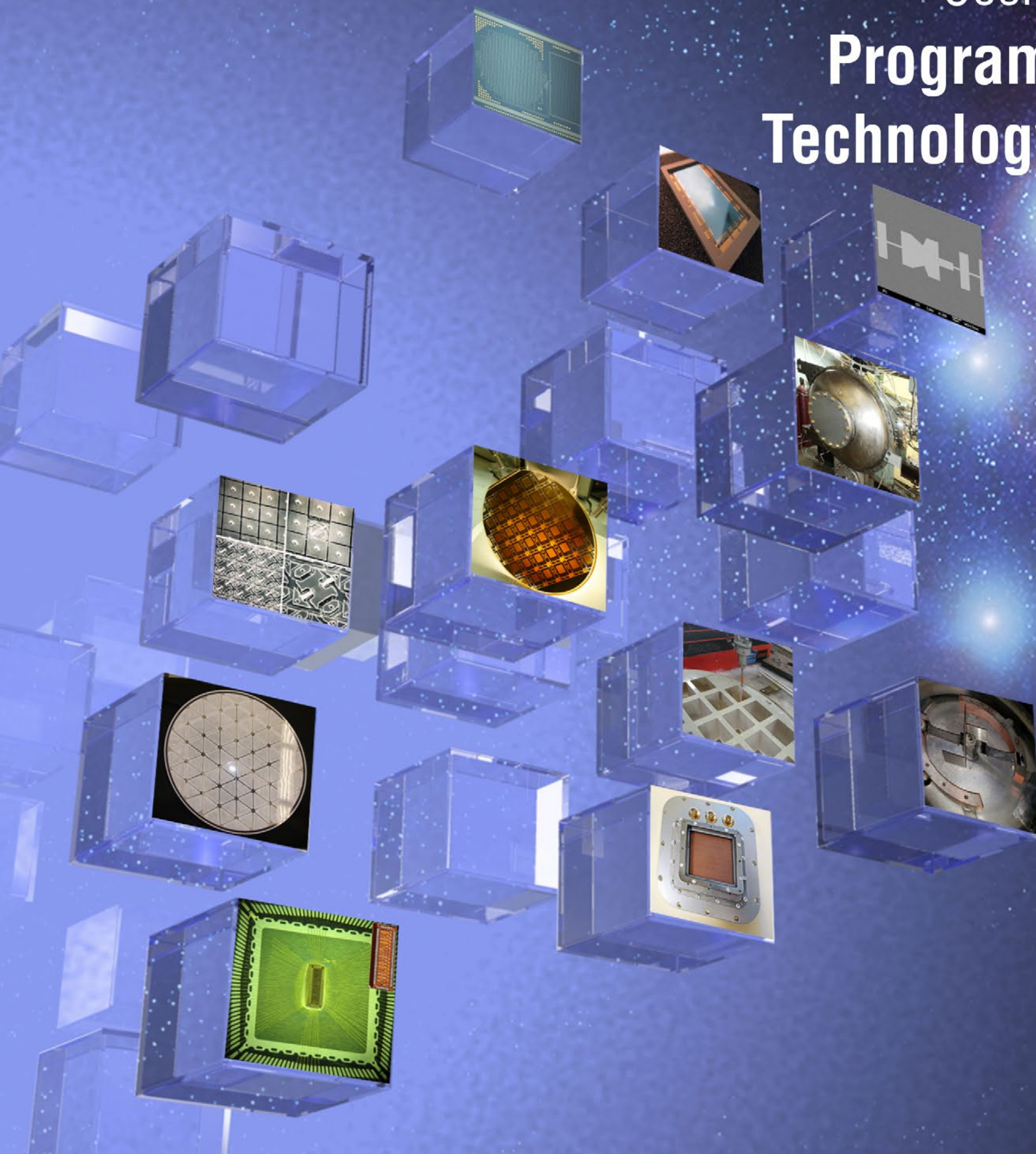
National Aeronautics and Space Administration

Cosmic Origins

Program Annual Technology Report



Cosmic Origins
Program Office
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Executive Summary

What is the Cosmic Origins Program?

From ancient times, humans have looked up at the night sky and wondered. Are we alone? How did the universe come to be? How does the universe work? The second question is the focus of NASA's Cosmic Origins (COR) Program. Scientists investigating this broad theme seek to understand the origin and evolution of the universe from the Big Bang to the present day, determining 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 through the birth and eventual death of all subsequent generations of stars. The COR Program's purview includes the majority of the field known as astronomy, from antiquity to the present.

One surprising result was the recent discovery that the universe is expanding at an ever-accelerating rate, the first hint of what we now call dark energy. This mysterious entity appears to account for 75% of the mass-energy in the universe. Another 20% is dark matter, so called because it is non-luminous and cannot be directly observed, so we only see it through its effects on regular matter, which comprises only 5% of the total. Another recent discovery was that special polarization in the cosmic microwave background supports the notion that in the split-second after the Big Bang, the universe inflated faster than the speed of light! This doesn't defy Einstein's Theory of Relativity since space itself was expanding, and no matter or energy was moving through space faster than light. The most exciting aspect of this grand enterprise today is that we're finally able to develop the tools needed to make such discoveries.

Why is COR Technology Development Critical?

A 2008 Space Review paper noted that a robust technology development and maturation program is crucial to reducing flight project schedule and cost over-runs: "*…in the mid-1980s, NASA's budget office found that during the first 30 years of the civil space program, no project enjoyed less than a 40% cost overrun unless it was preceded by an investment in studies and technology of at least 5 to 10% of the actual project budget that eventually occurred*" [1]. Such a technology maturation program is most efficiently addressed through focused R&D projects, rather than in the framework of flight projects, where "marching armies" make the cost of delays unacceptably high.

The 2010 Decadal Survey, New Worlds, New Horizons in Astronomy and Astrophysics (NWNH) stressed that "*Technology development is the engine powering advances in astronomy and astrophysics, from vastly extending the scientific reach of existing facilities to opening up new windows on the universe. All of the Astro2010 PPPs [Program Prioritization Panels] emphasized the critical importance of technology development, and each stressed the urgent need to augment existing funding levels to realize important programs essential to reducing the technical, cost, and schedule risk of planned missions. Mission- or project-specific technology development must reach an acceptable level before accurate costs can be determined, priorities set, and construction scheduled. Failure to develop adequately mature technology prior to a program start also leads to cost and schedule overruns*" [2].

Due to such considerations, NASA requires flight projects demonstrate technology readiness level (TRL) 6* for all technologies they need by Preliminary Design Review (PDR). However, this requirement can only succeed if it relies on a process that correctly identifies and adequately funds development of relevant "blue sky" investigations to TRL 3†, and matures technologies to TRL 5‡, or 6, addressing the so-called "mid-TRL gap." These technologies then enable robust mission concepts, allowing the community to focus on proposed missions' scientific relevance in their strategic planning.

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* TRL 6: "System/sub-system model or prototype demonstration in a relevant environment." NPR 7123.1B, Appendix E.
† TRL 3: "Analytical and experimental critical function and/or characteristic proof-of-concept." NPR 7123.1B, Appendix E.
‡ TRL 5: "Component and/or breadboard validation in relevant environment." NPR 7123.1B, Appendix E.

NASA Headquarters (HQ) Science Mission Directorate (SMD) Astrophysics Division set up three program offices to manage all aspects of the three focused astrophysics programs. The Program Offices shepherd critical technologies toward the goal of implementation into program-relevant flight projects. These offices follow Astrophysics Division guidance, and base their recommendations on science community input, ensuring the most relevant technologies are solicited and developed. The COR Program Office, located at NASA's Goddard Space Flight Center (GSFC), serves as HQ's implementation arm on COR Program-related matters. The Astrophysics Division achieves efficiency by having the same staff and physical facilities serve both COR and Physics of the Cosmos (PCOS) Program Offices.

The technology development and maturation process identifies existing and emerging needs. This introduces a potential customer, NASA, to possible providers of technologies. It also identifies providers of technologies and expertise, the Program principal investigators (PIs), to potential customers and collaborators beyond NASA. This encourages industry and other players to invest in enabling technologies for future missions, and promotes formation of productive collaborations.

One notable success for the COR technology development program was that an upgrade to the *Stratospheric Observatory for Infrared Astronomy* (SOFIA) *High-resolution Airborne Wide-bandwidth Camera* (HAWC) implemented new far-infrared (Far-IR) detectors matured using COR funding (H. Mosely, GSFC). Another such success story is the adoption of the H4RG near-infrared (NIR) detector by the *Wide-Field Infrared Survey Telescope* (WFIRST). This is an example of a technology matured using COR Strategic Astrophysics Technology (SAT) funding being infused into a study/flight project. Two PIs are due special thanks for this latter success. B. Rauscher of GSFC and S. Anglin of Teledyne carried forward the H4RG technology maturation far enough to allow it to graduate to project-level technology status.

What's in this Report? What's New?

This fourth Program Annual Technology Report (PATR) summarizes the Program's technology development activities for fiscal year (FY) 2014. The PATR serves four purposes.

1. Summarize the technology gaps identified by the astrophysics community;
2. Present the results of this year's technology gap prioritization by the COR Technology Management Board (TMB);
3. Report on newly-funded COR SAT projects, if any; and
4. Detail progress, current status, and activities planned for the coming year for all technologies supported by COR Supporting Research and Technology (SR&T) funding in FY 2014.

The Astrophysics Division has awarded 11 COR projects to date, intended to enable future COR missions to help answer the question "How did the universe form, and how did it evolve to its present form?" These projects develop telescopes, optics, coatings, and detectors from the Far-IR to the far-ultraviolet (Far-UV), applicable to the highest-ranked potential future COR missions. Seven projects continue from previous years, each reporting significant progress over the past year, with several prepared for TRL advancement review. One more began in 2014, "Development of Digital Micro-Mirror Devices" (Z. Ninkov, RIT).

We thank the PIs of our ongoing projects for their informative reports (see Appendices A and B). Since there was no COR SAT call for proposals last year, there are no new project starts planned for FY 2015.

Following this year's technology gap prioritization, the Program Office is recommending NASA HQ first solicit and fund technology developments related to high-reflectivity coatings for NIR through ultraviolet (UV); high-quantum efficiency (QE) and/or photon-counting, large-format detectors; affordable, light-weight, large-aperture optics; nanometer-level wave-front sensing and control; and high-efficiency multi-object spectrometers (MOS).

1. Program Science Overview

The goal of the COR Program is to understand the origin and evolution of the universe from the Big Bang to the present day. On the largest scale, COR's broad-reaching science question is to determine how the expanding universe grew into a grand cosmic web of dark matter enmeshed with galaxies and pristine gas, forming, merging, and evolving over time. COR also seeks to understand how stars and planets form from clouds in these galaxies; how stars create the heavy elements essential to life–starting with the first generation of stars to seed the universe, and continuing through the birth and death of stars to today. The majority of the field known as astronomy, from antiquity to the present, falls within the purview of COR.

Background

The Program encompasses multiple scientific missions aimed at meeting Program objectives, each with unique scientific capabilities and goals. The Program was established to integrate those space, suborbital, and ground activities into a cohesive effort that enables each project to build on the technological and scientific legacy of its contemporaries and predecessors. Each project operates independently to achieve its unique set of mission objectives, which contribute to the overall Program objectives.

Current COR missions

Hubble Space Telescope (HST)

The launch of HST in 1990 began one of NASA's most successful and long-lasting science missions. Over 24 years, HST relayed over a million observations back to Earth, shedding light on many of the great mysteries of astronomy. HST has helped determine the age of the universe, peer into the hearts of quasars, study galaxies in all stages of evolution, find proto-planetary 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 11th anniversary of its launch, provides sensitive infrared (IR) observations that allow scientists to peer into cosmic regions hidden from optical telescopes, such as dusty stellar nurseries, the centers of galaxies, and still-forming planetary systems. Many of its investigations have focused on objects that emit very little visible light, including brown dwarf stars, extra-solar 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 other missions have completed operations but are still in their data analysis phase prior to final release of their scientific data products. These include:

Herschel Space Observatory

The US 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, but data refinement and analysis will continue until 2017.

Galaxy Evolution Explorer (GALEX)

GALEX has conducted a wide-imaging survey in two UV bands, intended to trace the history of star formation 80% of the way back to the Big Bang. In June 2013, GALEX was decommissioned, but the final (privately obtained) data set became available to the 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 hot dusty galaxies halfway across the universe. WISE was decommissioned in February 2011, and the release of its full reprocessed data set occurred in November 2013.

In 2014, the COR Program development portfolio includes:

COR SR&T

The COR Program Office manages the investment of SR&T funds in a variety of avenues to advance COR technology needs. Appendix B details recent progress of projects supported during FY 2014.

Future Mission Concept Development

The COR Program Office conducts mission concept studies to assist in scoping future activities including technology development priorities and plans, when appropriate. During FY 2014, no Program-sponsored mission concept studies were active. The Program Office continues to follow two independent studies of a future UV/Visible mission, which would bring new capabilities to the astronomical community in a post-HST and post-GALEX era, and will incorporate their findings into future Program activities.

Pre-Formulation Mission Study: Wide-Field Infrared Survey Telescope

WFIRST is a NASA observatory designed to perform wide-field imaging and slit-less spectroscopic surveys of the NIR sky. It is the top-ranked large space mission in NWNH. Because the survey data will address major COR science questions, such as galaxy evolution, the COR Program supported pre-formulation studies and technology development until late 2013, when they were moved into the WFIRST study.

The following missions currently under development satisfy important COR science objectives, although they are managed outside the COR Program.

Stratospheric Observatory for Infrared Astronomy

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. SOFIA was declared fully operational in May 2014, equivalent to launch of a space mission. The SOFIA Program Office and aircraft are based at NASA's Armstrong Flight Research Center (AFRC), with science mission operations based at NASA's Ames Research Center (ARC). Because SOFIA science is well-aligned with COR science, and because SOFIA represents an important platform for maturation of COR technologies that may be applicable to future space missions, certain SOFIA science objectives are considered strategic in relation to the applicable criteria described in Section 4.

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

US astrophysics priorities were redefined in 2010 when the National Research Council (NRC) released the NWNH report, causing 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 high value on COR missions relating to Cosmic Dawn (the science theme most 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 COR; however, several of its recommendations are directly relevant to the Program.

- The NWNH report's first priority space recommendation, 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 4m 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 Astrophysics Division's Astrophysics Implementation Plan (AIP), released in December 2012, clarified this exceeded available budgets.
- The report also strongly recommended an augmentation to the Explorers 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.

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 Program is committed to managing available funds strategically to ensure the Program fosters missions that continue to accomplish COR science objectives.

The COR Program is committed to preparing for the next UV/Visible astrophysics mission. NWNH recommends developing technology for a large UV/Visible mission to continue and extend HST's science accomplishments, through a 4m-class mission covering wavelengths shorter than HST's key range. However, the COR Program 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 developing a consensus set of science objectives and requirements, summarized in a white paper. The overall goal of the workshop was to combine 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, suitable for general astrophysics at UV and visible wavelengths. Two other independent groups are currently exploring science cases for future very large UV/Visible/NIR observatories. The COR Program expects to use findings from these studies to help guide technology needs. Most technology development toward future UV/Visible missions is also expected to benefit the Explorers Program.

In 2012, the Program studied the feasibility of an instrument contribution to SPICA, then slated for launch around 2022. Near-term budget limitations constrained NASA's ability to participate at the desired level. The Program concluded that based on the readiness level and development risk of possible NASA-provided SPICA instruments, all possible instrument contributions required funding beyond what was available, and could not meet JAXA's schedule constraints. Since then, SPICA was rescoped and its planned launch significantly delayed, to around 2025. The COR Program is currently working with the Far-IR community to identify alternate ways the US community can address SPICA science goals identified in NWNH. A Program-sponsored workshop on the future of Far-IR space astrophysics was held in May 2014, to identify the most pressing science questions that can be addressed with Far-IR techniques, and to build community consensus regarding Far-IR astrophysics.

SOFIA, which provides a platform for observations across the IR spectrum, will start its Science Cycle 3 at the beginning of 2015. The recently selected upgrade to SOFIA's HAWC includes the installation of polarimetric optics and new Far-IR detectors. The new detectors were matured using COR funding in prior years, providing an example of how COR technology development investment can be handed off to a flight project once the appropriate TRL is reached.

The activity given first priority in NWNH for a future large space mission, WFIRST, is managed by the Exoplanet Exploration Program (ExEP) at the Jet Propulsion Laboratory (JPL), so it is not formally within the COR Program's suite of future missions. The WFIRST pre-formulation mission study, using a 2.4m repurposed telescope termed the *Astrophysics Focused Telescope Assets* (AFTA), is working toward a possible new start in 2017. The COR Program, in conjunction with the Cosmic Origins Program Analysis Group (COPAG), is examining how AFTA mission concept capabilities will address COR science goals. In support of this high-priority mission activity, the COR Program funded detector development through the SAT Program in FY 2013 until the work was moved into the WFIRST study office in FY 2014.

2. Program Strategic Technology Development Process and Portfolio

The COR Technology Development Process

A primary function of the COR Program Office is to develop and administer a technology development program, supporting innovative concepts for implementing strategic COR missions. The Program Office facilitates, manages, and implements the technology policies of the Program. The goal is to coordinate infusion of technology into COR missions, including the crucial phase of transitioning nascent technologies into targeted projects' mission technology programs when projects are formulated. This PATR is an annual, comprehensive document detailing COR technology development activities over the past year.

The COR technology management plan details the process for identifying and prioritizing COR technology gaps, enables maturation of high-priority technologies, and injects them into new missions. A key objective of this process is to formulate and articulate the needs of the Program, through a process of careful technology gap evaluation, guided by the priorities set forth in the AIP. The AIP describes the Astrophysics Division's planned implementation of the space-based priorities identified in the NWNH report, modified by more recent budgetary developments. For example, this includes the decision not to participate in the original version of SPICA, and instead concentrate on planning work for future UV/visible missions. The Program Office's process thus supports the AIP's prioritized complement of missions and activities to advance COR science priorities.

The process (Fig. 2-1), unchanged from prior years, firmly integrates the science community's inputs, through the decadal survey process and their ongoing identification of technology gaps, submitted via the COPAG or directly through the Program Office website. The Program Office charges its TMB to determine which technology developments will meet Program objectives, and prioritize annually the technology gaps submitted over the prior 12 months for further development consideration. The TMB ranks technology gaps based on Program objectives, strategic ranking of relevant science/missions, benefits and impacts, and timeliness. The TMB, a Program-level functional group, provides a formal mechanism for input to, and review of, COR technology development activities. The NASA Astrophysics Roadmap, "Enduring Quests, Daring Visions," released in December 2013, also informs TMB deliberations. The Roadmap does not offer a vetted strategic plan, but strives to inspire and challenge the community to pursue the missions and technologies needed over the coming three decades to address NWNH-identified science goals.

Program Office priority recommendations inform Astrophysics Division decisions on which technologies to solicit in the upcoming annual SAT call for proposals, and guide selections. HQ's investment considerations are made within a broader context, and other factors apparent at the time of selection may affect funding decisions. HQ evaluates resulting technology development proposals, considering overall scientific/technical merit, programmatic relevance, and cost reasonableness given the scope of work. Awardees work to mature their technologies from their initial TRL, normally 3, to higher TRLs, up to 5 or 6. PIs report their progress and plans to the Program Office periodically, and submit their technologies to TRL advancement reviews when appropriate. Progress in these projects allows injection of newly mature technologies into NASA missions and studies, enabling and enhancing their capabilities with acceptable programmatic costs and risks.

TRL above the approved entry level for each technology is not official until the TMB has vetted and concurred with the development team's assessment. When a PI believes their team has demonstrated the required progress, he or she may request a review to present their case for TRL update. The Program Office then convenes the TMB, consisting of Program Office and HQ senior staff and subject matter experts, to assess the request and, when warranted, approve the TRL update. The typical forum for such a request is during the PI's end-of-year presentation to the Program Office, but it can be made at any time. Several PIs with projects in the COR portfolio are planning to go through TRL vetting this coming year.

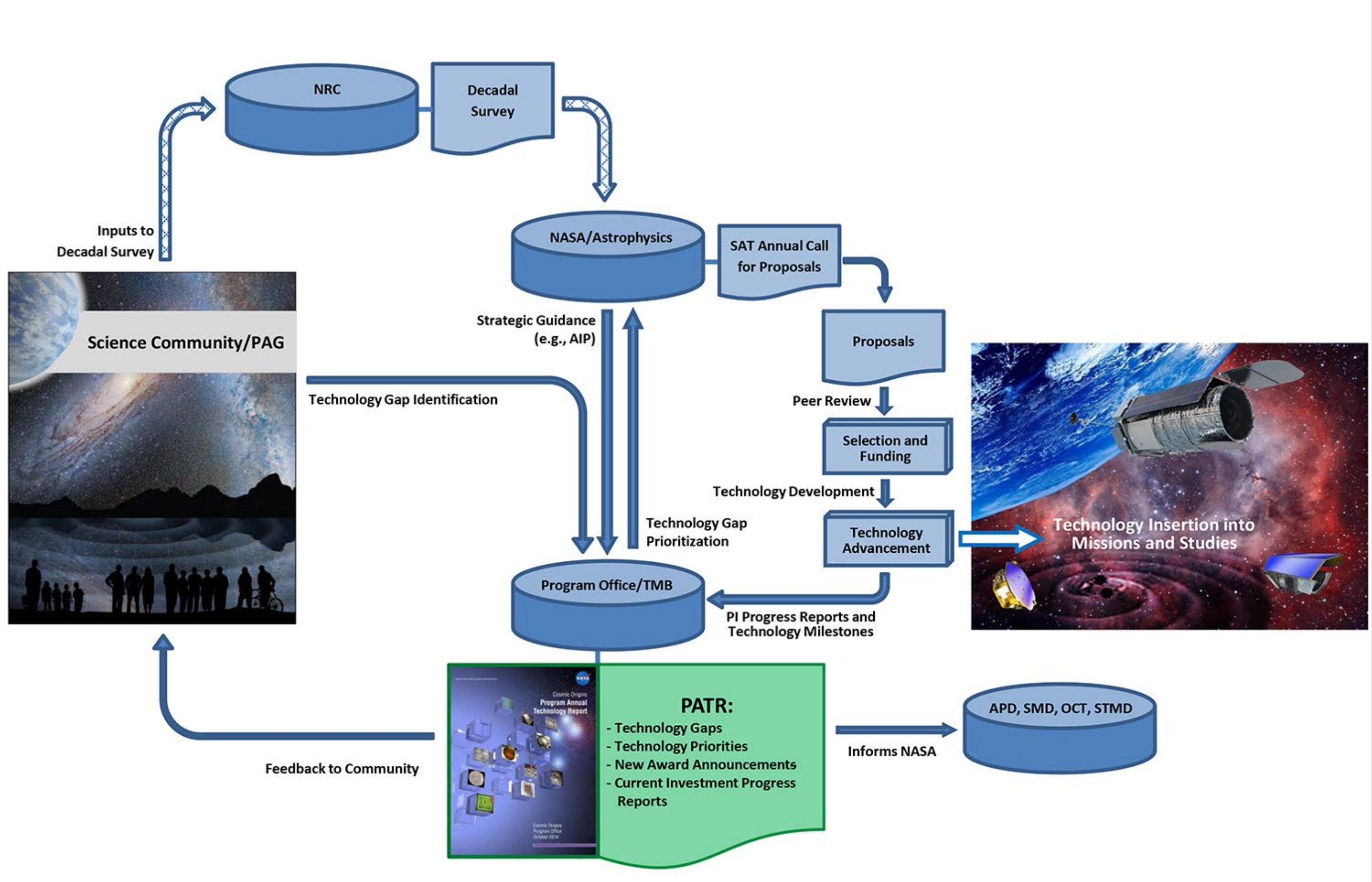


Fig. 2-1. *The COR technology development process receives community input as to technology gaps, recommends priorities, manages SAT-funded activities, and informs NASA and the science community about progress.*

This technology development process improves the relevance of COR technology investments, provides the community a voice in the process, and promotes targeted external technology investments by defining needs and identifying NASA as a potential customer.

The PATR plays an important role in the Program's technology development process. Through PI reports and quad charts, it describes the status of all technologies funded through the Program. It captures technology gaps articulated by the scientific community, and recommends a prioritized list of technologies for future solicitation and funding. The PATR is an open source for the public, academia, industry, and the government to learn about the status of enabling technologies required to fulfill COR science objectives. The PATR informs NASA organizations, including but not limited to the Astrophysics Division, and updates the community regarding technology development progress, as input for future technology gap submissions. Technological progress and programmatic decisions change the landscape of requirements for COR needs; therefore, the process is repeated annually to ensure continued relevance of priority ranking.

Involvement of the scientific community does not start and end with the decadal survey and technology gap submission. This community is a key stakeholder in Program technology development activities, providing feedback and inputs to the technology development process, participating in COPAG committees and workshops, Program workshops, ad-hoc studies, and as developers through responses to solicitations.

The COR Technology Development Portfolio as of 2014

For FY 2014, the driving objective is to maintain progress in key enabling technologies for a Large UV/Optical/IR (LUVOIR) mission, COR-related instruments for SOFIA, and other COR missions.

There have been 11 COR SAT projects awarded to date, eight funded prior to 2014. Two more, announced in the 2013 PATR, began in late 2013. When additional funding became available in early 2014, one more was awarded (Z. Ninkov, RIT). Table 2-1 provides top-level information for eight of the 11, including where in Appendices A and B each is described more fully. The three projects not listed are no longer active. One was funded for one year, another was taken over by WFIRST/AFTA as mentioned above, and a third was succeeded by a follow-on project with the same PI, which is listed. Appendix A provides single-page "quad chart" summaries for each project. Appendix B provides PI reports, detailing development status, progress over the past year, and planned activities for the near future. The appendices provide technology overviews and status, not flight implementation details. Additional information can be obtained by contacting the COR Program Office or the PIs directly. Contact information for each PI appears at the end of his or her report in Appendix B.

Technology Development Title	PI	Institution	Start Year & Duration	Current TRL	Quad Chart & PI Report Locations
Kinetic Inductance Detector Arrays for Far-IR Astrophysics	J. Zmuidzinas	Caltech	FY13; 3 yrs	3, 6	p. 43, p. 52
Cross-Strip Micro-Channel Plate Detector Systems for Spaceflight	J. Vallerga	UC Berkeley	FY12; 3 yrs	4§	p. 44, p. 59
High-Efficiency Detectors in Photon-Counting and Large Focal Plane Arrays (FPAs)	S. Nikzad	JPL	FY13; 3 yrs	4	p. 45, p. 70
A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping	I. Mehdi	JPL	FY14; 3 yrs	4	p. 46, p. 77
Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes	P. Stahl	MSFC	FY14; 3 yrs	3 – 5	p. 47, p. 85
Ultraviolet Coatings, Materials, and Processes for Advanced Telescope Optics	K. Balasubramanian	JPL	FY13; 3 yrs	3	p. 48, p. 92
Enhanced MgF_2 and LiF Over-Coated Al Mirrors for FUV Space Astronomy	M. Quijada	GSFC	FY12; 3 yrs	4	p. 49, p. 103
Development of Digital Micro-Mirror Device Arrays for Use in Future Space Missions	Z. Ninkov	RIT	FY14; 2 yrs	3	p. 50, p. 114

Table 2-1. *COR Strategic Technology Development Portfolio as of FY 2014.*

The Astrophysics Division is open to co-funding when possible, as it has with two technology development projects in the PCOS Program with the Space Technology Mission Directorate (STMD). Another instance was collaboration on a special STMD solicitation, funding two "thin-film physics or optical coatings" investigations under the Early-Stage Innovation (ESI) solicitation. These studies, targeted for cosmic microwave background (CMB) applications, started in late 2013 and were titled "Bioinspired Broadband Antireflection Coatings at Long Wavelengths for Space Applications" (Peng Jiang, University of Florida), and "Broad Bandwidth Metamaterial Antireflection Coatings for Measurement of the Cosmic Microwave Background" (Jeff McMahon, University of Michigan). Both projects seek to develop anti-reflection (AR) coatings that reach absorption levels near 90% for frequency bands relevant to CMB studies [3].

§ TRL 4: "Component and/or breadboard validation in laboratory environment." NPR 7123.1B, Appendix E.

Benefits Enabled by COR SATs

As presented at the 2014 SPIE conference in Montreal [4], the Technology Development for COR (TCOR) section of the SAT program (Table 2-2) received 14 proposals in FY 2010, its first year; 24 in 2011; and 13 in 2012. Due to budgetary constraints, no COR SAT solicitation went out in 2013. Of the first set, three proposals were selected, with five more the following year, then three in the latest round. The historical selection rate for proposed SAT investigations for the three cycles now stands at 22%, reasonably high for technology development solicitations.

Solicitation Year	TCOR Proposals		Proposal Success Ratio
	Submitted	Selected	
2010	14	3	21%
2011	24	5	21%
2012	13	3	23%
2013	Not solicited	N/A	N/A
Total to Date	51	11	22%

Table 2-2. *Number of TCOR SAT proposals and awards.*

As reported by Perez *et al.* [4], TCOR-funded projects have provided significant positive outcomes. One example, mentioned above, is a COR SAT-supported development of new H4RG near-IR (0.7-2.0 μm) detectors, which were later adopted by WFIRST/AFTA. Current progress indicates the technology can meet the required performance levels for this mission.

Over the past year, the Program presented posters of all then-current COR and/or PCOS technology development projects at the American Astronomical Society (AAS) meeting in Maryland (January 2014), the SPIE meeting in Montreal (June 2014), and the High Energy Astrophysics Division meeting in Chicago (August 2014). In the first of these, the Program held a successful SAT poster session with about 20 poster participants. A Special Oral Session about the SAT program was held during an evening session, and was very well received. Figure 2-2 shows a collage from that poster session, and Fig. 2-3 shows the SPIE poster.

The main benefit of the SAT program is in maturing technologies across the mid-TRL gap, so they can be injected into strategic COR missions. It is to be expected that where appropriate, these newly matured technologies will be implemented in ground-based and suborbital experiments, as well as Explorers and Probe-class missions. These may well extend beyond the COR Program, to PCOS, ExEP, and even outside the Astrophysics Division.

Over and above the obvious benefit of supporting technology maturation, selection for SAT funding offers additional benefits to PIs, research groups, institutions, and the community. During the preparation of this PATR, the Program Office surveyed current PIs as to additional benefits resulting from their SAT funding. The following is based on responses from five PIs. The Program Office intends to formalize this survey and expand this section in the 2015 PATR.

Fig. 2-2. *The Program held a well-received SAT poster session at the 2014 American Astronomical Society meeting in Maryland.*

Several PIs were able to leverage SAT funding to obtain internal funding, contributed materials, and/or facility and equipment usage. Most PIs hired students and post-doctoral fellows to assist their technology development work (on average, three or four per project), helping train the next generation of researchers and technologists needed to support future missions. At least one of those students recently converted to full-time employment status within the organization, indicating the program is helping train and shape the future astrophysics work force. One PI went on to partner with another institution to propose a sub-orbital investigation. Another was asked for his help in coating UV optics for Explorer missions.

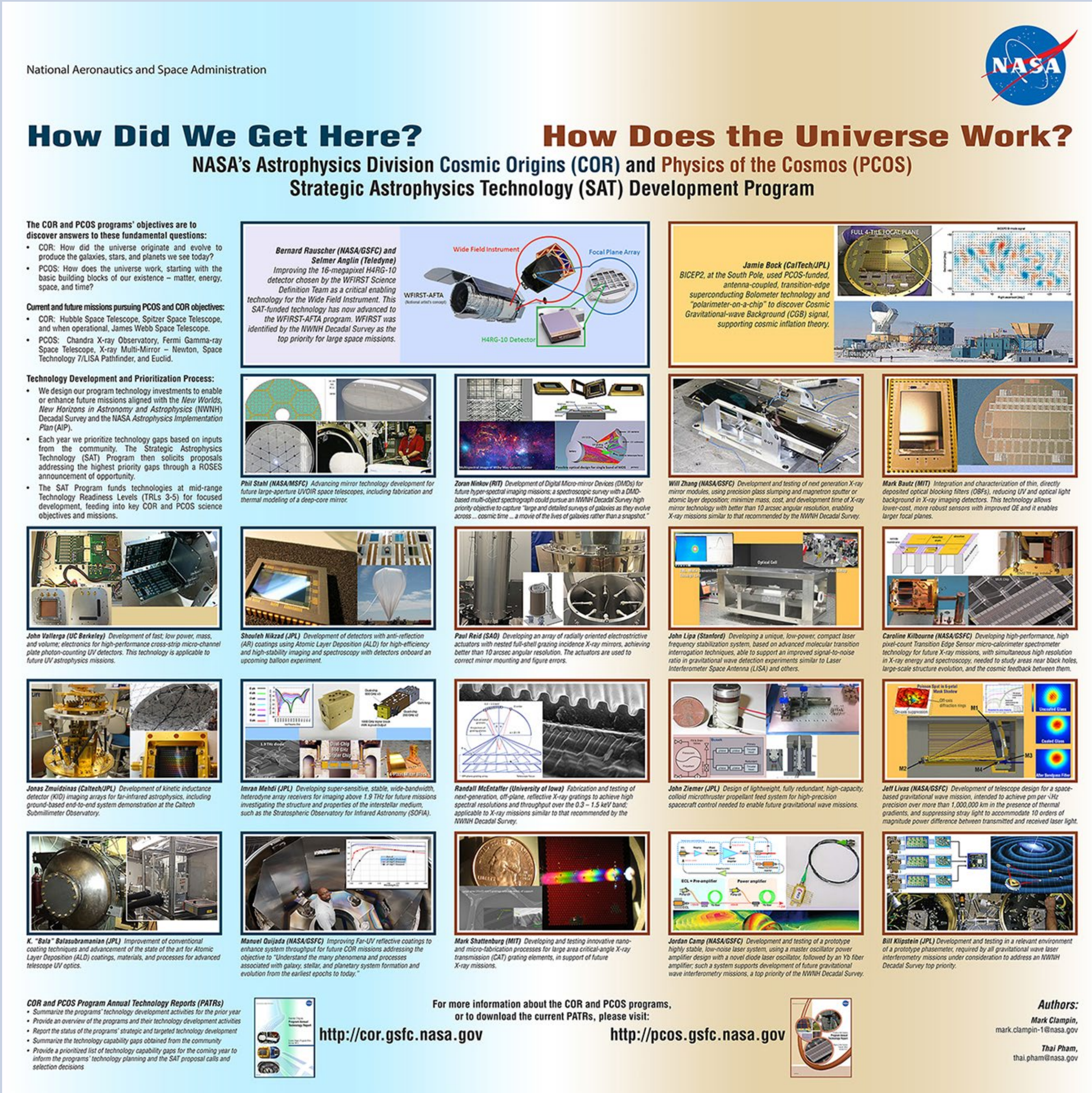


Fig. 2-3. *Poster presented at the 2014 SPIE meeting in Montreal. The Program promotes exposure of current technology development projects, highlighting their progress at national and international meetings.*

3. Program Technology Gaps

Anyone may identify a COR-related technology gap, and submit it to the Program Office directly through the COR website, or via the COPAG. Technology gaps may be submitted throughout the year. However, to allow timely consideration by its TMB, the Program Office sets a deadline for inclusion in the current year's ranking. In 2014, the deadline was set for June 30. For reasons described below, this deadline will likely be moved to June 1 starting 2015.

To maximize the likelihood of high priority ranking, the Program Office encourages submitters to include as much of the information requested as possible. More importantly, the Program Office asks submitters to describe a technology capability gap, not a specific implementation process or methodology. The technology's goals and objectives should be clear and quantified. Additionally, a complete description of the needed capability with specific performance goals based on mission needs is very valuable. Such information serves several important purposes.

1. The TMB is best able to assess the identified technology gap;
2. NASA HQ is best able to develop precise technology development proposal calls; and
3. The community is clearly informed and best able to match candidate technologies to mission needs.

Aside from submitter information, the technology gap form requests the following information:

- **Technology gap name:** Identifies the gap, and optimally the type of mission filling it would enable.
- **Brief description:** Summarizes the technology gap and associated key performance criteria. In general, well-defined technology gaps receive higher priority than vague ones.
- **Assessment of current state of the art:** Describes the state of the art, allowing the TMB to appreciate the gap between what's available and what's needed.
- **TRL:** Specifies the current TRL(s) of the technology per NASA Procedural Requirements (NPR) 7123.1B Appendix E with clear justification. The SAT program funds projects to advance technologies from TRL 3 up to TRL 5 or 6, so those already at TRL 6 are unlikely to rank well because TRLs higher than 6 are beyond the mandate of the SAT program.
- **Target goals and objectives:** Details the goals and/or objectives for a candidate technology to fill the described gap. For example, "*The goal is to produce a detector with a sensitivity of X over a wavelength of Y to Z nm*." Technology gaps with clearly quantified objectives may receive higher priority than those without quantified objectives.
- **Scientific, engineering, and/or programmatic benefits:** Describes the benefits of filling the technology gap. If the need is enabling, this should describe how and why. If the need is enhancing, it should describe, and if possible quantify, the impact. Benefits could be better science, lower resource requirements (*e.g.*, mass, power, etc.), and/or programmatic (*e.g.*, reduced risk, 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 gaps with greater potential mission benefits receive higher scores.
- **Application and potential relevant missions:** Technologies enabling or enhancing missions ranked highly by the AIP, or at least by NWNH, will be scored higher. Technologies applicable to a wide range of COR missions, as well as PCOS and/or ExEP missions will rank better.
- **Time to anticipated need:** Specifies when the technology will need to reach TRL 6 to support anticipated mission needs. Technology gaps with shorter time windows relative to required development times receive higher priority.

Technology Gaps Submitted to the 2014 TMB

The technology gaps list for 2014 included 20 new entries, and the COPAG requested the TMB also consider the 17 gaps from the previous year. After the Program Office removed duplicate entries, 25 gaps remained. Almost all technologies developed to close these gaps would enable and/or enhance high-priority strategic missions per the AIP and/or NWNH. The COR TMB reviewed the 25 gaps it received from the Program Office, and, as appropriate, folded five entries into others that were near-duplicates, or that offered wider application. Three proposed gaps were deemed outside the COR charter and disregarded. Following this step, the TMB scored and ranked the resulting 17 unique technology gaps (Table 3-1). The technology gaps include:

- Improvements in UV, visible band, and near-IR detection and optics;
- Far-IR direct and heterodyne detectors and supporting technologies;
- High-performance, affordable LUVOIR telescopes, including wavefront sensing and control;
- Far-IR cryogenic telescopes, optics, and interferometers;
- Wide-bandwidth receiving systems; and
- High-performance cryo-coolers and sub-Kelvin coolers.

The Program Office will continue to solicit and compile technology gap submissions in the future. However, the Program Office would like to expand its collaboration with the COPAG to ensure the gaps ranked by the TMB are unique and compelling. To that end, the Program Office suggests that starting next year the COPAG will take the list compiled by the Program Office and consolidate similar and/or overlapping technology gap entries. Having the COPAG do so prior to TMB prioritization would serve several important purposes:

- Allow experts in the relevant fields to clarify submissions and combine related and overlapping technology gaps, such that the resulting entry is more compelling, and potentially merits higher priority ranking;
- Ensure the final list accurately reflects the community-assessed gaps; and
- Make the process of generating unique technology gaps more transparent to the community.

To accommodate this intermediate step, the cutoff deadline will likely move from June 30 to June 1 starting next year.

Table 3-1. Technology Gaps Evaluated by TMB in 2014

Name of Technology	High-QE, large-format UV detectors
Description	Future NASA UV missions require high quantum efficiency (QE>70%), large-format (>2k×2k pixels) detectors for operation at 90-350 nm or broader for imaging and spectroscopy. Red-leak (longer wavelength) suppression is highly desirable for some applications, *i.e.*, visible blind UV detectors as well as radiation hardness.
Current State of the Art	Previously flown micro-channel plate (MCP) based UV detectors have QE of ~5-20% (wavelength-dependent), require high voltage, and can be difficult to fabricate. Current flight UV-imaging detectors (HST/STIS, HST/COS, FUSE, GALEX) are based on MCP arrays that use CsI and CsTe photocathodes with modest QEs (10-30%). Higher-QE photocathodes (30-80%) using cesiated p-doped GaN have been produced in the lab, but have not yet been integrated into full detector systems. Si-based CCDs have been produced and flown with modest QEs in the near-ultraviolet (NUV; 170-300 nm; HST/WFC3). Recent developments with atomic-level control of back-illuminated detector surface (delta doping with molecular beam epitaxy) and anti-reflection coating (atomic layer deposition techniques) have provided high-efficiency UV response (> 50%) for solid state Si detectors (electron-multiplied CCD) but the Si detectors are not visible-blind and require filters. Electron-multiplied CCDs (EMCCDs), electron-bombarded CMOS (EBCMOS) and MCP methods (ceramic and glass) compete for highest QE and largest formats.
Current TRL	3
Performance Goals and Objectives	Produce large-format, high-QE (>70%), low-noise (< 5 electrons root-mean-square, rms), and radiation-hard (operate at L2 for years) UV-sensitive detector arrays routinely, that can be used in a variety of Explorer, medium, and strategic missions. The particular strategic mission identified is a LUVOIR telescope.
Scientific, Engineering, and/or Programmatic Benefits	High-performance detectors can increase the science impact of missions by ×10-1000, depending on areal coverage and QE.
COR Applications and Potential Relevant Missions	The science impact of cost-constrained, aperture-constrained future missions is dramatically improved by reaching near-perfect detector sensitivity (high QE) and large-format arrays. This is an enhancing technology for a large UV/Visible/Near-IR mission. The 2010 Decadal Survey noted the importance of technology development for a future 4m-class UV/visible mission for spectroscopy and imaging. For example, the *Advanced Technology Large-Aperture Space Telescope* (ATLAST) mission concept identified a UV imager and UV spectrograph as key instruments. Benefits will also accrue to UV planetary, heliospheric, and Earth missions.
Time to Anticipated Need	As early as possible since mission definition and capabilities are built around detector performance. The goal is to reach TRL 5 by 2019 for consideration in the 2020 Decadal Survey for a large UV/Visible/Near-IR astrophysics mission to start in the 2020s. Significant improvements can be applied quickly in suborbital missions to increase technology readiness for all missions.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)	
Name of Technology	**Photon-counting large-format UV detectors**
Description	Future NASA UV missions, particularly those devoted to spectroscopy, require high-QE, low-noise, large-format, photon-counting detectors for operation at 90-350nm or broader. Red-leak (longer wavelength) suppression is highly desirable for some applications.
Current State of the Art	Previously-flown UV detectors obtain ~5-20% QE (wavelength dependent), require high voltage, and can be difficult to fabricate. Silicon-CCD detectors are TRL 4-5. Other technologies (MCP; avalanche photo-diode, APD; Electron-Bombarded CCD, EBCCD; with GaN Photocathodes) are TRL 2[§§]-4.
Current TRL	2 – 5
Performance Goals and Objectives	The goal is to produce large-format (>2k×2k pixels), high-QE (> 50%), low-noise (<10^{-7} ct/pixel/s) UV-sensitive detectors routinely that can be used 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.
Scientific, Engineering, and/or Programmatic Benefits	High-performance detectors can increase the science impact of missions by ×10-1000, depending on areal coverage and QE.
COR Applications and Potential Relevant Missions	The science impact of cost-constrained, aperture-constrained future missions is dramatically improved by reaching near-perfect detector performance. The 2010 Decadal Survey noted the importance of technology development for a future 4m-class UV/visible mission for spectroscopy and imaging. Benefits will also accrue to planetary, heliospheric, and Earth missions in the UV band.
Time to Anticipated Need	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. To support Explorer AOs in the second half of this decade, a focal-plane technology development + flight testing project should be started in 2014 – 2015 (*i.e.*, immediately). This would allow time for a suborbital mission to fly in 2017 – 2020.

