arrays for Astrophysics Missions

Prepared by: Shouleh Nikzad (Jet Propulsion Laboratory)

Summary

Future ultraviolet (UV)/optical large-aperture telescopes will require high quantum efficiency (QE), low-noise, large-format, space-qualified UV detectors. Future medium-class concepts (probes) could be furnished with flagship-class science capabilities if the large shortfalls in detector performance were made up. Recognizing this fact, the NASA Advisory Committee/Astrophysics Subcommittee charged the Cosmic Origins Program Analysis Group (COPAG) with assessing technology priorities. The COPAG, in its 2012 Technology Assessment, judged that UV photon-counting detectors with large formats and low noise were *mission enabling* and, therefore, the highest priority. The 2012 Cosmic Origins (COR) Program Annual Technology Report (PATR) made a similar finding. Because future frontier UV capabilities will exploit high-resolution, wide-field, highly multiplexed imaging spectroscopy and wide-field high angular resolution imaging, the key detector performance requirements are high efficiency, low noise, and large, scalable formats. A detector that is capable of providing a factor of 3–10 improvement in UV efficiency over those in the *Hubble Space Telescope* (HST) must do so without introducing a commensurate increase in noise.

Our team recently demonstrated high QE, solid-state, UV photon-counting arrays in a small format by applying Jet Propulsion Laboratory's (JPL) back illumination processes including thinning, delta doping technology [Hoenk1992a, Nikzad1994, Blacksberg2008, Hoenk2011, Nikzad2012], and advanced antireflection (AR) coatings using atomic layer deposition (ALD) [Hamden2011, Nikzad2012] to commercially available Electron Multiplied Charge-Coupled Devices (EMCCD) [Jarram2001, Hynecek2001]. Using molecular beam epitaxy (MBE) and ALD to achieve atomic-scale control over the device surface and film interfaces, JPL's technology is unique in producing silicon detectors with exceptional stability and world-record QE (50–80%) throughout the UV–see Figure 1 [Nikzad2012] and [Hamden2012]. The performance of this Solid-state Photon-counting Ultraviolet Detector (SPUD) represents a breakthrough in single photon counting UV detectors.

In this 3-year program, which began in mid-January 2013, we will further develop these high-efficiency solid-state photon-counting UV detectors and advance the technology through the following steps: 1) Increasing detector format size in response to the requirements of future missions for large pixel count, 2) Characterizing the detector noise performance in realistic spectroscopic and imaging applications, 3) On-sky validation over a wide range of flux levels using astrophysical imaging and spectroscopic instruments, and 4) Flight testing of the detector on the synergistic Faint Intergalactic Redshifted Emission Balloon (FIREBALL) balloon experiment–flight accommodation and operations are already funded by the Advanced Research Projects Agency (APRA)–during a 2015 launch. In this effort, we will also be demonstrating the manufacturability, versatility, and reliability of back-illuminated delta-doped high-efficiency silicon imagers in photon counting and other platforms, such as devices designed for broadband detection. This latter objective takes advantage of the development of the past 3 years of high-throughput processes for delta doping using JPL's new 8-inch wafer capacity silicon MBE at JPL and the associated techniques to produce high-efficiency detectors (Figure 1).

This technology maturation plan will create a routine and reliable source for production of high-efficiency and innovative UV/optical detector arrays for the community. The versatile and robust fabrication techniques presented can have a major impact on future instrument capabilities and scientific discoveries.

