National Aeronautics and Space Administration

Physics of the Cosmos
Program Annual Technology Report

Physics of the Cosmos
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http://pcos.gsfc.nasa.gov

Executive Summary

Welcome to the third *Program Annual Technology Report* (PATR) for the Physics of the Cosmos (PCOS) Program of the NASA Astrophysics Division. It has been an active year for technology development in the PCOS Program. The Program invested in 12 technology development projects with Principal Investigators (PIs) from academia, industry, and multiple NASA centers. The projects span technology areas from telescopes and optics to detectors and electronics to microthruster subsystems, with applicability to the highest-ranked potential future PCOS missions. Within the Program Office (PO), the processes for prioritizing technology needs continue to mature and evolve to ensure that the calls for proposals and investment decisions are aligned with program needs.

This is the third year in which the PCOS PO has implemented the program technology needs prioritization process. This process serves to inform the calls for proposals for SAT funding and the selection of grant recipients. The technology needs list provided by the Physics of the Cosmos Program Analysis Group (PhysPAG) and the community in 2012 was very extensive and it continues to reflect the technology needs for potential future missions. Therefore, the PCOS Technology Management Board (TMB) prioritized from that same list of technology needs. In addition, the TMB referenced the new technology roadmap documents being prepared for potential X-ray and gravitational wave missions. The prioritization process was streamlined this year by reducing and simplifying the prioritization criteria. Also, the release of the *Astrophysics Implementation Plan* (AIP) provided additional guidance to the TMB for assessing relative mission rankings. The AIP articulates the NASA Astrophysics Division's near-term plans for achieving the Decadal Survey's recommendations within current budget constraints.

The ongoing technology development projects are each summarized in a single-page quad chart format in Appendix A. Each project is also described and statused in more detail in the PI reports collected in Appendix B. The majority of these critical technology developments is funded through the PCOS Strategic Astrophysics Technology (SAT) grants; two are co-funded with the NASA Space Technology Mission Directorate (STMD). Projects include those targeted for potential future gravitational wave, X-ray, and cosmic microwave background missions. Each PI report summarizes the project's progress over the past year and plans for the next. Over this past year, each project team reported significant progress and several projects plan to request Technology Readiness Level (TRL) advancement review.

The PCOS Program is pleased to announce the "Advanced Antenna-Coupled Superconducting Detector Arrays for CMB Polarimetry" project, with principal investigator James Bock of Jet Propulsion Laboratory, as the new recipient of SAT funding for a FY 2014 start.

The results of this year's technology needs prioritization are presented in this PATR. The highest-ranked technology needs include infrared (IR) detectors, precision telescopes, microcalorimeters, phasemeters, and segmented mirror technology. These results are provided to aid decision makers at NASA Headquarters (HQ) in processes such as the SAT process that ultimately result in the funding of selected technologies.

Introduction

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

The PCOS Program seeks to shepherd critical technologies for NASA toward the goal of implementation into project technology development plans. These technologies can then serve as the foundation for robust mission concepts, allowing the community to focus on the scientific relevance of the proposed missions in subsequent strategic planning. These technology development status reports cover six developments continued from previous years as well as six developments that were newly awarded last year.

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

Section 3 of this report summarizes the extensive technology needs collected from the astrophysics community last year, which the TMB re-prioritized this year. The majority of the technology needs were provided by the PhysPAG. The PO greatly appreciates inputs from all submitters, especially the PhysPAG, for the time, attention, and organization that were invested in collecting and processing the information.

The prioritization results will be referenced by the Program over the upcoming year as the calls for technology development proposals are drafted and investment decisions are made. The TMB is cognizant that investment decisions will be made within a broader context, and that other factors at the time of selection may affect their decisions. In the coming year, the expected European Space Agency (ESA) L2 (L-class, or Large, mission) decision is likely to precipitate changes in prioritization. The technology needs prioritization will be forwarded to other NASA programs–e.g., Small Business Innovation Research (SBIR) and other STMD–or Office of the Chief Technologist (OCT) technology development planning groups as requested. As part of NASA's recognition of the critical role that space technology and innovation will play in enabling both future space missions and enhancing life here on Earth, STMD was created in February of this year. STMD will develop the cross-cutting, advanced, and pioneering new technologies that are needed for NASA's current and future missions. The OCT serves as principal advisor and advocates matters that concern agency-wide technology policy and programs. OCT also leads the NASA technology transfer and commercialization efforts by integrating, tracking, and coordinating all of NASA's technology investments across the agency.

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

- be transparent by informing the community of the technology needs collection and prioritization process, along with the resulting prioritization for the year, while maintaining an open forum for community input into the process;
- communicate to the community PCOS technology development investments and their progress through this annual report;
- ensure the development of the most relevant technologies by following the guidance of the HQ Astrophysics Division; and
- leverage PCOS technology investments by defining PCOS technology needs in order to encourage external technology investments that will benefit PCOS science.

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

1. Program Overview

Physics of the Cosmos (PCOS) science addresses the fundamental physical laws and properties of the universe. The science objectives of the Program are to probe Einstein's General Theory of Relativity and the nature of spacetime, better understand the behavior of matter and energy in its most extreme environments, expand our knowledge of dark energy, precisely measure the cosmological parameters governing the evolution of the universe, test the inflation hypothesis of the Big Bang, and uncover the connection between galaxies and supermassive black holes. Physics of the Cosmos lies at the intersection of Physics and Astronomy. It uses the universe–the cosmic scale, the diversity of conditions, and the extreme objects and environments–as a laboratory to study the basic properties of nature.

A primary function of the Program Office (PO) is to develop and administer an aggressive technology program. The PO facilitates, manages, and implements the technology policies of the PCOS Program. The goal is to coordinate the infusion of technology into PCOS missions, including the crucial phase of transitioning a wide range of nascent technologies into a targeted project's mission technology program when a project is formulated. The PO oversees technology development applicable to PCOS missions, funding for which is supported by the PCOS Supporting Research and Technology (SR&T) budget. This *Program Annual Technology Report* (PATR) is an annual, comprehensive document detailing the technologies currently being pursued and supported by PCOS SR&T.

Background

The PCOS Program encompasses multiple scientific missions aimed at meeting Program objectives, each with unique scientific capabilities and goals. The Program was established to integrate those missions into a cohesive effort that enables each project to build upon 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. The current PCOS operating missions are:

- *Chandra*
- *X-ray Multi-Mirror Mission* (XMM–Newton)
- *Fermi Gamma-ray Space Telescope*
- *Planck*
- *Nuclear Spectroscopic Telescope Array* (NuSTAR)

There are two missions in development in the PCOS portfolio, and both are ESA-led:

- *Space Technology 7/Laser Interferometer Space Antenna* (LISA) *Pathfinder* (ST7/LPF)
- Euclid

LPF, scheduled for launch in 2015, is a technology demonstration mission, the purpose of which is to retire technical risks for the LISA gravitational wave mission. LPF will validate a number of key technologies for LISA-like gravitational wave detectors, including inertial reference sensors, ultra-low-noise drag-free flight, and micro-Newton thrusters. The mission contains two payloads, the European LISA Technology Package (LTP) and NASA's ST7 experiment.

A major development since the 2012 PATR is that on January 10, 2013, a Memorandum of Understanding (MOU) was signed for NASA to officially join ESA's Euclid mission. The NASA portion of Euclid is a

PCOS project that is managed by the NASA Jet Propulsion Laboratory (JPL). Euclid is on schedule for a 2020 launch, and will include a 6-year photometric and spectroscopic survey of about a third of the sky. Euclid's scientific objectives to better understand dark energy, gravity, and dark matter are aligned with those of NASA's PCOS Program. NASA will provide detectors and associated cryogenic electronics for one of Euclid's two instruments, the Near Infrared Spectrometer Photometer (NISP).

For other future missions, the PCOS portfolio is focused on technology studies rather than mission development, given the budget realities since the release of the National Research Council's (NRC) New Worlds, *New Horizons in Astronomy and Astrophysics* (NWNH) report. The priorities of the NASA Headquarters (HQ) Science Mission Directorate (SMD) Astrophysics Division are outlined in the *Astrophysics Implementation Plan* (AIP), which was released since the 2012 PATR. As a reminder, the highly ranked NWNH priorities in the PCOS portfolio are:

- *Laser Interferometer Space Antenna* (LISA)
- *International X-ray Observatory* (IXO)
- *Inflation Probe*

The decadal committee ranked as the highest-priority large mission the *Wide-Field Infrared Survey Telescope* (WFIRST). WFIRST is envisioned to settle fundamental questions about the nature of dark energy, as well as open up a new frontier of exoplanet studies. WFIRST is a mission in the ExoPlanet Exploration Program at JPL that will do exoplanet and dark energy science.

Following NWNH and the Astrophysics Implementation Plan (AIP), the Inflation Probe is given lower priority among the three priorities and, therefore, PCOS will not perform an Inflation Probe mission study before 2015. Technology roadmaps for a future gravitational wave mission and a future X-ray mission have been completed in FY13 and are available on the PCOS website. In FY14, there will be a mission study for a Probe-class X-ray mission with a calorimeter.

In the coming year, ESA may choose a science theme for its L2/L3 (L-class, or Large, mission) launch opportunities (in 2028 or 2035). That decision would likely have an impact on the PCOS technology portfolio if NASA and ESA decide to collaborate on the selected L2 mission since two of the candidate mission concepts are in PCOS. There are two scientific themes that, if chosen, would align well with the PCOS priorities for gravitational waves and X-ray astronomy. These are "The Gravitational Universe," submitted in a White Paper led by K. Danzmann of the Max Planck Institute for Gravitational Physics, and "The Hot and Energetic Universe," submitted by K. Nandra of the Max Planck Institute for Extraterrestrial Physics. These are largely the same teams that submitted the Next Generation Gravitational-wave Observatory (NGO) and the Advanced Telescope for High-Energy Astrophysics (ATHENA) concepts for consideration for L1. These European-led missions are those which would have superseded LISA and IXO, respectively. If either of these science themes is selected for L2 or L3 in the ESA Cosmic Visions process, NASA may play a role and technology development funding may be appropriately focused toward that opportunity.

PCOS Program Technology Development

The PCOS SR&T funds a variety of technology developments that are determined to be necessary for the advancement of PCOS science missions. To make these determinations, the PCOS PO pursues a strategic vision that follows the space-based priorities set forth in the AIP, which is the NASA HQ SMD Astrophysics Division's implementation of the NWNH report. Specifically, the PCOS PO adopts the prioritized complement of missions and activities to advance the PCOS science priorities.

The PCOS technology management plan details the process that identifies PCOS technology needs, enables the maturation of those technologies in a prioritized fashion, and inserts them into new missions responsively. The process diagram (Fig. 1–1) illustrates the annual cycle by which this is achieved. Starting at the left, scientific needs and requisite technologies are derived from the current astrophysics community, and are presented into the Program's technology development cycle.

The Physics of the Cosmos Program Analysis Group (PhysPAG) provides analyses through the NASA Advisory Council (NAC) process. Meanwhile, the PCOS PO convenes its Technology Management Board (TMB), which prioritizes the technologies and publishes them annually in this PATR. The TMB recommends these priorities to NASA HQ, which solicits proposals for technology development. Grants are awarded to selected technology developers based on consideration of overall scientific and technical merit, programmatic relevance, and cost reasonableness. These developers provide written and oral progress reports to the TMB. The written reports are compiled in the Appendices of this PATR. Technological progress and programmatic decisions change the landscape of the requirements for the scientific needs; therefore, this process is repeated annually to ensure the continued relevance of the ranking.

This PCOS PATR plays an important role in the Program's technology development process. It describes the status of all technologies funded through PCOS SR&T, captures technology needs as articulated by the scientific community, and recommends a prioritized list of technologies for future funding. The PATR is an open and available source for the public, academia, industry, and the government to learn about the status of applicable mission concepts and the enabling technologies required to fulfill the PCOS Program scientific objectives.

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

The PCOS TMB is a Program-level functional group that provides a formal mechanism for input to and review of the Program technology development activities. The TMB prioritized those technologies identified by the community and communicated via the PhysPAG or directly submitted to the PCOS Program website. This prioritization informs the merit-based selection of technology development investment. This report, the annual PCOS PATR, is the means of disseminating this information publicly. The PCOS PO works to ensure that the broad astronomy community is informed of these technology developments. It is expected that new starts for missions will lead to project specific technology development efforts.

For Fiscal Year (FY) 2014, the driving objective is to maintain progress in those technologies that are either key enabling technologies for a future U.S.-led mission or establish a clear connection to a possible future contribution to the ESA L-class missions, such as ATHENA or NGO, via the Strategic Astrophysics Technology (SAT) call.

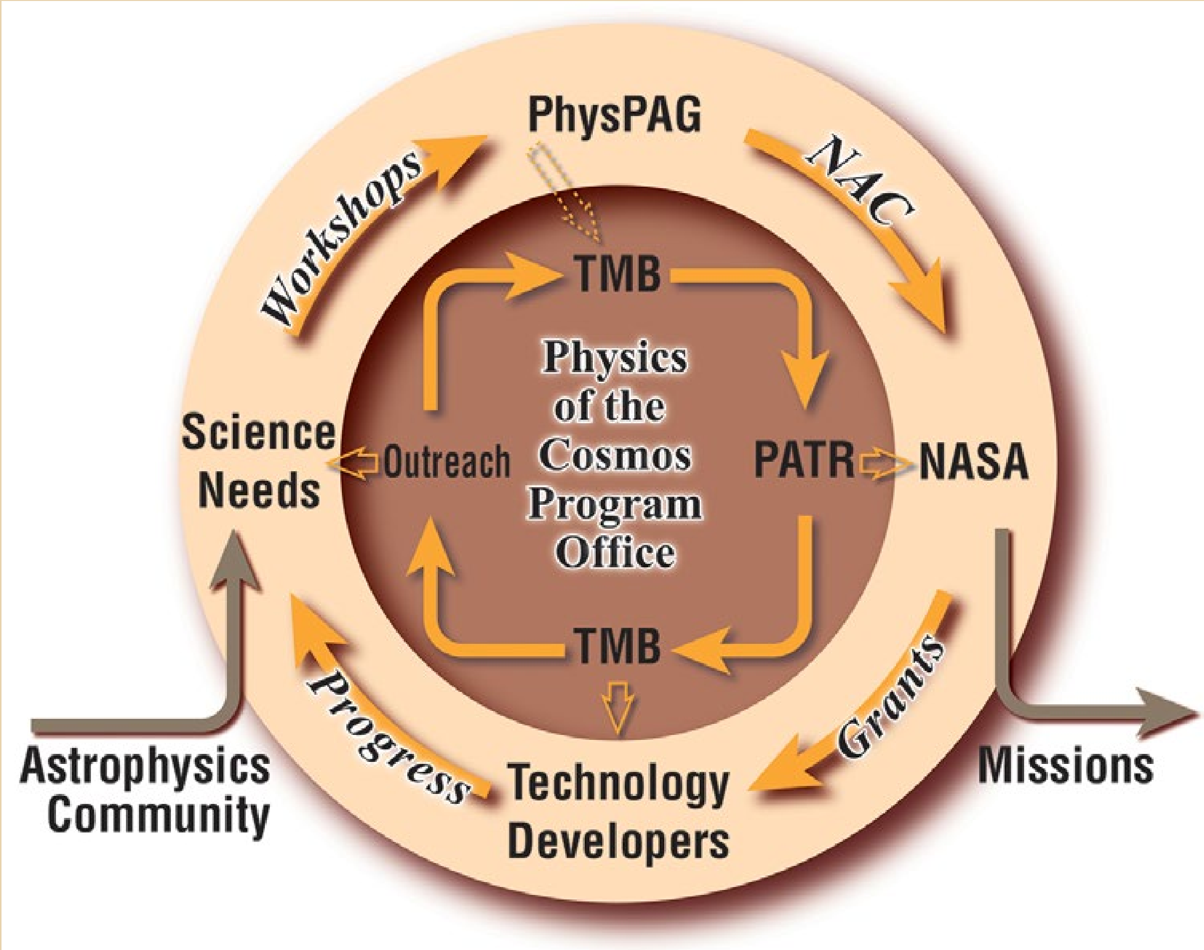

Figure 1-1. This diagram illustrates the PCOS annual technology management process.

2. Program Strategic Technology Development Portfolio

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

It is noteworthy to point out that the last two technology developments shown in Table 2-1 are being co-funded by the PCOS Program and the Game Changing Development Program of NASA's STMD. When possible, the programs leverage their limited funding to advance technologies that meet the goals of both programs, and these two developments fit those opportunities; simultaneously, they ranked highly among all the proposals submitted. These collaborative investments are "win-win-win" opportunities for the PCOS Program, STMD, and the technology developer. The PCOS Program looks forward to forging a relationship with STMD and creating more of these opportunities in the future.

Technology Development Title	PI	Institution	Start Year and Duration	Approved TRL	See Appendix A for Quad Chart and Appendix B for Status
Gravitational Wave Mission Phasemeter Technology Development	W. Klipstein	JPL	FY12 1 year	4	A-1, B-2
Directly Deposited Optical Blocking Filters for Imaging X-ray Detectors	M. Bautz	MIT	FY12 2 years	5	A-2, B-10
Planar Antenna-Coupled Superconducting Detectors for Cosmic Microwave Background (CMB) Polarimetry	J. Bock	Caltech/JPL	FY12 2 years	3	A-3, B-18
Off-Plane Grating Arrays for Future Missions	R. McEntaffer	University of Iowa	FY12 2 years	3	A-4, B-26
Moderate Angular Resolution Adjustable Full-shell Grazing Incidence X-ray Optics	P. Reid	Smithsonian Astrophysical Observatory (SAO)	FY12 2 years	3	A-5, B-34
Critical-Angle Transmission (CAT) Gratings for High-Resolution Soft X-ray Spectroscopy	M. Schattenburg	Massachusetts Institute of Technology (MIT)	FY12 2 years	3	A-6, B-40
Next Generation X-ray Optics: High Angular Resolution, High Throughput, and Low Cost	W. Zhang	GSFC	FY13 2 years	3	A-7, B-45
Demonstrating Enabling Technologies for the High-Resolution Imaging Spectrometer of the Next NASA X-ray Astronomy Mission	C. Kilbourne	GSFC	FY13 2 years	4	A-8, B-53
Colloid Microthruster Propellant Feed System	J. Ziemer	JPL	FY13 2 years	3	A-9, B-62
Telescopes for a Space-based Gravitational-wave Observatories	J. Livas	GSFC	FY13 2 years	3	A-10, B-69
Laser Frequency Stabilization *(*This technology development is co-funded with STMD.)*	J. Lipa	Stanford University	FY13 2 years	3	A-11, B-78
Adjustable X-ray Optics with Sub-Arcsecond Imaging *(*This technology development is co-funded with STMD and it is the only APRA project that the PO oversees.)*	P. Reid	SAO	FY13 3 years	2	A-12, B-85

Table 2-1. PCOS Strategic Technology Development in FY 2013.

Stratigic Astrophysics Technology Selection for FY14 Start

The latest proposal selection for funding under the PCOS SAT solicitation was announced in October 2013. This selection was based on the following factors: 1) the overall scientific and technical merit of the proposal, 2) the programmatic relevance of the proposed work, and 3) the cost reasonableness of the proposed work. The technologies of this proposal have recently been selected for funding and have not yet begun work, and hence each project's status is not presented this year. Their progress in the first year will appear in the 2014 PCOS PATR. Table 2–2 lists the proposal title, along with the name and institution of the PI, the start year and duration, the entry TRL, and the location of the abstract in Appendix B.

Proposal Title	PI	Institution	Start Year and Duration	Starting TRL	See Appendix B for Abstract
Advanced Antenna-Coupled Superconducting Detector Arrays for CMB Polarimetry	J. Bock	Jet Propulsion Laboratory	FY14 2 years	3-4	B-92

Table 2-2. PCOS Strategic Astrophysics Technology (SAT) Award for Start in FY 2014.

The PCOS Program funds SAT proposals in order to advance the maturation of key technologies to the point at which they are feasible for implementation in space flight missions. The scope of the PCOS Program is focused on the advancement of those technologies most critical to making substantive near-term progress on the recommendations of the NWNH and the resulting Astrophysics Implementation Plan. Three technology areas are called out on 2012 PCOS SAT solicitation as being of particular interest for the Program: technologies for X-ray astrophysics, for gravitational wave astrophysics, and for CMB polarization measurements.

The PCOS SAT proposal selected for a start in FY 2014 advances several technologies that are important for CMB polarization measurements: microwave antenna characteristics (extended frequency capabilities, multi-color antennas, and tapered antenna far-field beam measurements), wafer particle susceptibility, and microwave resonator Superconducting Quantum Interference Device (SQUID) multiplexer. The goal is to pursue the CMB polarization technology development program as recommended by NWNH.

3. Program Technology Needs

The technology needs list provided by the community for 2012 was very extensive. It incorporated the highest-priority PCOS missions that are consistent with the AIP for this decade. Because of these factors, the PO streamlined the technology needs prioritization this year by using the inputs that were provided last year. Therefore, and in concurrence with the PhysPAG Executive Committee, the PCOS Program did not solicit additional community inputs for technology needs this year. In addition to the 2012 needs list, the TMB also reviewed the technology needs identified in the X-ray and the gravitational wave Technology Development Roadmaps (TDRs), which were in final development during the time of our prioritization. All of the technologies called for in the two TDRs were already included in the 2012 needs list. The information provided in the TDRs was used to better define the existing technology needs.

With the technology needs available for prioritization, the PCOS TMB proceeded to prioritize all of the technology needs according to the revised and shortened set of prioritization criteria, which will be discussed in Section 4 of this report.

The full set of technology needs available for prioritization is shown in Tables 3-1 through 3-13. The first 12 tables were submitted by the PhysPAG. The Technology Science Analysis Group (TechSAG) of the PhysPAG, working with the community, developed a TDR with supporting tables to capture the needs as identified by the science and research community. The "Technology Roadmap Table" summarizes the mission concepts in roadmap format, with the missions and the mission concepts identified in the columns phased by time. The roadmap is organized into three sections: 1) missions recommended by the most recent Decadal Survey, plus Fundamental Physics, requiring technology development in the present decade; 2) near-term "push" mission concepts that require development of emerging technologies starting now and extending into the next decade; and 3) long-term "push" concepts needing emerging technology development into the following decade. Table 3-13 summarizes the technology needs submitted directly to the PO last year through the PCOS website.

The PhysPAG, which is chaired by a member of the NASA Astrophysics Subcommittee, provides this support as part of their community coordination and analysis of scientific and technological issues impacting NASA's PCOS Program. A technology need can be identified by anyone and provided to the PO for prioritization in either of two ways. The first is to work with the PhysPAG to include it in the consolidated listing in response to the solicitation by the PO. The second is to submit it to the PO through the PCOS Program website: http://pcos.gsfc.nasa.gov/technology.

Although technology needs are solicited annually and collected by the end of June to begin the annual prioritization process, they can be submitted to the PO at any time. The process is for the PO to pass on all the inputs received via the PhysPAG website for consolidation prior to delivering the list to the PO. The inputs are then used by the PCOS TMB to evaluate and prioritize all of the needs according to a set of prioritization criteria.

The PO encourages that inputs include as much of the information requested as possible and, most importantly, that the technology need be submitted as a capability that is required and 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. This allows: 1) the TMB to best assess the need; 2) NASA HQ to develop precise technology development proposal calls; and 3) the research community to be clearly informed in order to best match candidate technologies to mission needs. If specifying the technical parameters is not possible due to the competition sensitivity of the information, then the submitter should consider specifying the ranges or targets of the important technical parameters. When relevant, the submitter should quantitatively and qualitatively explain how the need exceeds the current state of the art. Additionally, a clear description of potential relevant NASA missions or applications is also needed for the prioritization process. The more compelling and relevant the case, the more likely it is that it will receive favorable prioritization and/or funding recommendations.

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

- **Brief description:** summarizes the technology need and the associated key performance criteria for the technology. In general, technology needs that are well defined will tend to receive higher prioritization than those that are vague.

- **Goals and objectives:** details the goals and/or objectives for a candidate technology to fill the described need. For example, "The goal is to produce a detector with a sensitivity of *X* over a wavelength of *Y* to *Z* nm." Technology needs with objectives that are clearly quantified may receive higher prioritization than those without quantified objectives.

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

- **Tipping point:** provides a timeframe during which the technology can be brought to a level where its eventual viability can be assessed. This can be when the technology reaches the mid-TRL thresholds (4, 5, or 6).

- **NASA capability:** describes NASA's current capability to implement and/or access the technology.

- **Benefit:** describes the scientific, engineering, and/or programmatic benefits of fulfilling the technology need. If the need is enabling, then describe how and/or why. If the need is enhancing, then describe, and if possible quantify, the impact. Benefits could be scientific (e.g., better science output), engineering (e.g., lower mass), or programmatic (e.g., reduced cost or schedule). For example, "Material *X* is 50% stronger than the current state of the art and will enable the optical subsystem for a 2-m telescope to be *Y* kg lighter." Technology needs with greater potential mission benefits will receive higher prioritization.

- **NASA needs:** details specific needs and performance requirements for NASA mission concepts.

- **Non-NASA but aerospace needs:** details specific needs and performance requirements for applications outside of NASA mission concepts but within the aerospace sector

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- **Non-aerospace needs:** describes specific needs and performance requirements for all other needs (not covered in the previous two categories).

- **Technical risk:** describes the known technical risks in developing the technology.

- **Sequencing/timing:** describes when the technology will be needed to support anticipated mission needs. Technology needs with shorter time windows relative to required development times will receive higher prioritization.

- **Time and effort:** estimates the duration and scope of the technology development effort.

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

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

- **Technology is enabling or enhancing:** describes whether fulfilling the technology need is required to meet the associated missions' objectives, which makes the technology enabling, or whether it is an enhancing technology, because fulfilling the need would have significant benefits but is not absolutely required.

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

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

Technology Roadmap - PhysPAG Technology SAG - 10/15/11 *

Decadal Survey 2010 (New Worlds New Horizons)

	WFIRST	LISA	IXO-like	Inflation Probe	Fundamental Physics
		Table 1	Table 2	Table 3	Tables 4a, 4b
Science Summary	Study the nature of dark energy via BAO, weak lensing and SnIa, IR survey, census of exoplanets via microlensing.	Probe black hole astrophysics & gravity signatures from compact stars, binaries, and supermassive black holes.	Conditions of matter accreting onto black holes, extreme physics of neutron stars, chemical enrichment of the Universe.	Study the Inflationary Epoch of the Universe by observing the CMB B-mode polarization signal.	Precision measurements of space-time istoropy and gravitational effects.
Architecture	Single 1.5 m diaiameter telescope, with focal plane tiled with HgCdTe (TBD).	Three space craft constellation, each in Keplerian orbit. Sub nm displacement measured by lasers (Michelson interferometer).	Single 2.5 - 3 m grazing incidence 20 m focal length X-ray telescope.	High-throughput cooled mm-wave meter-class telescope with large-format polarization-sensitive detector arrays.	Individual spacecraft for space-time measurement and gravitational effects. Multiple spacecraft for precision timing of interferometric measurements.
Wavelength	0.6 to 2.0 μm	Interferometer λ= 1.064 μm - gravity wave period 10-10,000 sec.	0.3 to 40 keV	1 - 10 mm	
Telescopes and Optical Elements	Wide FOV, ~1.5 m diameter mirror.	Classical optical design; Surface roughness < 1 λ/30, backscatter/ stray light.	lightweight, replicated X-ray optics.	High-throughput, light, low-cost, cold mm-wave telescope operating at low backgrounds; Anti-reflection coatings; Polarization modulating optical elements.	
		Alignment sensing, Optical truss interferometer, Refocus mechanism.			Coupling of ultra-stable lasers with high-finesse optical cavities for increased stability.
	Classic telescope structure - HST heritage	Athermal design with a Temp gradient Dimensional stability: pm/sqrt(Hz) and um lifetime, angular stability < 8 nrad.	lightweight precision structure		
Detectors & Electronics	HgCdTe CMOS (H4RG?)	Laser: 10 yr life, 2W, low noise, fast frequency and power actuators; Quadrant detector, low noise, 10 yr life, low noise (amplitude and timing) ADC's.	X-ray calorimeter central array (~1,000 pixels); 2.5 eV FWHM @ 6 keV, extended array; 10 eV FWHM @ 6 keV. High rate Si detector (APS). High resolution gratings (transmission or reflection).	Large format (1,000 - 10,000 pixels) arrays of CMB polarimeters with noise below the CMB photon noise and excellent control of systematics.	Molecular clocks/cavities with 10^{-15} precision over orbital period; 10^{-17} precission over 1-2 year experiment. Cooled atomic clocks with 10^{-18} to 10^{-19} precision over 1-2 year experiment.
Coolers & Thermal Control	Passively cooled telescope, actively cooled focalplane?	Low CTE materials, passive thermal shielding, power management for avionics thermal stability.	Cryocooler needed to cool detectors and other parts of instruments.	Passive Spitzer design plus cooling to 100 mK.	Thermal stability/control, less than 10^{-8} K variation.
Distributed Space Craft		Spacecraft in separate Keplerian orbits. No formation flying or station-keeping. Low contamination μ-Newton thrusters with low thrust noise.			Applicable as precision timing standard in distributed constellations.

Near Term Push Technologies **

	Advanced mm-wave/far-IR Arrays	Next Generation Hard X-ray Observatory	Next Generation EUV/Soft X-ray Observatory	Next Generation X-ray timing	Next Generation Medium-energy γ-ray Observatory	21cm Cosmology Array
	Table 3	Tables 5a, 5b	Table 6	Table 7	Table 8	Table 9
Science Summary	Enhanced sensitivity or reduced resources for the Inflation Probe; far-infrared astrophysics.	Hard X-ray (5-600 keV) imaging all sky survey for BHs.	Spectroscopy of million degree plasmas in sources and ISM to study composition.	EOS of neutron stars, black hole oscillations, and other physics in extreme environments.	Signatures of nucleosynthesis in SNR, transients, and other sources; AGN and black hole spectra.	Track evolution of Universe from the Dark Ages (before the first stars), through Cosmic Dawn, and into the Epoch of Reionization using the highly-redshifted 21 cm hyperfine transition of neutral hydrogen.
Architecture	High-sensitivity, large-format, multi-color focal planes for mm-wave to far-infrared imaging, polarimetry & spectroscopy.	Two wide-field (~130 x ~65 deg) coded mask telescopes. Full sky each ~95 min (5a); Alternatively a Nu-STAR architecture (5b).	Focusing optics with high resolution spectrometers based on advanced gratings.	large (>3 m^2) pointed arrays of solid state devices, with collimation to isolate sources or with arrays of concentrators.	Single platform designs to measure γ-ray lines.	Synthesis array of long-wavelength receptors distributed over a notional area of 10 km operating in an environment with extremely low levels of radio frequency interference.
Wavelength	30 μm - 10 mm	Two architecture concepts within 5-600 keV range	5-500 Angstroms	2-80 keV	100 keV - 30 MeV	5–30 m
Telescopes and Optical Elements	Large throughput, cooled mm-wave to far-infrared telescope operating at background limit.	Coded aperture imaging: ~5 mm thick W and ~2.5 mm holes; ~0.5 mm W and ~0.2 mm holes.	Gratings, single and multilayer coatings, nano-laminate optics.	Either X-ray concentrators or collimators.	Compton telescope on single platform.	Polyimide film-based dipole antennas.
		Hard X-ray grazing incidence telescope with multilayer coatings.	Actuators			Self-deploying magnetic helices
		(5a) 5 arcmin aspect requirement; (5b) 5 arcsec aspect requirement.	Arcsecond attitude control to maintain resolution.	Moderate accuracy pointing of very large planar array.		
Detectors & Electronics	Very large format (> 10^5 pixels) focal plane arrays with background-limited performance and multi-color capability.	CZT detectors matched to system requirements.	Photocathodes, micro-channel plates, crossed-grid anodes.	>3 m^2 Si (or CZT or CdTe) pixel arrays or hybrid pixels, with low-power ASIC readouts, possibly deployable.	Cooled Ge; arrays of Si, CZT or CdTe pixels and ASIC readouts.	Low-power radio frequency (RF) components, capable of operation and survival under large temperature variations.
Coolers & Thermal Control	Cooling to 50 - 300 mK	LHP to radiators for -~30 deg (Si) and ~-5 deg (CZT) over large areas (5a).		Passive cooling of pixel arrays.	Active cooling of germanium detectors.	Science antennas not thermally controlled, electronics controlled only to the minimal level necessary, most likely at high temperature extremes.
Distributed Space Craft			Use low-cost launch vehicles for single payloads with few month mission duration.			Science antennas must be distributed, likely location is lunar far side.

Long Term Push Technologies **

	Beyond LISA (Big Bang Observer)		Beyond IXO (Gen-X)	Next Generation γ-ray Focusing
	Table 10		Table 11	Table 12
Science Summary	To directly observe gravitational waves resulting from quantum fluctuations during the inflation of the universe.		Observe the first SMBH, study growth and evolution of SMBHs, study matter at extreme conditions	Signatures of nucleosynthesis in SNR, transients, and other sources.
Architecture	Four Michelson interferometers each of three s/c (~12 s/c total), ~50,000 km separation, LISA-like.	Constellation of at least 2 cold atom differential accelerometers, 10,000 km measurement baseline.	16 m (50 m^2 grazing incidence telescope with 60 m focal length).	2-platform designs to measure γ-ray lines.
Wavelength	Visible & near IR: gravity waves periods of ~1-10 sec	Gravity wave periods 0.01 - 10 Hz	0.1-10 keV	100 keV-3 Mev
Telescopes and Optical Elements	~3 m precision optics	~ One meter precision optics (l/1000)	Lightweight adjustable opitcs to achieve 0.1 arcsec. High resolution grating spactrometer.	Focusing elements (e.g., Laue lens) on long boom or separage platform.
	LISA Heritage	Wavefront sensing with cold atoms; large area atom optics	0.1 arcsec adjustable optic	
	LISA Heritage	10 W near IR, narrow line	Extendale optical bench to achieve 60 m focal length.	Long booms or formation flying.
Detectors & Electronics	Laser interferometer, ~1 kWatt laser, gravity reference unit (GRU) with ~100x lower noise.	Megapixel CCD camera	Gigapixel X-ray active pixel sensors, magapixel microcalorimeter array.	Scintillators, cooled Ge
Coolers & Thermal Control	LISA Heritage	Sun-shield for atom cloud.	Cryocooler <100 mK with 1 mK stability (IXO Heritage).	Active cooling of germanium detectors.
Distributed Space Craft	~12 s/c total ~50,000 km separation, sub-micron position control.	Multi-platform s/c system to support above architecture.		2-platform formation flying is one approach.

Table 1: LISA Technology

Name of Technology	Laser	Phasemeter system	Alignment Sensing	Telescope	Gravitational Reference Sensor	Thrusters
Brief description of the technology	LISA laser requires power of P=2W in a linear polarized, single frequency, single spatial mode. It requires fast actuators (BW > 10kHz) for intensity and frequency stabilization to enable laser phase locking and relative intensity noise of $<10^{-6}$/rtHz. Shot noise limited at 1mW laser power above 2 MHz.	The phasemeter measures the phase of laser beat signals with ucycl/rtHz sensitivity. It is the main interferometry signal for LISA. The phasemeter consists of a fast photo receiver which detects the beat signal, an ADC which digitizes the laser beat signal, and a digital signal processing board which processes the digitized signal.	Alignment sensing in interferometric space missions like LISA or formation flying missions is required to maintain the alignment between the individual spacecraft. This is done with differential wavefront sensing between a local and the received laser beam. The missing key element is a four element fast, non-dispersive photo detector.	LISA and also formation flying missions require telescopes to exchange laser fields for position and alignment sensing. The requirements for these telescopes include unusual length and alignment stability requirements at the pm and nrad level. Scattered light from within the telescope could affect the interferometric measurements.	Gravitational Wave detectors (LISA and LISA follow-on missions) as well as other fundamental physics missions require gravitational reference sensors. For LISA, the residual acceleration of the GRS has to be in the sub-fg/rtHz range. ESA has developed a gravitational reference sensor for the LISA pathfinder and will test it in flight in the upcoming years. This reference sensor consists of a proof mass in an electro-static housing. Key technologies include magnetic cleanliness, charge mitigation, gas damping, thermal noise, and actuator noise.	Thrusters for in-space operation with very low noise, tunable thrust, long lifetime (> 5 years) are required for LISA, LISA follow-on missions, and for formation flying missions. LISA needs low noise with less thrust (uN/rtHz and 100uN thrust). The requirements for formation flying missions are mission specific. They are likely to require more thrust but can also tolerate more noise compared to LISA.
Goals and Objectives	The goal is to reach TRL 6 in 2015 with a laser system that meets LISA requirements.	The goal is to reach TRL 6 by 2015 with a phasemeter system that meets LISA requirements. This system is essential to support tests of other subsystems at the ucycl/rtHz level and should be developed as soon as possible.	The goal is to reach TRL 6 by 2016 with the alignment sensing system. It should be developed together with the phasemeter system. Understanding the capabilities and the sensitivity of the alignment sensing system enables more targeted technology developments for LISA and allows to develop realistic designs for formation flying mission.	Athermal telescope designs have to be developed to meet the length and alignment requirements. Materials have to be tested for creep at the pm/nrad level. Study ways to predict and reduce the effects of back scatter on the interferometry.	The initial goal has to be the support of the LISA pathfinder and technology import to learn as much as possible form the pathfinder. This could raise the TRL above 6 immediately. Future R&D depends on the outcome of the pathfinder mission. The lessons learned should help to evaluate how far this technology can be pushed or if radically new ideas should be investigated.	TRL 6 for colloid thrusters meeting the LISA requirements. Scalability of these and other thrusters to meet formation flying requirements needs to be investigated.
TRL	Between TRL 4 and 5. Requires now efforts towards space qualification and testing in relevant environment.	TRL 5. The phasemeter has been demonstrated but only with single element photodetectors and most of the components are not space qualified.	TRL 4. This might just be testing commercially available quadrant detectors and identifying one that meets the requirements.	TRL 4 for length and alignment stability 2 for backscatter.	Pathfinder GRS: TRL > 6	Colloids: TRL 6
Tipping Point	Laser meeting these requirements exist already. Several designs have reached TRL 4. A focused effort could increase this to TRL 6 or at least identify the issues in a fairly short time.	The main missing elements are the quadrant photodetector and ADC's with low enough timing jitter. A focused effort could solve this problem in a fairly short time.	A survey of the available quadrant detectors and simple tests of the most promising ones might be sufficient to get this to TRL 6.	Length and alignment stability: This requires to build a real LISA telescope and test it. Note that a 40cm telescope is not a gigantic investment but developing the measurement capabilities requires some funding. The coherent backscatter has never been seriously analyzed and an initial minor investment would make a huge difference.	Yes, if NASA can take advantage of the LISA pathfinder.	This should be an ongoing effort
NASA capabilities	NASA's capabilities in this area appear to be restricted to testing and space qualification. Commercial laser companies or specialized groups in academia have the expertise and capabilities to collaborate with NASA on this effort.	NASA does not have the capabilities to develop the individual components alone but could collaborate with industry to design and test them. NASA and some groups in academia have the expertise to test these components and later the entire system.	NASA and several university groups have the capability to test these components. If the currently available components don't meet the requirements, NASA needs to work with industry to improve them.	NASA has the capability to build a 40cm LISA telescope but the capabilities to measure the length and alignment variation need to be developed. NASA (and many others) could analyze and test the back scatter.	ESA is building it and collaborates with NASA on the pathfinder.	Well within NASA capabilities
Benefit	It would allow to define the interfaces between the laser and all other subsystems in LISA. This simplifies and in some cases enables R&D on other important components. The laser system itself would also be useful for other laser interferometric missions such as formation flyers, multiple aperture missions, or Grace-follow on missions.	The capability to measure noise at the ucycl/rtHz level is essential for the R&D on many other components. Having a well tested phasemeter system would enable and accelerate the R&D in general.	Maintaining the relative alignment between multiple components on one spacecraft and between separated spacecraft is essential for LISA and for formation flying missions.	The telescope is another key part of LISA and formation flying missions. Off-axis telescope with additional interferometer to control length and alignment of the components are an alternative but would increase mass and complexity.	A gravitational reference sensor with sub fg/rtHz residual acceleration is critical for gravitational wave missions. Making sure that NASA has access to this technology should be one of the top priorities.	Formation flying would be a game changer. Thrusters are only a part of this. On going effort.
NASA needs	LISA and other laser interferometric missions such as formation flying missions, Grace follow-on.	LISA is the main customer but other interferometric space missions are planning to use similar phasemeter. Having a completely characterized system with ucycl/rtHz sensitivity would meet many NASA needs.	Required for LISA and formation flying missions. Having a completely characterized system with ucycl/rtHz sensitivity would meet many NASA needs.	On-axis telescopes which passively meet the requirements would significantly simplify LISA and formation flying missions.	LISA and LISA-follow on missions depend on it.	Formation flyer depend on it. Need for LISA solved with pathfinder demonstration except for lifetime.
Non-NASA but aerospace needs	Formation flying might have commercial and national security applications in the form of smaller satellite missions.	Formation flying might have commercial and national security applications in the form of smaller satellite missions.	Formation flying might have commercial and national security applications in the form of smaller satellite missions.	Formation flying might have commercial and national security applications in the form of smaller satellite missions.	No non-NASA needs known	Formation flying might have commercial and national security applications in the form of smaller satellite missions.
Non aerospace needs	Non. Non space-qualified lasers which meet the requirements are commercially available.	Science and Engineering applications.	Science and Engineering applications.	No non-NASA needs known	No non-NASA needs known	No non-NASA needs known
Technical Risk	The technical risk is low. Several commercial systems exists that meet the requirements except space qualification. No commercial company will space qualify a LISA laser to commercialize it.	Technical risk is low. The main challenge is to get the temperature dependent dispersion under control.	Technical risk is low. The main challenge is to get the temperature dependent dispersion under control without reducing bandwidth and area to much.	Technical risk for the longitudinal and alignment stability is low. Materials have been tested at the sub-pm level. The main challenge appears to be to develop the capabilities to perform the experiments. Backscatter: No risk. This is an assessment if on-axis telescopes will meet the requirements or if substantial R&D is required to develop an off-axis telescope.	ESA is taking most of the financial risk right now. If the pathfinder reaches the performance, technical risks for NASA are minimal.	Continuous development. Technical risk low
Sequencing/Timing	Should come as early as possible. The development of many other components depends on the specific laser system.	Should come as early as possible. The development of many other components depends on the availability of a phasemeter with ucycl/rtHz sensitivity.	Requires phasemeter. Should start before phasemeter development is finished and should be finished 1-2 years after phasemeter is at TRL 6.	Length and alignment: The current status is sufficient for planing purposes. Tests on real models should start 2017. Backscatter: Start immediately as small effort.	The timing is set by ESA	Continuous development.
Time and Effort to achieve goal	3 year collaboration between industry and NASA.	3 year collaboration between industry, academia, and NASA.	2 year collaboration between academia and NASA.	3 year academia project	Effort and time depends on form of collaboration with ESA.	Continuous development.

Table 2: IXO-Like X-ray Telescope

Name of Technology (256 char)	Thermal formed (slumped) glass mirror segments	Large-scale alignment and mounting of thin glass mirror segments	Gratings for dispersive x-ray spectrometer	Large area x-ray calorimeter	Wide Field Detector
Brief description of the technology (1024)	Thermally form, to precision mandrels, thin glass sheets into Wolter I mirror segments. Includes cutting mirrors to appropriate size, and coating with x-ray reflective material.	Thousands of mirror segments need to be aligned to one another, made confocal, and mounted in a flight housing. Mounting must not distort the mirror figure.	High ruling density off-plane (OP) reflective and critical angle transmission (CAT) x-ray gratings for dispersive x-ray spectroscopy.	X-ray calorimeter for high resolving power non-dispersive spectroscopy coupled with moderate angular resolution imaging. Includes development of calorimeter pixel multiplexing, refrigeration, energy resolution, and field size (total number of pixels).	High-speed silicon imagers with active electronic elements in each pixel and large numbers of parallel readout channels.
Goals and Objectives (1024)	Requirement for perfectly aligned primary-secondary mirror pair are 3.3-6.6 arc-sec HPD for 5-10 arc-sec HPD mission, respectively. Manufactureability requirements drive fabrication yield and fabrication time/mirror segment. Need TRL 6 by 2014 for future mission development.	Alignement requirement for multiple segments and multiple shells is ~ 1.5 to 3 arc sec HPD. Figure distortion due to mounting and alignment must be less than 1.2 to 2.5 arc sec HPD. System must survive launch seismic and acoustic loads. TRL 6 by 2016 for future mission development.	Development of gratings with resolving power lambda/delta-lambda > 3000 over wavelengths of ~ 1.2 to 5 nm. High efficiency required to make use of full resolving power. Many individual grating cells or plates must be coaligned. TRL 6 by 2018.	Develop large format (~ 100 to 1000 sq. mm area) detector with < 2.5 eV resolution. May include smaller pixels in central area and larger, lower resolution (< 10 eV), surrounding pixels. Minimize readout time and increase pixel multiplexing. TRL 6 by 2018.	Achieve CCD-like performance (5 electrons read noise or better, 50 microns depletion depth or better) in a 100mm focal plane mosaic Megapixel imager with kHz frame rates. Need TRL 6 by 2016–2018 for future IXO-like mission.
TRL	Estimate current TRL at 4 - 5. Have achieved ~ 8.5 arc-sec HPD, but have not yet demonstrated manufacturing times required for large area telescopes.	Estimate current TRL at 3. Mirror segment pairs have been aligned and mounted to < 1.5 arc sec HPD. Figure distortion due to mounting exceeds requirements. Have not yet demonstrated alignment and mounting of mirror segments from multiple shells.	Estimate current TRL 4. Single reflective OP gratings have been made but have not yet demonstrated resolving power of several thousand. Lithographically made CAT gratings have also been manufactured, but with insufficient efficiency.	TRL 4. 2.5 eV resolution has been demonstrated over limited number of detector pixels. Multiplexing 8 to 16 pixels has been demonstrated.	Currently at 4 for various different devices..
Tipping Point (100 words or less)	Better than 6.6 arc sec HPD will demonstrate performance for 10 arc sec mission positively rated by ASTRO2010. Process needs to be industrialized to make large scale production credible.	Moderate - alignment requirements met but mounting deformation ~ 5 times too high. Significant development still required.	Modest improvement in resolution will result in meeting science requirements.	10 mm x 10 mm detector area provides large enough area for small field of view telescope.	Moderate. Different device architectures currently meet individual requirements, but no device yet meets all requirements. Need lower noise in hybrid devices and/or deeper depletion in monolithic devices; thus development is still required.
NASA capabilities (100 words)	NASA GSFC leads in development of thermal forming and is fully equipped to continue experimentation.	NASA GSFC and SAO have developed alignment mounting techniques. Alternatives or similar approaches could be developed in optics industry.	NASA does not have capability but development capabiilty exists at MIT, Univ. of Colo., and Iowa State.	NASA has developmetn capabilities, as do other research labs (NIST, MIT), and some European facilities.	NASA does not have this capability. Current commercial CMOS APS devices do not meet X-ray detection requirements, but FFRDC and commercial organizations (e.g. Lincoln Lab., Teledyne, Sarnoff) have development capbilities.
Benefit	Thin mirror segments enable collecting area to exceed 1 sq m with existing launch vehicles. > 10x area of Chandra and better resolution than XMM. This enables study of early Universe, BH dynamics and GR, and WHIM.	Thin mirror segments enable collecting area to exceed 1 sq m with existing launch vehicles. > 10x area of Chandra and better resolution than XMM. This enables study of early Universe, BH dynamics and GR, and WHIM.	Gratings yield the high resolving power spectrum over the 0.1 to 1 keV bandwidth.	Calorimeter provide high spectral resolution with higher rate capability than CCDs, and still provide imaging capabillities matched to telescope performance.	Better low-energy QE, better time resolution and count-rate capability, larger field of view, better radiation tolerance, less susceptible to contamination. Would allow game-changing X-ray imager capabilities.
NASA needs	Required for moderate to large collecting area x-ray telescopes.	Required for moderate to large collecting area x-ray telescopes.	Gratings are required for and high-resolution (resolving power R>3000) spectroscopy in the energy band below 1 keV; e.g., for spectroscopy of WHIM. Need 10x resolving power of Chandra gratings.	Required for high spectral resolution observations over large bandwidth. Necessary for studying BH dynamics and merger history, GR, NS EOS.	Needed for large area X-ray telescope missions. Could also have applications for UV, optical and IR.
Non-NASA but aerospace needs	NONE	NONE	NONE	Large formats also required for infrared and submillimeter observations.	Potentially interesting for night-vision applications.
Non aerospace needs				May have applications with X-ray microscopes for medical research	Potential medical applications
Technical Risk	Low - current performance within ~ 30 per cent of requirements	Moderate - alignment requirements met but mounting deformation ~ 5 times too high. Major development still required.	Moderate - improvements in efficiency required to produce useful technology	Low	Moderate: different device architectures currently meet different requirements, but no device meets all requirements.
Sequencing/Timing	As early as possible - "heart" of a telescope	As early as possible - "heart" of a telescope	Early in mission development as could drive spacecraft design, including focal plane design	Early in mission development as could drive spacecraft design, including focal plane design	As early as possible, since these devices could enable otherwise infeasible small (e.g., Explorer missions in this decade.
Time and Effort to achieve goal	3 year collaboration between NASA and industry	5 year collaboration between NASA and industry	3 - 5 year NASA funded development. Choose instrument development teams by AO	3 - 5 year NASA funded development. Choose instrument development teams by AO	~5 year NASA-funded collaboration involving universites, FFRDC and industry.