§§ TRL 2: "*Technology concept and/or application formulated.*" NPR 7123.1B, Appendix E.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	High-efficiency UV multi-object spectrometers
Description	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; micro-shutter arrays; fiber-fed spectrographs; and integral-field spectrometers).
Current State of the Art	DMD is at TRL 5, based on European studies for Euclid, and particle-radiation tests at LBL. Micro-shutters for longer wavelengths (> 0.6microns) are at TRL 6. Low-scatter Echelle gratings are currently at TRL 2.
Current TRL	2 – 6
Performance Goals and Objectives	Routinely produce large-format, high-QE, moderate-resolution systems, that can be used in a variety of Explorer, medium, and strategic missions. Key performance criteria for customization, maturation, and characterization of object selection components (such as DMDs, micro-shutters, or reconfigurable fibers) for UV/Vis/NIR space astronomy include: 1. Sensitivity over the spectral interval 0.20-1.7 microns, (0.9-1.8 nm for DMDs); 2. Effective sky background blockage, *e.g.*, zodiacal light; and 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 include scattered light control comparable to the best first-order diffraction grating currently flying (HST-COS), ~10^{-5} of peak intensity at $\Delta\lambda$ = 10 Å from fiducial wavelength λ_0. 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.
Scientific, Engineering, and/or Programmatic Benefits	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 slit-less spectra of a field, but not slit spectra of multiple objects in a field. A UV/visible slit selector (DMD, micro-shutter array, or multi-fiber) 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.
COR Applications and Potential Relevant Missions	UV-visible-IR slit selectors are needed for astrophysics, heliospheric, and Earth-science missions.
Time to Anticipated Need	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.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Photon-counting visible and NIR detector arrays
Description	Future Vis/NIR missions require high-QE, low-noise, fast, photon-counting detector arrays to cover the visible and NIR (400-2500 nm). Important spectroscopic features extend from ozone at 260 nm through at least 2.5 μm. For the NUV through ~900 nm, EMCCDs (operated in Geiger mode) are envisioned, though these would benefit from further development. There is currently no photon-counting detector for ultra-low-background astronomy at wavelengths > ~900 nm, where several important spectral features lie.
Current State of the Art	EMCCD with 1 Mpixel has been used to count photons in the visible with greater than 60% QE. Reducing clock-induced charge would be beneficial. HgCdTe arrays in the NIR have been used to count photons at much higher dark count rates. The state of the art for NIR photon counting is arguably HgCdTe APD arrays. These were pioneered by the defense community for laser communications and laser range-gated imaging. They have also benefitted from substantial NASA investment for LIDAR, but are lower TRL (~3). In the last ~5 years, several groups including U. Hawaii and the European Southern Observatory have begun working with APD arrays for astronomy, for which the initial application is wavefront sensing. Although promising, we are not aware of any group having achieved the <<0.01 e-/s/pixel dark current rates required for spectroscopic biomarker detection with coronagraphs. Moreover, there are practical reasons why achieving good impact ionization gains may be inconsistent with the required ultra-low dark current using existing HgCdTe fabrication technology.
Current TRL	3
Performance Goals and Objectives	QE > 80% with read-noise < 1 e- rms and dark current < 0.004 e-/s/pixel. Detector format array of 4 Mpixel. Wavelength range from 400 to 2500 nm but one detector array does not have to cover the full wavelength range, *i.e.,* developing separate visible and NIR photon-counting detector arrays is acceptable. Superconducting detectors for Ultraviolet/Optical/Infrared (UVOIR) may be of particular interest. Although superconductors require more cooling than semiconductors, they face no dark-count rate challenge and promise quantum-limited detection with built-in spectral resolution. Arrays of transition edge sensors (TES) and microwave kinetic inductance detectors (MKID) have already been used at telescopes for UVOIR astronomy. Spectral resolutions of R ~ 10 have been achieved, and R ~ 100 is feasible. Relevant technologies include TES, kinetic inductance detectors (KID), and superconducting tunnel junctions (STJ).
Scientific, Engineering, and/or Programmatic Benefits	High-performance detectors can increase the science impact of missions by ×10-1000, depending on areal coverage and QE. Photon-counting visible and NIR detector arrays will enable coronagraphic spectroscopy for bio-signature characterization and starlight suppression wavefront sensing. Superconducting detectors may be especially interesting. Because of the very small superconducting gap (compared to semiconductor band gaps), it is possible to detect and count individual photons with minimal read noise and dark current, though they would need to be optimized for the required spectral resolution. Moreover, by exploiting the energy resolution these technologies offer, it should be possible to achieve spectroscopic resolution R ≥ 70 in the pixel. These essentially quantum-limited detectors could potentially mitigate cost and complexity associated with spectrograph optics.
COR Applications and Potential Relevant Missions	This is a key technology for a LUVOIR mission. The ATLAST mission concept identified an Exo-planet Imager (Near-UV) and Spectrograph (300 - 2500 nm) as key instruments for the mission and these need visible photon-counting detectors for starlight suppression wavefront sensing and control, and spectroscopy. Future missions with spectroscopic drivers could operate ~×100 faster than present. Distant missions (beyond the Zodiacal dust cloud) will observe significantly faster (> ×10) even in imaging applications. This technology can also be used in a wide variety of suborbital, Explorer, Probe, and strategic missions.
Time to Anticipated Need	The goal is to reach TRL 5 by 2019 for consideration in the 2020 Decadal Survey for a LUVOIR astrophysics mission to start in the 2020s. This is a potential game-changing technology that would undoubtedly change the missions that are proposed.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Very-large-format, high-QE, low-noise, radiation-tolerant detectors for the UV/Vis/NIR
Description	Observations in astronomy typically require a combination of large format, high throughput (QE), and low noise to achieve photon- or sky-background-limited sensitivity over the full field of view (FOV) of a telescope or spectrograph. Large-format, high-QE detectors with very low intrinsic read-noise and dark current are essential in the UV, where sky background is low; and in some Vis/NIR applications where high cadence (time-domain studies and some coronagraphic exo-planet searches) or high spectral resolution are needed. Detector arrays need to provide deep full wells and low persistence in high radiation environments. They also need to be mosaicable in Gpix formats.
Current State of the Art	Current state of the art includes technologies that achieve only a part of the required capability. Flight systems (*e.g.*, *Kepler*, GAIA) include moderate-sized focal plane arrays (~0.1 Gpix) using mosaicked CCDs with modest noise performance (~1-5 e-/pix per read, and dark current of 0.01 e-/s/pix). Alternately, they use individual MCP detectors (*e.g.*, 4k×4k pixels, 0.016 Gpix) with low to moderate QE (10-40%), zero read-noise (photon-counting) capability and very low dark current (<0.000001 e-/pix/s). The current best UV-optical detector for space astronomy is HST's UVIS CCD, but even this detector is deficient because of severe charge-transfer inefficiency caused by radiation damage. CCDs and HgCdTe arrays in few-megapixel formats are at TRL >6. However, CCDs are not radiation-hard. Radiation-hard HgCdTe arrays theoretically have sensitivity through the NUV when the substrate is removed. Scientific use in this wavelength regime hasn't been explored extensively and there is the potential of severe QE degradation or even device damage. In general, hybrid CMOS detectors (including HgCdTe) have higher readout noise than the best CCDs. Estimated current cost is > ~0.1 $/pixel.
Current TRL	4
Performance Goals and Objectives	Target goals for detector arrays are: • Pixel-count 1-4 (0.25-1) Gpix UV/Vis (NIR); • Pixel size 5-10 (10-20) microns UV/Vis (NIR) to achieve diffraction-limited imaging given typical telescope designs; • QE > 0.5 UV (> 0.9) (Vis/NIR); • Read-noise: < 0.1 (< 1) e-/pix/read UV (Vis/NIR); • Dark current: <0.000003 (<0.00003) e-/s/pix UV (Vis/NIR) at typ. operating temperatures; • Well-depth: > 2 x 10^5 e-; • High ionizing-radiation tolerance; and • Cost <0.01-0.001 $/pixel.
Scientific, Engineering, and/or Programmatic Benefits	Detector QE and FOV determine instrument grasp, or etendue, which sets instrument survey power. Higher etendue allows deeper or wider astronomical surveys with space-based telescopes on much shorter timescales. It also enables instrument designs that exploit the telescope aperture size (geometrical area) and full working FOV. Relevant experience with UV, Vis, and/or NIR detectors that simultaneously achieve all these technical goals are essential for maximizing science return of future space observatories. These detectors are crosscutting technologies, applicable for astrophysics, planetary, and space sciences. Biological, medical, and security/surveillance applications will also benefit from pushing the limits of sensor technology, particularly for low-light imaging. High-performance detectors can increase the science impact of missions by ×10-1000, depending on areal coverage and QE. Deep full wells with low persistence and radiation tolerance enable transit imaging and spectroscopy at all wavelengths.

COR Applications and Potential Relevant Missions	COR science requires deep multi-wavelength measurements of galaxies and Active Galactic Nuclei (AGN) to study their evolution from the formation of the first stars and black holes to structures observed on all scales in the present-day universe. High priority is given to observations of unseen phenomena such as the cosmic web of intergalactic and circumgalactic gas, resolved light from stellar populations in a representative sample of the universe, UV imagery of early galaxies to improve distance estimates with photometric redshifts, or detailed studies of the stellar evolution process. Potentially relevant missions include the next LUVOIR space telescope, and probe-class missions that can conduct wide-field surveys. These detectors would greatly benefit Explorer-class missions, enabling them to obtain science currently only available with much larger apertures. They would also greatly increase the science return of small-sat or suborbital experiments that can advance technology while addressing one or more COR science objectives.
Time to Anticipated Need	Detector arrays meeting all target goals specified here (in each major band, UV, Visible, NIR) should be elevated to TRL 6-7 by 2018 or 2019, in time to be incorporated at low risk and high cost confidence in mission designs proposed for the next decadal survey Rapid development and availability of these arrays will enable numerous classes of missions from suborbital, Explorer, Probe, and strategic mission even sooner.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Large-format, low-noise far-infrared (FIR) direct detectors
Description	Future FIR missions require large-format detectors optimized for the very low FIR 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.
Current State of the Art	Single detectors are at TRL ~5, but demonstrated array architectures are lagging at TRL ~3. Sensitive, fast detectors (TES bolometers and MKIDs in small arrays) are at TRL 3 for application in an interferometric mission
Current TRL	3
Performance Goals and Objectives	Detector format of at least 16×16 with high fill 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.
Scientific, Engineering, and/or Programmatic Benefits	Sensitivity reduces observing times from many hours to a few minutes (≈100× faster), 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 proto-galaxies with an interferometer.
COR Applications and Potential Relevant Missions	FIR detector technology is an enabling aspect of all future FIR 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).
Time to Anticipated Need	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 have been identified. To support Explorer AOs in the second half of the 2010 – 2020 decade, a focal-plane technology development + flight-testing project should be started in 2014 – 2015. This would allow time for a suborbital mission to fly in 2017 – 2020.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Ultralow-noise FIR direct detectors
Description	Future FIR missions require detectors optimized for the very low FIR 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.
Current State of the Art	Single detectors are at TRL ~3.
Current TRL	2
Performance Goals and Objectives	Detector sensitivities with noise-equivalent powers of $\approx 3\times10^{-21}$ W/$\sqrt{\text{Hz}}$ are needed for spectroscopy, arrayable in a close-packed configuration in at least one direction.
Scientific, Engineering, and/or Programmatic Benefits	Sensitivity reduces observing times from many hours to a few minutes ($\approx\times100$ faster). Overall observing speed can increase by factors of thousands.
COR Applications and Potential Relevant Missions	FIR detector technology is an enabling aspect of all future FIR 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).
Time to Anticipated Need	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 have been identified.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	**Heterodyne FIR detector arrays and related technologies such as THz local oscillators (LOs)**
Description	Suborbital and space missions, as well as NASA's SOFIA observatory, could achieve a significant observational capability increase by upgrading from single-pixel coherent (heterodyne) spectrometers to arrays. Heterodyne focal plane arrays are needed 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 intermediate frequency (IF) bandwidth, LOs that are tunable but which can be phase-locked, and accompanying system technology including optics and low-cost, low-power digital spectrometers. Specifically, LO sources at frequencies above 2 THz that can generate ≥10 mW of power will be essential for large-format heterodyne receiver arrays to observe many spectral lines important for COR (*e.g.*, HD at 2.7 THz and OI at 4.7 THz). Largely because of the lack of such sources, the only large arrays developed thus far are direct detectors or heterodyne receivers below 1 THz.
Current State of the Art	For SOFIA, only single-pixel receivers have been developed for flight; arrays of 16 pixels are approaching TRL ~4. LOs above 2 THz are at TRL ~2.
Current TRL	2 – 3
Performance Goals and Objectives	Develop broad tunable bandwidth array receivers for operation at frequencies of 1-5 THz. Arrays of 10 to 100 pixels are required to build on the discoveries of *Herschel* and exploit the sub-millimeter/FIR region for astronomy. Should include optics and accompanying system components. For LOs, sources with output power levels ≥10 mW at frequencies above 2 THz.
Scientific, Engineering, and/or Programmatic Benefits	Ability to observe and map spectral lines (such as OI at 4.774 THz) to study star formation and galaxy evolution. Development of such systems and associated technology will make imaging observations over ×10 faster. They'd also significantly benefit laboratory spectroscopy and biomedical imaging.
COR Applications and Potential Relevant Missions	Needed for future sub-mm/FIR suborbital missions (instruments for SOFIA and balloon missions such as *Stratospheric Terahertz Observatory,* STO and *Galactic/Xtragalactic ULDB Spectroscopic Stratospheric Terahertz Observatory*, GUSSTO) and for potential small-sat and Explorer missions beyond *Herschel*. Solar system studies of planetary atmospheres will directly benefit. For Earth observing, focal plane arrays will improve coverage speed and provide small spot sizes with reasonably-sized antennas.
Time to Anticipated Need	The next round of SOFIA instruments will need to reach TRL 6 by the end of the decade (*i.e.*, 3-5 years).

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Affordable, lightweight, large-aperture telescopes
Description	Future UV/Vis/NIR telescopes will require ever-larger apertures to answer questions raised by HST, JWST, *Planck*, and *Herschel*, and to complement the ≥30m ground-based telescopes coming online in the next decade. Such large UVOIR space telescopes will require: 1. 10m or greater aperture; 2. Diffraction-limited optical quality; 3. UV to NIR wavelength coverage; and 4. Starlight suppression to enable exo-planet observations. Investments are needed in segmented mirrors to prove mirror system performance, stability, UV compatibility, low mass, and low cost. These include detailed model-based analysis of mirror system performance, especially addressing dynamic and thermal stability to the levels required for coronagraphy; and mirror system testing to validate the models. Segmented architectures provide a low-cost, low-risk approach that leverages the significant investment made by NASA for JWST. Telescope cost evaluation has made many smaller UV-VIS missions appear nonviable. A capability is needed to design and build larger telescopes than those that can be currently proposed with cost credibility and low cost risk. Many telescopes are currently limited by historical and expected costs (or mass), rather than by launch vehicle fairing size. For lack of alternatives, cost models link the cost of Explorer telescopes to those of expensive great observatories. Innovative ways to construct lightweight telescope mirrors and optical telescope assemblies (OTAs) are emerging, also using Lean Manufacturing methods, but the benefits are not yet in place for Explorer missions. New technologies may enable rigid monolithic primary mirrors, or affordable but reliable deployment techniques for segmented apertures to provide increased capabilities.
Current State of the Art	Primary mirror segment technologies have been developed at the needed size (1.2-1.4 m) by NASA and other agencies. ULE glass and SiC-based designs offer alternatives to the Be mirrors used by JWST at lower cost and faster production rates (lightweight 1.3 m Be and SiC mirrors are TRL 6. Borosilicate glass mirrors are at TRL 5). Thermal control has been demonstrated for figure stability and figure control with actuators. Lightweight ULE segments with alignable edges, offering <10 nm rms surface figure error (projected), <5 Å micro-roughness (projected) and <25 kg/m^2 total at 1.4 m. SiC mirrors using actuated hybrid mirrors have been demonstrated at 0.5-1.35 m size, <14 nm rms surface figure error, <10 Å micro-roughness (projected), <25 kg/m^2 total at 1.4 m. SMEX 40 cm and MidEx 80 cm affordable with existing technology. Extreme lightweighted Zerodur demonstrated at 1.2 m (TRL 4) Diffractive optics demonstrated at laboratory brass-board level (TRL 3) Frozen membrane mirror technology in early stages of development (TRL 3)
Current TRL	3 – 5
Performance Goals and Objectives	Decrease OTA areal density, including primary, its support structure, and mass of additional hardware required to produce an image (*e.g.*, wavefront control system or chromatic corrector), from current trends of 74 kg/m^2 (JWST) to OTA areal densities on the order of 10-36 kg/m^2 or less, surface figure error of 5 to 10 nm rms, and mechanical and thermal wavefront error stability <7 pm rms/10 min. Telescope fabrication time should be short enough to not be a significant schedule driver. Similarly, primary development cost should be reduced by half or more from current trends (*e.g.*, areal cost < $2M/m^2). A demonstration space-borne OTA using new lightweight mirror technology should be constructed at the 1.5m scale or larger to address both scientific relevance and TRL (*e.g.*, 1.5+ m primary optic for SMEX with a Pegasus; 3+ m primary optic for a MidEx with a Taurus or Minotaur; 5+ m primary optic for a Probe with an Atlas V or Falcon 9; 3m primary optic for a balloon-borne payload).

Scientific, Engineering, and/or Programmatic Benefits	Scientific: more collecting area increases sensitivity; larger diameter enables greater angular resolution. Both allow increased and better science for cost- and time-constrained missions addressing key astrophysics questions from cosmic birth to Exo-Earths. Engineering: lower mass primary allows lighter structure, larger margins; simplified deployment concepts and mechanisms allow larger apertures in smaller launch vehicles. Programmatic: shorter development schedule may remove telescope from critical path and reduce cost. Lighter and cheaper telescope allows greater allocation of mass and money for the science instrument.
COR Applications and Potential Relevant Missions	This is an enabling technology for a LUVOIR mission. The ATLAST mission concept has identified segmented mirrors in an active optical system as its second highest priority technology area for investment after starlight suppression. More generally, the number and cadence of new missions is extremely constrained by available NASA budget. We must maximize the science obtained by those that can be executed. By filling this technology gap, we may achieve MidEx-class science with a SMEX budget and launch vehicle, probe-class science with a MidEx, and larger mission science with probe-class implementation, and reduce risk for future flagship missions by demonstrating key technologies that enable those outlined in the Astrophysics Roadmap.
Time to Anticipated Need	Need to achieve TRL 5-6 by 2018 to be considered in the 2020 Decadal Survey. MidEx AO expected in 2018. Decisions about probe-class missions also in 2017 or 2018. SMEX and additional AOs in subsequent years.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Sensing and control at the nanometer level or better
Description	Diffraction-limited space telescopes require pointing accuracy on the order of $\theta \sim 0.1\ \lambda/D$. Technologies are required that provide high degree of thermal and dynamic stability, and wavefront sensing and control (*i.e.*, very stable materials, actuators with ~1nm step sizes, systems for rigidizing backplane structures, etc.). Techniques to detect relative distances over picometer length scale could include capacitive sensing, laser-based trusses, generalized interferometric sensing, or nested combinations of these techniques. Must have a path to spaceflight qualification.
Current State of the Art	Capacitive sensing is used in control of air-gapped etalons to the 10 pm level. Stabilized lasers systems are used with ground-based and space-based interferometers. New techniques utilize dual laser frequency methods, laser trusses and broadband laser interferometry. Sub-10 pm level sensitivities have been demonstrated in the laboratory with laser systems, with path to space qualification.
Current TRL	3
Performance Goals and Objectives	Measurement sensitivity and stability of 10 pm over one hour, where the long exposure is driven by the integration time to collect sufficient photons to close control loops on active wavefront control. Develop autonomous, closed-loop, onboard wavefront sensing and control with > 100 Giga-floating point operations/s/W and a control bandwidth of 1 per 5 min.
Scientific, Engineering, and/or Programmatic Benefits	Enables NIR/Vis/UV large diameter telescopes that require active optics and high-stability deformable mirrors (adaptive optics) for observation of faint objects. This will also enable sophisticated coronagraphs that require one part in 10^{10} contrast, as needed for exo-planet spectroscopy, where for a 8-16m coronagraphic telescope, a system-level wavefront error of order 1 nm is required; wavefront stability of approximately 10 pm/hour; and pointing control of roughly 1 nanoradian.
COR Applications and Potential Relevant Missions	ATLAST, ST2020, LUVOIR, and others to be considered in the upcoming decadal survey.
Time to Anticipated Need	Anticipate this should be at TRL 5 or greater by late 2018 – early 2019 to influence the next decadal survey and help show plausibility for advanced observatory mission concepts.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Large, cryogenic, FIR telescopes
Description	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 these telescopes be operated at temperatures, depending on the application, as low as 4K. Collecting areas on the order of 50 m^2 are needed.
Current State of the Art	JWST Be mirror segments may meet requirements now, so TRL 5 with an extremely expensive technology; TRL 3 exists for other materials.
Current TRL	3 – 5
Performance Goals and Objectives	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 FIR surface quality/figure of ~1μm rms.
Scientific, Engineering, and/or Programmatic Benefits	Low-cost, lightweight cryogenic optics are required to enable development of large aperture FIR telescopes in the 2020's. Large apertures are required to provide the spatial resolution and sensitivity needed to follow up on discoveries from the current generation of space telescopes.
COR Applications and Potential Relevant Missions	This is a key enabling technology for any future FIR mission.
Time to Anticipated Need	Should come as early as possible since technology is applicable to small, medium, and large missions. Needed by 2020 for the next large FIR astrophysics mission.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)	
Name of Technology	**FIR interferometer**
Description	Interferometry in the FIR provides sensitive integral field spectroscopy with sub-arcsec angular resolution and R ~ 3000 spectral resolution. It could resolve proto-planetary and debris disks; and measure the spectra of individual high-z galaxies, probing beyond the confusion limits of single-aperture FIR telescopes. A structurally-connected interferometer would have these capabilities. Eventually, a formation-flying interferometer would provide *Hubble*-class angular resolution. Telescopes need to operate at temperatures as low as 4K.
Current State of the Art	Wide-FOV spatio-spectral interferometry has been demonstrated in the lab at visible wavelengths with a test-bed that is functionally and operationally equivalent to a space-based FIR interferometer.
Current TRL	2
Performance Goals and Objectives	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-arcsec imaging and Fourier Transform Spectroscopy over the entire spectral range 25-400 microns in an instantaneous FOV >1 arc minute.
Scientific, Engineering, and/or Programmatic Benefits	40m-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.
COR Applications and Potential Relevant Missions	Wide-field spatio-spectral interferometry is a key enabling technology for a FIR astrophysics mission consistently given high priority by the FIR astrophysics community. Potential applications also exist in NASA's planetary and Earth science programs.
Time to Anticipated Need	Continuation of prototype efforts expected to yield mature technique in time for 2015 balloon flight. To enable credible discussion of a FIR interferometer, recognized as a critical future investment, must reach TRL 6 well in advance of 2020 Decadal Survey (*e.g.*, by ~2018).

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	High-performance, sub-Kelvin coolers
Description	Optics and detectors for FIR, millimeter, and certain X-ray missions require very low temperatures of operation, typically in the tens of milli-Kelvin. 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
Current State of the Art	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.
Current TRL	3 – 4
Performance Goals and Objectives	A cryo-cooler 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.
Scientific, Engineering, and/or Programmatic Benefits	Sub-Kelvin cryo-coolers are required to achieve astrophysical photon background-limited sensitivity in the FIR 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 FIR and X-ray.
COR Applications and Potential Relevant Missions	This technology is a key enabling technology for any future FIR mission. Sensors operating near 100 mK are envisioned for future missions for X-ray astrophysics, measurements of the CMB, and FIR imaging and spectroscopy. It is applicable to missions of all classes (balloons, Explorers, probes, and flagship observatories).
Time to Anticipated Need	Beneficial to undertake soon, to take advantage of existing development momentum, to allow time for system integration and cryo-thermal system performance verification, and enable balloon and Explorer applications in advance of the 2020 Decadal Survey. To support an Explorer AO in the second half of this decade, a focal-plane technology development + flight testing project should be started in 2014 – 2015. This would allow time for a suborbital mission to fly in 2017 – 2020.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Advanced cryo-coolers
Description	Cryo-coolers are required for achieving very low temperatures (*e.g.*, ~4K) for detectors and/or optics for COR missions. Eliminating the need for expendable materials (cryogens) will increase achievable lifetime and reduce system mass and volume. Improvements are needed in terms of flyability and performance, especially low power consumption and low vibration levels.
Current State of the Art	Cryo-coolers capable of ultralow temperatures (<0.1 K) based on magnetic refrigeration and quantum tunneling through normal-insulator-superconductor junctions have been demonstrated. For the several-Kelvin temperature designs, the current state of the art includes pulse tube, Stirling, and Joule-Thomson coolers which are at high TRL but these are expensive, and do not yet have good enough performance. An example is the development of 6K cooler system for MIRI which has been extremely problematic, slow, and costly. Coolers are largely custom developments (*e.g.*, *Planck*, *Herschel*) and while successful, this is a major deterrent to small and medium missions as well as to more ambitious missions using cooled telescopes. TRL for FIR interferometric mission application is 4.
Current TRL	3 - 4
Performance Goals and Objectives	Several mission concepts require sustaining temperatures of a few Kelvin, with continuous heat lift levels of a few dozen to ~200 mW at temperatures ranging from 4K to 18K. Other concepts could benefit from greater heat lifts at somewhat higher temperatures. All this needs to be accomplished with <200W input power. Such coolers need to be compact, and impose only low levels of vibration on the spacecraft. Large FIR telescopes are likely to pose more stringent requirements, if a cryo-cooler is used to cool the primary mirror. In some applications, a sub-Kelvin cooler will be implemented, and an advanced few-Kelvin cryo-cooler able to maintain the sub-Kelvin cooler's hot zone at a steady (*e.g.*) 4K will be very beneficial.
Scientific, Engineering, and/or Programmatic Benefits	Cryo-coolers able to operate near 4K, cooling detectors and optics directly, as well as serving as a backing stage for ultralow temperature (sub-Kelvin) coolers will enable large FIR telescopes, as well as ultra-low-noise operation of cryogenic detectors for other bands. Increased heat lift, lower mass, lower volume, increased operational lifetime, and reduced cost will enable such missions to fly extended durations without wasting critical resources on cooling. Large-capacity cryo-coolers are required to achieve astrophysical photon-background-limited sensitivity in the FIR and meet sensitivity requirements to achieve the science goals for future FIR telescopes or interferometers.
COR Applications and Potential Relevant Missions	This technology is a key enabling technology for any future FIR mission. It is applicable to missions of all classes, including balloons, Explorers, probes, and flagship observatories. For example, it would improve performance of STO2 long/ultra-long duration balloon, SOFIA instruments, and a FIR Surveyor (Roadmap), but other Explorer missions would also be very positively impacted.
Time to Anticipated Need	No FIR missions are called out by NWNH. Thus the timeline for this need is driven by possible Explorer and suborbital missions. Developing and implementing new cryo-coolers in such missions would enable consideration of a large FIR mission in the 2020 Decadal Survey. The earliest possible missions would start with the upcoming SMEX call in FY 2014 or 2015. Immediate funding would take advantage of current development momentum, allowing time for system integration and cryo-thermal system performance verification. Tests on balloons could start anytime.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)	
Name of Technology	**Wide-bandwidth, high-spectral-dynamic-range receiving system**
Description	Receiving systems consisting of an antenna and associated electronics to amplify, filter, and sample the highly redshifted neutral hydrogen signals from Cosmic Dawn, *i.e.*, at redshifts z > 10. The desired signals of interest have amplitudes of milli-Kelvins to potentially a few hundred milli-Kelvin (measured as brightness temperatures), relative to Galactic and other foreground emissions at the level of 1000 to 10,000K, implying spectral dynamic ranges of order 1 million or more (60 dB). Further, signals of interest are generated over a wavelength range comparable to their central wavelength. Finally, given signal weakness, the antenna and associated electronics either must not introduce spectral features at levels comparable to those expected from the signals of interest or the spectral behavior of the antenna and associated electronics must be stable and sufficiently capable of being characterized to the level need to calibrate and remove any such spectral features.
Current State of the Art	Notional designs exist for full systems; proof-of-concept subsystems have been demonstrated in laboratory environments, and the individual components likely to be used in a full system have been demonstrated in relevant environments. A demonstration of subsystems and a full system in a relevant environment has not yet been accomplished.
Current TRL	4
Performance Goals and Objectives	The goals of a program to address this gap are two-fold: 1) Demonstrate the capability to make measurements of sky-averaged highly redshifted neutral hydrogen signals. 2) Demonstrate capability to collect highly redshifted neutral hydrogen signals in a manner that they can be later imaged. If the first goal can be met, the technology capability required for the second goal will also be met. A system capable of fulfilling the first goal can be divided into three key sub-systems: I. Antenna: Proof-of-concept antennas able to receive signals over at least a 3:1 wavelength range have been constructed. The objective is to construct an antenna with a sufficiently stable frequency response that it changes by only a small amount over the expected range of temperatures to which a space-based antenna would be exposed; II. Analog Receiver: The receiver amplifies and if necessary filters and conditions for further processing signals collected by the antenna. The Receiver must be able to be characterized at a level sufficient to allow extraction of the cosmological hydrogen signal at a level of 1 part per million of the signals received by the antenna. Designs for such receivers exist. The objective is to construct one in a laboratory environment, demonstrate its performance, and then construct one for the thermally-controlled environment expected for a spacecraft; and III. Digital Spectrometer: The spectrometer converts analog signals to digital and forms them into spectra with sufficient spectral resolution to detect the cosmological hydrogen signal. Digital spectrometers with the required performance have been developed in a laboratory environment. The objective is to implement a spectrometer with flight-qualified hardware in the thermally-controlled environment expected for a spacecraft.
Scientific, Engineering, and/or Programmatic Benefits	This technology capability would benefit studies of “Cosmic Dawn,” one of the three science objectives for this decade as identified by the NWNH report. Studies of the highly redshifted neutral hydrogen signals will probe the Epoch of Reionization (EoR), NWNH science frontier discovery area, and address the science frontier question “What were the first objects to light up the universe and when did they do it?” from the Origins theme. Studies of highly redshifted neutral hydrogen signals may also be able to probe into the true Dark Ages, before any stars had formed. Such studies would complement COR objectives, and address goals of the PCOS Program.
COR Applications and Potential Relevant Missions	The application is for space- and lunar-based missions designed to find highly redshifted (z > 10) signals from neutral hydrogen. Potentially relevant missions described in the Astrophysics Roadmap include a precursor lunar orbiter mission (Introduction to Chapter 6 of the Astrophysics Roadmap) and an eventual Cosmic Dawn Mapper.
Time to Anticipated Need	Two to three years for a precursor lunar orbiter mission.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	Band-shaping and dichroic filters for the UV/Vis
Description	Bandpass filters are employed throughout astronomy, and efficient transmissive designs are now quite standard in the Vis/NIR. To facilitate accommodation in standard instrument designs, there is a pressing need for high-efficiency UV-transmitting bandpass filters. Because some classes of UV detectors have significant visible light sensitivity, UV transmitting "red-blocking" filters are also of high value. Finally, UV/Vis/NIR dichroic filters are useful in creating multiple channels in an instrument, allowing simultaneous observation using band-optimized instrumentation and detectors over the widest possible FOV.
Current State of the Art	Current state of the art includes UV-transmission filters with efficiencies of <10-20% below 180nm and <50% between 180-280 nm. Red-blocking "Woods filters" with low efficiency (<10-15%) and lifetime issues have been employed for solar-blind imaging. Dichroic filters have been designed for the UV, for example the far-ultraviolet (FUV)/NUV split in the GALEX instrument, but efficiency in each channel (50/80%) and effective bandwidth in each channel (<50 nm) is limited at current state of the art.
Current TRL	4
Performance Goals and Objectives	• Filter transmittance in UV for R~5 bandpass filter: >50% (FUV), > 80% (NUV); • Red-blocking transmittance: >50-75% (UV), < 0.0001%-0.01% Vis-NIR; • Dichroic: Mid-UV Split: R (FUV) > 0.8, T (NUV) > 0.9; • Bandwidth: FUV (100 nm), NUV (100-200 nm); • Minimum wavelength: 100-105 nm; and • Dichroic: UV/Vis Split: R (UV) > 0.9, T (Vis) > 0.9.
Scientific, Engineering, and/or Programmatic Benefits	High efficiency and low noise resulting from out-of-band rejection, and multi-channel instruments using dichroics allow deep astronomical surveys to be conducted with space-based telescopes on much shorter, feasible timescales, and enables instrument designs that exploit the aperture size (geometrical area) and full working FOV of the telescope. Relevant experience with UV, Vis, and/or NIR filters and dichroics that achieve the technical goals set forth above are essential for maximizing the return of future space observatories. This technology is crosscutting, with applications across astrophysics, planetary and space sciences. Commercial applications similarly benefit from high throughput and band-rejection.
COR Applications and Potential Relevant Missions	COR science requires deep multi-wavelength measurements of galaxies and AGN to study their evolution from the formation of the first stars and black holes to structures observed on all scales in the present day universe. High priority is observations of unseen phenomena such as the cosmic web of intergalactic and circumgalactic gas and resolved light from stellar populations in a representative sample of the universe. Potentially relevant missions include a LUVOIR space telescope, Explorer and Probe-class missions that can conduct wide-field surveys and small-sat experiments that can advance technology while addressing one or more COR science objectives.
Time to Anticipated Need	Ideally, filters and dichroics meeting target goals specified above will have been advanced to TRL 6-7 by the end of this decade (2018 – 2019), in time to be incorporated at low risk and high cost confidence in mission designs proposed for the next decadal survey.

Table 3-1. Technology Gaps Evaluated by TMB in 2014 (continued)

Name of Technology	**High-reflectivity mirror coatings for UV/Vis/IR**
Description	High-reflectivity, highly uniform mirror coatings with low polarization are required to deliver high-throughput UV observations, and support high-contrast imaging via starlight suppression. High-reflectivity coatings would allow multiple reflections without throughput penalty in the UV, and provide very wide bandpasses. This capability includes: 1) High reflectance broadband mirrors for the UV/Vis/NIR; 2) Access to the FUV (90-105 nm) spectrum, with minimal impact to sensitivity and wavefront in Vis and NIR; 3) Ultra-high reflectance for multi-mirror instruments with high degrees of multiplexing (Integral Field Units, IFUs; or MOS), particularly in the UV and FUV; and 4) Safe, effective, reliable, last-minute or in-flight mirror cleaning technologies.
Current State of the Art	The best current coatings provide >90% reflectivity for wavelengths 300-2500 nm and longer, ~ 85% reflectivity for 120-300 nm, and <50% for 90-120 nm. Current coatings can provide 2% uniformity and 1% polarization in reflected light. Conventional technologies such as chemical vapor deposition with precision controls have been developed for producing high-performance mirror coatings on large-diameter substrates. New coating technologies such as atomic layer deposition (ALD) have potential to produce higher performance, but have only been applied to small optical components (< 0.5m) Existing approaches for mirror cleaning (*e.g.*, CO_2 snow, or electrostatic wands with AC excitation), do not remove molecular contamination. Promising methods (*e.g.*, electron or ion beams) could clean off molecular layers as well as dust on substrates.
Current TRL	Current coatings 3; new coating technologies 3 (ground), 1 (space); mirror cleaning 1 – 2
Performance Goals and Objectives	1) Develop coatings with excellent UV and FUV efficiency, particularly in the 90 to 2500 nm range (> 90% for as much as possible of this spectral range); 1a) Also develop coatings with excellent UV and acceptable IR efficiency; 2) Develop high-uniformity coatings (<1-0.1%), over a large spectral range (90-2500 nm), with low polarization (< 1%) for wavelengths 400-1000 nm, for high-contrast imaging; 3) Develop techniques to apply these coatings to large optics (0.5-4+ m) as well as to smaller instrument optical elements; and 4) Develop techniques for last minute ground, or in-flight cleaning technology, to remove molecular coatings as well as dust.
Scientific, Engineering, and/or Programmatic Benefits	High coating reflectivity in UV makes possible high-performance optical systems that can be highly-multi-passed, significantly increasing potential impact of future missions. Wideband coatings could enable a combined UV to IR mission with very broad scientific potential from general astrophysics to exo-planet imaging and spectroscopy. The availability of effective, safe, last-minute ground-based cleaning technologies, or in-flight cleaning technologies, could reduce the high cost of keeping equipment clean for a decade in clean rooms. Mirror-cleaning technology could simplify mirror processing before launch and reduce schedule (cost) and mitigate the risks of re-coating. Post-launch cleaning would improve on-orbit performance and could extend mission life.
COR Applications and Potential Relevant Missions	NWNH noted the importance of technology development for a future ≥4m class UV/visible mission for spectroscopy and imaging. This technology would support the next generation of UV missions, including Explorers, medium-size “Probe” missions, and large (>4m apertures) future UV/Vis/IR telescopes, and is key for NASA’s next LUVOIR mission. All future missions with optics, particularly missions with an important FUV or UV component, will benefit from improved coatings. Benefits will also accrue to planetary, heliospheric, and Earth missions utilizing the UV band.

Time to Anticipated Need	The technology needs to reach TRL 5 by 2019, if a LUVOIR astrophysics mission, starting in the 2020s is to receive favorable consideration in the 2020 Astrophysics Decadal Survey. Availability of this technology, at TRL 6, by 2018 would enable a strong UV or FUV Explorer to be selected late this decade. Starting technology work in 2015 would support flight-testing on a suborbital mission to fly in 2017 – 2020. Mirror cleaning would be immediately useful, for missions already in development.

4. Program Technology Priorities and Recommendations

Background

As part of its annual technology prioritization process, the Program Office convened a TMB to prioritize the technology gaps submitted. The TMB followed an agreed-upon set of evaluation criteria, resulting in the priorities shown below. TMB membership included senior staff from NASA HQ Astrophysics Division, the COR Program Office, STMD, and the Aerospace Corporation. For 2014, the TMB used a prioritization approach similar to that used in prior years, with a streamlined set of four criteria. These included strategic alignment, benefits and impacts, applicability, and timeliness.

- **Strategic alignment:** How well does the technology gap align with the science and/or programmatic priorities of the AIP or current programmatic assessment?
- **Benefits and impacts:** How much impact would filling the technology gap have on notional COR mission(s)? To what degree would such technology enable and/or enhance achievable science objectives, reduce cost, and/or reduce mission risks?
- **Scope of applicability:** How crosscutting is the technology? How many Astrophysics programs and/or mission concepts could benefit from this technology?
- **Time to anticipated need:** When does the technology need to be at TRL 6? The Astrophysics Division requires that critical/enabling technology used by projects be at TRL 6 at Key Decision Point (KDP) B, and non-critical/enhancing technology be at TRL 6 at KDP C**. Note that this requirement is more stringent than general NASA guidelines.

The TMB assigned weighting factors, reflecting the relative importance placed on each criterion. Each technology gap received a score of 0 to 4 for each criterion. The scores were multiplied by their respective weights, and the products were summed. Some technologies could be scored based on several missions or mission classes. In such cases, the TMB scored each scenario independently; assigning the highest overall score (*e.g.*, a gap might receive an overall score of 91 for a highly aligned mission, but only 75 for a less-aligned class of missions, in which case it was assigned the higher score). Table 4-1 details the criteria descriptions, weighting factors, and TMB scoring guidelines.

This process provides a rigorous, transparent ranking of technology gaps based on the Program's goals, community scientific rankings of relevant missions, Astrophysics Division priorities as outlined in the AIP, and the external programmatic environment. Since the SAT program is intended to promote development and maturation of technologies relevant to missions and concepts identified as strategic, the strategic alignment criterion is driven by the AIP, which is in turn based on NWNH, but also reflects the impact of more current budget realities.

** See NASA Procedural Requirement 7120.5E to learn more about project KDPs.

Criterion	Weight	Max Score	Max Weighted Score	General Description/ Question	4	3	2	1	0
Strategic Alignment	10	4	40	How well does the technology align with COR science and/or programmatic priorities of AIP or current programmatic assessment?	Applicable mission concept receives highest AIP consideration	Applicable mission concept receives medium AIP consideration	Applicable mission concept receives low AIP consideration	Applicable mission concept not considered in AIP but was positively addressed in NWNH	Not considered by the AIP or NWNH
Benefits and Impacts	9	4	36	How much impact does the technology have on notional mission(s)? To what degree does it enable and/or enhance achievable science objectives, reduce cost, and/or reduce mission risks?	Critical and key enabling technology - required to meet mission concept objective(s); without this technology mission(s) will not be launched	Highly desirable technology - not mission-critical, but provides major benefits in enhanced science capability, reduced critical resources need, and/or reduced mission risks; without this technology mission(s) may be launched, but likely results would be severely degraded	Desirable - offers significant science or implementation benefits but not required for mission success; if technology is available, would almost certainly be implemented in mission(s)	Minor science impact or implementation improvements; if technology is available, would be considered for implementation in mission(s)	No science impact or implementation improvement; even if available, technology would not be implemented in mission(s)
Scope of Applicability	3	4	12	How crosscutting is the technology? How many Astrophysics programs and/or mission concepts could benefit from this technology?	Applies widely to COR mission concepts and both PCOS and ExEP mission concepts	Applies widely to COR mission concepts and either PCOS or ExEP mission concepts	Applies widely to COR mission concepts	Applies to a single COR mission concept	No known applicable COR mission concept
Time To Anticipated Need	3	4	12	When does technology need to be at TRL 6? (Critical/enabling technology must be at TRL 6 by KDP B; Non-critical/enhancing technology by KDP C)	TRL 6 needed within 5 years (before 2020)	TRL 6 needed within 6 to 10 years (2020 - 2024)	TRL 6 needed within 11 to 15 years (2025 - 2029)	TRL 6 needed within 16 to 20 years (2030 - 2034)	TRL 6 needed in more than 20 years (2035 or later)

Table 4-1. *Clear, strategic criteria provide a rigorous, transparent process for prioritizing technology gaps.*

Results

As mentioned above, in 2014, the COR TMB received 25 technology gaps. As a first step, the TMB considered which entries were close enough to each other that combining them and scoring them together would strengthen their case, resulting in 20 gaps. Of these, three were deemed outside the COR charter. Following that step, the TMB scored a final set of 17 gaps. After reviewing the scores, the TMB binned the technology gaps into three groups based on a number of factors, including primarily a natural grouping of overall scores. The groups were as follows (with all entries within a group ranked equally):

Priority 1: Technologies the TMB determined to be of the highest interest to the COR Program. Filling these gaps would provide key enabling technologies for the highest-priority strategic COR missions. The TMB recommends SAT calls and award decisions address these technology gaps first.

1. High-Reflectivity Optical Coatings for UV/Vis/NIR;
2. High-QE, Large-Format UV Detectors;
3. Photon-Counting Large-Format UV Detectors;
4. Affordable, Light-Weight Large Aperture Optics;
5. Wavefront Sensing and Control at the Nanometer Level; and
6. High-Efficiency UV Multi-Object Spectrometer.

Priority 2: Technologies the TMB believes would be critical, highly desirable, or desirable for strategic COR missions. The TMB recommends that should sufficient funding be available, SAT calls and award decisions address closing these technology gaps as well.