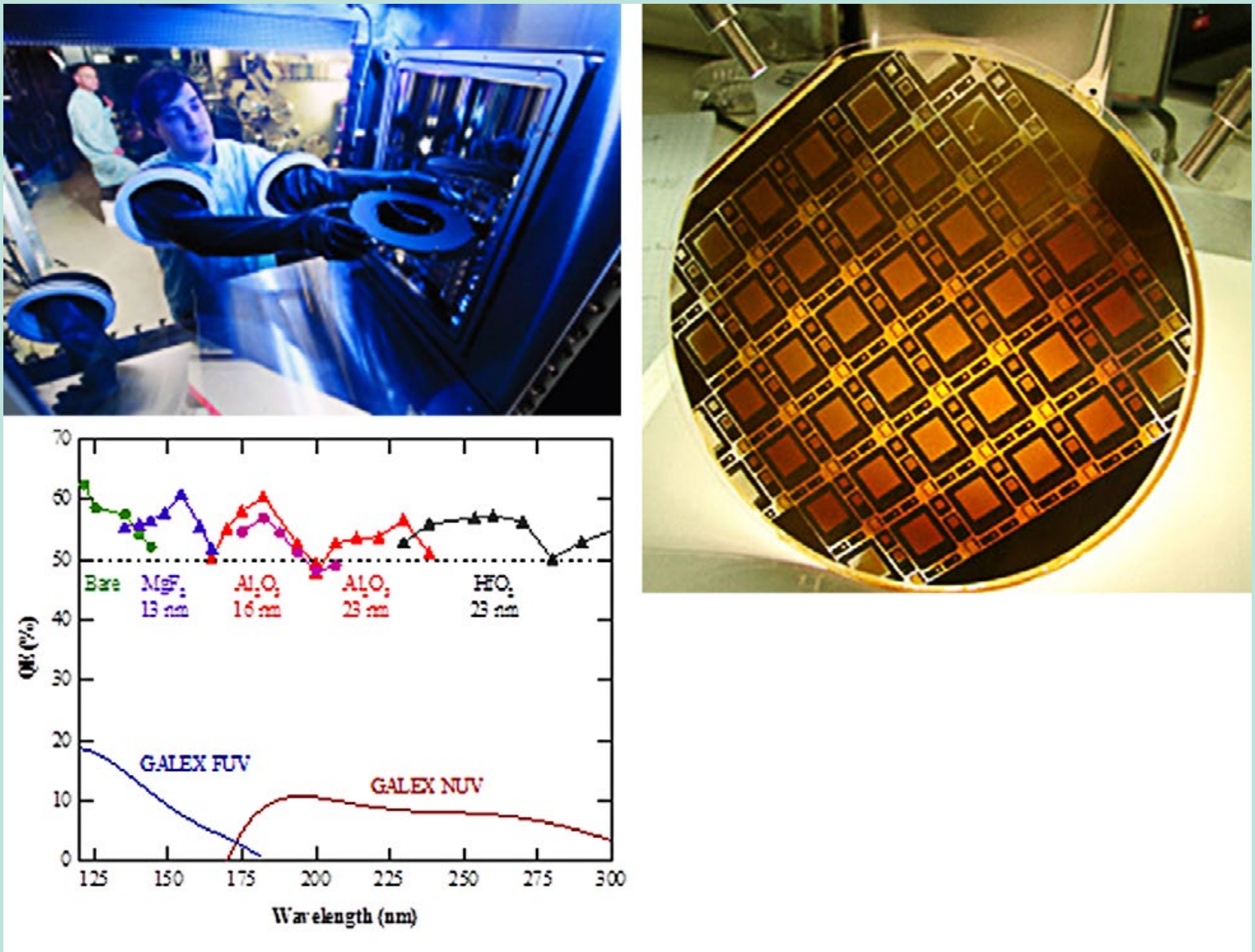

Figure 1. *Facilities with large wafer capacity at JPL (above, left) for high throughput delta doping of the state of the art Charge-Coupled Device (CCD) and complementary metal-oxide semiconductor (CMOS) imagers. Silicon imagers can be processed for back illumination as 150-mm wafers in these facilities. Shown on the right is a photograph of an 8-inch wafer with CMOS imagers ready for delta doping. The wafer is thinned using the end-to-end post-fabrication processing facilities at JPL. Below left shows the world record QE achieved by applying this end-to-end processing. The QE of ALD-AR coatings on delta-doped CCDs in the 120–300 nm wavelength range is above 50% for the entire range (above left). All data are obtained for n-channel low-noise 1k × 1k CCDs. Magenta circles are data obtained from delta-doped and AR-coated 0.5 megapixel EMCCDs. For comparison, microchannel plate (MCP)-based Galaxy Evolution Explorer (GALEX) detectors with cesium iodide (CsI) photocathodes (far ultraviolet, or FUV) and cesium telluride (Cs2Te) (near ultraviolet, or NUV) photocathodes have been plotted. A factor of 5–15 improvement over this detector performance has been demonstrated.*

This development is a team effort with JPL (Drs. Shouleh Nikzad and Michael Hoenk and team), the California Institute of Technology (Caltech) (Prof. Chris Martin and group), Columbia University (Prof. David Schiminovich and group), and Arizona State University (ASU) (Paul Scowen and group). The team's complementary expertise in materials, detectors, instrument building, and observational science allows us the unique capability to carry out the objectives of this effort.