Table 3: Technologies for the Inflation Probe

Technology	Detectors			Optical system	Cryogenic system	Push Technology[b] Advanced mm-wave / far-IR Arrays
	Sensor Arrays	Multiplexing	Optical Coupling			
Brief Description of Technology	The Inflation Probe requires arrays of polarization-sensitive detectors with noise below the CMB photon noise at multiple frequencies between ~30 and ~300 GHz for foreground removal[a]; up to 1 THz for Galactic science.	Multiplexed arrays of 1,000 - 10,000 low- temperature detectors will be required for the Inflation Probe.	The Inflation Probe requires coupling the light to the detectors with exquisite control of polarimetric systematic errors.	High-throughput telescope and optical elements with controlled polarization properties are required; possible use of active polarization modulation using optical elements.	The Inflation Probe requires cryogenic operation, passive radiators, mechanical cryo-coolers, and sub-Kelvin coolers.	Detector arrays with higher multiplexing factors and multi-color operation may provide simplified implementation for the Inflation Probe, and have diverse space-borne applications in X-ray calorimetry and far-infrared astronomy.
Goals and Objectives	Demonstrate arrays in sub-orbital instruments, and demonstrate the background-limited sensitivity appropriate for a satellite-based instrument in the laboratory.	Demonstrate multiplexed arrays of thousands of pixels in ground- and balloon-based instruments.	Demonstrate arrays of polarization-sensitive receivers with sufficient control of polarization systematics in sub-orbital and ground-based instruments.	Demonstrate all elements of an appropriate optics chain in sub-orbital and ground-based instruments.	Develop stable and continuous sub-Kelvin coolers appropriate in space for expected focal plane thermal loads.	Develop higher multiplexing factors with micro-resonators; demonstrate multi-color operation with antenna-coupled detectors to reduce focal plane mass.
TRL	**TES:** (TRL 4-5) Noise equivalent power (NEP) appropriate for a satellite has been demonstrated in the laboratory, and TES instruments have been deployed and used for scientific measurements in both ground-based and balloon-borne missions. **HEMT:** (TRL 4) Flight heritage, but extension to 3 QL noise, access to higher frequencies and lower power dissipation requires demonstration.	**TDM:** (TRL 4-5) Ground based arrays of up to 10,000 multiplexed pixels are working on ground-based telescopes. Kilopixel arrays will shortly fly in balloons. **FDM:** (TRL 4-5) Ground based arrays of up to 1,000 multiplexed pixels are working on ground-based telescopes, and initial balloon flights have occurred.	**Planar antenna polarimeter arrays:** (TRL 4-5) Ground based arrays deployed and producing science, balloon-borne arrays will soon be deployed. **Lens-coupled antenna polarimeter arrays:** (TRL 4-5). Ground based arrays deployed. **Corrugated feedhorn polarimeter arrays:** (TRL 4) Corrugated feeds have extensive flight heritage, but coupling kilopixel arrays of silicon platelet feeds to bolometers requires maturation. Ground-based arrays in this configuration are soon to be deployed.	**Millimeter-wave AR coatings:** (TRL 2-5) multi-layer to single-layer coatings. **Polarization modulators:** (TRL 2-4) half- wave plate modulators, variable polarization modulators, or on-chip solid-state modulators	Technology options for the sub-Kelvin coolers include He-3 sorption refrigerators, adiabatic demagnetization refrigerators, and dilution refrigerators. TRL for all options varies considerably from TRL 3 to TRL 9. Planck and Herschel provide flight heritage for some of these systems.	**MKID:** (TRL 3) Appropriate sensitivity needs to be demonstrated, small ground-based instruments are in development. **Microresonators:** (TRL 3) 2,000-channel ground-based MKID instruments are in preparation. Laboratory systems using microwave SQUIDs have been developed for small TES arrays. Hybrid combinations are possible. **Multi-color pixels:** (TRL 2) Multi-band lens-coupled antennas have shown proof of concept, but must meet exacting CMB requirements.
Tipping Point	For the TES, demonstrate appropriate sensitivity at all relevant wavelengths. For HEMTs, improved noise performance and low power dissipation.	For TDM and FDM, demonstrate full- scale operation on a balloon-borne instrument.	Extensive analysis of data from ground-based and balloon experiments is required to demonstrate control of systematics. Demonstrations required at all wavelengths of interest.	Demonstrate relevant optical system designs, including reflective and refractive optics, millimeter AR coatings, and polarization modulators.	Space cooling system can be leveraged on current technology efforts, but must provide extremely stable continuous operation	MKID instruments must demonstrate sensitivity in full sub-orbital instrument. For microresonators, a breakthrough is required on the room- temperature readout electronics. Multi-band pixels must be used in sub-orbital instrument.
NASA Capabilities	National labs (JPL, GSFC, NIST, and Argonne) and University groups (Berkeley) have extensive experience with the design and fabrication of arrays that have been used in previous missions in this wavelength range.			NASA and many University groups have developed and deployed optical systems as described here.	NASA has extensive heritage appropriate to the task, and some elements are commercially available.	National labs (JPL, GSFC, NIST, and Argonne) and University groups (Berkeley) have extensive experience with the design and fabrication of arrays.
NASA needs	The technology developed would leverage many other missions requiring low-temperature superconducting detectors, including **IXO**, **Generation-X**, and future far-infrared missions such as **SPIRIT**, **SPECs, or SAFIR.**		Pixel optical coupling technologies are candidates for future far-infrared missions such as **SPIRIT**, **SPECs, or SAFIR.**	Improvements in optical systems will benefit **SPIRIT**, **SPECs, or SAFIR.**	Developments will benefit any other future satellite mission requiring sub-Kelvin cooling, including **IXO**, **SPICA**, **SAFIR**, etc.	The technology developed would leverage many other missions requiring low-temperature superconducting detectors, including **IXO**, **Generation-X**, and future far-infrared missions such as **SPIRIT**, **SPECs, or SAFIR.**
Non-NASA aerospace needs	Arrays of sensitive bolometers may have national security applications either in thermal imaging of the earth, or in gamma spectroscopy of nuclear events.					
Non aerospace needs	Sensitive mm-wave bolometer arrays have applications in remote sensing, including concealed weapons detection, suicide bomber detection, medical imaging, and sensing through fog.					
Sequencing/Timing	Should come as early as possible. The entire Inflation Probe system is dependent on the capabilities of the sensors, and a new generation of ground-based and sub-orbital experiments are predicated on a rapid expansion in focal plane capability.			Early test of optical elements needed to gauge system issues.	The cryogenic system is specialized for space and not as time-critical.	These advanced options should be pursued in parallel to reduce cost and implementation risk.
Time and Effort to Achieve Goal	5-year collaboration between NASA, NIST, and university groups.				Leverage current development for space-borne coolers.	5-year collaboration between NASA, NIST, and university groups.

[a]Information on foregrounds across a broader range of frequencies (5 GHz to 1 THz) from sub-orbital and ground-based experiments is essential for optimizing the choice of bands for the Inflation Probe.
[b]Near-term push technology from the PCOS TechSAG table, defined as emerging technologies needed for applications in the next decade.

Table 3: Technologies for the Inflation Probe

Computational Requirements

A common feature of the many of the technological developments for next generation missions is that they will enable us to detect fainter signals, in many cases by gathering correspondingly larger and richer data sets. The computational cost and complexity of the management and analysis of these data sets will therefore increase in step with the technology. For example, a next-generation CMB satellite mission (Inflation Probe) would likely follow two generations of path-finder suborbital experiments, with the data volume—and, hence, analysis cost—increasing by an order of magnitude with each generation. Note further that a 1000-fold increase in computational cost over the next 15 years exactly mirrors Moore's Law, requiring us to stay on the leading edge of high performance computing over this period simply to keep up with the data.

At the same time the computational systems employed to perform these analyses are also developing, with the pursuit of Moore's Law leading to increasingly hierarchical, heterogeneous systems. In the immediate future high performance computing systems will feature extraordinary (1M+) core counts over many-core and/or hybrid CPU/GPU nodes. Computing on these systems will be qualitatively different, requiring significant changes to our software to take advantage of their capabilities.

Any program of mission technology development must therefore be accompanied by a parallel track of appropriately targeted software development if we are going to realize the full scientific potential of the data we gather on the high-performance computing systems that will be available to us.

Table 4a: Fundamental Physics: Atom Interferometer for Gravitational Radiation

Name of Technology (256 char)	High brightness cold atom sources	Large area atom optics	Low phase noise laser source	Extended space structures/booms
Brief description of the technology (1024)	Science objectives require high repetition rate cold atomic sources, which run at low input power and deliver high flux.	Wavefront sensing is realized with cold atoms.	Narrow line, space-qualified, continuous-wave lasers are required for atom wave-packet manipulation in atom interferometers.	Long-baseline deployable booms are required for envisioned gravity wave sensors.
Goals and Objectives (1024)	The goal is to develop a high repetition rate (10 Hz) atomic sources capable of delivering >1e8 atoms/shot at temperatures less than 1e-6 K, in a compact (10 cm x 10 cm x 10 cm) form factor and requiring low input power (< 10 W).	Goal is to mature atom optics to a level where atomic wave packets are separated by meter scale distances, where current state of art is cm scale.	Laser must achieve >1 W output power at 780 nm with a linewidth < 1 kHz.	Extend deployable booms from 100 m to 300 m.
TRL	TRL is 5.	TRL 3.	TRL is 5.	TRL is 5.
Tipping Point (100 words or less)	This is the core sub-system for any atom interferometric sensor. A three year focussed program should bring TRL to level 6.	Large area atom optics have recently been demonstrated in the laboratory in compact apparatus.	A two year development program will result in a space qualified system.	A 2 year development program will result in the required structures.
NASA capabilities (100 words)	NASA does not have capability in this area. There are currently DoD and commercial efforts pursuing this technology development.	NASA does not have a group with expertise in this area, but collaboration with university and commercial groups is feasible.	NASA has capability in this area. Suitable groups exist in industry.	NASA does not have capability in this area. Industry capability exists for smaller commercial and defense systems.
Benefit	Such sources enable gravity wave antennas based on atom interferometry. They also support gyroscope developments for precision pointing applications, gravity gradiometers for geodesy and deep space navigation, inertial measurement units for constellation formation flying, and attitude determination for precision pointing applications.	Direct detection of gravitational radiation is one of the primary objective of relativitistic astrophysics. Atom optics realized as a gravitational radiation detector could be revolutionary.	The laser source is the essential subsystem for the interferometry.	Large booms enable novel space structures.
NASA needs	High flux atom sources are the core components for precision atom interferometer-based gravity wave antennas, gravity gradiometers and inertial measurement units.	Gravitational wave detection using differential accelerometry is a novel path to meeting identified astrophysics goals for study of coalescing systems.	These laser sources are required for atom interferometer-based instruments.	Large deployable booms enable atom-based gravity wave antennas.
Non-NASA but aerospace needs	These sources are core components for next-generation inertial measurement units. Development for of non-NASA sources currently funded by DoD.	Large area atom optics enable accelerometer and gyroscope sensors.	Laser sources are core components for atom interferometric sensors.	Large, rigid, deployable structures may enable novel DoD systems.
Non aerospace needs	Applications to gravitational sensors for geophysics and oil/mineral exploration.	Large area atom optics enable compact gravitational sensors for geophysics and oil/mineral exploration.	Similar lasers have commercial applications in, for example, remote sensing systems.	None known.
Technical Risk	Technical risk is low. Design principles have been established an validated in design and prototype testing of DoD-relevant systems.	Technical risk is moderate. The appropriate techniques have been demonstrated in ground-based laboratory systems.	Technical risk is low.	Technical risk is low.
Sequencing/Timing	Should come as early as possible.	Should come as early as possible.	Should come as early as possible.	Should be concurrent with laser and atom source development. System trades depend on size of boom.
Time and Effort to achieve goal	3 year collaboration between industry and NASA	3 year collaboration between NASA, academia and industry.	2 year collaboration between industry and NASA	3 year collaboration between NASA and industry.

Table 4b: Fundamental Physics: Next Generation Clocks

Name of Technology (256 char)	Arrays of Rb clocks for high stability	New atomic media for compactness	Advanced cold atom microwave clocks
Brief description of the technology (1024)	Exploit mature Rb clock technology to achieve breakthrough in stability by producing packages with multiple units in package and combine outputs to get stability. The outputs would be combined by optimal iterative techniques. The resultant clock signals and frequencies would have with lower Allan variance than is currently available.	Exploit new technologies, such as Hg ions, to produce new compact designs for clocks delivering high stability and increased accuracy.	Take advantage of 30 years of science and technology in the area of laser cooling of atoms (Rb and/or Cs) that has resulted in tremendous improvement in performance of atomic frequency standards and clocks. Cold atom microwave clocks have demonstrated stability and accuracy about 100x better than traditional cell-based Rb frequency standards. Accuracy
Goals and Objectives (1024)	The goal of this area is to produce space qualified clocks that have very stable output with characteristics superior to individual clocks in both accuracy any long term performance. The objectives would be to demonstrate on orbit performance within 5 to 7 years.	The goal of this area is to produce space qualified clocks that have very stable output with characteristics superior to current individual clocks in both accuracy any long term performance. The objectives would be to demonstrate on orbit performance within 5 to 7 years.	The goal of this area is to develop and produce space qualified atomic clocks based on laser cold atoms and develop necessary commercial sources. The objectives would be to demonstrate on orbit performance within 5 to 7 years.
TRL	TRL is between 4 and 5. Requires efforts towards space qualification and testing in relevant environment.	TRL is between 4 and 5. Requires efforts towards space qualification and testing in relevant environment.	TRL ranges from 5 to 8. Additional work required for space qualification and reliability testing in relevant environment and development of reliable commercial sources. But space qualified hardware has already been built for the first cold atom microwave atomic clock demonstration mission that is scheduled to fly on the ISS in late 2013 (ESA ACES mission).
Tipping Point (100 words or less)	Prototypes components and subsystems exist and testing ensembles in relevant environment will bring to flight readiness quickly. Requires focused effort and demonstration to validate concepts.	Ground based and laboratory devices exist operating in controlled environments that could be directed toward flight read units quickly. Requires focused effort and demonstration to validate concepts.	Laboratory devices exist and operate in controlled environments that could be directed toward flight units relatively quickly. Transition to space qualified instruments is primarily detailed engineering, testing and validation. Particularly the validation of suitable semiconductor lasers that are now commercially available but relative to long-term reliability in space.
NASA capabilities (100 words)	No NASA center currently working on this technology. Commercial interests are limited since GPS applications are currently employed for positioning and timekeeping. Defense labs are investigating ground based concepts.	JPL currently working on Hg ion technology for ground based use and as possible long term option for GPS satellites.	There was a previous effort at JPL to develop cold atom atomic clocks for space as part of the old micro-gravity physics program. Other centers such as Goddard and Ames have also expressed interest.
Benefit	More stable and accurate space qualified clocks of benefit to multiple missions and applications in concert with GPS.	More stable and accurate space qualified clocks of benefit to multiple missions and applications in concert with GPS.	Atomic frequency standards (clocks) are a critical component of navigation and communication systems. Advanced atomic frequency standards will enable future enhancements and capabilities for navigation and communications.
NASA needs	More stable and accurate space qualified clocks of benefit to multiple missions and applications in concert with GPS.	More stable and accurate space qualified clocks of benefit to multiple missions and applications in concert with GPS.	More stable and accurate space qualified clocks of benefit to multiple missions and applications in concert with GPS.
Non-NASA but aerospace needs	Other time-keeping customers would include DoD. Remote sensing could also exploit e.g., in SAR or image time-tagging.	Other time-keeping customers would include DoD. Remote sensing could also exploit e.g., in SAR or image time-tagging.	see below, and note that time/frequency and navigation dominated by space-based GPS. Space remains key for future

Table 5a: Next Generation Hard X-ray

Name of Technology (256 char)	Large-Area, finely pixelated,thick CZT Detectors	Low-Noise, Low-power ASICs for Solid State Detectors	Active shield using avalanche photdiode
Brief description of the technology (1024)	A large array (4.5 m^2) of imaging (0.6 mm pixel) CZT detectors are needed to perform the first hard X-ray survey (5-600 keV) with well-localized (<20" at 5-sigma threshold) sources down to 0.06 mcrab (5-150 keV). Thick CZT detectors (0.5 cm) allow broad-band energy coverage for GRBs and black holes, from stellar to supermassive.	Low power ASICs (<20 microW/pixel) are needed to provide accurate time of arrival and energy for each photon but with low aggregate power per square meter.	BGO scintillators read out by two light guides on opposite edges, each coupled to two Avalanche Photo Diodes used as active shields to reduce in flight atmospheric albedo and cosmic-ray induced backgrounds.
Goals and Objectives (1024)	The goal is to achieve CZT detectors with 0.6mm pixels, 4 keV trigger threshold, and 2.4' angular resolution when used as imagng detectors for a 2m focal length coded aperture telescope.	A reduction of power consumption by a factor of ~4 compared to current designs (e.g. NuSTAR) is needed to implement the large detector array with typical solar panels and batteries. A low energy threshold of ~5 keV is needed.	The goal is to minimize cosmic ray induced internal background and to reduce the physical size of the active shielding system.
TRL	TRL is 6. Prototype detectors, with2.5mm pixels and ~15 keV threshold and tiled array packaging, have flown on ProtoEXIST in 2009. Detectors with 0.6mm pixel size and ~6 keV threshold scheduled forballoon flight test in Sept. 2012.	TRL is 5. Portions of the functionality have been demonstrated but a full prototype that meets both the noise and power requirements has not yet been produced.	TRL is 5. BGO shields and APD readouts are well developed, but the compact packaging has not been demonstrated. Prototype designs are planned for flight.
Tipping Point (100 words or less)	Designs have reached TRL 6. Successful balloon flight test with 0.6mm pixel detectors close tiled in a 16cm x 16cm imaging array will increase the TRL to 7-8.	The lower-power ASIC is the key requirement, but a more compact ASIC readout using microvias rather than wirebonds is highly desirable. Successful design and fabrication will allow systems to be tested in relevant environments.	Prototypes to be flown.
NASA capabilities (100 words)	NASA's capabilities support test but pixel arrays are custom procurements under development by University groups with support from NASA and commercial sources.	NASA (or DoE) has not yet developed an ASIC that meets these requirements. The NuSTAR ASIC, designed and developed at Caltech is the prototype but does not meet the power or more compact readout (with microvias) requirements.	NASA has experience with scintillators and test capabilities. Scintillators and avalanche photodiodes can be procured from commercial sources.
Benefit	Thick pixelated CZT detectors will provide good position and energy resolution for an unprecedentedly broad energy range.	The ASIC is the principal limiting factor for the power budget, energy resolution, time resolution. ASIC performance directly translates into mission performance improvements.	Compact active shielding is important for NASA astrophysics missions and can produce reductions in mass and volume.
NASA needs	Pixelated CZT detectors of this type can be applied to various missions that need large area wide-field imaging and spectroscopy with broad energy coverage.	Low power, low-noise ASICs coupled with pixelated CZT detectors of this type can be applied to various missions that need large area wide-field imaging, and spectroscopy.Microvia readout is particularly important for compact packaging.	Compact active shielding is important for NASA astrophysics missions and can produce reductions in mass and volume
Non-NASA but aerospace needs	Space-based monitoring programs in other agencies	Space-based monitoring programs in other agencies	
Non aerospace needs	Nuclear medicine and ground-based nuclear materials detection applications	Nuclear medicine and ground-based nuclear materials detection applications	
Technical Risk	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Technical risk is moderate given access to (rare) analog ASIC design expertise. The history of analogous flight projects shows this task must not be underestimated.The main challenge is to get low power with low noise.	Technical risk is low.
Sequencing/Timing	CZT detectors with the required pixel size are currently being adapted from those flown on ProtoEXIST1. ProtoEXIST2 will incorporate 0.6mm pixels over tiled detector for balloon flight test in 2012.	ASICS based upon the NuStar ASIC are currently being adapted. Reduced power will be easier to achieve than microvia readout.	This concept will be tested in ProtoEXIST 2-3 and compared with existing active shielding concepts.
Time and Effort to achieve goal	3 year collaboration between University, industry and NASA	3 year collaboration betweenUniversity, industry and NASA	3 year collaboration between University, industry and NASA

Table 5b: High-Resolution Imaging Hard X-ray Observatory

Name of Technology (256 char)	High resolution hard X-ray technology	Depth graded multilayer coatings	Very-finely-pixelated CZT detectors with associated custom-built direct-readout electronics.
Brief description of the technology (1024)	Hard X-ray grazing incidence optics with multilayer coatings with at least 5" angular resolution	Depth graded multilayer coatings for hard X-ray optics, to increase the maximum graze angle using Bragg reflection, allowing a larger field of view and / or extended energy range.	Finely pixelated detectors are needed that match the angular resolution of the optics, up to an order of magnitude finer spatial resolution than current NuSTAR detectors, with single-photon-counting and spectral resolution.
Goals and Objectives (1024)	Goals & Objectives: Achieve a HPD of 5 arc sec using, tightly nested full shell or segmented optics. Methods such as improved replication techniques or post-fabrication figure correction techniques will be used to achieve the required angular resolution.	Enlarge field of view and energy range with good throughput for high resolution hard x-ray imaging telescopes	The spatial resolution of these detectors will need to oversample the point spread function of the optics to preserve optic angular resolution. Pixel size is a function both of angular resolution and focal length. Single photon-counting capability is required with spectral resolution < 1 keV.
TRL	3-4 overall. Replication techniques more advanced than post-fabrication correction techniques.	4 to 5	2 to 4
Tipping Point (100 words or less)	Tipping Point: Mounting of multiple light-weight, high resolution optics yet to be demonstrated. Post fabrication figure correction on full optics not yet demonstrated.	good throughput at energies above 80 keV yet to be demonstrated	Challenge is mainly in the custom readout: accommodating whole electronic channels within tiny areas while preserving noise and threshold capabilities. May also be challenges with bump bonding crystal to readout.
NASA capabilities (100 words)	Facilities for replicated and full-shell optics exist at NASA facilities (Goddard, MSFC). Techniques for post-fabrication figure correction exist, such as differential deposition at MSFC and active optics control at SAO.	NASA funded capabilities at SAO and GSFC	NASA-funded capabilities exist at Caltech, for example.
Benefit	High-angular- resolution hard X-ray imaging will make possible detailed mapping of supernova remnants, black hole jets, etc. at >10 keV extending the work of Chandra to higher energies	Enlarging the usable field of view for high resolution hard X-ray telescopes improves science for extended sources and allows for serendipitous science. Also extends energy range for broader coverage.	Appropriate detectors and ASICs are crucial to the success of a future high resolution hard X-ray imaging mission
NASA needs	required to advance hard X-ray science to allow detailed spectroscopic imaging	Needed to support hard-x-ray high-angular resolution observatory.	Required to support hard-x-ray, high-angular- resolution observatory.
Non-NASA but aerospace needs			
Non aerospace needs	medical imaging ?		homeland security, medical imaging
Technical Risk	Moderate - significant improvements to NuSTAR-like mirrors and focal plane detectors are needed to achieve the required angular resolution	Low	moderate - significant increase in number of pixels over current hard x-ray detectors
Sequencing/Timing	as early as possible - "heart" of a telescope	Development of techniques would need to be in parallel with optics development.	Detector and readout electronics development must proceed in parallel with optics development. The pixel size must be appropriately matched to the optics.
Time and Effort to achieve goal	5 year collaboration between NASA and industry	5 year collaboration between NASA and industry	5 year collaboration between NASA and industry

Table 6: Next Generation EUV/Soft-X-ray Mission

Name of Technology (256 char)	Extended Duration Rockets	EUV or Soft X-ray detector systems	Gratings
Brief description of the technology (1024)	Modest launch vehicles capable of putting a few hundred kg in orbit for a few weeks, but also supportive of the objective of converting existing sounding rocket payloads into short-life satellites.	Existing EUV detectors suffer from low quantum efficiency which must be compensated by long observing time. Improved photocathodes and electronics improvements can be multipliers for system performance numbers	High-resolution blazed gratings for high power, replicated by emerging nanolayer technologies. This capability delivers high spectral resolution to analyze source spectral lines and separate them from spectral features of the interstellar medium.
Goals and Objectives (1024)	The goal is to reach flight readiness around 2015	The goal is to reach TRL 6 by 2015	The goal is to reach TRL 6 by 2015
TRL	Suitable vehicles have been tested a few times, hence have TRL 9. Satellite systems to match have not been developed	4 TRL is between 4 and 5. Requires efforts towards space qualification and testing in relevant environment.	TRL is 2 for new designs. Prototyping for new concepts has only begun
Tipping Point (100 words or less)	A single demonstration flight, such as was done for the SPARTAN concept in the 1980s would bring the concept to maturity	Pixel designs require custom ASIC development to meet targets for power combined with noise level.	Prototypes exist involving nano-fabrication using high-Z materials to deliver performance at higher energies.
NASA capabilities (100 words)	NASA's capabilities at WFF are central to this concept. There is no realistic alternative but DoD may be able to contribute constructively.	NASA's does not have an engineering group producing detectors of this kind but suitable commercial sources exist	NASA has no appropriate facilities but they also exist in other government departments and in industry.
Benefit	The benefit of a short orbital mission over a sounding rocket flight is roughly the ratio of the durations, i.e., $10^{6.5}$ s / $10^{2.5}$ s, or 10^{4}.	The detector unit is crucial for envisioned next-generation systems	Gratings and multilayer coatings are essential for normal incidence spectrometers. Fabrication technologies for both are applicable at X-ray and UV wavelengths.
NASA needs	Mission capability intermediate between sounding rockets and explorers enables a strategy for maintaining the astrophysics community and training students in a time of lean budgets	The detectors that support EUV can with modifications be used on optical/NUV missions planned for later years	Gratings remain the preferred way to reach high spectral resolution at these energies
Non-NASA but aerospace needs	There is synergy with DoD use of similar LV and satellite systems, creating potential for partnershiops	potential remote sensing applications	potential remote sensing applications
Non aerospace needs	Not applicable, by definition	Can be used in synchrotron and laser plasma research	Can be used in synchrotron and laser plasma research
Technical Risk	Technical risk is low; development paths are straightforward	Technical risk is low but there is some risk of backsliding in the industrial capabilities.	Technical risk is moderate for completely new approach.
Sequencing/Timing	Needed immediately to establish programmatic viability	Should come as early as possible. Development of other system components depends on it.	Essential to development of explorer class mission
Time and Effort to achieve goal	Moderate effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA

Table 7: Next Generation X-ray Timing

Name of Technology (256 char)	Pixelated Large-Area Solid State X-ray Detectors	Low-Noise, Low-power ASICs for Solid State Detectors	Thin, Lighweight X-ray Collimators	Thin, lightweight X-ray concentrators	Point source optimized concentrators .	Lobster eye X-ray optics for All-sky Monitors
Brief description of the technology (1024)	X-ray timing science objectives call for achieving several square meters of X-ray sensitive collection, over range 2-30 keV, obtaining time of arrival and energy for each photon. Silicon pixel arrays, silicon drift detectors, pixel arrays of high-Z materials, or hybrids are possible choices but all need development.	Low power ASICs are needed to provide accurate time of arrival and energy for each photon but with low aggregate power per square meter.	Requirements of new X-ray timing instruments built around solid state elements require re-thinking design of the collimator unit that provides source isolation. In order to not dominate the mission mass and volume budgets, the collimator must be much thinner and lighter than previous honeycomb colllimator designs.	Lightweight concentrators can focus X-ray beams onto small detectors; Concentration allows sensitivity gains of >1000 over pure collimation.	Concentrators optimized to provide large collecting area for much lower mass than typically seen in X-ray optics.	The Lobster optic gives wide-field focusing in the X-ray band for use in transient and GRB monitors. The focusing gives sensitivities that are factors of 30-100 higher than non-focusing scamers and CCD imagers.
Goals and Objectives (1024)	The goal is to achieve large area detectors that are thick enough to have significant stopping power above 30 keV. The technology should reach TRL 6 in by 2014, to meet opportunities for near-term explorers.	The ASIC must achieve noise performance good enough to allow a low energy threshold of <= 2 keV and and energy resolution <= 600 eV with a total power budget less than 100 W/m^2. The ASIC must reach TRL 6 by 2014 to meet opportunities for near-term Explorers.	The goal is to produce collimators with FWHM <= 1 deg that are <1 cm thick, and have stopping power sufficient to effectively collimate X-rays at 50 keV.	Goal is to provide several square meters of effective area concentrated on to a beam a few arc-min HPD, over energy ranges from 0.3 to 30 keV	provide an order of magnitude improvement in effective area/mass ratio for 1 arcminute class optics to provide a large collecting area for future X-ray timing missions. Reduce cost compared to normal arcminute class optics by more than 50%.	Develop a full-scale Lobster module with optic ad CCD detector. The detector-optic separation should be 50 cm. The field of view should be 1.0 sr. The spectral resolution should be <200 eV FWHM at 1 keV. The angular resolution should be 5 arcsec FWHM.
TRL	TRL is between 4 and 5. Requires efforts towards space qualification and testing in relevant environment.	TRL is 3. Portions of the functionality have been demonstrated but a full prototype that meets both the noise and power requirements has not yet been produced.	TRL is 3 for new designs. Prototyping for new concepts has only begun	TRL for micro-channel plate optics/concentrators with area ~100 cm^2 and ~5arcmin beam is 6 to 7; TRL for 1 m^2 with ~arcmin beam is ~4	TRL5	The technology is currently available for small modules with 30 detector-optic separation and 0.1sr field of view, suitable for Explorer versions The advance need for a future strategic mission is for longer focal length and wider field-of-vew (larger area optics). The TRL for this advance configuration is TRL = 5.
Tipping Point (100 words or less)	Designs have reached TRL 4. A focused effort could increase this to TRL 6. A few cycles of fabrication and test are realistically necessary, but must be coordinated with ASIC development.	The ASIC is the key ingredient in achieving a system that meets the performance requirements. One successful design and fabrication will allow systems to be tested in relevant environments. An ASIC within power requirements needs to be demonstrated, mated to a detector.	Prototypes exist involving nano-fabrication using high-Z materials to deliver performance at higher energies.	Small prototypes exist, but mass production and quality control need to be expanded. quality control includes large scale figure and surface roughness.	Achieving > 200 cm^2/kg (effective area @ 1 keV/mirror mass)	Fabrication of a laboratory test unit with large-area Lobster optic and test-grade CCDs.
NASA capabilities (100 words)	NASA's capabilities support test but pixel arrays are custom procurements from commercial sources.	NASA's does not have an engineering group producing custom ASICs of this kind but suitable groups exist in DoE or at commercial sources.	NASA has nano-fabrication facilities but they also exist in other government departments and in industry.	None.	GSFC has produced light weight X-ray optics in the arcminute class delivering ~ 20 cm^2/kg @ 1 keV. MSFC has produced heavier mirrors which have superior imaging capability.	Small pieces of Lobster optic that have been tested in the X-ray beam at GSFC. A laboratory CCD was used at the focus. The tests were successful and produced nice images.
Benefit	The transition of X-ray missions from gas proportional counters to solid state designs will allow a 5-10x increase in effective area and a quantum leap in detector reliability.	The ASIC is the principal limiting factor for the power budget, energy resolution, time resolution. ASIC performance directly translates into mission performance improvements.	Older collimator designs are needlessly high in areal density (gm/cm^2) and have vertical thickness that is disadvantageous if detector units are stacked for launch and then deployed. Older collimator designs can needlessly dominate the mass budget for explorer-class missions.	Current concentrators have masses that are typically a significant fraction of the payload. lightwieght systems may reduce the mass by 10x	Would support mutiple missions (gneral X-ray timing science, millisecond pulsar timing array for gravitational radiation detection, cheap light buckets for high speed arcminute class spectroscopy missions, planetary XRF)	Enable a new generation of wide-field, sensitive X-ray telescope.
NASA needs	Pixelated silicon detectors of this type can be applied to various missions that need large area X-ray timing, wide-field imaging, and spectroscopy.	Low power, low-noise ASICs coupled with pixelated silicon detectors of this type can be applied to various missions that need large area X-ray timing, wide-field imaging, and spectroscopy.	Thin, light collimators with good stopping power can be used in a variety of NASA and laboratory settings.	Lightweight concentrators can be used in a variety of NASA missions using X-ray sensors	X-ray communication (XCOM) receivers optics	Future gamma-ray bursts and X-ray sky monitor missions.
Non-NASA but aerospace needs	Such devices might be used in certain envisioned applications such as X-ray navigation of satellites.	Such devices might be used in certain envisioned applications such as X-ray navigation of satellites.	Collimators might function in flight X-ray systems for applied uses.	Possible use in nagivation systems using X-ray pulsar timing.	intelligence community	Applicable in aerospace for materials studies and medical imaging.
Non aerospace needs	Non space-qualified systems exist to meet non-space needs such as inspections.	Similar ASICS have commercial applications, but any connection is really via maintaining development teams that can support space and non-space needs.	Such collimators could be used for X-ray detector systems on the ground where collimation was a requirement	Concentrators at energies >10keV have medical applications.		This technology has wide application for materials studies and medical imaging.
Technical Risk	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Technical risk is moderate given access to (rare) analog ASIC design expertise. The history of analogous flight projects shows this task must not be underestimated.The main challenge is to get low power with low noise.	Technical risk is moderate for completely new approaches. Lacking such investment there would be fallback to older designs mis-matched to requirements, resulting in sub-optimized mission performance.	Low	Low	Low
Sequencing/Timing	Should come as early as possible. Development of other system components depends on detector unit parameters. Some ongoing development under NASA APRA.	Should come as early as possible. Development of other system components depends on ASIC power performance. No active US program. Europeans modifying particle physics detectors.	Should come fairly early in mission development because it drives overall system characteristics.	Should come fairly early in mission development.	Should come fairly early in mission development.	Should come fairly early in mission development.
Time and Effort to achieve goal	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA

Table 8: Next Generation Gamma-Ray - Compton

Name of Technology (256 char)	Solid State Detector Arrays	Advanced Scintillators and Readouts	ASICS	Active Cooling
Brief description of the technology (1024)	High spectral resolution is needed to obtain nucleosynthesis signatures and spatial resolution is needed to isolate sources and maximize signal to noise. This leads to Compton telescope designs with solid state detector arrays. Si, CZT, and CdTe do not need cooling. Ge delivers better resolution.	Modern scintillator materials (e.g., LaBr3, SrI2, Cs2LiYCl6:Ce (CLYC)) possess improved efficiency, light output, and time response. This permits greatly improved Compton telescope response and background rejection at reasonable cost, building directly off the experience of COMPTEL. New readout devices, such as Silicon Photo-Multipliers or Plasma Panel Sensors, reduce mass, volume, and fragility compared to PMTs. PPS offer potential for large areas at very low cost.	Low power ASICs are needed to provide accurate energy for each photon but with low aggregate power per square meter. ASICs for PMT/SiPM must accept higher input charge than for semiconductor detectors due to much higher gain. Development of ASICs couples directly to detector and readout technologies.	Germanium arrays need active cooling below 100K. Si and CZT also benefit from active cooling to reduce noise performance to desired levels. Small-scale applications are likely in reach while larger missions pose a greater challenge.
Goals and Objectives (1024)	The goal is to reach TRL 6 in 2015, to meet opportunities for near-term explorers	The goal is to reach TRL 6 in 2015, to meet opportunities for near-term explorers	The goal is to reach TRL 6 by 2015	The goal is to reach TRL 6 by 2015
TRL	TRL is between 4 and 5 depending on whether it is Si, CZT, CdTe or Ge. TRL for Ge may be higher for smaller-scale missions. Requires efforts toward space qualification and testing in relevant environment.	TRL is 5 for "traditional crystal" (LaBr3,SrI2,Cs2LiYCl6:Ce (CLYC))/PMT combination. TRL is 3 for alternate (cheaper) material growth (e.g., polycrystalline). TRL for SiPM readouts currently at 4. Requires efforts towards space qualification and testing in relevant environment. TRL for PPS for scintillator readout currently only at 2.	TRL is essentially undefined until the detector is specified. The ASIC is specific and integral to the detector and developed in co-evolution with it.	TRL is between 4 and 5. Primary effort is achieving large scale in heat removal per unit time and depends on scale of mission. Effort required towards space qualification and testing in relevant environment.
Tipping Point (100 words or less)	Designs have reached TRL 4. A focused effort could increase this to TRL 6. A few cycles of fabrication and testing are realistically necessary, but must be coordinated with ASIC development.	Designs have reached TRL 4. A focused effort could increase this to TRL 6. A few cycles of fabrication and test are realistically necessary, including balloon test flights.	Pixel and strip designs require custom ASIC development to meet targets for power combined with noise level.	Breakthroughs in refrigeration would make larger Ge arrays feasible, but also can enhance performance of room temperature semiconductors. This becomes increasingly important for larger missions.
NASA capabilities (100 words)	NASA's capabilities support test but solid state detectors are custom procurements from commercial sources.	NASA's capabilities support test but scintillators are custom procurements from commercial sources. SiPMs are COTS.	NASA has engineering groups producing custom ASICs at GSFC but suitable groups also exist in DoE or at commercial sources.	Refrigeration development capabilities exist in NASA and in industry.
Benefit	The detector array is the primary factor determining system performance, setting the size scale, sensitivity and other factors, enabling the entire mission concept, hence the science.	The detector array is the primary factor determining system performance, setting the size scale, sensitivity and other factors, enabling the entire mission concept, hence the science.	. Detector capability alone without an ASIC suitably matched to it could lead to prohibitive system power and make the concept unworkable. Multiple turns of development are likely needed.	. Solving refrigeration for for these applications could be enabling for other missions.
NASA needs	NASA needs medium-energy gamma-ray instruments to advance understanding of nuclear astrophysics and particle acceleration sources, including the Sun. Lunar prospecting is another application. Technical investment in this energy range applies to concepts that scale from near-term explorer to next generation missions.	NASA needs medium-energy gamma-ray instruments to advance understanding of nuclear astrophysics and particle acceleration sources, including the Sun. Lunar prospecting is another application. Technical investment in this energy range applies to concepts that scale from near-term explorer to next generation missions.	Specifically co-developed ASICs are required for the application of detector technologies. If the material is Ge, the ASIC is probably external to the refrigeration, but still needs to be low power.	Refrigeration is a general need for Ge detectors in space use and also improves performance of other detectors, e.g. limiting heating from electronics.
Non-NASA but aerospace needs	Such devices might have applied uses, including charged particle and other environmental monitoring done from space platforms including space weather	Such devices might have applied uses, including charged particle and other environmental monitoring done from space platforms	ASICs are an integral part of the system hence contribute similarly to detectors for non-NASA needs.	
Non aerospace needs	Detector systems have use in sea-level environmental monitoring e.g., for nuclear materials as well as nuclear medicine.	Detector systems have use in sea-level environmental monitoring e.g., for nuclear materials as well as nuclear medicine (e.g., SiPMs are being heavily investigated for PET systems),etc.	ASICs are an integral part of the system hence contribute similarly to detectors for non-aerospace needs;	
Technical Risk	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units. Cost risk may drive material preferences.	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units. Cost risk may drive material preferences.	Technical risk is low to moderate given access to (rare) analog ASIC design expertise. The history of analogous flight projects shows this task must not be underestimated.The main challenge is to get low power with low noise.	
Sequencing/Timing	Should come as early as possible. Development of other system components depends on detector unit parameters. Only modest programs in Ge and CZT are ongoing.	Should come as early as possible. Development of other system components depends on detector unit parameters. Only modest programs in LaBr3, advanced organics, and SiPMs are ongoing.	ASIC design must be matched to design of the detector element and cannot precede it, but should be roughly simultaneous.	Refrigeration system needs to be designed as part of mission system engineering.
Time and Effort to achieve goal	Minimal effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA	to iii. Minimal to moderate effort depending on scale of mission. 3 year collaboration between industry and NASA.

Table 9: 21 cm Cosmology Array

Name of Technology (256 char)	Low-frequency, wide-bandwidth, low-mass science antennas	Ultra-low power, temperature resistant, radiation tolerant analog electronics	Ultra-low power, temperature resistant, radiation tolerant digital electronics	Autonomous low-power generation and storage	Low-mass high capability rovers	High-data rate lunar surface transport mechanism
	been tested in field, but not relevant environment. Requires efforts to test in relevant environment, and potentially space qualification, depending upon antenna type		feature size, supply voltage, and demonstrate in relevant environment.	operating temperature environment, and technology development, depending upon selection.	payload/rover mass ratio and increase traverse speed.	possible space qualification. Depending upon technology, requires mass reduction and increase in data rate transmission.
Tipping Point (100 words or less)	Antennas have been deployed in the field, but not in a relevant environment. A focused effort could increase this technology to TRL 6 in a fairly short time			Renewed production of Pu for radioisotope thermal generators and related technologies		
NASA capabilities (100 words)	NASA, in collaboration with JPL and NRL, has been a leader in developing and testing one of the leading technologies for future lunar antennas.			NASA has produced multiple generations of radioisotope thermal generators.	NASA has produced several generations of rovers for planetary science missions	NASA has partnered with other groups to demonstrate high data rate transfer in some of the relevant technologies.
Benefit						
NASA needs	LRA, potential Heliophysics and Planetary Science missions	All NASA missions could benefit from lower power analog components, particularly for digitization.	All NASA missions could benefit from lower power digital components.	LRA, outer solar system Planetary Science missions	LRA, missions both scientific and exploration to other solar system bodies	LRA, other lunar surface missions
Non-NASA but aerospace needs	None	Likely commercial and DoD benefits to lower power analog components	Likely commercial and DoD benefits to lower power digital components	None	Autonomous rovers also useful for DoD needs	Potential DoD needs for high data rate transfers
Non aerospace needs					Commercial operations in harsh environments	
Technical Risk	Technical risk limited to obtaining electromagnetic performance at minimal mass. Materials for space-based antennas are well developed.		Technical risk is low. Low-power digital electronics have been demonstrated in space, and a technology roadmap exists for future development.		Technical risk is low. Rovers are a mature technology, but further work is needed on autonomous navigation and reducing the mass of rovers.	
Sequencing/Timing	Continuous development, but potentially parallel with electronic and rover developments.	Continuous development, but potentially linked to antenna developments.	Continuous development, but potentially linked to antenna developments.	Continuous development.	Continuous development, but potentially linked to antenna and data transport developments.	Continuous development, but potentially linked to electronics and rover developments.
Time and Effort to achieve goal	7 year collaboration between NASA, academia, and industry	7 year collaboration between NASA, academia, and industry	7 year collaboration between NASA, DoD, academia, and industry	5–7 year collaboration between NASA, academia, and industry	7–10 year collaboration between NASA, DoD, academia, and industry	7 year collaboration between NASA, DoD, academia, and industry

Table 9: 21 cm Cosmology Array

H I 21 cm Cosmology and PCOS

After the formation of the cosmic microwave background (CMB, z ~ 1100), the dominant baryonic component of the intergalactic medium (IGM) was neutral hydrogen, which produces a well-known hyperfine transition at a rest wavelength of 21 cm (frequency of 1420 MHz). The 21 cm brightness temperature of an IGM gas parcel at a redshift z, relative to the CMB, is (Madau et al. 1997; Furlanetto et al. 2006)

$\delta T_b \approx 25$ mK X_{HI} $(1 + \delta)$ $[(1 + z)/10]1/2$ $[1 - TCMB(z)/TS]$ $[H(z)/(1 + z)/dv_{||} /dr_{||}]$

where XHI is the neutral fraction, δ is the fractional IGM overdensity in units of the mean, TCMB is the CMB temperature, TS is the spin (or excitation) temperature of this transition, H(z) is the Hubble constant, and $dv_{||} /dr_{||}$ is the line-of-sight velocity gradient.

All four of these factors contain unique cosmological or astrophysical information. From the PCOS perspective, the two most interesting are H(z) and the "redshift-space distortions" $dv_{||} /dr_{||}$ encapsulated in the line-of-sight velocity gradient. The other factors are of more relevance to the Cosmic Origins (COS) these, as the dependence on δ traces the development of the cosmic web and the other two factors depend on the ambient radiation fields in the Universe.

During the **Dark Ages** (30 < z < 100), before the first stars, X_{HI} ~ 1, and the H I gas was influenced only by gas collisions and absorption of CMB photons. The gas cooled rapidly as the Universe expanded, and the resulting cold temperatures caused the 21 cm signal to appear in absorption, relative to the CMB.

1. Because the H I 21 cm transition is a *spectral line*, the evolution of the signal can be tracked with redshift. This capability is in marked contrast to CMB measurements, which can be performed at only a single redshift. As a result, H I 21 cm measurements have the potential to probe a much larger volume of the Universe, obtaining a much larger number of modes with which to constrain cosmological parameters.
2. The evolution of the H I 21 cm signal in this epoch should depend only upon cosmological parameters (Ω_m, Ω_Λ, H_0, …). Any deviations would represent evidence of additional energy injection into the IGM, such as by dark matter decay.

The H I 21 cm signal is expected to disappear at z ~ 30 as the continuing expansion of the Universe decreased the gas density, thereby reducing the collision rate. Absorption of CMB photons then drove the spin temperature into equilibrium with the CMB. (The signal should reappear at lower redshifts, but these redshifts are more relevant to the COS theme.)

Table 10: Beyond LISA

Emerging technologies that have the potential for radical improvement in a measurement capability over the next 30 years:

A) High stability optical platforms:
Includes optical benches, telescopes, etc., requiring passive thermal insulation for temperature stability. Hydroxide or silicate bonding for precision alignment capability and dimensional stability. Precision materials such as Silicon Carbide and single crystal silicon.

B) Precision interferometry:
Requires CW single-frequency and frequency-stabilized lasers for space (GSFC applications so far are pulsed). Digital techniques including coded modulation for time-of-flight resolvable interference, and flexible in-flight changes. Time-Domain Interferometry (LISA's equal-path-length synthesis techniques).

C) Frequency combs:
Could be used for LIDAR/remote sensing applications to distinguish types of vegetation and resolve shrubs vs. trees on a slope. Requires frequency stabilization, pulsed lasers, and good detectors.

D) Single-mode fiber optic technology for space (now using multimode, mostly):
Now developed for wavelengths not usually used in space: 1550 nm
Fiber Bragg Gratings for frequency stability, references, and filters.
Modulators, isolators, and circulators. No alignment required and lightweight.
Changing traditional wavelengths to take advantage of telecom technology where possible.

E) Scattered light suppression:
Includes masks and apodization, black coatings, and cleaning/particulate/contamination techniques.

F) Optical communications:
Phase-array capabilities would obsolete DSN or single-pointing-capable telescopes. Orbiting TDRS-style relay network could obsolete DSN, form basis of a high reliability space-borne NETWORK for long-duration space flights/bases but also comm-constrained missions such as to the outer planets.

Technologies that cut across many different potential applications:

High Stability and/or fiber optics: atom interferometry, LISA, Grace, Exoplanets
Frequency combs: LIDAR/Remote sensing, atom interferometry
Scattered light suppression: atom interferometry, LISA, Grace, Exoplanets
Precision interferometry: optical communications, LISA, Grace

<u>Measurement techniques</u> that could enable new NASA missions not currently thought about in present agency strategic planning:

Precision interferometry and phase-sensitive optical detection (good for optical comm)
Frequency combs (sort of part of precision interferometry)
Time-Domain Interferometer.