1. Band-Shaping and Dichroic Filters for UV/Vis;
2. Photon-Counting Visible and NIR Detector Arrays;
3. High-Performance Sub-Kelvin Coolers;
4. Very-Large-Format, Low-Noise Visible and NIR Detector Array;
5. Large-Format, Low-Noise Far-IR Direct Detectors; and
6. Heterodyne Far-IR Detector Arrays.

Priority 3: Technologies the TMB deemed supportive of COR objectives, but scoring lower than Priority 1 and 2 technology gaps.

1. Ultralow-Noise Far-IR Direct Detectors;
2. High-Efficiency Cryo-coolers;
3. Wide-Bandwidth, High-Spectral-Dynamic-Range Receiving Systems;
4. Far-IR Interferometer; and
5. Large, Cryogenic Far-IR Optics

5. Closing Remarks

This 2014 COR PATR serves as the current snapshot of the dynamic state of technology development managed by the Program Office and provides future directions for technology planning and maturation. As we complete another year of COR technology development activities, we see many positive developments.

Our technology development portfolio is growing, and continues to deliver excellent progress. All funded technologies are maturing toward higher TRLs. COR SAT investments are generating benefits beyond the direct advancement of strategic technologies. These include PIs leveraging their SAT funding to obtain internal funding, contributed materials, and/or facility and equipment usage; hiring students and post-docs, thereby training our future astrophysics workforce; and generating research collaborations and other partnerships, in support of COR science goals.

Our established and streamlined technology gap prioritization process continues to adhere to AIP and NWNH strategic guidance, with the TMB assigning the most significant weight in technology gap prioritization to strategic alignment. As a result, the Astrophysics Division continues to fund projects addressing technology gaps identified by the TMB as having the highest priority.

The latest set of highest-priority TMB-recommendations submitted to the Astrophysics Division include high-performance UV detectors and multi-object spectrometers, affordable lightweight optics and nanometer-level wavefront sensing and control, and high-reflectivity UV/Vis/NIR coatings.

To continue and support the ever-evolving technology needs of the COR community, we continue to interact with the broad scientific community through the COPAG, through various workshops, via public and educational outreach activities, and at public scientific conferences. 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 proven process. Each year, we incorporate new lessons learned and make appropriate improvements to our process.

We would like to thank the COR scientific community, the PIs and their teams, and the COPAG for their efforts and inputs that make this annual report current and meaningful. We welcome continued feedback and inputs from the community in developing next year's PATR. For more information about the Program and its activities, and to provide your feedback and inputs, please visit the COR website.

References

[1] J. Mankins, "*The critical role of advanced technology investments in preventing spaceflight program cost overrun,*" The Space Review, December 1, 2008. Available at www.thespacereview.com/article/1262/1. Accessed May 2014.

[2] National Research Council, "*New Worlds, New Horizons in Astronomy and Astrophysics,*" Washington, DC: The National Academies Press, 2010. Available at www.nap.edu/catalog.php?record_id=12951. Accessed May 2014.

[3] M. Perez, M. Garcia, and L. LaPiana, "*Cosmic Origins Technologies, NASA HQ,*" Cosmic Origins Newsletter, September 2014, Vol. 3 No. 2. Available at http://cor.gsfc.nasa.gov/newsletters/COR_NL_Sept2014-Final.pdf. Accessed September 2014.

[4] M. Perez, B. Pham, and P. Lawson, "*Technology maturation process: The NASA strategic astrophysics technology (SAT) program,*" Proc. SPIE, Montreal, June 2014.

Appendix A
Program Technology Development Quad Charts

Kinetic Inductance Detector Arrays for Far-IR Astrophysics

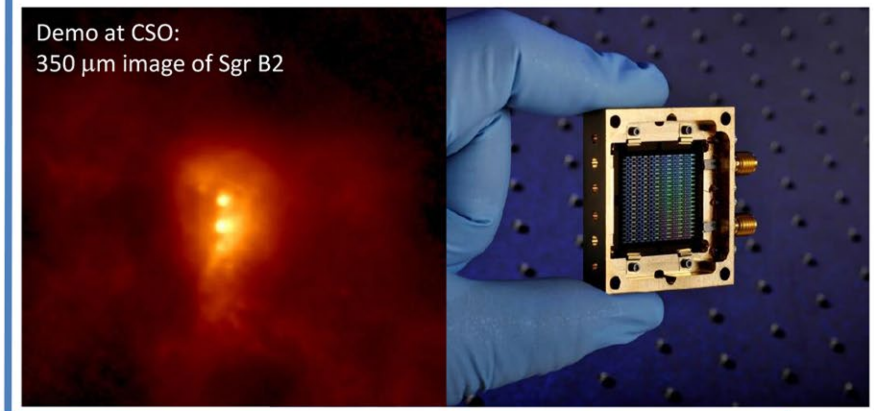
PI: Jonas Zmuidzinas/Caltech

Description and Objectives:

- Half of the electromagnetic energy emitted since the big bang lies in the far-IR. Large-format far-IR imaging arrays are needed to study 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-IR 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) and aluminum absorber-coupled, frequency-multiplexed kinetic inductance detectors.



Approach:

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

Key Collaborators:

- Goutam Chattopadhyay, Peter Day, Darren Dowell, Rick Leduc (JPL)
- Matt Holllister, Attila Kovacs, Chris McKenney(Caltech)

Development Period:

- March 2013 – February 2015

Accomplishments and Next Milestones:

✓ Successful 350 μm telescope demo at the Caltech Submillimeter Observatory (image above)
✓ Photon-noise-limited 350 μm lens-coupled arrays
✓ Operation of detector in dark w/ NEP≈2×10^{-19} WHz$^{-1/2}$
- First optical tests of space-sensitivity arrays (Fall 2014)

Application:

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

TRL $_{In}$ = **3** *TRL $_{PI\text{-}Asserted}$* = **3, 6** *TRL $_{Target}$* = **4-6**

Cross-Strip MCP Detector Systems for Spaceflight

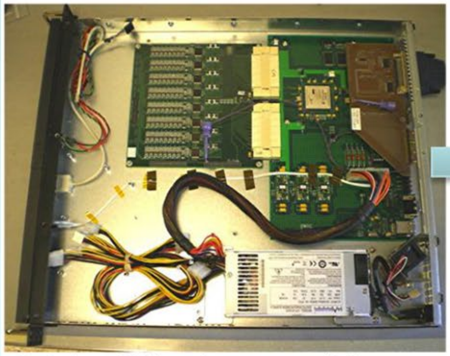
PI: John Vallerga/ U.C. Berkeley

Description and Objectives:

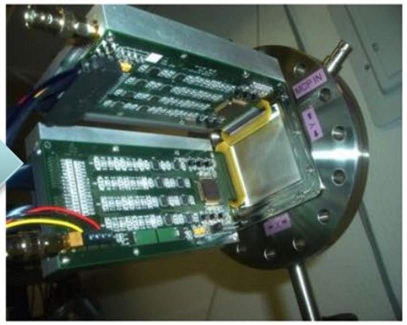
- Cross strip (XS) MCP photon-counting UV detectors have achieved high spatial resolution (12µm) at low gain (500k) and high input flux (MHz) using laboratory electronics and decades-old ASICs. We plan to develop and mature to TRL 6 a new ASICs ("GRAPH") that improves this performance and includes amps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

Key Challenge/Innovation:

- A new ASIC with amplifiers x5 faster yet with noise characteristics similar to those of an existing amplifier ASIC
- GHz analog sampling and a low-power ADC per channel
- FPGA control of ASICs



Existing 19" rack mounted XS electronics



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

Approach:

- We will develop the ASIC in stages, 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 two runs of the full-up GRAPH design (CSA, preamp, and "HalfGRAPH"). 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 2012 – April 2015

Accomplishments and Next Milestones:

- ✓ Completed 50-mm detector design and fabrication
- ✓ Confirmed detector performance with PXS electronics
- ✓ Designed, fabricated, and tested first ASIC amplifier
- ✓ Designed, fabricated, and tested first half-GRAPH1 ASIC
- Design and fabrication of FPGA board (Oct. 2014)
- Design and fab of second version of both ASICs (Fall 2014)
- Environmental tests of Detector + ASICs (Spring 2015)

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
- Fluorescence lifetime imaging (FLIM) for biology
- Neutron radiography/tomography for material science

$TRL_{In} = 4$ $TRL_{Current} = 4$ $TRL_{Target} = 6$

High-Efficiency Detectors in Photon-Counting and Large FPAs for Astrophysics Missions

PI: Shouleh Nikzad/JPL

Description and Objectives:

- Affordable, high-efficiency, high-stability imaging arrays are an efficient and cost-effective way to populate UV/Optical focal planes for spectroscopic missions and 4m+ UV/O telescope as stated in the NWNH Decadal Survey

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:

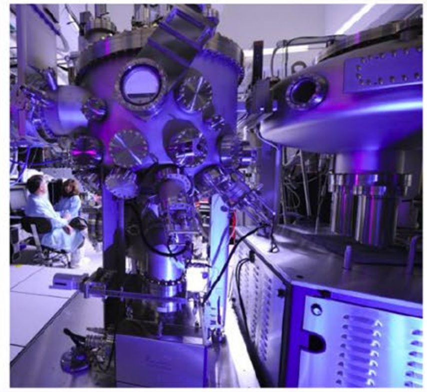
- Develop and produce 2 megapixel AR-coated, delta-doped electron multiplied CCDs (EMCCDs) using JPL's 8" capacity silicon molecular beam epitaxy (MBE) for delta doping and atomic layer deposition (ALD) for AR coating.
- Perform relevant environment testing
- Perform system-level evaluation on-sky to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

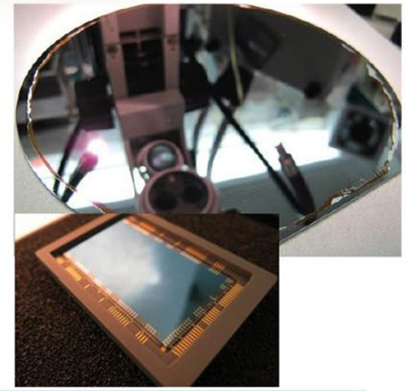
Key Collaborators:

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

Development Period:

- January 2013 – December 2015





Accomplishments and Next Milestones:

- ✓ First 2 Mpixel devices produced from first wafer; several devices packaged as bare delta-doped, several coated with AR layers; devices functional and imaged well in UV; QE measurement ongoing
- ✓ Characterize & validate performance (iterative, first done in FY 2014 Q1)
- ✓ Narrowband AR developed for FIREBall, demonstrated on smaller arrays; QE characterization ongoing.; detectors under evaluation
- ✓ Evaluate performance in astrophysics-relevant and mission-relevant environments (on-sky and FIREBall). Engineering run at Kitt Peak
- Three wafers in various processing stages; complete first of next three wafers in FY 2014 Q4
- Evaluate environmental performance – thermal (FY 2014 Q2 – FY 2015 Q4)
- Technology demonstration run (~ Nov 2014)

Application:

- Large-aperture UV/Optical telescope, Explorers, spectroscopy mission, UV/Optical imaging

TRL_{In} = **4** *$TRL_{Current}$* = **4** *TRL_{Target}*= **5-6**

A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping

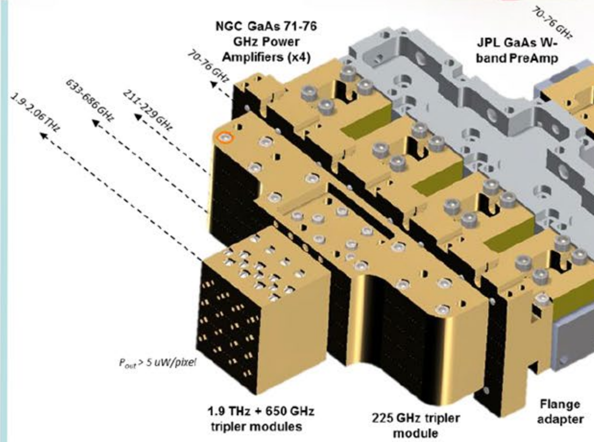
PI: Imran Mehdi/JPL

Description and Objectives:

- Heterodyne technology is necessary to answer fundamental questions such as how do stars form? How do circumstellar disks evolve and form planetary systems? What controls the mass-energy-chemical cycles within galaxies?
- We will develop a 16-pixel heterodyne receiver system to cover both the C+ and the O+ lines.

Key Challenge/Innovation:

- Lack of solid-state sources in the THz range is perhaps the single most important challenge towards implementing array receivers
- Low-power back-end spectrometers
- Multi-pixel receiver characterization and calibration protocols



16-pixel 1.9 THz all solid-state LO source

Approach:

- Use JPL-developed membrane diode process to construct tunable sources in the 1.9 - 2.06 THz range
- Use novel, waveguide-based, active-device, power-combining schemes to enhance power at these frequencies
- Design and build compact, silicon, micro-machined housing for HEB mixer chips
- Use CMOS technology for back-ends/synthesizer
- Characterize and test multi-pixel receivers to validate stability and field performance

Key Collaborators:

- Paul Goldsmith (Science Lead), Jon Kawamura, Jose Siles, Choonsup Lee, and Goutam Chattopadhyay (JPL)
- Frank Chang (UCLA)
- Sander Weinreb (Caltech)

Development Period:

- October 2013 – September 2016

Accomplishments and Next Milestones:

- ✓ Completed system architecture design and interface controls
- ✓ Designed mixer devices
- ✓ Designed multiplier devices
- Fabricate mixer devices (in progress)
- Fabricate multiplier devices (in progress)
- Assemble multiplier chains
- Assemble mixer arrays
- Integrate and test receiver
- Integrate and test receiver system

Application:

- Array receivers for airborne platforms such as SOFIA
- Heterodyne array receivers for future suborbital and space missions
- Array receivers for submillimeter-wave ground telescopes

$TRL_{In} = 4$ $TRL_{Current} = 4$ $TRL_{Target} = 5$

Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes

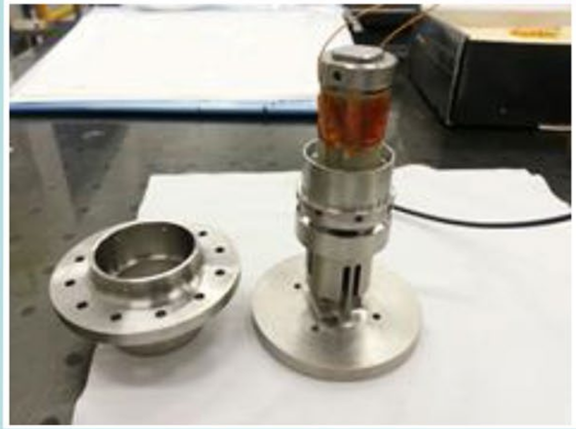
PI: Philip Stahl/MSFC

Description and Objectives:

- Mature TRL of key technology challenges for the primary mirror of future large-aperture Cosmic Origin UVOIR space telescopes
- Pursue 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



Actuator designed, fabricated, and tested at Exelis

Approach:

- Provide guidance and risk reduction for science community to make an informed decision for the 2020 Decadal Survey
- Advance key technology required to enable four different implementation paths
- Develop science and engineering requirements for traceable mirror systems, determine their associated mass, then select a launch system or descope mirror systems and science requirements

Key Collaborators:

- Dr. Scott Smith, Ron Eng, Mike Effinger (NASA/MSFC)
- Bill Arnold (Defense Acquisition Inc.)
- Gary Mosier (NASA/GSFC)
- Dr. Marc Postman (STScI)
- Laura Abplanalp, Gary Matthews, Rob Egerman (Exelis)

Development Period:

- September 2011 – September 2016

Accomplishments and Next Milestones:

- ✓ Designed, fabricated, and tested actuator successfully
- ✓ Received commitment from new partner for three boules to make a 1.5m diameter x200 mm thick mirror
- ✓ Initiated 1.5m mirror design
- ✓ Initiated MOR pathfinder specimen fabrication
- ✓ Initiated 4m & 8m design & analysis tasks
- Award Exelis Phase 2 contract (July 2014)

Application:

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

*TRL_{In} = **3 - 5+** $TRL_{Current}$ = **3 - 5+** TRL_{Target}= **3+ - 6***
(values depend on specific technology)

Ultraviolet Coatings, Materials, and Processes for Advanced Telescope Optics

PI: K. 'Bala' Balasubramanian / JPL

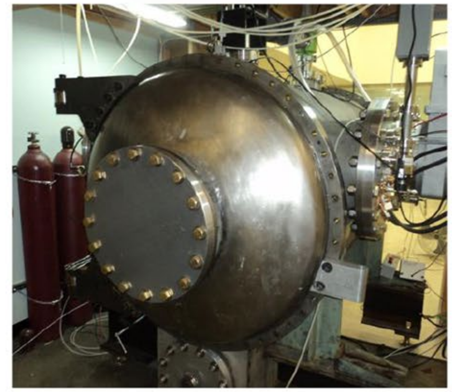
Description and Objectives:

- "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 the Cosmic Origins and Exo-Planets programs. 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 (ALD) will be developed.

ALD chamber at JPL



1.2m coating chamber at Zecoat Corp.

Approach:

- Develop a set of experimental data with MgF_2-, AlF_3-, and LiF-protected Al mirrors in the wavelength range 100 -1000 nm for a comprehensive base of measurements, enabling full-scale developments with chosen materials and processes
- Study enhanced coating processes including ALD; improve characterization and measurement techniques

Key Collaborators:

- Stuart Shaklan, Nasrat Raouf, Shouleh Nikzad (JPL)
- Paul Scowen (ASU)
- James Green (U. of Colorado)

Development Period:

- January 2013 – December 2015

Accomplishments and Next Milestones:

✓ Upgraded coating chamber with sources, temperature controllers, and other monitors to produce various coatings; upgraded measurement tools at JPL and U. of Colorado
✓ Produced and tested coatings with fluorides such as MgF_2 and AlF_3
✓ Fabricated preliminary bi-layer protective coatings
✓ Established ALD coating tools and process at JPL

- Enhancements to conventional coating techniques being developed
- Further improve ALD and other enhanced coating processes for protected and enhanced aluminum mirror coatings (2015)
- Produce and characterize test coupons representing 1m-class mirror (2015)

Application:

- Technology developed through this project will enable future astrophysics and exo-planet missions intended to capture key spectral features from far-UV to near-IR

TRL_{In} = 3 $TRL_{Current}$ = 3 TRL_{Target} = 5

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

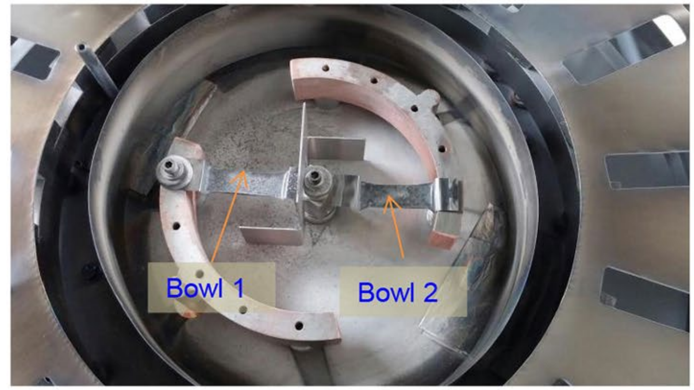
PI: Manuel A. Quijada (NASA/GSFC)

Description and Objectives:

- Development of high-reflectivity coatings to increase system throughput, particularly in the far-UV spectral range
- Study other dielectric fluoride coatings and other deposition technologies such as Ion Beam Sputtering (IBS), known to produce nearest-to-ideal morphology optical thin-film coatings and thus low scatter

Key Challenge/Innovation:

- Achieving high reflectivity (> 90-95%) in the 90 - 250 nm range
- Scaling up coatings to large diameter (meters) mirror substrates



Coating fixture for dual-dielectric deposition in 2m coating chamber

Approach:

- Retrofit a 2m coating chamber with heaters/thermal shroud to perform Physical Vapor Depositions at high temperatures (200-300 C) to further improve performance of Al mirrors protected 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:

- Javier del Hoyo, Steve Rice, Felix Threat, Jeff Kruk and Charles Bowers (NASA/GSFC)

Development Period:

- October 2011 – September 2014

Accomplishments and Next Milestones:

- ✓ Completed shroud and heater installation and performed initial Al+MgF_2 coatings in 2m chamber
- ✓ Completed parameter-optimization study of physical vapor deposition study of lanthanide trifluoride coatings
- ✓ Performed coating study of Al+MgF_2 slide distribution in a 1m diameter
- Perform Al+LiF coatings in 2m chamber (Jul 2014)
- Narrow-band reflector using GdF_3/MgF_2 dielectrics (Sep 2014)

Applications:

- FUV missions investigating the formation and history of planets, stars, galaxies, and cosmic structure; and how the elements of life in the universe arose

TRL $_{In}$ = **3**   *TRL* $_{PI\text{-}Asserted}$ = **4**   *TRL* $_{Target}$ = **4**

Development of Digital Micro-Mirror Device Arrays for Use in Future Space Missions

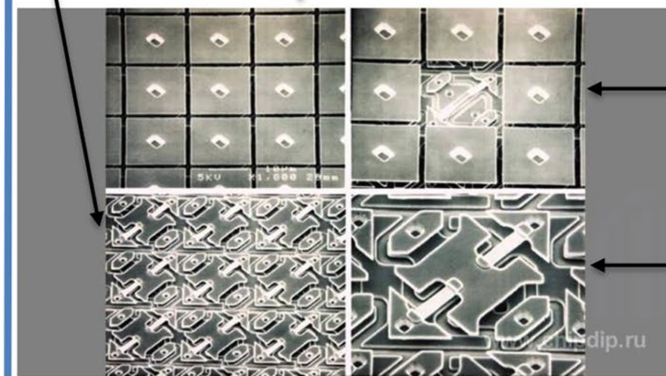
PI: Zoran Ninkov/Rochester Institute of Technology

Description and Objectives:

- There is a need for a technology to allow for selection of targets in a field of view that can be input to an imaging spectrometer for use in remote sensing and astronomy.
- We are looking to modify and develop Digital Micromirror Devices (DMD) for this application.

Key Challenge/Innovation:

- Existing DMDs need to have the commercial windows replaced with appropriate windows for the scientific application desired. Also compact, flexible control electronics need to be developed.



Approach:

- Use available 0.7 XGA DMD devices to develop window removal procedures and then replace window with a hermetically sealed Magnesium Fluoride (and other materials) one.
- Develop a radiation-hard, FPGA-based electronics package to control the DMD.

Key Collaborators:

- Sally Heap, Manuel Quijada (NASA/GSFC)
- Massimo Robberto (STScI)
- Alan Raisanen, Antonio Mondragon (RIT)

Development Period:

- May 2014 – April 2016

Accomplishments and Next Milestones:

- Purchase DMDs and pre-test (Jul 2014)
- Purchase windows and test (Aug 2014)
- Re-window DMDs (Nov 2014)
- Select best UV window vendor (Apr 2015)
- UV-test UV XGA DMD at GSFC (May 2015)
- Re-window Cinema DMD (Jan 2016)
- Reverse-engineer drive electronics (Mar 2016)

Application:

- Can be used in any hyper-spectral imaging mission.
- Galaxy Evolution Spectroscopic Explorer

$TRL_{In} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 4$

Appendix B
Program Technology Development Status

Kinetic Inductance Detector Arrays for Far-IR Astrophysics

Prepared by: Jonas Zmuidzinas (PI; Caltech); Goutam Chattopadhyay, Peter Day, C. Darren Dowell, and Rick Leduc (JPL); Matt Hollister, Attila Kovacs, and Chris McKenney (Caltech)

Summary

This is a two-year project initiated in 2013, focusing on the development of sensitive detector arrays for far-infrared (far-IR; λ=50-500 μm) astrophysics. The detectors must be exquisitely sensitive, capable of measuring a power as low as 10^{-16} to 10^{-19} W in a one-second measurement, known as the noise-equivalent power (NEP). Not surprisingly, the detectors operate at very low temperatures, typically in the range 0.1 – 0.3 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, had several hundred detectors. The largest ground-based instruments, *Submillimetre Common-User Bolometer Array-2* (SCUBA-2) on the *James Clerk Maxwell Telescope* (JCMT), and the *Atacama Pathfinder EXperiment* (APEX) *Microwave Kinetic Inductance Detector* (A-MKID) *camera*, now contain 10,000 and 20,000 pixels, respectively. However, far-IR arrays remain very expensive, difficult to produce and operate, and remain a significant impediment for future development of the field.

The goal of our project is to develop and demonstrate far-IR detector arrays using kinetic inductance detectors (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. A ground-based demonstration of an imaging detector sensitive to a single polarization was performed in April 2013, using the *Caltech Submillimeter Observatory* (CSO). A second CSO demonstration, this time with a dual-polarization detector and with optimized radiation coupling, is planned for 2014. The CSO KIDs are made from titanium nitride (TiN), an excellent choice given the relatively high photon background for ground-based and airborne imagers. Aluminum KIDs are likely a better choice for low-background space applications; within the last year aluminum devices were designed, fabricated, and tested in the dark with encouraging results. Finally, as part of the system design of KID instruments, a chirped-readout approach was developed recently and is nearing the point of on-sky testing at CSO, where it can be compared with the more traditional fixed-tone readout.

Background

The universe shines very brightly at far-infrared wavelengths. In fact, about half 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, based on a handful of early far-IR observations of galaxies. It 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 differently, 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 this band 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, cool to temperatures below 10 K, and 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 to 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/near-IR. Such far-IR studies can be performed locally by imaging sites of star formation in the Milky Way. 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) and the largest ground-based optical telescopes.

Decadal Survey reports provide a long history of strong support for far-IR astrophysics. In 1982, the Field Report 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*, launched by ESA in 2009. The 1991 Bahcall Report recommended the *Stratospheric Observatory for Infrared Astronomy* (SOFIA) airborne observatory, a prime platform for far-infrared 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 IR Observatory* (SAFIR) telescope, was recommended in the 2001 McKee-Taylor report. 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, the 2010 Decadal Survey, New Worlds, New Horizons in Astronomy and Astrophysics (NWNH), made while facing a difficult budget outlook, included a ground-based project that relies on similar array technology (the 25-m *Cerro Chajnantor Atacama Telescope*, CCAT). The NWNH recommendations also included hardware/science involvement in the Japanese *Space Infrared Telescope for Cosmology and Astrophysics* (SPICA) far-IR space mission, and increased support for NASA's balloon program – another prime platform for far-IR astrophysics. Finally, NWNH emphasized many science themes that are highly relevant for far-IR, including the origins of stars and galaxies, and cosmic dawn. The technology being developed in our project thus connects strongly to a broad cross-section of Decadal recommendations, not only in NWNH 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 circa 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 8 array tiles, each with 1280 detectors, for a total of ~10^4 pixels. However, the transition edge sensor (TES)/Superconducting Quantum Interference Device (SQUID) technology used for SCUBA-2, while 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] [2] 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 two-year project, our goal is to perform laboratory demonstrations of KID arrays suitable for airborne, balloon, and space platforms; and to perform an end-to-end, full-system demonstration of an instrument on a ground-based telescope. The key performance specifications are shown in Table 1. Meeting performance requirements is often an iterative process, requiring several cycles of array design, fabrication, and test. Our schedule (achieved milestones marked with a check mark) for these tasks is approximately as follows.

- Space - laboratory demonstration:
  - ✓ April 2014 – Design, fabrication, and test effort leading to successful operation of a suitable device in dark;
  - o Second half of 2014 – Testing of device with small, known optical load; and
  - o First half of 2015 – Second iteration of detector development, including optimal coupling.
- Ground – on-sky demonstration with CSO telescope:
  - ✓ April 2013 – End-to-end system demonstration, but with some limitations (single polarization, sensitivity somewhat worse than background limit); and
  - o August 2014 – Second system demonstration (dual polarization, better sensitivity, on-sky test of chirped readout).
- Balloon – laboratory demonstration:
  - ✓ Previous iterations of tested devices designed primarily for ground-based work have satisfied this performance requirement.
- SOFIA – laboratory demonstration:
  - o First half of 2015 – Test of efficiency and sensitivity for λ = 90 µm operation.

Platform	Optical power	NEP_{phot} (W $Hz^{-1/2}$)	NEP_{goal} (W $Hz^{-1/2}$)	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

Table 1. *Performance specifications for far-IR continuum detectors relevant to this project.*

The second demonstration on the CSO, listed as optional in last year's Program Annual Technology Report (PATR), is now a scheduled, key activity. This schedule also shows some prioritization of work on the low-background detector for space over the work on the SOFIA detector, since the performance requirement for the latter is similar to that for the ground-based detector.

Progress and Accomplishments

Titanium nitride KIDs targeting NEP ≈ 10^{-16} W $Hz^{-1/2}$

The 12-month reporting period began soon after first on-sky testing of JPL far-IR (λ = 350 µm) KIDs. These detectors were made from titanium nitride, which has convenient properties for the far-IR [3]. Overall, this end-to-end system demonstration at CSO in April 2013 was very successful, and images of astrophysical sources were obtained with quality equivalent to those produced by facility far-IR imagers. However, the detector design had not been optimized prior to the observing run, resulting in sensitivity not reaching the photon-background limit.

In the past year, work on higher background (NEP ≈ 10^{-16} W $Hz^{-1/2}$) detectors focused on design and implementation of dual-polarization response (Fig. 1), introduction of a micro-lens array to the detector package for radiation concentration, and tuning of the Ti vs. N ratio and hence critical superconducting temperature to achieve best sensitivity. Further improvements were made to the method of coupling the KIDs to the readout line, and to the fabrication process. Three methods for silicon micro-lens array fabrication were pursued in the last 12 months – laser machining by commercial source (Veldlaser), gradient-index lenses designed and micro-machined by our own team, and anisotropic etching using a mask of hemispherical photo-resist bumps. A Parylene film applied by a commercial vendor is used for anti-reflection coating. The laser-machined and gradient-index lenses have been tested optically with the KID arrays and shown to work well in concentrating the radiation and improving responsivity.

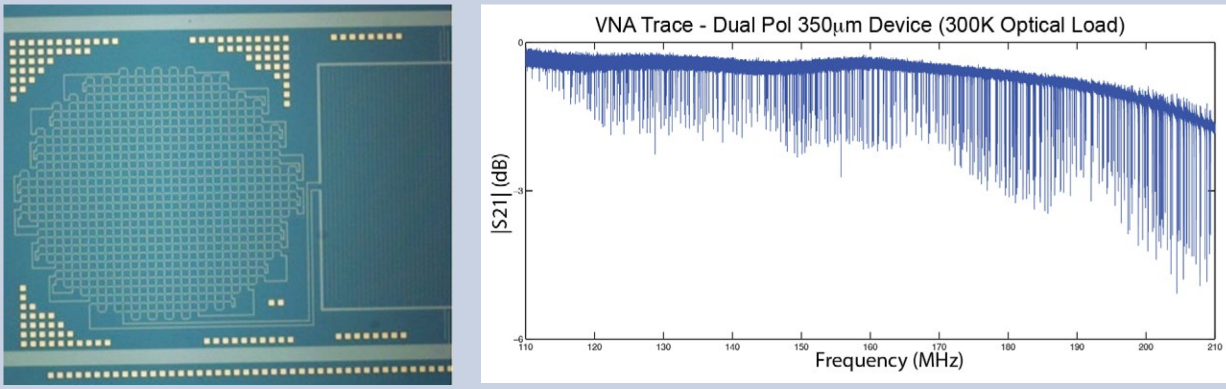


Fig. 1. Left: *Micrograph of single detector (TiN KID) in an array that will be tested on the CSO telescope in August 2014. The square grid with circular boundary at left is the photosensitive inductive element of the KID with a 540-μm diameter, appropriate for a micro-lens-coupled device operating at 350 μm.* Right: *Vector Network Analyzer "sweep" of frequency range occupied by the KIDs, showing absorbed power at the resonance of each of the ~500 detectors.*

As a result of detector design improvements, the TiN detectors are background-limited at 350 μm for 100 K to 300 K loads in the lab. An array of 488 such detectors with the Veldlaser micro-lenses will be brought to CSO for follow-up testing and system demonstration in August 2014.

There was no dedicated effort on the balloon 350-μm or SOFIA 90-μm detectors within the past 12 months. However, as part of the work on the ground-based detector, some devices have been tested with 220- and 350-μm filter bands and with cryogenic blackbody loads consistent with the tabulated background for a balloon-borne application, in several cases showing photon-background-limited performance.

Aluminum KIDs targeting NEP ≈ 10^{-18} W $Hz^{-1/2}$

While TiN KIDs cover a broad wavelength range for detectors operating with > pW background power, Aluminum KIDs are more appropriate for ~fW backgrounds. In general, the volume of a KID optimized for NEP scales with background power [4]. At the small volume needed for space backgrounds, the much lower resistance of Aluminum in the IR makes it easier to satisfy the condition for efficient radiation absorption for a device with convenient surface area.

Our own work on Al KIDs for the far-IR began in the last 12 months. We fabricated KID arrays (Fig. 2) using aluminum absorbers with an absorber line-width of 150 nm on a 15-μm pitch and a volume of 38 μm^3. The 20 nm thick aluminum has a per square resistance of 1 ohm, resulting in an effective absorber resistance of 100 ohms, appropriate for matching to radiation through silicon.

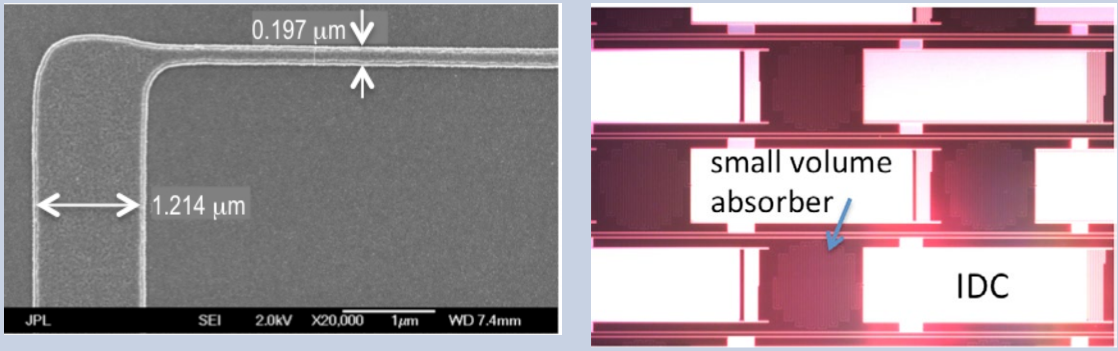


Fig. 2. Left: *Micrograph showing a section of the small volume aluminum absorber. Lines as narrow as 150 nm were fabricated using the deep UV stepper lithography system at JPL's Micro-devices Laboratory. Narrower lines were fabricated using e-beam lithography.* Right: *A section of an array of aluminum Lumped Element Kinetic Inductance Detectors (LEKIDs) with 150-nm line-width. The pixel design is similar to the TiN design shown in Fig. 1; the major difference is a much smaller area filling factor for the aluminum absorber, due to the much lower resistivity of aluminum vs. TiN.*

We have two lithographic tools we can use to achieve these 150-nm wide lines, the Canon fpa3000-EX6 5x deep ultraviolet projection lithography stepper, and the JEOL JBX-9300 FS electron-beam lithography system. The e-beam tool can easily achieve these dimensions, but the patterns are serially written and the process is slow and costly. The stepper exposes in a parallel fashion one field at a time and is faster, but is limited in resolution and depth of focus, requiring significant lithographic optimization to achieve these dimensions. We have produced KID devices using each approach.

Array sensitivity was estimated using thermal calibration. In this method, the array base temperature is swept, and the frequency response to the thermally generated quasi-particle population is measured to derive the response to input optical power. In order to convert from optical power to quasi-particle density changes, the recombination time needs to be known, but is not straightforward to infer from response time measurements when the resonance frequency is in the ~300 MHz range, because the resonator response time is normally slower than the quasi-particle recombination time. To estimate detector sensitivity, we have assumed a recombination time of 1 ms, which has been previously measured for aluminum. The derived sensitivity of ~$2\mathrm{x}10^{-19}$ W $\mathrm{Hz}^{-1/2}$ (Fig. 3) is very encouraging. Future measurements will focus on characterizing the optical response using a black body thermal source and on measuring the optical power range over which the arrays achieve background-limited performance.

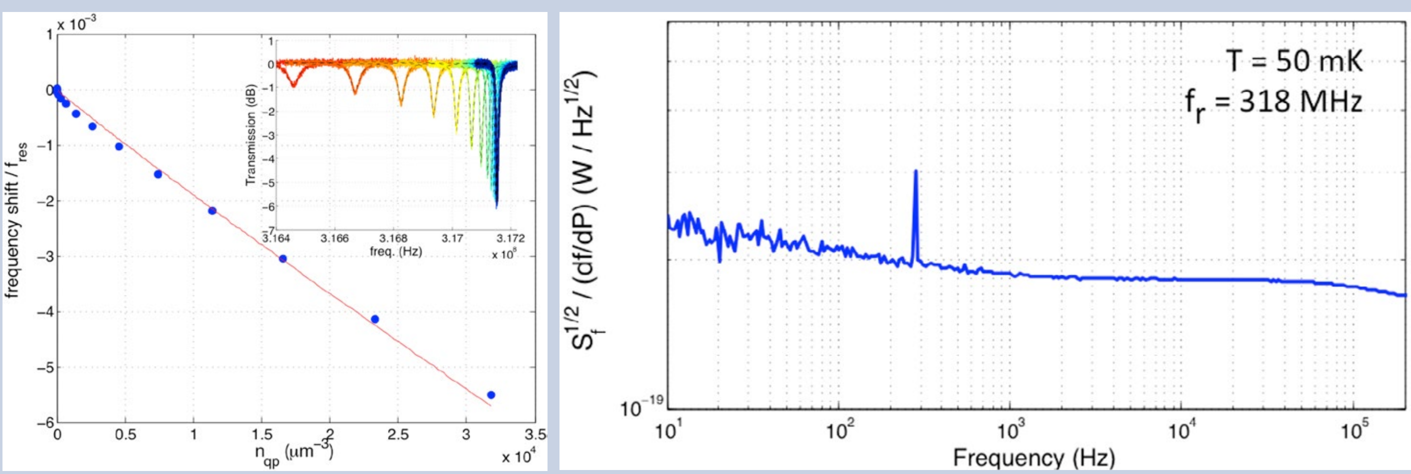


Fig. 3. Left: *Calibration of detector sensitivity using thermal measurements. The resonance frequency is measured vs. bath temperature (inset). The response of the detector to absorbed power is inferred from the measured frequency shift vs. thermal quasi-particle density.* Right: *Measured frequency noise spectrum expressed in NEP units using the thermal response data and assuming a quasi-particle lifetime of 1 ms.*

Chirped readout for KIDs

In a traditional KID readout, each of the resonances is excited with a fixed tone, and the time-variable amplitude and/or phase shift of the tone due to changes in incident radiation is recorded. This works well in many instruments, and is the primary readout technique for our CSO 350-µm demonstration camera. However, the fixed-tone readout loses sensitivity when the resonances shift by ~half a line-width or more. A chirped readout (Fig. 4) addresses this issue; the entire frequency band containing the resonances is excited in a successive manner, and resonant frequencies can be tracked even if they move significantly.

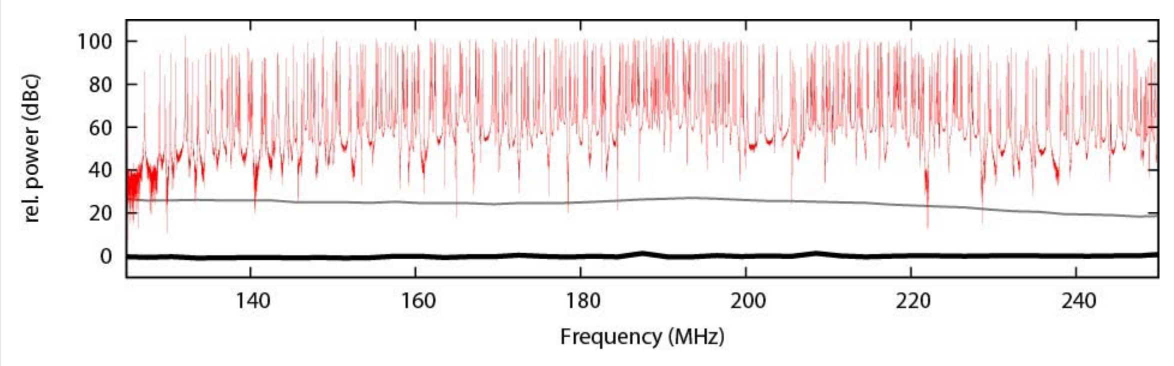


Fig. 4. *Spectrum of KID resonances measured with a chirped readout. In this implementation, a brief radio-frequency chirp is applied to the input line. Then, during a "listening" period, the output signal is digitized and Fourier-transformed, and the resonators that are ringing due to the chirp excitation are identified and stored. The chirping and identification can be done at kHz rates. This particular chirp test was performed on the 2nd generation 350-µm KID, and the signal (red) to noise (upper black) ratio was sufficient for the readout noise to be negligible.*

Our first chirp readout implementation was tested in September 2013 using a PC-based system containing a Pentek Analog-to-Digital and Digital-to-Analog Converters (ADC/DAC) board and a Graphics Processing Unit (GPU) board. During these initial tests, we successfully read out all pixels in the 1st generation 350-µm array in the 125-250 MHz range, at up to 3.6 kHz readout rate, outputting spectral channels in a selected bandwidth. Since then, we made progress in the following areas.

- Real-time searching and fitting of resonances to spectra on the GPU, allowing us to record line frequencies (or shifts) directly. In January 2014, we successfully tested line extraction using centroids on 2nd generation 350-µm devices. Since then we also implemented a maximum-likelihood method. Both approaches are optimal, *i.e.,* they both achieve the Cramer-Rao lower bound for extracting frequency information from resonant spectra.
- Improved dynamic range by optimizing excitation and readout amplification. The inherent readout noise floor (DAC and ADC) corresponds to a resonator frequency noise of ~10 mHz $s^{1/2}$ for ~1000 resonators. Thus, the chirp readout noise is well below background-limited performance (BLIP) for 1st-generation 350-µm devices (Noise-Equivalent Frequency Shift, NEFS ≈ 400 mHz $s^{1/2}$), and should be below BLIP for future instruments. Readout noise may be further suppressed with respect to BLIP using higher responsivity devices, if necessary.
- Implemented real-time matching of extracted lines to a fixed catalog of resonances (on the GPU), to output the same channels at all times, and thus produce 'detector' time streams. This mode will be tested in July 2014.

Path Forward

The devices designed, fabricated, and tested so far show significant progress toward TRL advancement and applicability for future far-IR astrophysics instruments. The next steps are as follows.

- Demonstrate dual-polarization, background-limited operation of a ground-based 350-μm detector, planned for CSO in August 2014;
- As part of the CSO run, perform an on-sky test of the chirped readout and compare with the fixed-tone readout;
- Perform an optical test of the aluminum detector with very low inferred NEP suitable for space applications; and
- As resources allow, perform a 90-μm lab demonstration of a higher background detector suitable for a suborbital instrument.

References

[1] Day, Peter K., Henry G. LeDuc, Benjamin A. Mazin, Anastasios Vayonakis, and Jonas Zmuidzinas. "*A broadband superconducting detector suitable for use in large arrays,*" Nature 425, no. 6960 (2003): 817-821.

[2] Doyle, Simon, P. Mauskopf, J. Naylon, Adrian Porch, and C. Duncombe. "*Lumped element kinetic inductance detectors,*" Journal of Low Temperature Physics 151, no. 1-2 (2008): 530-536.