Background

The National Research Council's Decadal Survey for Astronomy and Astrophysics, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) (Blanford et al., 2010) recommends, as a priority, path-finding work toward a 4-meter+ UV/optical flagship mission as a successor to HST. Also anticipated is great emphasis on Explorer missions in this decade.

The COPAG evaluates and recommends technology investments toward the large-aperture UV/optical telescope, and the Exoplanet Program Analysis Group (ExoPAG) has also embraced this recommendation. In both of these scientific focus areas, high efficiency, high angular and spectral resolution, and single photon counting are priorities. Furthermore, these recommendations set as a goal very large format (>100 megapixel) high QE, UV-sensitive detectors. Frontier astrophysical investigations are necessarily conducted at the limits of resolution, etendue, and sensitivity. The NWNH recommendations reflect the new scientific opportunities enabled by technological breakthroughs in large-scale detector fabrication.

A future 4-m+ UV/optical telescope mission will require significant detector advances beyond HST, GALEX, and Far Ultraviolet Spectroscopic Explorer (FUSE) detector technologies, particularly in QE, spectral responsivity in the UV, resolution, and pixel count. Our primary performance metric, detector UV QE, represents a dramatic increase (5–10×) over previous missions (Figure 1). Dramatically increasing the efficiency of the detectors could allow Explorer-class or Probe-class missions to perform Flagship mission science.

A solid-state detector with high efficiency and photon counting offers scalability and reliability that are necessary and attractive features for reliable, high performance and cost effective instruments. Because of its greatly improved QE, low background, photon-counting, and large formats, SPUD will enable high-efficiency high-resolution UV absorption-line spectroscopy, faint-sky intergalactic medium (IGM) emission spectroscopy, multi-object and imaging UV spectroscopy, and efficient wide-field UV/optical imaging, at the Explorer, Probe, and Flagship scales. SPUD optimized for visible light would enable integral field spectroscopy required for exoplanet characterization, which must be photon-counting because of the low background in space for diffraction-limited optical spectroscopy.

SPUD optimized for visible light would enable integral field spectroscopy required for exoplanet characterization, which must be photon-counting because of the low background in space for diffraction-limited optical spectroscopy.

The detector technology discussed here represents an example of the power of the technology. The QE and response stability of our single photon counting UV detector can be applied to practically any silicon imager architecture that might be called for in the next generation of instruments and applications. Our effort is a direct response to the needs of future NASA missions, including the NWNW (also known as the Astro2010 Decadal Survey) recommendations for a 4-m UV/optical telescope and UV detector and coatings technologies. This effort directly responds to the Strategic Astrophysics Technology (SAT) call for high QE, large format, photon counting, and ultralow noise detectors. The ALD films developed under this effort also advance the UV coatings for optics. Because of the dramatic efficiency increase in the detector, *Hubble*-class science will be possible with smaller-size apertures. This effort is likely to have a great impact on future Probe- and Explorer-class missions.

Objectives and Milestones

Milestone	**Year 1**				**Year 2**	**Year 3**
	Q1	Q2	Q3	Q4		
Demonstrate Large format SPUD and other Delta-doped Silicon Imagers						
Procure wafers of standard larger format EMCCDs	Δ					
Thin, bond, Delta dope, and AR coat (iterative)		Δ		Δ	Δ	
Incorporate sample AR coatings					Δ	
Characterize device functionality and QE		Δ			Δ	Δ
Validate by system level evaluation on sky and suborbital						
Disseminate devices to partners for evaluation & feedback					Δ	
Deploy for On-sky Observation, evaluation						Δ
Deploy for suborbital (funded balloon FIREBALL)						Δ
Demonstrate Manufacturability and Versatility of Process						
Establish throughput and yield by testing devices produced in multiple wafers						
Demonstrate process on high purity large-format CCD						

Demonstrate detector in large format, i.e., from 0.5-megapixel format to 2-megapixel format (FY13 Q3-Q4)