Table 11: Gen-X-like Ultra-Light X-ray Telescope

Name of Technology (256 char)	**Thermally formed (slumped) glass mirror segments as substrates for Wolter I or Wolter-Schwarzschild adjustable optics**	**Adjustable grazing incidence X-ray optics by deposition of piezoelectric thin fim actuator layer on mirror back surface.**	**Mounting and alignment of adjustable optic mirror segments using thin film.**	**Figure correction control using thi film piezo adjusters for adjustable grazing incidence optics.**
Brief description of the technology (1024)	**Thermally form, to precision mandrels, thin glass sheets into Wolter I mirror substrates for adjustable optics. Includes cutting mirrors to appropriate size, and coating with X-ray reflective material. IXO-like technology as starting point.**	**Deposit full surface thin layer of low voltage piezoelectric material on back surface of conical mirror segment. Deposit pattern of electrodes (piezo cells) and printed leads with taps on mirror side edge for power connection.**	**Thousands of mirror segments need to be aligned to one another, made confocal, and mounted in a flight housing. Mounting must not distort the mirror figure.**	**Need the ability to connect ~ 400 separate power signals to the actuators on a single mirror, presumeably using semiconductor-like technology. Develop software for figure correction using calibrated adjuster impulse functions, either on the ground with direct optical feedback, or on-orbit using X-ray point source imaging.**
Goals and Objectives (1024)	Require ~ 5 arc sec HPD performance from perfectly aligned primary-secondary mirror pair before figure correction and piezo deposition. Figure error and rouhgness requirements different from IXO-like; greater requirement on roughness and mid frequency errors which cannot be corrected by adjusters. TRL 6 by 2014 to be consistent with adjustable mirror sub-orbital flight in 2016.	Require > 1 um thick piezoelectric layer with |piezo coefficient| > ~ 5 Coulombs/sq m, leakage current < ~ 10 micro-A/sq cm. Piezo cell size ~ 1 sq cm - 2 sq cm (~ 200 to 400 per mirror segment). TRL 6 by 2018 with sub-orbital flight in 2016-2017. Piezo voltages < 50 V with minimal power consumption (i.e., micro-amp leakage current). Optimization of influence function shape by shape of piezo cell and size/shape of cell electrode and electrode pattern. This isnecessary to improve correction bandwidth and minimize introduction of pattern errors.	Require < 0.25 arc sec HPD alignment, including confocality. Mounting distortion of mirrorfigure < 2-3 arc sec HPD. TRL 6 by 2015, with several aligned mounted mirror pairs on sub-orbital demonstration flight in 2016-2017.	Piezoelectric adjuster power connections should not distort the mirrors. Control algorithms should converge reasonably rapidly. On-orbit approaches, if feasible, need to be completed in reasonable time period of five year mission (i.e., figure correction on time scale of 1 week to 1 month, max).
TRL	TRL 3: need to modify slumping process to change glass type and mandrel release layer for smoother roughness and mid frequency errors.	TRL 2: Have demnstrated deposition of piezoelectric layer on glass of sufficient thickness and high enough piezo coefficient, and have demonstrated ability to energize piezo cell and locally deform mirror in rough agreement with model predictions. Perating voltages < 20V and leakage currents of 10s of microamps.	TRL 2 - 3: Modification of IXO-like mission mirror mounting and alignment. Need to align better than IXO-like requirements, but distortion from mirror mounting is less critical (can be fixed during figure correction).	TRL 3: Semiconductor industry already bonds to hundreds of contact points at low voltage. Optimization algorithms exist. Need to demonstrate with actual computer programming. Need to demonstrate on-orbit adjustment is feasible within allotted time.
Tipping Point (100 words or less)	Demonstration of smooth mid frequency figure and roughness through use of sputtered release layer, along with sucessful slumping of high temperature glass. These will demonstrate feasibility of ultimate goals.	Repeatable high yield deposition of piezo material (with patterned electrodes) without minimal (a few microns) deposition distortions. Also, demonstration of significant lifetime when energized. Successful sounding rocket flight in 2016-2017..	Demonstration of alignment of mirror pairs from multiple shells to < 0.25 arc sec, including focus. Successful sounding rocket flight in 2016-2017.	Demonstration of correctability via software simulation.
NASA capabilities (100 words)	NASA GSFC leads in development of thermal forming and is fully equipped to continue experimentation.	NASA does not have the capability to develop this technology, but NASA funded investigators are developing the technology (SAO+PSU+MSFC)	NASA GSFC and SAO have developed alignment mounting techniques. Alternatives or similar approaches could be developed in optics industry.	NASA and many organizations have the capability to do software development. Software under development for adjustable X-ray optics at SAO.
Benefit	Thin mirror segments enable collecting area to exceed 1 sq m with existing launch vehicles. > 10x area of Chandra.	Adjustable thin grazing incidence optics enable Chandra-like imaging or better with > 10x collecting area. Will revolutionize study of the early Universe.	Adjustable thin grazing incidence optics enable Chandra-like imaging or better with > 10x collecting area. Will revolutionize study of the early Universe.	
NASA needs	Required for moderate to large collecting area X-ray telescopes. Required for adjustable optics X-ray telescopes with sub-arc second imaging.	Required for adjustable optics X-ray telescopes with sub-arc second imaging.	Required for moderate to large collecting area X-ray telescopes. Required for adjustable optics X-ray telescopes with sub-arc second imaging.	Required for adjustable optics X-ray telescopes with sub-arc second imaging.
Non-NASA but aerospace needs				
Non aerospace needs	Potential for synchrotron optics and X-ray lithography. Also plasma diagnostics.	Potential for synchrotron optics and X-ray lithography. Also plasma diagnostics.	Potential for synchrotron optics and X-ray lithography. Also plasma diagnostics.	Potential for synchrotron optics and X-ray lithography. Also plasma diagnostics.
Technical Risk	Moderate - significant changes between Gen-X-like requirements and IXO-like requirements, although overall performance levels are similar.	High: Current TRL is low and significant technical development necessary to achieve TRL 6 including; elimination of deposition deformations, increased deposition yield, optimization of influence function shape, demonstration of lifetime in space environment, deposition on curved mirrors.	Moderate: requires several factors improvement over currently achieved alignment levels for segmented mirrors, but difficulty is mitigated by reduced sensitivity to mirror segment deformation due to mounting by virtue of being able to correct mounting deformations during figure correction.	Low to Moderate:
Sequencing/Timing	As early as possible - "heart" of a telescope	As early as possible - the critical technology for an adjustable optic telescope, which is the critical technology for a large area sub-arc second broad band X-ray telescope.	As early as possible - "heart" of a telescope	Not critical for early demonstration, but should be resolved by 2015 for sub-orbital flight demonstration.
Time and Effort to achieve goal	3 year collaboration between NASA and industry	5 year collaboration between NASA and industry	5 year collaboration between NASA and industry	3 year collaboration between NASA and industry

Table 12: Next Generation Gamma-Ray - Laue

Name of Technology (256 char)	pixelated Ge or CZT detectors	ASICS	focusing optics
Brief description of the technology (1024)	High spectral resolution is needed to obtain nucleosynthesis signatures and spatial resolution is needed to isolate sources and maximize signal to noise. In this approach signal to noise is optimized using a focusing optical element in front of the detector array, thereby reducing the total number of detectors but requiring operation at higher count rates. Germanium and CZT have been considered as materials.	Low power ASICs are needed to provide accurate time of arrival and energy for each photon but withability to handle higher counting rates produced by focusing	Science objective is achieved in a set of narrow energy bands but with high signal to noise in those bands achieved using focusing optics
Goals and Objectives (1024)	The goal is to reach TRL 6 in 2015, to meet opportunities for near-term explorers	The goal is to reach TRL 6 by 2015	The goal is to reach TRL 6 by 2015
TRL	TRL is 4 for CZT or Ge. Requires efforts towards space qualification and testing in relevant environment.	TRL is essentially undefined until the detector is specified. The ASIC is specific to the detector and developed in co-evolution with it.	TRL is 4.
Tipping Point (100 words or less)	Designs have reached TRL 4. A focused effort could increase this to TRL 6. A few cycles of fabrication and test are realistically necessary, but must be coordinated with ASIC development.	Pixel designs require custom ASIC development to meet targets for power combined with noise level.	If a breakthrough in optics is not achieved, the preferred option will be Compton telescopes meaning larger array dimensions but without optics
NASA capabilities (100 words)	NASA's capabilities support test but strip arrays are custom procurements from commercial sources.	NASA has engineering groups producing custom ASICs at GSFC but suitable groups also exist in DoE or at commercial sources.	N ASA has no special facilities but they exist in other government departments, industry, and elsewhere, with choice of source depending on requirements and approach
Benefit	The detector array is the primary factor determining system performance, setting the size scale, sensitivity and other factors, enabling the entire mission concept, hence the science.	Detector capability alone without an ASIC suitably matched to it could lead to prohibitive system power and make the concept unworkable. Multiple turns of development are likely needed.	Producing optics for this application would be largely mission specific and not transferable to other uses, but the optical solution is enabling for this approach to a medium gamma-ray mission.
NASA needs	NASA needs a next generation medium-energy gamma-ray mission to advance understanding of nuclear astrophysics and black hole sources.	The detector alone is not sufficient and requires the ASIC. If the material is Ge, the ASIC is probably external to the refrigeration, but still needs to be low power.	Without optical system the NASA needs for a medium-energy gamma-ray mission are most likely to be achieved using Compton telescope designs.
Non-NASA but aerospace needs	none	none	none
Non aerospace needs	Detector systems mightconceivably find use in sea-level environmental monitoring but would face competition from other approaches.	ASICs are an integral part of the system hence contribute similarly to detectors;	
Technical Risk	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Technical risk is low to moderate given access to (rare) analog ASIC design expertise. The history of analogous flight projects shows this task must not be underestimated.The main challenge is to get low power with low noise.	Technical risk is moderate for completely new approaches.
Sequencing/Timing	Should come as early as possible. Development of other system components depends on detector unit parameters.	Should come as early as possible. Development of other system components depends on ASIC power performance.	Should come first in mission development because it is a prerequisite
Time and Effort to achieve goal	Minimal effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA	Moderate effort, 3 year collaboration between industry and NASA

Table 13. Technology Needs Submitted to PCOS Program Office Via Email

Name of Technology Need	Plastic Lens Coatings	Piezoelectric Adjustable X-ray Optics	Broadband X-ray Polarimeter	Finely pixelated detectors for high angular resolution hard X-ray imaging.	Microvia (TSV) ASIC flip-chip bonding for close-tiled large area imaging detector readout
Brief Description of Technology Need	High-throughput optics with large fields of view, high stability, spectral resolution, and uniformity at many different temperatures as identified in NASA's "Science Instruments, Observatories, and Sensor Systems" Roadmap, November, 2010.	Light-weight grazing incidence optics which can be highly nested, with a figure which can be adjusted via in-plane piezoelectric elements to achieve a telescope with 0.5 arcsecond resolution for 1 keV X-rays.	Non-imaging broadband X-ray polarimeter	Development of room temperature solid state X-ray detectors with 100 micron spatial resolution covering the 1 keV-100 keV energy range. The focal plane instrumentation could use Cadmium Telluride (CdTe), Cadmium Zinc Telluride (CZT), or Si detectors, or a combination of such detectors.	Close-tiled large area arrays of active-pixel imaging detectors require the new technology of through Silicon vias (TSVs) that enables 3D connections of pixel data and control/power lines for each ASIC that is flip-chip bonded to an imaging detector (top) and mother board (below). This enables gap-less tiling of large area imaging detectors for wide-field telescopes with greatly reduced complexity and cost.
Goals and Objectives	The goal is to develop large lightweight Fresnel optics (using polymethyl methacrylate) with high throughput operating in the near UV (330-400 nm). The objectives are to develop manufacturing processes that reduce surface roughness to minimize the total integrated scatter losses and to develop a anti-reflective coating to minimize reflective losses.	Goal is a 3m^2 0.1 to 10 keV X--ray telescope, with 0.5 arcsec half power diameter imaging. Objectives are to demonstrate that 1--2 micron thick piezoelectric material can be deposited on curved, thin glass mirror elements of 200mm x 200mm dimensions; divided into a grid of 400 cells; and the cells independently activated to correct slope errors on spatial frequencies less than 0.05 per mm to 0.4arcsecond rms. Align the elements and shells to within an overall budget of 0.25 arcsec, including confocality.	Allow X-ray polarimetric observations over 0.1 keV-200 keV energy range with a photon detection efficiency exceeding 60%.	Recent advances in mirror technology make it possible to fabricate hard X-ray mirrors with <10 arcsec HPD angular resolutions. We need a detector technology for the focal plane instrumentation of state-of-the-art hard X-ray telescopes equipped with such high-angular resolution mirrors.	Develop low cost industrial processes to fabricate linear array of 87 through-silicon vias (TSVs) on 200um pitch. The TSVs are 100um diameter through a 300um thick Si wafer and applied prior to ASIC fabrication with connection traces to each group of TSVs on the top surface of the wafer.
TRL	4 - Polymethyl methacrylate (PMMA) has been tested in space so the material, itself, is at a high TRL level. The UV absorption and spectral index has been measured in the laboratory as a function of temperature. Fresnel lenses have been designed using this material and manufactured in diameters up to 1.5 meters. To reduce the scattering loss, the manufacturing technique needs to be refined to obtain a RMS surface roughness of <20 nm. A UV anti-reflective coating has been developed for PMMA and demonstrated on small samples. The technique for applying this coating to large lenses needs to be developed.	2 - TRL 2: Have deposited piezo cells on thin, flat glass pieces, and measured general agreement with finite element analysis predictions. IXO--like alignment has achieved TRL 3, and is starting point for further development. Slumping of thin glass is at TRL 3.	3 - In the 2-10 keV energy range, the GEMS soft X-ray polarimeter is at TRL 6; in the 20-60 keV energy range, the X-Calibur hard X-ray polarimeter is at TRL 4. Concepts exist (TRL 3) for extending polarimetric coverage to lower energies, and to improve the performance in the 5-20 keV energy range. The GEMS and X-Calibur polarimeters could be used together to make a polarimeter covering the 2-60 keV energy range. The detector hybrid would need some optimization.	4 - The NuSTAR mission uses CZT detectors with an ASIC with an energy threshold of 2 keV and a pixel pitch of 600 microns. We have made prototype measurements with 350 micron CdTe and CZT pixel detectors. Other groups have made exploratory measurements with detectors with 100 microns spatial resolution.	3 - TSV technology is available for 3D memory applications but not yet developed for ASIC fabrication. Low cost application to Si wafer processing not yet available.
Tipping Point	This lens technology is being pushed by the large international JEM-EUSO collaboration. Working with our Japanese and Europeans, we believe that the goals and objectives stated above can be reached in 2 years.	Produce an aligned and tested X-ray Optic pair, Jan 2015.	Already Achieved	Laboratory demonstration of 100 micron pixel pitch detectors with 1-2 keV energy threshold and excellent energy resolution (~ 1 keV FWHM).	2 year program could develop and demonstrate TSV technology for ASIC fabrication. This would allow two prototype development runs at an ASIC foundry: 1) develop TSV fabrication and connectivity from upper to lower surface pads on standard sized 300um thick Si wafers; and 2) substitute TSVs for WBs on NuSTAR ASIC for full wafer of TSV-ASICs.
NASA Capabilities		PSU/SAO have brought this technology to TRL 2, and are working toward TRL3 using internal funding plus NASA APRA plus a Moore foundation grant.			
Benefit/Ranking	Knowledge the UV background for observations of extensive air showers (EASs) from space will enable such observations to be made over the large areas needed for scientific investigations of extreme energy cosmic rays. Knowledge of this background will determine the duty cycle for EAS observations. Measurements of UV transient background signals will also provide information that will permit the design of trigger electronics which detects EAS signals while avoiding background.	This enables NASA to have an X-ray Observatory with angular resolution of 0.5 arcsec, comparable to Chandra, but with greater than 10 times the collecting area. That in turn enables detection of the first supermassive black holes in the early universe and following their growth-tree to the present time, studying the extreme physics of black holes and neutron stars, and the chemical enrichment of the Universe. Gives a sensitivity and angular resolution synergistic with major Observatories in the radio, mm, IR and optical wavelengths which are coming on-line by the end of this decade.	Technology will allow us to test models of black hole accretion, to sudy particle acceleration in compact objects, and to probe fundamental physics (General Relativity, Lorentz Invariance, neutron star equation of state).	Enable hard X-ray AGN census over z=0 to z=6 redshift range.	Closely tiled arrays of active pixel sensors are required for large area imaging detectors, e.g. each 20 x 20mm and with 32 x 32 pixels that are readout and controlled by ASIC flip-chip bonded to the detector. Such detectors cannot now be close-tiled (with no gaps) since present technology requires each ASIC to be connected with ~90 wirebonds along one edge. The wirebonds (WBs) themselves are expensive and incur risk for each detector. Elimination of WBs would allow active-pixel imaging detectors to be seamlessley tiled and flip-chip bonded to power and digital control on a single board. For X-ray (CMOS-Si) and hard X-ray/Gamma-Ray CdZnTe (CZT) detectors, elimination of WB gaps will reduce background on each detetector, thereby increasing sensitivity, and allow larger area imaging arrays to be accomodated in the same physical space. This technology will reduce cost, technical risk, and fabrication complexity for large-scale imager development.

Table 13. Technology Needs Submitted to PCOS Program Office Via Emai (Page 1 of 2)

Table 13. Technology Needs Submitted to PCOS Program Office Via Email

NASA Needs/Ranking	The "Science Instruments, Observatories, and Sensor Systems" Roadmap identifies "High-throughput optics with large fields of view, high stability, spectral resolution, and uniformity at many different temperatures" as one of six major challenges to support NASA's mission needs.	Required for any moderate to large collecting area grazing incidence, sub--arcsecond imaging telescopes. This satisfies a need for high resolution imaging and therefore photon--limited sensitivity down to a flux of 10^--19 ergs per cm^2 per s.	Broadband energy coverage with high detection efficiency; high reliability; low mass; low complexity.	The detector technology has to be combined with high-angular resolution mirrors. For a mission concept, see: http://arxiv.org/abs/1205.3691 .	This technology would greatly benefit proposed future missions such as Epoch of Reionization Energetic X-ray Survey (EREXS; formerly EXIST) and Wide-field X-ray Telescope (WFXT), both submitted in response to NNH11ZDA018 and presented at the XMAC on Dec. 15, 2011.
Non-NASA but Aerospace Needs	High throughput Fresnel optics is applicable to solar concentrators and large high throughput Fresnel optics for optical communications. The anti-reflective coating technology we propose to develop is applicable to a wide range of NASA missions operating in wavelengths from the UV to the Far infrared				This technology would likely be of interest to DoD reconnaissance imaging satellites incorporating wide-field, high time resolution spectral-imaging.
Non-Aerospace Needs	Potential military dual use applications for the anti-reflective coatings we propose to develop include Sun-Wind-Dust goggles, laser safety eye protective spectacles, chemical/biological protective face masks, ballistic shields for explosive ordnance disposal personnel, and vision blocks for light tactical vehicles. Commercial applications include solar panels, greenhouse enclosures, sports goggles and windows for public transport vehicles and armored cars.	Potential for synchrotron optics and x-ray lithography. Also plasma diagnostics.		Medical imaging (SPECT)	The ASIC-TSV technology proposed here would be of significant benefit to both Medical Imaging and Homeland Security, both of which use close-tiled arrays of high resolution imaging detectors for hard X-rays that require active pixel sensors. It would greatly improve imager resolution (by eliminating detector gaps) and cost (by eliminating complex wirebonds).
Technical Risk	There are two technical risks. The first is that manufacturing techniques cannot be developed or refined sufficiently to obtain the required surface roughness. The second is that a technique for uniformily applying the anti-reflective coating to the large Fresnel lenses cannot be developed.	Moderate risk for slumping thin glass and performing alignment. High risk for piezoelectric adjustment of elements to the 0.5 arcsecond level. For the optical adjustment, significant technical development is necessary to achieve TRL 6 including; elimination of deposition deformations, increased deposition yield, optimization of influence function shape, demonstration of lifetime in space environment, and deposition on curved mirrors.	Low	Low	TSVs have been developed by IBM and Samsung on prototype scales for integrating 3D memory modules. There should be minimal risk in applying this processing to large area wafers to allow fabrication of TSVs in Si wafers before (or possibly during) the standard 2D surface processing of an active pixel sensor ASIC, such as the 32 x 32 pixel (604um pitch) NuSTAR ASIC.
Sequencing/Timing	This optics technology described above is being pushed by the JEM-EUSO collaboration for use in the JEM-EUSO instrument that is planned for launch in 2017. Working with the Japanese and Europeans, we believe that the goals and objectives stated above can be reached in 2 years, which is in time to manufacture the flight lenses. The throughput of the optics is one of the factors that determine the signal strength. The second is the efficiency of the focal surface detector. The efficiency of the JEM-EUSO focal surface is ~25% using existing proved technology (multianode PMTs). New technology (backside illuminated silicon PMTs) is under investigation that could raise this to ~40%. If that technology were to mature rapidly, it would reduce the throughput requirement for the optics. We do not anticipate this technology will mature fast enough for the JEM-EUSO mission.	This is the "heart" of an X-ray Observatory Telescope, and is needed as early as possible. Specifically, will be needed by 2015 to conceive a mission which could be presented to the 2020 decadal survey committee for possible flight in the later 2020's.	Ideally, the technology should be at TRL 6 at the time of the next SMEX or MIDEX announcement of opportunity.	Ideally, the technology should be at TRL 6 at the time of the next SMEX or MIDEX announcement of opportunity.	Demonstration ASIC could be produced in 2 years. Phase 1 ~6mo: develop TSV technology on already-thin (300um) Si wafers and demonstrate top-bottom surface connectivity with flip chip bonding. Phase 2 ~1.5years: post-process Si wafer with precision-placed TSVs into ASICs connected on top-surface of Si wafer and verify performance by dicing ASICs and flip chip bonding them to pixelated CZT detectors for performance validation in ProtoEXIST3 (or similar) detector system.
Time and Effort to Achieve Goal	We propose a two-year effort conducted in collaboration with our Japanese and Italian JEM-EUSO partners. The plan is to do the lens manufacturing in Japan and the testing in the US. The optics design work will be a shared effort of our Japanese and Italian collaborators. The anti-reflective coating development will be done in collaboration with AGILTRON Inc. who has developed the coating technology under an SBIR. We expect that this will be an 8 person-year effort.	3 year collaboration between NASA/industry and University/Research institutions to reach TRL 4. Additional 3 years to reach TRL 6	2-8 years; the energy range from 2-60 keV can be addressed with a short-term program (2 years of one R&D group); extending the energy range beyond this boundaries will take longer. Extension to higher energies is relatively simple by scaling up an existing Compton polarimeter in size. There exist concepts for <2 keV polarimeters, but the detection efficiency is rather low.	A 3 years targeted research program of 1-2 groups will give the required technology. The R&D requires the fabrication and tests of suitable detectors and readout ASICs.	2 years, total: Phase 1 and first year of Phase 2 with industrial partner (e.g. IBM); final 0.5 year at Harvard and GSFC for integration and testing in appropriately modified ProtoEXIST3 detector system.

Table 13. Technology Needs Submitted to PCOS Program Office Via Emai (Page 2 of 2)

4. Program Technology Priorities And Recommendations

Background

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

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

- **Strategic Alignment:** How well does the technology need align with scientific and/or programmatic priorities, as determined by the AIP or current programmatic assessment? A technology related to a mission ranked highly by a major directive or review process should receive a higher score.

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

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

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

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

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

Table 4-1. Technology Needs Prioritization Criteria.

This process provides a rigorous, transparent ranking of technology needs based on the Program's goals, community scientific rankings of the relevant missions, the priorities of the NASA HQ Astrophysics Division as outlined in the AIP, and the external programmatic environment. The goals for the PCOS Program are driven by the AIP, which is based on the NRC's 2010 NWNH Decadal Survey report. The AIP includes highly ranked science missions and technology development for dark energy, gravitational waves, X-ray astronomy, and cosmic inflation and gives priorities based on current budget realities.

In 2012, the TMB ranked 70 technology needs for PCOS. For 2013, the 2012 need list was combined with inputs from the X-ray and gravitational wave TDRs, as mentioned in Section 3. Additionally, some needs from 2012 were found to be duplicative or not applicable. Thus, after the additions, combinations, deletions, and redefinitions, the needs list for 2013 had a total of 70 technology needs that were ranked by the TMB.

Results

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

Priority 1: Contains technology needs that the Board determined to be of the highest interest to the PCOS Program. These technology needs are enabling for the highest- priority potential PCOS missions in the areas of dark energy, gravitational wave, and X-ray science. The Board recommends that technology funding be applied to these technology needs first.

Priority 2: Contains technology needs that are enabling for a potential Inflation Probe mission or enhancing for a gravitational wave or X-ray mission.

Priority 3: Contains other technology needs that are deemed to be supportive of PCOS objectives but received lower scores in the prioritization than the Priority 1 and 2 technology needs.

Table 4-2 shows all 70 technology needs and their prioritization into the three bins.

Priority	Technology Need	Science
1	Large format mercury cadmium telluride CMOS IR detectors, 4k × 4k pixels	Dark Energy
	Telescope design with stringent length (pm) and alignment (nrad) stability with low straylight	Gravitational Wave
	High-resolution X-ray microcalorimeter	X-ray
	Phasemeter	Gravitational Wave
	Segmented mirrors	X-ray
2	Lasers	Gravitational Wave
	Large format (1,000–10,000 pixels) arrays of CMB polarimeters with noise below the CMB photon noise and excellent control of systematics	Inflation
	Microthrusters	Gravitational Wave
	Polarization modulating optical elements	Inflation
	Off-plane gratings	X-ray
	Critical angle gratings	X-ray
3	Very large format (1E5 pixels) focal plane assembly with background-limited performance and multi-color capability	Far-IR
	Cooling to 50–300 mK	Far-IR
	Stable and continuous sub-Kelvin coolers for detectors	Inflation
	High-rate X-ray silicon detector (active pixel sensor).	X-ray
	Large throughput, cooled, mm-wave to far-IR telescope operating at background limit	Far-IR
	Optically blind X-ray CCD detectors	X-ray
	High-throughput, light, low-cost, cold, mm-wave telescope operating at low backgrounds	Inflation
	High-throughput, anti-reflection coatings with controlled polarization properties	Inflation
	Optical bench	Gravitational Wave
	Arcsecond attitude control to maintain resolution	X-ray
	Molecular clocks/cavities with 1E-15 precision over orbital period; 1E-17 precision over 1–2 year experiment.	Fundamental Physics
	Cooled atomic clocks with 1E-18 to 1E-19 precision over 1–2 year experiment	Fundamental Physics
	Coded aperture imaging: ~5 mm thick width and ~2.5 mm holes; ~0.5 mm thick width and ~0.2 mm holes	X-ray

Table 4-2 (continued)

Priority	Technology Need	Science
3	Finely pixelated cadmium zinc telluride (CZT) detectors for hard X-rays	X-ray
	Application Specific Integrated Circuit (ASIC) on each ~20 × 20 mm crystal	X-ray
	Compton telescope on single platform	Gamma
	Cooled germanium (Ge)	Gamma
	Arrays of Si, CZT, or cadmium telluride (CdTe) pixels	Gamma
	Active cooling of germanium detectors	Gamma
	Gravitational Reference Sensor (GRS)	Gravitational Wave
	Coupling of ultra-stable lasers with high-finesse optical cavities for increased stability	Fundamental Physics
	Loop Heat Pipe (LHP) to radiators for ~-30 deg (Si) and ~-5 deg (CZT) over large areas	X-ray
	No optics; source isolation by collimator	X-ray
	Low power (ASIC) readouts	X-ray
	Passive cooling of pixel arrays	X-ray
	ASIC readouts	Gamma
	1 m precision optics (1/1,000)	Gravitational Wave
	Wavefront sensing with cold atoms	Gravitational Wave
	Large area atom optics	Gravitational Wave
	Gigapixel X-ray active pixel sensors	X-ray
	Megapixel microcalorimeter array	X-ray
	Long booms or formation flying	Gamma
	Depth graded multilayer coatings for hard X-ray optics	X-ray
	Sun-shield for atom cloud	Gravitational Wave
	Thermal stability/control less than 1E-8 K variation	Fundamental Physics
	Hard X-ray grazing incidence optics with multi-layer coatings with at least 5-arcsec angular resolution	X-ray
	Lightweight adjustable optics to achieve 0.1 arcsec high resolution grating spectrometer	X-ray
	Low-frequency, wide-bandwidth, low-mass science antennas	21 cm cosmology
	Advanced scintillators and readouts for gamma-ray detection	Gamma
	Lightweight, high throughput Fresnel optics	Near UV
	Photocathodes, microchannel plates, crossed grid anodes	X-ray
	>3 m^2 Si (or CZT or CdTe) pixel arrays or hybrid pixels—possibly deployable	X-ray
	3 m precision optics	Gravitational Wave
	Laser interferometer ~1 kW laser	Gravitational Wave
	Gravity Reference Unit (GRU) with ~100× lower noise	Gravitational Wave
	10 W near-IR, narrow line	Gravitational Wave
	Extendable optical bench to achieve 60 m focal length	X-ray
	Scintillators, cooled Ge	Gamma

Table 4-2 (continued)

Priority	Technology Need	Science
3	Active cooling of Ge detectors	Gamma
	Thin, lightweight X-ray collimator	X-ray
	Point source optimized X-ray concentrator	X-ray
	Broadband X-ray polarimeter	X-ray
	Finely pixelated detectors for high angular resolution hard X-ray imaging.	X-ray
	Focusing elements (e.g., Laue lens) on long boom or separate platform	Gamma
	Ultra-low power, temperature resistant, radiation tolerant analog electronics	21 cm
	Ultra-low power, temperature resistant, radiation tolerant digital electronics	21 cm
	Autonomous low-power generation and storage	21 cm
	Lobster eye X-ray optics for all-sky monitors	X-ray
	Megapixel CCD camera	Gravitational Wave

Table 4-2. Technology needs categorized in order of priority.

Background Information on 2013 Evaluation Criteria Changes

Following the prioritization exercises for 2011 and 2012, a scoring analysis was performed to understand the correlation of scores for the technology needs for the 11 criteria used in those years. From this analysis, as expected from the criteria definitions themselves, it was determined that several criteria could be combined and others eliminated without significantly changing the final rankings. That is, the process could be simplified without changing the final result. Thus, for 2013, the number of evaluation criteria was reduced from 11 to 4, as described in Table 4-3.

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

Table 4-3. Summary of evaluation criteria changes for 2013

5. Closing Remarks

This PCOS 2013 PATR serves as the current snapshot of the dynamic state of technology development managed by the PCOS PO and provides future directions for technology maturation. This document serves to:

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

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

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

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

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

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

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

The PO would like to thank the PCOS scientific community, the PIs and their teams, and the PhysPAG for all of their efforts and inputs that make this annual report current and meaningful.

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

Appendix A
Program Technology Development Quad Charts

Phasemeter Technology Development in the Post-LISA Era

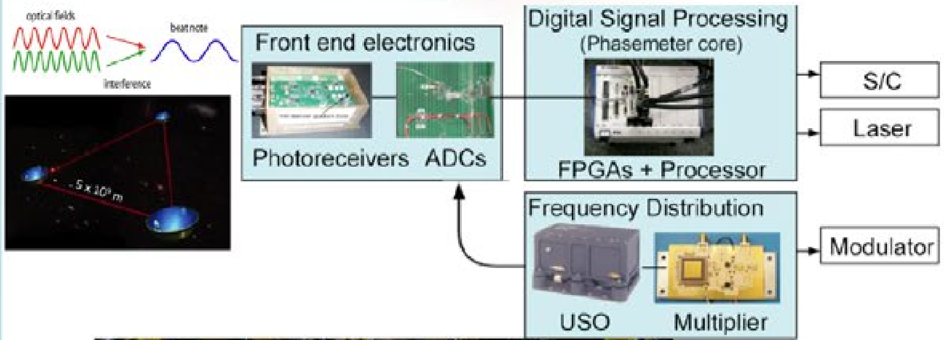
PI: William Klipstein/JPL

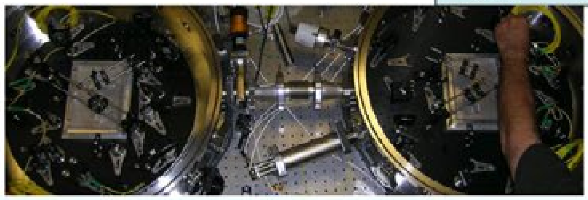
Description and Objectives:

- NASA's investment in the LISA phasemeter provides a strategic advantage for Gravitational Wave Missions
- We will evaluate phasemeter performance under stressing conditions considered for mission design alternatives and mature the analgo signal chain

Key Challenge/Innovation:

- Phasemeter provides "photons to bits" readout of the laser interferometer.
- Only NASA's LISA phasemeter meets demanding accuracy requirements in the presence of noise





Approach:

- We will leverage NASA investment in the LISA phasemeter and our interferometer testbed
- Use existing TRL 4 phasemeter, simulation tools, noise simulators, and different lasers in the testbed
- Build a pre-amplifier board and use with photoreceiver and phasemeter prototype in the interferometer testbed to demonstrate viability of point design for higher TRL build

Accomplishments and Next Milestones:

- Develop model of low light phasemeter performance limits (Feb 2012) ✓
- Build and Test analog signal chain pre-amp board (April 2012) ✓
- Characterize phasemeter modifications for handling high laser frequency noise/high heterodyne frequencies (Sept 2012) ✓
- Determine viability of tracking noisier lasers at low powers/higher noise (Nov 2012) ✓

Key Collaborators:

- Ted Ozawa, Bob Spero, Kirk McKenzie, Brent Ware, Glenn de Vine, Chris Woodruff, Jeff Dickson (JPL)

Application:

- Gravitational-wave missions based on laser interferometry: variants of LISA

Development Period:

- FY12

TRLin = **4-5** *TRLout* = **4-5**

Deposited Blocking Filters for X-ray Detectors

PI: Mark Bautz/MIT MKI

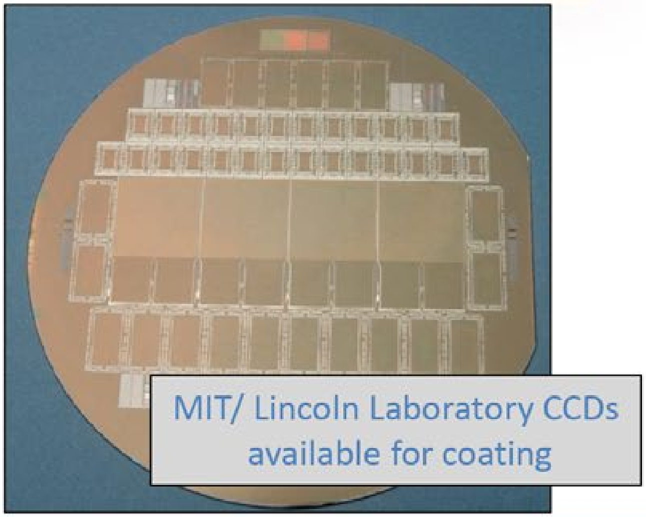
Description and Objectives:

- Silicon Imaging X-ray detectors require filters to block noise/background from UV and optical light
- Filters must be thin (<300 nm) to transmit X-rays
- State-of-the-art, free-standing filters use fragile, thin substrates
- Objective: deposit blocking filter directly on CCD X-ray detector, eliminating substrate

Key Challenge/Innovation:

Innovations/Benefits:

- Filter deposited on detector requires no fragile substrate
- Allows cheaper, more robust sensors (no vacuum housing!)
- Improves QE & makes larger focal planes practical
- Challenges:
- Deposit filter directly without compromising CCD performance
- Deposit sufficiently thin, uniform filters



Approach:

- Exploit existing stocks of (engineering grade/flight spare) X-ray CCD detectors at MIT Lincoln Laboratory
- Screen, thin, passivate, package & apply filters to detectors
- Filter is Al with AlO_2 cap
- Start thick (220 nm Al), get progressively thinner
- Use existing MIT facilities for X-ray characterization
- Use existing & upgraded facilities for optical characterization

Key Collaborators:

- MIT Kavli Institute (Bautz, Kissel et al.l)
- MIT Lincoln Laboratory (Suntharalingam, Burke, Ryu, O'Brien)

Development Period:

Jul 1, 2012 – Jun 30, 2014

Accomplishments and Next Milestones:

- First detectors identified and screened: Oct 2012
- Optical characterization facility tested (ND4 filter): Nov 2012
- Uncoated detector characterized (X-ray/optical): Feb 2013
- First coated detector characterized: Apr 2013
- Demonstrated Improved coating mask process: May 2013
- BI processing complete on 4 wafers: June 2013
- Verified good X-ray performance, BI CCD with filter: June 2013
- Complete BI processing, 8 add'l wafers: Oct 2013

Application:

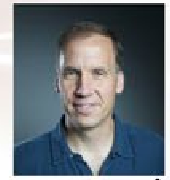
Every X-ray imaging or grating spectroscopy mission

- Explorers (Lobster…)
- "Probes" (XAP,AEGIS, N_XGS, AXSIO, WFXT…)
- Flagship (IXO…)

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

Planar Antenna-Coupled Superconducting Detectors for CMB Polarimetry

PI: Jamie Bock/JPL

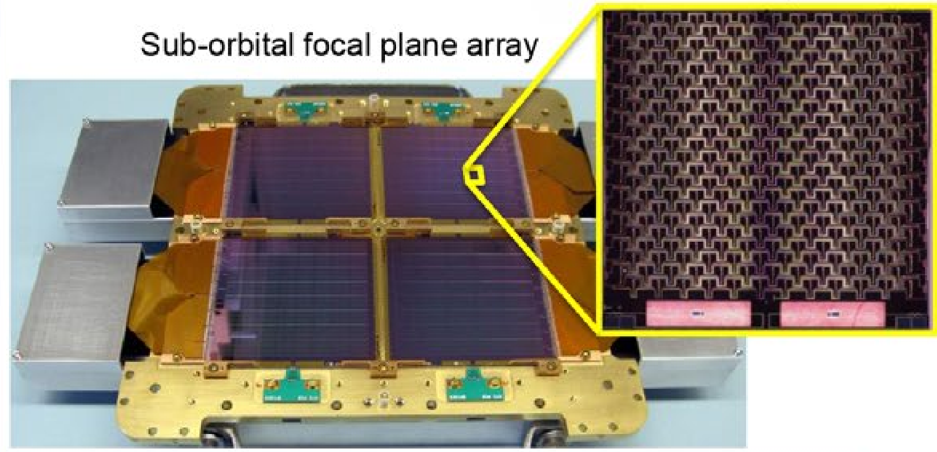


Description and Objectives:

- Advance antenna-coupled superconducting detector technologies for space requirements:
    - Antenna design & performance
    - Propagation losses
    - MKIDs for CMB science
    - TES stability & cosmic ray response
    - Modular focal plane units

Key Challenge/Innovation:

- RF propagation properties of antennas
- Detector sensitivity, stability & particle susceptibility



Sub-orbital focal plane array

Antenna-coupled TES

Approach:

- Planar antennas provide entirely lithographed fabrication with no coupling optics
- Design scales to all bands required for the Inflation Probe from 30 – 300 GHz
- Detectors provide photon-limited sensitivities in space
- Antenna provide excellent polarization and beam-matching properties
- Modular focal plane unit for large focal plane arrays

Key Collaborators:

- Peter Day, Warren Holmes, Henry LeDuc, Koko Megerian, Hien Nguyen, Roger O'Brient, Anthony Turner (JPL)
- Sunil Golwala, Howard Hui (Caltech)

Development Period:

- Jan 2012 – Dec 2013

Accomplishments and Next Milestones:

- Demonstrated improved polarized beam matching
- Demonstrated new tapered-beam antennas
- Developed new Nb process with reduced loss
- Tested particle response in multiplexed TES sensors
- First test of modular focal plane unit completed
- Dielectric loss devices completed and awaiting test
- Frame mitigation particle device masks completed

Application:

- NASA Inflation Probe mission
- Explorer & International CMB missions
- Technology commonalities with Far-IR and X-Ray missions

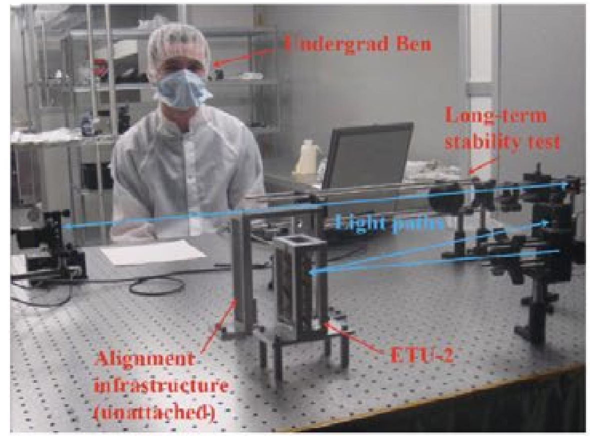
*TRLin = **3***   *TRLcurrent est. by PI = **4***   *TRLtarget = **5***

Off-Plane Grating Arrays for Future Missions

PI: Randall L McEntaffer/University of Iowa

Description and Objectives:

- Fabricate an aligned assembly of off-plane gratings capable of achieving spectral resolutions > 3000 ($\lambda/\delta\lambda$) with high throughput over the 0.3 – 1.5 keV band thus advancing the OP-XGS technology to TRL 5
- Provide an XGS ready for observatory specific TRL 6 development



Alignment testing at U. of Iowa

Key Challenge/Innovation:

- Increasing fidelity of groove profile
- Alignment of multiple gratings into a single module

Approach:

- Fabricate next-generation off-plane gratings
- Performance test gratings for efficiency and resolution
- Development alignment system and metrology
- Replicate gratings
- Alignment and performance testing of multiple gratings in a single medium fidelity module mount

Key Collaborators:

- Will Zhang – GSFC
- Steve O'Dell – MSFC
- Webster Cash – Univ. of Colorado

Development Period:

- Jan 30, 2012 – Jan 29, 2014

Accomplishments and Next Milestones:

- Achieved high diffraction efficiency and verified theoretical resolution of 900 in 1st order at 0.93 keV Mg Kα line, >1300 in 2nd order, limited by facility capabilities (McEntaffer, et al. 2013, Exp. Astro., 36, 389)
- Fabricated and currently testing module mount and integrated alignment and metrology hardware (see above picture)
- Calculated and theoretically verified alignment tolerances (Allured & McEntaffer, 2013, Exp. Astro., in press)
- Purchased nanoimprint lithography tool for grating fabrication
- Performance testing of aligned gratings – 4th qtr 2013
- Module trade study – 4th qtr 2013

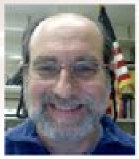
Application:

- Large X-ray observatories
- Explorer class missions
- Suborbital rocket investigations

*TRLin = **3***   *TRLcurrent est. by PI = **4***   *TRLtarget = **5***

Moderate Angular Resolution Adjustable Full-Shell Grazing Incidence X-Ray Optics

PI: Paul Reid/SAO



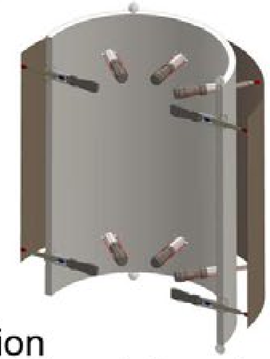
Description and Objectives:

- Improve the angular resolution of full-shell replicated optics to better than 10 arcsec using electrorestrictive actuators
- Demonstrate technical viability by x-ray testing a double shell of mirrors thereby achieving TRL 4

Key Challenge/Innovation:

- Mounting actuators to Ni/Co metal shells and then correcting figure errors
- Mounting nested shells interspaced with actuators

Reaction structure and mounting components



Cross section of full shell mirror, internal reaction structure, and mounting actuators

Approach:

- Full shell replication of Ni/Co mirrors
- Fabrication of central reaction structure
- Mounting of mirror shells to reaction structure using controllable actuator assemblies
- Correction of mounting and figure errors by applying voltage to actuators
- Measurement by mechanical, optical, and x-ray test
- Addition of second outer shell

Key Collaborators:

- Brian Ramsey and Stephen O'Dell (MSFC)
- Stephen Murray (JHU)

Development Period:

- April 2012 – March 2014

Accomplishments and Next Milestones:

- Completed re-work of reaction structure
- Completed all parts and tooling fabrication
- Completed dry-fit of actuator components
- Started assembly of mirror / actuator system
- Single shell assembly complete, September 2013

Application:

- Wide field moderate angular resolution missions
- Wide Field X-ray Telescope (WFXT)
- Notional Wide Field Imager (N-WFI)

TRLin = ***3*** *TRLcurrent est. by PI* = ***3*** *TRLtarget* = ***4 - 5***

Development of Fabrication Process for Critical-Angle X-ray Transmission Gratings

PI: Mark Schattenburg/MIT MKI

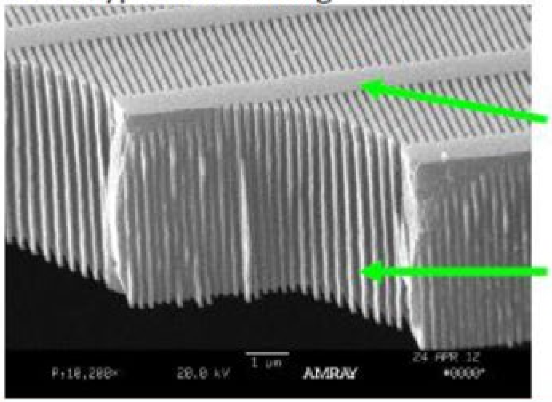
Description and Objectives:

- Develop key technology to enable a Critical-Angle X-ray Transmission Grating Spectrometer (CATGS), advancing to TRL-6 in preparation for proposed mid- and large-size missions over the next two decades
- Develop improved grating fabrication processes and procure advanced etching tool and other infrastructure in order to accelerate technology development

Key Challenge/Innovation:

- Development of nanofabrication technology for the silicon nanomirror grating elements
- Development of microfabrication processes for the integrated grating support mesh

Prototype CAT Grating



Approach:

- Integrated wafer front/back-side fabrication process using silicon-on-insulator (SOI) wafers
- Wafer front side: CAT grating structure
- Wafer back side: Level 1 & 2 support mesh structure
- CAT grating fabricated by deep reactive ion-etching (DRIE) followed by KOH polishing
- Bonded to expansion-matched metal support frame (Level 3)
- X-ray testing of prototypes at synchrotrons and MSFC facility

Key Collaborators:

- William Zhang (GSFC)
- Steve O'Dell (MSFC)

Development Period:

- FY12-FY14

Accomplishments and Next Milestones:

- Selected vendor for purchasing a DRIE tool after extensive evaluations, and currently finalizing the installation plan.
- Developed an oxide deposition & annealing process that allows oxide membranes to remain flat under low tensile stress.
- Demonstrated 31x31 mm^2 CAT grating with KOH polish, currently preparing additional high quality samples for X-ray tests.
- CY 2013: Demonstrate integrated 31x31 mm^2 CAT grating with KOH polish
- CY 2013: X-ray resolution tests with GSFC mirrors at MSFC

Application:

- Flagship x-ray missions
- Explorer-type x-ray missions
- Laboratory x-ray analysis (materials science, energy research)

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

Next Generation X-ray Optics: High-Resolution, Lightweight, and Low-Cost

PI: William W. Zhang/GSFC

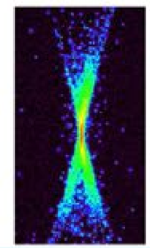
Description and Objectives:

- Develop a lightweight x-ray mirror technology to achieve better than 10" HPD angular resolution, advancing it to TRL-5 and making it ready to enable missions planned for both 2010's and 2020's
- Mature and perfect this technology to minimize cost and schedule
- Prepare ways to achieve significantly better than 10" resolution while keeping the mass and cost at similar levels

Key Challenge/Innovation:

- Fabrication and metrology of mirror segments
- Alignment and bonding of mirror segments

A Technology Development Module (TDM) containing three pairs of parabolic-hyperbolic mirror segments



X-ray image HPD=12 arcsecs

Approach:

- Precision glass slumping to make mirror substrates
- Using magnetron sputter or atomic layer deposition to maximize x-ray reflectance
- Using interferometer, null lens, and interferometric microscope to conduct measurement
- Using Hartmann tests to align mirror segments
- Developing precision epoxy bonding techniques

Key Collaborators:

- Michael Biskach, Kai-Wing Chan, Ryan McClelland, Timo Saha (GSFC)
- Stephen O'Dell (MSFC)

Development Period:

- Oct 2012 – Sept 2014

Accomplishments and Next Milestones:

- Successful slumped mirror substrates to achieve better than 10" HPD
- Successfully coated mirror substrates with 15nm of iridium without distortion
- Repeatedly co-aligned and bonded multiple mirror pairs and achieved 12" HPD x-ray images
- Refine mirror bonding process to fully realize mirror segment potential of 6.5" HPD
- Reduce gravity distortion by building a vertical x-ray beam to test mirror modules

Application:

- Flagship x-ray missions
- Explorer type x-ray missions
- Medical research and diagnosis

*TRLin = **3***   *TRLcurrent est. by PI = **4-5***   *TRLtarget= **5***

X-ray Microcalorimeter Spectrometer (XMS)

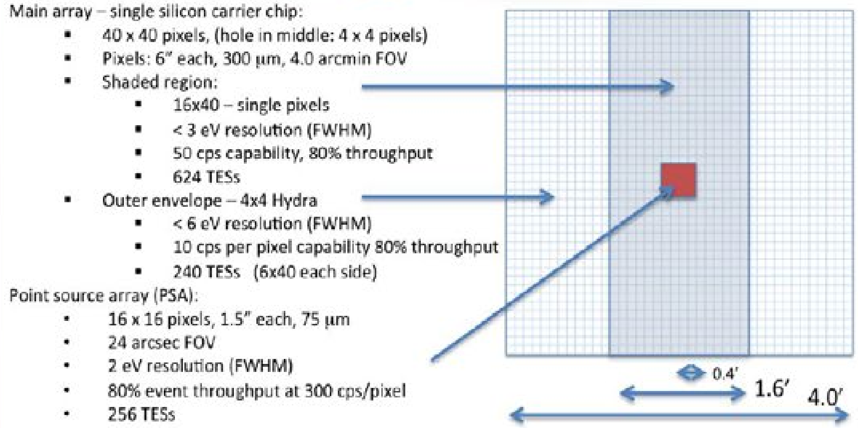
PI: Caroline Kilbourne/GSFC

Description and Objectives:

- Advance the core XMS detector-system technologies (kilo-pixel-scale arrays of TES calorimeters and matched multiplexed SQUID read-out)
- Develop and demonstrate options for an expanded focal plane and higher per-pixel count rates
- Develop critical technologies needed for the thermal, electrical, and mechanical integration of the detector and read-out components

Key Challenge/Innovation:

- Producing all the components close enough to their design specifications for them to work well together
- Maintaining modularity in a focal-plane design with adequate magnetic shielding



Concept for AXSIO focal plane, showing the components associated with the proposed read-out demonstrations

Approach:

- Integrate 32x32 TES arrays with matched SQUID MUX components optimized for low crosstalk, low stray inductance, acceptable power dissipation, and imposed requirements on the room-temperature electronics
- Demonstrate multiplexed readout of multi-absorber (hydra) TES devices and Code-Division Multiplexed (CDM) read-out of fast TES pixels
- Investigate component technologies for focal-plane assembly

Key Collaborators:

- S. Bandler, S. Smith, J. Adams, S. Porter, R. Kelley (662)
- J. Chervenak (553), K. Irwin, R. Doriese, C. Reintsema (NIST)

Development Period:

- Oct 2012 – Sept 2014

Accomplishments and Next Milestones:

- 2x8 multiplexed demo of portion of 8x8 TES array (2008)
- Production of 32x32 arrays with microstrip wiring (2010)
- Upgraded the MUX control electronics to double the line rate over that of the 2x8 demo (2012)
- Progress on components needed for TRL demonstrations (2013)
- Complete TRL-5 demonstration of core array, including vibration and radiation testing (2014)
- Complete TRL-4 demonstration of extended array (2014)
- Perform CDM demonstration of XMS-type pixels (2014)

Application:

- AXSIO, nCal, or any other XMS-based mission

*TRLin = **4+*** *TRLcurrent est. by PI = **4+*** *TRLtarget = **5+***
(core array technologies)

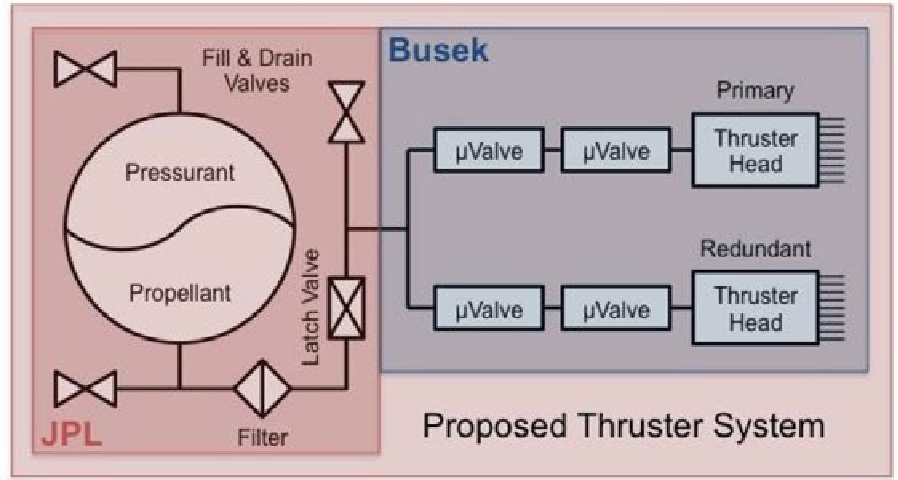
Colloid Microthruster Propellant Feed System

PI: John Ziemer/JPL

Description and Objectives:

The goal of this work is to develop a new colloid thruster feed system to TRL 5 that can support any gravity wave observatory concept with a clear path to TRL 6 once the system is defined

- Design tank and feed system with full redundancy
- Design, fabricate, and test stainless steel diaphragm tank
- Design, fabricate, and test new Microvalves
- Integrate and test feed system components



Key Challenge/Innovation:

- Replace the heavy spring-loaded bellows design from ST7 with a light-weight pressurized diaphragm tank
- Use the new Busek Microvalve (Phase II SBIR) to reduce complexity while providing redundancy

Approach:

- Teaming arrangement between flight-house tank vendor, Busek for the Microvalve, and JPL to manage, perform I&T
- Use standard liquid-fed propulsion flight design guidelines and practices – the new technology is in the pieces, not the systems engineering approach
- Four tasks related to each objective, plus a management task, each with a JPL expert lead
- Hold peer reviews at each meaningful milestone: requirements definition, design, and test

Key Collaborators:

- Busek on Microvalve and systems engineering
- Flight-tank manufacturer (likely AMPAC)
- JPL electric propulsion and flight propulsion groups

Development Period:

- Jan 2013 – Sept 2014

Accomplishments and Next Milestones:

- Busek contract in place, orders for microvalve parts are in place
- Busek awarded Phase IIE SBIR with matching funds for PCOS work, which will help with developing and testing additional components between the microvalves
- Next quarterly meeting will be in early October to review system requirements
- Found new supplier for tank fabrication; contract negotiations are ongoing

Application:

- Drag-free gravity observatories
- Precision pointing of large observatories
- Small spacecraft main propulsion

TRLin = ***3-4*** *TRLcurrent est. by PI* = ***3-4*** *TRLtarget* = ***5***

SAT Telescope Development

PI: Jeff Livas/GSFC

Description and Objectives:

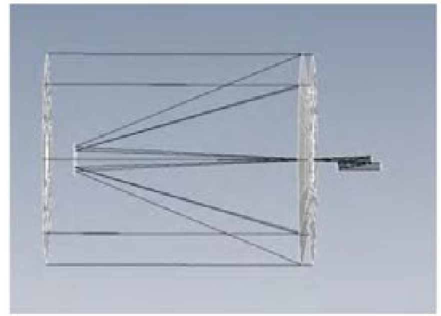
- Establish a complete telescope design meeting optical, mechanical, thermal, and manufacturability NGO requirements for US contribution to L2 mission
- Fabricate and test a prototype

Key Challenge/Innovation:

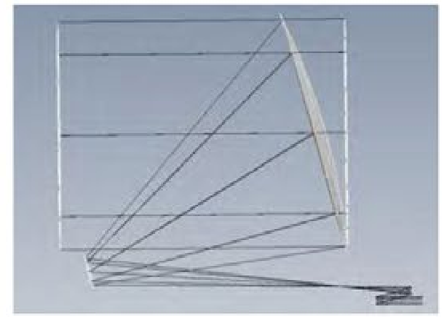
Conflicting requirements:

- On-axis design more stable for thermal environment but higher scatter
- Off-axis design lower scatter but more difficult to build (hence expensive)
- Can an on-axis design meet requirements? Or
- Can an off-axis design be manufactured?