[3] Leduc, Henry G., Bruce Bumble, Peter K. Day, Byeong Ho Eom, Jiansong Gao, Sunil Golwala, Benjamin A. Mazin *et al.*, "*Titanium nitride films for ultrasensitive microresonator detectors*," Applied Physics Letters 97, no. 10 (2010): 102509-102509.

[4] Zmuidzinas, Jonas. "*Superconducting microresonators: Physics and applications*," Annu. Rev. Condens. Matter Phys. 3, no. 1 (2012): 169-214.

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Cross-Strip MCP Detector Systems for Spaceflight

Prepared by: John Vallerga (Space Sciences Laboratory, UC Berkeley)

Summary

Micro-Channel 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 University of California (UC) Berkeley's Space Sciences Laboratory 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 12μm 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 [1]. 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 has been successfully flown on a rocket flight in 2014 [2].

The goal of this Strategic Astrophysics Technology (SAT) program is to raise the Technology Readiness Level (TRL) of this XS technology by:

1. Developing new Application Specific Integrated Circuits (ASICs) that combine optimized faster amplifiers and associated Analog to Digital Converters (ADCs) in the same chip(s);
2. Developing a Field Programmable Gate Array (FPGA) circuit that will control and read out groups of these ASICs so that XS anodes of many different formats can be supported; and
3. Developing a spaceflight-compatible 50 mm XS detector that can be integrated with these electronics and 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 cost and development risk for future Explorer-class missions. New technological developments in photocathodes (*e.g.*, GaN) or MCPs (*e.g.*, low background, surface engineered borosilicate glass MCPs) could be accommodated into this design as their TRLs increase.

Since the start of our three-year project in April of 2012, we have designed and constructed a 50-mm XS detector with a new low-noise anode, and have demonstrated its excellent performance using our best laboratory electronics. The first versions of our ASICs have been designed, fabricated, and tested; and the second versions are soon (Fall 2014) to be submitted to a foundry for fabrication.

Background

The 2010 Decadal Survey, New Worlds, New Horizons in Astronomy and Astrophysics (NWNH), commenting on UV astronomy, noted *"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 [3][4]. Our SAT program plans to take our successful XS technology that achieves the performance goals above in the laboratory, and raise its TRL by lowering its mass and power and qualifying it for space use.

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.*, 80, 160) whose individual outputs must all be digitized and analyzed. The advantage of this technique over existing and previous MCP readout techniques (wedge and strip, delay-line, intensifiers) is that the anode capacitance per amplifier is lower, resulting in lower noise. 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 [5], thereby increasing the dynamic range of MCP detectors by up to two orders of magnitude. They can also be readily scaled to large (> 100 mm × 100 mm) or other unique formats (*e.g.*, circular for optical tubes, rectangular for spectrographs, and even curved anodes to match curved MCP focal planes). The XS readout technology is mature enough to be presently used in the field in many laboratory environments producing quality scientific results [6][7] and is ready for the next step of development – preparing for an orbital or deep-space mission implementation.

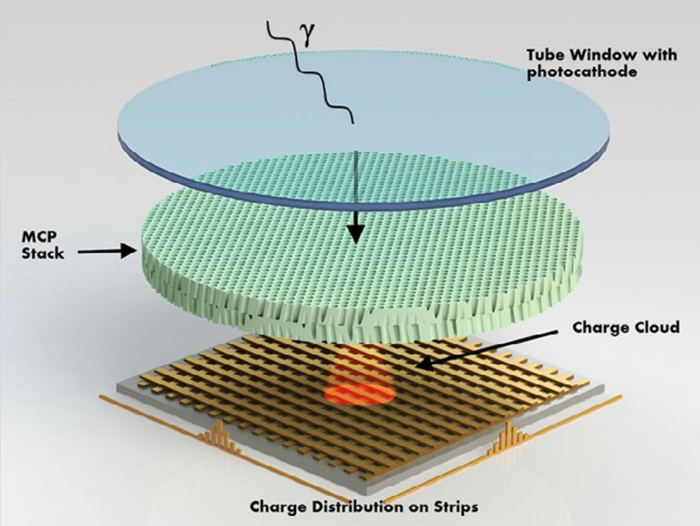

Fig. 1. *Schematic of a cross-strip readout behind an MCP stack.*

Our current XS readout electronics, called the Parallel XS (PXS) electronics, consists of a preamplifier board placed near the MCP anode and a rack-mounted set of electronics containing ADCs and FPGAs. The existing PXS electronics performance presently meets or exceeds ALL of the specifications of the previous flight systems mentioned above. However, the PXS laboratory electronics are too bulky and 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 an 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 an XS readout using our new ASICs. The new ASICs and FPGA control electronics will be integrated into a compact package so the performance of the whole detector system 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 UV sounding rocket programs (*e.g.*, at Johns Hopkins University, JHU, and the University of Colorado) currently use MCP detectors. 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:

a) An optimized front-end charge-sensitive amplifier matched to the anode strip load capacitance with fast signal rise and fall times to minimize event "collision;"
b) Fast (~GHz) analog sampling to fully characterize both amplitude and arrival time of the intrinsically fast input charge pulse;
c) Digital conversion of the analog samples in the ASIC, avoiding complex, bulky, and high-powered discrete ADCs downstream; and
d) 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.

The original proposal called for an ASIC that included a multichannel preamp and an analog sampling and digitization circuit controlled externally by an FPGA. We soon realized that optimization of the analog amplifiers and digital circuits is best done using different fabrication technologies (IBM 130 nm 1.2V CMOS process, 250 nm for the digital) and noise performance would also improve by not mixing the digital and front-end analog on the same piece of silicon. The original name for the combined ASIC (never built) was called the Gigasample Recorder of Analog Waveforms from a Photodetector (GRAPH) but after separation of the amplifiers, the sampling digitizer has been named the "HalfGRAPH."

2. FPGA system to read out HalfGRAPH ASICs

Our proposed parallel XS readout system is not simply comprised of the new ASICs. New board assemblies must be designed, laid out, and constructed to couple these ASICs to our existing XS anodes, minimizing stray load capacitances and incorporating 64 Low Voltage Differential Signaling (LVDS) pairs. These "Digitizer ASIC" boards must send their signals to a new FPGA board that not only has a new input interface, but 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), currently in APRA development. Key issues for the XS MCP detector implementation include a low-mass, robust construction scheme that accommodates the capability for a high-vacuum sealed-tube configuration. Without incurring excessive costs, a reasonable format to accomplish this is ~50 mm. Our expectations are spatial resolution of ~20 µm, background rates < 0.1 events cm^{-2} sec^{-1}, low fixed-pattern noise and long lifetime, ~50% quantum efficiency over much of the extreme-UV (EUV) – far-UV (FUV) band, multi-megahertz rate capability with low dead-time, and detector mass of a few hundred grams. The design and construction of brazed body assemblies provides for the best packaging and diversity of applications, so this is one of the core tasks. The overall configuration represents a device compatible with 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 implementation of much larger-format devices for large optics/missions.

Progress and Accomplishments

Three parallel efforts are expected to come together in the final year of this program – ASIC design and fabrication at the University of Hawaii; FPGA control electronics at UC Berkeley; and 50 mm XS detector design, also at UC Berkeley. Initial versions of the ASICs have been fabricated and tested, as has the 50 mm detector (although using the PXS readout electronics).

ASIC Design

We have so far fabricated two ASICs – the 16-channel charge-sensitive amplifier called "CSA_v2" (Fig. 2) and the 8-channel HalfGRAPH. The CSA_v2 successfully amplifies signal, though with a very high noise value. The HalfGRAPH also did not work as expected, because the internal digital to analog converters

(DACs) that bias many of the circuit elements could not be set via the shift register (which did work). We believe we have traced this mistake to the conversion of an existing design to a different design and modeling software (from Tanner to Cadence). We are proceeding to redesign the HalfGRAPH (version 2), fixing this error as well as others identified. Therefore, we have no results to present for the HalfGRAPH, and the section below discusses this new design of the HalfGRAPH2.

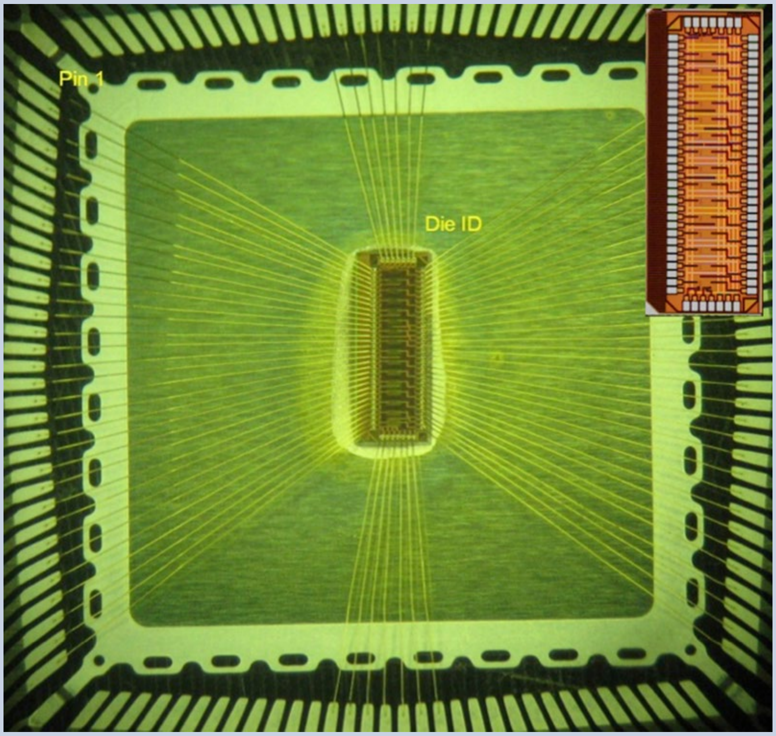

Fig. 2. *CSAv2 mounted on 128-pin package with 16 inputs on the left and 16 outputs on the right. (Inset – die close-up).*

CSAv2

Our goal for the new preamp was to maintain the noise figure of the existing PreShape32 of around 1000 e- root-mean-square (rms) but to increase the waveform speed, doubling the rise-time to 20 ns and significantly decreasing the time back to baseline to < 100 ns to reduce pileup at high event rates. At an MCP gain of 10^6, the largest signal expected on a single strip is on the order of 50 fC. We chose the number of channels per die to be 16 to help with the fan-in from the 80 inputs from the 50 mm anode. The amplifier should also be able to drive the input of the HalfGRAPH and the short trace between them.

The resultant die (Fig. 2) was fabricated and bonded in a 128-pin package. Initial results were disappointing, requiring extremely careful biasing to keep the signal stable while minimizing noise. The amplifier demonstrated a 22 ns rise-time and an ~80 ns return to baseline, achieving our timing goals. However, the best noise performance achieved by biasing the circuit was ~2300 e- rms. In terms of gain, the chip exhibits inconsistent behavior from channel to channel. Computer simulations reveal several design flaws that contribute toward a suboptimal noise floor. Measuring and modeling the behavior of the CSAv2 has led to important insights on what to redesign for the next version of the amplifier.

In parallel to measurements and simulations, a more basic study investigated better coupling between the stages using circuit analysis tools in the Octave programming language. A transfer function was identified which gives good pulse-shaping having the pulse rise and fall time enclosed between 50 ns. The gain ratios of the preamplifier and shaper are yet to be defined. The CSA is undergoing a redesign addressing these issues by resizing the input capacitor, providing a better power supply rejection ratio, adding internal DACs for each channel, and improving the basic architecture of the amplifier.

Half-GRAPH2

HalfGRAPH2 is a 16-channel, 1 giga-sample per second waveform digitizing chip with 12-bit resolution (Fig. 3). It is being designed in the Taiwan Semiconductor Manufacturing Company (TSMC) 0.25 µm CMOS technology, using Tanner EDA design and simulation tools. The circuit's heritage is the TeV Array Readout with GSa/s sampling and Event Trigger (TARGET) ASIC used for photomultiplier waveform sampling in a Cherenkov telescope array [8]. Each channel of this digitizer chip has a 2-stage analog storage mechanism. In the first stage, a short sampling array is subdivided into two sample windows each with 32 switched-capacitor storage cells. In the second stage, in a ping-pong fashion, as one sample window is filling, the other is transferred into a larger storage array. This storage array has 8192 cells, organized as two banks of 64 rows of 64 samples each (also called a storage window) for every channel. This results in a continuous sample of 8.192 µs in length before being overwritten in a circular buffer fashion.

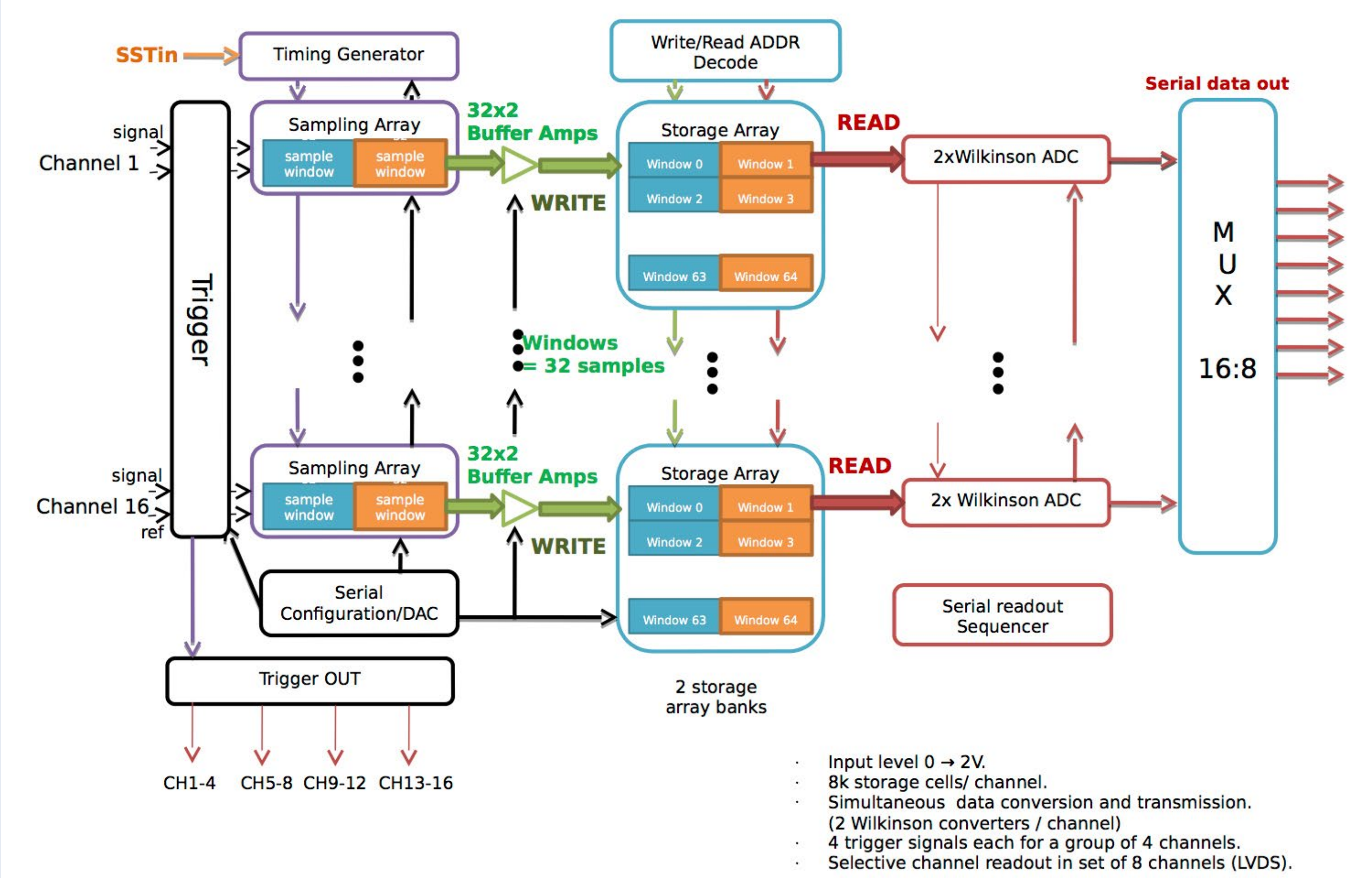

Fig. 3. *Functional schematic of the HalfGRAPH2 ASIC design (described in detail in the text).*

The input analog trigger circuit has four digital output lines that notify a control FPGA of a new event. A trigger pulse is set in place if the measured signal on a channel is higher than a preset threshold. Trigger lines are organized to cover channels 1-4, 5-8, 9-12, and 13-16. This allows finer localization of the strip where the event occurred. The trigger arrival into the FPGA marks the address in the storage array of the samples for that event.

In order to digitize the acquired signal, each channel uses two banks of 12-bit Wilkinson ADCs. An FPGA selects the storage window to be digitized. Thirty two analog samples in parallel on all 16 channels of the storage window are converted concurrently into digital values using comparators, a voltage ramp, and counting (12-bit counter) with a 500-MHz dual-phase clock until the comparator fires when the ramp exceeds the analog value on the cell. It takes 4.1 µs to complete the digitization. At this point the 32 time samples of 12-bit data are sent out serially over LVDS lines with a 250-MHz clock to the FPGA in 1.5 µs (=12*32/250 MHz). This is done for a subset of 8 channels in parallel, chosen by the FPGA based on trigger information, allowing the centroid calculation using the properly filtered amplitude derived from the waveform. When the data transfer starts, the next window is digitized by the second Wilkinson converter which takes over the next transmission, saving 1.5µs.

Because the FPGA has the address of the events in the storage array, it can prevent overwriting of those cells. Therefore, the throughput of the system is limited by the ADCs' 4.1μs conversion time. The maximum throughput of one channel is 240 kHz, but there is no dead-time at rates below this frequency due to the multiple buffering. With five independent ASICs per axis, the event rate that can be supported is 1.2 MHz. The readout rate can be greatly increased by decreasing the bit resolution. For a 10-bit converter, the event rate could reach 5 MHz. Since the event data will be digitally filtered by the FPGA processing, 10 bits will most likely be more than enough to achieve high signal-to-noise ratio.

The 16-to-eight multiplexer allows selection of a group of eight channels out of 16, thus reading out all 16 channels is not necessary. During the operation, a total of eight strips will be transferred per event, allowing the centroid calculation with the properly filtered amplitude derived from the waveform samples. Meanwhile, during data readout, fresh events are stored in the storage array being prepared to read out. This allows multi-hit readout system operation as long as the storage array does not overflow.

The HalfGRAPH2 design and simulation is far along, with a goal of submission to the foundry in early September 2014. We are using the Tanner EDA tools that were used for the working TARGET ASICs, providing strong confidence that these chips will operate properly. Scaling from the TARGET designs, we expect the power consumption to be on the order of ~10 mW/channel (quiescent), so for 160 channels (X and Y) the total power is expected to be 1.6 W, but higher for high event rates.

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 resources have started. The HalfGRAPH2 will have an LVDS line per channel to meet our throughput requirements, and if we design for 80 × 80 channels, that would mean 160 LVDS lines running at 250 MHz. Our scheme to avoid this is to use a simple but fast FPGA (*e.g.*, Spartan) to divide by four the number of LVDS lines required, by condensing four 250 MHz lines into a single GHz LVDS line into the downstream FPGA. These rates are not a problem for current-generation FPGAs, even flight-qualified ones.

50 mm XS Detector

There are two key aspects to our new flight-like 50 × 50 mm XS detector design. The first is a photolithographic and laser-cut XS anode design made with polyimide. Polyimide's dielectric constant is a factor of three less than alumina ceramic, resulting in lower individual strip capacitance, and therefore lower amplifier noise. The top strip pattern is first etched in the copper, and then a laser ablates 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. 4, installed in the 50 mm XS detector, with the measured strip capacitances matching 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. 5). The other key aspect of our detector is using a Kovar and ceramic brazed body to mount the MCPs over the XS anode. This technique is used in vacuum image tube construction to make a strong, robust, and clean detector that can survive launch stress. Figure 4 shows the brazed body mounted over our XS anode onto a vacuum back-plate with three high voltage (HV) feed-throughs (the MCPs have been removed to show the anode below).

Imaging Results with 50 mm detector

As the readout ASICs are still under development, we used our existing PXS_II electronics and the 64-channel amplifier boards to read out the central 64 × 64 strips of this 80 × 80 XS anode. This corresponds to a central active area of 40 mm × 40 mm. The results below use a stack of two MCPs from Photonis USA with 10 μm pores on 12.5 μm centers 53.7 mm × 53.7 mm and 60:1 L/d ratio (600 μm thick each). We measured the spatial resolution and linearity, and acquired flat fields to measure the UV response uniformity to 183 nm light from a Hg pen ray lamp.

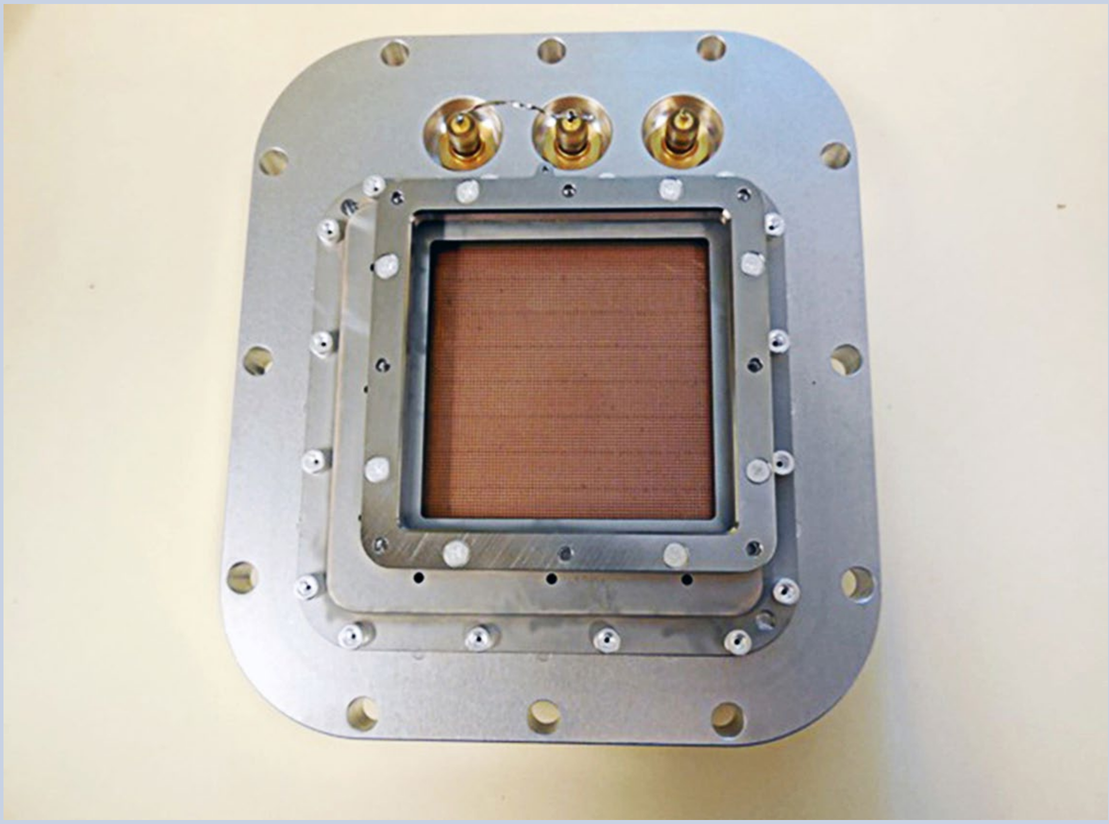

Fig. 4. *View of windowless 50 mm XS detector mounted on a vacuum flange with three HV feed-throughs showing the XS anode (MCPs removed).*

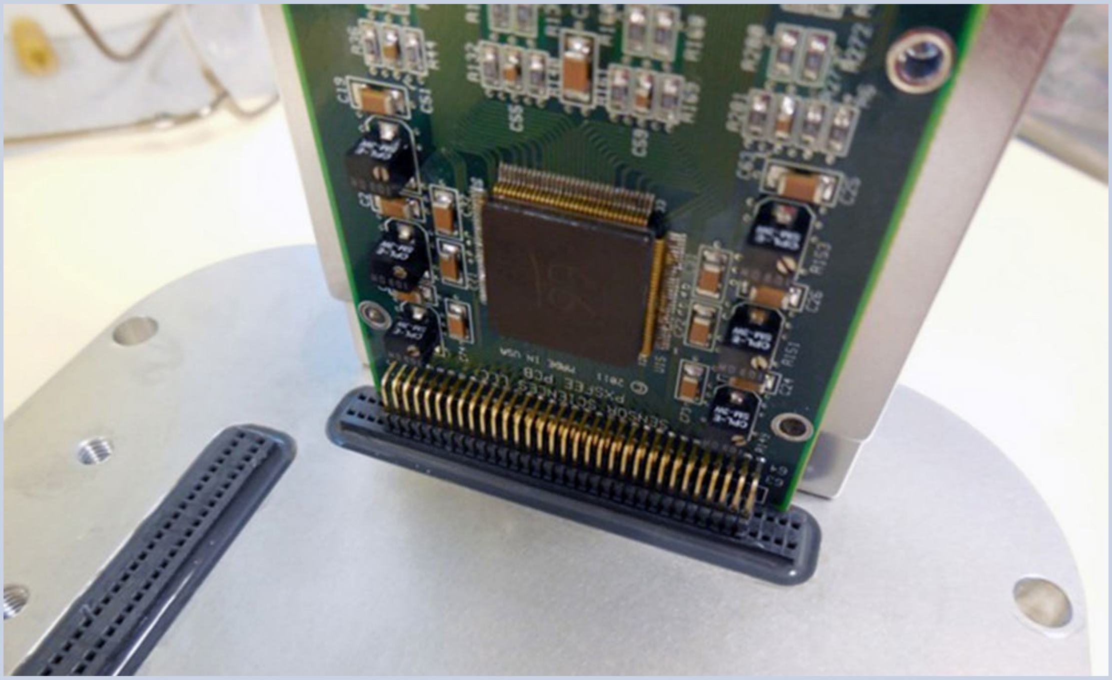

Fig. 5. *External side of detector showing 80 contact feed-throughs (×2) sealed with epoxy and a 64-channel preamp board plugged into one axis.*

To measure the spatial resolution, we used a pinhole mask grid mounted directly on the input MCP. The pinholes are 10 μm in diameter and spaced 1 mm apart on a square grid (Fig. 6), an excellent method of sampling the Point Spread Function (PSF) across the field of view. To measure the spatial resolution, we had to bin the X,Y event data to 8192 × 8192 (5 μm pixels) to resolve the PSF. The inset of Fig. 6 shows the X dimension PSF (top strips) of a single pinhole. The average spatial resolution in the X and Y dimension was 17.5 μm FWHM and 22 μm FWHM, respectively.

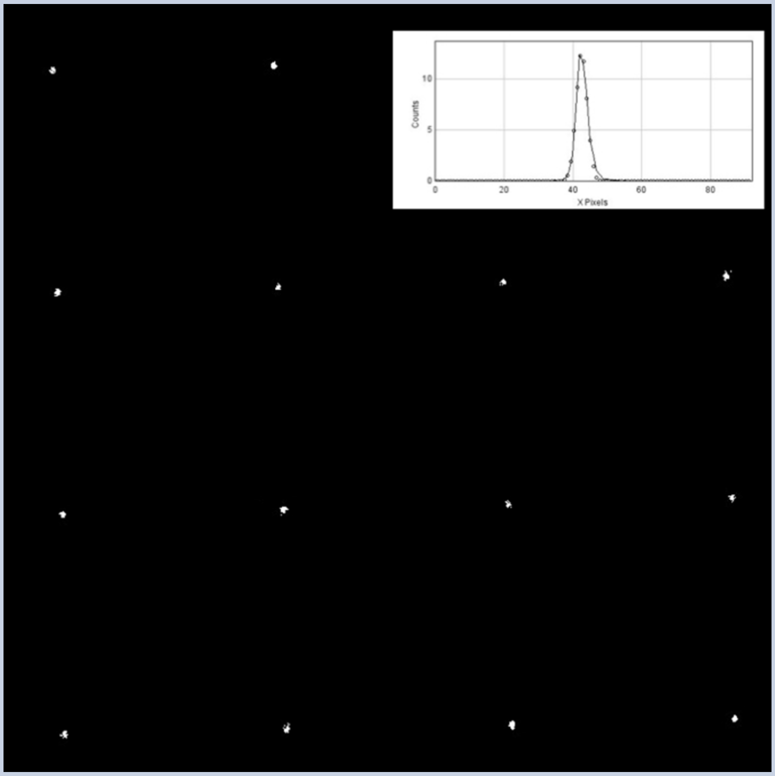

Fig. 6. *UV image of pinhole mask of 10 μm holes on 1 mm square grid. Inset shows the PSF of a single hole with resolution of ~4 pixels FWHM (20μm).*

The detector linearity can also be measured with the pinhole mask data, as the pinholes are uniformly spaced at 1 mm. Figure 7 show the residuals (in μm) to a linear fit to the pixel position of the pinhole vs. pinhole number. The ±15 μm deviation from zero is smaller than the detector spatial resolution measured above, and comparable to the hexagonal 12.5 μm pore spacing. This measurement attests to the accuracy of the photolithographic anode strip regularity.

No detector has a perfectly flat response. For MCP detectors, a uniform input illumination can reveal variations in the MCP sensitivity plus nonlinearities in the X,Y determination of the charge cloud centroid by the anode. To measure response flatness, we collected more than 30 billion counts to achieve 460 counts per 5 μm pixel. Figure 8 is a small, 2.5 mm × 2.5 mm section of a UV flat field. There is a hint of fixed pattern noise and compressing the data in both dimensions reveals the presence of a differential nonlinearity at the strip spacing in the Y (bottom) dimension. The effect is at the 3% level peak-to-peak, and can be corrected with a lookup table. We used this flat field to divide another flat field taken the next day (140 counts per 5 μm pixel) and binned to 20 μm pixels. The second flat had only 34% of the counts of the first flat, but the resultant divided image (Fig. 9) shows no fixed pattern and is consistent with Poisson statistics expected from the two images. The inset of Fig. 9 is the histogram of the image pixel values, and has a standard deviation of 2.3%.

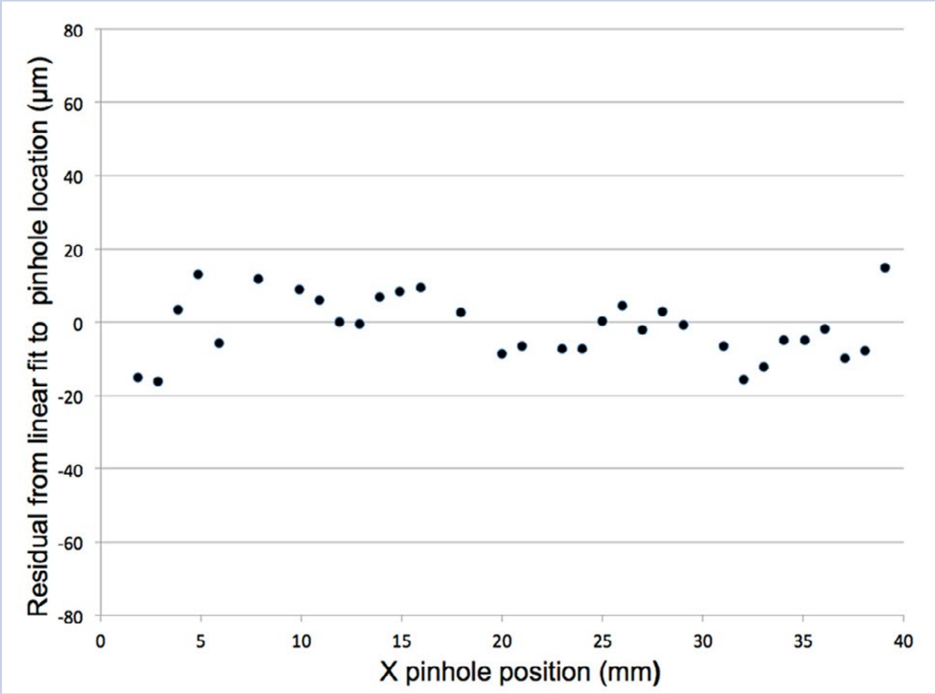

Fig. 7. *Residuals to linear fit of derived pinhole position across central 40 mm of the 50 mm XS detector.*

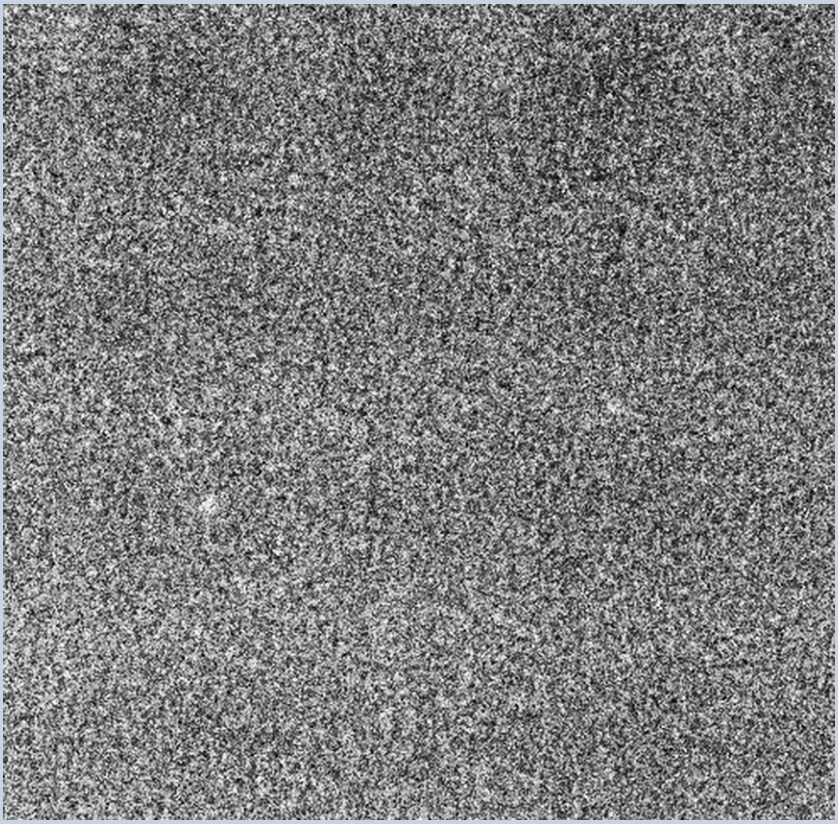

Fig. 8. *Small section of very deep (2500 cts/pxl) flat field showing a small but noticeable fixed pattern noise.*

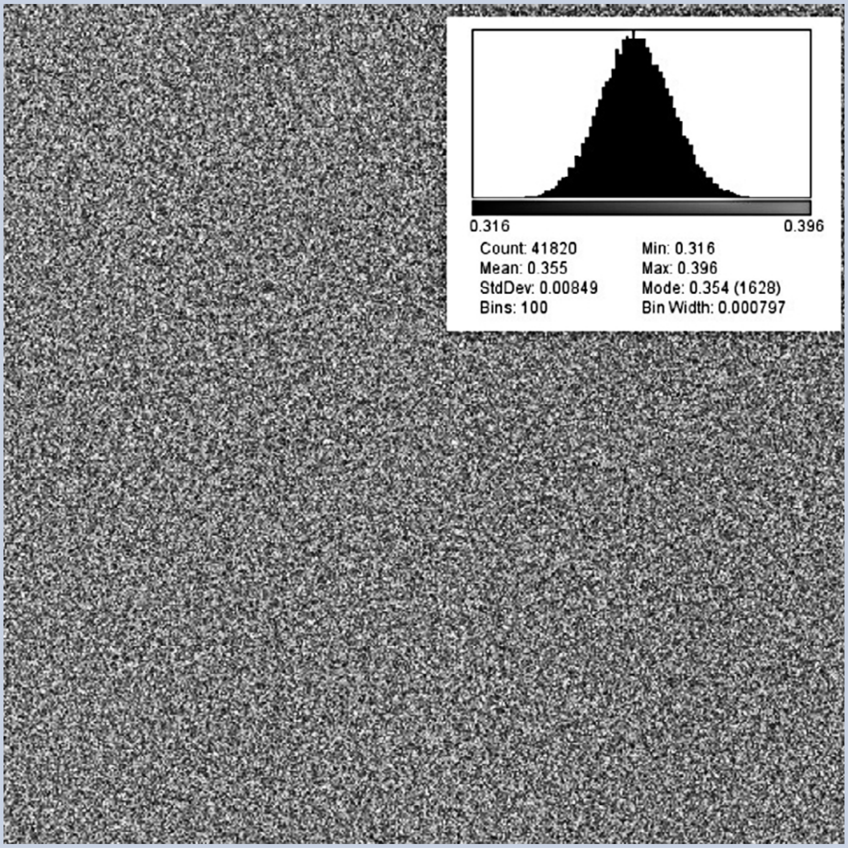

Fig. 9. *Same image as Fig 8, but divided by deeper flat field. Residual variation is consistent with the expected Poisson counting statistics (2% standard deviation, inset).*

Final Year Plans

By early Fall 2014, we will submit the second CSA and HalfGRAPH digital ASIC designs for fabrication. The first articles (expected to be received in early winter) will be tested with our existing and new FPGA board designs. We will start full performance testing of the 50-mm detector and anode using the new ASIC XS electronics and begin environmental testing.

References

[1] Siegmund O., Vallerga J., Jelinsky P., Michalet X., and Weiss, S., *"Cross Delay Line Detectors for High Time Resolution Astronomical Polarimetry and Biological Fluorescence Imaging,"* Proc. IEEE Nuclear Science Symposium, ISBN: 0-7803-9222-1, pp. 448-452, (2005).

[2] Hoadley K., France K., Nell N., Kane R, Schultz T.B., Beasley M., Green J.C., Kulow J.R., Kersgaard E, and Fleming, B.T. *"The assembly, calibration, and preliminary results from the Colorado high-resolution Echelle stellar spectrograph (CHESS),"* Proc. SPIE, 9144, (2014)

[3] Scowen, P. *et al.*, *"The Star Formation Observatory (SFO) mission to study cosmic origins,"* Proc. SPIE, 7010, 115 (2008)

[4] Sembach, K; Beasley, M; Blouke, M; Ebbets, D; Green, J; Greer, F; Jenkins, E; Joseph, C; Kimball, R; MacKenty, J; McCandliss, S; Nikzad, Sh; Oegerle, W; Philbrick, R; Postman, M; Scowen, P; Siegmund, O; Stahl, H. P; Ulmer, M; Vallerga, J; Warren, P; Woodgate, Bruce; Woodruff, R, *"Technology Investments to Meet the Needs of Astronomy at Ultraviolet Wavelengths in the 21st Century,"* Astro2010: The Astronomy and Astrophysics Decadal Survey, Technology Development Papers, no. 54, 2009

[5] Vallerga, J., Raffanti, R., Tremsin, A., Siegmund, O., McPhate, J., and Varner, G., *"Large-format high-spatial resolution cross-strip readout MCP detectors for UV astronomy,"* SPIE Vol. 7732, pp. 2010

[6] Michalet X., R. A. Colyer, J. Antelman, O.H.W. Siegmund, A. Tremsin, J.V. Vallerga, S. Weiss, *"Single-quantum dot imaging with a photon counting camera,"* Current Pharmaceutical Biotechnology 10 (5), pp. 543-558 (2009).

[7] Berendse, F. B., Cruddace, R. G., Kowalski, M. P., Yentis, D. J., Hunter, W. R., Fritz, G. G., Siegmund, O., Heidemann, K., Lenke, R., Seifert, A., and Barbee, T. W., Jr., *"The joint astrophysical plasmadynamic experiment extreme ultraviolet spectrometer: resolving power,"* Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 6266, pp.31. (2006)

[8] Bechtol, K., Funk, S., Okumura, A., Ruckman, L. L., Simons, A., Tajima, H., Vandenbroucke, J., and Varner, G. S., *"TARGET: A multi-channel digitizer chip for very-high-energy gamma-ray telescopes,"* Astroparticle Physics, 36, pp.156-165, (2012)

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

Prepared by: Shouleh Nikzad (PI; JPL), Chris Martin (Caltech), David Schiminovich (Columbia University), Paul Scowen (ASU), and Michael Hoenk (JPL)

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 Cosmic Origins Program Annual Technology Report (PATR) reported 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 capable of providing a factor of 3-10 improvement in UV efficiency over those in *Hubble Space Telescope* (HST) must do so without introducing a commensurate increase in noise.

Our team demonstrated a high-QE, solid-state, UV photon-counting array in small format by applying JPL's back-illumination processes including thinning, delta-doping technology [1][2][3][4][5][6], and advanced anti-reflection (AR) coatings using atomic layer deposition (ALD) [5][7] to commercially available Electron-Multiplied Charge-Coupled Devices (EMCCDs) [8][9]. 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 (Fig. 1) [5][10]. The performance of this Solid-state Photon-counting Ultraviolet Detector (SPUD) represents a breakthrough in single-photon-counting UV detectors.

In this three-year program, which began 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 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 the detector on the synergistic balloon experiment *Faint Intergalactic medium Red-shifted Emission Balloon* (FIREBall), flight accommodation and operations already funded by APRA, the Astrophysics Research and Analysis program) 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 over the past three years of high-throughput processes for delta doping using JPL's new 8-inch wafer capacity silicon MBE and the associated techniques to produce high-efficiency detectors (Fig. 1).

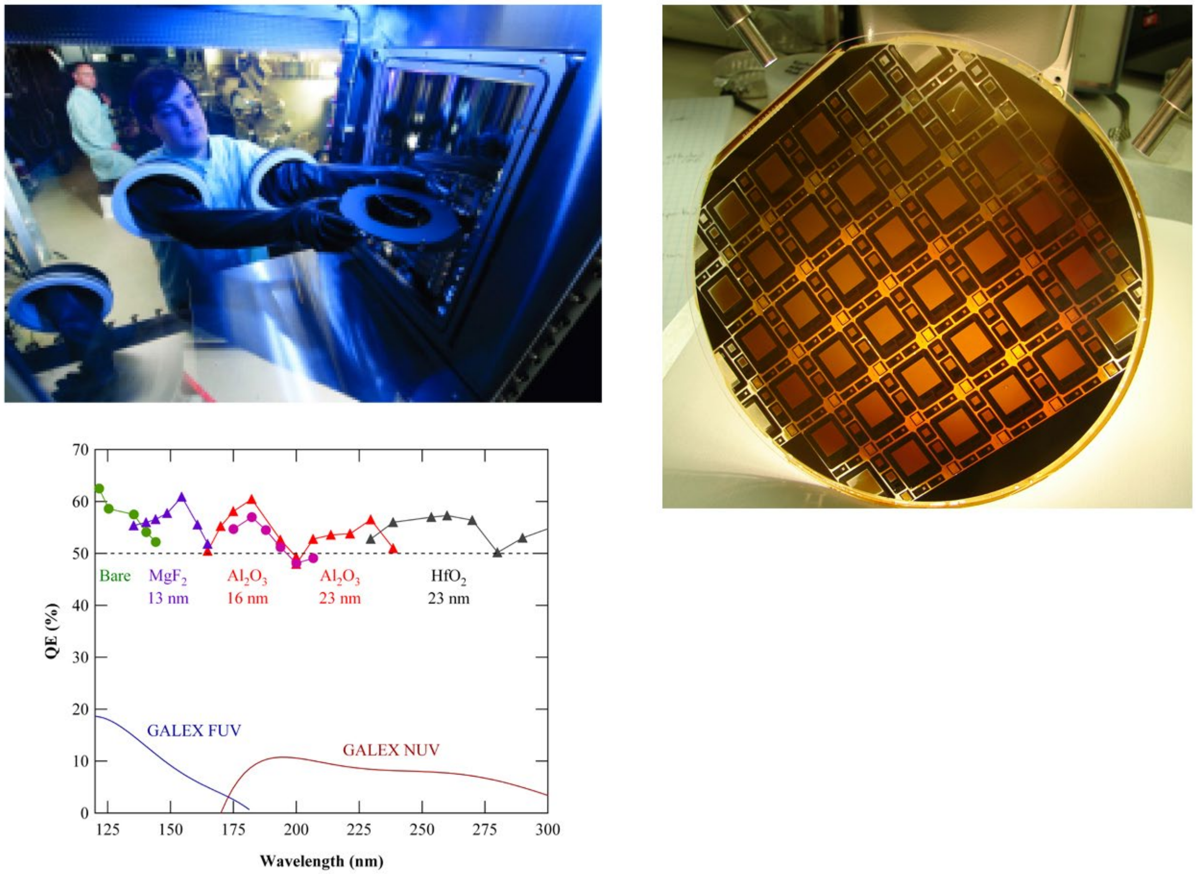

Fig. 1. Top left: *JPL facilities with large wafer capacity for high-throughput delta doping of state-of-the-art CCDs and CMOS imagers. Silicon imagers can be processed in these facilities for back illumination as 150 mm and 200 mm wafers.* Right: *An 8" wafer with CMOS imagers ready for delta doping. The wafer is thinned using JPL's end-to-end post-fabrication processing facilities.* Bottom left: *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 is above 50% for the entire range. 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. QE of Micro-Channel Plate (MCP)-based* Galaxy Evolution Explorer *(GALEX) detectors are shown for comparison.*

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.