Measure detector QE, noise, and its performance for spectroscopic and imaging applications (first results in FY14 Q1)

Advancing the manufacturability and reliability of SPUD and as a byproduct for other high-efficiency silicon imagers. Revised the number of wafers that will be procured and revised the associated processing workforce. A reduced number (~5) of wafers of SPUD and other silicon imagers (e.g., full depletion, delta-doped and AR-coated wafers) will be processed. (Iterative, first results in FY14 Q4)

Performing environmental tests of the detector (Thermal: FY14 Q3, Radiation: FY15 Q4)

On-sky validation over a wide range of flux levels using astrophysical imaging and spectroscopic instruments (FY15 Q1)

Flight testing of the detector on the synergistic and balloon experiment FIREBALL (FY15 Q3)

Progress and Accomplishments

Excellent progress has been made in all major objectives. The major accomplishments are listed below:

Because of the revised funding profile, we in turn needed to revise the subcontract values. To that end, we requested and received revised statements of work (SOWs) from two of the university partners. One university is under contract and work is under way to send funds to the other two universities.

We have selected and procured the electron-multiplied array wafers from the vendor. Wafers were fabricated and we have received, inspected, and prepared these device wafers. Processing has commenced by bonding of the device wafers to handle the wafers prior to thinning. This bonding step allows the wafers to be thinned down to about 8–10 microns. We have prepared our thinning setup to begin for thinning the wafers once the bonding is completed.

We continued the development on small arrays to both save time and funds while in parallel working on larger arrays. We fabricated small (0.5 megapixel) AR-coated (single layer), delta-doped electron-multiplied CCDs to use for basic testing and AR coating developments.

We performed the maintenance work on the Molecular Beam Epitaxy (MBE) in order to prepare for delta doping of the wafers once they are bonded and thinned.

We performed modeling of the multilayer AR coatings for improvement of the QE that can be obtained in the narrowband balloon window around 200 nm.

Using ALD, we deposited films on bare wafers and on small delta-doped arrays. Characterizing these devices showed good QE, but we also detected a shift in the peak position. A number of experiments were performed by depositing ALD on silicon substrates and dielectric layers to determine the source of the shift in the peak position. Based on data obtained in these experiments, it was determined that the film nucleation was delayed when the substrate (or the underlying layer) was aluminum oxide as opposed to silicon. Using these findings, we recalibrated the ALD system and devised a process to hit the right position for the peak of the response.

A new ALD system was received, installed, and commissioned at JPL. Process transfer and development have commenced on the new ALD system. ALD is used in this task to produce an AR coating. The previous, older ALD also went through maintenance and repair and is online. The new ALD system has higher capacity for more films and has a more efficient plasma process and better thermal control. A few multilayer films for broadband coatings were deposited on blank wafers and devices and testing is pending.

Testing of the small (0.5 megapixel) AR-coated (single layer), delta-doped electron-multiplied CCDs showed very good agreement in position of peaks in the QE. To ensure absolute QE measurements, the characterization setup was put through recent calibration.

We hosted a visit from the COR technology group (Advanced Concepts and Technology Office Chief Technologist and Astrophysics Division Chief Technologist) at JPL to discuss the objectives and status of this task.

Abstracts were submitted to the International Society for Optical Engineering (SPIE) Optics and Photonics and were accepted for oral presentations. A paper is also under preparation for submission to Applied Optics on the subject of narrowband, ALD-AR coatings.

Our effort has graduate student involvement from Caltech, Columbia University, and ASU. Their work on this project forms a major part of their theses. Graduate student Erika Hamden from Columbia University visited JPL for shorter periods, three times in the past 6 months in order to produce AR-coated samples and to interact with the JPL team. She plans an extended stay in August 2013. Graduate student Alex Miller (Arizona State University) has begun an extended stay this summer to work on the characterization of detectors. He will take this knowledge back to ASU and will modify the test setup to accept the detectors under development in this task.