On- vs Off-axis Designs



On-axis



Off-axis

Same prescription

Approach:

- Use LISA reference and the ESA NGO/eLISA
- "Yellow Book" to generate requirements
- L3/SSG for basic design (off-axis SiC recommended)
- Fabricate a prototype from the design
- Verify for compliance with specifications

Key Collaborators:

- Code 551: Joe Howard/Peter Hill/John Hagopian/
- Petar Arsenovic/Vince Bly/Len Seals/Ron Shiri
- Code 543: John Crow

Development Period:

- Oct 2012 – Sept 2014

Accomplishments and Next Milestones:

- Oct 2012: Study contract awarded
- Feb 2013: Begin lab work with COTS telescope
- Apr 2013: Study contract results available
- May 2013: Start custom telescope procurement
- Sep 3, 2013: Synopsis posted; waiting for RFP
- Sep 2013: Stray light measurement capability demo
- Sep 2014: Custom telescope delivery
- Nov 2014: Stray light < 10^{-10} demo
- Mar 2015: Telescope pathlength stability demo

Application:

- Flagship gravitational wave missions
- Precision interferometric metrology applications such as laser ranging

*TRLin = **2***   *TRLcurrent est. by PI = **3***   *TRLtarget = **3+***

Laser Stabilization with CO

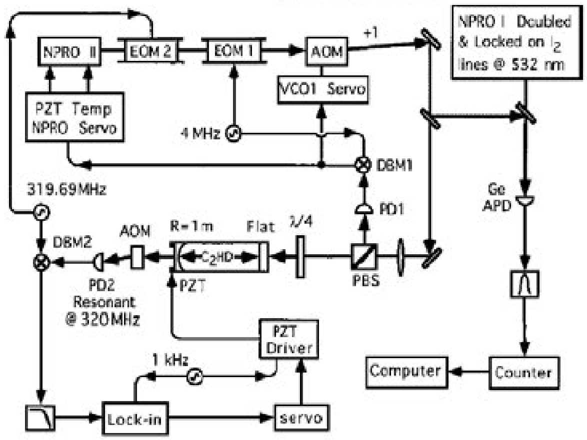
PI: John Lipa/Stanford University

Description and Objectives:

- Develop a laser operating near 1570 nm with improved noise performance and mid-term frequency stability, for missions that could use a highly coherent light source near the telecom band.
- Performance goals are to achieve substantially lower noise than Iodine-stabilized lasers, the current gold standard for transportable systems. Goal is to achieve an Allan deviation of ~ 2×10^{-15} in a one second measurement time.

Key Challenge/Innovation:

- Noise performance of lasers on short and intermediate time scales



JILA laser stabilization system using C_2HD (1999)

Approach:

- Set up a bench-top model of laser system for CO based on existing system at JILA for C2HD near 1064 nm
- Perform functional tests on system
- Set up a second system to allow detailed noise performance measurements
- Upgrade optics and electronics to achieve noise performance goal

Key Collaborators:

- Jan Hall, JILA, Bob Byer, Stanford, Sasha Buchman, Stanford, Shailendhar Saraf, SN&N Electronics

Development Period:

- Jan 2013 – Dec 2014

Accomplishments and Next Milestones:

- Bench-top optics system completed on schedule
- Gas cell being upgraded to reduce optical loss
- Performance testing starts 11/13
- Portable breadboard completion 4/14

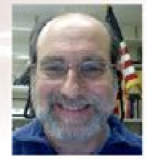
Application:

- Applications would be tests of fundamental physics, gravity wave observation, precision spectroscopy and Doppler, formation flying, trace gas detection.

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

Adjustable X-Ray Optics with Sub-Arcsecond Imaging

PI: Paul Reid/SAO

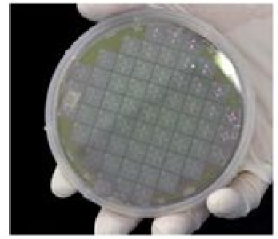


Description and Objectives:

- Develop adjustable light weight x-ray optics with sub arcsecond performance
- Create the enabling optics technology for a large aperture high resolution x-ray mission (SMART-X) for selection at the next Decadal Survey

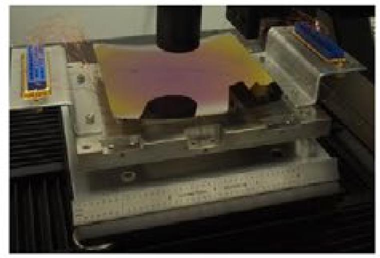
Key Challenge/Innovation:

- Sub-arcsecond optics fabricated with traditional methods are too heavy; light, thin replicated optics performance is limited to ~7"
- By coating thin glass optics with piezoelectric material, whose shape can be altered by applying a voltage, we can correct unwanted figure distortions improving performance to <1"



Adjustable mirror with strain gauges on every cell

Mirror pair during alignment



Piezo induced figure changes being measured on a cylindrical mirror

Approach:

- Deposit piezoelectric material (PZT) on conical thermally formed glass
- Mount and align a piezo coated mirror pair
- Correct unwanted figure distortions by adjusting the voltage applied to the piezo material
- Prove out performance using x-ray testing

Key Collaborators:

- Susan Trolier Mckinstry (PSU)
- Brian Ramsey and Stephen O'Dell (MSFC)

Development Period:

- Feb 2013 – Jan 2016

Accomplishments and Next Milestones:

- Demonstrated predicable, repeatable deformations on cylindrical optics that matched values predicted by models
- Completed mounting and aligning of mirror pair using first generation mount; starting mount design improvement phase
- Deposited strain gauges on piezo cells
- Calculated PZT life of > 30-50 years from accelerated lifetime test results
- Next: mount / align improved conical optics in TRL-4 mount

Application:

- Large aperture and high resolution x-ray mission for the 2020s (Square Meter Arcsecond Resolution X-ray Telescope, SMART-X)

*TRLin = **2***   *TRLcurrent est. by PI = **3***   *TRLtarget = **4***

Appendix B
Program Technology Development Status

Gravitational Wave Mission Phasemeter Technology Development

Prepared by: William Klipstein (Jet Propulsion Laboratory, California Institute of Technology)
Phasemeter core team members: Glenn de Vine, Kirk McKenzie, Robert Spero, and Brent Ware

Summary

Phasemeter technology development during FY12-13 focused on two areas. The primary thrust of work was to demonstrate the viability of the phasemeter under different credible mission scenarios in which requirements differ from those of the *Laser Interferometer Space Antenna* (LISA). This will allow mission and design trades aimed at reducing the cost of a gravitational wave mission as well as to reduce the implementation risk of the phasemeter, a core piece of LISA-specific technology not addressed by LISA Pathfinder. A second seeks to mature the technology readiness of the analog signal chain by assembling and testing a pre-amp board designed under previous funding.

Overview and Background

The driving LISA Instrument Metrology and Avionics System (LIMAS) requirement is to make an accurate measurement of the phase of the interferometric beat note between pairs of laser beams, both for the interspacecraft and local interferometry. LISA-specific challenges include microcycle/√Hz phase precision in the presence of large laser frequency fluctuations and a low signal-to-noise ratio (SNR) environment, and tracking the large changing Doppler shift over the frequency range of 4–18 MHz. The primary science phase measurements are to be provided in a low-pass filtered version allowing representation at 3 Hz sampling rate while representing a 1 Hz useful bandwidth.

In addition to measuring the phase of the primary heterodyne signal, the LISA phasemeter must perform several additional functions:

- Provide a low-latency, high-bandwidth output suitable for use in a laser phase-locking control system.
- Isolate and measure the phase of side-tones used for clock noise transfer.
- Provide an absolute phase measurement of different photoreceiver quadrants to support wavefront sensing.
- Demodulate pseudo-noise modulation to extract spacecraft range, clock offset information, and optical communication signals.

The phasemeter supports approximately 76 tracking channels per spacecraft.

The Phasemeter Subsystem is a digital phase-locked loop that is optimized to extract the phase from multiple carriers in a heterodyne beat note signal in the gravitational wave mission science photoreceiver. The phase is proportional to the separation between spacecraft, and measurements of the distances between the spacecraft and measurements of the laser noise are combined on the ground in a post-processing algorithm, Time Domain Interferomery (TDI) to extract the spacecraft separations to an accuracy of about 10 picometers. Figure 1 shows the main components of the subsystem.

The front-end electronics is a low-noise, high-bandwidth quadrant detector that is paired with a fast analog-to-digital converter (ADC). Incoming light from a distant spacecraft is mixed with light from a local laser to generate interference fringes on the photodetector. These fringes are not stationary because the spacecraft are in constant motion, but the orbits are carefully chosen such that the beat note is a radio frequency (RF) between 1 and 20 MHz.

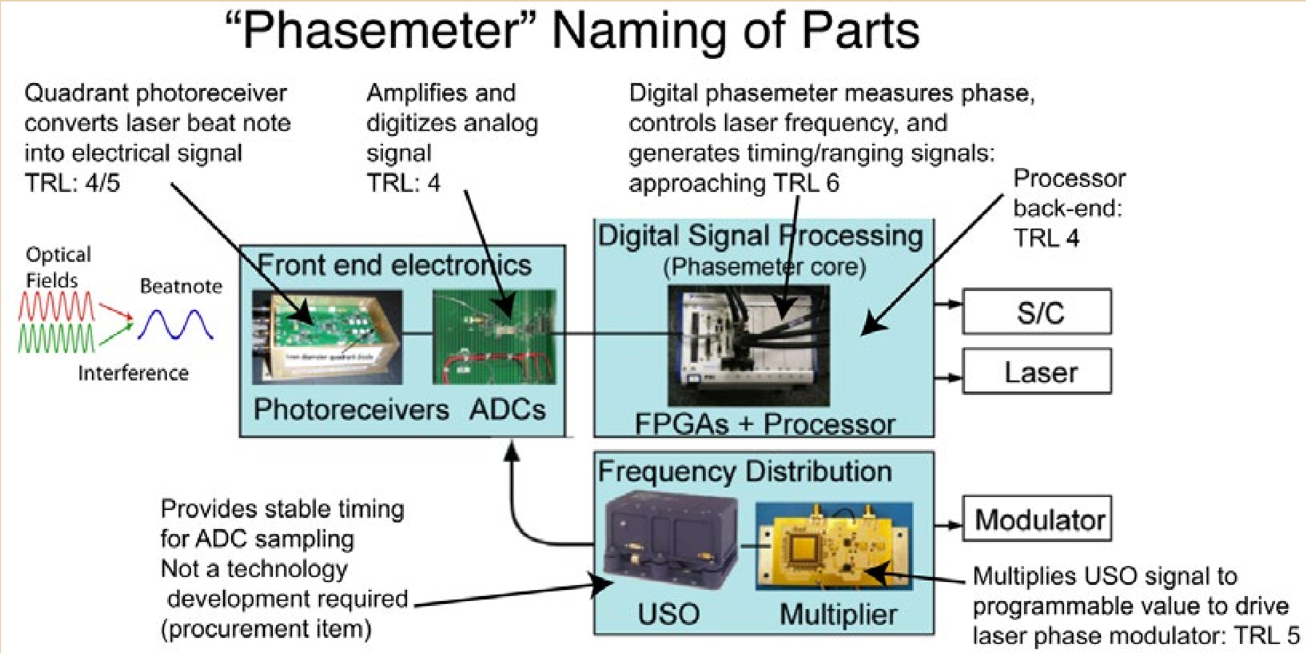


Figure 1. *The Phasemeter provides photons-to-bits read out of the heterodyne beat note in the laser interferometer gravitational wave detectors in space.*

With the dissolution of the NASA-European Space Agency (ESA) collaboration on LISA, NASA commissioned a study to look at alternate mission architectures. All the leading concepts relied on laser interferometry, but had different assumptions about orbital parameters that would vary the received signal power (which impacts shot noise), different Doppler shifts and, in some cases, the use of different types of lasers that have different noise characteristics.

Phasemeters are general-purpose equipment required for laser interferometers in space. We have been developing phasemeters targeting LISA's requirements, following a path described in the LISA Technology Development Plan (2005). We had previously proposed adapting our phasemeter to the Space Interferometry Mission (SIM), but at the time our design maturity was too low for infusion in to that mission. The Earth Science Decadal Survey Tier III mission, *Gravity Recovery and Climate Experiment-II* (GRACE-II), will use laser interferometry to improve over the precision of the current microwave system; indeed, the LISA phasemeter adapted the digital-phase-locked-loop architecture of the BlackJack global positioning system (GPS) receiver used in the microwave instrument to meet LISA's more demanding requirements. A technology demonstration of interspacecraft interferometry is planned for *Gravity Recovery and Climate Experiment Follow-On* (GRACE-FO) using a simplified version of the LISA phasemeter.

Methodology and Technology Readiness Level

This work relies heavily on NASA's investment in phasemeter development and in the development of our interferometer-system testbed, which allows testing of the phasemeter in a relevant signal environment.

All gravitational wave mission concepts under consideration (except for the less-mature atom interferometer concepts) are heterodyne interferometers requiring a phasemeter. All concepts rely on TDI to overcome limitations of laser frequency noise. Through our LISA work we have developed unique insights that can be adapted (for orbital dynamics, laser noise, signal strength, modulation/demodulation schemes) to understand the risks and opportunities in alternate mission concepts, each of which would require a phasemeter much like the one we have developed.

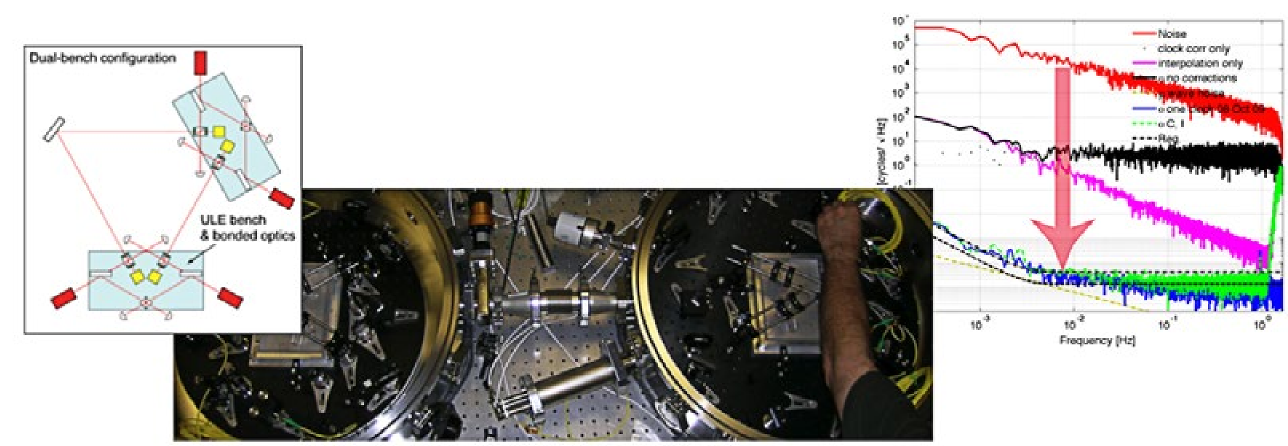


Figure 2. *The Phase Measurement System has been demonstrated to TRL-4 in a testbed that will be used for the current work. Some of the component technologies have advanced beyond TRL-4.*

We have used this testbed to demonstrate the Interferometer Measurement System to TRL-4, as shown in Figure 2 and published in Physical Review Letters (2010)[3]. We have advanced the TRL of the digital heart of the phasemeter to TRL-5 and the photoreceiver to TRL4/5. These TRL assessments were made against LISA's requirements. With the recent studies for ways to realize the same science at reduced cost, there have been proposals that would increase the separation, use lower power lasers, smaller telescopes, and have different orbital dynamics. The primary objective of the proposed work is to evaluate our phasemeter capability against these different stressing environments. We start with our phasemeter performance models to predict our sensitivities to different input parameters, and then test these models through simulations and from direct tests with our LabVIEW system design software-based TRL-4 phasemeter. We also have different types of laser, including Non-Planar Ring Oscillator (NPRO) lasers, Distributed Feedback (DFB) lasers, External Cavity Laser (ECL) lasers that we can use to test for alternate noise types. We also have the ability to generate simulated noise, although we intend to improve that capability with this task.

Objectives of the Phasemeter Technology Development Task for 2012/2013

Two main phasemeter tasks through calendar year 2012 were funded through the Technology Management Board. Here we update the phasemeter technology development tasks and plan from the 2012 PATR. As a result of partial funding of proposed tasks for FY13 some of the planned work has been rephrased to start in FY14 as described below.

1. TMB Tasks and Milestones

TMB 2012 Task 1: Design and demonstrate modifications to the phasemeter that support relaxation of LISA's requirements on laser noise, orbital parameters, and received optical power

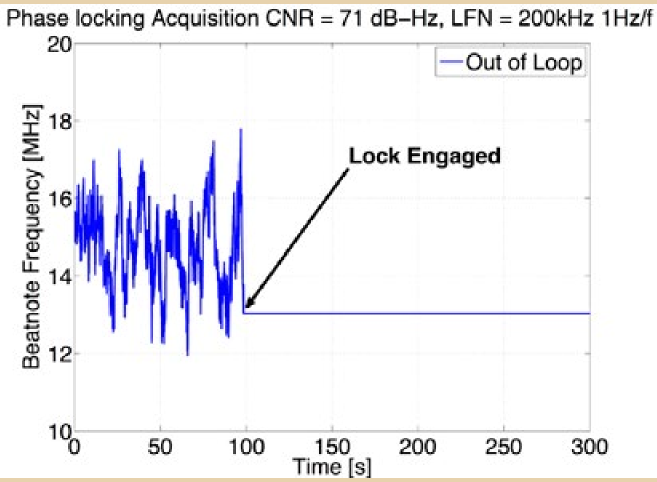
The LISA phasemeter was designed to support the point design baselined for LISA. We propose a series of design parameter studies to demonstrate compatibility with a wider phase space of gravitational wave mission parameters.

Task 1a) Demonstrate phase locking and phasemeter readout with low received optical power compared to LISA's 100 picoWatts.

Status: *Objective achieved.*
We have developed analytical models of the interplay between shot noise and phasemeter performance. Prior to this work our phasemeter would acquire signals down to 40 pW. In this work we realized that our acquisition algorithms needed to be changed to pick out the smaller signal in the presence of other types of physical laser noise, including Relative Intensity Noise (RIN) and large laser frequency noise (20 times larger than commercial NPRO frequency noise). We demonstrated acquisition and stable tracking down to 3 pW in our testbed (Figure 3a).

An output of the initial demonstration was a realization of the importance of the resonant relaxation oscillation (RRO) peak in the laser intensity noise (Figure 3b). Specifically, the amplitude of this RRO peak is larger than the heterodyne signal amplitude for LISA-like signals. Thus, to maintain precision and avoid saturation in the analog-to-digital converter, an analog high pass filter must be added to the analog signal chain to filter this RRO peak.

We also explored lower limits of phasemeter tracking with an all-digital experiment. This test demonstrated tracking with white phase noise that is equivalent to the shot noise level for 12 femtoWatts received optical power, whilst in the presence of large laser frequency noise. This performance verification at the equivalent of a factor of 1000 less optical power than LISA's baseline, demonstrates the phasemeter capability in extreme conditions, and yields a result very close to the predicted theoretical limits[1].



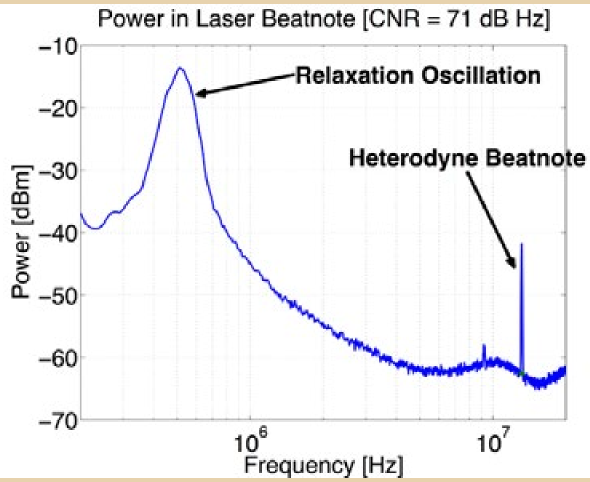


***Figure 3**. The phasemeter can track and lock even in the presence of large technical noise, such as relative intensity noise (left). The phasemeter digital tests show tracking with white phase noise equivalent of 12 femtoWatts (right).*

1b) Design and test modifications to the phasemeter to work with lasers with higher/different intrinsic noise than the LISA NPRO laser.

- *NPROs have extremely low intrinsic noise compared to other candidate lasers. We have NPROs, fiber lasers, distributed Bragg reflector, distributed feedback, and external-cavity diode lasers available in our lab.*
- *The goal was to show compatibility with a range of laser "characteristics," not to downselect any particular laser (known to require modification to phasemeter).*

Status: *Objective achieved.*
In studying the interplay between laser noise and phasemeter design, we further developed our analytical understanding of the limits to phasemeter performance as it applies to laser frequency noise. Previously, LISA considered laser frequency noise primarily in the science bandwidth below 1 Hz, but the phasemeter tracking is sensitive to noise at high frequencies, in the range of a few kHz to a few hundred kilohertz, determined by the design of the phasemeter tracking loop bandwidth and noise parameters. An analytical model of the phasemeter indicated we should have significant margin on tracking the LISA laser frequency requirement. This margin was confirmed with an all-digital stress test of the phasemeter showing successful tracking of laser frequency noise much greater than the nominal LISA laser frequency noise level (laser frequency noise up to ~1 MHz/rtHz × 1 Hz/f tracked compared to 10 kHz/rtHz × 1 Hz/f for a single laser[2]).

Experimental tests with DFB lasers showed the LISA phasemeter was unable to track, without modification, due to excess white frequency noise above 1 kHz. This deficiency is inline with expectations from an analytical model developed under this task, and therefore alternative methods or modifications were needed to enable tracking and characterization. The three paths we investigated were:

a. *Using a frequency divider on the heterodyne signal to mitigate phase noise.* This works by improving the effective phasemeter bandwidth compared to the noise. This also allows the phasemeter to work with higher Doppler shifts. A division factor of 50 was required to reliably track the DFB laser. We integrated a single-bit divider into the phasemeter and showed its enhanced tracking capabilities. However the performance of the system is reduced, now limited by the single-bit quantization noise. A multi-bit divider is planned but is not completed.

b. *Increased the digital phase-locked-loop (DPLL) bandwidth to handle higher noise.* Increasing the DPLL bandwidth enhances the ability to track laser frequency noise with white or 1/f spectral shape. Conversely, an increased bandwidth degrades the tracking ability at low-light power levels: meaning higher received optical power is a necessary outcome for lasers with large intrinsic frequency noise.

c. *Developing analysis tools and frequency discriminators to properly characterize power-law noise as well as spurs in the spectrum.*

   In pursuing the limits of phasemeter performance in the presence of laser frequency noise, we developed a set of frequency noise requirements that capture stochastic noise as well as spurs in the spectrum and discontinuities; we developed as well the experimental capability to assess performance against these requirements by acquiring, storing, and analyzing large quantities of time-domain laser frequency noise data in a "suitcase tester."

   This suitcase tester was used to test a GRACE-FO Engineering Model laser from Tesat, which, while being NPRO lasers, turn out to have noise up to 200 kHz/rt(Hz) at 1 Hz (1/f), compared to laboratory NPROs which are approximately 20× quieter. This allowed characterization of laser performance without requiring a working phasemeter. While GRACE-FO paid for this testing, it relied extensively on techniques and equipment developed under the TMB and former LISA technology development tasks. TMB funding directly mitigated a risk to GRACE-FO.

Along with the technical achievements related to this task described above, an outcome of this investigation is the appreciation of the significance of higher-frequency noise and the tools to measure and understand the interplay between phasemeter design and laser frequency noise. This work suggests how the characteristics of NPRO lasers are naturally suited to high precision interferometry in a way other lasers, e.g., the DFB laser. This understanding, coupled with measurements and mitigation strategies developed for physical noise of flight-like lasers, (frequency spurs, frequency jumps, large laser relative intensity noise at the relaxation oscillation) appears likely to be the most enduring value of this work and will enable informed decisions about candidate lasers for this application.

FY12 Task 2: This was a simpler effort to assemble and test the analog signal chain between the photoreceivers and the digital phasemeter.

Status: *Objective achieved.*

We built and tested a four-channel analog signal chain board, enough for a pair of quadrant detectors. This board was tested experimentally in the optical testbed (Figure 4) along with the LISA quadrant photoreceivers and the LISA phasemeter. This experimental test met the signal chain noise performance requirement.

Remaining work for FY13

1. **Differential Wave Front Sensing Development**
   We will use our interferometer testbed the quadrant photoreceivers, analog-signal-chain and phasemeter developed under TMB and the LISA project to demonstrate differential wave front sensing. This is an element of LISA interferometry capability not previously experimentally tested in the LISA interferometry testbed.
2. **Complete the tool set for evaluating noise from real lasers against the demonstrated capabilities of the phasemeter.**

Phasemeter development/optimization

Simplify phasemeter architecture, digital tracking, and internal filters to increase overall efficiency. We aim to increase scalability and reduce communication between FPGA and processor.

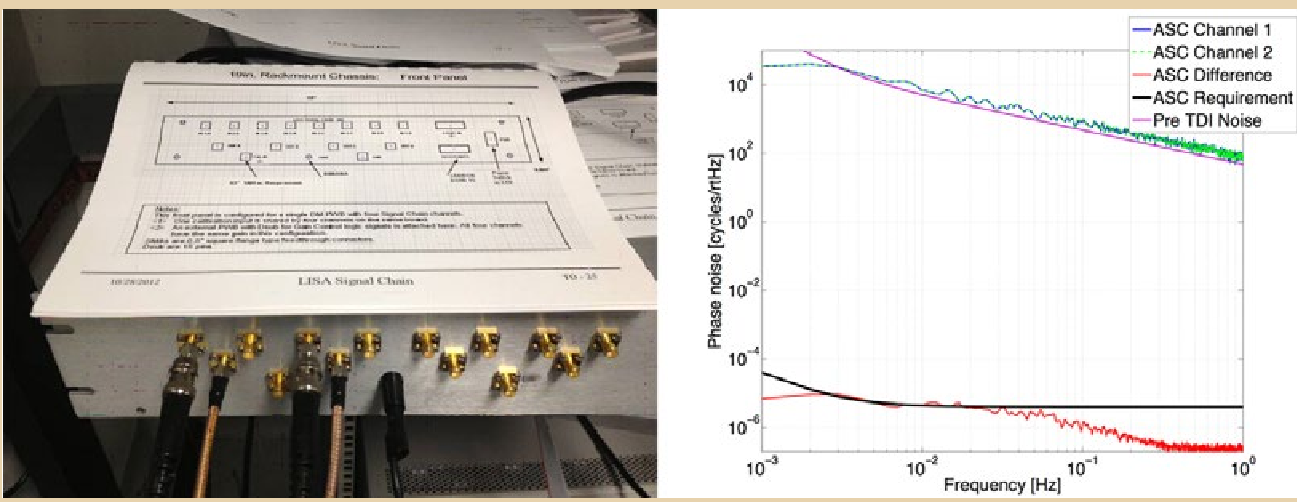


Figure 4. *Analog signal chain box completed and tested to requirements with LISA Quadrant Photoreceiver.*

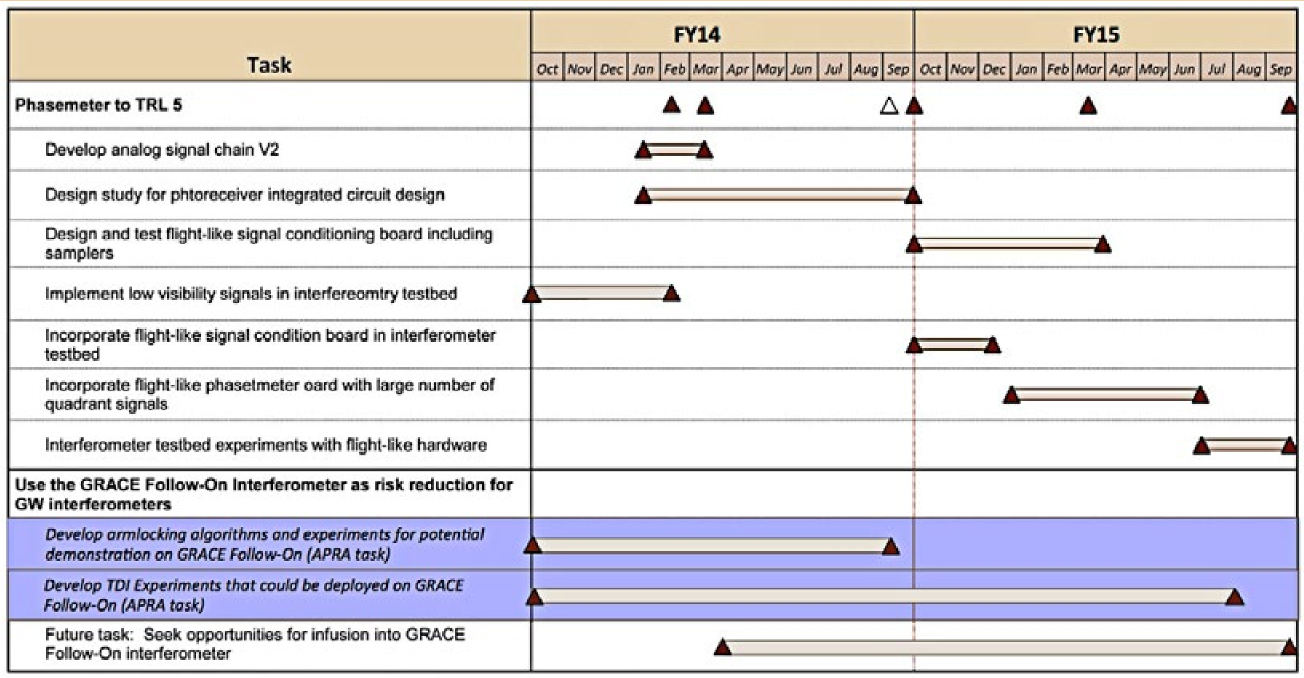


Figure 5. *Milestones for: the phasemeter to reach TRL-5 and to use GRACE-II as risk reduction for Gravitational Wave Interferometers. Blue shaded tasks are funded a ROSES-APRA grant.*

Future Tasks and Milestones

Future work on the phasemeter and test bed will focus on continuing to advance the TRL of the phasemeter toward TRL-5, maintaining the phasemeter as a viable strategic capability for gravitational wave missions, and looking for opportunities to reduce risk to future missions using the planned GRACE-FO interferometer.

The primary objectives of FY14/15 activities are to:

1) Complete the assessments of phasemeter performance as it relates to gravitational wave mission parameters and component technologies.
2) Maintain NASA as a viable partner in the (likely) scenario that ESA and NASA will partner in some form (ESA or NASA led).
3) Explore opportunities to leverage the GRACE-FO interferometer technology demonstration to reduce the risk of a future gravitational wave mission.

Proposed tasks for FY14/15:

1) Develop analog signal chain V2
2) Design study for photoreceiver integrated circuit design
3) Design and test flight-like signal conditioning board in interferometer testbed
4) Implement low visibility signals interferometer testbed
5) Incorporate flight-like signal conditioning board in to interferometer testbed
6) Incorporate flight-like phasemeter board with large number of quadrant channels
7) Interferometer testbed experiments with flight-like hardware
8) Explore opportunities to leverage the GRACE-II interferometer technology demonstration to reduce the risk of a future gravitational wave mission.

The Astrophysics Research and Analysis (APRA) program has funded a ground-based study of risk-reduction experiments that could take advantage of the similarities between the Laser Ranging Interferometer planned for GRACE-FO. Should this work be successful, follow-on tasks to implement flight experiments would represent a high value-to-cost ratio validation of key LISA interspacecraft interferometer concepts.

The tasks (1–7) put the phasemeter on a 2- to 3-year path to TRL-5 for an investment of approximately $400k–$500k/year. These tasks are currently unfunded, with opportunities being sought through the Strategic Astrophysics Technology program. Milestones for these tasks over the next two years are shown in the Milestone Schedule in Figure 5.

The GW interferometer risk reduction activities (task 8) are partially funded: conceptual development and algorithm demonstration are funded under the ROSES-APRA program (blue shaded tasks) through FY15. We are seeking opportunities for funding the flight implementation of this project on GRACE-FO starting mid FY14.

References

[1]Viterbi, A.J., Phase-locked loop dynamics in the presence of noise by Fokker-Planck techniques, Proceedings of the IEEE, vol.51, no.12, pp.1737

[2]The LISA Frequency Control White Paper, D. A. Shaddock, K. McKenzie, R.Spero, et al., ESA document LISA-JPL-TN-823, (2009).

[3]G. de Vine, B. Ware,K. McKenzie, R E. Spero, W. M. Klipstein, and D. A. ShaddockPhys. Rev. Lett. 104, 211103 (2010).

Contact:
bill.klipstein@jpl.nasa.gov

Directly-Deposited Optical Blocking Filters for Imaging X-ray Detectors

Prepared by: M. Bautz and S. Kissel (Massachusetts Institute of Technology, Kavli Institute for Astrophysics & Space Research); K. Ryu and V. Suntharalingam (MIT Lincoln Laboratory)

Summary

We aim to raise the technology readiness level (TRL) of enhanced charge-coupled device (CCD) detectors capable of meeting the requirements of X-ray grating spectrometers (XGS) and wide-field X-ray imaging instruments for small, medium and large missions. Because they are made of silicon, all X-ray CCDs require blocking filters to prevent corruption of the X-ray signal by out-of-band (mainly optical and near-IR) radiation. We endeavor to replace the fragile, extremely thin, free-standing blocking filter that is current standard practice with a much more robust filter deposited directly on the detector surface.

Although high-performance, backside illuminated (BI) CCDs have flown with free-standing filters (e.g., one of our detectors on *Suzaku*) and other, relatively low-performance CCDs with directly deposited filters have flown (e.g., on the XMM-Newton Reflection Grating Spectrometer), a high-performance, BI CCD with a directly deposited filter has not yet been demonstrated. Our effort will be the first to show that such a filter can be deposited on an X-ray CCD that meets the requirements of a variety of contemplated future instruments.

This 2-year Strategic Astrophysics Technology (SAT) program began on July 1, 2012. It is a collaboration between the Massachusetts Institute of Technology (MIT) Kavli Institute for Astrophysics and Space Research (MKI) and MIT Lincoln Laboratory.

Background

The past 2 decades have brought extraordinary progress in X-ray astronomy, in large measure as a result of unprecedented capabilities in X-ray imaging and grating spectroscopy. Beginning with the launch of the *Advanced Satellite for Cosmology and Astrophysics* (ASCA) in 1993, and continuing to the present, concurrent operation of *Chandra*, XMM-Newton, *Swift*, and *Suzaku*, much of this success has been enabled by the X-ray photon counting CCD. CCDs will likely remain essential to many X-ray instruments for some time to come. In fact, three missions scheduled for launch in the next few years (e-Rosita, Astrosat, and Astro-H) feature these detectors. Moreover, a number of future mission concepts include instruments relying on CCDs. Such instruments address a broad range of important scientific objectives. For example, as noted recently in the *X-ray Mission Concepts Study Report* (XCSR) commissioned by NASA's Program Office for the Physics of the Cosmos (PCOS)[1], several high-priority scientific questions identified by the Astro-2010 Decadal Survey (Astro2010)[2] are best addressed by an X-ray Grating Spectrometer (XGS), which requires large-format X-ray imaging detectors. Specific science goals for an XGS are summarized in Table 1. The report notes that an XGS could be deployed either along-side an X-ray micro-calorimeter on a probe-scale mission, or as the sole instrument in a more modest, dedicated mission. XGS technology has therefore been identified as a priority 1 (highest-priority) need in a previous PCOS Program Annual Technology Report (PATR)[3].

Large-format X-ray imaging detectors are also required for many missions envisaged for the Explorer program, which Astro2010 deemed "a crown jewel of NASA space science." For example, an Explorer XGS has been proposed for a focused study of the warm-hot intergalactic medium[4]. Other future

Explorers will exploit the power of rapid-response X-ray imaging, so clearly demonstrated by *Swift*, but with much wider fields of view. As noted in[5], a wide-field X-ray imager (WFI) on an agile spacecraft can address a variety of important science objectives (see Table 1), ranging from the nature of the first galaxies to high-energy time-domain astrophysics with unprecedented sensitivity[5]. An especially exciting prospect is the identification of sources that may be detected by ground-based gravitational wave observatories later in this decade[6, 7].

Science Question	Measurement	Instrument
How does large scale structure evolve?	Find & characterize the missing baryons via high resolution absorption line spectroscopy of the WHIM.	XGS
How does matter behave at high density?	Measure the equation of state of neutron stars through spectroscopy.	XGS
How are black holes connected to large scale structure?	Determine energetics & mass flows in AGN outflows; probe hot galaxy halos via absorption spectroscopy.	XGS
When did the first galaxies emerge & what were they like?	Identify high-redshift galaxies via gamma-ray bursts	WFI
What new discoveries await in the time domain?	Monitor the entire sky with high sensitivity to find & study gravitational wave sources & other transients	WFI

***Table 1**: High-priority science drivers for future instruments featuring large-format imaging X-ray detectors. Adapted from the PCOS X-ray Mission Concepts Study Report[1]. Directly-deposited optical blocking filters (OBF) will improve the performance and reliability, while reducing cost and risk, of instruments addressing these questions. XGS=X-ray Grating Spectrometer; WFI = Wide-Field Imager.*

Our program aims to raise the technology readiness of advanced OBF technology required for these instruments. If successful, our effort will improve instrument sensitivity, robustness, and reliability, while at the same time reducing mass, complexity, risk, and cost. Our approach is to replace the fragile, free-standing optical-blocking membrane of current practice with a filter deposited directly on the detector surface. A directly-deposited filter can be thinner, and thus lead directly to better instrument sensitivity than a free-standing one. Moreover, directly-deposited filters do not require the heavy, complex, and expensive vacuum housings used in current instruments, and of course are much more robust than free-standing filters. The key challenge for our program is to demonstrate that blocking filters can be applied directly to the sensitive entrance surfaces of modern CCD detectors without compromising spectroscopic resolution.

To minimize cost, our program makes use of existing stocks of engineering grade detectors produced for past programs at MIT Lincoln Laboratory. We apply so-called ‘back-illumination’ processing to these detectors, and then use coating facilities at Lincoln to apply blocking filters. X-ray and optical performance testing is then conducted at MIT’s Kavli Institute for Astrophysics and Space Research. We have also joined forces with the Regolith X-ray Imaging Spectrometer (REXIS), an MIT student instrument for NASA’s *Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer* (OSIRIS-REx) mission, to incorporate directly-deposited blocking filter technology into a flight program.

Objectives and Milestones

Silicon X-ray imaging detectors require blocking filters to prevent ambient visible and ultraviolet (UV) background light from adding noise and degrading X-ray spectral resolution. As noted previously, most such detectors flown to date have used fragile, free-standing filters comprised of thin plastic substrates coated with aluminum. Free-standing filters must usually be protected from acoustic ground-handling and launch loads in heavy vacuum enclosures equipped with complex door mechanisms. This project aims to show that adequate blocking filters can be deposited directly on a detector, eliminating the need for fragile, free-standing filters. To the extent that they allow the elimination of the plastic film, such filters could also improve soft X-ray (E < 1 keV) detection efficiency.

A key challenge in this project is to demonstrate that directly deposited blocking filters provide the requisite optical blocking performance without compromising the spectral resolution of the detectors in the soft band. The latter depends critically on the electric fields present just inside the entrance surface of the detector, and these fields in turn require precisely controlled implant density profiles. Our aim is to deposit blocking filters in such a way that the surface fields are not affected by the deposition process or the filter itself. A secondary objective is to demonstrate that such filters are sufficiently robust to survive the repeated thermal cycling any such detector is likely to experience.

Our approach is to use existing CCD detectors fabricated for previous programs at MIT Lincoln Laboratory. These detectors (with some exceptions) are front-illuminated, so a part of our task is to perform back-illumination processing. Good X-ray response requires that a molecular beam epitaxy process be used to treat the back (entrance) surface. We then systematically apply aluminum blocking filters of various thicknesses, and characterize both the optical blocking of the filter and the X-ray performance of the devices.

Our original plan entailed four tasks:

Task 1: Select and thin existing CCID41 wafers and apply backside treatment
The target detectors for this project (Lincoln Laboratory model CCID41, as now in use in *Suzaku*) were stored in wafer form as front-illuminated (FI) devices (typically four devices to a wafer). Using wafer-probe equipment, we identify the functional devices. We then subject selected wafers to a custom back-side treatment process, involving wafer thinning and molecular beam epitaxy passivation, which has already been shown to provide good X-ray results. Selected BI devices are packaged (removed from the wafer and installed in suitable test packages) for subsequent test at MKI.

Task 2: Establish baseline X-ray performance
We use established X-ray characterization facilities and procedures at MKI to verify suitable X-ray performance of the BI (but uncoated) devices.

Task 3: Apply filters and characterize filter-equipped devices
We use established thin-film deposition facilities at MIT Lincoln Laboratory to deposit aluminum blocking layers, and then package and test the filter-equipped devices. Filters are applied at the wafer level, with control areas masked to allow direct comparison of filtered and unfiltered areas of each device. We contemplate three cycles of filter deposition and test (one wafer per cycle), applying a relatively thick filter in the first cycle, and then progressing, after successful test, to progressively thinner filters. In so doing we will span the range of filter thicknesses required by future instruments. All filters will be capped with a 10-nm aluminum oxide (Al_2O_3) layer to improve robustness and provide UV blocking. Both optical rejection and X-ray spectral resolution will be measured in the characterization protocol.

Task 4: Test robustness and stability
To verify temporal stability and robustness of the coatings to repeated thermal cycling experienced by CCD detectors during instrument development and test, we will perform thermal cycling and long-term (6–8 months) stability measurements.

Soon after the program started, we decided to alter the sequence of the program for two reasons. First, we discovered that a number of BI devices were already available at MIT Lincoln. To make the best use of these we needed to develop a filter deposition process that would accommodate individual chips as well as full wafers. Second, we learned that the MIT team developing REXIS, a student instrument for NASA's OSIRIS-REx mission, wished to fly X-ray CCDs with directly-deposited blocking filters. We have decided to collaborate with REXIS because by doing so we gain the opportunity to demonstrate much higher technology readiness level for our process than we could achieve in our original program. REXIS is scheduled for delivery in 2015; OSIRIS-REx plans a 2016 launch. Although this collaboration has entailed some re-planning, we expect to achieve our objectives as scheduled.

Major milestones and our progress in achieving them are summarized in Table 2. We describe our progress in more detail in the following section.

Milestone at completion of:	Success Criteria	Status as of June 2013
1. BI processing	Wafer-probe testing of BI wafers shows:	• 4 FI wafers processed, yielding 13 devices w/ at least some functionality
	• ≥ 3 wafers with functional devices; • ≥ 10 functional devices total	• 10 other functional BI devices identified as single chips • 8 more FI wafers now in BI process
2. X-ray test of baseline BI device	X-ray performance demonstrated per protocol specified in proposal	• Complete. X-ray performance of one device characterized; performance is acceptable
3. 1st device with thickest directly-deposited filter	Packaged device delivered to MKI	• Complete. 220nm Al deposited with 'liftoff ' coating process • Plan to repeat with device coated via 'shadow-mask' process
4. X-ray and optical testing of device with thickest filter	X-ray & optical tests done per protocol specified in proposal	• Complete (220nm Al deposited with 'liftoff ' coating process) • Plan to repeat with device coated via 'shadow-mask' process.
5. X-ray and optical testing of device with thinnest filter	X-ray & optical tests done per protocol specified in proposal	• Planned. Thin filter to be 70nm Al
6. Thermal cycle test	X-ray & optical tests done per protocol specified in proposal	• Planned for second half of year 2
7. Long-term stability test	X-ray & optical tests done per protocol specified in proposal	• Planned for second half of year 2

Table 2: *Project Milestones and Status*

Progress and Accomplishments

At the mid-point of our 2-year project, we have formally achieved four of the seven milestones listed in Table 2, although, as discussed below, we plan further work on milestones 3 and 4. Our work in year 1 culminated in completion of back-illumination processing of four wafers, and X-ray and optical characterization of a BI CCD equipped with a directly-deposited blocking filter. In the process of achieving these goals, we conducted a thorough inventory of available detectors, screened them to identify functional devices, characterized the purity and uniformity of our aluminum coatings, evaluated alternative filter deposition protocols, and selected a preferred one. Highlights of this work are described below.

CCD inventory, selection and back-illumination processing (milestone 1)

Our proposal aimed to select devices from among 12 FI wafers (with four devices per wafer) and subject a subset of these wafers to BI processing and subsequent filter deposition. Early in the program we identified an additional 16 devices in single-chip form which had already been subjected to the appropriate BI processing. Careful screening of these devices for functionality, dark current, and cosmetics showed that the detector inventory was adequate to support both our filter deposition program and the REXIS instrument development.

We elected to perform back-illumination processing of the 12 wafers in two groups. Processing of the first group of four wafers has been completed; 13 of the devices have some functionality. Remarkably, the BI processing actually reduced the dark current in most devices tested. The second, 8-wafer group is now being processed. Figure 1 shows an individual wafer before and another wafer after back-illumination. Four CCID41 devices are seen in the middle of the wafer in the left panel of the figure, which shows the 'front' or electrode side of the wafer. The smooth, nearly featureless backside of the wafer after processing is shown in the right panel. The lights and filter grid of the clean bench are seen in reflection in this image.

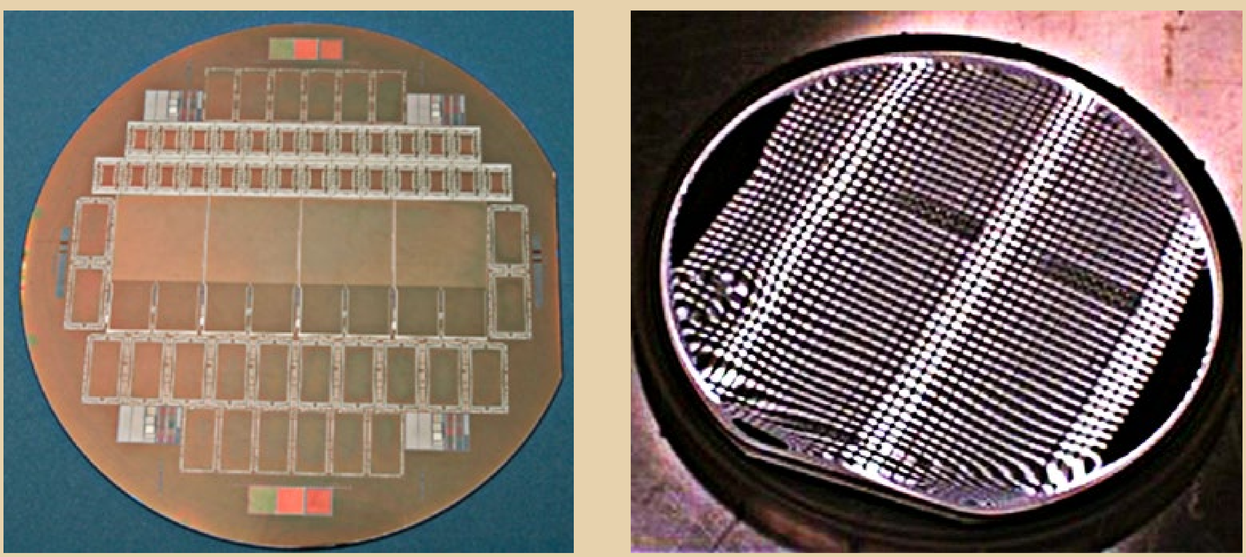


Figure 1. *Silicon wafers containing four CCID41 detectors before (left) and after (right) thinning and molecular-beam expitaxy back-illumination processing.*

Filter deposition process development and evaluation (milestone 3)

Our nominal OBF consists of a layer of aluminum (with thickness ranging from 220 nm to 70 nm, depending on intended application) capped by a thin (~10 nm) layer of Al_2O_3 to provide UV blocking and to protect the aluminum. We evaluated two methods for aluminum deposition: low-voltage thermal evaporation and electron-beam (e-beam) evaporation. We measured UV/optical transmission, uniformity, and elemental purity of test coatings applied to fused-silica substrates. Both methods produced acceptable films, and we selected the thermal process for its simplicity and perceived lower risk to the detectors. Energy-dispersive X-ray fluorescence spectroscopy found no detectable contamination in the coating, with an upper limit on tungsten contamination (from the evaporation boat) of no more than 1% by mass. Sheet resistance maps of test coatings showed good uniformity, with thickness variations across a 200 mm wafer of less than 6.6% peak to peak, and with variations within the area occupied by a single CCD of typically 0.3%.