This development is a team effort with JPL (Drs. Shouleh Nikzad and Michael Hoenk and team), 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 on the objectives of this effort.

Background

The 2010 Decadal Survey, New Worlds, New Horizons in Astronomy and Astrophysics (NWNH) [11] recommends, as a priority, path-finding work towards a 4m+ UV/Optical flagship mission as a successor to the HST. Great emphasis on Explorer missions is also anticipated in this decade.

The COPAG evaluates and recommends technology investments toward a 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 a priority. Furthermore, these recommendations set as a goal very-large-format (> 100 megapixels) 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 4m+ 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- to 10-fold) over previous missions (Fig. 1). Dramatically increasing detector efficiency could allow Explorer-class or Probe-class missions to perform what is currently considered 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 scale. SPUD optimized for visible light would enable integral field spectroscopy required for exo-planet characterization, which must be photon-counting because of the low background in space for diffraction-limited optical spectroscopy.

The QE and response stability of our SPUD 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 NWNH recommendations for a 4m+ 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, HST-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

Table 1 shows the project's milestones and schedule.

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 and feedback					Δ	
Deploy for on-sky observation, evaluation						Δ
Deploy for suborbital (funded balloon FIREBall)						Δ
Demonstrate process manufacturability and versatility						
Establish throughput and yield by testing devices produced in multiple wafers						
Demonstrate process on high-purity large-format CCD						
Environmental testing						
Noise, QE, with temperature, illumination. Lifetime testing.						

Table 1. *Project milestones and schedule.*

The major objectives are as follows:

- Demonstrate detector in large format, *i.e.*, starting from 0.5-megapixel format to 2-megapixel format (Fig. 2) (FY 2013 Q3-Q4);
- Measure detector QE, noise, and performance for spectroscopic and imaging applications (first results in FY 2014 Q1);
- Advance the manufacturability and reliability of SPUD and, as a byproduct, those of other high-efficiency silicon imagers. Revised the number of wafers to be procured and 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 FY 2014 Q4);
- Perform environmental tests of the detector (thermal – FY 2014 Q3);
- Validate on-sky over a wide range of flux levels using astrophysical imaging and spectroscopic instruments (FY 2015 Q1); and
- Flight-test detector on the synergistic and balloon experiment FIREBall (FY 2015 Q3).

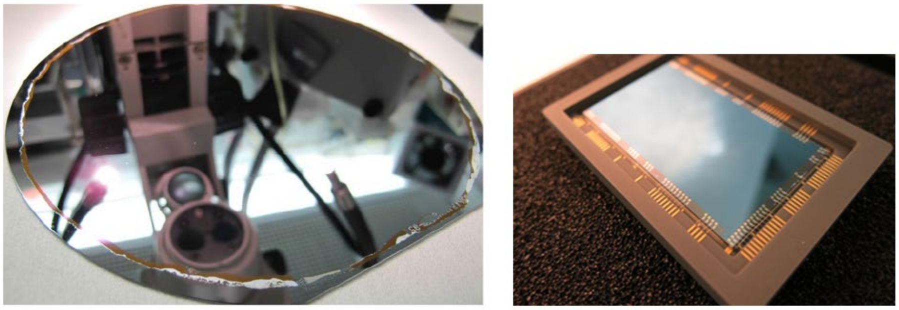

Fig. 2. *The first 2-megapixel arrays have been processed. QE measured on this device is not absolute but suggested lower than expected values. As a mitigating step, all process steps including MBE (for delta doping) were reevaluated, and possible contamination sources were removed. The next wafers are in various processing steps. One is entirely prepared for delta doping.*

Progress and Accomplishments

Much has been accomplished this year and the major accomplishments are listed below.

Demonstrate Large-Format Detector

We selected and procured the electron-multiplied array wafers from the vendor in the first years. Device wafers were fabricated, and we received, inspected, and prepared these for post-fabrication processing. Processing includes bonding of device wafers to handle wafers prior to thinning. This bonding step allows the wafers to be thinned down to about 8-10 microns. After thinning, wafers are carefully cleaned, and MBE growth for delta doping takes place. Wafer is then patterned and pads are exposed for wire-bonding. Devices are packaged as bare delta-doped or are AR-coated prior to packaging.

AR Coatings Development

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

Testing 0.5-megapixel arrays – AR-coated (single layer), delta-doped EMCCDs showed very good QE peak agreement. Extensive calibration of the characterization setup ensured accurate absolute QE measurements. We performed maintenance work on the MBE to prepare for delta doping of the wafers once they are bonded and thinned.

Characterizing Device QE, Dark Noise, Noise, and Uniformity

We use two characterization systems at JPL for QE measurements. One is equipped with a 1m monochrometer that can be evacuated for far-UV measurements down to Lyman alpha. The other is equipped with a 0.5m monochrometer and is suitable for measurements in the 300-1000 nm range. Several wafers with multiple devices were delta-doped and many QE measurements were performed. We use the QE measurement as the first and main feedback to ensure device processing worked as intended. This serves as a methodical and effective process. We also characterize the dark current and uniformity. The Caltech group procured a low-noise readout electronics system (NuVu) controller and have been preparing to measure dark current and read noise at a high-gain operation mode. The Caltech readout and dewar system (Fig. 3) is also planned for FIREBall.

Fig. 3. *The Caltech dewar and characterization setup for low-noise measurements expected to fly on FIREBall.*

On-Sky Observations

The ASU team is mainly responsible for obtaining on-sky data from large-format delta-doped arrays. Several multilayer films for broadband coatings were designed. One wafer was processed for producing the device for on-sky observations. The wafer was diced and AR coatings were tested on multiple devices. Coatings were deposited on blank wafers and devices and then tested. One coating was deemed superior. A 12-megapixel, 10-micron array was delta-doped and AR-coated with this broadband coating and delivered to the ASU team (Fig. 4). The ASU team made one expedition to Kitt Peak for an engineering run. A science run is in planning.

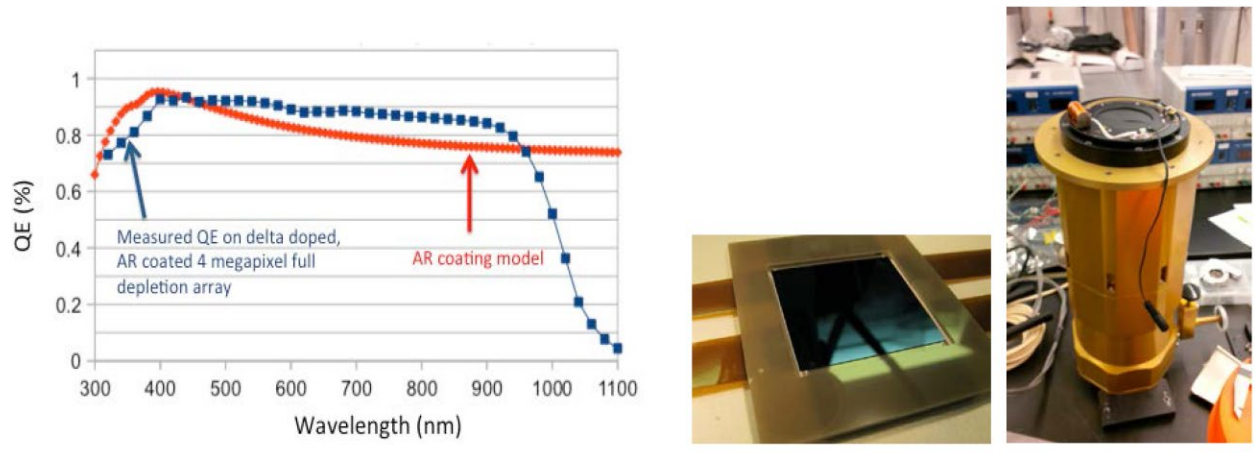

Fig. 4. *QE of a broadband AR-coated, delta-doped 12-megapixel p-channel CCD (designed at LBNL and fabricated at Dalsa).*

Other Accomplishments

Abstracts were submitted to SPIE Optics and Photonics (2013) and were accepted for oral presentations (2013). April Jewell, a NASA Postdoctoral Program (NPP) fellow working on ALD processes chaired an ALD session and presented an invited talk. A paper is also under preparation for submission to Applied Optics on the subject of narrowband, ALD AR coatings. Two posters and an oral presentation were given at the SPIE Astronomical Telescopes and Instrumentation meeting in Montreal (June 2014).

Our effort has benefited from the work of several graduate students from Caltech, Columbia, and ASU, whose work on the project forms a major part of their theses. Graduate student and NASA Space Technology Research (NSTR) fellow Erika Hamden from Columbia University has had some short stays and visits at JPL. Graduate student Alex Miller (ASU) had an extended stay last summer to work on detector characterization. He is the main ASU graduate student on this task and was part of the Kitt Peak engineering run expedition. He will take this knowledge back to ASU and modify the test setup to accept detectors under development in this task. Caltech graduate student Nicole Lingner works on the low-noise readout of photon-counting detectors.

Path Forward

We will complete processing of the next two wafers for fabrication of 2-megapixel arrays. In parallel, we have been working on calibration of our characterization setup for QE measurements so they are closer to absolute QE which we will continue and complete. We will evaluate and characterize the QE, dark noise, and uniformity of devices from the second and third wafer serially. The Caltech group will characterize engineering-grade single-photon-counting devices and evaluate them for the FIREBall flight, and then move on to characterizing both the bare delta-doped 2-megapixel arrays as well as the arrays with narrowband FIREBall coatings. Collaborators at ASU will complete modification of their readout system and will carry out a science run at Kitt Peak. A proposal for time at Kitt Peak was submitted to take the broadband delta-doped detector for on-sky observation to evaluate them for realistic astrophysics signal levels. We will process more wafers, incorporating feedback from these in-depth characterizations to improve processes if needed. As we process multiple wafers, we will demonstrate detector throughput and yield. By applying the techniques to single-photon-counting platforms and other designs, we demonstrate the versatility of our processes.

References

[1] "*Growth of a Delta-Doped Silicon Layer by Molecular-Beam Epitaxy on a Charge-Coupled Device for Reflection-Limited Ultraviolet Quantum Efficiency*," M.E. Hoenk, P.J. Grunthaner, F.J. Grunthaner, M. Fattahi, H-F. Tseng and R.W. Terhune, Appl. Phys. Lett., 61, 1084 (1992).

[2] "*Delta-doped CCDs: High QE with Long-term Stability at UV and Visible Wavelengths*," S. Nikzad, M.E. Hoenk, P.J. Grunthaner, R.W. Terhune, F.J. Grunthaner, R. Winzenread, M. Fattahi, and H-F. Tseng, Proc. of SPIE, 2198, 907 (1994).

[3] "*Near-100% Quantum Efficiency of Delta Doped Large-Format UV-NIR Silicon Imagers*," J. Blacksberg, S. Nikzad, M.E. Hoenk, S.E. Holland, and W. Kolbe, IEEE Trans. On Electron Devices 55 3402, (2008).

[4] "*Delta-doped back-illuminated CMOS imaging arrays: Progress and prospects*," M. E. Hoenk, T. J. Jones, M. R. Dickie, F. Greer, T. J. Cunningham, E. R. Blazejewski and Shouleh Nikzad, Proceedings of the SPIE 74190 74190-74115 (2009).

[5] "*Silicon Detector Arrays with Absolute Quantum Efficiency over 50% in the Far Ultraviolet for Single Photon Counting Applications*," S. Nikzad, M.E. Hoenk, F. Greer, E. Hamden, J. Blacksberg, B. Jacquot, S. Monacos, Chris Martin, D. Schiminovich, P. Morrissey, Applied Optics, 51, 365 (2012).

[6] "*Delta-doped CCDs As Stable, High Sensitivity, High Resolution UV Imaging Arrays*," S. Nikzad, M.E. Hoenk, P.J. Grunthaner, R.W. Terhune, R. Winzenread, M. Fattahi, H-F. Tseng, and F.J. Grunthaner, Proc. of SPIE, 2217, 355 (1994).

[7] "*Antireflection Coatings Designs for use in UV Imagers*," E. Hamden, F. Greer, M.E. Hoenk, J. Blacksberg, T.J. Jones, M. Dickie, B. Jacquot, S. Monacos, C. Martin, P. Morrissey, D. Schiminovich, S. Nikzad, Applied Optics, 50, 4180-4188 (2011).

[8] "*LLLCCD—Low Light Level Imaging without the need for an intensifier*," P. Jarram, P. Pool, R. Bell, D. Burt, S. Bowring, S. Spencer, Proc. SPIE 4306, 178 (2001).

[9] "*Impactron – A New Solid State Image Intensifier*," J. Hynecek, IEEE Transaction on Electron Devices, 48 No. 10, 2238-2241 (2001).

[10] "*UV photon-counting CCD detectors that enable the next generation of UV spectroscopy missions: AR coatings that can achieve 80-90% QE*," E. Hamden, D. Schiminovich, S. Nikzad, and C. Martin, Proceedings of the SPIE, 8453, High Energy, Optical, and Infrared Detectors for Astronomy V, 845309 (2012).

[11] "*New Worlds, New Horizons in Astronomy and Astrophysics*," Blandford *et al.*, National Academy of Sciences, (2010).

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A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping

Prepared by: Imran Mehdi (PI; JPL, Caltech) and Paul Goldsmith (JPL, Caltech)

Summary

This task was proposed under the 2012 Strategic Astrophysics Technology (SAT) call and was funded in January 2014 for a period of three years. Heterodyne spectroscopic instruments are the only technical possibility for obtaining velocity-resolved spectra in the far-infrared (Far-IR). Building on the *Heterodyne Instrument for the Far Infrared* (HIFI) hardware developed by JPL, the focus of this task will 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 Technology Readiness Level (TRL) 5. This receiver system enables science beyond HIFI for next generation of heterodyne instruments on platforms including long-duration and ultra-long-duration balloons, and aircraft observatories such as *Stratospheric Observatory for Infrared Astronomy* (SOFIA). GaAs Schottky diode-based high-power multipliers pumped by W-band power amplifier modules, superconducting hot electron bolometer-based mixers, low-power cryogenic intermediate frequency (IF) amplifiers, and a digital backend will be integrated and demonstrated in a modularized 16-pixel receiver with TRL 5. The proposed approach will result in a modular architecture for Far-IR array receivers for upcoming suborbital and space-based Cosmic Origins observing opportunities.

This work is carried out by a team of JPL scientists and technologists, including Imran Mehdi, Paul Goldsmith, Jon Kawamura, Jose Siles, Robert Lin, Choonsup Lee, Bruce Bumble, and Jeff Stern. During the past six months, two of the multiplier diode stages and the mixer devices were designed and fully simulated. Currently, both multiplier and mixer devices are being fabricated at JPL's Micro-Devices Laboratory.

Background

The details of the evolution of molecular clouds and the formation of the next generation of stars out of the dust and gas in these dense regions remain mysterious. It is abundantly clear from a large number of *Herschel* photometric observations with the *Photodetector Array Camera and Spectrometer* (PACS) and the *Spectral and Photometric Imaging Receiver* (SPIRE), that the dust is filamentary in nature, and that the filaments contain a large number of dense cores [1][2][3][4]. Many of these are self-gravitating and likely to form stars, but evidence of star formation is far from universal. What cannot be determined from the photometry is the velocity structure of these filaments, or their relationship to the various phases of the Interstellar Medium (ISM). Photometry cannot trace the processes that lead to the origin of the filaments and the likelihood that stars will form in the cores that form within them [5][6][7][8]. Velocity information is required to assess the role of turbulence and gravity in determining the kinematics of the ISM and its evolution into new stars. Not surprisingly, the best tracers of velocity are the strongest available lines – CII and OI, which are complementary in that they trace different regimes of extinction. The molecular tracer CH can be used as a surrogate for H2, and thus traces the total gas column density. CH has a ground state that interacts strongly with magnetic fields through the Zeeman Effect making it a potential tracer of magnetic fields.

High-spectral-resolution observations will facilitate determination of velocity along the line of sight, allowing the relative motions and states of the ISM to be mapped and correlated with the observed dust structures and evolution of starless and pre-stellar cores. Simultaneous observation of combinations of lines correlated with previous photometric maps allows direct observation of the interactions between ISM phases and the connection of the gas with the dust. High resolution is required to understand the turbulence and dynamics of this interaction, as well as to de-convolve the contributions along the line of sight. Understanding how star formation proceeds in galaxies other than the Milky Way – with different metallicities and at different times in the evolution of the universe – is currently one of the hottest topics in astronomy, but understanding these sources will require advanced spectroscopy and better understanding of “prototypical” nearby sources in our own and nearby galaxies. Figure 1 shows heterodyne observations through the Milky Way in CII, HI, and CO, showing how they trace different, but interrelated regions in the interstellar medium.

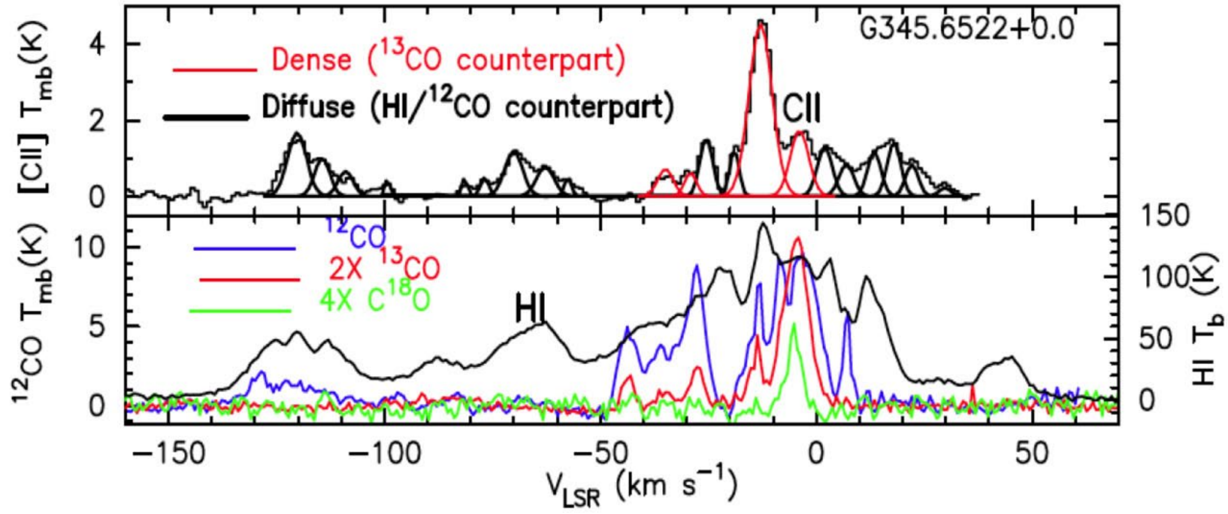

Fig. 1. Upper panel: Herschel *HIFI spectrum of CII emission in the Galactic Plane at longitude 345.65 [9]. The overall profile has been broken up into Gaussian components; those in red are obtained from the ^{13}CO spectrum (below).* Lower panel: *Corresponding ^{12}CO, ^{13}CO, C^{18}O, and HI spectra. Comparison shows that the strongest CII emission is associated with molecular emission (Photo-Dissociation Regions, PDRs), but that a significant fraction originates in the diffuse ISM where HI is seen, and where there is no carbon monoxide due to the low visual extinction. A resolution of 3×10^4 or 10 km/sec would smear out the CII line profile significantly and drastically reduce the information obtained [9].*

In order to answer questions raised in the 2010 Decadal Survey, New Worlds, New Horizons in Astronomy and Astrophysics (NWNH) [10; PSF1&2; GAN1&2], heterodyne array receivers in the Far-IR range will be required. HIFI provided the first glimpse into the universe in this frequency range but had only a single pixel and the mission has now been decommissioned (after using up the cryogen). Technology being developed under this task will allow one to map large areas of the sky instantaneously and provide contextual information that is difficult to patch with single pixel systems. At the conclusion of this work, we intend to demonstrate a 16-pixel array receiver covering 1.9-2.07 THz with a TRL of 5.

Objectives and Milestones

The main objective of this task is to advance the heterodyne array receiver technology from TRL 4 to 5. This will be accomplished by building and characterizing a 16-pixel 1.9 THz array receiver that can enable mapping of the C+ line on platforms such as long-duration balloons and aircraft observatories. The technology is also compatible with flight instruments, and can be utilized for future submillimeter-wave instruments for astrophysics. The proposed scheme of the 16-pixel array receiver is shown in Fig. 2 with only a single 1 × 4 module shown for clarity. The signal from the telescope is combined with the local oscillator (LO) signal via a diplexer, and then fed into the mixer element via a machined feed-horn. This approach provides the flexibility of quasi-optical coupling and redundancy since each mixer is pumped by a dedicated LO chain. The mixer and IF amplifier are cooled to cryogenic temperature (4K) to provide high sensitivity.

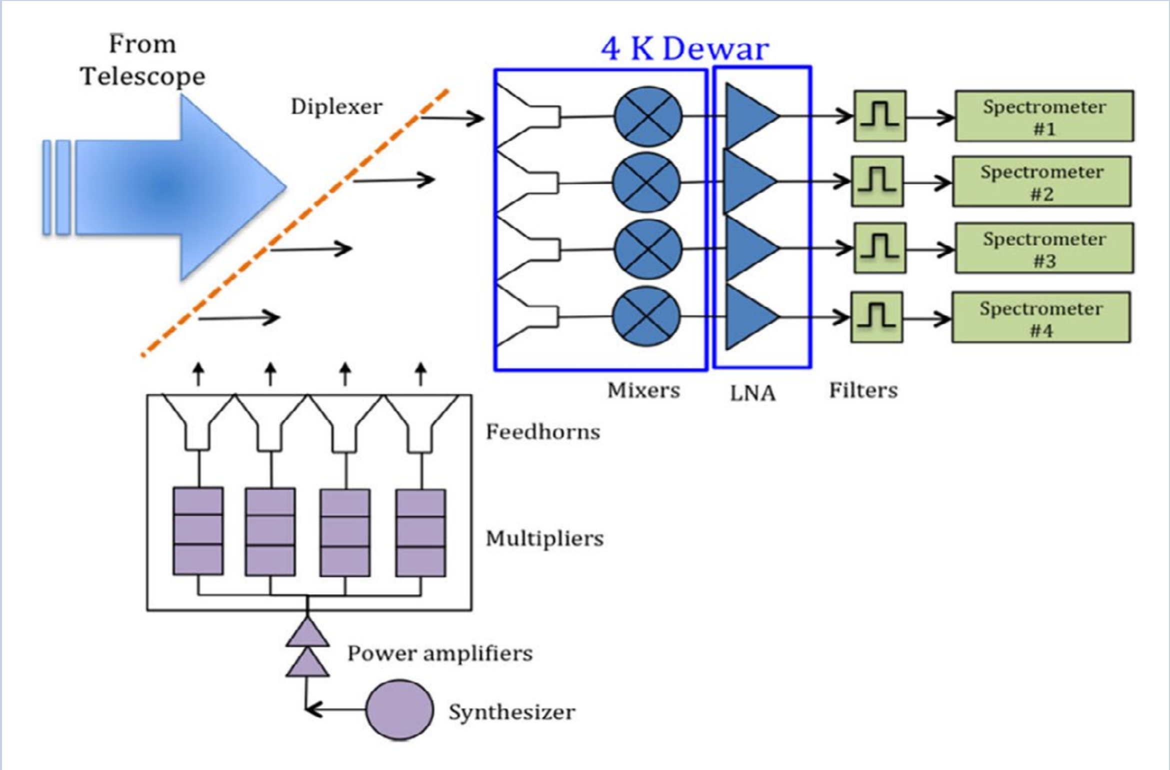

Fig. 2. *Proposed architecture for a submillimeter-wave array receiver.*

The receiver system can be divided into three sub-systems, namely:

1. LO sub-system;
2. Mixer and IF amplifier sub-system; and
3. Backend sub-system.

All three sub-systems have been demonstrated in single-pixel systems. The proposed task will bring all three sub-systems together to define the 'relevant environment' as a functional 16-pixel array receiver. A number of technical problems have to be addressed for building up the array receiver. The architecture of the system, especially the LO sub-system, is critical as all of the LO signals need to be phase-locked. By demonstrating the operation of this 16-pixel receiver system, we will validate it as TRL 5. Further TRL advancement would then require determination of the relevant environment (balloon, aircraft, space-borne, etc.) and environmental tests such as thermal and Radio Frequency (RF) cycling, etc., consistent with the selected platform.

Table 1 lists the major milestones associated with the full three-year development effort. Funding for this task was made available in January 2014 and significant progress has already been accomplished. A number of devices have been designed and optimized to provide power over the desired frequency band. Tasks that have been completed are indicated.

Progress and Accomplishments

LO sub-system

The proposed LO subsystem is shown in Fig. 3. In the last few months, significant progress has been made in accomplishing the goal of making a 16-pixel LO sub-system. A commercially-available microwave monolithic integrated circuit (MMIC) has been identified that can be used as the power amplifier. The waveguide block for this MMIC was designed and is shown in Fig. 4 along with its expected performance. These components are expected to be ready for testing toward the end of summer 2014.

	Milestone	Completed by	Status
System design and interface control			
	System architecture design	March 2014	Completed
	Interface definition	June 2014	Completed
	Production of 3-D controlled drawing	August 2014	In progress
Development of high-sensitivity HEB mixer array			
	Design of mixer devices and waveguide housing	July 2014	In progress
	Fabrication of HEB devices	September 2014	In progress
	Fabrication of waveguide housing	October 2014	
	Assembly of 4-pixel receiver	December 2014	
	Fabrication of optimized HEB circuits	April 2015	
	Fabrication of updated waveguide housings	June 2015	
	Assembly and testing of 16-pixel receiver	December 2015	
Development of 16-pixel LO subsystem			
	Design of first stage tripler	March 2014	Completed
	Design of second and third stage triplers	May 2014	Completed
	Fabrication of first and second stage multiplier chips	October 2014	In progress
	Fabrication of first and second stage multiplier blocks	December 2014	
	Packaging and testing of first and second stage blocks	March 2015	
	Design of last stage including power splitter	May 2015	
	Fabrication of last stage tripler chips	November 2015	
	Fabrication of last stage tripler waveguide block	February 2016	
	Procurement of power amps	February 2016	
	Integration of LO subsystem	April 2016	
	Characterization of 16-pixel LO	May 2016	
Procurement of backend subsystem			
	Selection of CMOS-based backend subsystem	June 2015	
	Selection and testing of low-power IF amps	August 2015	
	Procurement of backend and IF amps	December 2015	
System integration and validation			
	Assembly of 16-pixel receiver	July 2016	
	Test and validation of 16-pixel receiver	December 2016	

Table 1. *Progress is being made in completing major milestones related to this task.*

The second stage tripler (633-690 GHz) chip has also been designed and is currently being fabricated. The chip's schematic and expected performance are shown in Fig. 5. These results assume 55 mW of input power which should be available. The chip utilizes on-chip power combining thus reducing the loss associated with waveguide power combiners.

Hot Electron Bolometer (HEB) mixer devices

HEB mixers provide one of the most sensitive detectors in this frequency range. The HEB mixers for this task will be packaged in specially fabricated waveguide housings. We believe that by using 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 towards arrays.

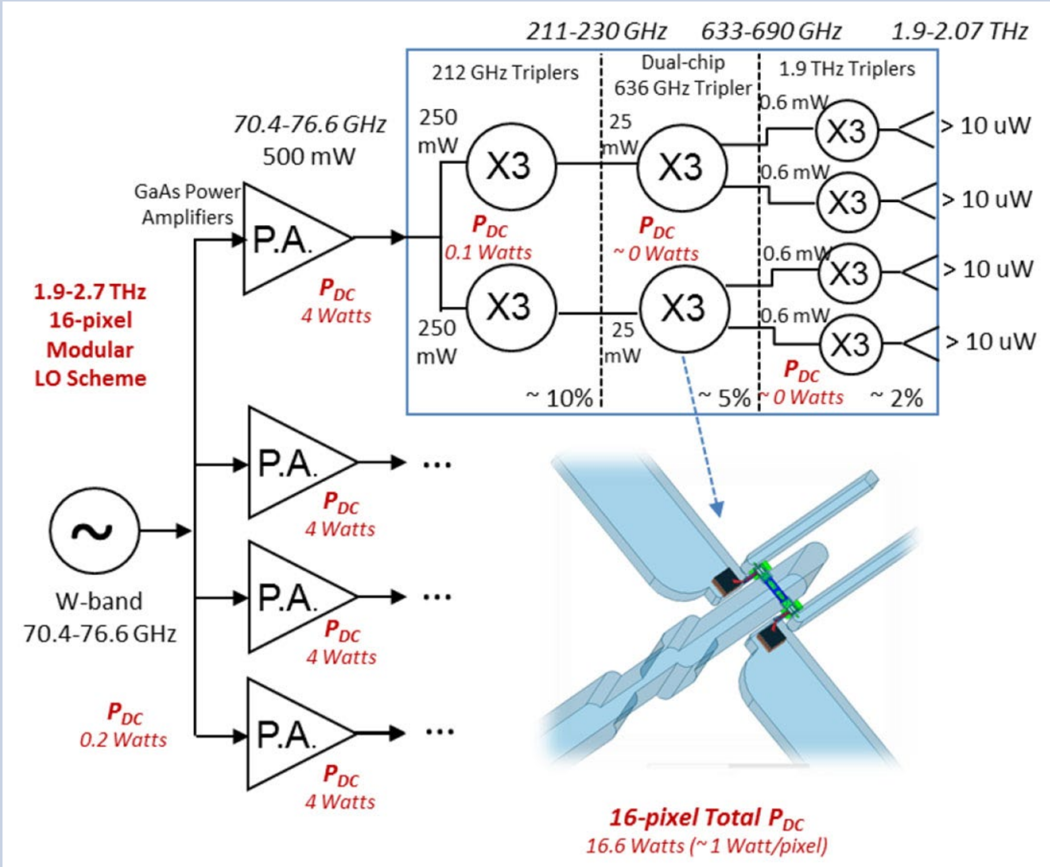

Fig. 3. *A modular LO system allows for a compact 16-pixel array receiver.*

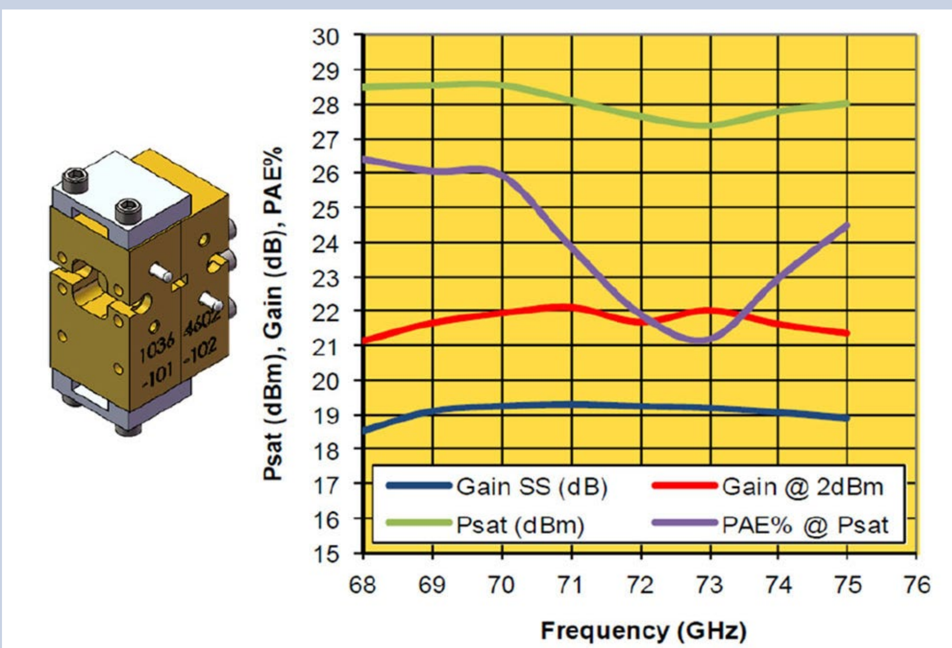

Fig. 4. *A commercially-available MMIC amplifier will be packaged in a waveguide block for insertion into the LO system. The curves show the expected gain, saturated power, and power-added efficiency (PAE) performance as a function of frequency.*

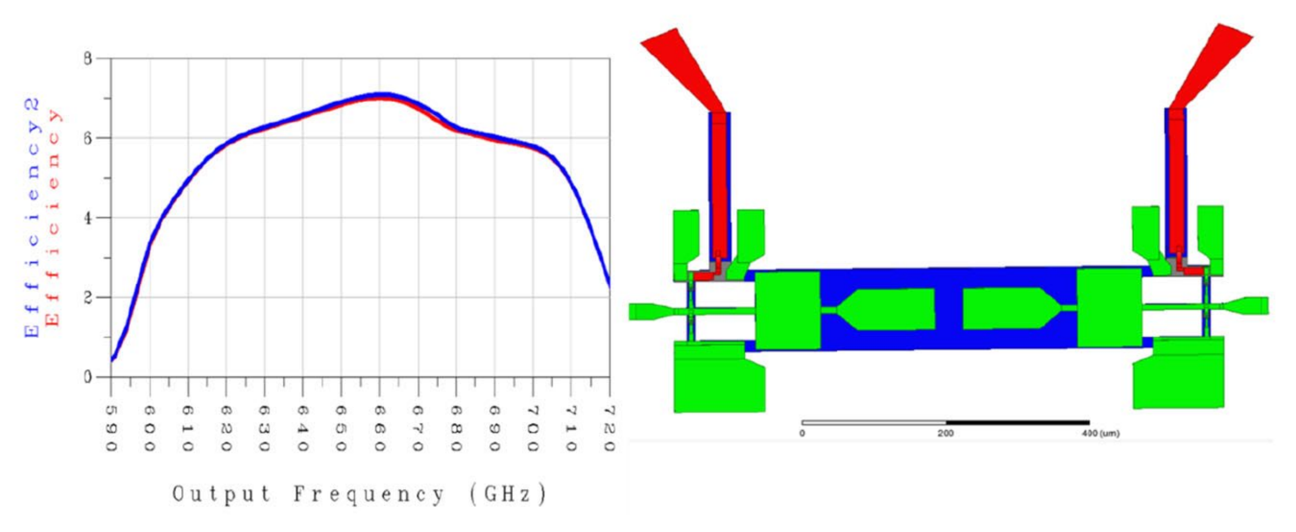

Fig. 5. *An optimized second-stage tripler will provide sufficient power to pump the final-stage tripler, which will produce the 1.9 THz power required to pump the HEB mixers.*

Since the waveguide block requires very small features (< 25 microns), a novel approach of putting the waveguide blocks has been developed. The channel for the mixer chip (the most critical part of the design) is formed directly by silicon micro-machining. This small silicon piece is then used in the larger metallic waveguide block. This eliminates the micro-plating step, and results in fairly robust waveguide structures. This approach was validated at 2.7 THz and will be used for the mixers needed under this task.

Two mixer designs have been completed (Fig. 6). The first uses a bowtie antenna to couple the signal, and sits perpendicular to the input signal waveguide. The second 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 are now being fabricated.

Path Forward

In the next year, the focus of the task will be to assemble and test a 1 × 4 front-end receiver module. The multiplier and mixer devices are expected to be fabricated by September 2014. Orders for machining of the waveguide housings are already in place, and we expect to receive these in September 2014 as well. Detailed characterization of this receiver will allow us to make any adjustments needed for the 16-pixel receiver. The 1 × 4 receiver is expected to be fully characterized by end of 2014. Most of Fiscal Year (FY) 2015 will be spent fabricating the hardware for the 16-pixel receiver, and FY 2016 will be used to integrate the full receiver and carry out a detailed characterization.

Acknowledgement

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

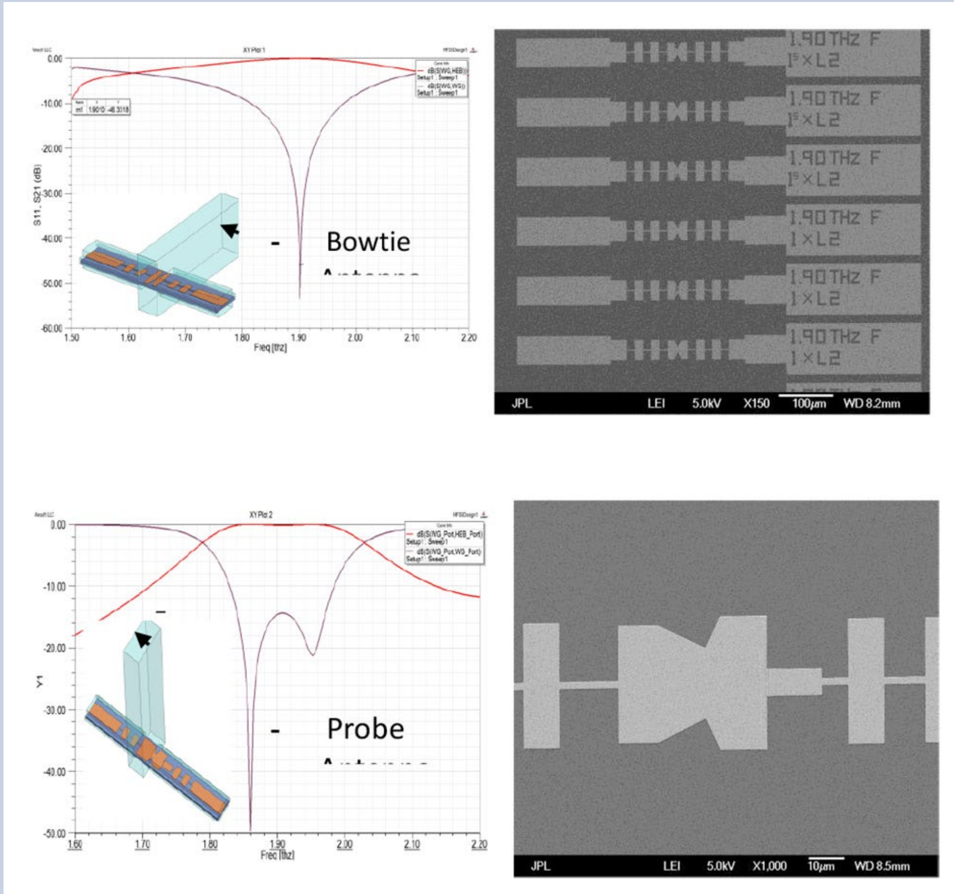

Fig. 6. *Two HEB designs have been optimized for this task to cover the desired frequency band. Both offer good performance over the required frequency range to cover [CII] and [OI] fine structure lines. These chips are currently being fabricated.*

References

[1] S. Molinari, *et al.*, 2010, "*Clouds filaments, and protostars: The Herschel Hi-GAL Milky Way*," Astron. & Astrohys. 518, L100

[2] Ph. André, *et al.*, 2010, "*From filamentary clouds to prestellar cores to the stellar IMF: Initial highlights from the Herschel Gould Belt Survey*," Astron. & Astrophys. 518, L102

[3] A. Menshchikov, *et al.*, 2010, "*Filamentary structures and compact objects in the Aquila and Polaris clouds observed by Herschel*," Astron. & Astrophys. 518, L103.

[4] V. Konyves *et al.*, 2010, "*The Aquila prestellar core population revealed Herschel*," Astron. & Astrophys. 518, L106

[5] P. Padoan, M. Juvela, A.A. Goodman, A. Nordlund, 2001, "*The turbulent shock origin of proto-stellar cores*," Astrophys. J. 553, 227

[6] T. Nagai, S.-I. Inutsuka, & S.M. Miyama, 1998, "*An origin of filamentary structure in molecular clouds*," Astrophys. J. 506, 306

[7] P. Ocvirk, C. Pichon & R. Teyssier, 2008, "*Bimodal gas accretion in the Horizon-MareNostrum galaxy formation simulation*," Mon. Not. R. Astron. Soc. 390, 1326

[8] F. Nakamura & Z.-Y. Li, "*Magnetically regulated star formation in three dimensions: the case of the Taurus molecular cloud complex*," 2008, Astrophys. J. 687, 354

[9] W. D. Langer, T. Veluswamy, J. L. Pineda, P. F. Goldsmith, D. Li, and H. W. Yorke, "*C+ Detection of Warm Dark Gas in Diffuse Clouds*," Astronomy & Astrophysics, vol. 521, no. L17, October 2010.

[10] "*New Worlds, New Horizons in Astronomy and Astrophysics*," Decadal Survey report from the Committee for a Decadal Survey of Astronomy and Astrophysics; National Research Council, ISBN 0-309-15800-1, 2010, also available at http://www.nap.edu/catalog/12951.html.

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Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes

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

Summary

The Advanced Mirror Technology Development (AMTD) project is in Phase 2 of a multiyear effort, initiated in FY 2012, to mature toward the next Technology Readiness Level (TRL) six critical technologies required to enable 4m or larger ultraviolet, optical, and infrared (UVOIR) space telescope primary mirror assemblies for general astrophysics and ultra-high contrast observations of exo-planets. AMTD continues to achieve all of its goals and has accomplished all its milestones to date. We have done this by assembling an outstanding team from academia, industry, and government with extensive expertise in astrophysics and exo-planet 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. Our results were presented to the Cosmic Origins Program Analysis Group (COPAG) and Mirror Tech Days 2013, and published in proceedings papers of the 2013 SPIE Optics & Photonics Symposia.

Overview and Background

UVOIR measurements provide robust, often unique, diagnostics for investigating 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 exo-planets? 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 2010 Decadal Survey, New Worlds, New Horizons in Astronomy and Astrophysics (NWNH), an advanced, large-aperture UVOIR telescope is required to enable the next generation of compelling astrophysics and exo-planet science. NWNH also noted present technology is not mature enough to affordably build and launch UVOIR telescopes that are diffraction-limited at visible (or shorter) wavelengths, with apertures larger than 4m. According to the 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 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 Technology Assessment Roadmap (SIOSS), technology to enable a future UVOIR or high-contrast exo-planet mission needs to be at TRL 6 by 2018, so 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 telescopes to TRL 6 by 2018. Because we cannot predict the future, we are pursuing technologies which can enable either monolithic or segmented architectures.