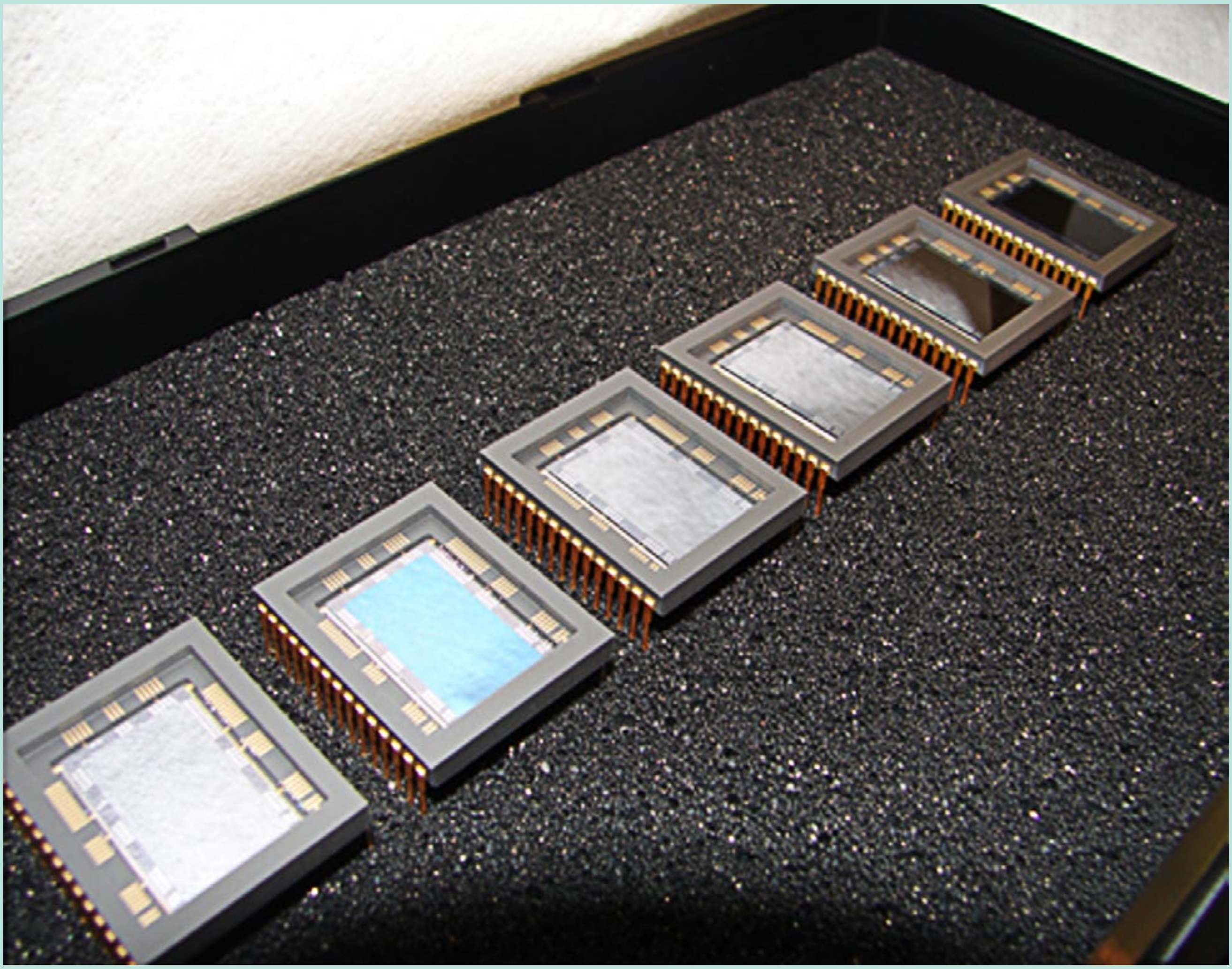

Figure 2. *This photograph shows 0.5-megapixel high-efficiency detectors produced by thinning and delta doping at the wafer level. Three of the detectors are AR coated for various bands, including one device with the multilayer coatings for the 200-nm atmospheric window of the balloon. Preliminary measurements show an 80% QE.*

Path Forward

We will complete the first round of processing of the first 2-megapixel arrays by processing the first wafer (first iteration). We will evaluate and characterize the QE and noise and uniformity of devices from the first wafer. Collaborators at Caltech will further characterize single photon counting devices and evaluate them for the flight of FIREBALL. Collaborators at ASU will take the broadband delta-doped detectors for on-sky observation to evaluate them for realistic astrophysics signal levels. We will process more wafers that incorporate feedback from this in-depth characterization in order to improve processes if needed. As we process multiple wafers, we will demonstrate the throughput and yield of the detectors. By applying the techniques to single photon counting platforms and other designs, we demonstrate versatility of our processes.