In order to apply filter coatings at the single-chip level as well as at the full-wafer level, and to allow for the possibility of a filter thickness that varies with position on the device, we investigated two processes for masking parts of a detector during coating deposition. One of these, the 'liftoff' process, entails patterning of photoresist before filter deposition so that photoresist covers areas that are not be coated. Following filter deposition, the photoresist is dissolved, leaving the filter only on regions not initially covered with photoresist. A second process, the 'shadowmask' process, relies on a mechanical fixture to shield regions of the detector that are not to be covered by a filter. Although we succeeded in depositing filters with both processes, the shadowmask process provided superior yield and sufficient mask location accuracy. While our first X-ray test results (reported below) were obtained with a device coated using the liftoff process, we plan to use the shadowmask process for all further masked filter deposition work. At present the only known limitation on this process is that the device to be coated must be precision cleaned before filter deposition to prevent the formation of pinholes in the filter.

X-ray and optical performance of a CCD with directly-deposited blocking filter (milestones 2 and 4)

To date we have performed X-ray and optical testing on one CCD with a directly-deposited OBF. This device is shown in its package in Figure 2. This early test device differs in some important respects from the detectors we will test in the next phase of our program: It features an anti-reflection coating—89 nm of hafnium oxide (HfO_2) and 53 nm of silicon dioxide (SiO_2), installed for a prior program—beneath its 220 nm-thick aluminum (Al) blocking filter, and the blocking filter was masked using our (now less-preferred) 'liftoff' masking technique. This device has served as pathfinder for our testing protocols, and has allowed us to confirm that an OBF can be successfully deposited on a high-performance BI CCD.

Figure 2. *Photograph of packaged CCID41 with directly-deposited OBF. The dark strip on the right was left uncoated for comparison purposes.*

As is illustrated in Figure 2, the masking process allowed us to leave a small portion of the device without an Optical Blocking Filter (OBF). X-ray measurements made in the uncoated and coated regions show that the OBF has very little effect on the spectral resolution of this device even at energies as low as 277 eV, as shown in Figure 3. This result demonstrates that an OBF can be deposited directly on a high-performance X-ray CCD without serious degradation of X-ray response. We must confirm this result on devices without a buffering anti-reflection coating during the next phase of our program. We note that the line response this energy of this device has a full-width at half-maximum (FWHM) of about 75 eV. We expect better performance from subsequent, higher-quality devices. These detectors will allow a more sensitive search for the effects of the OBF on spectral resolution.

We have also made preliminary measurements of the transmission of the OBF in the visible (500–1000 nm wavelength) and X-ray (0.1–2 keV energy) bands. The X-ray measurements are consistent with the nominal thickness of the OBF. The visible measurements show an optical density ranging from 4.3 to 5.0 in this band, which is somewhat lower than a naïve calculation based on bulk optical constants would suggest. We plan to investigate this discrepancy in greater detail with higher-quality devices.

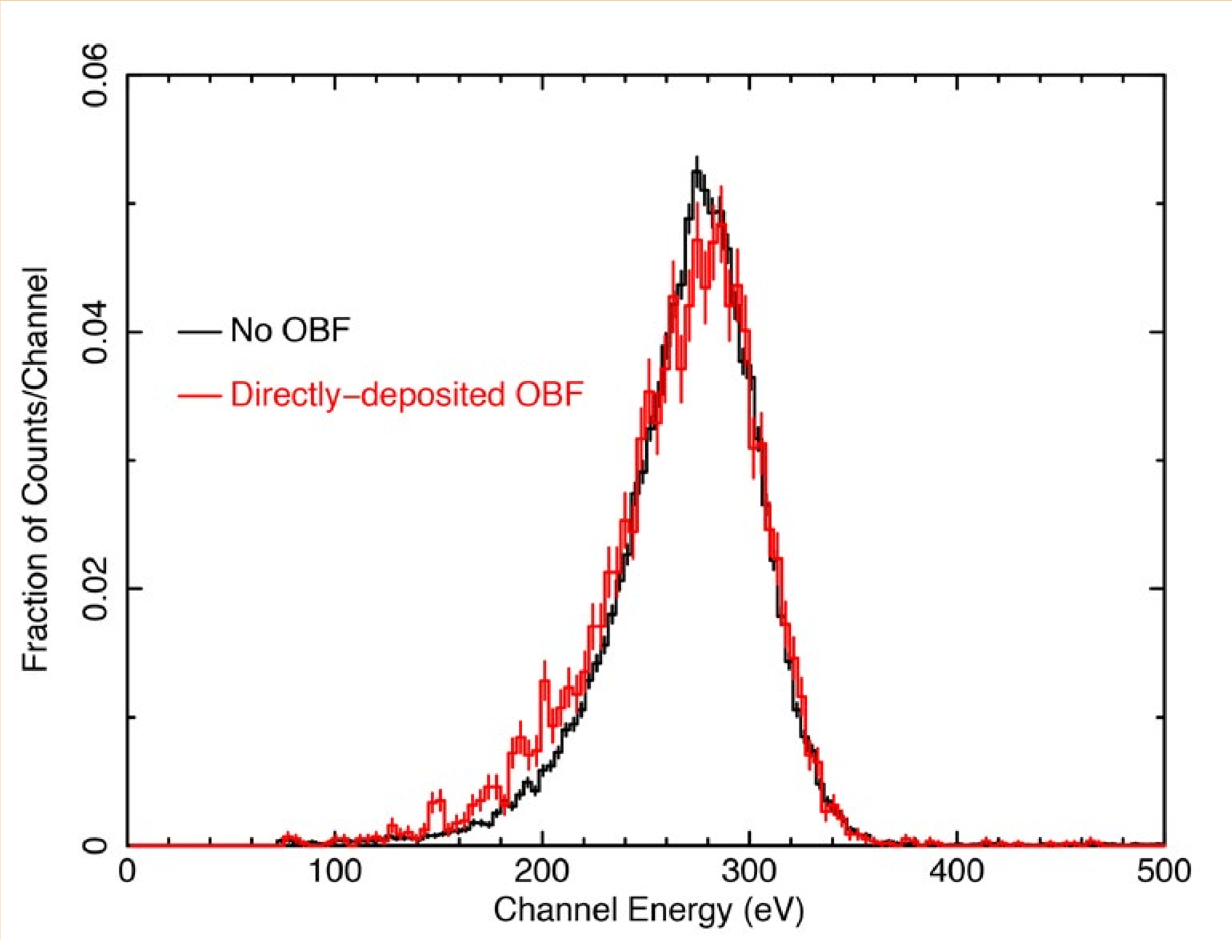


***Figure 3**. Measured X-ray spectral response at 277 eV from regions with (red) and without (black) a directly deposited OBF. The histograms have been normalized to have the same integrated area. The OBF has very little effect on spectral resolution even at this low X-ray energy.*

Path Forward

In the second year of our program we plan to do the following (milestone numbers refer to Table 2):

- Coat, package, and characterize X-ray and optical performance of higher-quality devices on which the OBF is deposited using our preferred ('shadowmask') masking protocol. We plan three OBF thicknesses, ranging from 220 nm to 70 nm. This work will address milestones 4 and 5.
- Subject selected devices to thermal cycle tests simulating typical ground-handling and flight conditions. The detailed protocols are discussed in our proposal. This work addresses milestone 6.
- Devise and execute a long-term (at 6–8 months) stability test to investigate the robustness of our OBFs. This work addresses milestone 7.
- Characterize REXIS engineering model CCDs with OBFs deposited at the full-wafer level. These devices will ultimately be subjected to environmental tests tailored to the OSIRIS-REx mission. While not originally part of our project, this work will provide the basis for validation of directly-deposited OBFs at a very high level of technical readiness.

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Contact:
mwb@space.mit.edu

Planar Antenna-Coupled Superconducting Detectors for CMB Polarimetry

Prepared by: James J. Bock (Jet Propulsion Laboratory, California Institute of Technology)

Summary

We are developing antenna-coupled superconducting detectors for sensitive, spaceborne cosmic microwave background (CMB) polarization measurements. Antenna-coupled bolometers are attractive because they have the sensitivity to realize photon-limited performance, and can be naturally adjusted to cover the entire frequency range, 30–300 GHz, needed to monitor and subtract polarized Galactic emission, in a single technology. Planar antennas are compact and low-mass, and naturally scale up to the large-array formats required by the NASA Inflation Probe, a future fourth-generation CMB satellite. New designs can provide system-level improvements–multi-color response for higher focal plane density, noise stability for scanning operations, and radio frequency (RF) multiplexing for simplified cold readout electronics.

Our program builds on experience from developing successive generations of devices developed for the *Planck* satellite and sub-orbital experiments. We are first advancing the RF design and material processing that affects the optical performance and beam formation of the antennas. We are also developing attributes of two detectors compatible with antenna coupling, Transition-Edge Superconducting (TES) bolometers and Microwave Kinetic Inductance Detectors (MKIDs). This parallel sensor development is attractive due to the RF multiplexed readout for MKIDs, which has a significantly simpler implementation compared with the Superconducting Quantum Interference Device (SQUID) current amplifiers used with TES bolometers. We are developing MKIDs appropriate for low-photon backgrounds, and characterizing cosmic ray susceptibility and $1/f$ noise in TES bolometers. Finally, we are developing a modular focal-plane unit designed to scale up to the large multi-band focal planes needed for space.

This 2-year program began in January 2012 and includes Peter Day, Warren Holmes, Henry LeDuc, Kriekor Megerian, Roger O'Brient, Hien Nguyen, and Anthony Turner from NASA's Jet Propulsion Laboratory (JPL). Our most notable program accomplishment is to have developed an improved fabrication process that reliably produces high optical efficiency and extremely well matched polarized beam patterns.

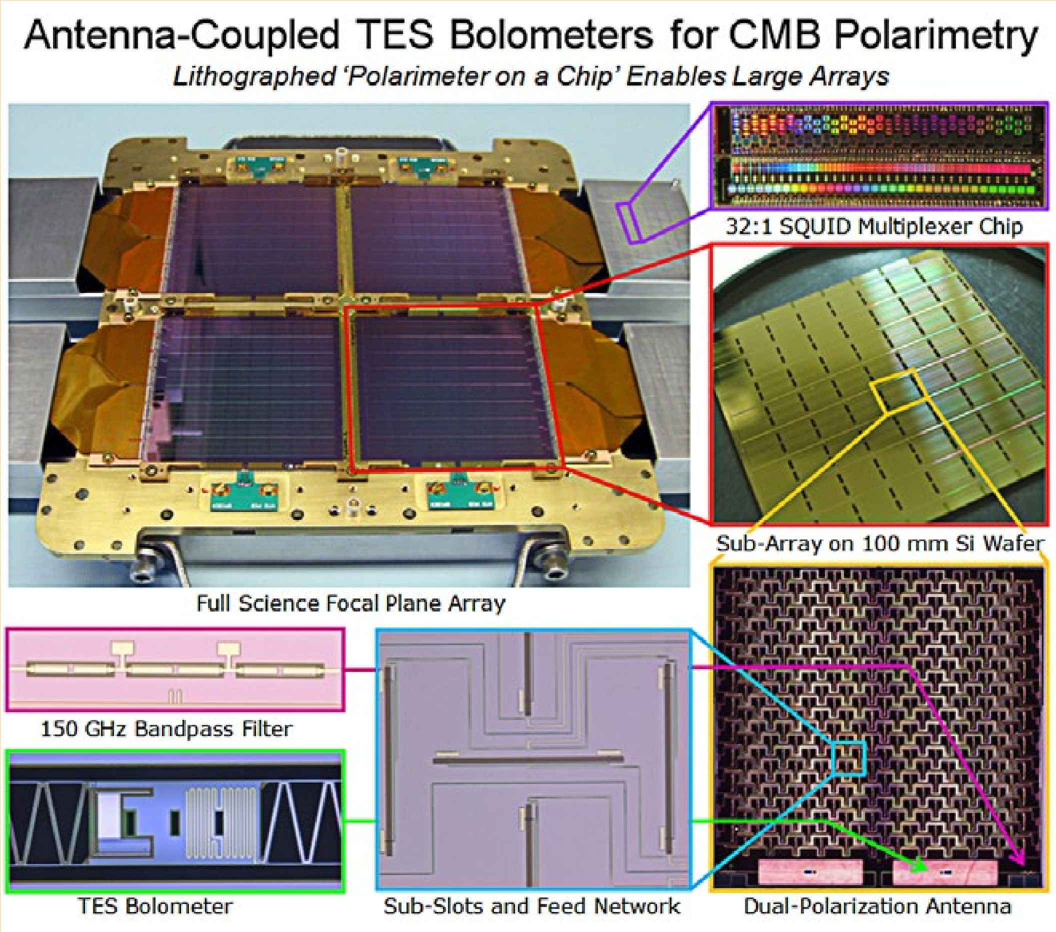


Figure 1. *Overview of a planar antenna-coupled TES bolometer array for CMB polarimetry. A full science plane array with four 150 GHz wafers and 512 bolometers is shown in the upper left. The focal plane has 16 32:1 multiplexed SQUID readout chips, located in magnetically shielded boxes next to the focal plane. Leads from the detectors are carried on superconducting aluminum (Al) kapton flex cables to the readout SQUIDs. Array wafer components include: sub-arrays made on 100 mm wafers with 8×8 antenna-coupled devices; dual-polarization antenna-coupled TES bolometer; section of the antenna showing combination of sub-slots with two microstrip feed networks for the two polarizations; band-defining filter at the antenna output; thermally isolated TES bolometer and gold (Au) absorber.*

Background

The NASA Inflation Probe will measure CMB polarization to fundamental limits, in order to extract all the cosmological information from the CMB. The CMB is thought to carry an Inflationary polarization signal imparted by a gravitational-wave background produced ~10^{-32} seconds (s) after the Big Bang singularity. The Inflationary polarization signal is sensitive to the energy scale and shape of the Inflationary potential, and can be clearly distinguished from polarization produced by matter density variations due to its distinctive B-mode spatial signature. In addition, a B-mode polarization signal from gravitational lensing imparted by large-scale structure is sensitive to neutrino mass and dark energy. Finally, the CMB contains an E-mode polarization signal which probes the history of reionization. The expected role for a space mission will be to comprehensively measure all of the polarization signals over the entire sky down to astrophysical limits. These measurements require a factor of ~20 sensitivity increase over the bolometers currently observing the CMB in the European Space Agency (ESA)/NASA *Planck* satellite.

Detecting the polarization signature of the inflationary gravitational-wave background, or ruling it out to low levels–is arguably the most important goal in cosmology today. The first recommendation of the 2003 National Research Council (NRC) report, Connecting Quarks with the Cosmos, is to "Measure the polarization of the CMB with the goal of detecting the unique geometric signature of Inflation," In 2005, the Task Force on CMB Research identified polarization as the highest priority for the CMB field and established a target sensitivity for a future orbital mission dedicated to this goal. The 2010 Decadal Survey of Astronomy and Astrophysics describes detection of the Inflationary polarization signal as "the next great quest of CMB research" and prominently recommended supporting CMB technology in the coming decade in preparation for a dedicated space mission, its second-ranked medium initiative for space:

> "The committee recommends a technology selection and mission development to design a mission to study the signal.... ranging between the notional budget used here ($60M) up to a significant ($200M) mission-specific technology program starting mid-decade."

This proposal supports the Einstein Inflation Probe in NASA's Physics of the Cosmos Program, addressing the objective in the NASA 2010 Science Plan to "understand the origin and destiny of the universe, and the nature of black holes, dark energy, dark matter, and gravity" as part of the goal for NASA Astrophysics to "discover how the universe works, explore how the universe began and evolved, and search for Earth-like planets." Furthermore, the development of these detector technologies has relevance to other areas of NASA astrophysics, in particular the low-background TES/MKID sensors needed for future spaceborne far-infrared astronomy and a shared core technology base with X-ray superconducting calorimeters.

The enabling technology for the Inflation Probe is large multi-wavelength arrays of background-limited, polarization-sensitive detectors. The Planck bolometers achieved near-background limited performance with 52 individual detectors and readouts. Achieving improved sensitivity thus mostly depends on developing larger formats. Such large arrays not only require scalable (i.e., multiplexed) readouts and detectors, but also scalable optics to replace individual corrugated feedhorns and discrete optical filters. Antenna-coupled detectors represent such a scalable technology. The coupling optics are planar and entirely lithographed. Furthermore, the antenna design can be scaled to cover the range of operating frequencies (30–300 GHz) required for galactic foreground removal. Antenna-coupled bolometer array technology has rapidly advanced, and is currently being applied to CMB studies from ground-based and sub-orbital platforms in a search for B-mode inflationary polarization. However, a range of issues remains to advance this technology from sub-orbital applications to readiness for spaceborne measurements. Our program addresses these mid-technology readiness level (TRL) issues, including improvements in the RF design and fabrication, development of scalable focal plane modules, and superconducting detector noise performance and particle susceptibility.

Objectives and Milestones

Our objectives span a range of issues to advance the readiness of antenna-coupled bolometers. On the antennas, we are working to improve the efficiency, polarization matching, and fabrication reproducibility. We are advancing two detectors compatible with antenna coupling, TES bolometers and MKIDs. For large arrays, the RF multiplexed readout for MKIDs is significantly simpler than the SQUID current amplifiers used with TES bolometers, and we will develop and test MKIDs for low-photon backgrounds. For TES bolometers, we are characterizing cosmic ray susceptibility and $1/f$ noise. Finally, we are developing a modular focal-plane unit designed to scale up to large multi-band focal planes.
Advanced development builds upon current antenna-coupled detector technology to address specific challenges for a space mission. This work falls into four categories:

Milestone	Status
Antennas: Uniformity *Develop uniform feed networks*	Completed May 2012
Antennas: Polarization Matching *Develop compensations to minimize polarized beam displacement*	Completed May 2012
Antennas: Tapering *Develop tapered Gaussian planar antennas*	Completed June 2012
Dielectrics: Loss *Measure loss in improved materials: PECVD nitrude, amorphous Si*	Sept. 2012 *New Nb etchback process* July 2013 *Test losses at 250 GHz*
Dielectrics: Vias *Develop and test via process*	Sept. 2013
MKIDs: Sensitivity *Demonstrate NEP under Einstein Inflation Probe optical loading*	Dec. 2013
MKIDs: Stray Coupling *Measure and eliminate stray coupling*	Dec. 2013
TES Sensors: Particles *Test particle response to develop mitigation techniques*	Oct. 2012 *Tested readout susceptibility* Aug. 2013 *Test of frame mitigation*
TES Sensors: Stability *Demonstrate stability with pair differencing and bias switching*	Sept. 2013
Focal Plane Module *Develop modular focal plane unit and test noise, B-shielding, stray light*	Dec. 2012 *Fab and thermal test complete* July 2013 *Integrate with SQUIDs and detectors*

- new antenna designs to provide improved sidelobe control and polarization matching;
- improved propagation materials to allow flexible multi-color antennas;
- developing MKID sensors appropriate to CMB photon levels and improving the stability and particle susceptibility of TES detectors; and
- a modular focal-plane unit for building large spaceborne focal plane arrays.

Progress and Accomplishments

Our proposal milestones have been adjusted somewhat in response to both external factors and unexpected technical developments. In response to a 65% reduction in year 1 funding, we delayed work on MKID sensors well into year 2. A breakthrough in developing a new process that addressed the dominant source of optical loss and antenna mismatch earlier than planned affected our milestones on dielectric materials. Finally plans for particle susceptibility testing were modified in response to new information from a detailed analysis of cosmic ray events in *Planck* satellite data.

In year 1 we successfully demonstrated an improved antenna feed network that reduces cross-coupling between the two polarizations in the feed network. This cross-coupling manifested itself as a horizontal displacement between the vertical and horizontal polarization beams. The variations in propagation velocity were related to the properties of the niobium (Nb) and depend on the patterning and deposition process. We developed a new etchback Nb fabrication process that both reduced the phase shifts that caused beam mismatches and significantly improved optical efficiency. We made specialized loss test devices and found that losses in our niobium/silicon oxide/niobium ($Nb/SiO_2/Nb$) striplines followed a $\sim\nu^2$ dependence, characteristic of losses in the Nb due to impurities or stress, rather than losses in the dielectric as we had anticipated. We developed a Nb etchback process with a new etch chemistry and have since found antenna uniformity, efficiency and matching have been improved and give reliable results over multiple fabrication runs.

Early in year 1 we developed a new tapered-beam antenna, which simulates a Gaussian beam pattern. Compared to earlier tophat designs, the Gaussian profile reduces secondary sidelobes, and such control is especially important in conjunction with an ambient-temperature telescope. We developed three tapered designs for three different antenna sizes, and found the beam pattern closely matched theoretical expectations.

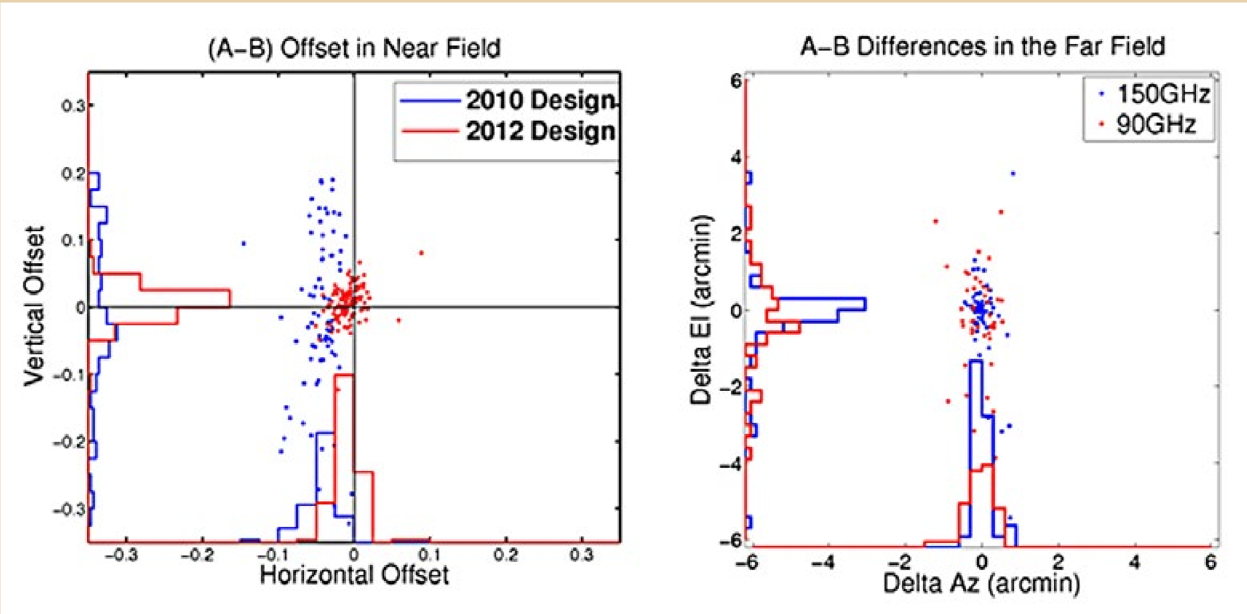


Figure 2. *Left: Beam displacement between pairs of polarized detectors, measured in the far-field of the antennas (essentially the 'near-field' aperture plane of the telescope). Changes to the feed network design and improvements in material processing have reduced both the large vertical scatter and the horizontal offset. Right: Measured polarized beam displacements in the far-field of a 25-cm refracting telescope.*

In October 2012 we completed first tests of particle susceptibility using a radioactive Sulfur-35 (167 keV beta) source. This test was primarily designed to measure the interaction of particles with the time-domain multiplexed SQUID readout system, and indeed we found that a fast particle event causes the readout system to skip a flux quantum. Hits with energies above ~10 keV often caused the readout system to lose lock temporarily, leading to a step discontinuity. This discontinuity is always of the same magnitude (one flux quantum). The readout software has been updated to account for these events by intermittent SQUID resets. In these initial tests we observed no clear evidence of hits to the silicon frame, consistent with our expectations from its large heat capacity, and will require testing with more energetic particles in a beam line.

Members of our team have been participating in the reduction of *Planck* flight data, which is heavily affected by particle upsets. The particle event channel in Planck that most affects data we now associate with energy deposited in the detector silicon (Si) frame, not the detector itself. Therefore we have altered our plans for particle testing to first test of a frame with additional heat capacity and conductance to

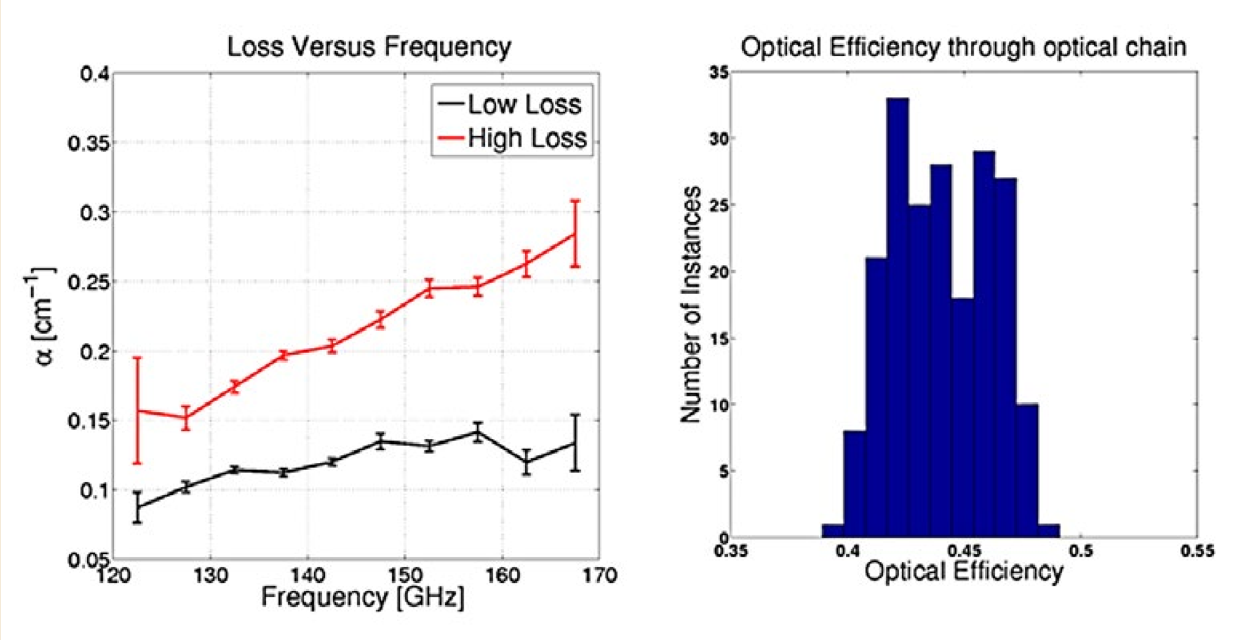


Figure 3. *Left: Loss measured in niobium/silicon oxide/niobium (Nb/SiO_2/Nb) microstrip. An improved Nb deposition and etch process has reduced the loss seen in first-generation devices that was dominated by losses in the Nb. Right: Measured end-to-end optical efficiency in a recent focal plane produced with the new Nb process.*

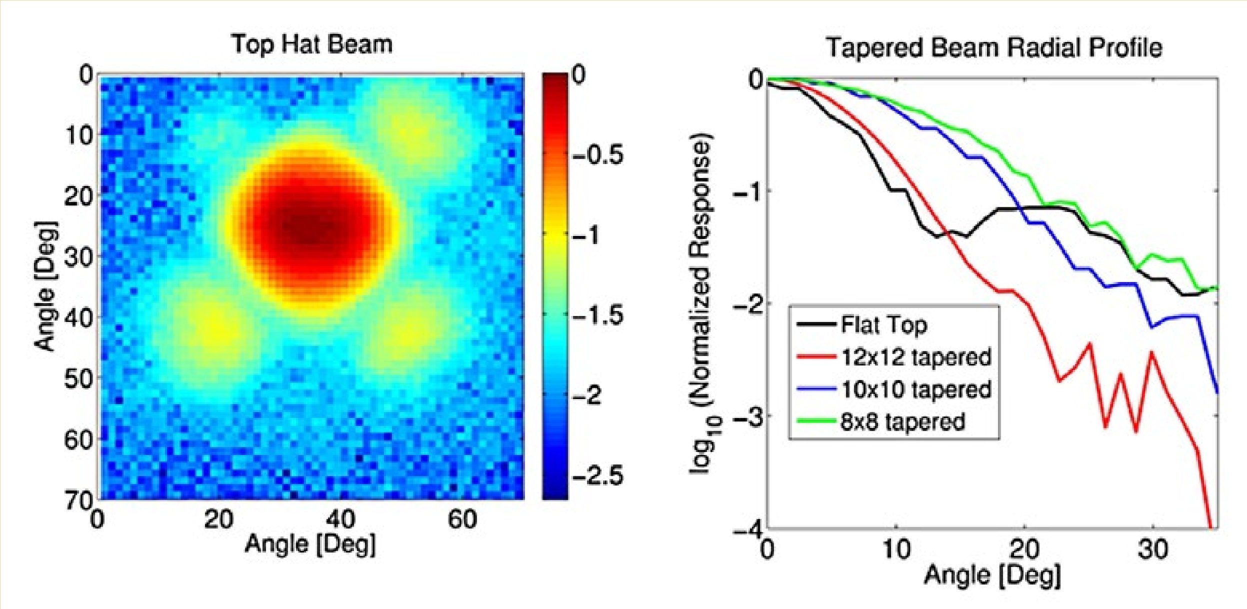


Figure 4. *Left: Antenna beam pattern for a standard flat-top antenna, plotted in power on a log10 color scale, showing the sinc-function secondary lobe pattern. The upper left secondary lobe is vignetted by the cryostat window (note the wide angular range required for this measurement. Right: Radial averages computed on measured beam maps for a flat-top antenna (black) and three Gaussian tapered antennas (red, blue, green). Tapering broadens the beam and suppresses the secondary lobes.*

case side by side with an unaltered flight bolometer. Our expectation is this thermally engineered frame will have reduced long-time constant cosmic ray events, a result that would have important implications for the design of a spaceborne detector system.

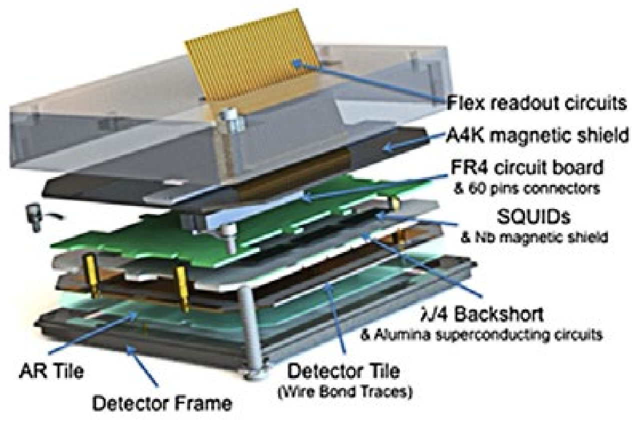
For observations on large angular scales, instrument noise must be stable on time scales of the scan period. We have thus investigated ways to reduce the contribution of $1/f$ noise to our TES bolometers and readout system. Initial measurements found excellent noise stability after differencing signals within a polarization pair (~20 MHz $1/f$ knee), but identified a substantial common-mode noise contribution within each readout column. A correlation analysis traced this common-mode noise to the TES bias circuitry in the readout electronics, which we have since modified. We now achieve much-improved low-frequency noise performance in individual detectors, with a median $1/f$ knee ~50 MHz over full detector arrays. Further reduction of $1/f$ drift may be possible, after further investigation of the source of the remaining $1/f$ noise.

Our SAT work on MKID sensors has focused on two areas: improving the noise equivalent power (NEP) needed to be photon background limited for CMB loadings, and reducing direct pickup. To improve the NEP, we have concentrated design work on MKIDs using titanium nitride (TiN) at lower resonant frequencies. TiN itself is an excellent material because it shows a very high kinetic inductance fraction due to its large penetration depth while having remarkably low loss. We use the increase in responsivity at low resonator frequency to reduce the impact of two-level system (TLS) noise.

We have developed a design that uses inductive coupling between the mm-wave microstrip and the inductive section of a lumped-element TiN MKID resonator. The inductive coupling turns the section of the mm-wave microstrip with TiN inductor next to it into a lossy termination. The same design also offers a solution to the direct absorption problem. The inductive portion of the resonator sits behind a ground plane that shields it from direct illumination, creating a short-circuit condition that prevents a free-space mm-wave from being absorbed. We use a parallel-plate geometry for the capacitor, inherently self-protecting against absorption of mm-wave radiation because it presents no gap across which a mm-wave voltage can be developed.

Ultimately, we will make this capacitor using crystalline silicon by fabricating on a Silicon-on-Insulator (SOI) wafer. To demonstrate that the basic design works, we will first make the capacitor using amorphous silicon (aSi). There are indications that the TLS noise in aSi may be low enough, but crystalline Si offers a loss tangent at least an order of magnitude lower, providing a factor of three additional gain in TLS noise.

We have been developing a modular focal-plane assembly that is suited to the construction of the large focal-plane arrays needed for space. This modular construction enables testing and qualification of individual sub arrays that include detectors and readout amplifiers, complete with integral magnetic shielding. We designed a prototype module in year 1 and completed preliminary thermal tests of the dimensional stability. In year 2 we completed a revised design which has now been fabricated. The module uses a new flux-modulated SQUID readout, and these chips were first tested with representative bolometers to confirm the modulation curves and noise performance. We recently completed a detector sub-array so we now have all the components to begin integration and testing.



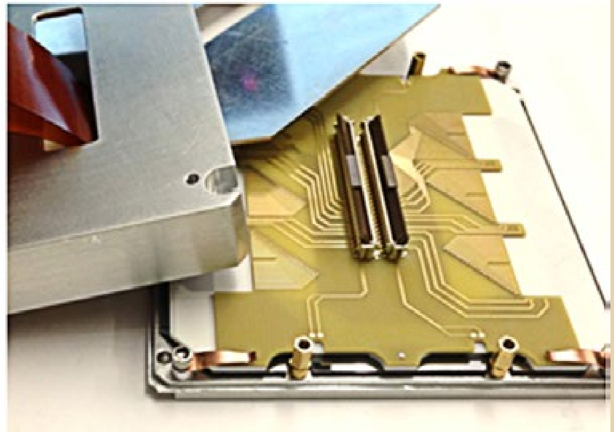


Figure 5. *Left: Modular focal-plane unit design incorporating an array of 128 bolometers operating at 95 GHz. The unit includes a quartz anti-reflection wafer, a detector wafer, an alumina circuit board for the SQUIDs that doubles as a λ/4 retro-reflector, a FR4 circuit board for routing wires with vias to a flex I/O cable, and integral magnetic shields. The modules are densely square-packed (light enters from the bottom). Right: Assembled components of the thermal/ mechanical prototype module.*

Path Forward

Our next dielectric test devices will use the new Nb etchback process and will target losses at higher frequencies, 200–300 GHz with silicon dioxide and silicon nitride dielectrics. These loss test devices have already been fabricated and testing is scheduled for July 2013. Stability testing of TES bolometers will be measured in a low-background environment during the integration of the SPIDER balloon experiment in late summer. MKID detector milestones are planned at the end of year 2 that involve a new ground plane design to shield the detector and prevent stray coupling. The focal-plane module will be assembled with the new flux-modulated SQUID chips and detector sub-array in early July. We will test noise performance and magnetic shielding with the detectors at the end of July.

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Contact
james.j.bock@jpl.nasa.gov

Off-plane Grating Arrays for Future Missions

Prepared by: Randall L. McEntaffer (University of Iowa)

Summary

High-resolution X-ray spectroscopy is a scientifically relevant technology capable of addressing many key science objectives such as detecting the large fraction of missing baryons thought to exist in the warm-hot phase of the intergalactic medium. Such observations will require a combination of high effective area and high spectral resolving power at energies below ~2 keV. These measurements can be enabled for future missions through the use of an X-ray grating spectrometer incorporating large-area optics, high-resolution gratings, and sensitive Charge-Coupled Device (CCD) cameras. Technology development efforts are occurring in each of these key areas in order to increase the readiness of such spectrometers.

Here, we describe progress made during the second year of a multi-year technology development effort for an Off-Plane X-ray Grating Spectrometer (OP-XGS) (McEntaffer, et al. 2011). Much of this development was achieved during our Strategic Astrophysics Technology (SAT) program, which started in January of 2012 and ends in December of 2013. Our team consists of collaborators from academic institutions (the University of Iowa, and the University of Colorado), NASA centers (Goddard Space Flight Center, GSFC, and Marshall Space Flight Center, MSFC), as well as an international partner (the Open University, UK). We are investigating a novel grating fabrication method that utilizes standard semiconductor industry lithography approaches. We also assess the performance of the resulting gratings, and the challenges involved with incorporating them into aligned assemblies. Over the past 1.5 years we have made significant advancements in each of these areas. The results from the first year of our study include identification of the preferred fabrication technique involving electron beam lithography, measurement of the high grating efficiency resulting from this fabrication technique, and initial analysis of our necessary alignment tolerances (see the Progress and Accomplishments section, and McEntaffer, et al. 2013). Once complete, our development effort will position the OP-XGS for flight system development upon identification of the next spectroscopic X-ray observatory.

Background

The purpose of this study is to advance high-resolution X-ray spectroscopy and its application in future NASA missions. Specifically, the project will concentrate on improving the technology readiness level (TRL) of off-plane reflection grating spectroscopy for soft X-rays (0.3–1.5 keV). This technology has applications in a variety of NASA missions from suborbital rockets, to Explorer class missions, to large observatories. It has been baselined for a proposed Explorer mission, the Warm-Hot Intergalactic Medium Explorer (WHIMEx), and is applicable to many other mission concepts such as the Advanced X-ray Spectroscopinc Imaging Observatory (AXSIO), the Notional X-ray Grating Spectrometer (N-XGS), and the Square Meter Arcsecond Resolution Telescope for X-rays (SMART-X). Soft X-ray grating spectrometers with high throughput and high spectral resolving power can address many top science questions such as:

What controls the mass-energy-chemical cycles within galaxies?
How do baryons cycle in and out of galaxies, and what do they do while they are there?
What are the flows of matter and energy in the circumgalactic medium?
How do black holes work and influence their surroundings?
How do massive stars end their lives?
What controls the masses, spins, and radii of compact stellar remnants?
What are the progenitors of Type Ia supernovae and how do they explode?

These science goals can be addressed with high-quality X-ray spectra as specifically stated in the *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) Decadal Survey. At the lowest energies, the most efficient method of obtaining high spectral resolving power is through the use of grating spectrometers. High resolution spectra could address a number of important astrophysical goals such as studying the dynamics of clusters of galaxies, determining how elements are created in the explosions of massive stars, and revealing most of the "normal" matter in the universe that is currently thought to be hidden in hot filaments of gas stretching between galaxies.

In order to achieve these science goals the OP-XGS must be capable of producing spectral resolving powers >3000 ($\lambda/\delta\lambda$) with high throughput over the soft X-ray energy band, 0.3–2.0 keV. The major limiting factor is obtaining the spectral resolving power requirement. In the context of off-plane reflection gratings, this requires customization of the groove profile to obtain blazed facets with high groove density that varies along the groove direction. Holographic recording of the groove profile has been the standard method for off-plane grating fabrication, but has limitations in obtaining the desired custom profile. We are developing a new fabrication method that utilizes common lithographic techniques borrowed from the semiconductor industry. Electron beam (e-beam) lithography enables tighter control over the groove profile during recording while various etching steps can be used to shape the facets to the desired blaze. An optimal groove profile will cancel any grating induced aberrations to the telescope focus while maximizing throughput and resolving power over our wavelength band of interest. Once fabricated, the gratings will be aligned into an array to increase the overall collecting area of the spectrometer. Alignment tolerances must be met so that every spectrum from every grating overlaps at the focal plane without alignment induced distortion. We have analyzed our alignment tolerances and are currently developing medium-fidelity mounts to position gratings and measure their placement. Therefore, at the highest level, our development plan can be described as two main paths: 1) a study of the custom fabrication of gratings to increase the fidelity of the groove profile, and 2) a study of alignment methods for populating large arrays of gratings.

Progress made during the development of the OP-XGS has been detailed in the two previous years' Program Annual Technology Reports (PATR) of the Physics of the Cosmos (PCOS) Program. The PCOS program has identified X-ray reflection gratings as a critical technology for development in this decade to address X-ray science goals. In this role, we have also contributed a development roadmap detailing the efforts and milestones necessary to advance the OP-XGS to flight readiness. This has been incorporated into the recent PCOS Technology Development Roadmap (TDR).

Objectives and Milestones

The development of an OP-XGS for future X-ray missions follows a set of objectives defined by our three main programs: 1) an SAT grant to study grating fabrication techniques, grating substrate and module mount material, and the alignment of gratings; 2) a Roman Technology Fellowship (RTF) to refine the fabrication and replication of medium- to high-fidelity gratings; 3) an Astronomy and Physics Research and Analysis (APRA) grant to launch a suborbital rocket payload incorporating slumped glass X-ray optics, an aligned array of off-plane gratings, and a soft X-ray sensitive CCD camera. The synergy between these projects allows for an extensive and detailed set of OP-XGS development project milestones:

1. Grating fabrication trade study; compare holographic and e-beam lithography groove recording techniques–completed first quarter of 2012.
2. Initial grating fabrication trials; use e-beam lithography to write the groove profile at the correct density with an accurate line space variation–completed early second quarter of 2012.

3. Performance test initial gratings
   a. Test diffraction efficiency of gratings over 0.3–1.5 keV band–completed second quarter of 2012.
   b. Test spectral resolving power of gratings–completed 3rd quarter 2012.
4. Quantify alignment tolerances–completed 1st quarter 2013.
5. Fabricate low-fidelity module mount and quantify performance in placement and metrology–completed 2nd quarter 2013.
6. Perform module mount trade study; compare placement via precision actuators versus placement directly onto precision ground bosses–planned for 3rd/4th quarter 2013.
7. Design medium-fidelity module mount–planned for 3rd/4th quarter 2013, dependent on module mount trade study.
8. Fabricate a blazed master grating–began 1st quarter 2013, ongoing development throughout project.
9. Performance test blazed master grating–initial results obtained in 1st quarter 2013, extensive testing planned for first two quarters 2014.
10. Design a large format mask for large format grating fabrication–completed 1st quarter 2013.
11. Perform grating substrate trade study–planned for 4th quarter 2013 into 1st quarter 2014.
12. Fabricate large-format master–planned 2nd/3rd quarter 2014.
13. Performance test large-format, blazed gratings–planned for 3rd/4th quarter 2014.
14. Develop replication technique–planned for 2014.
15. Performance test replicas–planned for 4th quarter 2014, possibly into 1st quarter 2015.
16. Replicate gratings for module population–planned for early 2015.
17. Fabricate medium-fidelity grating mount–planned for early 2015.
18. Align replicas into module–planned for mid-2015.
19. Performance and environmental testing of medium-fidelity module of aligned gratings–planned for 3rd/4th quarter 2015.
20. Design a monolithic mount incorporating optics and gratings simultaneously–planned for 2nd/3rd quarter 2014.
21. Co-align three sets of parabola/hyperbola/grating channels–planned for 3rd/4th quarter 2014.
22. X-ray performance test monolithic mount–planned for 4th quarter 2014.
23. Increase fidelity of module design–planned for 1st quarter 2015.
24. Co-align and performance/environmental test at least three parabola/hyperbola/grating channels–planned for 2nd/3rd quarter 2015.
25. Incorporate monolithic mounts into a suborbital rocket payload–early 2016.
26. Integrate with system architecture and CCD camera–throughout 2016.
27. Launch suborbital OP-XGS–early 2017.

Progress and Accomplishments

In the months prior to June 2012, we concentrated our efforts on the goals of the first year of the SAT program, since it was the only identified project at that time. The accomplishments made during this time are detailed in the previous years' PATR. These follow the first three milestones above. In summary, we completed a grating fabrication trade study that gave preference to e-beam lithography based on customizability, replication ease, substrate material independence, and cost. We also fabricated our initial gratings using e-beam lithography resulting in a high-density (6033 grooves/mm), radial profile matching the convergence of an 8.4-m X-ray telescope beam. We tested these gratings for diffraction efficiency at the Physikalisch Technische Bundesanstalt (PTB) beamline of the Berliner Elektronenspeicherring-Gesellschaft fur Synchrotronstrahlung (BESSY) II synchrotron light facility and obtained absolute efficiencies >40% when summing orders, consistent with our performance goals. In addition to the 2012 PATR, we published our findings in McEntaffer, et al. 2013.

Over the past year, we have made significant progress on all fronts of our grating development program. During this time our group has been awarded RTF and APRA grants to bolster our efforts and refine our path for the coming years, as outlined previously in the Milestone list. Therefore, our goals for the existing SAT program were altered slightly to merge more seamlessly with these programs, but largely remained the same. First, we completed our performance testing of the e-beam lithography gratings. We performed spectral resolving power tests using the Stray Light Facility (SLF) at MSFC (Milestone 3b). This test utilized slumped glass optics from our collaborators at GSFC to produce the focused beam. We obtained the theoretical spectral resolving power of 900 for 1st order 1.25 keV Mg Kα X-rays (Figure 1). We also measured 2nd order and obtained a resolving power of 1300 with a theoretical expectation of 1800. However, this measurement was limited by the facility beam length. The high-quality X-ray mirrors were able to resolve the X-ray source, thus limiting the spectral resolving power, and leading to the lower measured value. Higher orders were inaccessible due to limited focal plane coverage by the CCD camera. The details of the test and results are given in McEntaffer, et al. 2013. Future testing will refine the source size and provide larger focal plane coverage to probe 3rd and 4th order where theoretical resolving powers are 2700 and 3600, respectively, consistent with the performance requirement of future X-ray missions.

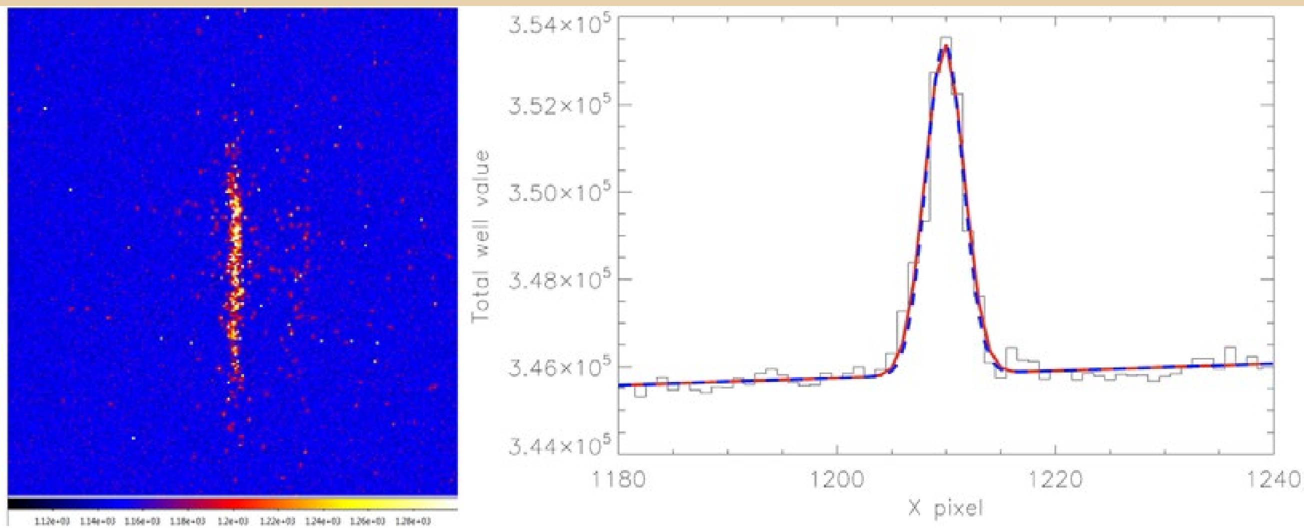
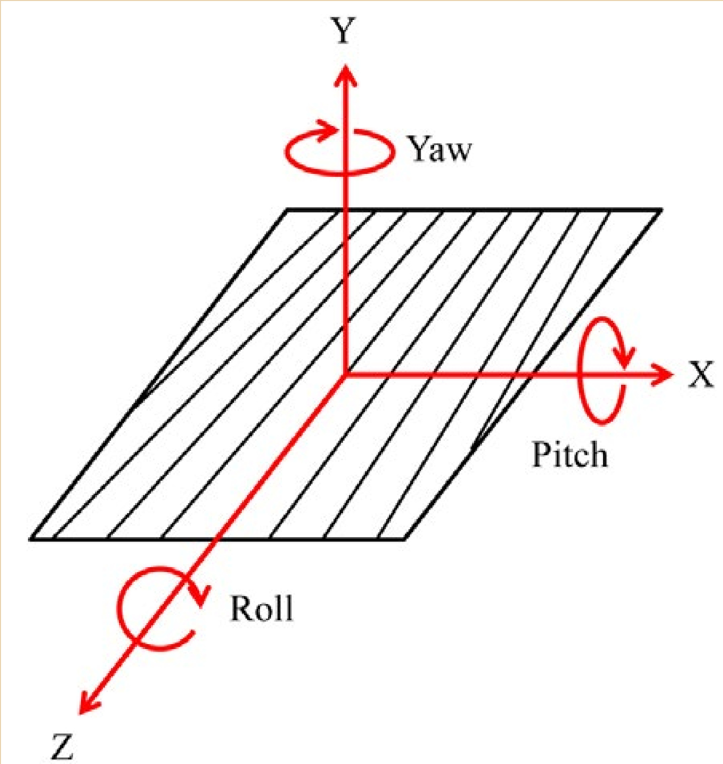


Figure 1: *Left – CCD image of the 1st order Mg Kα spectral line. Right – CCD count histogram with best fit line spread function in red and theoretical expectation derived via raytrace in dashed blue.*

We have also made significant progress in the area of grating alignment (Milestones 4, 5, and 6). To quantify the alignment tolerances, we adopt the formalism of Harvey and Vernold (1998) to determine the anticipated diffraction pattern from a grating with arbitrary orientation relative to the incident beam. We then manipulate the grating in all six degrees of freedom (DOF) and determine the effect to the line spread function (LSF). To maintain spectral resolving power we ensure that the line position is maintained to within a full-width-at-half-maximum (FWHM) of the LSF. To maintain effective area we ensure that the position is maintained to within the half-power-diameter (HPD) of the telescope (assumed to be 10 arcseconds). This analysis results in the tolerance values listed Figure 2. The full analytical formalism and raytrace verification of these tolerances is presented in Allured and McEntaffer, 2013.