Phase 1 advanced technology readiness of 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; and
- Integrated Model Validation.

Phase 2 continues technology development on three of these key technologies.

- Large-Aperture, Low-Areal-Density, High-Stiffness Mirror Substrates;
- Support System; and
- Integrated Model Validation.

Critical to AMTD's success is our integrated team of scientists, systems engineers, and technologists; and our science-driven systems engineering approach.

Progress and Accomplishments

During FY 2013/14, four of our six critical technologies had activity and TRL has been advanced in all four 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 (4m to 8m) monolithic and (8m to 16m) segmented primary mirrors require larger, thicker, and stiffer substrates.

Accomplishment: In FY 2012/13, AMTD partner Exelis successfully demonstrated a new 5-layer 'stack & fuse' process for fabricating deep-core mirror substrates. Using this new process, a 43 cm diameter 'cut-out' of a 4m diameter, 40-cm thick, < 45 kg/m^2 mirror substrate was fabricated (Fig. 1). This demonstrated the technology can make mirrors with sufficient thickness for a 4m to 8m class mirror.

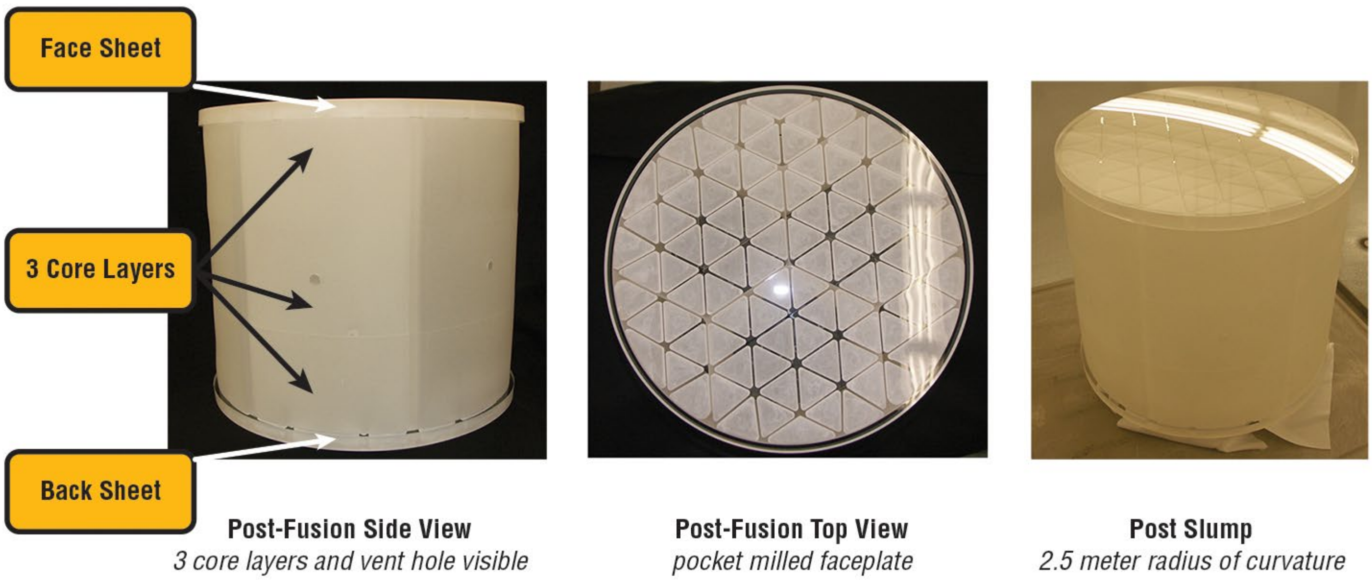

Fig. 1. *Deep core mirror attributes and at different processing stages.*

In FY 2013, Exelis tested the core-to-core Low Temperature Fusion (LTF) bond strength using 12 Modulus of Rupture (MOR) test articles (Fig. 2). Additional MOR testing was performed on 50 samples in FY 2014. The resulting Weibull 99% survival strength value was determined to be 50% above the most conservative design allowable value for margin of safety calculations at the core-to-plate LTF bond. The data on the 50 samples ranged from 60% to 250% above this design allowable value.

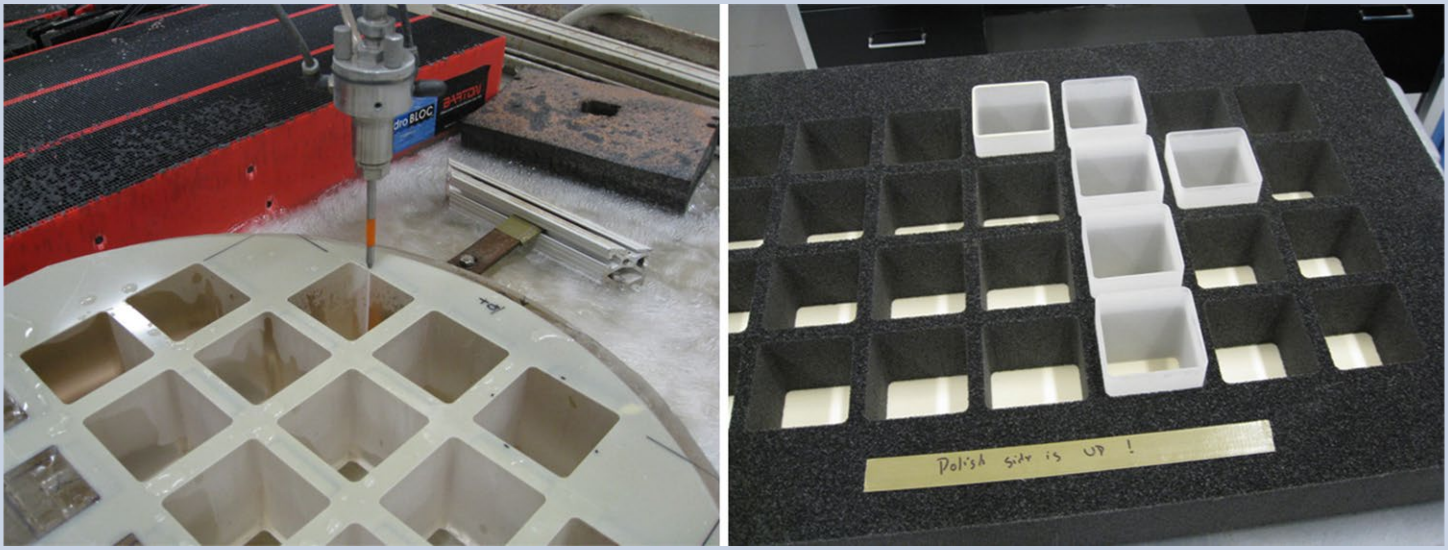

Fig. 2. *MOR test-article fabrication.*

Also in FY 2013/14, Exelis started designing a 1.5m diameter, 200 mm mirror (Fig. 3), to be fabricated via the deep core technology. This mirror will be fabricated under AMTD Phase 2, demonstrating the lateral scalability of the process.

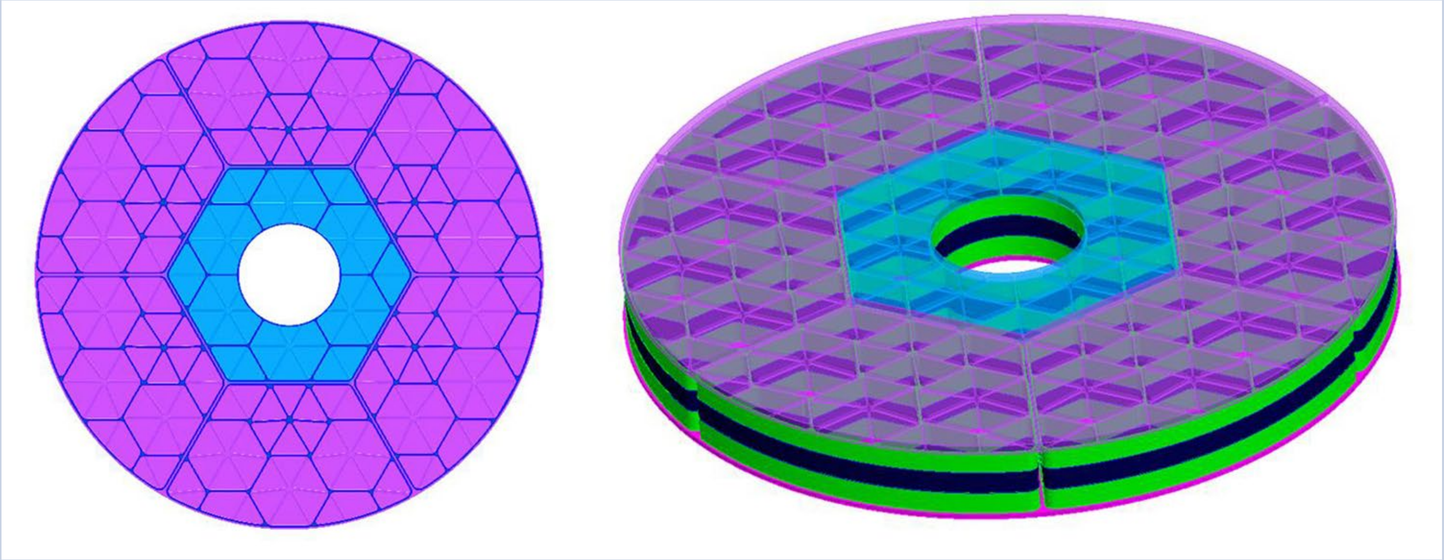

Fig. 3. *Preliminary design for 1.5m mirror.*

Support System

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

Accomplishment: We continue to develop our modeling tool in Visual Basic for ANSYS Finite Element Modeling (FEM). This tool allows rapid creation and analysis of detailed mirror designs. In FY 2013/14, we added the ability to design a mirror support and integrate that support to the mirror substrate via kinematic and hexapod mechanisms (Fig. 4). The result is a tool capable of rapidly designing complete mirror systems and transferring a high-resolution mesh to various mechanical and thermal analysis tools. Currently, we are exercising this tool by developing point designs for thermal and mechanical analysis. For the duration of our effort, we will continue to refine the tool and optimize candidate point designs. Also, we continue to employ undergraduate interns to support these efforts.

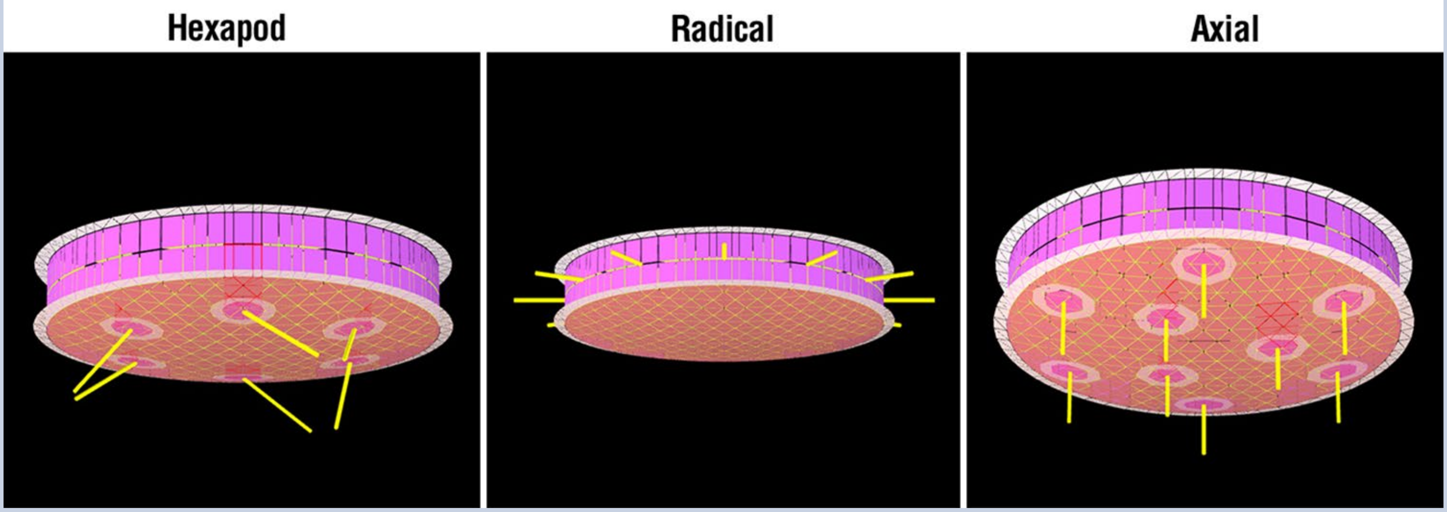

Fig. 4. *Different support types demonstrated by mirror modeler.*

Segment-to-Segment Gap Phasing

Need: To achieve diffraction-limited performance at a wavelength of 500 nm, the figure error of the primary mirror surface needs to be less than 10 nm root-mean-square (rms). For a segmented mirror, it is necessary to co-phase the mirror segments to less than 5 nm rms (Fig. 5).

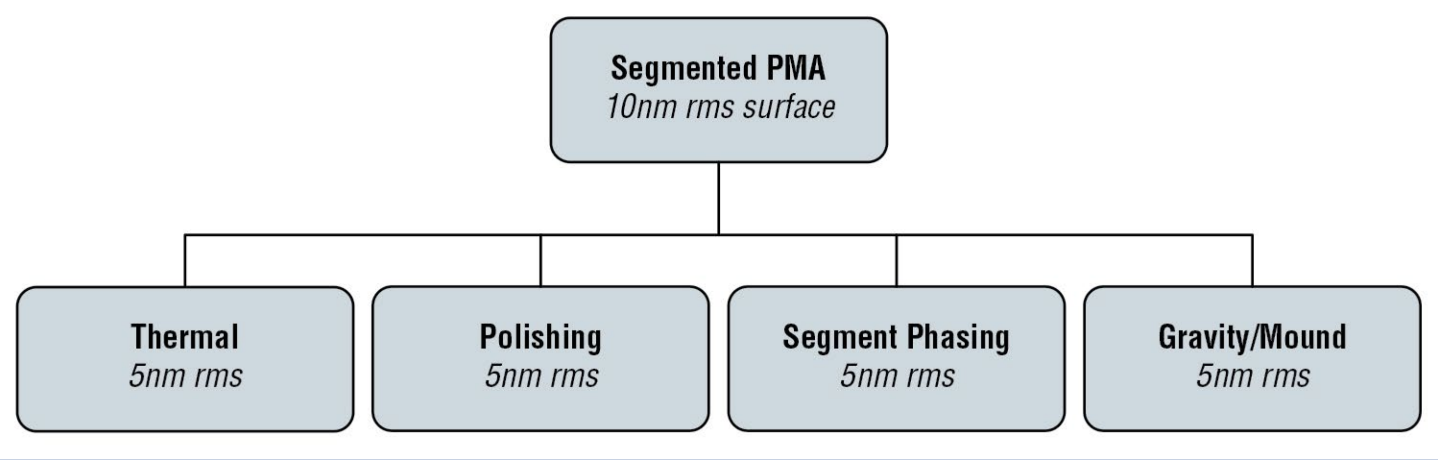

Fig. 5. *PMA general requirements.*

Accomplishment: In FY 2013/14, under the Phase 1 Statement of Work, Exelis designed, built, and characterized the 'fine' stage of a low-mass, two-stage actuator (Fig. 6) which could be used to co-phase mirror segments to the required tolerance. This effort is complete and will not be continued in Phase 2.

Property	Performance
Mass	0.313 Kg
Axial stiffness	40.9 N/µm
Test Range	14.1 µm
Resolution	6.6 nm (noise-limited result) [expected is 0.8 nm]
Accuracy	1.1 µm

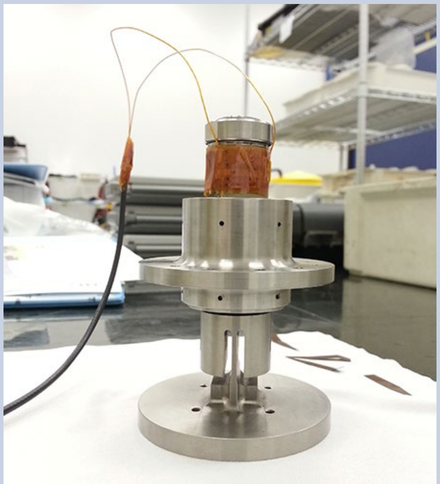

Fig. 6. *Actuator and its performance test results.*

Integrated Model Validation

Need: On-orbit performance is determined by mechanical and thermal stability. As future systems become larger, compliance cannot be 100 percent 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 (PSF), pointing stability, jitter, thermal stability, and vibro-acoustics and launch loads.

Accomplishment: AMTD partner Goddard Space Flight Center (GSFC) continues to develop a suite of MATLAB®-based tools for using structural-thermal-optical performance (STOP) and jitter-integrated models to calculate optical path-length difference (OPD) maps and line of sight (LOS) errors (Fig. 7).

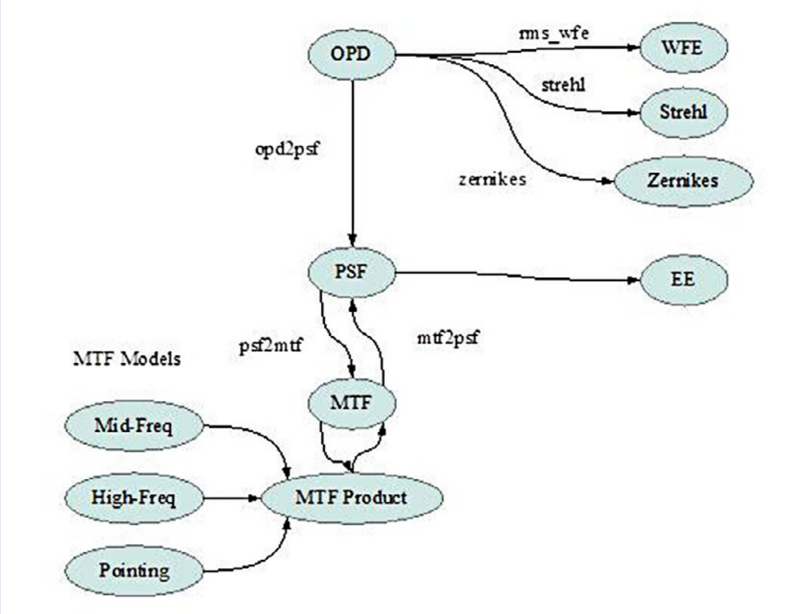

Fig. 7. *Fast Response Simulator for Telescopes (FaRSiTe).*

These can be used to generate high-fidelity PSF simulations and compute standard metrics associated with imaging systems (Modulation Transfer Function, Encircled Energy, Zernike Coefficients, etc.) plus user-defined metrics. This progress represents an advance over the previous state-of-the-art, in which performance estimates from multiple 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).

Additionally, we analyze the static and dynamic mechanical and thermal performance of candidate mirror designs generated by our modeling tool.

Finally, in Phase 2 we will generate mechanical and thermal performance predictions and then characterize that performance for the 1.5-m Ultra-Low Expansion (ULE) mirror to be manufactured by Exelis and a 1.2-m Zerodur© mirror owned by Schott North American.

Path Forward

AMTD has quantifiable milestones for each key technology. Below is the Phase 2 proposed schedule (Fig. 8). Unfortunately, Phase 2 was not fully funded, and the modal, vibration, and acoustic tests are not in the baseline plan. In addition, because of a combination of funding and contracting constraints, the Schott mirror thermal characterization test has been shifted to FY 2015. AMTD Phase 1 FY 2013/14 tasks were accomplished, and all FY 2014/15 tasks are on schedule.

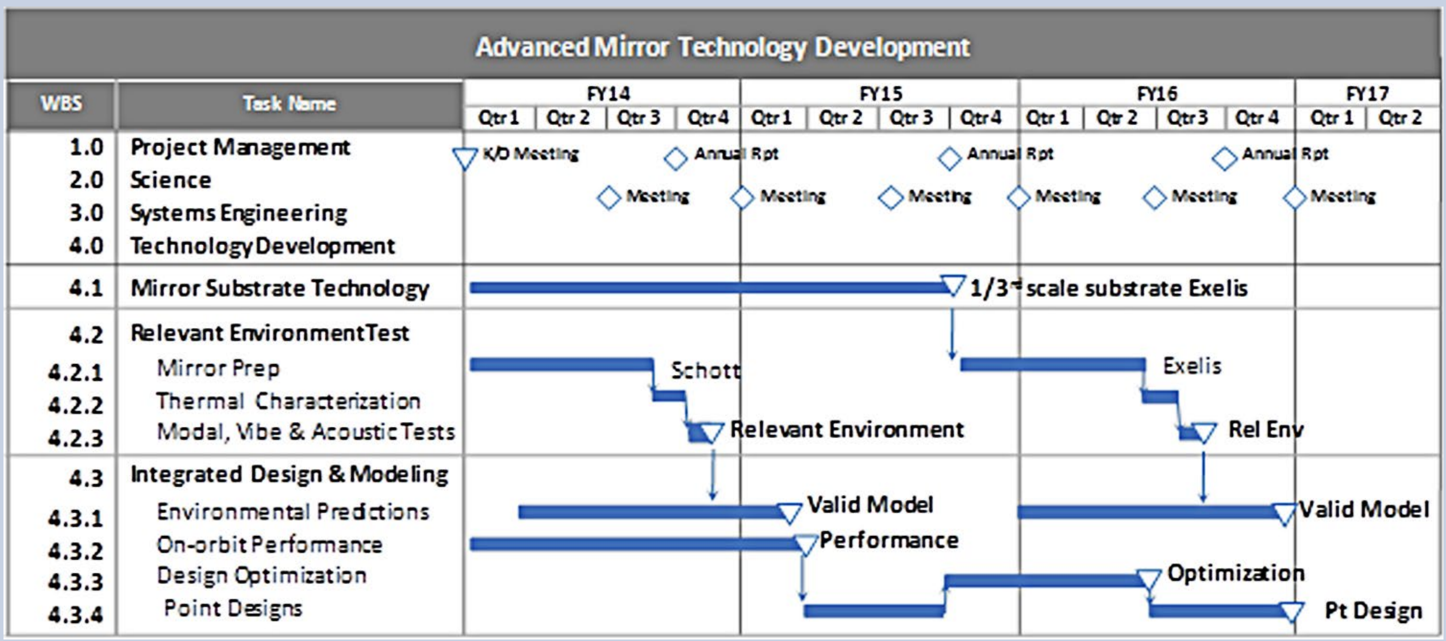

Fig. 8. *Proposed AMTD Phase 2 schedule.*

AMTD Publications

1. Stahl, H. Philip, *et al.*, *"Overview and Recent Accomplishments of the Advanced Mirror Technology Development (AMTD) for large aperture UVOIR space telescopes project,"* Proc. SPIE 8860, 2013, DOI: 10.1117/12.2022362
2. Stahl, H. Philip, W. Scott Smith, Marc Postman, *"Engineering specifications for a 4 meter class UVOIR space telescope derived from science requirements,"* Proc. SPIE 8860, 2013, DOI: 10.1117/12.2024480
3. Arnold, William *et al.*, "*Next generation lightweight mirror modeling software*," Proc. SPIE 8836, 2013, DOI: 10.1117/12.2023509

4. Arnold, William *et al.*, *"Integration of Mirror design with Suspension System using NASA's new mirror modeling software,"* Proc. SPIE 8836, 2013, DOI: 10.1117/12.2023512.
5. Matthews, Gary, *et al.*, *"Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors,"* Proc. SPIE 8838, 2013, DOI: 10.1117/12.2024630.
6. Matthews, Gary, *et al.*, *"Thermal testing of a stacked core mirror for UV applications,"* Proc. SPIE 8837, 2013, DOI: 10.1117/12.2024644
7. Eng, Ron, *et. al.*, *"Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescopes: correlation of optical test results and thermal optical model,"* Proc. SPIE 8837, 2013, DOI: 10.1117/12.2025393
8. Sivaramakrishnan, Anand, Alexandra Greenbaum, G. Lawrence Carr, and Randy J. Smith, *"Calibrating apodizer fabrication techniques for high contrast coronagraphs on segmented and monolithic space telescopes,"* SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, Optics & Photonics, San Diego 2013.
9. Gersh-Range, Jessica A., William R. Arnold, Mason A. Peck, and H. Philip Stahl, *"Parametric finite-element model for evaluating segmented mirrors with discrete edgewise connectivity,"* SPIE Proceedings 8125, 2011, DOI:10.1117/12.893469

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Ultraviolet Coatings, Materials, and Processes for Advanced Telescope Optics

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Summary

Development of high reflectivity coatings, particularly for the ultra-violet part of the spectrum, is considered a technology challenge requiring materials research and process development. "*Studies of improved deposition processes for known UV reflective coatings (e.g., MgF_2)*" and "*investigations of new coating materials with promising UV performance*" are sought (Ref: NRA NNH11ZDA001N, page D.8-10). Specific expected capabilities of new space missions include "*Imaging at the diffraction limit with large aperture UV/optical (4m to 8m) telescopes (100-1000 nm)*" and "*High contrast imaging using an internal coronagraph (100-1000 nm)*" [1]. Our primary objectives address the need to develop new coating technologies for such advanced telescope optics.

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.

During the first year of our three-year project commencing in 2013, we investigated the applicability of common materials and known processes, and identified promising candidates [2][3][4]. MgF_2, LiF, and AlF_3 stand out as primary promising materials for protective coatings while GdF_3, LaF_3, and LuF_2 are potential materials to be considered. We produced coatings of some of these materials by conventional vacuum deposition process and measured their basic properties. Our initial results were reported in a poster paper presented at the American Astronomical Society (AAS) meeting in Baltimore, MD [5]. Preliminary results with coating experiments on Al mirrors protected with MgF_2 and AlF_3 are also reported here. We started developing an Atomic Layer Deposition (ALD) process to produce thin MgF_2 coatings. More recently, we produced films of AlF_3 also by ALD. Measurements with spectroscopic ellipsometry on such films are reported here.

Currently, a 1.2m coating chamber at our sub-contract vendor, Zecoat Corp. of Torrance, CA has been upgraded with an in-situ far-ultraviolet (FUV) reflectometer for diagnostics of growing films. Similarly, the ALD coating system at JPL has been fitted with necessary gas flow and controls for MgF_2 as well as AlF_3 coatings. Enhancements to measurement techniques at the University of Colorado have also been implemented for measuring reflectivity of samples from ~50 nm to 300 nm. Thus, the much needed system upgrades for advanced process development have been implemented in recent months. More process developments for protected Al coatings with these chosen materials are in progress.

Background

It has been recognized that at mid- to far-ultraviolet wavelengths (90 nm < λ < 300 nm), it is possible to detect and measure important astrophysical processes, which can shed light on the physical conditions of many environments of interest. For example, in the local interstellar medium (LISM) all but two (Ca II H and K lines) of the key diagnostic of resonance lines are in the ultraviolet [6]. In addition to the fruitful science areas that ultraviolet spectroscopy has contributed since the early 1970s, France *et al.* [7] have emphasized the role of ultraviolet photons in the photo-dissociation and photochemistry of H_2O and 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 [8].

The 2011 NASA Cosmic Origins Program Annual Technology Report [9] 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 bandpass (~100 nm to 300-1000 nm).*" More recently, the *Advanced Technology Large-Aperture Space Telescope* (ATLAST) technology team assessed and stressed the technology development for maturing mirror coatings for the FUV spectral range [10]. A comprehensive summary of the FUV science requirements (a Science Traceability Matrix, STM) was compiled by Paul Scowen, a Co-Investigator on our project [11]. High-reflectivity coatings covering the 100-120 nm spectral region are considered important for studying IGM. The Cosmic Origins Program Analysis Group (COPAG) assessed the degree of difficulty of achieving this as very high. This is indeed very challenging, particularly in the 100-300 nm band. "*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*" [1].

Objectives and Milestones

The main objectives of this three-year project are to a) explore materials and processes to produce protective coatings for Al mirrors to perform with high reflectivity over a wide spectral range from the FUV to near-infrared (NIR), and b) demonstrate fabrication of durable mirror coatings with chosen processes on distributed coupons representing a meter-class mirror. Conventional coating processes and advanced ALD processes are pursued and investigated to achieve these goals. During the reporting period from June 2013 to May 2014, the primary objectives were as follows.

1. Produce protective coatings by conventional techniques with enhanced process controls of fluorides such as LaF_3, AlF_3, Na_3AlF_6, and GdF_3, for example, in addition to MgF_2 and LiF; to develop a database; and to compare and choose the best candidates.
2. Produce/procure coatings of protected Al (Al+MgF_2 and Al+LiF) by conventional coating processes after producing single-layer fluoride coatings to establish a baseline performance of these coatings over the full spectrum.
3. Produce preliminary Al mirror samples with bi-layer protective overcoats with MgF_2, LiF, and AlF_3, the promising candidates.
4. Develop and optimize ALD process for absorption-free thin MgF_2 coatings, and conduct preliminary experiments with MgF_2-protected Al mirrors.
5. Develop ALD process for absorption-free thin AlF_3 coatings, and conduct preliminary experiments with AlF_3-protected Al mirrors.
6. 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 (extended to Year 3 due to reprioritization of objectives).

The major objectives listed above are adopted from our original proposal and reprioritized to start on the promising ALD process development early on.

Significant Progress and Accomplishments

Single-layer coatings of applicable transparent protective materials by conventional deposition process

To start, we produced single-layer coatings of MgF_2, LiF, AlF_3, LaF_3, Na_3AlF_6, and GdF_3 with conventional coating processes in a 1.2 m size chamber (Fig. 1) fitted with resistive sources, electron gun, ion gun, heater lamps, liquid nitrogen (LN) traps, cryo pumps, residual gas analyzers, and computer controls. The chamber can maintain pressures in the range of 2×10^{-7} to 1×10^{-6} Torr, and temperatures in the range of 20-200°C.

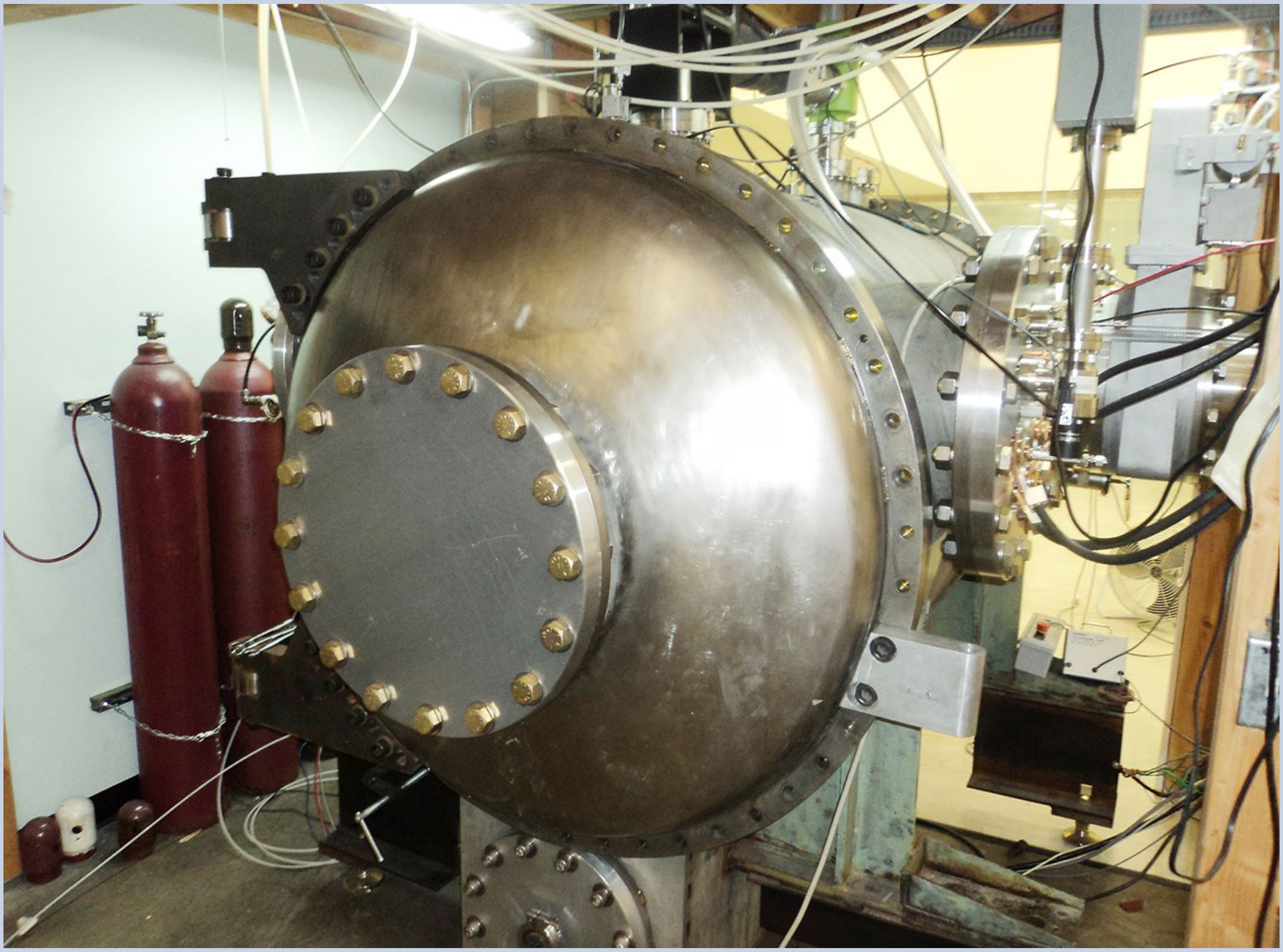

Fig. 1. *A 1.2 m coating chamber fitted with process controllers, thickness monitor, and gas analyzer (courtesy: Zecoat Corp).*

A sample transport and masking mechanism will soon be installed in the chamber (Fig. 2). This enables multiple coatings on different samples without breaking vacuum. A FUV optical monitoring system (schematic in Fig. 3) was installed in the system to measure reflected signal from the growing film during deposition and post-deposition, as well as conditions such as total pressure, water vapor and oxygen content, etc., for diagnostic purposes. Several coatings were prepared on fused silica and silicon substrates. Two inch diameter UV-grade fused silica substrates were specially prepared with one or both sides polished to provide regions over which coatings could be prepared in the same run, enabling multiple experiments and measurements with one sample. Spectral transmission characteristics of some of these coatings were measured (Fig. 4) with a state-of-the-art PerkinElmer Lambda 1050 spectrophotometer. Among these materials, MgF_2, LiF, and AlF_3 are considered the most promising, based on their UV transparency. The other, particularly high-index, materials could be employed in other multilayer devices such as filters and beam splitters.

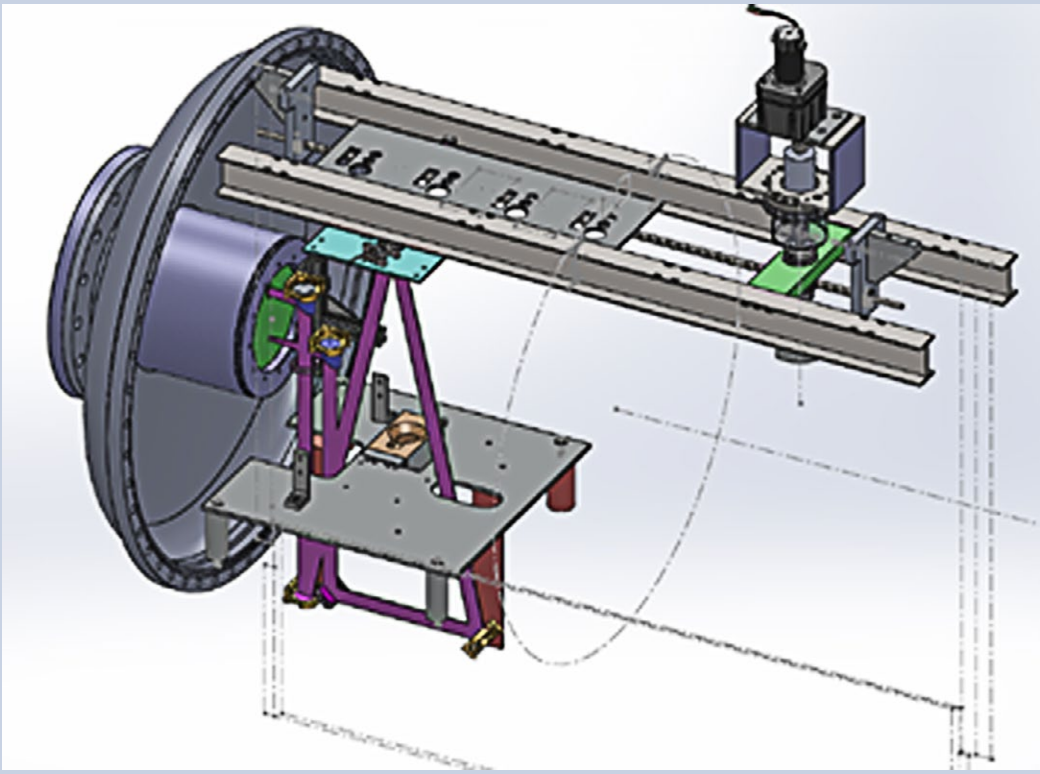

Fig. 2. *Upgrades to the coating chamber fitted with FUV optical monitoring system and sample transport and masking mechanism to enable multiple coatings without breaking vacuum (courtesy: Zecoat Corp.).*

In-situ FUV reflectometer measurements
The *in-situ* reflectometer system (Fig. 3) was employed to measure reflectivity change from the sample during the coating process and after completion of coating. The photo-multiplier tube (PMT) measures the total signal (total reflected energy from ~115 nm to ~165 nm of the D2 source spectrum) as reflected from the growing film.

An interesting diagnostic run (0069, Fig. 5) showed a maximum signal and then a drop after ~50 nm of Al coating, indicating a change in reflectivity due to chemical or structural modification of the film surface. During this run, a layer of MgF_2 (~26 nm) was added over a 150 nm Al film in the same run (Fig. 5, green trace) without breaking vacuum; signal (Fig. 5, blue trace) dropped and then increased with thickness of MgF_2, likely due to interference effect. A small thermally induced effect is also likely to affect these measurements. Further investigations are needed to understand the mechanisms, particularly after initial growth of the film. Such diagnostics are expected to help optimize the overcoat layer process.

Protected Al mirror coatings
Several coating experiments were conducted to produce MgF_2, AlF_3, and LiF overcoated Al mirrors with a conventional deposition process in the chamber described above. Table 1 lists the process parameters for these coating runs and the thicknesses of the various layers. Figure 6 shows the reflectance of

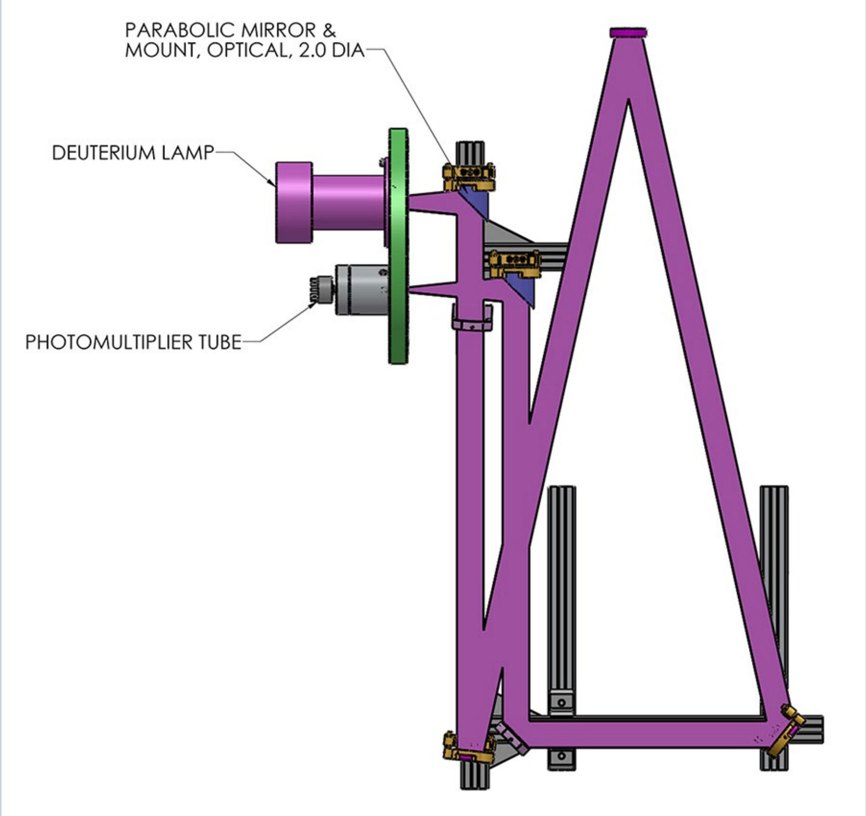

Fig. 3. *FUV reflectometer system inside the coating chamber for in-situ diagnostics of the growing film (courtesy: Zecoat Corp.).*

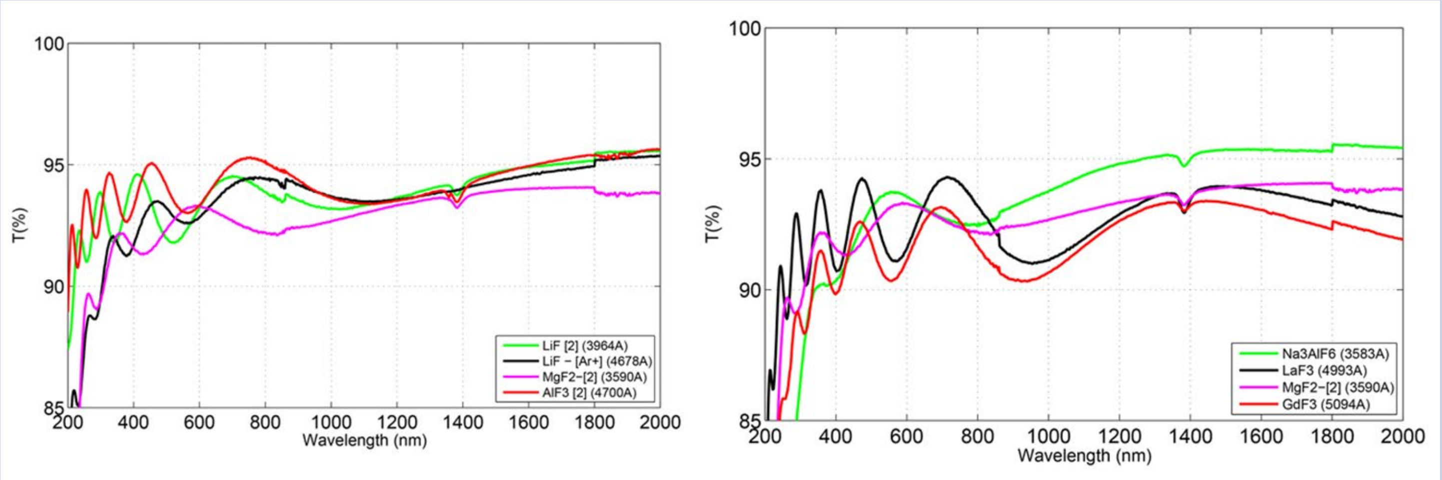

Fig. 4. *Transmittance spectra of single-layer coatings on UV-grade fused silica substrates (uncoated back side). The numbers in parentheses indicate thickness in Angstroms. Angle of incidence 0°.* Left: *Coatings of AlF_3, MgF_2, and LiF.* Right: *Coatings of GdF_3, MgF_2, LaF_3, and Na_3AlF_6.*

three samples over the spectral range 200-1000 nm eight months after fabrication and six months apart, with measurements in the FUV range pending. These preliminary experimental data indicate a preference for AlF_3 as protective layer, pending detailed process optimization and durability tests. Similarly, Fig. 7 shows the reflectance of bi-layer overcoated Al mirror samples from initial experimental runs in the same chamber. These samples remained in the lab in a dry nitrogen flow box except during measurements, involving a few days of exposure to normal lab environment with ~30-40% humidity.