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New COR SAT for 2014 Start
Advanced Mirror Technology Development Phase 2

Abstract submitted by: H. Stahl (MSFC)

Our objective is to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified Ultraviolet/Optical/Infrared (UVOIR) mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review. As identified by Astro2010, a new, larger UVOIR telescope is needed to help answer fundamental scientific questions, such as whether there is life on Earth-like exoplanets; how galaxies assemble their stellar populations; how baryonic matter interacts with the intergalactic medium; and how solar systems form and evolve. Advanced UVOIR Mirror Technology Development (AMTD-1) was a first step. Thus far, we have achieved all our goals and accomplished all our milestones. We did this by assembling an outstanding team (from academia, industry, and government with extensive expertise in UVOIR astrophysics and exoplanet characterization, and in the design/manufacture of monolithic and segmented space telescopes); by deriving engineering specifications for advanced normal incidence mirror systems needed to make the required science measurements; and, by defining and prioritizing the most important technical problems to be solved. We successfully demonstrated a new process for making 400-mm deep-core UVOIR mirrors, by making a 43-cm cut-out of a 150 Hz 4-m mirror and polishing it to <6 nm rms. We have also developed new, fast, and powerful integrated design and modeling capabilities. AMTD Phase 2 (AMTD-2) is the next step toward our goal. We have expanded our team to add expertise. Based on our Phase 1 results and Cosmic Origins (COR) Program Office (PO) guidance, we are focusing our efforts on three clearly defined next steps:

- Fabricate a scale model of 4-m class 400-mm thick deep-core Ultra-Low Expansion (ULE®) mirror. The purpose of this mirror is to demonstrate lateral scaling of the deep-core process to a larger mirror.
- Qualify two candidate mirrors (the #-scale mirror and a 1.2-m Extreme Lightweight Zerodur Mirror owned by Schott) by characterizing their optical performance from 250 K to ambient, and exposing them to representative vibration and acoustic launch environments.
- Continue to add capabilities to our integrated design and modeling tools to predict the thermal, vibration, and acoustic behavior of the candidate mirrors; validate our models; generate Pre-Phase-A point designs; and predict on-orbit optical performance–Point Spread Function (PSF), Jitter, Encircled Energy, Wavefront Error, Modulation Transfer Function (MTF), etc.

By the end of this 3-year effort, the TRL to design and built 4-m or larger primary mirror assemblies will have advanced by at least a half step by accomplishing specific, quantifiable engineering milestones traceable to science requirements. AMTD-1 demonstrated the ability to make a 400-mm deep mirror, at the 0.5-m scale, traceable to a UVOIR 4-m mirror (<6 nm rms surface figure on a 60 kg/m2 mirror). AMTD-2 will demonstrate that the deep-core process scales to ~1.5-m and will qualify two ~1.5-m class mirrors. AMTD-2 is the next step on the path toward advanced UVOIR telescopes that, once formulated, designed, and built, will extend humanity's insight into many of the fundamental questions NASA has been tasked to answer.

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New COR SAT for 2014 Start
A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping

Abstract submitted by: Imran Mehdi (JPL)

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. A number of large spatial surveys using the *Herschel* Photodetector Array Camera and Spectrometer (PACS) and Spectral and Photometric Imaging Receiver (SPIRE) photometers have determined that the dust emission is filamentary in nature at all scales that have been observed. In spite of the universality of the dust structures, large differences in the rates of star formation are observed. The physical processes that give rise to this structure and facilitate the onset of star formation remain the subject of a contentious debate between the effects of turbulence and magnetic fields. Another important open question is the transition between the atomic and molecular phases of the diffuse interstellar medium (ISM) and how this process determines the characteristics of denser material and how in turn this affects the star formation rate. The velocity structure of atomic and ionized gas associated with dense regions remains largely unknown and can only be obtained through spectroscopy. Separation of components of the ISM requires velocity-resolved atomic, ionic, and molecular line profiles. The recent Decadal Survey has highlighted questions that will require heterodyne technology to resolve–i.e., 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 what controls the mass-energy-chemical cycles within galaxies? The focus of this proposal would be to demonstrate a working 16-pixel heterodyne array receiver system. Most components for this system have been demonstrated but a full 16-pixel system needs to be tested to bring this technology to TRL 5. This receiver system enables science beyond the Heterodyne Instrument for the Far Infrared (HIFI) for the next generation of heterodyne instruments on platforms like the *Stratospheric Observatory for Infrared Astronomy* (SOFIA).