In summary, these tolerances are relatively loose in comparison to other optical systems such as the X-ray telescope, but still require a demonstration that they can be met. As a first step toward this goal we have constructed a low-fidelity module mount, with alignment infrastructure and metrology. Figure



DOF	2.35 σ		DOF	2.35 σ	
X	-317 μm	+317 μm	Pitch	-4.5"	+4.5"
Y	-124 μm	+124 μm	Yaw	-8.3"	+8.3"
Z	-1.56 mm	+1.56 mm	Roll	-22"	+22"

Figure 2: *Top – Definition of the six degrees of freedom. Bottom – Alignment tolerances for each degree of freedom (DOF).*

3 demonstrates our first engineering test unit (ETU-1) of the module mount and the Shack-Hartmann sensor (SHS) based metrology system used to measure the attitude of the grating. The concept involves placing an initial reference grating and measuring its surface normal with the SHS. Subsequent gratings are placed in the array and aligned to the reference grating by manipulation with picomotor actuators until the relative normals are consistent with alignment requirements. The design can tightly control five degrees of freedom with grating yaw (rotation about the grating normal) minimally constrained. Fine yaw alignment requires overlapping the spectra from each grating and must be done during X-ray tests.

Our ability to measure the gratings at the level of our alignment tolerances is determined by the quality of our wavefront sensor and the step size of our picomotor. Figure 4 displays our current measurement precision. The two plots on the left show SHS output for the light source (left) and a grating pre-master (center). The wavefront is currently ~λ/20 (rms) easily capable of measuring the ~λ peak to valley surface of the grating pre-master. The plot on the right of this figure shows the SHS measurement of the normal of a grating. The pitch picomotor was actuated by 10 encoder steps for every “Step #” in this figure. Therefore, we can measure ~2 arcseconds/10 stage steps for every angular degree of freedom, thus obtaining subarcsecond precision. Furthermore, the setup

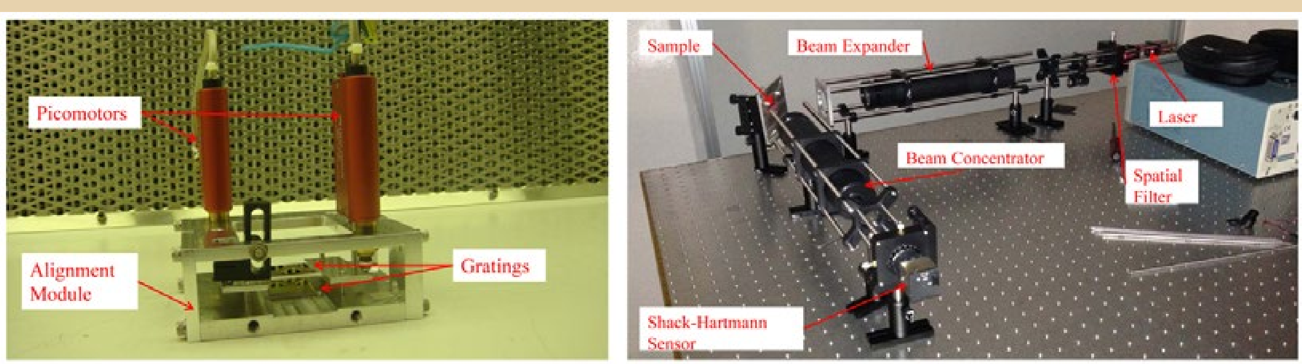


Figure 3: *Left – Low fidelity grating module mount (ETU-1) incorporating two gratings and two of three picomotors. Right - Alignment metrology setup using a Shack-Hartmann wavefront sensor.*

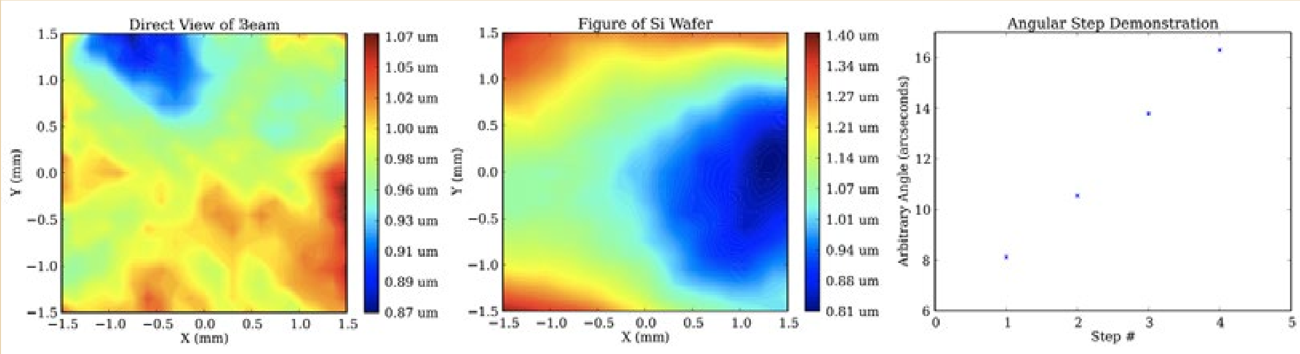


Figure 4: *Left – SHS measurement of the beam. Center – SHS measurement of a pre-master grating. Right – SHS measurement of a grating normal as a function of picomotor position.*

is very stable with measurement uncertainty at each angle roughly equal to the size of the data point. Although the setup is currently adequate, we will investigate necessary upgrades such as increasing the number of lenslets in the SHS array and quality of the source laser.

The developments made with ETU-1 refined a design for a second low/medium-fidelity module mount, ETU-2. This module is large format and uses high-fidelity beryllium (Be) substrates fabricated during the *International X-ray Observatory* (IXO) project. We are currently quantifying our tightest achievable tolerances using this unit. Results from these tests will be used to finalize the medium-fidelity module mount design. Figure 5 shows the test setup for alignment and measurement of ETU-2. We are also performing a long-term stability test to monitor components of our metrology system, such as wavefront stability/alignment, as well as changes in bonded gratings as a function of time and environmental conditions.

In addition to this alignment methodology using precision actuation of gratings, we are also investigating precision machining of the module mount to directly address each grating with no actuation necessary. We are working with General Dynamics (formerly Axsys Technologies) and have formulated a design. The module is being fabricated and alignment tolerances will be verified later in the year. This comparison of alignment methodologies also contributes to our module mount trade study to be completed during the remainder of the year.

Path Forward

In the coming years, our efforts will concentrate on achieving the list of milestones we presented above. The overarching goal will be to fabricate and test a medium-fidelity, populated array of aligned gratings. To reach this goal we must fabricate blazed gratings, replicate blazed gratings, fabricate a medium-fidelity mount, and align the replicas. These necessary tasks define our Milestones 6–19.

For the remainder of the current year we will continue our alignment studies and refine our module designs. We will begin a grating substrate trade study to quantify the pros and cons of Be versus silicon (Si) substrates. This study will concentrate on manufacturability, ease of replication, ease of alignment, mass, and thermal stability. Combined with the alignment methodology study, these findings will feed into the module mount trade study to determine mount material and fabrication techniques. Once these factors are determined, we will finalize the medium-fidelity module mount design and begin fabrication.

We have already begun fabricating blazed gratings. We have successfully demonstrated key techniques such as e-beam groove recording, nanoimprint pattern transferring, reactive ion-etching, and anisotropic

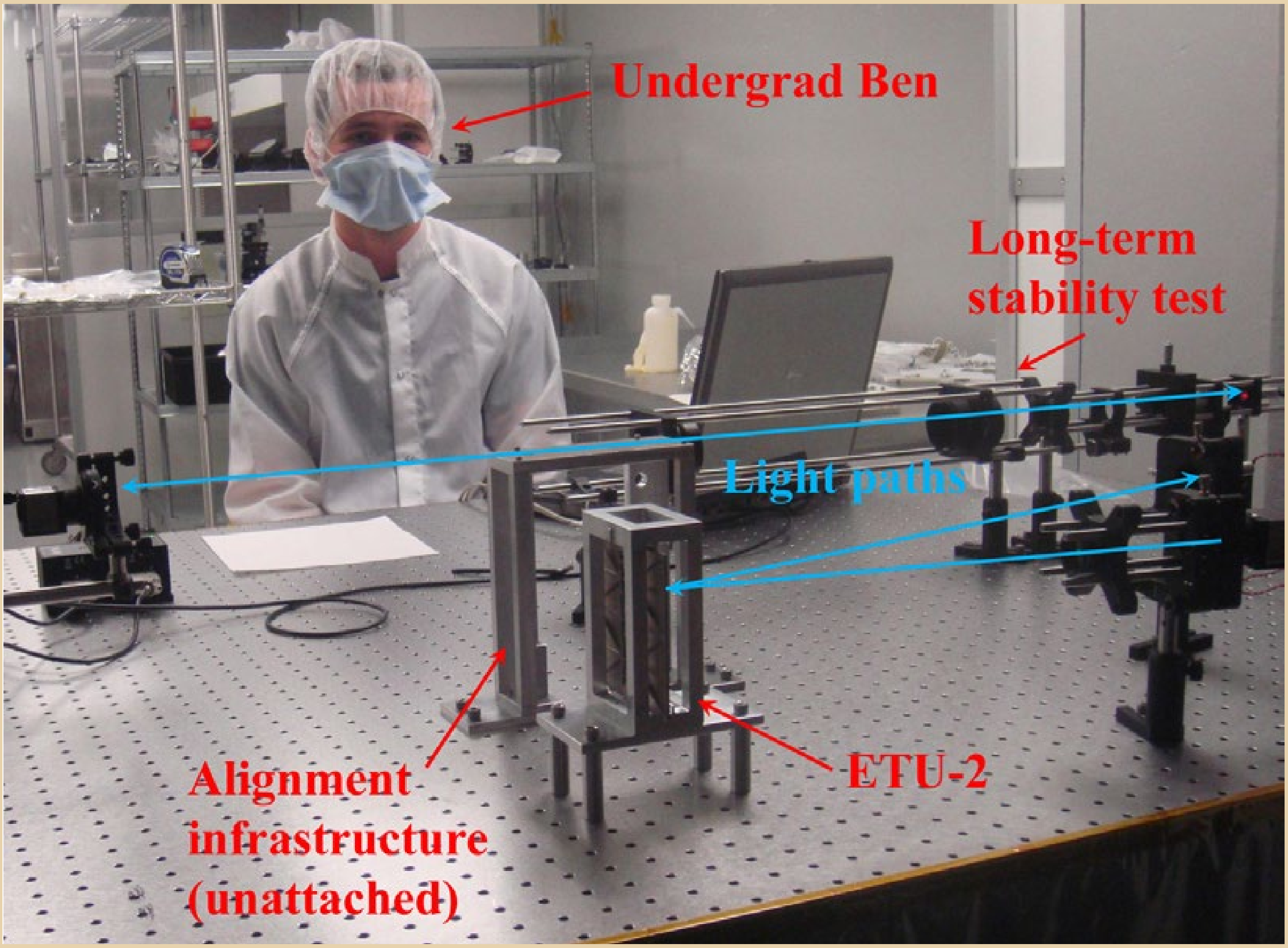


Figure 5: *Optics bench setup for grating alignment and metrology. The attitude of Be gratings within ETU-2 are being measured with a SHS system. A second SHS system is being used to monitor the long-term stability of metrology components and bonded gratings.*

wet etching. Preliminary tests on these gratings have shown the blaze effect on diffracted X-rays. Fine tuning of this process will be ongoing in the coming years. This effort will be accelerated by the acquisition of our own nanoimprint lithography machine, which will be in-house at the beginning of 2014. This machine is not only important in master fabrication, but also will be used for grating replication.

Once we are capable of producing large-format, high-fidelity groove profile replicas, we will populate a medium-fidelity module mount for performance and environmental testing. Verification of performance requirements before and after environmental testing will ready the OP-XGS for flight development given an identified X-ray spectroscopy mission.

The remainder of the existing SAT grant will be used to study the alignment of gratings within low fidelity module mounts with a goal of performance testing an aligned pair for spectral resolving power before the end of the year. To reach this goal, we will complete through Milestone 6 in the previous list. However, Milestones 7, 8, and 11 will be partially completed through studies achieved during the existing SAT. The remainder of the Milestones will necessitate other funding sources. Some of this funding will be provided by the RTF and APRA programs, but accomplishing Milestones 7–24 will require future SAT funding. For example, we are interested in studying monolithic mounts incorporating both optics and gratings. Such a module would greatly ease subsystem integration during payload assembly. The necessary mechanical and thermal interfaces will already be incorporated into the mount. Furthermore, this allows custom alignment of individual parabola/hyperbola/grating channels. Aligning each channel separately will greatly reduce the chance of grating induced aberration. This may be particularly important for future observatories working toward sub-arcsecond spatial resolution. Furthermore, Explorer- and Probe-class missions such as WHIMEx and N-XGS that are dedicated to grating spectroscopy should utilize monolithic mounts. Therefore, an in-depth study would benefit current as well as future NASA programs. In the near term, our preliminary design of the rocket payload optical assembly utilizes a monolithic mount. While developments necessary for the rocket program are planned, an in-depth study applicable to future missions is beyond the scope of the current suite of programs, and therefore has been proposed in the latest SAT solicitation. The synergy we have developed between the SAT, RTF, and APRA programs has allowed for a clear definition of the path forward and must be maintained in order to accomplish our goals.

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Contact:
randall-mcentaffer@uiowa.edu

Moderate Angular Resolution Adjustable Full-shell Grazing Incidence X-ray Optics

Prepared by: Paul B. Reid (Smithsonian Astrophysical Observatory), Stuart McMuldroch (SAO)

Summary

This Strategic Astrophysics Technology (SAT) investigation seeks to develop and demonstrate Technology Readiness Level 4 (TRL-4) for 3 to 5 arcsecond resolution, thin wall, full shell metal replica grazing incidence X-ray optics. We are using lead magnesium niobate (PMN) electrostrictive adjusters (Figure 1) to correct the lowest axial and azimuthal order figure errors to achieve X-ray imaging performance of 3 to 5 arcseconds (arcsec), from the current performance of 10 to 15 arcsec. We will accomplish this by using an array of actuators (adjusters) whose strain is oriented in the radial direction (that is, normal to the optical axis).

The radial adjusters connect a reference form, known as a reaction structure, the innermost mirror shell. These adjusters are arrayed azimuthally near the forward and aft ends of the mirror shell, as seen in Figure 2. Using an optical metrology Hartmann test, we determine the appropriate voltages for each adjuster to correct for alignment (as on the *Chandra X-ray Observatory*) and low-order azimuthal figure errors (as on the *International X-ray Observatory* technology development program). After achieving acceptable alignment and figure correction, voltage is removed from the adjusters, and the next layer of adjusters is installed at the identical axial and azimuthal positions of the preceding set. The next shell is also glued to the adjusters. Alignment and figure correction then proceeds with the next shell.

Such optics would be adjusted only once–during assembly and alignment–to remove low spatial frequency figure errors that limit the performance of full shell metal replica optics. Importantly, the electrostrictive adjusters hold their dimensions when voltage is removed. There is no leakage current, and they can maintain their dimensions for many years. The adjusters would also be used as part of the mirror shell alignment, and would form an integral part of the mirror mounting system and mirror assembly structure. Prior work[1] has suggested that nearly 98% of the lowest-order errors can be corrected. The grazing incidence mirrors will be nickel/cobalt (Ni/Co) electroplated thin shells similar to those on the High Energy Replicated Optics (HERO) balloon experiment. These adjusters are arrayed axially and azimuthally, as seen in Figure 2.

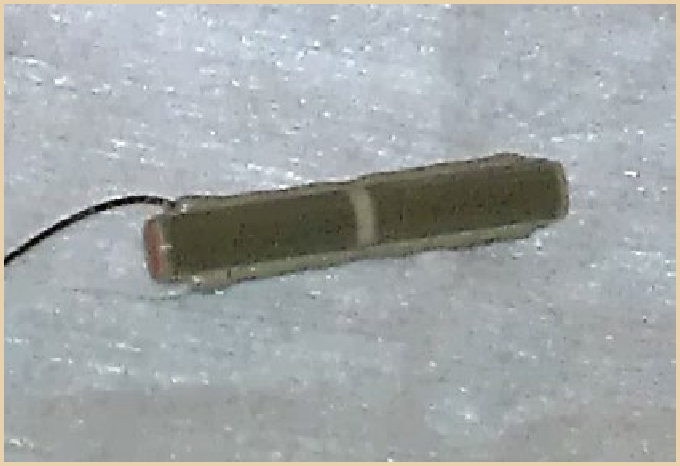

Figure 1: *A Xinetics radial electrostrictive adjuster. The adjuster is ~ 4 mm diameter and 25 mm long. Applying a voltage via the black and [barely visible] white leads changes the length of the adjuster. A property of electrostrictive devices is that they maintain their dimensions even when voltage is removed.*

This SAT program is funded for 2 years, with a planned start in Calendar Year 2013 (CY13). Initial funding was received by Smithsonian Astrophysical Observatory (SAO) in April 2012, resulting in a later than planned project start. A project kickoff meeting was held at the Physics of the Cosmos (PCOS) Program Office on December 6, 2012. At present, all funding has been received. Members of the X-ray optics team at the NASA Marshall Space Flight Center (MSFC) are essential to co-investigators (Co-Is) on the program. The team is responsible for providing the X-ray optics, the reaction structure, and supporting the mounting and metrology activities at SAO.

Major accomplishments (described in more detail below) include:

- Finite Element Model (FEM) modeling, that led to a significant reduction in the concept complexity of implementation and cost.
- Fabrication of the reaction structure.

Background

This technology is directly applicable to wide-field X-ray survey telescopes–such as the Wide Field X-ray Telescope (WFXT)–that will cover the bandwidth of 0.2–10 keV. The technology can also be employed to improve imaging of hard X-ray telescopes, although the limit to collecting area imposed by the space between mirror shells necessary to accommodate the adjusters will limit applicability to the lower end of the hard X-ray bandwidth.

Current performance of these types of X-ray mirrors is limited to the 15–30 arcsecond regime, although individual mirror shells and small telescopes have been made with resolution as good as 10 arcsecond. Improving imaging resolution by a factor of three to 10 (to 3–5 arcsecond) means that noise limited sources will have 1/10 to 1/100 the background, resulting in significantly higher signal-to-noise (S/N) and significantly lower minimum detectable flux levels. Achieving finer resolution will improve detection capability for hard X-ray sources, and provide more useful imaging for 0.2–10 keV objects.

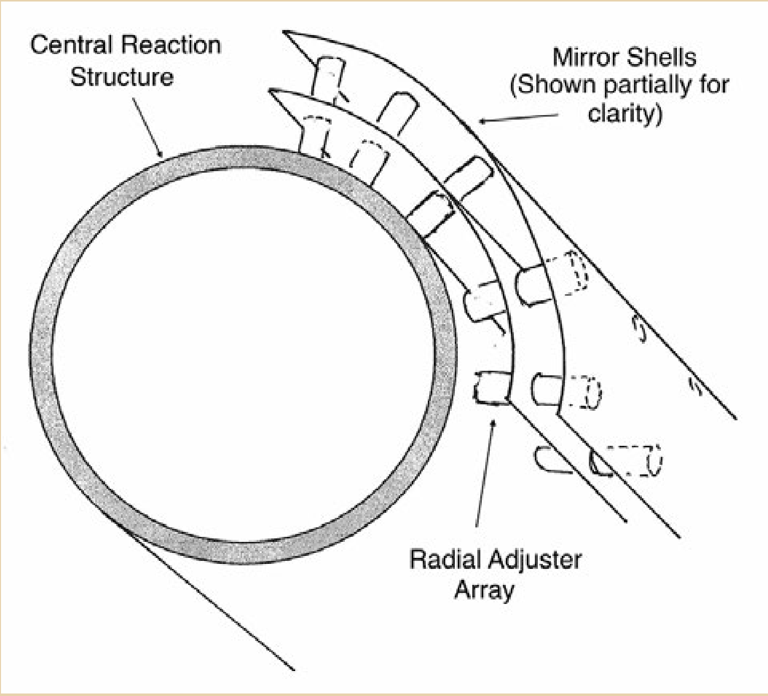

Figure 2: *Schematic representation of the radial adjuster approach. The adjusters have their long axis in the radial direction and are arrayed in the axial and tangential directions. While the schematic shows Gen-X segments, we envision this approach for several arc second resolution full shell metal replica mirrors.*

The tasks necessary to develop this technology are the demonstration of correction of low-order figure errors–roundness and delta-delta-radius (ddr)–resulting from electroforming full shell thin metal conical mirrors. The most common type of deformations of a full shell are ovalization–ovalization in phase at both ends of the mirror, or roundness error, and “crossed ovalization”–ovalization clocked by 90 degrees from one end of the mirror to the other, or ddr. These errors can be of appreciable amplitudes (one to tens of micrometers) and can significantly degrade imaging resolution. These thin shell mirrors are typically used in either hard X-ray telescope applications, or moderate-resolution, low-cost, moderate-area X-ray telescopes.

To demonstrate this approach, the major tasks are: (1) producing a thin (0.1 to 0.2 mm wall thickness) electroplated full shell mirror; (2) measuring the shape of that mirror, particularly its out-of-roundness; (3) mounting and correcting it using the radial adjusters; and then (4) remeasuring. The initial experiment will be with a single shell mounted to a reaction structure, and the follow-on experiment will use two shells mounted concentrically to the reaction structure. A coordinate measuring machine (CMM) will be used to make the first measurements. As accuracy improves, the Centroid Detector Assembly (CDA)–a pupil scanning Hartmann tester–will be used for higher accuracy measurements.

Objectives and Milestones

The major tasks and milestones are shown in the updated project schedule (Figure 3). SAO started this project in April 2012. As of last year’s report, we were about to complete requirements generation, fabrication of the large reaction structure, and the generation of the first large mirror shells (Tasks 1, 2, and 3, respectively). Since then we have fabricated the components for the mounting and adjustment of the mirror shells. Unfortunately, to meet requirements, we had to rework the reaction structure, thereby introducing a schedule slip, although the extra work was performed at no cost. We continued

TASK		FY 2013												FY 2014											
		OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP
Major Milestone	TBA = milestone															12/2 TRL 4								8/19 TRL 5	
Task 1	Requirements																								
Task 2	Fabricate 23 cm dia reaction structure																								
Task 2A	Re-design and re-fab									6/7															
Task 3	Fabricate 23 cm dia 0.2 mm thick Ni/Co shell									6/23		8/6													
Task 4	Single mirror ass'y test									6/11				10/31											
Task 5	Correlate measured data and finite element model										7/10				12/2										
Task 6	Correction of low order figure to 5 arcsec HPD level: TRL 4														11/1	12/2									
Task 7	Fabricate 15 cm diameter reaction structure														11/1			2/28							
Task 8	Fabricate 15 cm diam and 23 cm diameter Ni/Co mirror shells (1 each)															12/3	1/30								
Task 9	Two shell assembly test																		3/3				7/22		
Task 10	X-ray test: correction to < 5 arcsec HPD at 1 keV = TRL 5																						7/23	8/19	

Figure 3: *Revised program schedule.*

progressing with other activities, such as preparing the piezo actuators and assemblies and performing dry runs to help expedite future assembly activities. The reworked reaction structure is now being measured as the first step in the assembly process. We do not anticipate the reaction structure technical problems will affect the success of the project. The updated schedule accounts for the program delay as well as the projected improved schedule.

Progress and Accomplishments

Two significant accomplishments were achieved over the past year, (1) a major simplification of how we implement our approach, and (2) the fabrication of one of our two major pieces of hardware, the single shell reaction structure (Tasks 1, 2, and 2a).

Detailed FEM of the reaction structure and mirror shell error corrections resulted in a major simplification to our concept, while still achieving the same error correction efficiency. As we proceeded with detailed parts design of the reaction structure, we recognized the reaction structure was getting increasingly complex to machine, assemble, and use. Doing the additional modeling, we discovered that to correct the largest, lowest [spatial] frequency errors–roundness and ddr, both due to ovalization of the shell–we did not require adjusters arrayed throughout the mirror length, as indicated in Figure 2. We found the same error correction is achievable with adjusters arrayed azimuthally, but only at the forward and aft ends of the shell. Output from the FEM is shown in Figure 4. In this modeling case, a crossed-ovalization was applied to the mirror shell as a starting error. Crossed-ovalization means the major axis of the oval is rotated 90 degrees from one end to the other end, with the axial error and ovalization varying linearly with axial position between the two ends. The maximum-to-minimum (or peak-to-valley, P/V) starting error is 20 μm, and 4.17 μm, rms. The original actuator/reaction structure design incorporated

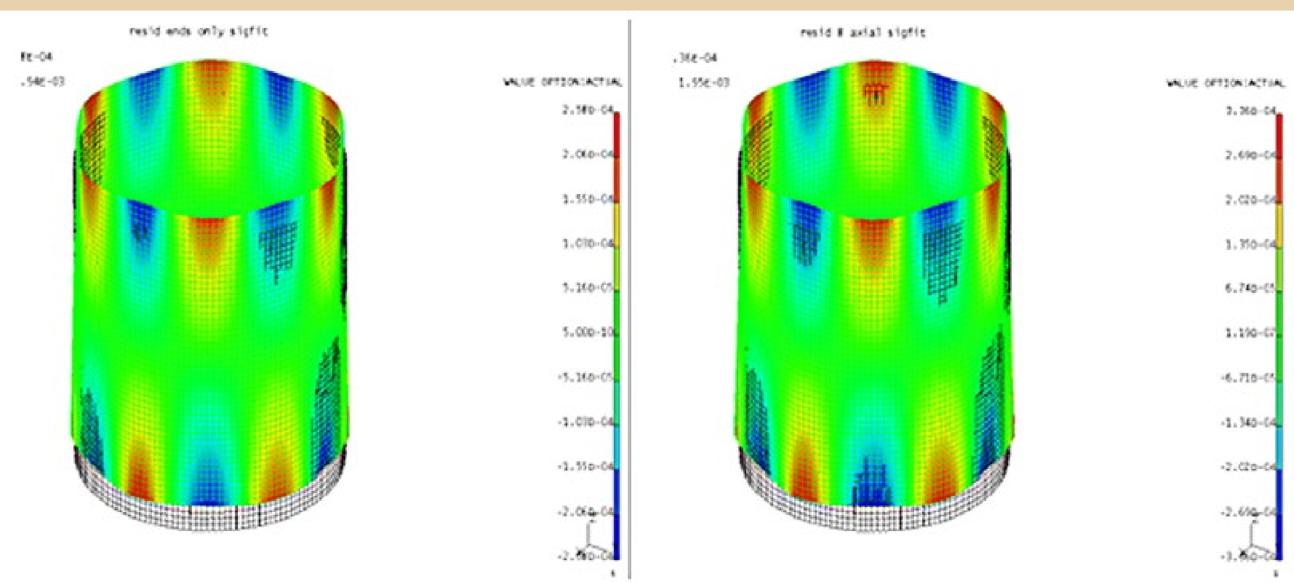

Figure 4: *Correction of a 20 micro-meter peak-to-valley error using 16 adjusters (8 at the forward end and 8 at the aft end, shown left), and using 64 adjusters (an array of 8 azimuthal × 8 axial, shown right). The starting error rms amplitude was 4.17μm. The residual error rms amplitudes are 0.10 μm for the 16-adjuster case, and 0.13 μm for the 64-adjuster case.*

64 adjusters in an 8 azimuthal × 8 axial array. Error correction for that configuration is shown on the right of Figure 4. The simplified design error correction is shown on the left, which incorporates just 16 adjusters, 8 each in a ring at each of the forward and aft ends of the shells. The 16-actuator case results in a 0.10 μm, rms (0.52 μm, P/V), comparing favorably to the 64-actuator residual of 0.13 μm, rms (0.67 μm, P/V). Thus, we achieve virtually identical performance while simplifying the assembly through the removal of approximately three-quarters of the components. This should significantly reduce cost and complexity.

Our second major accomplishment is completing the machining of the reaction structure, now redesigned for the 16-actuator approach. A photograph of the reaction structure is shown in Figure 5. The adjusters have been received at SAO, and the hardware for mounting and aligning the adjusters to the reaction structure are being completed.

Path Forward

Our baseline development approach utilizes the simplified approach we identified last year. In the short term, our most significant accomplishment will be the assembly of a single large mirror shell onto the reaction structure (Tasks 3 and 4). The assembly and initial test will take place at SAO, with X-ray testing conducted at MSFC in Q1 FY14 in support of TRL-4. The longer-term approach for reaching TRL-5 is predicated on successfully testing a multi-shell assembly. This is a significant step forward in the technology. We have begun analyzing different concepts for the multi-shell design to ensure leveraging our current work. A detailed description of the tasks we intend to accomplish during the next phase of the project follows:

Figure 5: *Left – photo of reaction structure for the 23 cm diameter single shell test. The structure is resting on a stage prior to being measured on the SAO CMM. Three mounting points can be seen at each end for six of the 16 adjusters. In the close-up photo, above right, can be seen a detail of the adjuster attachment points.*

- Correct low-order errors of a single full shell conical mirror (Tasks 4, 5, and 6). In this activity we will align and bond the mirror element and adjustors to the reaction structure (at SAO) and then measure our ability to adjust the shape of the mounted mirror. Mechanical measurements of mirror roundness and ddr will be made using the SAO CMM, with better than 1 μm rms accuracy. Figure measurements and changes in figure produced by the adjusters will be measured at SAO with the CMM.

- Correlate experimental results with FEM. This task could also be considered an intrinsic part of the previously described task. However, we break it out individually to highlight the critical importance of this task. This activity will also include updating the FEM so as to better represent reality, thus making it a useful tool for analyzing a broader range of test cases than can be performed experimentally in a 2-year program.

- Test the first mirror shell in X rays at MSFC Stray-light Test Facility (Task 6). Verify that the observed performance matches performance predicted via optical and mechanical metrology.

- Reach the first technology milestone (potentially TRL-4). Achieving the goals of the previously described steps of the investigation will represent both our first technology milestone and, we believe, demonstrate TRL-4.

- Demonstrate long-term performance stability. We will measure the stability of the electrostrictive devices, which should maintain their dimensions after voltage is removed (the condition is called electrically clamped, as charges are not free to move within the device). We will provide some limited testing of this by introducing deformations, removing voltage, and monitoring the mirror shape over time (part of Task 6).

- Fabricate a second smaller 15-cm reaction structure with an appropriately scaled mirror (Tasks 7 and 8). Currently we are developing our processes using a relatively large reaction structure and mirror shell.

- Once we are successful, we will apply our lessons learned to smaller mirrors that are harder to mount and align due to their size but are more representative of a flight assembly geometry.

- Two-shell mirror assembly and test in X rays (Tasks 9 and 10). We will first mount and align the inner smaller shell. We will then attach the outer shell and align that relative to the smaller mirror. In both cases, we will verify adjustment and alignment using mechanical and optical metrology. Finally, we will test the two-mirror shell telescope in X rays at the MSFC Stray-light Facility in support of achieving TRL-5.

Contact:
pried@cfa.harvard.edu

Critical-Angle Transmission (CAT) Gratings for High-Resolution Soft X-Ray Spectroscopy

Prepared by: Ralf K. Heilmann (Massachusetts Institute of Technology), Alex R. Bruccoleri (MIT), and Mark L. Schattenburg (MIT)

Summary

CAT gratings combine the advantages of traditional phase-shifting transmission gratings (relaxed alignment and figure tolerances, low mass, transparency at high energies) and blazed reflection gratings (high diffraction efficiency, high resolving power due to utilization of higher diffraction orders). In combination with grazing incidence X-ray mirrors and Charge-Coupled Device (CCD) detectors, they promise an increase of 5–10 in efficiency and 3–5 in resolving power over existing X-ray grating spectrographs.[1] Development of CAT grating fabrication technology has been supported by NASA under the Strategic Astrophysics Technology (SAT) program since January 2012.

The past year saw the successful combination of an advanced deep reactive-ion etch (DRIE) with a potassium hydroxide (KOH) polishing step, leading to an unprecedented combination of grating open area fraction and grating bar sidewall smoothness, both of which are essential for high-quality CAT gratings.

Background

Absorption and emission line spectroscopy, with the performance made possible by a well-designed CAT X-ray grating spectrometer (CATXGS), will target science objectives concerning the large-scale structure of the universe, cosmic feedback, interstellar and intergalactic media, and stellar accretion. Kinematics of galactic outflows, hot gas in galactic halos, black hole growth, the missing baryons in galaxies and the Warm Hot Intergalactic Medium (WHIM), and the effect of X-ray radiation on protoplanetary disks all pose questions that will be addressed by a CATXGS-carrying mission. All of these are high-priority *International X-ray Observatory* (IXO) science questions described in the *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) Decadal Survey, and addressed further in the NASA X-ray Mission Concepts Study Report (August 2012). A number of missions submitted as responses to NASA Request for Information (RFI) NNH11ZDA018L could be enabled with a CATXGS, such as the Advanced X-ray Spectroscopic Imaging Observatory (AXSIO), the Astrophysics Experiment for Grating and Imaging Spectroscopy (AEGIS), and the Square Meter, Arcsecond-Resolution X-ray Telescope (SMART-X), as well as the Notional X-ray Gratings Spectrometer (N-XGS) that was studied by the X-ray Community Science Team (CST).[2–4]

The soft X-ray band contains many important diagnostic lines–those from carbon (C), nitrogen (N), oxygen (O), neon (Ne), and iron (Fe) ions. Imaging spectroscopy with a spectral resolution of < 2 eV has been demonstrated with small transition-edge-sensor-based microcalorimeter arrays, providing resolution > 3000 for energies > 6 keV. However, toward longer wavelengths energy dispersive detectors cannot provide the spectral resolution that is required to address several of the NWNH high-priority science objectives. The only known technology capable of enabling high spectral resolving power in this band is wavelength-dispersive, diffraction-grating-based spectroscopy.

The technology currently used for grating-based soft X-ray spectroscopy was developed in the 1980s. The *Chandra* High Energy Transmission Grating Spectrometer (HETGS) carries polyimide-supported gold gratings with no more than 10% diffraction efficiency in the 1–5 nm wavelength band, but the whole moveable grating array only weighs about 10 kg. The *XMM-Newton* Reflection Grating Spectrometer (RGS) has more efficient grazing-incidence reflection gratings, but its mass is high (>100 kg) and it has low spectral resolving power (~300). CAT gratings combine the advantages of the HETGS and RGS gratings and promise up to 50% diffraction efficiency over a broad band with a resolving power >3000 for a 10-arcsec point spread function (PSF) telescope. They also offer near-ideal synergy with a calorimeter-based imager, since CAT gratings become increasingly transparent at higher energies. Thus high-resolution spectroscopy could be performed with a CATXGS in tandem with a calorimeter over the range of ~ 0.2–tens of keV. Figures of merit for many types of observations–such as the accuracy of line centroid measurement in absorption line spectroscopy–could be improved by more than an order of magnitude over *Chandra* and XMM. The new and patented CAT grating design relies on the reflection (blazing) of X rays from the sidewalls of free-standing, ultra-high aspect-ratio, sub-micron-period grating bars at grazing angles below the critical angle for total external reflection. Fabrication combines advanced and recent methods and tools from the semiconductor and micro-electro-mechanical systems (MEMS) industries with decades of patterning and fabrication methods developed at the Massachusetts Institute of Technology (MIT).

We are planning to bring CAT grating technology to TRL-6 by the end of 2018 in order to reduce technology risk and cost for future CATXGS-bearing missions before they enter Phase A. We therefore want to demonstrate efficient large-area (> 30 × 30 mm^2) CAT grating facets with minimal blockage from support structures. Facets will be mounted to thin and stiff frames, which can be then be assembled into grating arrays with sizes on the order of m^2.

Objectives and Milestones

The objective of this project is the demonstration of an aligned array of large-area, high-efficiency CAT gratings with minimal blockage from support structures that provides a resolution > 3000 in the soft X-ray band and maintains its performance after appropriate vibration, shock, and thermal testing. The array will consist of so-called grating facets mounted to a Grating Array Structure (GAS). Facets are comprised of a grating membrane–etched from a silicon-on-insulator (SOI) wafer–and a facet frame that holds the membrane.

Key project milestones:

1. Develop silicon (Si) lattice-independent anisotropic etch capable of achieving the required aspect-ratios for 200 nm-period gratings (DRIE at University of Michigan tool, completed in 2011).
2. Develop process for free-standing, large-area gratings with hierarchy of low-blockage supports (completed in 2012).
3. Combine and optimize dry- and wet-etch processes to obtain smooth grating bar sidewalls and narrow Level 1 (L1) supports (completed this year) and produce free-standing, large-area gratings with hierarchy of low-blockage supports (ongoing). Test X-ray efficiency (FY13/14).
4. Select, acquire, install, and test advanced DRIE tool at MIT (FY13/14).
5. Demonstrate CAT grating resolving power in an X-ray imaging system. Repeat with more than one grating or small array (FY13/14).
6. Develop grating facet/frame design, process for integration of CAT grating membrane and frame, and alignment of facets on a breadboard GAS (FY14/15).
7. Environmental and X-ray tests of grating facets (FY15).
8. Design of brass board GAS, alignment verification and environmental test of grating array (FY15/16).
9. Scale up grating fabrication, frame design, and membrane/frame integration to full size (mission dependent–FY15/17).
10. Design and build GAS prototype (FY17).
11. X-ray and environmental tests of GAS populated with full-size gratings (FY17/18).

Progress and Accomplishments

The key challenges in the fabrication of CAT gratings lie in their structure: small grating period (200 nm), small grating duty cycle (~40 nm-wide grating bars with 160 nm spaces between), and large depth (4–6 μm) result in ultra-high aspect ratios (100–150) and require nm-smooth sidewalls. In addition, the gratings should not be supported by a membrane, but instead be freestanding. Structures with such an extreme combination of geometrical parameters–or anything similar–have never been made before. Prior to this SAT award we have fabricated small KOH-wet-etched CAT grating prototypes that met all these requirements and measured their efficiency at a synchrotron source, demonstrating good agreement with theoretical predictions.[5–6] Due to their extreme dimensions and the requirement to be freestanding, CAT gratings must be supported by slightly "bulkier" structures. We use a so-called L1 cross-support mesh (period ~ 5–20 μm) that is integrated into the SOI device layer and etched at the same time as the CAT gratings. Unfortunately, the wet-etch that provides the nm-smooth CAT grating sidewalls leads to widening L1 supports with trapezoidal cross sections and unacceptable X-ray blockage.

We identified and developed (~2010–2012) an alternative process that can provide the required etch anisotropy for both CAT grating bars and L1 supports. This required the use of an advanced DRIE tool at the Lurie Nanofabrication Facility at the University of Michigan. In order to make large-area, freestanding gratings, we designed a high-throughput hexagonal Level 2 (L2) mesh that is etched out of the much thicker (~0.5 mm) SOI handle layer (back side). We developed a process flow that allows us to etch the CAT grating bars and the L1 supports out of the thin SOI device layer (front side), stopping on the buried oxide (BOX) layer, and to subsequently etch the L2 mesh with a high-power DRIE into the back side, again stopping on the BOX layer, without damaging the delicate front side structures. The BOX layer is removed with a wet hydrofluoric acid (HF) etch, and the whole structure is critical-point dried. We have fabricated several 31 × 31 mm^2 samples with decent yield.[7]

Unfortunately, DRIE on even the most advanced tools leaves the sidewalls of etched structures with several nm of roughness, which is detrimental to CAT grating efficiency. In the last year we have developed a combined DRIE/KOH polish approach that follows DRIE with a relatively short KOH "polishing" step that reduces sidewall roughness, and straightens and thins the grating bar profile (see Fig. 1). In this context, we had to develop a new alignment technique for our interference lithography patterning step and troubleshoot many conditions that would lead to post-DRIE gratings which did not survive the KOH polishing step.[8] We are currently integrating our new process into the fabrication steps for large-area, freestanding gratings.

Over the last year we have also engaged in extensive interaction with three vendors for an advanced DRIE tool to be installed at MIT and produced numerous samples for tool evaluation. A decision on which tool to buy is imminent. Having a dedicated tool in-house at MIT, instead of working with a tool at an open user facility in Michigan, will greatly improve and accelerate our process development.

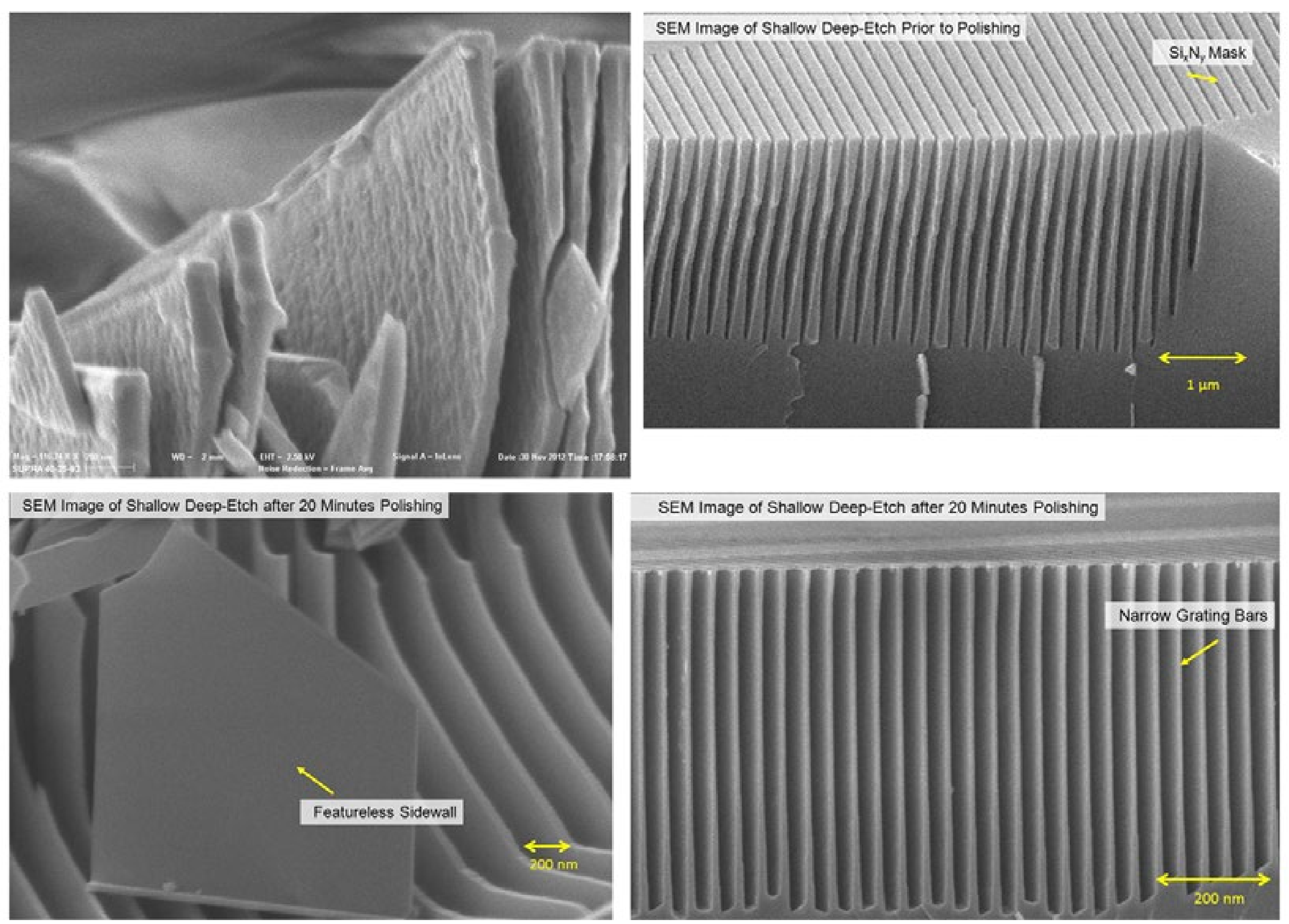

Figure 1: *Top left: Scanning Electron Micrograph (SEM) of a cleaved CAT grating section after DRIE, showing rough sidewalls. Top right: Cleaved cross section, showing non-ideal grating bar profiles after DRIE. Bottom left: Grating bar sidewall from DRIE'd grating after KOH polish. No roughness is visible in the SEM. Bottom right: Much straighter and deeper grating bars of DRIE'd sample after KOH polish.*

Path Forward

We are currently integrating the combined DRIE/KOH polish steps into the fabrication process for free-standing, large-area gratings with a hierarchy of low-blockage supports. We also will select, purchase, install, and test an advanced DRIE tool at MIT within the next few months. Once we have gratings with smooth sidewalls, we will measure their diffraction efficiency, followed by characterization of spectral resolution. If satisfactory performance is achieved, we will focus on subsequent milestones (see above), subject to funding.

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Contact:
marks@space.mit.edu

Next Generation X-ray Optics: High Angular Resolution, High Throughput, and Low Cost

Prepared by William W. Zhang (NASA/Goddard Space Flight Center) and
Stephen L. O'Dell (NASA/Marshall Space Flight Center)

Summary

This work is the continuation of the X-ray mirror technology development effort that was initiated and funded by the *Constellation-X* project and then by the I*nternational X-ray Observatory* (IXO) project until Fiscal Year (FY) 2011. Since FY 2012, the effort has been funded through the Strategic Astrophysics Technology (SAT) program. Led by NASA Goddard Space Flight Center (GSFC), in collaboration with NASA Marshall Space Flight Center (MSFC), this technology development is on track to achieve TRL-5 for building 10-arcsecond X-ray mirror assemblies by the end of 2014.

The objective is to advance astronomical X-ray optics by at least an order of magnitude in at least one of three key metrics, from the state of the art represented by the four major currently operating X-ray missions: *Chandra*, *X-Ray Multi-Mirror Mission* (XMM-Newton*)*, *Suzaku*, and NuSTAR. The three metrics are (1) *angular resolution*, (2) *mass per unit effective collecting area*, and (3) *production cost per unit effective collecting area*. The modular approach of this technology renders it appropriate for missions of all sizes–ranging from Explorers and Probes that can be implemented before the end of this decade, to flagship missions that can be implemented in the next decade.

Key areas of technology development include (1) fabrication of extremely lightweight substrates, (2) thin-film coating of these substrates to make them into X-ray mirror segments, (3) alignment and bonding of mirror segments to make mirror modules, and (4) alignment and integration of mirror modules into a mirror assembly. In the past year we have made progress in each of these areas, culminating in consistently making technology development modules that pass a battery of environment tests and produce X-ray images with a point-spread function of 11 arcseconds (half-power diameter, HPD). This is to be compared with the 17-arcsecond images we reported at the end of FY 2012.

Background

Astronomy in every waveband requires good optics. The last five centuries of astronomy are a history of technological advancements in optical fabrication and optical systems integration. Furthering our understanding of the cosmos requires telescopes with progressively larger collecting area and finer angular resolution. In the optical and other wavebands where photons can be reflected at normal incidence, a large mirror area directly translates into a large photon collecting area. An X-ray telescope, however, due to its grazing-incidence nature, requires a combination of a larger mirror area and thinner mirrors to achieve a larger photon collecting area.

Three metrics capture the essence of an X-ray optics technology: (1) angular resolution, (2) mass per unit photon collecting area, and (3) production cost per unit photon collecting area. Table 1 shows a quantitative comparison of this technology with state-of-the-art astronomical X-ray optics represented by the four currently operating missions: *Chandra*, XMM-Newton, *Suzaku*, and NuSTAR. The optics of each of these observatories represents a scientifically powerful compromise among these three metrics that was implementable in its specific technological, budgetary, schedule, and spaceflight opportunity context.

Mission	Year of launch	Mirror technology	Angular resolution HPD (arcsecond)	Mass per unit collecting area @ 1 keV (kg/m^2)	Production cost per unit collecting area @ 1 keV (2013 \$M/m^2)
Chandra	1999	Ground and polished Zerodur™ shells	0.5	18,000	~9,800
XMM-Newton	1999	Electroformed nickel shells	15	3,200	~360
Suzaku	2005	Epoxy-replicated aluminum segments	120	400	~88
NuSTAR	2012	Slumped-glass segments	58	400	~80
Near-term (2 y) objective	NA	Slumped-glass segments	10	~400	~80
Long-term (5–10 y) objective	NA	Polished and light-weighted single-crystal silicon segments	~0.1	~400	~80

Table 1. *Comparison of the objectives of this technology effort with the state of the art, as represented by four currently operating X-ray missions. Given the usual difficulty in ascertaining cost of a particular instrument or mission component, the cost numbers here are indicative although not necessarily exact.*

In comparison with *Chandra*, this technology would lower the mass and cost per unit collecting area by nearly two orders of magnitude. In comparison to XMM-Newton, it would reduce the mass per unit collecting area by a factor of eight and cost by a factor of three, while somewhat improving the angular resolution. In comparison with *Suzaku* and NuSTAR, it would improve the angular resolution by an order of magnitude, while preserving their advantages in mass and cost per unit collecting area.

A salient feature of this technology is that it uses a segmented design, as did *Suzaku* and NuSTAR. Such a design brings modularity and scalability, which are key factors to minimizing production cost and to enabling missions of any size, from small Explorer missions to large Flagship missions. Small and large mirror assemblies differ only in the number of identical mirror modules that need to be constructed, aligned, and integrated. Each of these modules would typically measure 200 mm by 200 mm by 400 mm (optical axial direction), with a mass of about 10 kg, making them easy to handle. Construction of many identical modules lends this process to mass production, offering substantial cost savings.

Objectives and milestones

The objectives of this work are twofold. In the near term (next 2 years or so), we expect to demonstrate an entire process for making mirror modules consistently and repeatedly that produce X-ray images better than 9-arcsecond HPD and that can pass all environment tests required for spaceflight. In the long term (next 5 to 10 years), we expect to improve continually every aspect of the process toward improving the angular resolution from 9-arcsecond to better than 1-arcsecond, with the ultimate goal of achieving diffraction-limited X-ray optics in the 2020s.

The same set of milestones can be used to measure progress toward realizing both near-term and long-term objectives. They differ only in the X-ray image performance measured in arcseconds. Each of the steps, or the milestones listed below, has two metrics attached to it at any given time: image quality and consistency.

1. Fabrication of mirror substrates;
2. Coating of substrates with a thin film of iridium or other material to enhance X-ray reflectivity;
3. Alignment of individual mirror segments and pairs of mirror segments;
4. Bonding of mirror segments;
5. Construction of mirror modules, requiring co-alignment and bonding of multiple mirror segments; and
6. Environment tests of mirror modules, with X-ray performance tests of mirror modules before and after environment tests.

Environment tests include vibration, acoustic, and thermal vacuum. X-ray performance tests include point-spread-function and effective-area measurements at several representative X-ray energies: 1.5 keV (aluminum Kα), 4.5 keV (titanium Kα), and 8.0 keV (copper Kα).

Progress and Accomplishments

We made progress in every area of the technology: forming-mandrel fabrication; substrate fabrication; coating; mirror alignment and bonding; and module design, analysis, construction, and testing.

Forming mandrel fabrication

Even though forming-mandrel fabrication is not part of the technology development per se, we need a steady supply of high-quality forming mandrels to enable fabrication of mirror substrates and to build mirror modules that contain progressively more mirror segments. In FY 2013 Q1, we successfully finished and qualified two pairs of forming mandrels–designated "356P/S" and "368P/S"–bringing the total number of mandrel pairs from three to five. Now we are using these mandrels for slumping substrates.