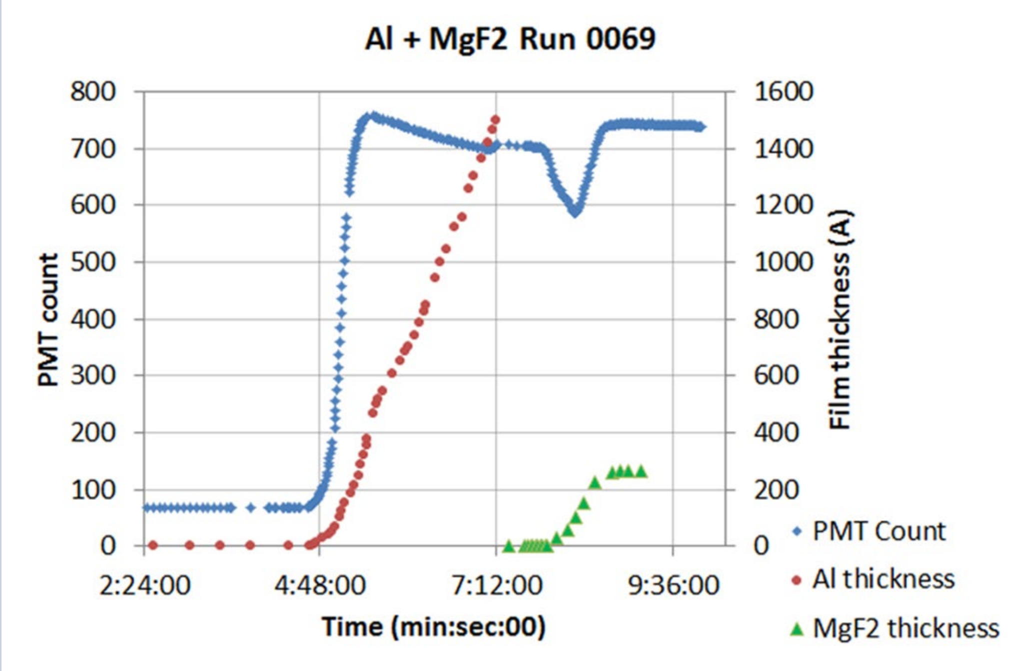

Fig. 5. *FUV monitor diagnostic signal while growing Al film followed by MgF_2 film.*

Run #	Coating	Base Press pre-coating (Torr)	Chamber Temp (°C)	Process	Layer Thickness (A)
0057	Al + MgF_2	3.6E-07	23.4 - 185.6	e-gun + resistive	1516 + 250
0058	Al + AlF_3	5.3E-07	22.5 - 177.0	e-gun + resistive	1284 + 675
0063	Al + LiF	1.7E-07	19.0 - 187.1	resistive	1520 + 255
0069	Al + MgF_2	2.6E-07	20	resistive	1510 + 266
0070	Al + AlF_3	2.0E-07	20	resistive	1519 + 480
0062	Al + LiF + MgF_2	2.6E-07	Al at 20°C, LiF and MgF_2 at ~200°C	resistive	1497 + 114 + 56
0065	Al + LiF + AlF_3	1.8E-07	Al at 20°C, LiF and AlF_3 at ~200°C	resistive	1516 + 168 + 60

Table 1. *Conventional coating process run details relevant to measured results in Figs. 6 and 7; 1" diameter fused silica and 2" diameter silicon wafer substrates were employed in each coating run.*

FUV reflectance measurement of samples at University of Colorado

An FUV reflectance measurement system (Fig. 8) has been in operation for many years at the University of Colorado, Boulder in Prof. James Green's laboratory. Several of our samples were tested there for FUV reflectivity in the 50-300 nm range. The system was recently upgraded with a new PMT and other alignment tools for precision measurements. Accurate positioning of the reflected beam on the PMT is ensured with adjustable stages and rotary fixtures. Figure 9 shows the measurement system internal details including its upgrades.

FUV reflectance of single-layer coated samples of MgF_2, LiF, and AlF_3 were measured. Figure 10 shows the results, pending ellipsometric characterization of refractive indices. These measurements helped establish procedures and upgrade system hardware. More coatings on silicon and glass substrates with tuned processes to be produced over the coming months will be tested at this facility.

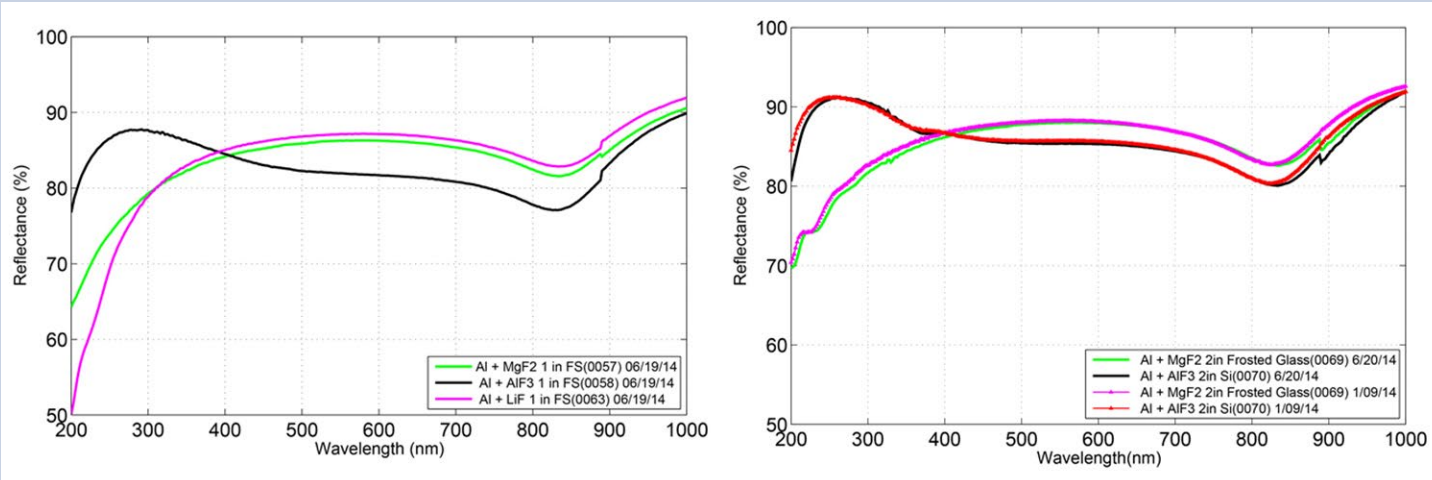

Fig. 6. *Reflectance measurements in the 200-1000 nm range for single-layer-protected Al mirror samples* Left: *Measurements for samples on fused silica substrates after about eight months from date of fabrication.* Right: *Measurements for samples on frosted glass and Si substrates, carried out six months apart. See Table 1 for process details.*

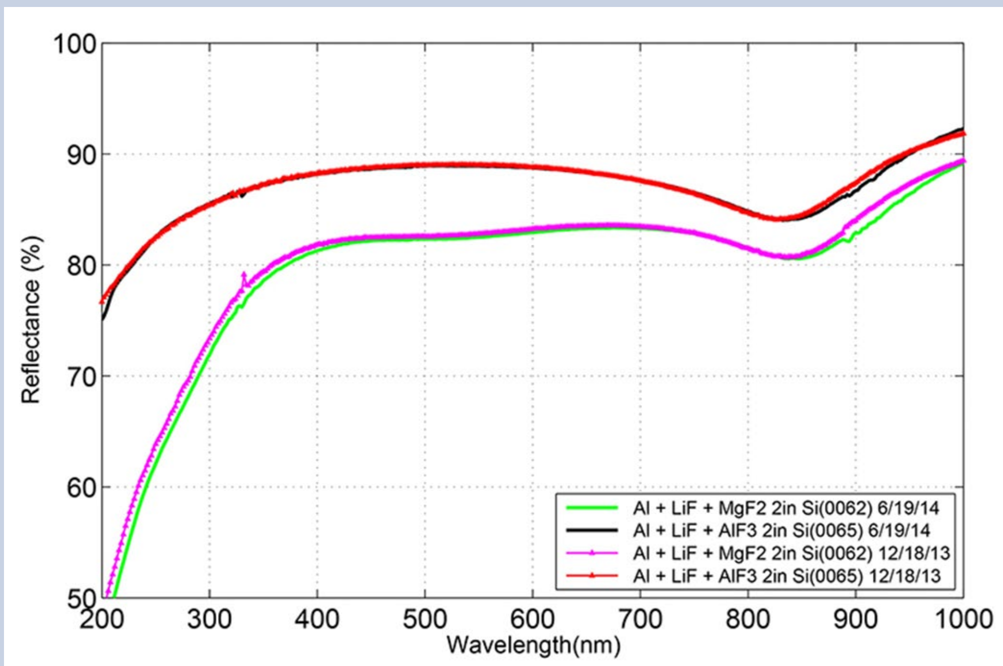

Fig. 7. *Reflectivity of Al+LiF mirror samples with MgF_2 and AlF_3 protective layers. Measured after six months, these samples, stored in dry nitrogen flow box except during measurements involving a few days of exposure to normal lab environment with ~30-40% humidity, show little degradation. Detailed environmental tests will be conducted soon to check their robustness. See Table 1 for process details.*

Atomic layer deposition

An ALD process is under development at JPL to produce MgF_2 and AlF_3 protective coatings for high-reflectivity mirrors with an Oxford OpAl® showerhead-style ALD reactor (Fig. 11).

ALD films were deposited using bis(ethylcyclopentadienyl) magnesium ($Mg(EtCp)_2$) and trimethyl-aluminum (TMA) as the metal-containing precursors, and anhydrous hydrogen fluoride (HF) as the fluorine-containing precursor in our Oxford reactor. Although metal fluorides are not common ALD

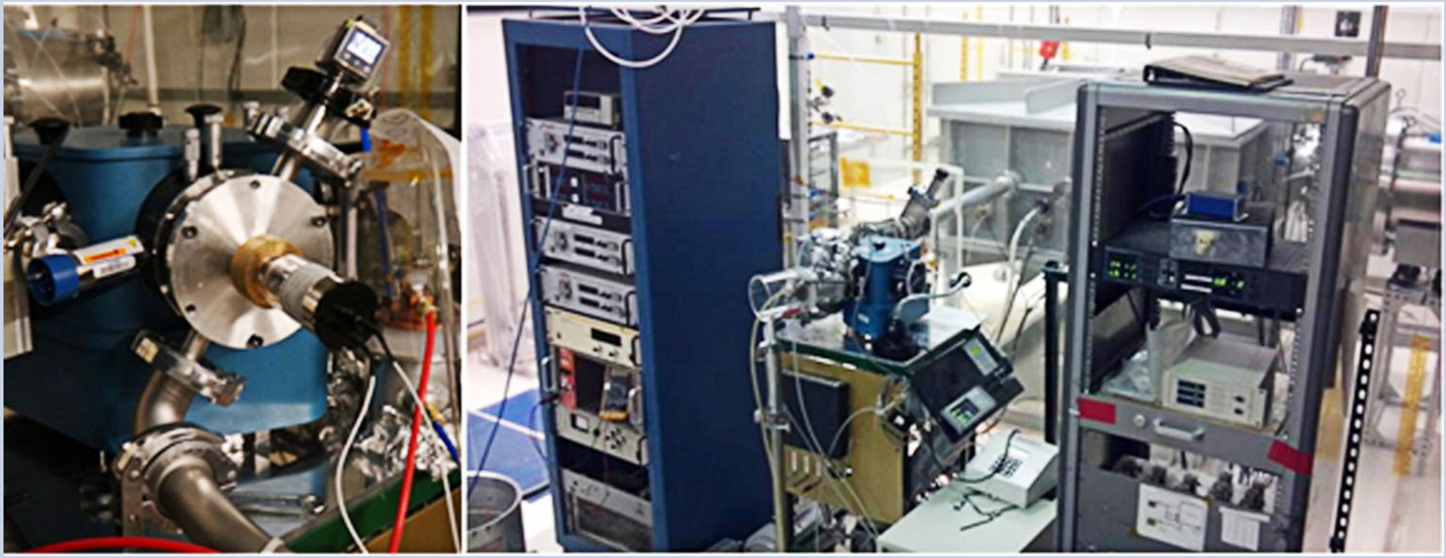

Fig. 8. *FUV measurement system at the University of Colorado. (Courtesy: Prof. James Green). The light sources include sealed Pt-Ne and deuterium discharge lamps, and windowless gas discharge systems. These can provide a host of emission lines from 40–200 nm. The vacuum tank is operated in a Class 2000 clean tent.*

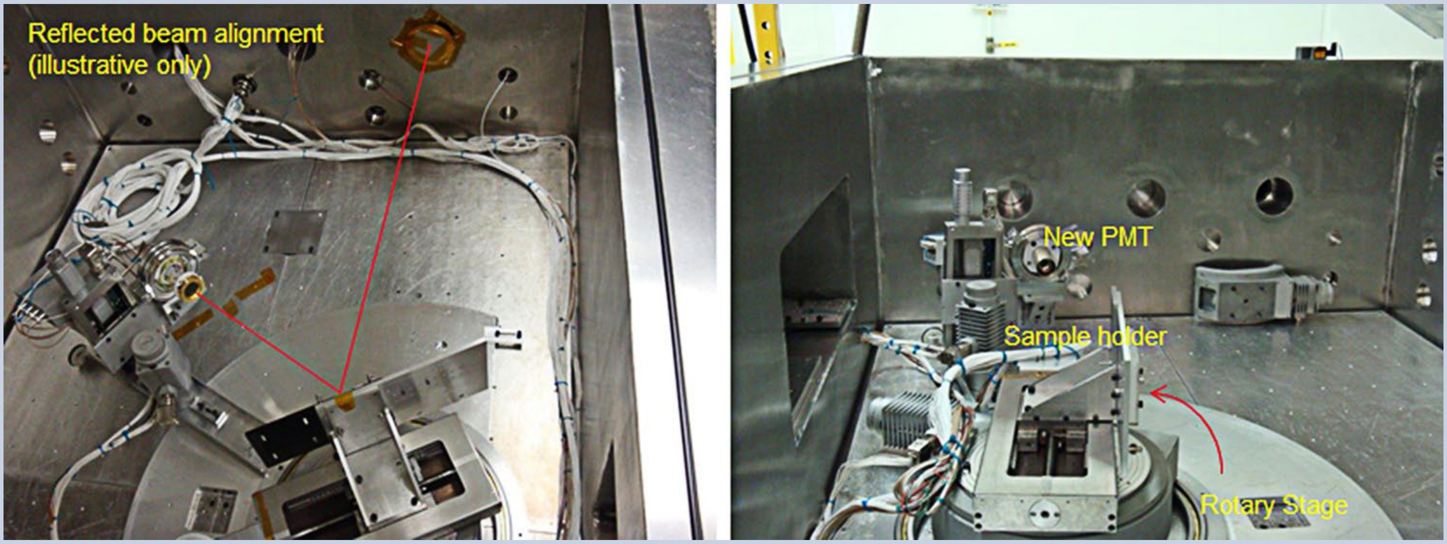

Fig. 9. *University of Colorado FUV measurement system showing the new PMT on a translation stage and sample holder on a rotation stage for accurate alignment.*

materials, there have been several previous reports of their deposition often using metal fluorides such as TaF_5 or TiF_4 as the fluorine-containing source [12][13]. This tends to result in residual metal contamination, which degrades FUV absorption properties, and results in a process which can only be performed at substrate temperatures greater than 250°C. As a result of this high deposition temperature, the fluoride films deposited with this method tend to crystallize readily, resulting in significant surface morphology undesirable for many optical applications. In contrast, the JPL-developed ALD process using HF results in fluoride materials with lower residual contamination that can also be deposited at low temperature resulting in smoother, denser films. An example of this is shown in Fig. 12, which compares a nano/polycrystalline TiO_2 film deposited by ALD at JPL to an ALD AlF_3 film of similar thickness that shows no significant surface features. Future Atomic Force Microscopy (AFM) studies will more precisely investigate the surface roughness of these materials as a function of process conditions.

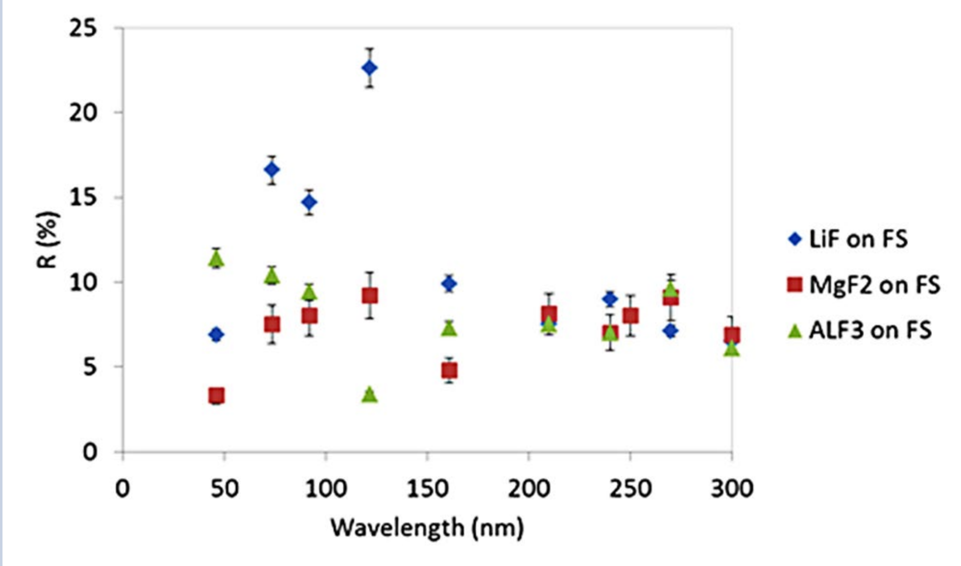

Fig. 10. *Measured reflectance of single layer LiF, MgF_2, and AlF_3 films on UV-grade fused silica substrates.*

Fig 11. *ALD coating system at JPL; gas feed-throughs and process controls enable AlF_3 and MgF_2 coatings development.*

As part of this effort, MgF_2 and AlF_3 were deposited at substrate temperatures ranging from 125°C to 250°C, with film thickness and refractive index measured by spectroscopic ellipsometry and monitored as a function of process conditions such as process purge times and substrate temperature. An example of this index modelling is shown in Fig. 13 for MgF_2. Both materials appear transparent (k=0) over the measurement range of 190-1000 nm. Recent reports on the same JPL ALD materials have also shown good optical performance at wavelengths down to 90 nm [14].

Typical ALD conditions involve heating of the $Mg(EtCP)_2$ precursor, which is then bubbled with Ar into the process chamber at exposure times of approximately 1s. TMA and HF are delivered by vapor draw at room temperature at shorter exposure times of 15-30 ms. The chamber is purged with Ar between each half-cycle exposure in the ALD process to ensure saturated, self-limiting deposition. We have demonstrated both MgF_2 and AlF_3 with thickness uniformities better than 1% over six inches in diameter. Initial X-ray Photoelectron Spectroscopy (XPS) measurements suggest the films are approximately stoichiometric and future studies will investigate how material composition changes as a function of process conditions.

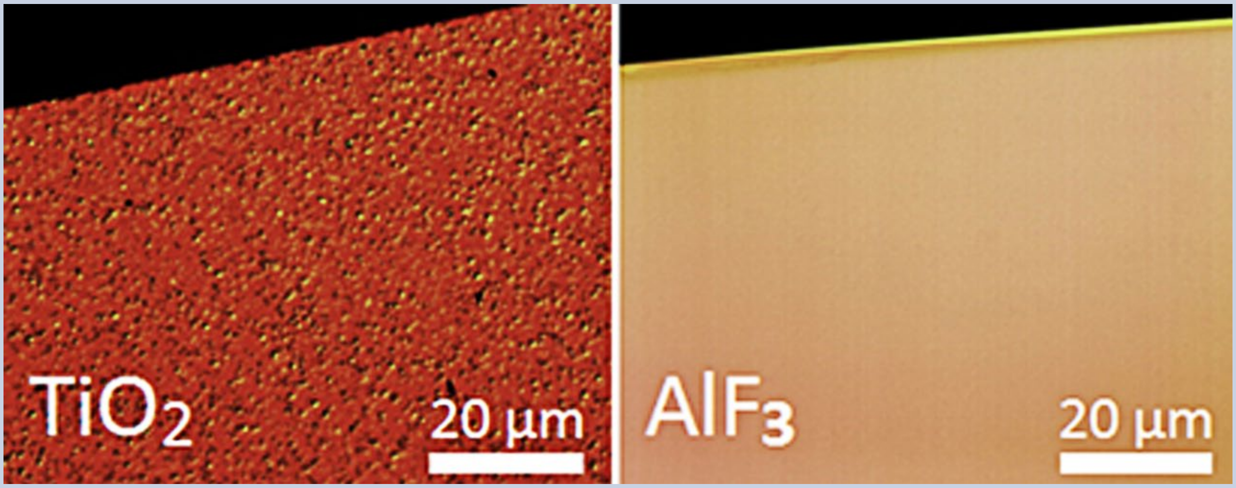

Fig. 12. *Optical interference micrographs of 100 nm TiO_2 deposited by ALD on silicon at 250°C showing significant grain structure, compared to a 100 nm AlF_3 deposited by ALD at 200°C imaged under similar conditions.*

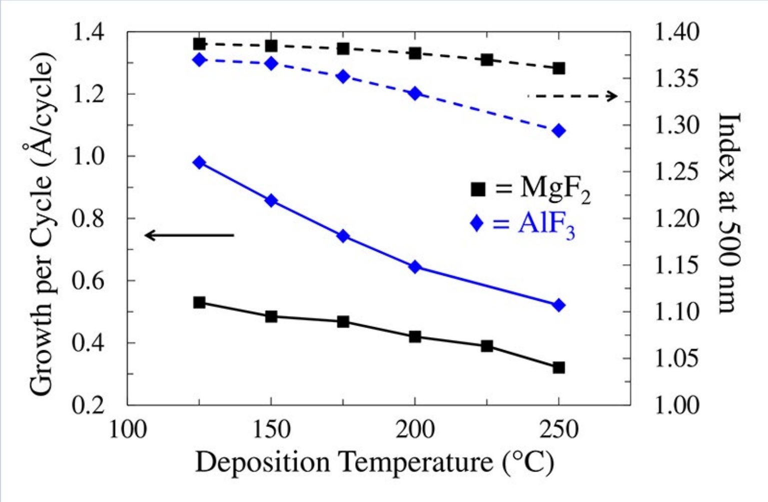

Fig. 13. *Refractive index and growth per cycle for ALD MgF_2 and AlF_3 deposited on HF-cleaned silicon substrates as characterized by spectroscopic ellipsometry.*

Path Forward

In the coming year, we plan to focus on optimizing deposition process parameters on the ALD and preparing samples of protected aluminum mirrors for reflectivity tests. With conventional deposition techniques, we plan to prepare MgF_2-, AlF_3-, and LiF-protected Al mirror samples with optimum process conditions and subject them to environmental tests with particular attention to FUV performance evaluation. Finally, we plan to coat a set of samples in a large chamber representing a meter-class mirror for uniformity and performance tests, thus advancing the technology development efforts towards the program objectives.

References

[1] Dalcanton, J., Hillenbrand, L., Sembach, K., Gardner, J., Lillie, C., Goldsmith, P., Leisawitz, D., Martin C. (Chair), 2011, "*COPAG Technology Assessment*," v.1.3.

[2] Bridou, F., *et al.*, "*Experimental determination of optical constants of MgF_2 and AlF_3 thin films in the vacuum ultraviolet wavelength region (60–124 nm), and its application to optical designs*," Opt. Communications, 283, 1351-1358 (2010).

[3] Keski-Kuha, *et al.*, "*Optical coatings and applications for ultraviolet space applications*," (NASA/GSFC) ASP Conference Series, vol. 164, JA Morse, *et al.;* eds. (1999).

[4] Yang, M., Gatto, A., and Kaiser, N. "*Aluminum-enhanced optical coatings for the VUV spectral range*," Proc. SPIE, vol. 5963 (2005).

[5] Balasubramanian, *et al.*, "*Protective coatings for FUV to NIR advanced telescope mirrors*," AAS 223 (Jan 2014) Poster paper on progress presented at the AAS meeting in Baltimore, MD.

[6] Redfield, S., "*The Local Interstellar Medium*," in ASP Conference Series 352, New Horizons in Astronomy, 79, arXiv:astro-ph/0601117v1 (2006).

[7] France, K. *et al.*, "*From Protoplanetary Disks to Extrasolar Planets: Understanding the Life Cycle of Circumstellar Gas with Ultraviolet Spectroscopy*," arXiv:1208.2270 [astro-ph.SR], (2012).

[8] Shull, *et al.*, "*The baryon census in a multiphase intergalactic medium: 30% of the baryons may still be missing*," The Astrophysical Journal, 759:23 (2012).

[9] Cosmic Origins Program Annual Technology Report, (2011) (http://cor.gsfc.nasa.gov/tech/COR_PATR_Final_110911.pdf and http://www.stsci.edu/institute/conference/copag2011/).

[10] Stahle, *et al.*, "*The Advanced Technology Large-Aperture Space Telescope (ATLAST)*," 224^{th} AAS Meeting, Boston (2014).

[11] Scowen, P, in http://cor.gsfc.nasa.gov/RFI2012/rfi2012-responses.php

[12] Pilvi, T. *et al.*, "*Study of a novel ALD process for depositing MgF_2 thin films*," J. Mater. Chem., 17, 5077 (2007).

[13] Mantymaki, M. *et al.*, "*Atomic Layer Deposition of LiF Thin Films from Lithd, $Mg(thd)_2$, and TiF_4 Precursors*," Chem. Mater. 25, 1656 (2013).

[14] Moore, C. *et al.*, "*Recent developments and results of new ultraviolet reflective mirror coatings*," presented at SPIE Astronomical Telescopes + Instrumentation, Montreal (2014).

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

Prepared by: Manuel A. Quijada (PI; NASA/GSFC); Javier del Hoyo and Steve Rice (NASA/GSFC)

Summary

This project started in Fiscal Year (FY) 2012, with an initial two-year duration through the end of FY 2013. However, a no-cost extension was requested at the beginning of FY 2013, and was granted. We are now in the final year that will conclude on September 30, 2014 (end of FY 2014).

This project includes three major tasks. The first, to demonstrate the viability of coating medium to moderately large (1m diameter) mirrors in a large (2m diameter) chamber to improve the far-ultraviolet (FUV) reflectance of aluminum (Al) mirrors protected with either magnesium fluoride (MgF_2) or lithium fluoride (LiF) overcoats. The gains in FUV reflectance were possible by employing a 3-step Physical Vapor Deposition (PVD) process developed in a smaller coating chamber on substrates of up to 3.5 cm diameter. Application of these high-performing coatings on large primary mirrors of a FUV astronomical telescope will enhance throughput and add flexibility to a system design certain to improve overall performance. The second task was to determine the refractive index (n) and absorption coefficient (k) of gadolinium and lutetium tri-fluoride (GdF_3 and LuF_3, respectively). These materials are considered high-index options that, when paired with a low index material such as MgF_2, could enhance the reflectance of Al mirrors over a narrow bandwidth centered in the range from 110 to 250 nm. A third task was 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.

Among the achievements of the past year, we completed assembly of heat-shield panels and installation of a halogen-quartz heater system in the 2m coating chamber. We performed end-to-end testing of the system and performed numerous coating runs of the 3-step PVD coating process for producing Al test coupons (2" × 2") protected with either MgF_2 or LiF films. These efforts produced the highest reflectance ever reported for mirrors at Lyman-Alpha (121.6 nm) wavelengths. We characterized a series of GdF_3 and LuF_3 films deposited on MgF_2 substrates to determine the optical properties and absorption cutoff for these films at FUV wavelengths. We performed dielectric designs by pairing either of these films with the low-index MgF_2 and demonstrated the reflectivity gains obtainable when these coatings are applied on MgF_2 substrates or Al coatings.

Background

The FUV region (90 to 150 nm) is relevant to many aspects of NASA's Cosmic Origins Program, particularly the Astrophysics Science Area Objective 2: "*Understand the many phenomena and processes associated with galaxy, stellar, and planetary system formation and evolution from the earliest epochs to today*." Many of the resonance lines for both low-ionization and high-ionization states of common atoms are found largely in this region. Some lines are found at longer wavelengths, 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 only found below 115 nm. 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 HD are found only in the FUV region as well. Understanding the abundance of D is an important test of Big Bang cosmology and of chemical evolution over cosmic time.

Despite the wealth of information obtainable, astrophysics observations in the FUV have been limited by poor performance in available optics coatings in this spectral region. It is hard to overstate the

Manuel Quijada

importance of producing high-performance reflective coatings, since improved reflectivity in itself would bring enormous throughput gains with the added benefits of more capable optical systems.

The FUV region from 90 to 115 nm has only been explored by a handful of NASA astronomy missions – *Copernicus* (also known as *Orbiting Astronomical Observatory 3*, or OAO-3) in the 1970s, *Hopkins Ultraviolet Telescope* (HUT), the *Orbiting Retrievable Far and Extreme Ultraviolet Spectrometer* (ORFEUS) shuttle payloads in the 1990s, and the *Far Ultraviolet Spectroscopic Explorer* (FUSE) in the 2000s. The FUSE observatory was the most extensive by far, but it was limited by modest effective area (20 cm^2 below 100 nm to 55 cm^2 above 102 nm) and a modest spectral resolution (R ~20,000). The FUSE mission made significant strides in mapping variations in D/H in the galaxy, but due to low reflectance of available coatings, lacked the sensitivity to study D/H in the intergalactic medium (IGM).

Aluminum is one of the few materials in nature with an intrinsic reflectance that exceeds 90% in the FUV spectral region. However, this metal quickly oxidizes when exposed to oxygen. This oxidation produces a thin aluminum oxide (Al_2O_3) layer that is responsible for the severely degraded reflectance performance (< 10%) that this material exhibits for wavelengths shorter than 150 nm. The most commonly used approach to avoid the formation of this oxide layer on Al, and hence avoid its low FUV performance is to apply either a thin MgF_2 or LiF layer. The typical thickness for either of these is approximately a quarter-wave of a design wavelength chosen anywhere between 90 and 150 nm. In addition to protecting against oxidation, these overcoats also produce a dielectric boost in reflectance centered at the chosen design wavelength. Until recently, the reported reflectance values obtained for either Al+MgF_2 or Al+LiF coatings were well short (< 83%) of the theoretical values at Lyman-Alpha (121.6 nm). This poor performance is attributed to the poor quality of overcoat films possible with conventional methods. The current project has improved the state-of-art by employing a 3-step PVD coating process that produces test coupons with a reflectance that approaches the theoretical limit (90-92%) at 121.6 nm.

Objectives and Milestones

The overall objective of this program is to improve mirror coating reflectance, particularly in the FUV. This mission-enabling technology specifically addresses the Technology Development for the Cosmic Origins Program (TCOR) under Section 2, titled "*Ultraviolet Coatings*." Specifically, we address:

1. Improved deposition processes for known FUV reflective coatings (*e.g.*, MgF_2 and LiF);
2. Investigation of new coating materials with promising UV performance; and
3. Examination of handling processes; contamination control; and safety procedures related to depositing coatings, storing coated optics, and integrating coated optics into flight hardware.

The first objective is to demonstrate or transfer to an existing 2m PVD chamber at GSFC the process for enhancing FUV reflectance of Al mirrors protected with MgF_2 or LiF layers. This process, which consists of reducing absorption in the overcoat layers, was originally implemented in a smaller PVD coating chamber which only allowed coating optics up to a few inches in diameter.

The second objective is to perform a limited materials study, via the PVD process, of the best materials identified in an earlier study [1], which examined a series of lanthanide trifluorides and found potential candidate materials beyond LaF_3. These high-index materials, when paired with a low-index layer (such as MgF_2), would facilitate the design and fabrication of all-dielectric reflectors and even interference filters for FUV. Our study concentrates on studying the optical properties of GdF_3 and LuF_3 films.

The third and final objective is to develop low-absorption MgF_2 thin-film coatings using a reactive IBS coating process expected to produce optical thin-film coatings as near as possible to ideal morphology. However, the energies involved in the IBS process make it difficult to maintain stoichiometry for certain materials. This shortcoming is addressed by flowing a fluorine-containing gas (*e.g.*, 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 achieved through IBS.

The main milestones reported in the FY 2012 Program Annual Technology Report (PATR) were:

1. Perform additional optimization of MgF_2 and LiF in small coating chamber (Sep. 2012);
2. Perform initial Al+MgF_2 coatings with 2m chamber (Nov. 2012);
3. Perform distribution study of Al+MgF_2 coatings with 2m chamber (Dec. 2012);
4. Perform initial Al+LiF coatings with 2m chamber (Jan. 2013);
5. Perform distribution study of Al+LiF coatings with 2m chamber (May 2013);
6. Characterize Lanthanide Trifluoride for FUV application (Nov. 2012);
7. Design and fabricate Lyman-Alpha reflector (Apr. 2013);
8. Optimize and characterize MgF_2 films using the IBS process (Nov. 2012); and
9. Optimize and characterize LiF films using the IBS process (Mar. 2013).

Milestone 2 suffered a notable schedule deviation, and was completed in May 2013. This had a ripple effect on completion dates for Milestones 3 through 5, caused by a five-month delay in procurement of key hardware (power supply and halogen/quartz heater system) and completion of thermal shields and installation of the lamp heaters inside the 2m chamber. It is important to note that these dates were based on the assumption of a two-year program that was due to conclude at the end of FY 2013. The one-year extension provided ample time for a successful completion of the unfinished tasks by the end of FY 2014.

It should be noted that Milestone 8 was reported in the 2013 PATR, where we stated that the MgF_2 films produced with the reactive IBS process were of very poor quality. The problem was traced to the fact that the fluorine contained in the Freon gas was quickly corroding the tungsten filament used in the ion-gun source of our IBS chamber. It was determined that progress could only be achieved with substantial investment in a new coating system, implementing a “filamentless” ion gun. This acquisition exceeded the available budget. Hence, this task and the related Milestone 9 were abandoned.

Progress and Accomplishments

2m Chamber Preparation

The first objective of this project was to scale up the process for improving FUV reflectance of Al+MgF_2 and Al+LiF mirrors. This objective was closely tied to upgrading the existing 2m coating chamber, allowing coating of large (up to 1m diameter) optics. Upgrading the chamber required the following steps:

- Design, fabricate, and assemble heat-shield panels to fit inside 2m chamber;
- Acquire a 6 kW power supply system to operate halogen quartz lamps as heating element in chamber; and
- Wire up power supply and heating elements inside chamber.

These tasks are related to Milestone 2 above, and were completed by May 2013. Since the 2013 PATR, we also tested heater and thermal shield performance.

Figure 1 shows the thermal profile of the time it takes the substrate to reach or exceed a 200°C target temperature. Earlier studies determined this was the minimum temperature required to achieve good MgF_2 film quality [2]. The blue curve in Fig. 1 shows the temperature profile with bare stainless steel heat panels. These data indicate heating with these panels was very inefficient since we were unable to reach our target temperature with the heaters on for over seven hours. This inefficiency was addressed by wrapping the heat-shield panels with Al foil. The red curve shows the substrate reached 206°C in under an hour.

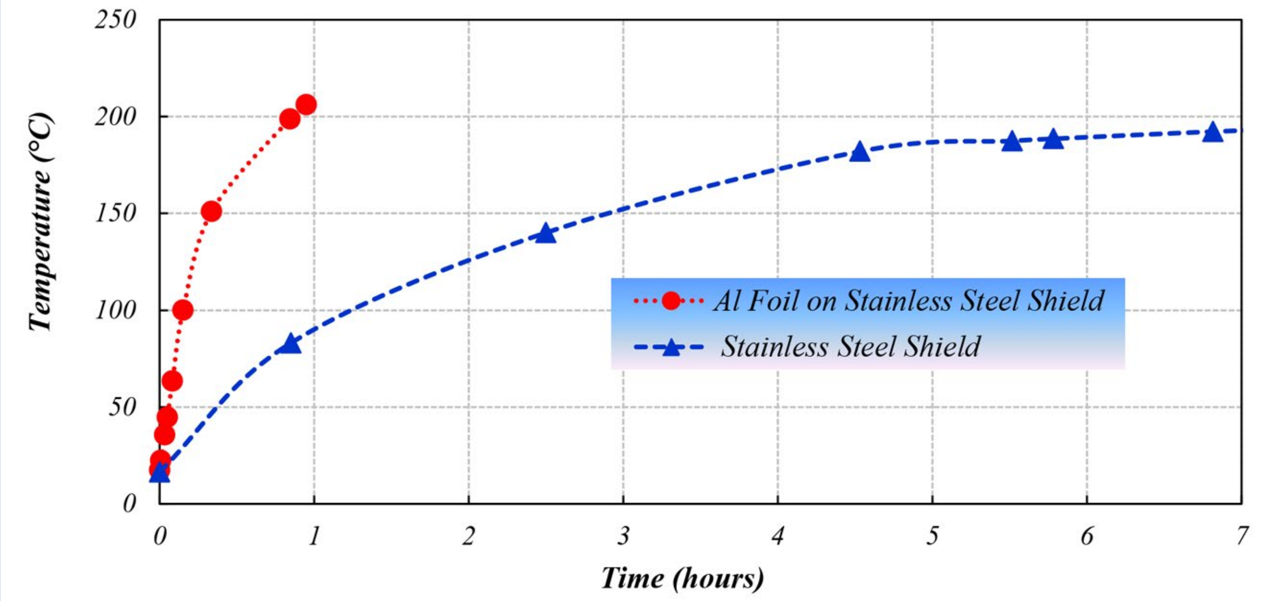

Fig. 1. *Substrate heating profile in 2m coating chamber.*

A second consideration in thin-film deposition, especially using a chamber as large as the one in this study, is thickness uniformity. Film thickness varies due to evaporation chamber geometry and collisions with residual gases that aggravate thickness non-uniformity. Figure 2 shows characterization of this non-uniformity in our 2m chamber. The data are reported as normalized thickness variation as a function of the radial distance from chamber center out to a 0.8m radius. Note the variation is as high as 50% when the substrate is held static during deposition, but rotating it reduces non-uniformity below 10%.

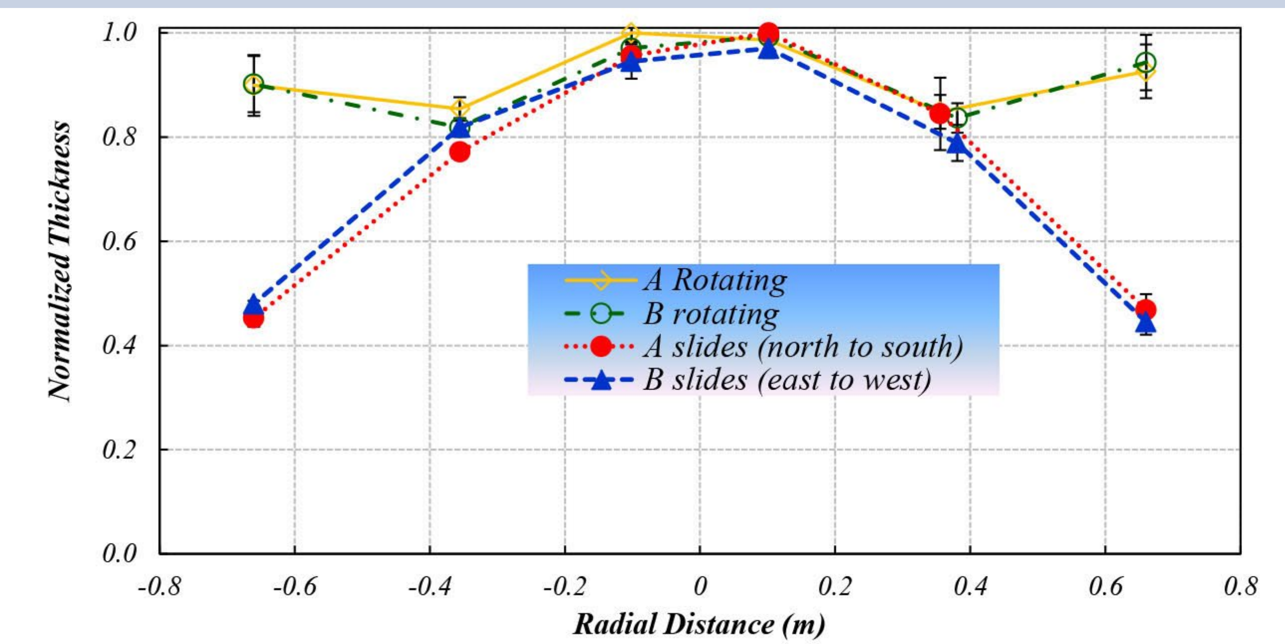

Fig. 2. *Thickness variation as a function of radial distance from center of 2m chamber.*

Reflectance of Al+MgF$_2$ Mirrors

Figure 3 displays reflectance results of Al+MgF_2 mirror coatings performed in the 2m coating chamber. The procedure applied an initial Al layer of 50 nm first, with the substrate at ambient temperature. This was followed by an initial 5 nm MgF_2 coating on top of the Al. The heaters then brought the substrate temperature up to 220°C for the last part of the MgF_2 deposition (≈ 20 nm). Several trials were required to optimize coating parameters such as vacuum cleanliness and deposition rate before reaching success in producing coatings with reduced absorption in the MgF_2 layer and higher FUV reflectance.