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Appendix C
Acronyms, Chemical Elements, and Units

Acronyms

4D	Four Dimensional
ADC	Analog-to-Digital Converter
AFTA	Astrophysics Focused Telescope Assets
AIP	*Astrophysics Implementation Plan*
ALD	Atomic Layer Deposition
AMTD	Advanced Mirror Technology Development
APRA	Astrophysics Research and Analysis
AR	Antireflection
ARC	Ames Research Center
ASIC	Application Specific Integrated Circuit
ASU	Arizona State University
Caltech	California Institute of Technology
CCAT	Cerro Chajnantor Atacama Telescope
CCD	Charge-Coupled Device
CEB1	CSAv1 Evaluation Board
CEB2	CSAv2 Evaluation Board
CMOS	Complementary Metal-Oxide Semiconductor
COBE	*Cosmic Background Explorer*
COPAG	Cosmic Origins Program Analysis Group
COR	Cosmic Origins
COS	Cosmic Origins Spectrograph
CSA	Charge Sensitive Amplifiers
CSO	Caltech Submillimeter Observatory
CTE	Coefficient of Thermal Expansion
DAC	Digital-to-Analog Converters
DFRC	Dryden Flight Research Center
DLR	German Aerospace Center
DRIE	Deep Reactive Ion Etching
DSB	Double Sideband
EE	Electrical Engineering
EELV	Evolved Expendable Launch Vehicle
EMCCD	Electron Multiplied Charge-Coupled Devices
ESA	European Space Agency
EUV	Extreme Ultraviolet
ExEP	Exoplanet Exploration Program
ExoPAG	Exoplanet Program Analysis Group
Far-IR	Far Infrared
FEM	Finite Element Model
FIREBALL	Faint Intergalactic Redshifted Emission Balloon
FPGA	Field Programmable Gate Array
FTS	Fourier Transform Spectroscopy
FUSE	*Far Ultraviolet Spectroscopic Explorer*
FUV	Far Ultraviolet
FWHM	Full-Width Half-Maximum
FY	Fiscal Year
GALEX	*Galaxy Evolution Explorer*
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*
HV	High Voltage
IBM	International Business Machines
IBS	Ion Beam Sputtering
IF	Intermediate Frequency
IGM	Intergalactic Medium
IR	Infrared
IRAS	Infrared Astronomical Satellite
ISM	Interstellar Medium
JAXA	Japanese Aerospace Exploration Agency
JFET	Junction Field-Effect Transistor
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
JWST	*James Webb Space Telescope*
KID	Kinetic Inductance Detectors
LISM	Local Interstellar Medium
LO	Local Oscillator
LVDS	Low Voltage Differential Signal
MBE	Molecular Beam Epitaxy
MCP	Microchannel Plate
MDL	Micro Devices Laboratory
Mid-IR	Mid-Infrared
MKID	Microwave Kinetic Inductance Detectors
MSFC	Marshall Space Flight Center
MTF	Modulation Transfer Function
MUX	Multiplexer
NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
Near-IR	Near-Infrared
NEP	Noise-Equivalent Power
NIR	Near-Infrared
NPR	NASA Procedural Requirements
NRC	National Research Council
NSF	National Science Foundation
NWNH	*New Worlds, New Horizons in Astronomy and Astrophysics*
NUV	Near Ultraviolet
OAO-3	*Orbiting Astronomical Observatory 3*
OCT	Office of the Chief Technologist
ORFEUS	Orbiting Retrievable Far and Extreme Ultraviolet Spectrometer
PACS	Photodetector Array Camera and Spectrometer
PATR	Program Annual Technology Report
PCB	Printed Circuit Board
PI	Principal Investigator
PMA	Primary Mirror Assembly
PO	Program Office