In FY 2013 Q2, we procured eight additional pairs of forming mandrel blanks, with diameters of about 200 mm. Rodriguez Precision Optics, Inc., of Gonzales, Louisiana, is fabricating these blanks, to be completed by the end of FY 2013. We are starting precision polishing of these blanks at GSFC and expect to complete them by the end of FY 2014. These will bring the total number of mandrel pairs from 5 to 13, ranging in diameter from 200 mm to 500 mm, allowing us to build technology development modules substantially similar to an IXO mirror module.

Substrate fabrication

Although not an emphasis of our FY 2013 work, we continued refining and simplifying the glass-slumping process. We brought the recently finished forming-mandrel pairs (356P/S and 368P/S) to producing acceptable substrates for making 10-arcsecond mirror assemblies. Overall we maintained consistency in making substrates that have a predicted imaging performance of 6-arcsecond HPD (two reflections). One additional variable that we started tracking in FY 2013 is the quality of cut edges of a substrate, important to precise alignment and bonding.

Coating

The bare glass surface of a substrate needs to be coated with about 20-nm iridium to maximize its X-ray reflectivity. The stress of the iridium film, measured in few to several giga-Pascal, severely distorts the substrate's figure, resulting in unacceptable degradation of image quality. In FY 2013 we investigated two methods of dealing with coating stress: (1) cancellation by coating both front (concave) and back (convex) surfaces of the substrate, and (2) thermal annealing to relieve the film stress.

We employed both atomic layer deposition (ALD) and magnetron sputtering to coat substrates. For ALD we worked with Arradiance, Inc., of Massachusetts, and with Beneq, of Finland. Arradiance coated a number of substrates with platinum; Beneq, a number of substrates with iridium. In general the ALD coating preserves the micro-roughness of the glass substrate, but simultaneous coating of both front and back surfaces did not result in undistorted mirror segments. Without exception, each ALD-coated substrate showed unacceptable distortion. Moreover, the distortion varied from one substrate to another, even for substrates that were coated in the same run. It is not yet clear why stresses on the front and back surfaces did not cancel each other and why the distortion or residual stress, if there was cancellation, varied from substrate to substrate. Resources permitting in the future, we might investigate potential reasons for these behaviors.

We also coated both front and back sides of mirror substrates in an in-house magnetron sputtering chamber, with results basically the same as observed for the ALD coating. As magnetic-sputtering coating of both sides required a break in vacuum between coating the front and the back, the thin-film thickness was probably not very uniform. Nonetheless the results were disappointing and called into question the feasibility of stress cancellation through two-sided coating.

With both ALD and sputter coated segments, we did find that post-coating thermal annealing significantly relieves coating stress. We expect our standard procedure going forward will be to coat and to anneal. The coating can be done using either ALD or magnetron sputtering, depending upon cost and convenience.

Mirror segment alignment and bonding

We procured from Praecis, Inc., of West Lebanon, New Hampshire, a precision temperature control unit and installed it in the mirror alignment and bonding laboratory, so as to reduce temperature fluctuations that distorted mirror segments and disturbed their alignment over periods of hours. The unit has been working as expected, creating a thermal environment that is stable within ±0.1°C over a period of several days. It also helps maintain a stable humidity level, which affects epoxy cure time and quality.

Increasing activity in the mirror alignment and bonding laboratory has led to a higher demand for electric power. Further increasing this need has been the installation of additional climate-control systems, both in the alignment laboratory and at the X-ray beam line. As of July 2013, work is under way to lay a new electrical cable to these facilities. Once the work is completed, by August 2013, sufficient electric power will be available to allow operation of all thermal control systems and to construct a vertical extreme ultraviolet (EUV) beam line. The vertical beam line will enable testing mirror modules with optical axis in the vertical direction, reducing image degradation by gravity distortion by more than an order of magnitude, paving the way for making and testing mirror modules with an X-ray imaging performance near 1-arcsecond HPD.

The alignment of each mirror entails the closed-loop operation of a hexapod, a beam of laser light, and an optical charge-coupled device (CCD) imager. In the past year we optimized both hardware and software for the entire operation, such that it is efficient, accurate, and user-friendly.

The most important factor in improving the imaging performance over the past year has been progress in bonding mirror segments to the module housing. As reported last year, each mirror segment is bonded to the housing at six locations, three on each side. The bonding procedure comprises three steps:

1. Fabrication and attachment of six precision-machined clips to the azimuthal edges of the glass mirror segment. Each clip constitutes a surface to which a pin can be bonded and distributes the stress over a larger area, to minimize localized stress that could fracture the glass.
2. Attachment of a precision pin to the clip.
3. Lock-down of the pin to the housing.

After investigating several aspects of making and attaching the clips, we determined that the clip should only have one side to be bonded to the mirror (as opposed to a U-shaped clip to be bonded to both surfaces of the mirror). One-sided clips are easier and cheaper to fabricate and attach, and typically allow a thinner bond line. The best material for making the clip is Kovar™, which matches the coefficient of thermal expansion of the Schott D263™ glass, ensuring that any temperature excursion during bonding and epoxy curing does not distort the mirror. Experimentation has led us to use an epoxy that produces the highest bond strength with minimal outgas.

The most important process improvement during the past year was to reduce the clearance between the pin and its bushing from tens of micrometers to approximately 2 micrometers, significantly decreasing the disturbance to the alignment of the mirror segment during epoxy curing. Consequently, as of July 2013, we consistently co-align and bond three pairs of mirror segments to make technology development modules (TDM) that produce 11-arcsecond images.

Mirror module design, analysis, construction, and testing

Incrementally refining the TDM design and improving the alignment and bonding procedures (described previously), we improved the imaging quality of three pair modules from 17-arcsecond–documented in the Program Annual Technology Report (PATR) report for FY 2012–to 11-arcsecond (Figure 1).

We performed a number of environment tests to investigate the mechanical strength of the bonds. At the Washington Laboratories, Ltd., in Frederick, Maryland, we conducted four vibration tests of a TDM (Figure 2), at progressively higher accelerations. Based upon the test results, we improved bond surface preparation, used epoxy with higher strength, and increased bond area to achieve higher bond strength. All test results agreed reasonably well with finite element analyses. All mirror segments survived the vibration tests intact. After the tests, one of the three mirror pairs showed degradation in X-ray imaging performance. We are investigating the cause and will consider the findings in refining the module construction process. We expect to conduct several more vibration tests in FY 2014, reaching full spaceflight qualification levels.

Additionally, we conducted an acoustic test of a TDM (Figure 3). Every mirror and epoxy bond survived the test. Furthermore, an X-ray image performance test and an optical alignment test each showed that all mirror segments maintained their alignment.

We also conducted two thermal vacuum tests of a TDM (Figure 4). In the first test, we cycled TDM four times between 10°C and 30°C in vacuum. After post-test visual inspection, optical tests, and X-ray tests showed that the TDM remained intact, we cycled the TDM four times between 0°C and 40°C in vacuum. Again the TDM remained intact. These tests conclusively demonstrate that the mirror segments are attached to the housing in a manner sufficiently robust to survive a wide range of temperature excursion. These important data will set the mirror assembly survival criteria, which will impact spacecraft thermal design.

Path forward

Our highest priority is perfecting the *mirror alignment and bonding process*. We want to maintain current momentum to improve the process, so as to build and to test TDMs that consistently achieve X-ray images with HPD < 9-arcsecond, needed for achieving 10-arcsecond mirror assemblies. (Coincidentally, 9–arcsecond HPD is the present limit imposed by gravity distortion when a module is tested with its optical axis in the horizontal direction.) The crux of the process lies in controlling the effect of epoxy cure on displacing and distorting the mirror segment. Out of necessity, epoxy (or other adhesive) is used to fill gaps that measure typically a hundred micrometers. In the course of cure, the epoxy will shrink and cause the gap to shrink, resulting in movement and/or distortion of the mirror segment. Our strategy is twofold. First, we shall continue to minimize the gap to be filled with epoxy, striving to use epoxy only as an adhesive–not a filler. This requires more precise mechanical matching of the different parts–including clips, pins, and the bushings. Second, we shall optimize the sequence in which the joints are glued and cured, so as to minimize the effect of epoxy shrinkage.

We shall continue to investigate the annealing of thin-film iridium to reduce or eliminate its stress. There are several factors to be evaluated. The first is the highest temperature that a coated mirror segment can be heated without causing permanent plastic deformation of the glass substrate. The second is film thickness uniformity. It is likely that the force due to residual stress is proportional to film thickness, both before and after annealing. Thickness uniformity is potentially a double-edged sword. It could help maintain figure as well as distort the figure. Detailed mapping of film thickness and of stress will help us understand the interplay between these factors.

As more forming mandrels are fabricated and qualified, we expect to make mirror substrates of different diameters. They will enable us to construct TDMs with more co-aligned mirror pairs.

Module design and analysis will focus on using the E60 material, a beryllium and beryllium-oxide matrix. E60 has many important properties–including low density (2.3 g cm^{-3}) and high stiffness.

We shall conduct more vibration tests of TDMs to approach full spaceflight qualification levels. Of course, we shall also conduct more X-ray and optical performance tests both before and after environmental testing, to ensure that TDMs suffer neither permanent misalignment nor figure degradation.

Meanwhile, we are in parallel fabricating lightweight single-crystal silicon mirror substrates. Our expectation is that we shall be able to make silicon substrates that will replace glass substrates, to enable mirror modules that can produce substantially better X-ray images.

Contact:
william.w.zhang@nasa.gov

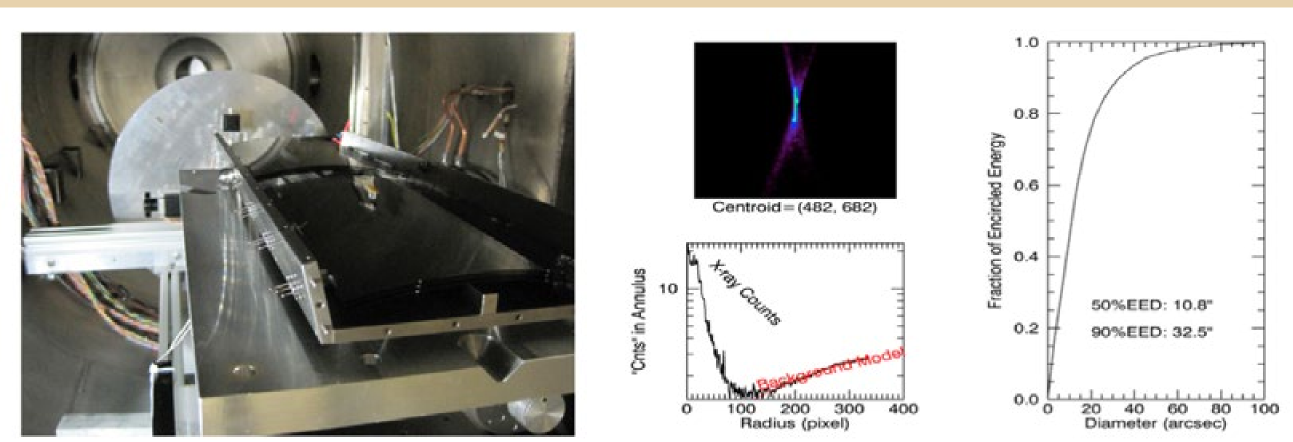

Figure 1. *Left: A TDM that contains three co-aligned and bonded primary–secondary (paraboloid–hyperboloid) mirror pairs, shown in an X-ray chamber for a full-illumination test. Right: Image with 8.0 keV (Cu Kα) X-rays, with a half-power diameter of 10.8-arcsecond and a diameter encircling 90% energy of 32.5-arcsecond.*

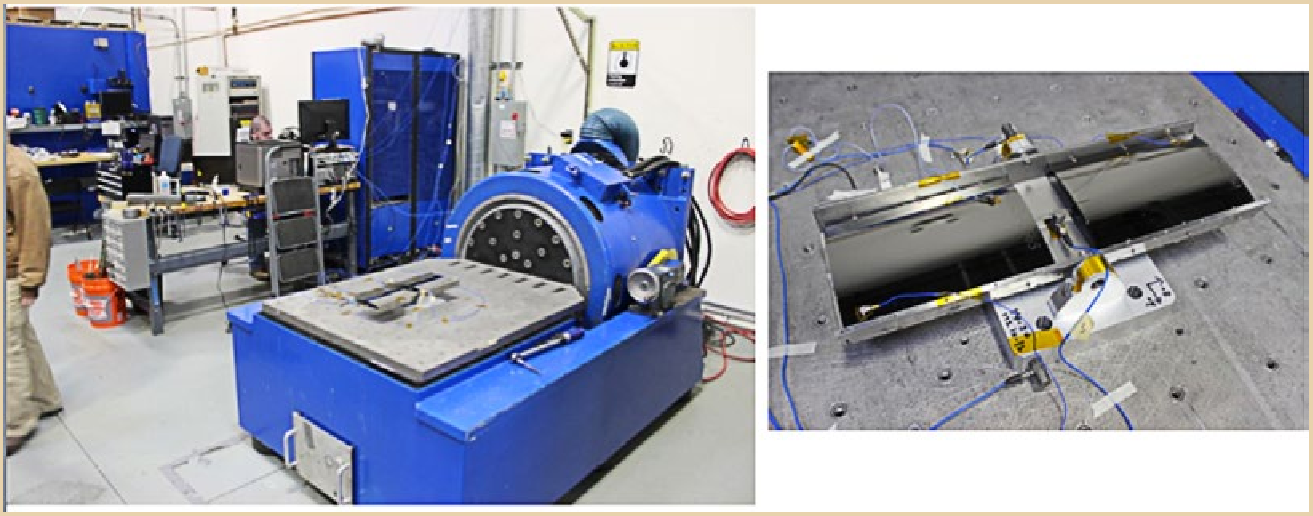

Figure 2. *A TDM on a vibration table at Washington Laboratories, Ltd., in Frederick, Maryland. This TDM was tested multiple times and all mirror segments survived. One mirror segment suffered a change in alignment, the cause of which is under investigation.*

Figure 3. *A TDM being tested in an acoustic chamber at NASA/GSFC. All mirror segments survived the test with their alignment intact.*

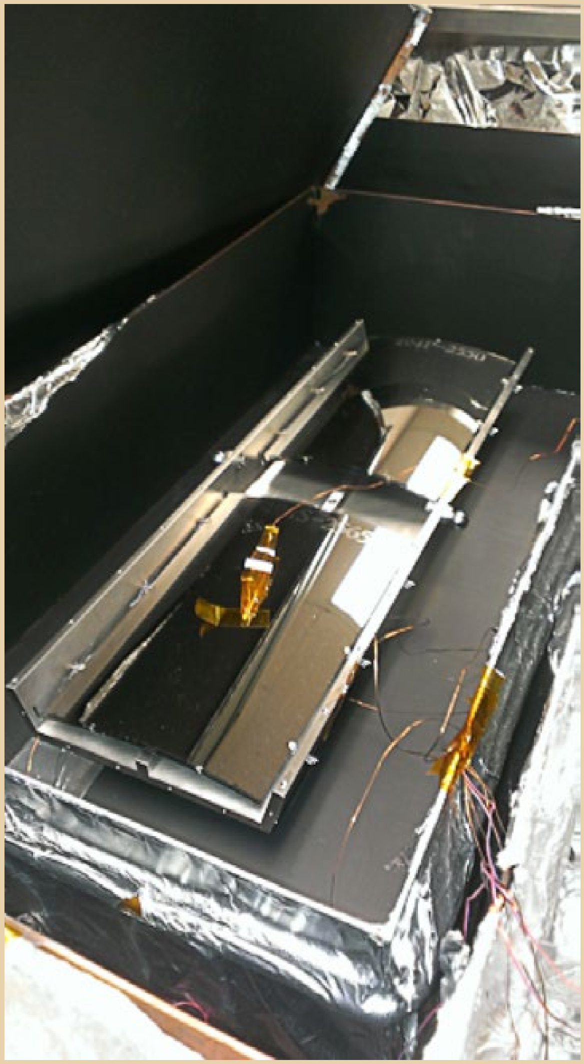

Figure 4. *A TDM in a thermal vacuum chamber at NASA/GSFC. It survived four cycles between 10ºC and 30ºC first and then four more cycles between 0ºC and 40ºC. The thermal cycling did not degrade the alignment and performance of the TDM.*

Demonstrating Enabling Technologies for the High-Resolution Imaging Spectrometer of the Next NASA X-ray Astronomy Mission

Prepared by: Caroline Kilbourne, Joseph Adams, Simon Bandler (NASA/Goddard Space Flight Center); Kent Irwin, Carl Reintsema, Joel Ullom (National Institute of Standards and Technology)

Summary

NASA Godard Space Flight Center (GSFC) (Principal Investigator/PI C. Kilbourne) and the National Institute of Standards and Technology (NIST)-Boulder (lead K. Irwin) are collaborating on a Research Opportunities in Space and Earth Sciences (ROSES) Strategic Astrophysics Technology (SAT) program to advance superconducting transition-edge sensor (TES) microcalorimeter technology toward Technology Readiness Level (TRL) 6. This project was approved for funding in Fiscal Year (FY) 2013 and 2014. Though the duration of this particular project is only 2 years, the GSFC and NIST microcalorimeter groups have been collaborating on the technology development for an imaging X-ray microcalorimeter spectrometer—TES microcalorimeter arrays and time-division multiplexed superconducting quantum interference device (SQUID) readout—since 1998. This collaboration previously brought the detector system to TRL 4, as evaluated by both NASA and the European Space Agency (ESA) during mission formulation for the *International X-ray Observatory* (IXO).

The primary goal of the current project is to advance the core X-ray Microcalorimeter Spectrometer (XMS) detector-system technologies to a strong demonstration of TRL 5. Additional objectives are to develop and demonstrate two important related technologies to at least TRL 4: position-sensitive TES devices and code-division multiplexing (CDM). These technologies have the potential to expand significantly the range of possible instrument optimizations; together they allow an expanded focal plane and higher per-pixel count rates without greatly increasing mission resources. The project also includes development of a design concept and critical technologies needed for the thermal, electrical, and mechanical integration of the detector and readout components into the focal-plane assembly. A verified design concept for the packaging of the focal-plane components will be needed for the detector system eventually to advance to TRL 6. In summary, the 2-year project is a targeted development and demonstration program designed to make significant progress in advancing the XMS detector system toward TRL 6, thus establishing its readiness for a range of possible mission implementations.

Background

The ability to perform broadband imaging X-ray spectroscopy with high spectral and spatial resolution was an essential capability of the mission concept for the IXO. Despite the fourth-place ranking of IXO in the 2010 National Research Council's (NRC) decadal review of astrophysics, the science focus of IXO was strongly endorsed in the review, as was investing in its key technologies. According to the NRC *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) Decadal Survey report: "Because of IXO's high scientific importance, a technology development program is recommended this decade with sufficient resources."

There does not exist, nor has there ever been, an X-ray observatory capable of high resolution in both imaging and spectroscopy simultaneously. The grating instruments of Chandra and the *X-ray Multi-Mirror Mission* (XMM-Newton) provide high-energy resolution (with higher resolving power at longer wavelengths), but with confusion between and spatial and spectral information for extended sources. The CCD instruments of *Chandra*, XMM-Newton, and *Suzaku* provide imaging capability commensurate with their optics, but only modest energy resolution. A new era of imaging high-resolution X-ray spectroscopy will begin with the launch of the *Astro-H Soft X-ray Spectrometer* (SXS) in 2015. The 5-eV energy resolution of the SXS microcalorimeter in the energy band of 0.2–10 keV will provide new understanding in many areas of X-ray astrophysics, but some of the key questions will remain unanswerable because of the limited number of spatial resolution elements (due both to the 6×6 array architecture and the angular resolution of the optics). The first mission concepts based on kilo-pixel scale X-ray microcalorimeters were formulated just before the turn of the century, and rapid progress in the development of TES arrays established that technology as the reference for a series of mission concepts.

There are a number of different ways forward for NASA to capitalize on its prior and continued investment in TES microcalorimeter development. Mission concepts such as the Advanced X-ray Spectroscopic Imaging Observatory (AXSIO) [Bookbinder et al., 2011] and the Notional Calorimeter X-ray mission (N-CAL) [Petre et al., 2012] are being advanced for a possible start this decade. In Europe a new mission concept known as the Advanced Telescope for High-Energy Astrophysics plus (ATHENA+) is being developed for a proposal for an ESA L2 launch opportunity. These are each envisioned as broadband, observatory-class missions in the direct lineage of the Constellation-X, X-ray Evolving Universe Spectroscopy (XEUS), IXO, and ATHENA mission concepts. The technology development program we are pursuing is merely an update to the IXO technology roadmap [Kilbourne and Doriese, 2010] that accounts for the more recent mission concept studies, therefore it is inarguably essential to the scientific program of AXSIO, N-CAL, and ATHENA+. Of the five key science questions used as the framework for the 2012 NASA X-ray Mission Concepts Study, the three that require an XMS with the capabilities of the SAT demonstration are:

- What happens close to a black hole?
- How does large-scale structure evolve?
- What is the connection between super-massive black hole formation and evolution of large-scale structure (i.e., cosmic feedback)?

The reference technology for these missions consists of molybdenum gold (Mo/Au) TES thermometers (operated at <0.1 K) with close-packed bismuth gold (Bi/Au) thermalizing X-ray absorbers on a 0.25–0.3 mm pitch. In the baseline time-division multiplexing (TDM) concept [Chervenak et al., 1999], the outputs from the dedicated input SQUIDs of individual TES pixels are coupled to a single amplifier, and multiplexing is achieved by sequential switching of these input SQUIDs. Energy resolution of better than 3 eV full width at half maximum (FWHM) at 7 keV is required, with a high-resolution live time of no less than 80% at a counting rate of 50 events/s/pixel, and a band pass of 0.1–12keV.

The integrated XMS detector-system technologies reached TRL 4 in March 2008 with the successful demonstration [Kilbourne et al., 2008] of multiplexed (2 column × 8 row) readout of 16 different pixels (in an 8 × 8 array) similar to those in the current XMS reference design. Reaching this milestone showed that the baseline technology approach is fundamentally sound. The detector pixels were sufficiently uniform to permit good performance under common bias, and the modest degradation of the detector performance while multiplexed was consistent with models. Resolution across 16 multiplexed pixels ranged from 2.6 eV to 3.1 eV, and the pulse time constant was 0.28 ms. This "2 × 8 demo" achieved the most fundamental goal of a demonstration of TRL 4 (as articulated in NPR 7120.8–NASA Research and Technology Program and Project Management Requirements and expanded in Mankin, 1995)–basic technological components were integrated to establish that they will work together. The performance approached the requirements of potential system applications (in terms of resolution, speed, pixel scale, and quantum efficiency.) However, consistent with the expectations for TRL 4, the validation was relatively low-fidelity compared with the eventual system application, since it is not possible to scale up the technologies used in the demonstration to what is needed for the flight system without further technology development. NASA and ESA technology assessments have agreed that the technology is at TRL 4.

Much of the ground between TRL 4 and TRL 5 has already been covered. An adequate pixel design is in hand. The main challenge at the pixel level is process control, which is a matter of tracking and controlling the superconducting transition temperature (T_c) of the Mo/Au TES and the heat capacity and thermalization of the Au/Bi absorber. At the array level, production of reliable 32 × 32 arrays with microstrip wiring is becoming routine [Chervenak et al., 2012]. The specific multiplexer architecture is based on the TDM used for the 2 × 8 readout demonstration, and well-defined specific changes are being implemented to increase the bandwidth, and thus improve and extend the performance of the demonstration to 16 rows (and beyond). Close to the required bandwidth and noise performance have been demonstrated. We are working to integrate all of these advances together to reach TRL 5 by the end of 2014.

The XMS roadmap has long contained the development of supporting technologies on feeder lines into the main technology-development roadway connecting the mid-range TRL milestones. High-density electrical interconnection is an example of such a technology. A present-day version of the XMS roadmap must also include on ramps for variants of the core technologies that either provide more margin with respect to the minimum performance requirements or enhance instrument capabilities. We are investing in three of these feeder lines in the current program—focal-plane assembly technologies, extended-array technologies, and CDM.

Focal-Plane Assembly Technologies

In order to progress from TRL 5 to TRL 6, even for the simplest array design, technologies need to be developed that permit compact thermal, electrical, mechanical, and magnetically shielded staging of the TES array, the particle veto, and the superconducting electronics. In order for these technologies to be ready for that later phase of system maturation, we need to begin development now of flight-suitable designs for magnetic shielding, kinematic mounting of full-sized detector chips with adequate heat sinking, and high-density modular wiring.

Extended Array Technologies for Expanding the Field of View

The XMS of IXO and the last version of *Constellation-X* included a second TES array outside of a core array. In this outer array, four pixels were to be read by a single TES, with discrimination among the four distinct absorbers achieved via pulse-shape analysis. The outer array was designed to expand the field of view without a commensurate increase in readout resources, at the cost of worse resolution (e.g., 6-eV FWHM). In the ESA review of the IXO Phase A study, the outer-array technology was assessed at TRL 3, which is why it was not included in the design of the ATHENA XMS. We are now working to bring the outer-array technology to TRL 4 through a multiplexed readout demonstration of an array of four-absorber TESs.

Code-Division Multiplexing

CDM [Irwin et al., 2010] is most easily understood via comparison to TDM. The circuits can look similar, but the modulation functions employed are different. TDM employs low-duty-cycle boxcar modulation functions that switch the input SQUIDs (one per TES) on and off one row at a time. In contrast, CDM uses Walsh codes, in which the coupling of the pixel signals is alternated in polarity. (In the simplest case of two-channel CDM, the sum of the signals is first measured, followed by the difference.) To extract the individual signals, multiplications by the inverse Walsh matrix are required.

Because signal is measured from every detector at each sample, instead of once per frame for TDM, CDM has a $\sqrt{N}$ amplifier noise advantage over TDM, where N is the scale of the multiplexing. The IXO/XMS noise budget had very little margin [Kilbourne, 2010], which is the reason the ATHENA resolution requirement was relaxed relative to IXO. CDM's eventual replacement of TDM in the roadmap will enable more capable implementations of XMS. It facilitates faster pixels with larger slew rates by providing the noise margin to allow the coupling of the TES to the input SQUID to be reduced. Thus we are working to advance CDM-based TES detector systems.

Objectives and Milestones

The ultimate goal of the XMS technology development program is to bring the entire detector system to TRL 6. However, because there are various evolving mission concepts in play, it is not possible to be as specific regarding the demonstration requirements as was possible in the roadmaps for the XMS instruments of *Constellation-X* and IXO. The final focal-plane design will incorporate one or more TES array types and a particle veto for background rejection, all read out with SQUID multiplexers. Common to all of the designs, even ones with composite focal-plane arrays, is a primary array that is similar to the original ATHENA 32 × 32 array (0.25 mm pixels, 3-eV FWHM, 50 events/s/pixel) that is augmented by technology enhancements that extend the capability of the instrument. Thus the highest priority is to advance the TRL of the core array and its TDM readout (milestone "A", below), with development of other possible components of the focal plane following closely behind.

ROADMAP

A) Core Array Prototype (TRL 5) Demonstration [2014]

Demonstrate multiplexed (3 columns × 32 rows) read-out of 96 different flight-like pixels on a 0.30 mm pitch in a 32 × 32 (or greater) array with > 95% of pixels achieving better than 3-eV resolution at 6 keV, using an analysis method consistent with the requirement of 80% live time at an X-ray rate of 50/s/pixel. Vibration testing of an array is required to validate the mechanical design of the pixels. Radiation testing of the detectors and readout is necessary to validate robustness in the space environment.

The details of this milestone depend on the mission concept, but meeting the ATHENA requirements (16 rows) is a minimum for this technology to be considered at TRL 5. For AXSIO, the demonstration should be done with 0.3 mm pixels and pushed to 32-row multiplexing.

B) Outer Array Feasibility (TRL 4) Demonstration [2014]

Demonstrate multiplexed (2 columns × 8 rows) read out of 16 four-absorber devices with better than 6-eV resolution on all 64 pixels and fall times of < 4 ms. The individual absorbers shall be at least 0.25 mm wide. Position discrimination must be achievable at energies down to a least 1.5 keV.

The outer array employs "thermal multiplexing," multiple absorber pixels connected to a single TES and distinguished by pulse shape. The TES channels themselves are then electrically multiplexed. For this roadmap, a useful milestone is to demonstrate multiplexed read out of four-absorber devices with absorbers the same size as the core-array pixels, as envisioned for AXSIO.

C) Outer Array Prototype (TRL 5) Demonstration [2015]

Demonstrate multiplexed (3 columns × 16 rows) read-out of 48 four-absorber devices with better than 6-eV resolution at 6 keV using an analysis method consistent with the requirement of 80% live time at an X-ray rate of 10/s/pixel, and position discrimination down to energies as low as 150 eV.

Note: Pushing this to 32-row multiplexing would enable larger focal planes.

D) Particle veto concept demonstration [2013]:
Demonstrate proof-of-principle, one-sided, anti-coincidence detector for particle veto and design a feasible scheme for its read out and integration behind the microcalorimeter array. *(This milestone was accomplished under an Astrophysics Research and Analysis (APRA) award.)*

E) Particle Veto Prototype (TRL 5) Demonstration [2016]
Demonstrate particle veto prototype on scale appropriate for size of focal-plane array with pulse time constant < 50 micro-seconds, energy resolution better than 1 keV, and ability to reject > 99.8% of minimum ionizing particle interactions depositing < 12 keV in the calorimeter array.

F) Point-Source Array High Count rate Feasibility [2013]
Demonstrate 2.5-eV resolution at 6 keV at a count rate of greater than 100 cps (unmultiplexed).

Note: This is a new array component added to AXSIO and a notional calorimeter-only mission inspired by the successful demonstration of fast TES pixels for solar physics, thus it is appearing on the roadmap for the first time.

G) Point-Source Array (PSA) Prototype (TRL 4) Demonstration [2015]
Demonstrate 2.5-eV resolution at 6 keV of close-packed PSA in a 2 × 4 multiplexed demonstration with x-rate count-rate capability of 300 cps, most likely integrating CDM readout.

H) Point-Source Array Prototype (TRL 5) Demonstration [2017]
Demonstrate 2 × 16 (32) read out of close-packed PSA with better than 2.0-eV energy resolution at a count rate capability of 300 cps.

I) Detector System Demonstration (TRL 6) [2019]
TRL 6 requires a system demonstration of integrated sensor and readout components, so the particular array components of the yet-to-be-defined targeted mission would need to be integrated at this time. Electrical/thermal interconnects and mechanical/thermal staging are approaching a flight-worthy design, but a flight design would not yet be fully realized in this demonstration. All pixels are biased, though not read out, in order to validate the thermal design.

The SAT program in progress aims to accomplish milestones A and B and to do essential groundwork for milestones G and I. Specifically, the proposed work plan is outlined below, with the major milestones marked by *.

FY13:

- prepare demonstration platforms at NIST and GSFC
- optimize and produce multiplexer components and electronics for TRL-5 demonstration
- prepare bias/interface chips for extended-array multiplexer test
- develop and perform mechanical analysis of chip-mounting schemes and suspensions
- determine promising magnetic-shielding geometries to test
- lay out and fabricate full-scale, electrical/mechanical-model array chips

FY14:

* complete TRL-5 demonstration of core array, including vibration and radiation testing
* complete TRL-4 demonstration of extended array
* perform CDM demonstration of XMS-type pixels in TRL-5 platform
- design and produce 32-row CDM components
- perform exploratory CDM demonstrations with 32 rows and with fast pixels

- test magnetic shielding designs
- refine chip-mounting schemes and suspensions; incorporate mechanical-model arrays
- perform feasibility study of compact wiring interfaces to route wires 90 degrees off the focal plane

Progress and Accomplishments

Demonstration Platforms:

Our work towards a TRL-5 demonstration started shortly after our successful demonstration of TRL 4 in 2008. Work on the larger arrays, funded largely through APRA, has succeeded, but the system-level demonstration has lagged for a number of reasons. The design and build-up of the demonstration platform leveraged multiple funded programs at GSFC and at NIST, so much so that nearly every component was designed and/or needed for another program. For instance, the platform itself is slated to become the TES spectrometer to be delivered by this collaboration to the Lawrence Livermore National Laboratory Electron Beam Ion Trap (EBIT) for laboratory astrophysics. Additionally, the platform locked in a readout architecture that seemed promising at the end of the *Constellation-X* program but has since been shown to have practical limitations. The concept was to reduce the number of SQUIDs in the series arrays (the SQUID amplifiers that read out each multiplexed channel) so that they dissipate low enough power to be operated at the 50-mK detector stage, minimizing stray inductance between the stages and thereby managing the associated bandwidth limit. However, the smaller gain of the low-power series arrays transferred design challenges from the SQUID stages to the room-temperature, low-noise electronics. We are now switching to a compromise approach that returns the series arrays to a higher-temperature stage but manages the impact of stray inductance via increased dynamic resistance of the multiplexer SQUIDs. This year we have continued to work toward a preliminary TRL-5-scale demonstration in the existing set-up before shipping it to EBIT, while at the same time optimizing components for the new approach and preparing a new dedicated test platform for it. In the existing system we have now demonstrated the bandwidth necessary for 16-row multiplexing at the required rates; the bandwidth is presently limited by the existing first-stage SQUIDs.

We have also commissioned an adiabatic demagnetization refrigerator, leveraged from other programs, to serve as a platform for testing sensor and readout components at temperatures down to 50 mK. The refrigerator contains a detector package configured for eight columns with up to 20 sensors each for 160 sensors total. This test platform has recently been used to validate improvements in the readout electronics, their firmware, and control software. A screen shot of the control environment for the 160-sensor array is shown in Fig. 1, which shows a trigger-rate map in the lower right corner. The test platform, which can be coupled to a range of photon sources, was particularly useful for the development and validation of firmware routines to rapidly detect shifts in SQUID working point and automatically recover a desired working point without intervention by the user or the controlling PC.

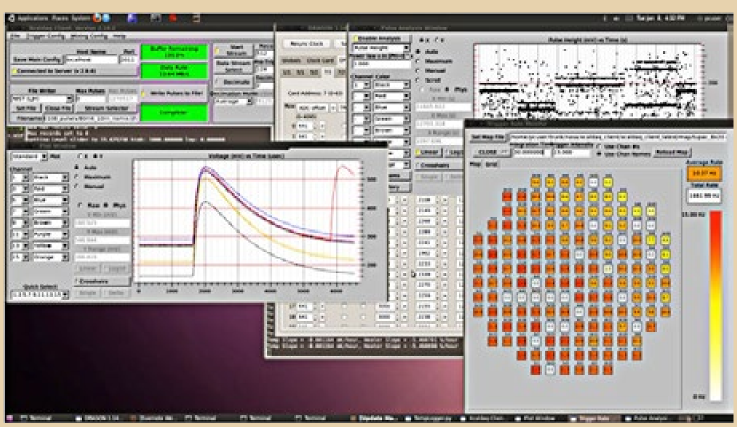

Figure 1: Display for data acquisition and visualization for 160-channel TES platform.

SQUID Multiplexer Components:

SQUID multiplexers with reduced crosstalk: While working to advance a multiplexed array platform to a higher technology readiness level, we discovered a pathological source of nonlinear, hysteretic crosstalk. A new generation of SQUID multiplexer chips, which will be used in the demonstration platform, has now been developed that eliminates this problem. This crosstalk would occur because the SQUID amplifiers for the 'off' channels could reside in one of two flux states, depending on the amount of current flowing through that channel before it was turned off. The level of crosstalk was dependent on which flux state the 'off' SQUID happened to inhabit. The hysteretic nature of this crosstalk process would make it difficult to correct in software.

We have now modeled, designed, fabricated, and tested a new SQUID multiplexer design that has only one flux state in the 'off' channels. We have shown that the new design does not exhibit the hysteretic crosstalk, which is important for a robust detector system. This chip design will be used in the next array demonstration platform. We have fabricated enough chips for the planned demonstration.

Improved, low-resonance series-array design: The SQUID multiplexer chip is followed by a series-array SQUID amplifier that boosts the signals to the level required by the room-temperature preamplifier. The series-array chips work well, but when operated at a lower temperature than 4 K, they sometimes exhibit resonance features that make it difficult to choose an optimal bias point for operation. This year, we have designed, fabricated, and tested a new series-array SQUID design with new resonance damping features that should enable robust array operation. This new design incorporates normal metal on some of the superconducting wires, which introduces loss at microwave frequencies, reducing resonances, but not at signal frequencies, so that it adds no signal-band Johnson noise. The arrays work very well at 4 K. Demonstration of low-resonance operation at lower temperatures is ongoing.

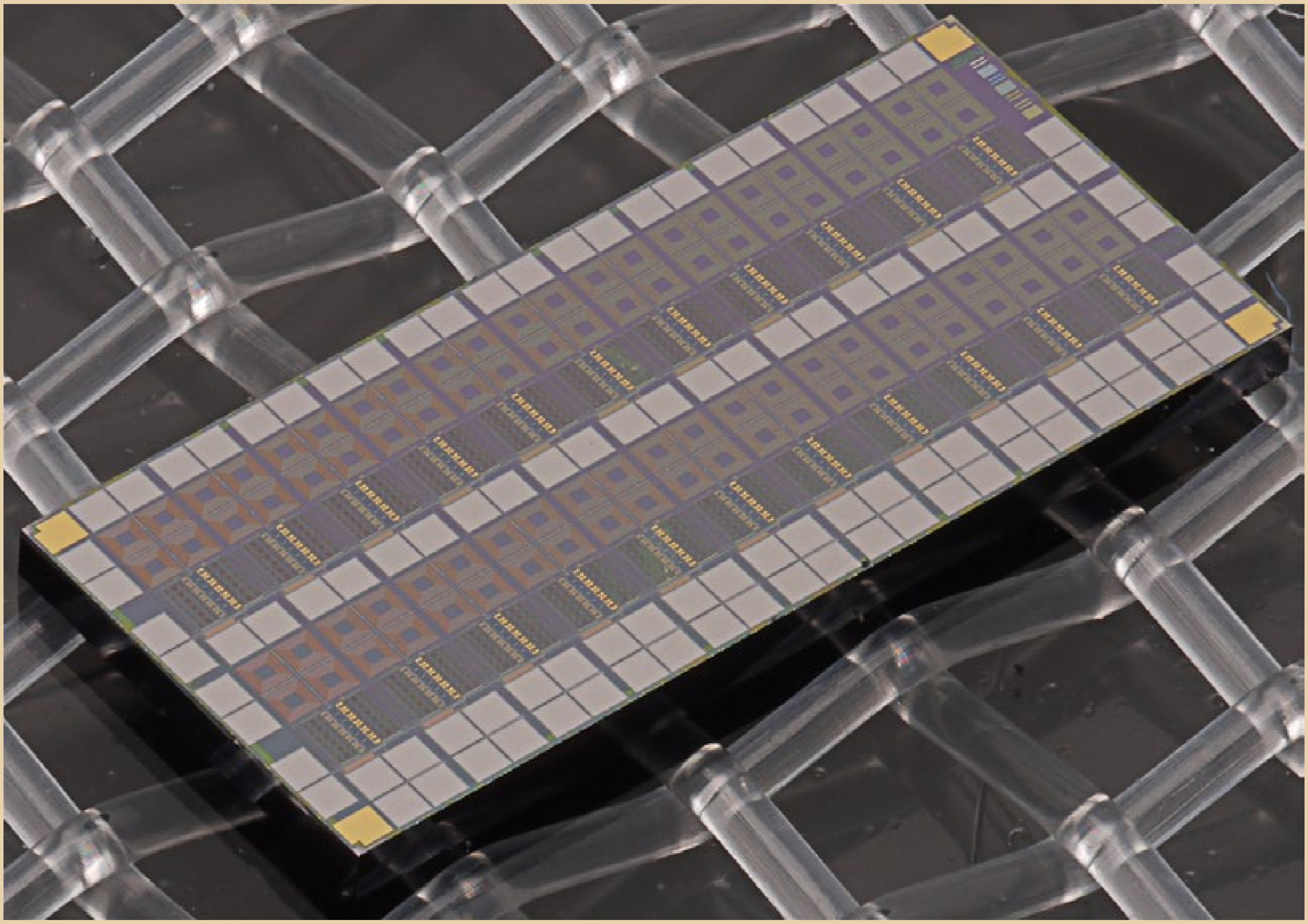

Figure 2: *Next-generation multiplexer chip that incorporates flux-actuated switches to overcome the on-chip bandwidth limitation in the prior design.*

Next-generation high bandwidth SQUID multiplexers: As we have developed higher-bandwidth wiring and preamplifier electronics, we are beginning to approach the point at which the speed of our SQUID multiplexers will be limited by the bandwidth of the multiplexer chip itself. This bandwidth is set by the coupling between the on-chip first-stage SQUID switches and the on-chip second-stage SQUID preamplifier. We have now developed a new multiplexer architecture that eliminates the second-stage SQUID amplifier, and thus this bandwidth limitation. This breakthrough will enable the next generation of large X-ray calorimeter arrays.

The design is based on three-junction flux-actuated switches originally proposed by Zappe (1977). The idea of using these switches in a time-division SQUID multiplexer was proposed by Beyer and Drung (2008). We have developed and now demonstrated a multiplexer design that is drop-in compatible with the array architecture being developed under this program. A photograph of one of the resulting SQUID multiplexer chips is shown in Fig. 2. We have demonstrated the fast cryogenic operation of these multiplexers. An additional design revision is required before these chips can be used with our X-ray calorimeters in order to optimize the coupling between the SQUID switches and the TES X-ray calorimeters. However, after that step is completed, this design will allow a significant step forward in X-ray multiplexer switching rates, and thus in the number of pixels that can be read on a single amplifier channel.

SQUID Multiplexer Electronics:
Firmware: A flux-jump-reset algorithm was completed and is functional, although some refinement is still required. (SQUID response is periodic in flux quanta; a flux jump can occur when the amplifier slew rate is exceeded and the feedback locks up an integral number of flux quanta away from nominal quiescence.) This algorithm handles over-range events as well. In a test at high photon rate and high dynamic range in photon energy, the through rates while using this algorithm were consistent with that expected from conventional photon detector statistics under pile-up conditions.

Hardware: Upgraded digital-feedback boards and a new power-control card (higher power handling capability and real-time monitoring) will soon be completed. We have produced a functional implementation of a commercial PCIe development board with a NIST 24-channel fiber optic transceiver daughter card and validated data rates up to 100 MB/s 16 channels at 50 Mbits/s/ch). Figure 3 shows a multiplexer electronics crate with clock, feedback, address, DC supply, and power-control cards in place.

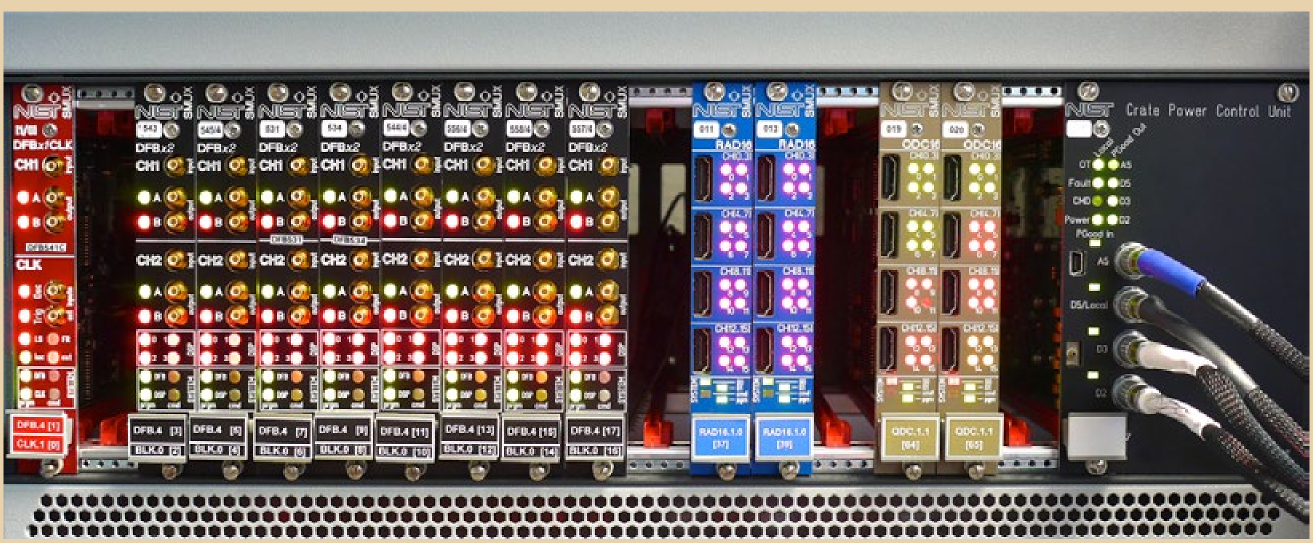

Figure 3: *SQUID multiplexer electronics crate with clock, feedback, address, DC supply, and power-control cards.*

Tests of system clock fidelity at 100 MHz were recently completely. The results suggest that the current system configuration (currently operated at 50 MHz) should support operation at 100 MHz. We are now focusing on achieving better timing resolution in our firmware designs.

We have begun development of an improved room-temperature voltage preamplifier to measure the output signals of SQUID series arrays. By shifting gain between the two stages of the existing preamplifier design, we obtained higher analog bandwidth. We have begun testing of a prototype three-stage preamplifier that should produce further bandwidth improvement.

Path Forward

The path forward is to follow the roadmap detailed in the "Objectives and Milestones" section. Until obstacles are encountered, there is no reason to think that the path forward will deviate from this roadmap, presuming sufficient resources are made available in the future.

Recent emphasis has been placed on improving the readout components and the system bandwidth to the level required for the TRL-5 demonstration, almost without regard to the details of the detectors. By the end of the current year, matched detectors and input SQUIDs must be produced. In order to meet the milestone schedule, with margin, we project starting to test in the core-array demonstration configuration starting in January 2014 and in the extended-array configuration in July 2014. Work on the supporting technologies, which has been proceeding at a low level in parallel with the main thrust of the past year, will be ramped up in the fall of 2013.

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Contact:
caroline.a.kilbourne@nasa.gov

Colloid Microthruster Propellant Feed System

Prepared by: John Ziemer (Jet Propulsion Laboratory) and Juergen Mueller (JPL)

Summary

The Colloid Microthruster Propellant Feed System Project is a 2-year technology development effort that began in early 2013 and focuses on increasing the capacity and reliability of colloid microthruster feed systems. Delivered for flight on the European *LISA Pathfinder* (LPF) mission in 2009, the Busek Colloid Micro-Newton Thruster (CMNT) represents the worldwide state-of-the-art in precision micropropulsion with the only other viable option being lower performance cold-gas thrusters. Precision micropropulsion is required for drag-free operation of a Gravitational Wave Observatory (GWO) and enables significant mass savings on Exoplanet observatories by replacing reaction wheels and associated vibration isolation stages. By using a new type of propellant storage tank, this technology development effort seeks to scale up propellant handling capacity by 20 times without significantly increasing the cluster mass over the current CMNT architecture. This work also includes developing and integrating the next generation of precision propellant flow control, the Busek microvalve, including reducing complexity in manufacturing and increasing reliability by using a dual-string redundant architecture. The ultimate objective at the end of this 2-year project is to raise the technology to TRL 5 in preparation for a long-duration test that would qualify the entire colloid microthruster system for a GWO.

Background

Almost all GWO concepts require microthrusters to maintain a drag-free environment for the inertial sensor instrument to meet the mission science objectives. Exoplanet observatories can also benefit from precision microthruster technology, replacing reaction wheels for spacecraft fine pointing without requiring elaborate vibration isolation stages. The current state-of-the-art microthruster in the U.S. is the Busek CMNT originally developed under the New Millennium Program for the Space Technology 7 (ST7) and the European Space Agency's (ESA) LPF technology demonstration mission. Two CMNT protoflight units, each with four thruster systems, have passed through environmental and spacecraft-level qualification testing. In 2009, the units were delivered and integrated onto the LPF Spacecraft, and are now awaiting launch in 2014 for a 60-day demonstration mission. As shown in Figure 1, the ST7 CMNT design includes a bellows propellant storage tank that is sized to provide up to 90 days of maximum thrust (30 μN). A full CMNT system has been tested for 3478 hours (approximately 145 days) of near continuous operation at an average thrust of about 18 μN. However, as detailed in the Physics of the Cosmos (PCOS) Program Annual Technology Report (PATR) (November 2011), two main issues remain to use the CMNT technology on a future GWO: developing a large enough propellant storage device and demonstrating lifetime adequate for a full science mission of at least 2 years. To reach TRL 6, the CMNT technology must be upgraded with a larger tank and the entire system must demonstrate the required lifetime with adequate margin (150% of expected operational time and maximum expected propellant consumption).

Under the Strategic Astrophysics Technology (SAT) and Technology Development for Physics of the Cosmos Missions (TPCOS) Program, over the next 2 years we will develop a new propellant storage tank and feed system to TRL 5 that would eventually be included in a TRL 6 system-level lifetime demonstration once mission requirements have been specified. The tank will be sized based on the longest expected mission duration of 5 years (see Table 1), with margin, providing up to 1 liter of propellant. The tank will use a metal-diaphragm blow-down design for long-term propellant compatibility and to reduce mass by at least a factor of two compared to the current state-of-the-art bellows design. Small metal-diaphragm propellant tanks have already been used in multiple U.S.

missile systems and for other space-based applications, but have not been demonstrated with colloid thrusters. The new feed system will also include the third generation of Busek's microvalve, currently being developed under a NASA Phase II Small Business Innovation Research (SBIR) program. The microvalve is responsible for the picoliter-per-second control of the propellant from the tank to the thruster head, demanding parts with micron-level tolerances, critical alignments, and challenging acceptance test protocols. While the ST7 microvalve already provides the necessary performance, typical production times were 8-20 weeks for each unit, including multiple iterations that did not meet leak rate, thermal performance, or cleanliness criteria (on average, only 16% of ST7 microvalves passed through acceptance testing). Busek's latest microvalve design focuses on manufacturability and reduced mass and cost while maintaining performance. At the end of the program, a new tank and microvalve will be tested together in a relevant thermal and dynamic environment (TRL 5), demonstrating the required performance and lifetime capacity for a GWO.

	ST7-DRS		LISA		GWO (2-Year)		GWO (5-year)	
	Science	Attitude	Science	Attitude	Science	Attitude	Science	Attitude
Average Thrust (μN)	20	N/A	10	30	10	30-100	10	30-100
Duration (hrs)	1400	0	60000	6000	16000	1800	40000	4000
Total Impulse (Ns)	100		2800		800-1200		1900-2900	
Propellant Mass (kg)	0.06*		1.5		0.4-0.6		1.0-1.5	

* ST7 propellant tanks are sized for full thrust, 30 μN, for 90 days, 0.15 kg of propellant.