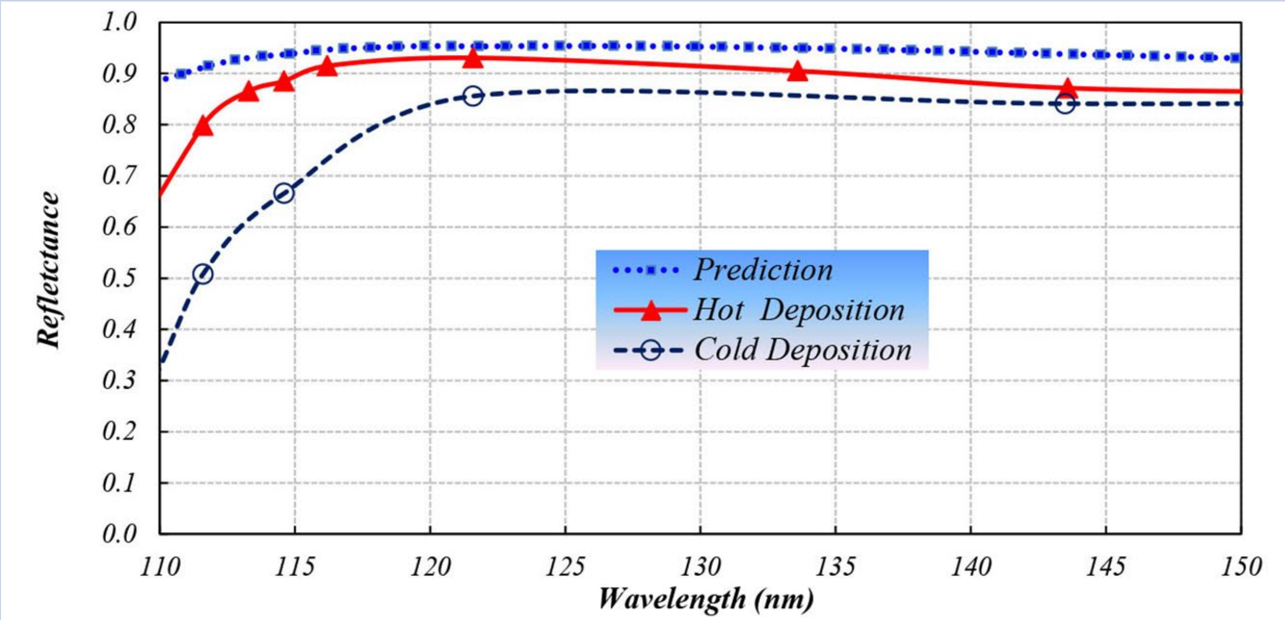

Fig. 3. *Predicted and measured FUV reflectance of Al+MgF_2 where MgF_2 was deposited at cold (ambient) and elevated (220°C) temperatures.*

The results indicate there might be further room for improvement since we did not reach the theoretical prediction. We also observed reflectance suppression in the 135-150 nm range. Similar behavior has been reported by others [3] and has been attributed to plasmonic absorption coupled with micro-roughness in the Al layer at those wavelengths.

This effect is an important consideration given that developing better-performing, more robust coatings will provide substantial gain in throughput when these coatings are used on FUV instrument reflecting surfaces. The results (Fig. 3) indicate that although data obtained on the enhanced process is still below the ideal case, reflectance reached predictions for bare Al at wavelengths close to 121.6 nm (91%). The results also indicate gains in reflectance for the "Hot" deposition are even more dramatic on the short wavelength side, pushing the useful range for this type of mirror coatings much closer to the natural cut-off wavelength of crystalline MgF_2.

Micro-Roughness of Al+MgF_2 Coatings

We performed a comparative surface study on Al+MgF_2 films prepared under ambient conditions and others where the MgF_2 layer was performed at temperatures as high as 220°C. Measurements were made using an ADE Phase-Shift MicroXAM surface profiler, a phase-sensitive, interferometer-based, non-contact instrument capable of providing highly reproducible surface mapping information at various magnification levels. It consists of an optical microscope with eyepieces and video display of images with a high-resolution camera. Two representative images taken with this instrument are shown in Fig. 4.

The surface roughness parameters derived from images like the ones in Fig. 4 are shown in Table 1. We first noticed the peak-to-valley numbers for the "Ambient" sample are approximately 2-3 times larger than for the "Enhanced" one. This observation suggests that heating the substrate during MgF_2

deposition could be providing a "flatter" surface profile, perhaps by relieving the stress of the MgF_2 films. The test mirror that was heated during the MgF_2 deposition had a 30% smaller root-mean-square (rms) micro-roughness parameter (S_q), suggesting a larger grain size for this sample.

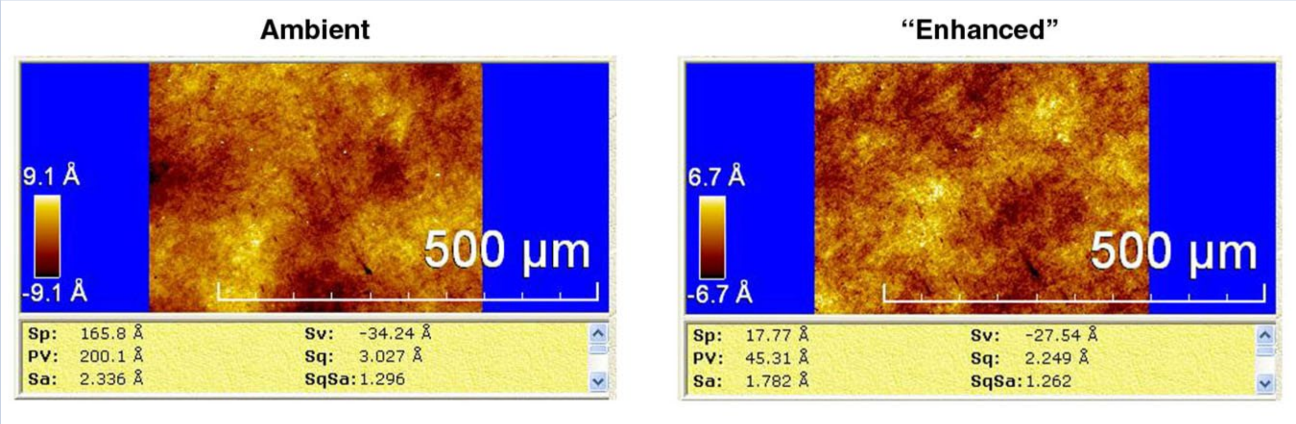

Fig. 4. *Comparative study of micro-roughness of Al+MgF_2 mirror coatings.*

AM2 13 01C	x20 mag/ angstroms	
	PV (Å)	S_q (Å)
Top left	75.58	6.146
Top right	101.2	5.196
Center	128	4.021
Bottom left	200.1	3.027
Bottom right	100	3.282
Average	120.97	4.3344

AMCT 13 01A	x20 mag/ angstroms	
	PV (Å)	S_q (Å)
Top left	45.31	2.249
Top right	40.19	2.331
Center	50.96	3.304
Bottom left	44.39	2.923
Bottom right	50.85	3.854
Average	46.34	2.9322

Table 1. *Micro-roughness (S_q) parameter determined on 5 locations of Al+MgF_2 slides produced with ambient (left) and hot (right) MgF_2 depositions.*

Reflectance of Al+LiF Mirrors

We now turn our attention to Al+LiF coatings done with a 3-step process similar to that used to produce the Al+MgF_2 mirrors discussed above. Results are shown in Fig. 5 along with a representative curve from the mirror coating used in the FUSE instrument prior to launch [5]. The coating parameters for the recently prepared Al+LiF sample include an Al layer (43 nm), followed by 8 nm of LiF. The sample was then heated and kept at 250°C during the final LiF layer deposition of 16.4 nm for a total LiF thickness of 24.4 nm. The data in Fig. 5 show reflectance values over 90% in the 110-125 nm range. This represents the highest-ever reported reflectance for Al+LiF coatings in this wavelength range. The FUSE data are still higher below 105 nm when compared to the recently prepared sample.

This observation is explained by noting that the total LiF thickness (24.4 nm) ended up being too large to produce enhancements at those lower wavelengths. We believe there is room for improvement, so efforts are under way to produce enhanced LiF coatings that approach the theoretical limit based on the optical constants of crystalline LiF. This expectation is consistent with the findings of Adriaens and Feuerbacher [5], since the process we are using is analogous to theirs. They found the overcoat layers of both LiF and MgF_2 were significantly improved and reflectivity increased at wavelengths shorter than 130 nm by annealing the deposited films at about 300°C for some 60 hours at a pressure of 10^{-7} Torr, using a heater built onto the substrate holder.

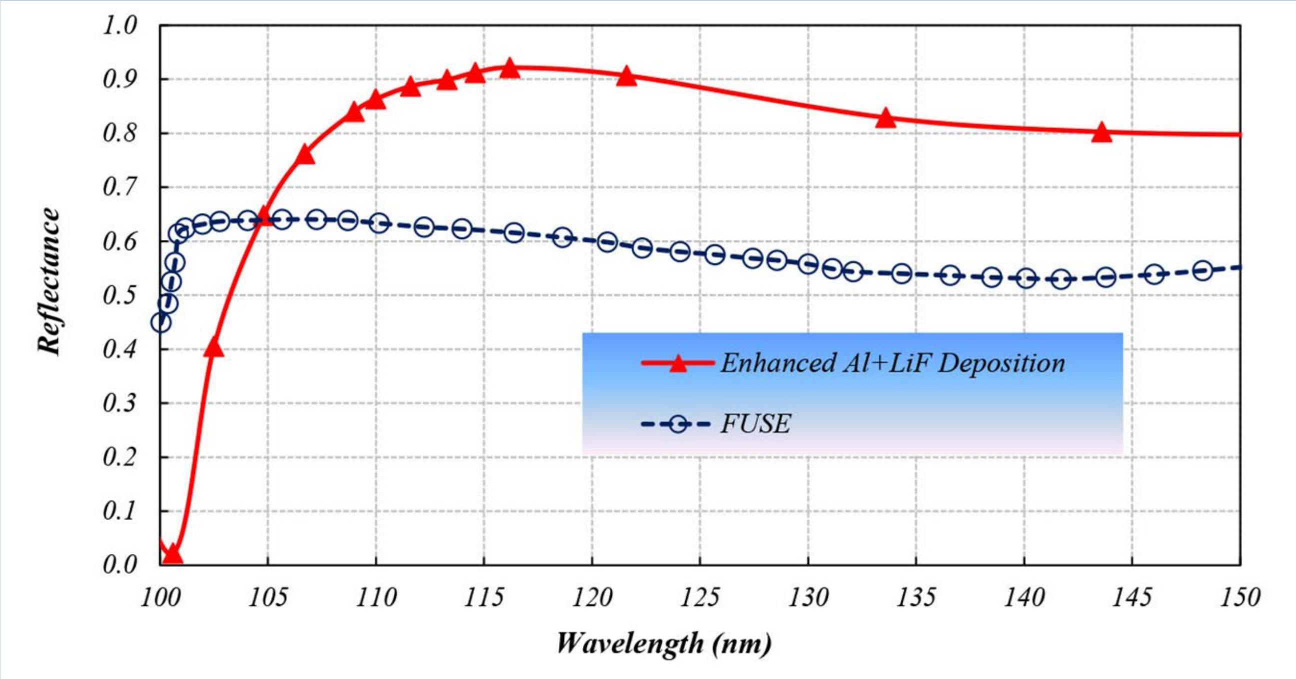

Fig. 5. *Reflectance comparison between a recently prepared Al+LiF sample and the FUSE primary mirror.*

Refractive Index of GdF_3 and LuF_3 Films

We grew a series of GdF_3 and LuF_3 films on MgF_2 substrates to determine their optical properties (refractive index, *n*, and absorption coefficient, *k*) at FUV wavelengths. The motivation was that an earlier study [1] showed the n values for both materials are higher than MgF_2 in the 250-600 nm range, and that their transparency could extend to much lower wavelengths due to their large band-gap energy. These materials may thus be viable alternatives to LaF_3 as high-index layers that, when paired with the lower index MgF_2, will enable production of multilayer coatings that could operate in the FUV range.

Figure 6 displays the measured transmission and reflectance for LuF_3 and GdF_3 films. It is important to point out that the bare MgF_2 had to be measured prior to depositing the films on the substrates. This was needed in order to characterize the film properties as accurately as possible, given the variations we observed in the transmission cut-off of MgF_2 substrates. The variation is quite evident in the red traces for both plots in Fig. 6, which represent the transmission of the bare MgF_2 before the LuF_3 and GdF_3 films were deposited. The transmission data for both films show their transparency (or $k \approx 0$) range may indeed extend to wavelengths close to the lower limit shown in the figure. The wavelength below which the material is no longer semi-transparent will be determined next.

The data shown in Fig. 6 provide the basis to determine the optical constants of LuF_3 and GdF_3 films grown on MgF_2 substrates. This is done by fitting the data to the Fresnel equations and solving for $n(\lambda)$ and $k(\lambda)$ from the measured transmittance ($T(\lambda)$) and reflectance ($R(\lambda)$) values. Since it is not possible to directly invert the equations given that the Fresnel formulae will have multiple roots, *i.e.*, different combinations of $n(\lambda)$ and $k(\lambda)$ will provide a solution to the measured $T(\lambda)$ and $R(\lambda)$ at a given wavelength λ, we had to employ root-finding numerical solutions based on the secant and Mueller method.

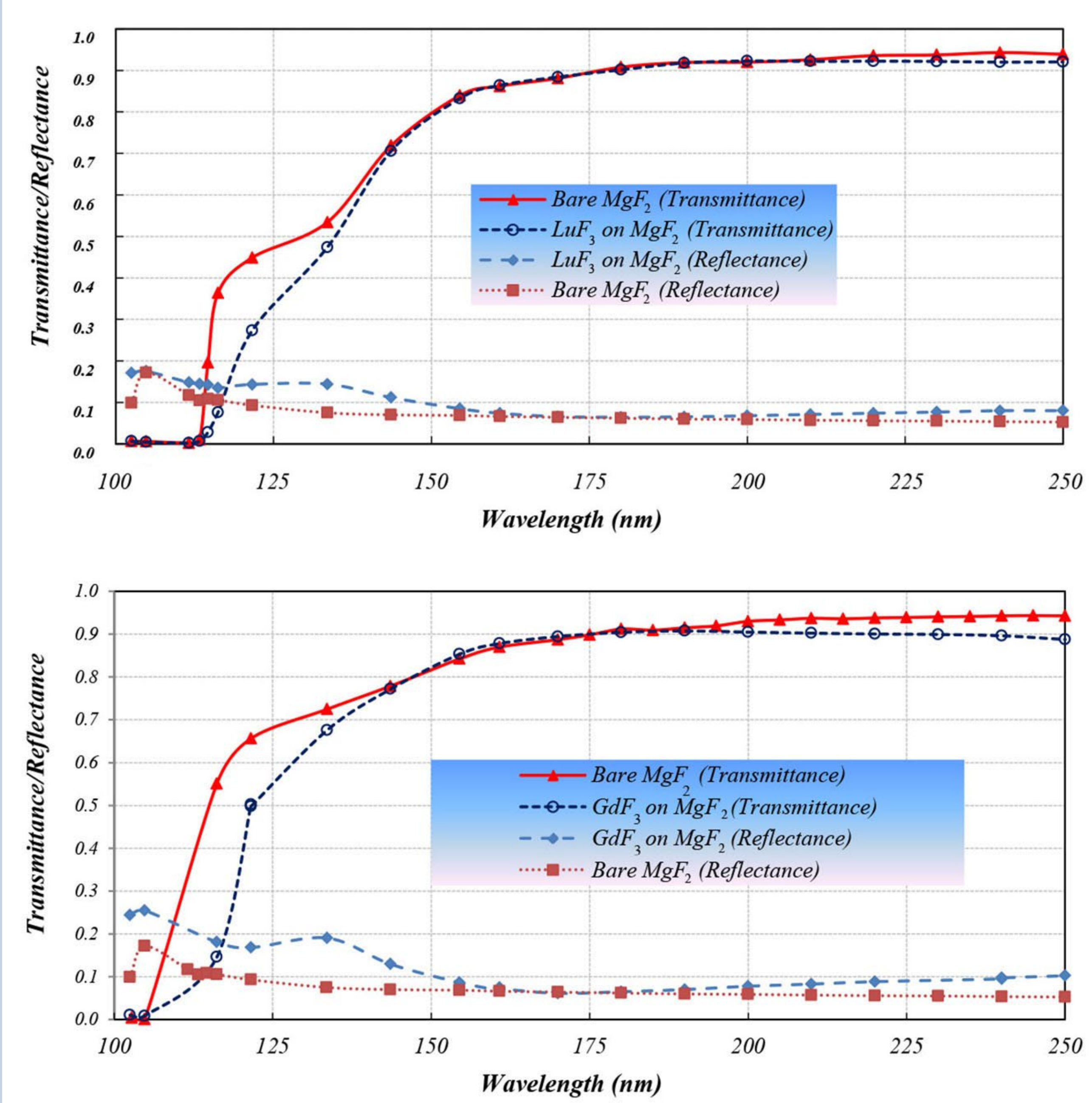

Fig. 6. *Transmittance and reflectance for LuF_3 (top) and GdF_3 (bottom) films along with data for their respective substrates (MgF_2).*

The results of these calculations are shown in Fig. 7, where $k(\lambda)$ is shown for GdF_3, LuF_3, and the MgF_2 substrate. The graph clearly shows the onset of absorption for GdF_3 and LuF_3 starts below 130 nm. Therefore, use of either material as a high-index alternative for a dielectric design may only be feasible for wavelengths longer than 130 nm. A final observation is that the $k(\lambda)$ values for MgF_2 remain nearly zero over the range shown in this figure. This is because this material has a lower cut-off wavelength and the data were derived from measurements on a crystalline MgF_2 piece that is more likely to have bulk properties than either the GdF_3 or LuF_3 films.

Figure 8 shows $n(\lambda)$ for GdF_3 and LuF_3 along with results for the MgF_2 substrates. The figure shows the index progressively increases in the 130-250 nm range, starting with MgF_2 ($n \approx 1.60$-1.40) followed by LuF_3 ($n \approx 1.80$-1.52), and finally GdF_3 ($n \approx 1.95$-1.60). The combination of the GdF_3/MgF_2 pair will provide greater contrast due to their respective refractive index values. This higher refractive index contrast offers a potentially successful dielectric design in the 130-250 spectral range with fewer layers.

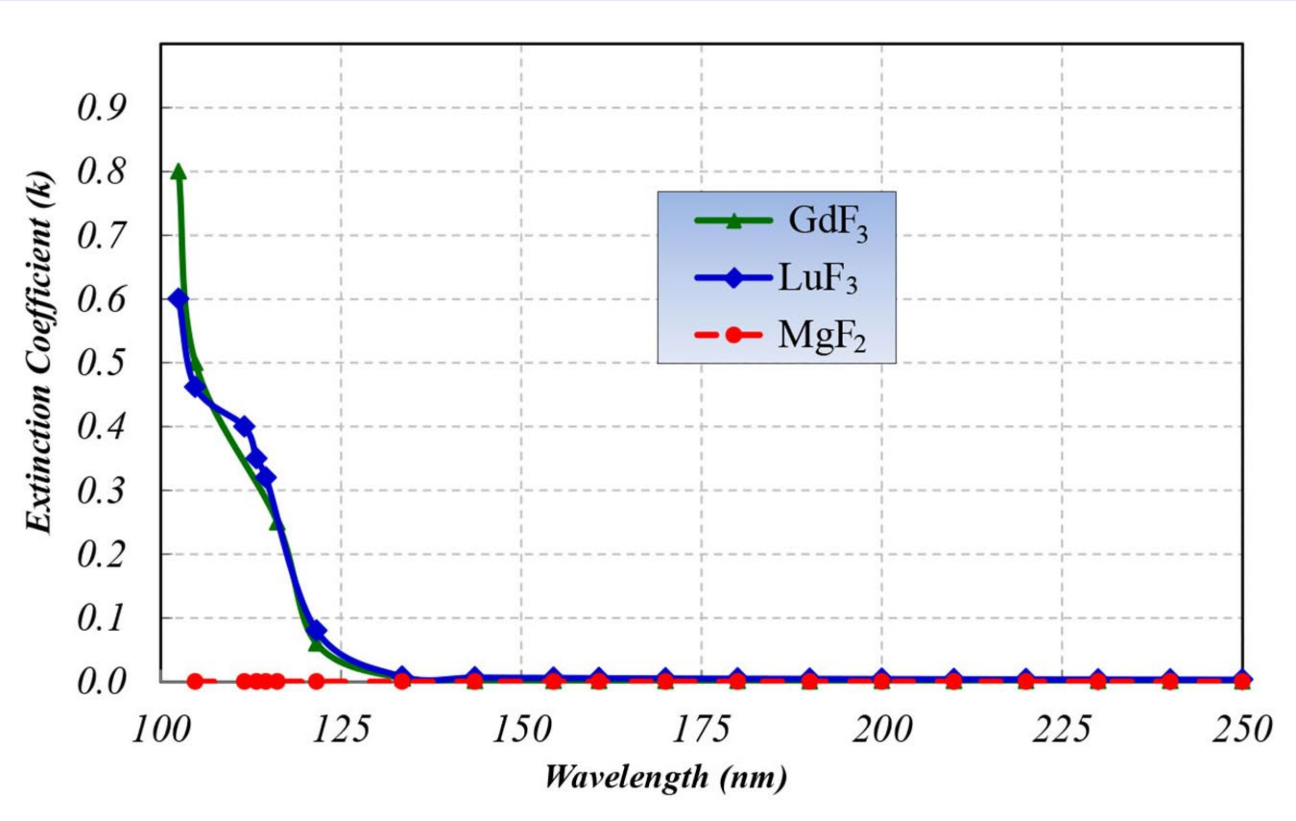

Fig. 7. *Extinction coefficient calculated from the data shown in Fig. 6.*

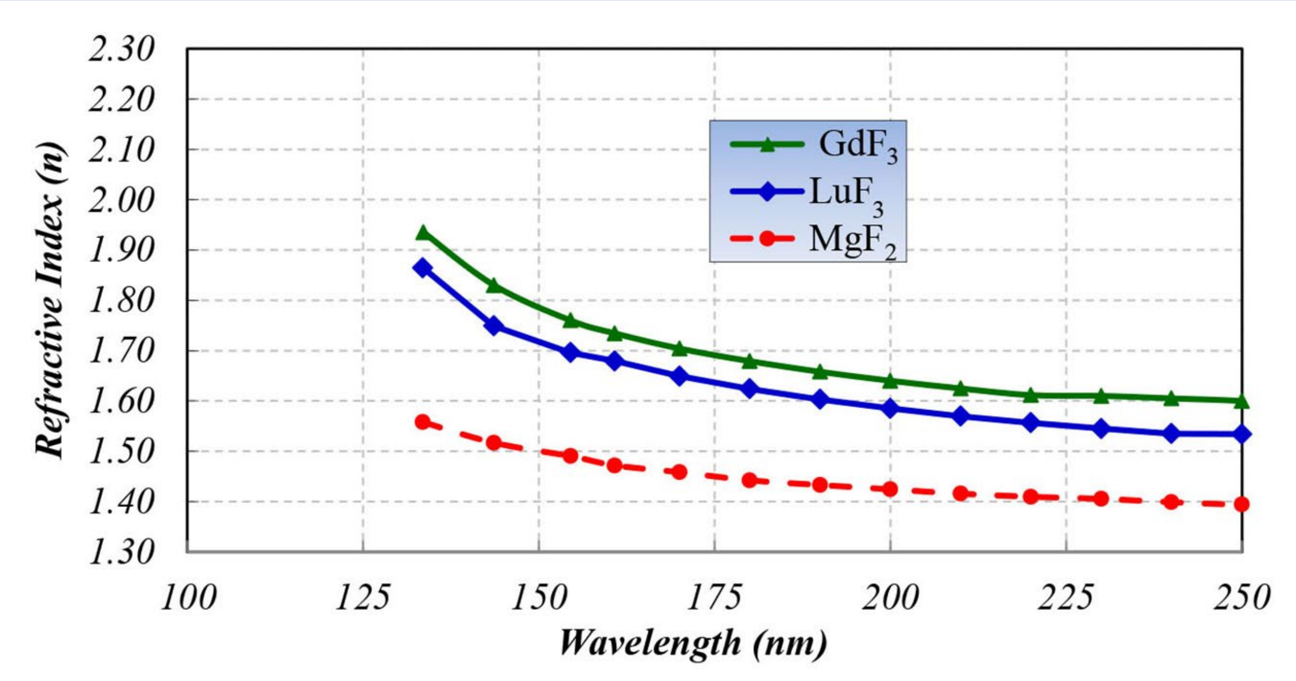

Fig. 8. *Refractive index derived from data shown in Fig. 6.*

Figure 9 shows two reflector models for a dielectric design with10 pairs of the GdF_3/MgF_2 on a MgF_2 substrate and 5 pairs of the GdF_3/MgF_2 on Al. The results show it is possible to achieve reflectors with reflectance values over 90% at selected wavelengths in the 130-160 nm range.

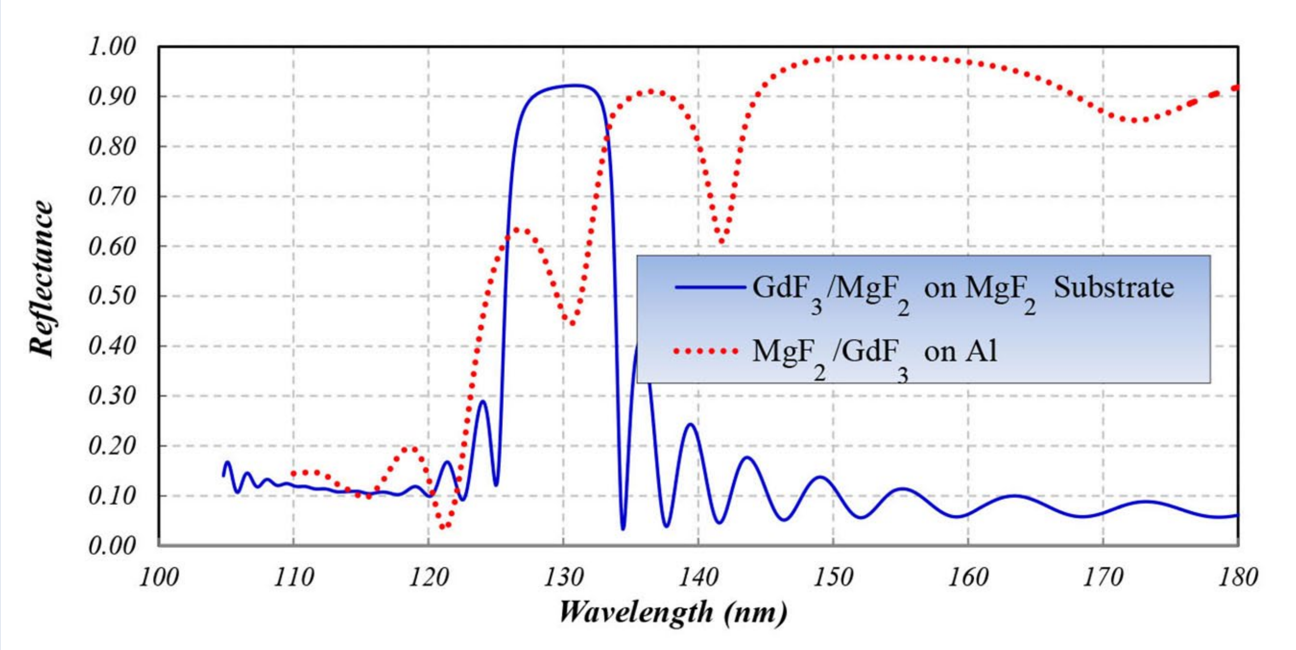

Fig. 9. *Reflector design using dielectric stacks of GdF_3/MgF_2 layer pairs on MgF_2 substrate (blue trace) or Al substrate (red trace).*

Path Forward

The actual fabrication of the reflector designs shown in Fig. 9, tied to completion of Milestone 7, will require the ability to coat more than one dielectric in our 2m coating chamber. The addition of a second bowl to the coating fixture in this chamber has already been completed (Fig. 10). We plan to pursue fabrication of a reflector design on Al by the conclusion of the performance period, which will end on September 30, 2014. The results of these efforts will be presented during the annual review scheduled for early December 2014.

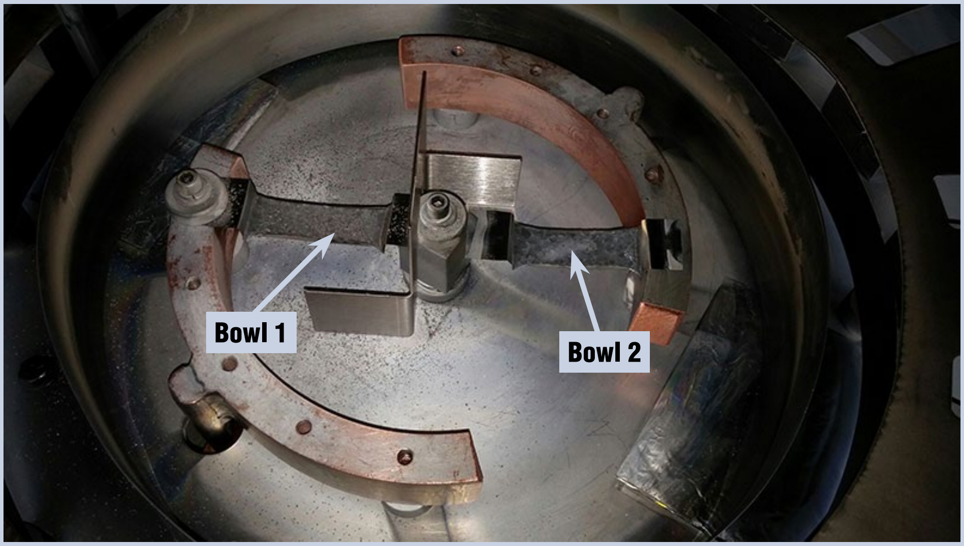

Fig. 10. *The 2-bowl coating fixture in the 2m chamber.*

References

[1] L. J. Lingg, J. D. Targove, J. P. Lehan, and H. A. Macleod, "*Ion-assisted deposition of lanthanide trifluorides for VUV applications*," Proc. SPIE 818 pp. 86-92 (1987).

[2] M. A. Quijada, S. Rice, and E. Mentzell, "*Enhanced MgF_2 and LiF Over-coated Al Mirrors for FUV Space Astronomy*," Proceedings SPIE 8450-78, pp. 1-10 (2012).

[3] J. I. Larruquert, J. A. Mendez, and J. A. Aznarez, "*Far-UV reflectance of UHV-prepared Al films and its degradation after exposure to O_2*," Appl. Opt. **33**, 3518 (1994).

[4] H.W. Moos, S. R. McCandiss, and J. W. Kruk, "*FUSE: Lessons Learned for future FUV missions*," Proc. SPIE **5488** (2004).

[5] M.R. Adriaens and B. Feuerbacher, "*Improved LiF and MgF_2 over-coated aluminum mirrors for vacuum ultraviolet astronomy*," Appl. Optics **10**, 77610F (1971).

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Deployment of Digital Micro-Mirror Device Arrays for Use in Future Space Missions

Prepared by: Zoran Ninkov (PI; RIT); Sally Heap and Manuel Quijada (NASA/GSFC); Massimo Robberto (STScI); and Alan Raisanen and Antonio Mondragon (RIT)

This SAT project was funded very recently, thus this PI report only outlines project objectives and plans. A full report will be included in next year's PATR.

Summary

In preparation for an expected announcement of opportunity for a NASA MIDEX or Explorer mission, this Strategic Astrophysics Technology (SAT) project will develop the essential component of a multi-object slit spectrograph (MOS) – a digital micro-mirror device (DMD) (Fig.1). The DMD functions as a slit mask (Fig. 2), enclosing the target while blocking light from extraneous sources, thereby increasing the signal-to-noise ratio of the spectra.

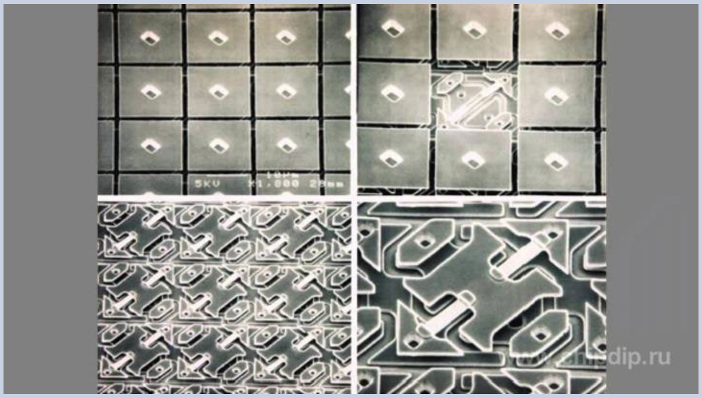

Fig. 1. Clockwise from top left: *DMD; DMD with one mirror segment removed, exposing driver; close-up of a single mirror segment's driver; and DMD with all mirror segments removed.*

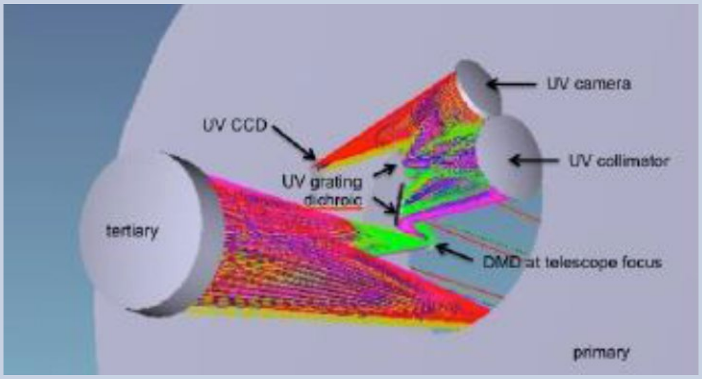

Fig. 2. *Example of UV MOS optical design, showing possible location of DMD.*

A large spectroscopic survey mission using a DMD-based MOS could pursue a 2010 Decadal Survey, New Worlds, New Horizons in Astronomy and Astrophysics (NWNH) high priority objective to capture "*large and detailed surveys of galaxies as they evolve across the wide interval of cosmic time - to have a movie of the lives of galaxies rather than a snapshot*."

For a successful mission, the DMD must operate in the ultraviolet (UV), down to 0.2 µm. The Texas Instruments (TI) DMD's window blocks UV light, preventing use of this commercial off the shelf (COTS) DMD for UV spectra. We plan to replace the commercial borosilicate window with a UV-transmitting (UVT) one, using coatings optimized for 0.2 - 1.6 µm light. We also plan to produce DMD driver electronics that can maintain long spectroscopic exposures of selected targets and be tolerant of particle radiation, allowing the DMD to operate in a space-based UV telescope.

Key Milestones

This SAT project began in mid-2014, and the following are the key milestones planned.

- Purchase DMDs and pre-test – 3rd quarter of calendar year (CY) 2014;
- Purchase windows and test – 3rd quarter of CY 2014;
- Re-window DMDs – 4th quarter of CY 2014;
- Select best UV window vendor – 2nd quarter of CY 2015;
- UV-test UV XGA DMD at NASA's Goddard Space Flight Center (GSFC) – 2nd quarter of CY 2015 (XGA, Extended Graphics Array, refers to a 1024 × 768 pixel resolution);
- Re-window Cinema DMD – 1st quarter of CY 2016; and
- Reverse-engineer drive electronics – 1st quarter of CY 2016.

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Appendix C – Acronyms

A

AAS . . . . American Astronomical Society
ADC. . . . . Analog to Digital Converter
AFM. . . . . Atomic Force Microscopy
AFRC . . . . Armstrong Flight Research Center (formerly Dryden Flight Research Center)
AFTA . . . . *Astrophysics Focused Telescope Assets*
AGN. . . . . Active Galactic Nuclei
AIP . . . . Astrophysics Implementation Plan
ALD . . . . Atomic Layer Deposition
ALMA. . . . . *Atacama Large Millimeter/submillimeter Array*
AMTD . . . . Advanced Mirror Technology Development
AO . . . . Announcement of Opportunity
APD . . . . Astrophysics Division
APD . . . . Avalanche Photo-Diode
APEX . . . . *Atacama Pathfinder EXperiment*
APRA . . . . Astrophysics Research and Analysis
AR . . . . Anti-Reflection
ARC . . . . Ames Research Center
ARRM . . . . *Asteroid Redirect Robotic Mission*
ASIC . . . . Application Specific Integrated Circuit
ASP . . . . Astronomical Society of the Pacific
ASU . . . . Arizona State University
ATLAST . . . . *Advanced Technology Large-Aperture Space Telescope*

B

BLIP . . . . Background-Limited Performance

C

Caltech. . . . . California Institute of Technology
CCAT . . . . *Cerro Chajnantor Atacama Telescope*
CCD . . . . Charge Coupled Device
CHESS . . . . *Colorado high-resolution Echelle stellar spectrograph*
CMB . . . . Cosmic Microwave Background
CMOS . . . . Complementary Metal-Oxide Semiconductor
COBE. . . . . *Cosmic Background Explorer*
Co-I . . . . Co-Investigator
COPAG . . . . Cosmic Origins Program Analysis Group
COR. . . . . Cosmic Origins
COS . . . . *Cosmic Origins Spectrograph*
CSA . . . . Charge-Sensitive Amplifier
CSO . . . . *Caltech Submillimeter Observatory*
CY . . . . Calendar Year

D

DAC. . . . . Digital-to-Analog Converter
DLR . . . . German Aerospace Center (*Deutsches Zentrum für Luft - und Raumfahrt e.V.*)
DMD . . . . Digital Micro-mirror Device

E

EBCCD. . . . . Electron-Bombarded CCD
EBCMOS . . . . . . Electron-Bombarded CMOS
EMCCD . . . . Electron-Multiplied CCD
EoR . . . . Epoch of Reionization
ESA . . . . European Space Agency
ESI. . . . . Early-Stage Innovation
EUV . . . . Extreme-Ultraviolet
ExEP . . . . Exoplanet Exploration Program
ExoPAG . . . . Exoplanet Program Analysis Group

F

Far-IR. . . . . Far-Infrared
FaRSiTe . . . . Fast Response Simulator for Telescopes
Far-UV . . . . Far-Ultraviolet
FEM . . . . Finite Element Model
FIR . . . . Far-Infrared
FIREBall. . . . . . . *Faint Intergalactic medium Redshifted Emission Balloon*
FLIM . . . . Fluorescence Lifetime Imaging
FOV . . . . Field of View
FPA . . . . Focal Plane Array
FPGA . . . . Field Programmable Gate Array
FUSE . . . . *Far Ultraviolet Spectroscopic Explorer*
FUV . . . . Far-Ultraviolet
FWHM . . . . Full-Width at Half-Maximum
FY . . . . Fiscal Year

G

GALEX. . . . . *Galaxy Evolution Explorer*
GFE . . . . Government-Furnished Equipment
GPU. . . . . Graphics Processing Unit
GRAPH . . . . Gigasample Recorder of Analog Waveforms from a Photodetector
GSFC . . . . Goddard Space Flight Center
GUSSTO. . . . . . . *Galactic/Xtragalactic ULDB Spectroscopic Stratospheric Terahertz Observatory*

H

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

I

IBS . . . . Ion Beam Sputtering
IF. . . . . Intermediate Frequency
IFU . . . . Integral Field Unit
IGM . . . . Intergalactic Medium
IR . . . . Infrared
IRAS . . . . *Infrared Astronomical Satellite*
ISM . . . . Interstellar Medium

J

JAXA . . . . Japanese Aerospace Exploration Agency
JCMT . . . . *James Clerk Maxwell Telescope*
JHU . . . . Johns Hopkins University
JPL. . . . . Jet Propulsion Laboratory
JWST . . . . *James Webb Space Telescope*

K

KDP. . . . . Key Decision Point
KID . . . . Kinetic Inductance Detector (or Device)

L

LBL . . . . Lawrence Berkeley National Laboratory
LDR . . . . Large Deployable Reflector
LEKID . . . . Lumped Element Kinetic Inductance Detector (or Device)
LIDAR . . . . Light Detection and Ranging
LISM . . . . Local Interstellar Medium
LLLCCD . . . . Low Light Level CCD
LN . . . . Liquid Nitrogen
LO . . . . Local Oscillator
LOS . . . . Line of Sight
LTF . . . . Low Temperature Fusion
LUVOIR . . . . Large Ultraviolet/Optical/Infrared
LVDS . . . . Low Voltage Differential Signal

M

MBE. . . . . Molecular Beam Epitaxy
MCP. . . . . Micro-Channel Plate
MIDEX. . . . . Medium-class Explorer
Mid-IR . . . . Mid-Infrared
MIRI . . . . *Mid-Infrared Instrument*
MKID. . . . . Microwave Kinetic Inductance Detector (or Device)
MMIC. . . . . Microwave Monolithic Integrated Circuit
MOR . . . . Modulus of Rupture
MOS . . . . Multi-Object Spectrograph
MOS . . . . Multi-Object Spectrometer
MSFC . . . . Marshall Space Flight Center

N

NAC. . . . . NASA Advisory Council
NASA. . . . . National Aeronautics and Space Administration
Near-IR . . . . Near-Infrared
NEFS . . . . Noise-Equivalent Frequency Shift
NEP . . . . Noise-Equivalent Power
NEXT. . . . . NASA Evolutionary Xenon Thruster
NIR . . . . Near-Infrared
NIS . . . . Normal-Insulator-Superconductor
NPP . . . . NASA Postdoctoral Program
NPR. . . . . NASA Procedural Requirements
NRA. . . . . NASA Research Announcement
NRC. . . . . National Research Council
NSTR . . . . NASA Space Technology Research
NUV. . . . . Near-Ultraviolet
NWNH . . . . New Worlds, New Horizons in Astronomy and Astrophysics (2010 Decadal Survey)

O

OAO-3 . . . . *Orbiting Astronomical Observatory 3*
OCT . . . . Office of the Chief Technologist
OPD . . . . Optical Path-length Difference
ORFEUS . . . . *Orbiting Retrievable Far and Extreme Ultraviolet Spectrometer*
OTA . . . . Optical Telescope Assembly

P

PACS . . . . *Photodetector Array Camera and Spectrometer*
PAE . . . . Power-Added Efficiency
PAG . . . . Program Analysis Group
PATR . . . . Program Annual Technology Report
PCOS . . . . Physics of the Cosmos
PDR . . . . Photo-Dissociation Region
PDR . . . . Preliminary Design Review
PI . . . . Principal Investigator
PMA . . . . Primary Mirror Assembly
PMT . . . . Photo-Multiplier Tube
PPP . . . . Program Prioritization Panel
PSF . . . . Point Spread Function
PSU . . . . Penn State University
PVD . . . . Physical Vapor Deposition
PXS . . . . Parallel Cross Strip

Q

QE . . . . Quantum Efficiency

R

RF . . . . Radio Frequency
RFI . . . . Request for Information
RIT . . . . Rochester Institute of Technology
rms . . . . Root-Mean-Square
R&D . . . . Research and Development

S

SAFIR . . . . *Single Aperture Far Infrared Observatory*
SAT . . . . Strategic Astrophysics Technology
SCUBA . . . . *Submillimetre Common-User Bolometer Array*
SEP . . . . Solar Electric Propulsion
SFO . . . . *Star Formation Observatory*
SIOSS . . . . Science Instruments, Observatory and Sensor Systems
SMD . . . . Science Mission Directorate
SMEX . . . . Small Explorer
SOFIA . . . . *Stratospheric Observatory for Infrared Astronomy*
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
STIS . . . . *Space Telescope Imaging Spectrograph*
STJ . . . . Superconducting Tunnel Junction
STM . . . . Science Traceability Matrix
STMD . . . . Space Technology Mission Directorate

STO . . . . *Stratospheric Terahertz Observatory*
STOP . . . . Structural-Thermal-Optical Performance
STScI . . . . Space Telescope Science Institute

T

TARGET . . . . TeV Array Readout with GSa/s sampling and Event Trigger
TCOR . . . . Technology Development for the Cosmic Origins Program
TES . . . . Transition Edge Sensor
TI . . . . Texas Instruments
TMB . . . . Technology Management Board
TRL . . . . Technology Readiness Level

U

UC . . . . University of California
ULE . . . . Ultra-Low Expansion
UV . . . . Ultraviolet
UVIS . . . . Ultraviolet and Visible
UVOIR . . . . Ultraviolet/Optical/Infrared
UVT . . . . Ultraviolet Transmitting

V

VUV . . . . Vacuum Ultraviolet

W

WFC . . . . *Wide-Field Camera*
WFIRST . . . . *Wide-Field Infrared Survey Telescope*
WISE . . . . *Wide-field Infrared Survey Explorer*

X

XGA . . . . eXtended Graphics Array
XPS . . . . X-ray Photoelectron Spectroscopy
XS . . . . Cross Strip