PSF	Point Spread Function
PVD	Physical Vapor Deposition
PXS	Parallel Cross Strip
QE	Quantum Efficiency
RF	Radio Frequency
RFE	Receiver Front Ends
RFI	Request for Information
RIBS	Reactive Ion-Beam Sputtering
ROIC	Readout Integrated Circuits
SAFIR	*Single Aperture Far Infrared Observatory*
SAT	Strategic Astrophysics Technology
SBIR	Small Business Innovation Research
SCA	Sensor Chip Assembly
SCUBA-2	Submillimetre Common-User Bolometer Array-2
SDT	Science Definition Team
SFO	Star Formation Observatory
SHARC-2	Submillimeter High Angular Resolution Camera 2
SIOSS	*Science Instruments, Observatory and Sensor Systems Roadmap*
SMA	Sub-Miniature version A
SMD	Science Mission Directorate
SMEX	Small Explorer
SNR	Signal-to-Noise Ratio
SOA	State-of-the-Art
SOFIA	*Stratospheric Observatory for Infrared Astronomy*
SOW	Statement of Work
SPICA	*Space Infrared Telescope for Cosmology and Astrophysics*
SPIRE	Spectral and Photometric Imaging Receiver
SPUD	Solid-state Photon-counting Ultraviolet Detector
SQUID	Superconducting Quantum Interference Device
SR&T	Supporting Research and Technology
SSB	Single Sideband
STEM	Science, Technology, Engineering, and Math
STMD	Space Technology Mission Directorate
STScI	Space Telescope Science Institute
TCOP	Technology Development Section for the Cosmic Origins Program
TES	Transition Edge Sensor
TMB	Technology Management Board
TRL	Technology Readiness Level
ULE	Ultra-Low Expansion
UC	University of California
USNO	U.S. Naval Observatory
UV	Ultraviolet
UVOIR	Ultraviolet/Optical/Infrared
VNIR	Visible to Near Infrared
VUV	Vacuum Ultraviolet
WFIRST	*Wide Field Infrared Survey Telescope*
WISE	*Wide-field Infrared Survey Explorer*
XS	Cross Strip

Chemical Elements

Al	Aluminum
AlF_3	Aluminum Fluoride
Al/LiF	Aluminum/Lithium Fluoride
Al/MgF_2	Aluminum/Magnesium Fluoride
Al_2O_3	Aluminum Oxide
Ar	Argon
C+	Carbon+
CII	Singly Ionized Carbon
Ca II	Singly Ionized Calcium
CF4	Freon®
CH	Methylidyne Radical
CO_2	Carbon Dioxide
Cs2Te	Cesium Telluride
CsI	Cesium Iodide
Cu	Copper
D	Deuterium
FS	Fused Silica
GaN	Gallium Nitride
GdF_3	Gadolinium fluoride
^3H	Helium-3
H	Hydrogen
H_2	Dihydrogen
H_2O	Water
HD	Deuterated Hydrogen
HgCdTe	Mercury Cadmium Telluride
InSb	Indium Antimonide
Ir	Iridium
K	Potassium
Kr	Krypton
LaF_3	Lanthanum Fluoride
LiF	Lithium Fluoride
LuF_3	Lutetium Trifluoride
MgF_2	Magnesium Fluoride
NII	Singly Ionized Nitrogen
Na_3AlF_6	Sodium Hexafluoroaluminate
OI	Neutral Oxygen
Pt	Platinum
Pt-Ne	Platinum Neon
Si	Silicon
SiC	Silicon Carbide
SiO_2	Fused Silicon
TiN	Titanium Nitride
W	Tungsten
Xe	Xenon

Units

Å	Angstroms
C	Celsius
cm	Centimeters
cm^2	Centimeters Squared
°	Degrees
e^-	Electrons
GHz	Gigahertz
Hz	Hertz
k	Kilo, or Thousand
K	Kelvin
kg	Kilograms
kHz	Kilohertz
km/s	Kilometer per Second
kW	Kilowatt
λ	Wavelength
m	Meters
m^2	Meters Squared
mA	Milliamp
mas	Milliarcsecond
mK	Millikelvin
mm	Millimeters
µm	Micrometers, or Microns
µW	Micro Watts
MHz	Megahertz
nm	Nanometers
pF	Pico Farad
rms	Root Mean Square
s	Seconds
sccm	Standard Cubic Centimeters per Minute
THz	Terahertz
V	Volts
W	Watts