Table 1. *The propellant mass requirements per thruster for all GWO concepts, including both science and attitude operations (orbit maintenance/acquisition), demand larger tanks than what will be demonstrated on ST7-DRS. The new tank will hold up to 1.52 kg (1 L) of propellant, covering all GWO options.*

The new feed system will use a more traditional diaphragm tank design, shown schematically in Figure 2. The thruster cluster mass can be nearly the same as ST7 despite the increase in propellant mass. This is achieved through a lightweight spherical stainless steel (304) tank design of a mere 76.2 μm (3 mm) wall thickness due to the low feed pressures required. The tank will be operated in blow-down mode from 2 atm to 1 atm. Although diaphragm tanks have been used extensively in space flight, our tank design is unique in that it uses EMI-Im (1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide) compatible, non-magnetic stainless steel material both for the shell, as well as the diaphragm. Standard elastomeric diaphragms used throughout the industry are not compatible with EMI-Im, and aluminum (Al) diaphragms, which are being used in some existing tank designs, would suffer pitting corrosion. In addition, the spherical tank design will be easier to clean and dry than bellows, resulting in a reduced risk of bubbles, contamination, and clogging. Compared to scaling up the original ST7 bellows system, the new feed system will realize mass savings of 19 kg per thruster cluster corresponding to 57 kg mass savings per spacecraft and 171 kg mass savings per mission consisting of three spacecraft.

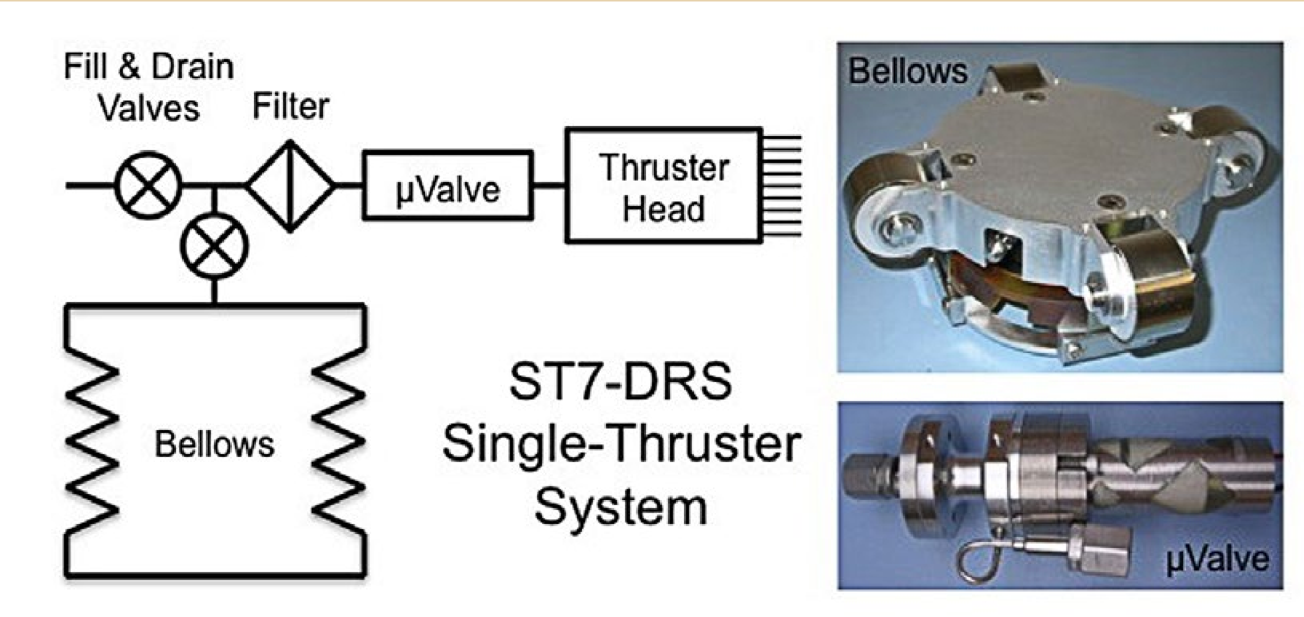

Figure 1. *Schematic of the current ST7 feed system and thruster head with photos of the bellows and Busek microvalve (not to scale) showing the heavy support structure required to pressurize the bellows, and the lack of redundancy in the overall system.*

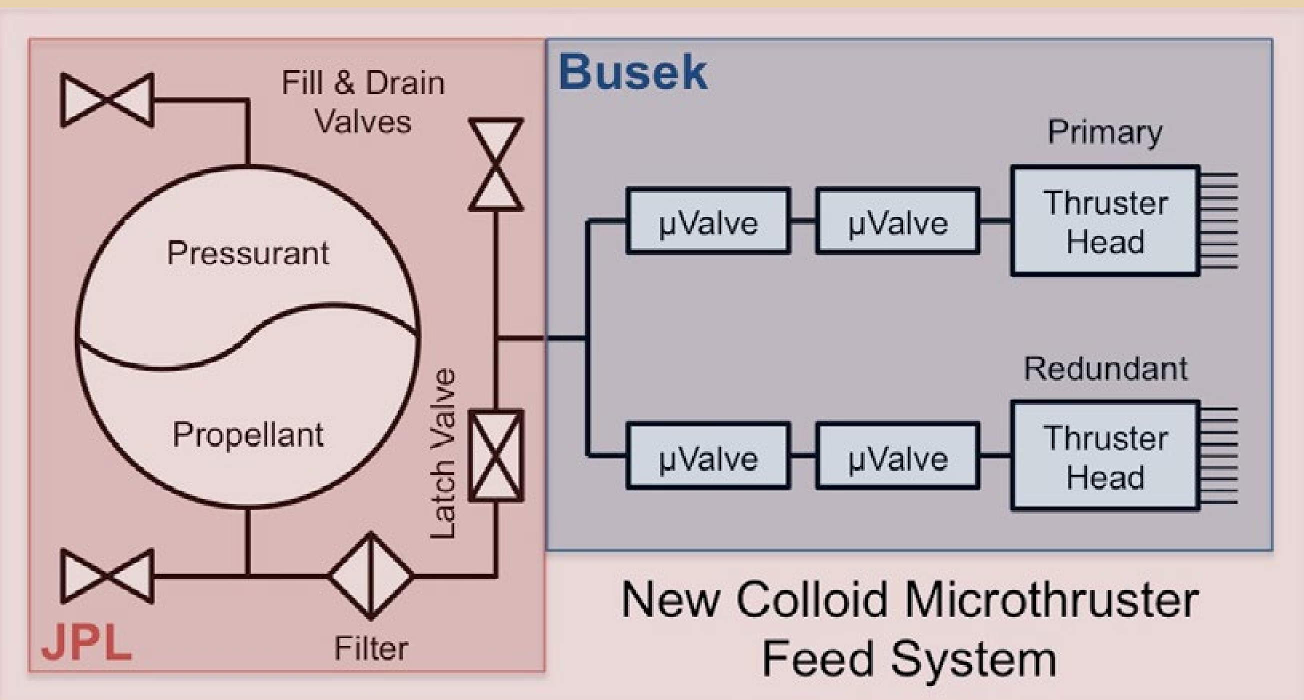

Figure 2*. Schematic of the new Colloid Microthruster Feed System, including a diaphragm tank developed by Jet Propulsion Laboratory (JPL) that will reduce the mass of the system by more than 50% compared to a scaled up bellows architecture. The feed system includes four Busek microvalves arranged in a fully redundant configuration with a simple, single propellant line interface. Each part will undergo environmental testing and the entire system will be assembled and tested at JPL to reach TRL 5.*

Objectives and Milestones

The objective of this project is to develop a lightweight, high-capacity feed system for future GWO colloid propulsion systems capable of meeting total impulse requirements corresponding to as much as 5 years of mission life. This will include a new, more reliable microvalve design and a metal diaphragm tank of 1 liter fuel capacity, both to be developed to TRL 5 in this project. In addition to component development, a complete feed system will be assembled and tested consisting of the propellant tank, two serially mounted valves for redundancy, and other required commercial off the shelf (COTS) feed system components to demonstrate system performance. In addition, we will update ST7 processes including cleaning, propellant loading, and priming, as well as functional, acceptance, and qualification test procedures.

The four main project objectives are as follows:

1. **Design the GWO tank and feed system with full redundancy.** Deliverables are feed system specifications and interface documents. We will conduct a peer review of the design with liquid propulsion system experts at the end of FY13.
2. **Design, fabricate, and qualify the stainless steel diaphragm tank.** Test tank to 2 atm maximum expected operating pressure (MEOP) and 1 liter, or 1.5 kg, fuel capacity. JPL will guide design of the tank, and an outside vendor will manufacture the tank. Deliverables will be a tank design, and two tank deliverables–one qualification unit and one test unit for an integrated system test, plus tank qualification. To reach TRL 5: Tank qualification, including environmental testing, will be performed at the vendor.
3. **Design and fabricate, acceptance, and environmental test the microvalves to reach TRL 5.** This work will be performed by the microvalve supplier for ST7, Busek Inc., leveraging experience gained with that program and the current Phase II SBIR for microvalve development. Deliverable will be a valve design, and two microvalve assemblies (containing two microvalves each, plus supporting hardware) for environmental testing and system integration with the new propellant tank.
4. **Integrate and test feed system components.** This objective includes integration of the tank with a microvalve assembly, including other COTS feed system components modified for EMI-Im use. No thrusters will be installed to keep testing costs down; instead, high-precision flow meters developed during the ST7 program will be used to verify system operation. The set-up will be used to develop and demonstrate feed system cleaning procedures, loading procedures, and full dynamic range control in Year 2.

Key Project Milestones

Year 1 (January 2013 to December 2013):

- Busek placed on contract for the long-lead microvalve and project support (complete)
- Long-lead propellant tank order submitted to vendor (delayed, estimated completion July 2013)
- Feed system component-level and system-level requirements complete (July 2013)
- Design Peer Review (August 2013)
- Prototype microvalve fabrication complete (September 2013)
- Assembly and Test Process Peer Review (December 2013)

Year 2: (January 2014 to December 2014):

- Release final assembly and test procedures based on Process Peer Review (January 2014)
- Development model microvalve fabrication complete (February 2014)
- Tank delivery to JPL (April 2014)
- Propellant drying complete (April 2014)
- Microvalve development model delivery to JPL (May 2014)
- Supporting feed system components delivery to JPL (May 2014)

- Tank environmental testing complete (August 2014)
- Microvalve environmental testing complete (August 2014)
- Environmental test results peer review (August 2014)
- Functional tests complete (November 2014)
- Final test results review (December 2014)

Progress and Accomplishments

The Colloid Microthruster Propellant Feed System Project has just started under contract at JPL in January of 2013. In summary, the first half-year of the project has focused on getting basic requirements set, letting contracts for the tank and microvalve procurements, and developing more detailed plans for testing to demonstrate TRL 5. While advances have been made in the design requirements and microvalve development, described later, the tank procurement task is behind schedule. Although the tank requirements and specifications have been completed, we have not yet secured a tank contract. The original proposed vendor, AMPAC, has been acquired by Moog, another well-known feed system vendor, in the time between the proposal and award for this effort. However, upon initial contact, Moog decided not to follow through with the originally quoted tank development. Recent efforts to find a new vendor have uncovered another option, Arde, Inc., although providing a slightly heavier tank, and discussions have re-started with Moog through alternate channels that appear to be promising. In either case, the tank contract will be issued by the end of July 2013, approximately 3 months behind schedule. With the schedule margin built into the original proposal, we believe the final deliverable schedule will still be met.

More detail on the progress and major accomplishments during the first 6 months of this project will now be broken down by objective:

1. Design the GWO tank and feed system with full redundancy

Specifications and baseline requirements for the critical parts of the feed system, the tank and microvalve, have been completed in March of 2013.

The diaphragm tank will be made of non-magnetic stainless steel and have a total volume of 2 liters, half of which will be filled with EMI-Im propellant. The tank will have a maximum design pressure (MDP) of 4 atm, approximately two times higher than necessary to achieve the full flow rate through the feed system based on experience with the CMNT system. The actual tank pressure will be set after testing, allowing for significant margin and safety while still achieving our mass target of 1 kg. The expulsion efficiency shall be greater than 99%, and qualification testing of the tank will include 25 expulsion cycles. Acceptance, qualification, expulsion, and burst test requirements have been documented in a detailed specification that is included for all vendor quotes.

The microvalve shall be designed to support flow rates up to an equivalent of 100 μN at 25°C. Flow rates shall be controlled to 0.1 μN equivalent through two microvalves in series. Allowable input pressures shall be up to 4 atm, matching the tank output specification. Acceptance, qualification, leak rate, and performance test requirements have been documented in a detailed specification that is under review.

2. Design, fabricate and qualify the SS diaphragm tank

As described previously, while the specification for the tank has been completed, we have not been able to secure a contract with a preferred vendor to procure the tank. Alternate vendors have been found, and discussions with the original vendor AMPAC (now owned by Moog) have re-started. The new tank contract should be in place by the end of July, with enough schedule margin to still meet the key project milestones described previously.

3. Design and fabricate, acceptance, and environmental test the microvalves

Busek has completed much of the development work on the third generation microvalve in preparation for the first delivery of prototype hardware to test by the end of FY13. Shown in Figure 3, the new microvalve is one quarter the size and made up of less than half the parts of the current state-of-the art CMNT microvalve. Busek has demonstrated an 90% yield on microvalve fabrication through inspection and 90% yield through acceptance testing, resulting in an 80% yield overall, compared to a 16% overall yield during the ST7 flight hardware fabrication campaign. Additionally, manufacturing and assembly time for a batch of four valves has been reduced to 3 weeks from a typical 6-week cycle for two valves during ST7. The combination of yield and manufacturing improvements should help to keep the prototype and development model builds on schedule.

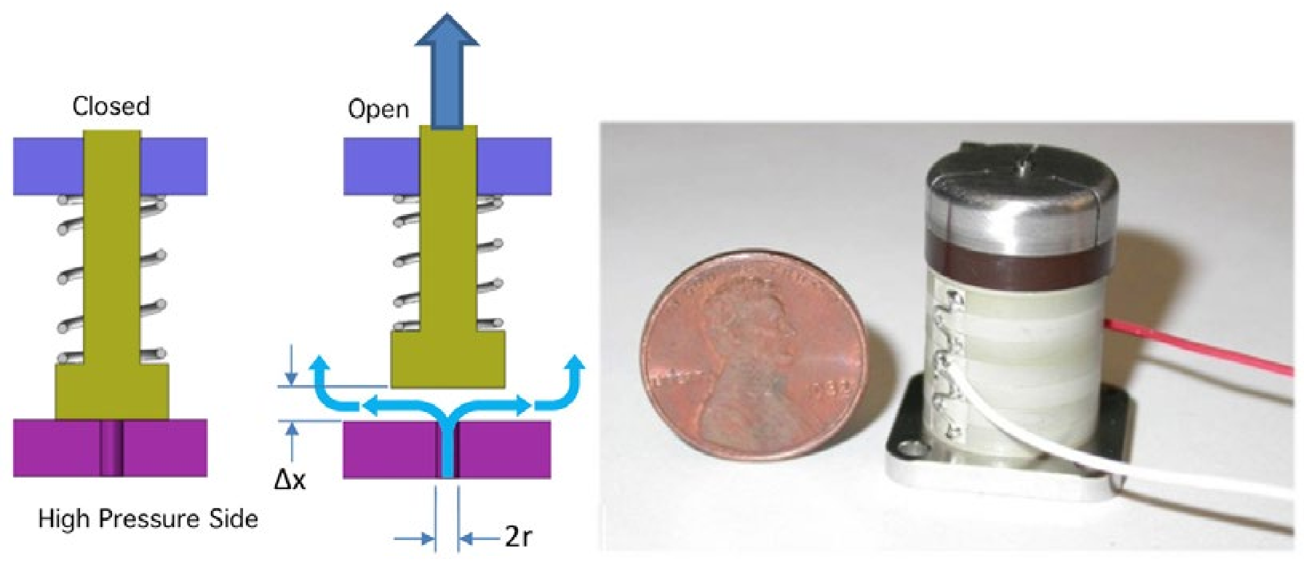

Figure 3: *Left; Schematic of valve mechanism. Right; Photo of prototype valve. The flat seal on the orifice normally is closed by spring force, while actuation force lifts the valve stem.*

4. Integrate and test feed system components

This objective is the focus of the second year of the project, once hardware is delivered. While some planning functions will occur in the second half of the first year, no work has been completed in this area to date.

Path Forward

Work on the Colloid Microthruster Feed System will continue as planned with the major near-term focus remaining on the tank vendor identification and part procurement with delivery set for April of 2014. Requirements and specifications will be peer reviewed this August. The first batch of microvalves will be made by Busek by the end of FY13. Testing will commence in preparation for the second round of demonstration model (DM) hardware delivery in May 2014. Once the hardware is in house, integration and test will begin at JPL with expected project completion in December of 2014.

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Contact:
john.k.ziemer@jpl.nasa.gov

Telescopes for Space-based Gravitational-wave Observatories

Prepared by: Jeff Livas (NASA/Goddard Space Flight Center)

Summary

The effort described in this section began in FY12 with a funding award from the Physics of the Cosmos (PCOS) Program Office, and is funded until FY14 with a 2-year Strategic Astrophysics Technology (SAT) grant, #11-SAT11-0027.

The goal is to develop a telescope suitable for precision metrology for a space-based gravitational-wave observatory[1][2][3][4], where the baseline application is to make a measurement of the separation of two spacecraft with a precision of 10^{-12} m/√Hz (1 pm/√Hz) over several million kilometers.

The telescope design for the *Laser Interferometer Space Antenna* (LISA) baseline mission may be adequately satisfied by a near diffraction-limited classical Cassegrain-style optical system–either on-axis or off-axis. By itself, therefore, it is not a particularly risky development item. The two main challenges are: 1) the requirement for dimensional stability at the picometer level for the primary-to-secondary mirror spacing in the presence of both axial and transverse temperature gradients, and; 2) the requirement for low stray light levels. Stray light levels must be extremely low because the distance measurement is made using interferometric techniques that are very sensitive to low light levels and, also, because the telescope is used to transmit a one-watt beam and receive a 100-picowatt beam simultaneously. The typical imaging application for a telescope does not have these requirements.

The telescope technology study effort will develop a set of suitable requirements for the LISA metrology application and investigate the two key design challenges both experimentally and with analysis.

The effort is supported by a small team of part-time engineers from the Optics Branch (Code 551) at NASA's Goddard Space Flight Center (GSFC), a mechanical engineer from the Mechanical Engineering Branch (Code 543) at NASA GSFC, and a postdoctoral fellow on loan from the University of Florida.

Name	Expertise	Code
Jeff Livas	Principal Investigator	663
John Crow	Mechanical	543
Joseph Howard	Optical Designer	551
Lenward Seals	Stray Light	551
Ron Shiri	EM Modeling	551
Shannon Sankar	Stray light measurement	663
Peter Hill	Mirror fabrication	551
Peter Blake	Mirror fabrication	551

Table 1: *Summary of the Prototype Telescope Team*

Background

The telescope technology development is intended to address the requirements for space-based gravitational wave detection. Gravitational waves are generated by any mass distribution with time-changing quadrupole moment[9]. The simplest example is a pair of masses gravitationally bound and orbiting around a common center of mass. The efficient generation of gravitational waves requires large compact objects moving at a large fraction of the speed of light. The simplest source is a pair of million-solar-mass black holes colliding. It is believed that black holes of this size are co-located at the center of galaxies, and therefore this source essentially represents the collisions of pairs of galaxies, one of the ways in which large-scale structure is formed in the Universe.

LISA addresses a number of science goals[10][11][13] but was specifically endorsed by the National Research Council's (NRC) *New Worlds New Horizons in Astronomy and Astrophysics* (NWNH) report (also known as the Astro 2010 Decadal Survey) as the third priority large-scale space mission (NWNH, Table ES.5, p. 8.) for three specific goals:

- Measurements of black hole mass and spin will be important for understanding the significance of mergers in the building of galaxies;
- Detection of signals from stellar-mass compact stellar remnants as they orbit and fall into massive black holes would provide exquisitely precise tests of Einstein's theory of gravity; and
- Potential for discovery of waves from unanticipated or exotic sources, such as backgrounds produced during the earliest moments of the universe or cusps associated with cosmic strings.

An example of other science that LISA can do is the study of galactic populations of binary stars [12], and the precision determination of cosmological distances in a manner independent from electromagnetic determinations.

The purpose of the telescope for the LISA baseline mission space-based gravitational wave observatory missions is to function as a precision beam expander to efficiently deliver optical power from one spacecraft to another.[14]

The telescope design for the LISA baseline mission may be adequately satisfied by a near diffraction-limited classical Cassegrain-style optical system–either on-axis or off-axis. By itself, therefore, it is not a particularly risky development item. The two main challenges are: 1) the requirement for dimensional stability at the picometer level for the primary-to-secondary mirror spacing in the presence of both axial and transverse temperature gradients, and; 2) the requirement for low stray light levels. Stray light levels must be extremely low because the distance measurement is made using interferometric techniques that are very sensitive to low light levels and, also, because the telescope is used to transmit a one-watt beam and receive a 100-picowatt beam simultaneously. The typical imaging application for a telescope does not have these requirements.

The immediate goal of this telescope technology development effort is to make a prototype telescope that meets the basic requirements for a space-based gravitational wave observatory and bring it to a Technology Readiness Level (TRL) 5 in time to be a serious candidate for a mission for the European L2 Cosmic Visions program. The effort as currently funded should result in a prototype with a TRL of 3+ or perhaps 4, and additional work will be required to reach TRL 5.

Objectives and Milestones

Overall objectives within the context of the international research community

The current situation for gravitational wave missions is uncertain, but Figure 1 shows one possible timeline. As mentioned in the previous section, the goal considered most likely at the current time is to develop technology for consideration for the L2 Cosmic Visions Program with a TRL-5 telescope by mid-2016.

Objectives specific to this development effort

The specific tasks and milestones for the work in progress are shown in Figure 2. The three milestones shown on the right-hand margin in red are discussed in detail in the Path Forward Section, and represent the endpoint of measurements on the two challenging requirements for the telescope: stray light performance and optical pathlength stability.

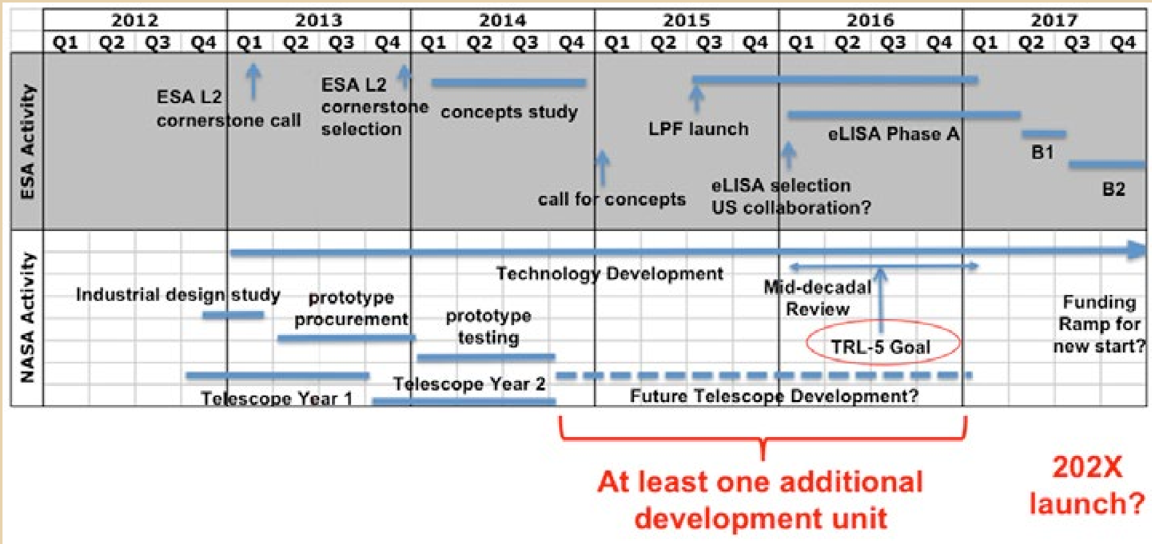

Figure 1: *Current best estimate of the context in which the telescope technology development takes place. The nominal goal is to develop a realistic prototype at the TRL-5 level by mid 2016 to be well positioned as a candidate technology to make the U.S.-led gravitational wave project team an attractive collaboration for an L2 mission.*

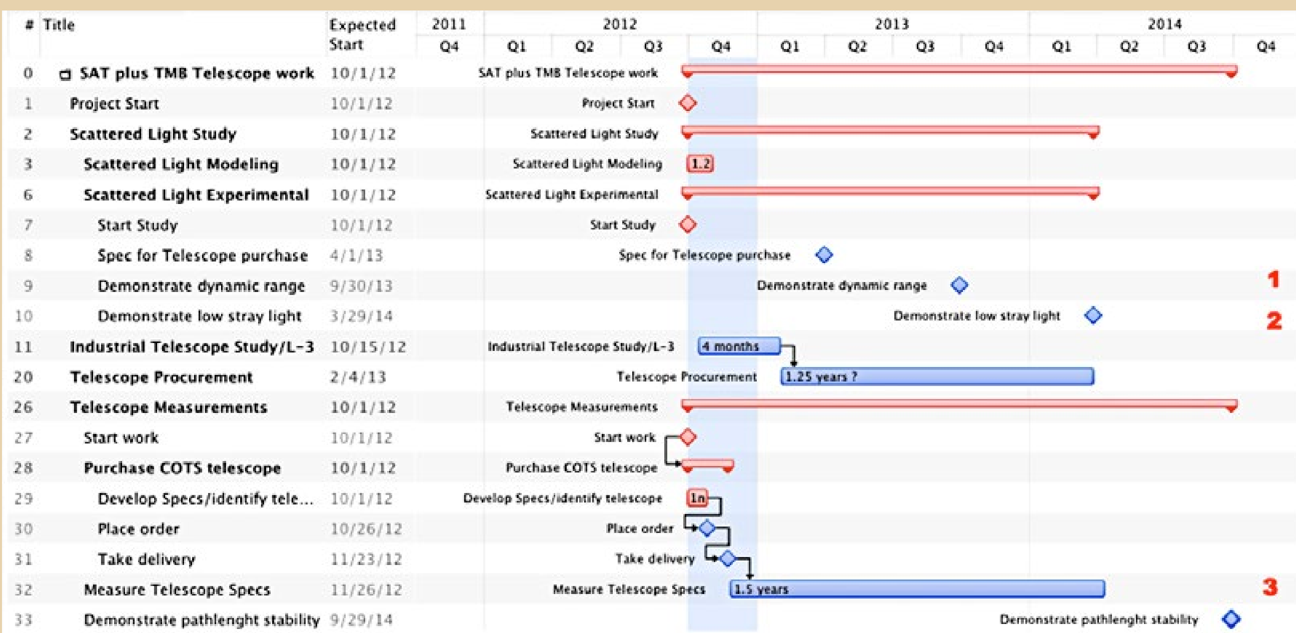

Figure 2: *Key milestones and tasks for the project. The three key milestones are flagged with bold red numbers on the right-hand border of the schedule.*

Some specific tasks include

- Complete industrial study by April 30: The expected completion date, per contractor, was February 28, the actual date was April 11, and the contractual obligation was April 30
- Initiate procurement of the prototype telescope: Paperwork was submitted to purchasing on May 28
- Development of optical and scattered light models to verify the designs supplied by the study contractor
- Design and fabrication of petaled masks for on-axis scattered light suppression: Work is in progress

Overall, the work is proceeding on schedule and meeting goals.

Progress and Accomplishments

Previous Work: High-Level Summary

As part of the early development work on the telescope, we constructed a prototype on-axis metering structure to maintain the primary-to-secondary mirror distance out of silicon carbide. We chose silicon carbide to avoid the outgassing problems with carbon fiber reinforced plastic (CFRP) composites[19], and to avoid temperature gradients expected under the anticipated operating environments. Figure 4 shows a photograph of the structure. It has four legs so that the shadow of the structure has four symmetric elements that match the symmetry of the main quad-cell detector. A four-legged structure is mechanically over-constrained, so future designs may support the secondary mirror differently (e.g., off-axis).

Figure 3: *This photograph shows a prototype silicon-carbide metering structure. No optics are included. See[19] for more details.*

Figure 4 shows the results of measurements with the prototype silicon-carbide structure showing that it is possible, at least in principle, to make a metering structure with the required stability[20]. The red curve shows that the metering structure closely follows the temperature fluctuations at frequencies below ~ 4 MHz. On-orbit the temperature fluctuations are expected to be roughly 100 times lower than in the test chamber, so the structure should meet the requirement. The challenge is to build a complete telescope (both the structure and the optics) with the required stability. Silicon carbide should work, and single-crystal silicon looks like a good candidate. Our experience with composites has not been as good[19, 21]. Other groups have made measurements with composites with different results[22, 23], but no one has succeeded in meeting all of the requirements simultaneously with a realistic design yet.

A stray light analysis has been started using the commercial non-sequential ray-tracing package FRED[22]. The analysis has focused on developing a model of the on-axis *evolved Laser Interferometer Space Antenna* (eLISA) telescope, including obstructions, based on the optical prescription and a mechanical model, plus some simplified assumptions for surface roughness and cleanliness for materials and coatings. We used a preliminary design for the eLISA optical bench courtesy of the University of

Glasgow[16] to define approximate locations for the detectors and field stops. The preliminary results show a scattered light power of 6×10^{-11} W (60 pW) on the detector for 1 W transmitted to the sky, and we expect a further reduction if polarization is taken into account. This level of stray light is below the expected 100 pW received signal from the far spacecraft, so it is approaching the right order of magnitude, but the simulation does not yet include all of the expected contributions.

The initial stray light assessment for the telescope design suggests that the performance of a telescope will be limited by surface contamination rather than surface roughness. It is expected the stray light performance of an off-axis design will be better than that of an on-axis telescope with the secondary mirror reflection suppressed simply because rays traced through the off-axis system tend to be reflected from surfaces with larger angles and, hence, lower stray light. However, it will be important to verify these expectations experimentally to be sure that it is possible to achieve the low levels in practice. Calculations and preliminary measurements[25, 26] have shown that special apodized masks similar to those used for planet-finding interferometers can be used to suppress reflections to roughly the required levels.

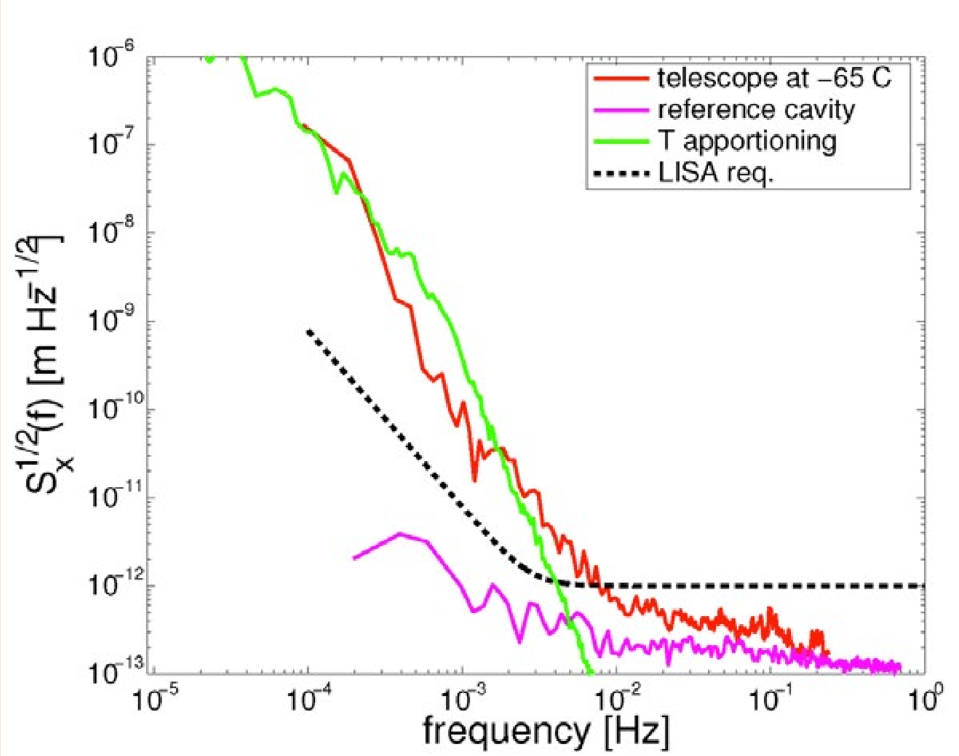

Figure 4: *Measurements from[20] show that the silicon-carbide metering structure can meet the requirements in principle. The dotted black line shows the requirement, and the magenta line entirely below the requirement is the performance of the reference cavity. The green line shows the expected fluctuations of the structure due to the measured thermal fluctuations and the known coefficient of thermal expansion. The red curve shows the measured performance of the telescope spacer at -65°C, showing it is likely limited by thermal fluctuations below about 4 MHz. Thermal fluctuations in the space environment are at least 100 times lower than in the test chamber here, so the expected on-orbit performance easily meets the requirements.*

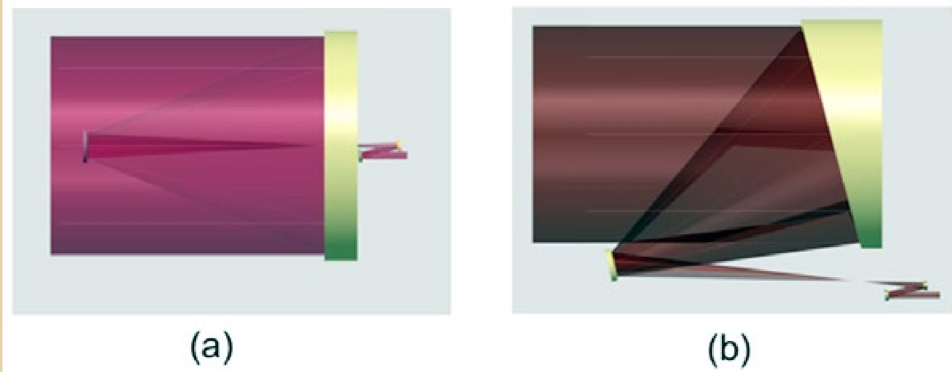

Figure 5: *On-axis design (a) and off-axis design (b) for a telescope that meets requirements for a space-based gravitational wave observatory.*

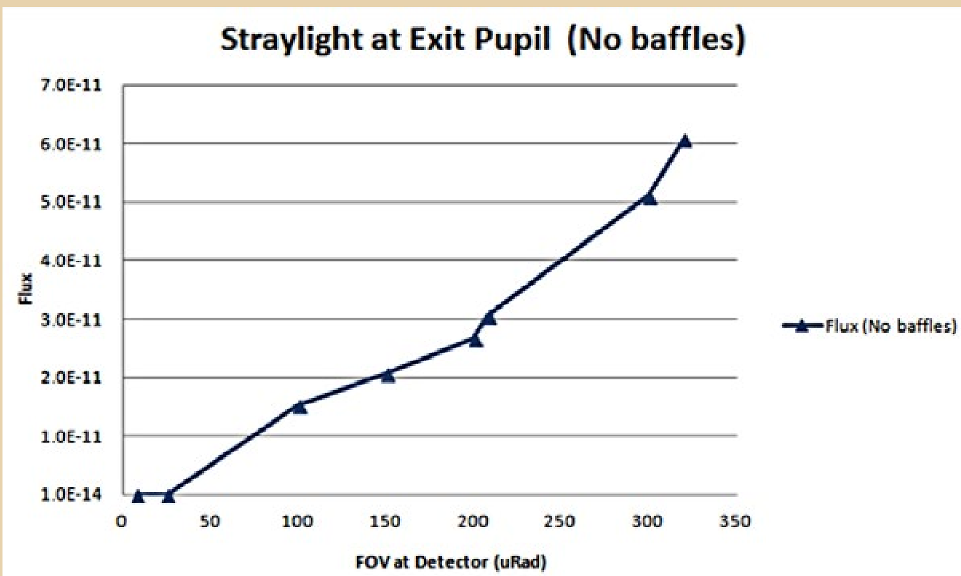

Figure 6: *This graph shows the modeled stray light performance of an off-axis. The requirement is for less than 10^{-10} at a 320 μradian field of view.*

Recent Accomplishments

The major accomplishment over the past year is to complete an industrial study of the telescope design. The study included a complete thermal, optical, and a partial mechanical analysis of two implementations: an on-axis design and an off-axis design, and two material systems: carbon fiber composite, and silicon carbide. The study contractor was also required to develop plans for manufacturing and verification testing of these designs. The net result was a recommendation for an off-axis implementation using silicon carbide. Figure 5 shows the two designs. The design on the right-hand side, Figure 5b, is the solution recommended by the industrial study.

An off-axis design was selected because stray light modeling showed that it would be challenging to suppress the narcissus (on-axis) reflection from the secondary mirror in an on-axis design. Once that reflection is suppressed, stray light performance of both designs was very similar. Figure 6 shows the modeled performance of an off-axis design showing it can meet requirements.

Silicon carbide was selected as the material of choice for the telescope. Carbon fiber composites had better off-the-shelf dimensional stability, but they add risk because of the known water absorption, which requires approximately 1–3 months of outgassing before performance testing can be done. This risk was judged to be unacceptable. It should also be noted that the effects of repeated water absorption and subsequent outgassing have not been investigated at the picometer level.

A summary of the work done before the completion of the industrial design study will be published in September[27].

Path Forward

The remaining work plan is to concentrate on developing the capability for testing the prototype telescope once it arrives so that the testing may be completed relatively rapidly. The two parts of the plan going forward follow the two difficult challenges for the design of the telescope: stray light and pathlength stability. The two parts have been translated into three distinct milestones, as shown in Figure 7.

Year	Milestone	Date	Milestone Description	Success Criteria
FY13	1	9/13	Stray light measurement capability	Demonstrated dynamic range of 10^{-10} per Table 1
FY14	2	3/14	Demonstration of low stray light	$<10^{-10}$ of transmit power per Table 1
FY14	3	9/14	Demonstration of low optical pathlength stability	1 pm $\sqrt{\text{Hz}}$ requirement per Table 1

Figure 7: *Key remaining milestones for the rest of the work plan, by Fiscal Year(FY).*

The first milestone is to demonstrate the measurement capability to detect low levels of scattered light in the presence of a high power source. The second milestone is to use that demonstrated capability to measure the scattered light from a prototype telescope that is designed to have low levels of stray light. Work is currently under way at GSFC to develop detectors and techniques that are sensitive enough. The current effort is looking at chopping techniques and low-noise circuitry with a room temperature detector. Part of the plan is to acquire a COTS telescope for practice and to get some experience with optics. We have borrowed a classical Schmidt-Cassegrain Questar telescope from the Optics Branch (Code 551), but the Schmidt corrector plate almost certainly will not meet either the stray light or the pathlength stability requirement. In addition, a scatterometer facility in the Optics Branch (Code 551) is being recreated for the purpose of measuring the scattering properties of individual mirrors, coatings, and substrates to validate the telescope model.

As part of this work, masks have been designed and fabricated to suppress the scattered light on-axis from a secondary mirror, and the team is in the process of evaluating the designs and comparing them against the model predictions. Once we have a validated model, we will use the designs to try to suppress the scattered light from a realistic secondary mirror.

The third milestone is to demonstrate the optical pathlength stability requirement. There is no milestone corresponding to the development of the stray light measurement capability because the plan is to take advantage of the capability already developed for measuring a silicon-carbide spacer at the University of Florida[19][20][21]. In practice, some work will be required to adapt the existing setup to a real telescope with optics instead of just a metering structure, and to improve the temperature measurement instrumentation.

A second iteration of the prototype telescope will almost certainly be required to reach the TRL-5 goal, if only to demonstrate operation of the subsystem in a relevant environment. See Figure 1 for the context and an estimate of the timing and schedule. This second iteration is not currently funded, and would be undertaken ideally as follow-on work to the current grant, or later as time and funding permit.

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Contact:
jeffrey.livas-1@nasa.gov

Laser frequency stabilization

Prepared by: John Lipa (Stanford University)

Summary

The project start date was 1-1-13 and the period of performance is 2 years.

The technical objective is to advance the development of a laser stabilization scheme that has very low noise into a unit that is low power and compact, and can be used in space for missions requiring extreme performance in optical frequency stabilization. The device will operate at a wavelength near 1568 nm using low pressure carbon monoxide (CO) gas as a molecular reference, with the possibility of migrating to near 1064 nm at a later date. The core technology has been demonstrated in the laboratory over the past 15 years and the ultimate performance as a stabilization system using CO is based on calculation. It is expected to approach that of ultra-cold neutral atom clocks that require multiple lasers and an extensive amount of equipment. The much lighter, simpler package we propose will allow the realization of a more practical ultra-stable optical reference for space use.

The target applications are to missions such as the *Laser Interferometer Space Antenna* (LISA) and Space-Time Assymmetry Research (STAR) [Braxmaier et al., 2007; Lipa et al., 2012] that require the ultimate in laser stability. Highly stable lasers are also important for a number of other astrophysical and fundamental physics missions that have been proposed, including the *Gravity Recovery and Climate Experiment Follow-On* mission (GRACE-II), the Principle of Equivalence Measurement (POEM), the Space Test of Universality of Free Fall (STUFF), the Quantum Interferometer Test of the Equivalence (QuITE) principle, the Primary Atomic Reference Clock in Space (PARCS), the Rubidium Atomic Clock Experiment (RACE), the Laser Astrometric Test of Relativity (LATOR) [Turyshev, 2007], and alternatives to LISA.

When combined with a space qualified optical frequency comb (currently under development at JPL, [Yu, 2012]), extremely high sensitivity spectroscopy over the entire near-infrared band is possible. This allows easy detection of trace gases in acquired samples, such as within the International Space Station (ISS), from a cometary surface or with a Mars rover, achieving sensitivities up to 100 times that of conventional techniques [Foltynowicz et al., 2008a]. This technology could also contribute to crew safety via early fire detection on long duration missions, and improve exploration capability in distant environments. The capability would also be available for ground applications such as advanced atomic clocks, gravity gradiometers, and optical frequency standards. Other longer-range uses include medical applications such as detection of volatile organic compounds for cancer screening and forensics, and in trace atmospheric gas studies using Light Detection and And Ranging (LIDAR) [Meras et al., 2008].

The project objectives are to 1) demonstrate the lowest short-term noise performance to date using a molecular gas transition as the reference medium, and 2) upgrade the design of the device from the optical bench level to the level where it has instrument-like compactness, power, and portability.

The team consists of the Principal Investigator (PI) and members of Stanford University optics groups, with consulting from Prof. Jan Hall of JILA.

Background

This project supports the goals of astrophysics by raising the TRL level of hardware that will increase our knowledge of fundamental laws of nature by providing improved laser frequency stability for use in space missions. It directly supports the Strategic Astrophysics Technology (SAT) program through the theme "Physics of the Cosmos" (PCOS). When applied in new space missions, the technology would have a direct impact on cosmology and astrophysics by improving our knowledge of the physics of the early universe. The primary NASA science question supported by this project is given in the 2010 Science Plan for the SMD: *"How do matter, energy, space, and time behave under the extraordinarily diverse conditions of the cosmos?"* This is derived from the goal: *"Discover how the Universe works, explore how the Universe began and developed…"* Our objective is to develop an extremely stable laser using advanced molecular transition interrogation techniques. The instrument can support an improved signal-to-noise ratio (SNR) in gravitational wave detection, and in scientific measurements related to the isotropy of space and the variation of clock frequencies with gravitational potential, frontiers of research in testing the limits of Einstein's theories of space, time, and gravity.

The second Baseline Objective for Astrophysics in the NASA Science Plan for 2007–2016 is: *"Investigate the nature of space-time through tests of fundamental symmetries."* Improved laser stabilities are an important aspect of technology development to support this objective. In the case of the search for Lorentz violations in the velocity of light due to boost, one needs to compare a cavity 'clock' with another reference such as a spectral line. This is the modern analog of the Kennedy-Thorndike experiment [Kennedy and Thorndike, 1932], one of the essential experimental foundations of special relativity. Thus atomic or molecular clock stability and noise performance are critical features of such an experiment. Hardware development for a space experiment of this type is proceeding at a low level as the STAR program mentioned earlier.

The project supports the National Research Council's (NRC) *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) Decadal Survey via improved technology for gravitational wave detection in space. In the case of gravitational wave detection in space, LISA requirements appear to be satisfied with free running Yttrium Aluminum Garnet (YAG) lasers [Astrium, 2009] using a combination of time delay interferometry [Tinto et al., 2002] and arm locking [McKenzie et al., 2009]. However it should be remembered that 14 orders of magnitude noise reduction are needed for a free running laser to make the measurements, a tall order for any electronic processing system. A prudent design would carry a very high margin of safety for dealing with "real world" electronics issues on the LISA spacecraft. With the elimination of the U.S. contribution to LISA and the search for cheaper alternatives by the Community Science and Core Teams established by the PCOS Program Office, it is clear that improved lasers would lessen the strain on some of the electronic systems contributing to the overall error budget. This would then allow a wider trade space to potentially reduce the mission cost and the complexity of the architecture, for example by using a shorter baseline than LISA, but with improved strain resolution.

Improved frequency stabilization using molecular gasses allows lower noise measurements or shorter measurement times for various physical phenomena. We project a theoretical improvement of up to a factor of 50 in noise reduction for measurement times of up to 10^4 seconds (s) using a CO molecular-referenced laser as opposed to an Iodine stabilized laser, which is the current state-of-the-art. An example of the current status of Iodine laser frequency control is given in Argence et al., 2010. The demonstrated noise performance of this Iodine system 'meets' LISA specifications but at the price of requiring 14 orders of magnitude further noise reduction using interferometry and arm locking techniques. Our approach tries to reduce the basic laser noise further, allowing some relaxation of the signal processing requirements and broadening the trade space for the optics system. An essential feature of our approach is to make use of cavity resonance techniques to enhance the signal from a low-pressure gas sample that has a very narrow molecular transition line width.

The top-level development plan is to develop the spectroscopy setup for the CO transition of interest at the laboratory instrument level, then transition to a more flight prototypical design on which the desired performance will be demonstrated.

Objectives and Milestones

The overall aim of the work is to develop greatly improved laser frequency stabilization using a molecular gas. The intent is to advance the state of the art from TRL 3 to TRL 4+. The work can be loosely divided into four main phases. The first phase has focused on setting up a basic bench-top spectroscopy system operating with a CO gas cell. Initially the optical setup will consist of an external cavity around the gas cell to establish functionality. This part was completed on schedule. During this period we have also started to set up a medium finesse Ultra-Low Expansion (ULE) cavity and thermal control system to act as a short-term optical reference system. When this system is operational, the gas cell subsystem will be evaluated for potential upgrades. An important decision point will be whether to build/buy an improved design. Independent of this choice, we will improve the thermal stability of the gas cell to around 50 microdegrees rms on a time scale of days. The completion of this assembly will establish the second major milestone. During the latter part of this task the basic unit will undergo testing to establish functionality and verify the expected level of performance.

In the second phase we will focus on converting the instrument to the breadboard level. The optics system will be repackaged to the point where it becomes a more compact, portable instrument. The first turn-on of this portable breadboard instrument assembly will constitute the next major milestone, about 15 months into the program. In addition, a custom vacuum chamber will be procured to establish proper thermal control of critical optical components. This setup is not intended to replicate the vacuum environment of space, but to eliminate gas conductive and convective heat transfer. Also, it will not include most active components of the system because they will be commercial parts. Nevertheless, the planned vacuum testing will give some information related to space operation. The completion of the first phase of testing with the vacuum system will constitute the third major milestone of the project and is expected in mid-2014.

In the third phase the portable breadboard system will be extensively operated to demonstrate functionality and to start performance testing. The outer layer of the thermal control system will be thermally stressed to simulate variable heat inputs from a spacecraft and determine system sensitivities. To demonstrate frequency stability performance, it will be necessary to set up a second unit and perform comparison measurements. This will be fabricated from the bench-top system by converting its optics to work with a second integrated gas cell. It will be completed at around the 18-month timeframe for use with the upcoming performance tests. The response of the system to variations of vacuum and heating conditions will be measured by comparing the frequency of the system under test with that of the upgraded bench-top system. Testing will be documented to the level required to allow performance predictions in the final operating environment. The completion of these performance level tests will constitute the next major milestone, expected around 20 months after start.

In the final phase the portable breadboard unit will be upgraded using the lessons learned to date, and some critical electronics items will be implemented at the board level. Some of this work will have been started in the second and third phases as manpower loading permits. To minimize unnecessary development effort here, board-level work will be restricted to functions not already demonstrated elsewhere at TRL5 or above. For example, we will not attempt to build power supplies, radio frequency (RF) frequency drivers, computer boards, frequency counters, etc., all of which have been demonstrated on other programs. However, we do plan to interface to them so that we can operate the setup under laboratory computer control. Software drivers will probably be done in LabVIEW system design software. The upgrades to the system will be taken as close as possible to the brassboard level under the time and budget constraints. Testing and upgrading is expected to be a continuous process during this period. A major technology milestone in this phase will be a performance demonstration at a fractional frequency stability $\delta f/f$ of 2×10^{-15} or better with 1s averaging. This is about seven times the estimated photon noise-limited performance with CO, and an order of magnitude better than Iodine.

We estimate this task will be completed about 20 months into the project. After this test cycle, we will perform long-term testing to evaluate the stability and repeatability of the reference frequency. The final month will be reserved for documenting the test performance demonstrating agreement with analytical predictions, and documenting the nature of the laboratory environment.

Key milestone list:

6-1-13: First turn-on of complete bench-top system (completed)

7-1-13: First turn-on of optical cavity reference setup (in progress)

9-1-13: Bench-top system operational with CO (in progress)
Success criterion would be to have reached a frequency instability, $\delta f/f \sim 10^{-13}$ in a 1s measurement time

1-1-14: Completion of flight prototype gas cell
Success criterion would be to have demonstrated a leak-tight cell to a level of 10^{-8} standard temperature and pressure (STP) cc/s air sensitivity.

3-1-14: Completion of portable breadboard instrument assembly
Success criterion would be to have reached a frequency instability, $\delta f/f \sim 10^{-14}$ in a 1s measurement time

4-1-14: Start testing in vacuum environment

6-1-14: Complete first round of vacuum testing
Success criterion would be to have reached a frequency instability, $\delta f/f \sim 10^{-14}$ in a 1s measurement time in a vacuum

6-1-14: Complete upgrade of bench-top system

8-1-14: Complete breadboard performance testing
Success criterion would be to have reached a frequency instability, $\delta f/f \sim 2\times10^{-15}$ in a 1s measurement time in a vacuum

11-1-14: Complete breadboard frequency stability testing in vacuum
Success criterion would be to have reached a frequency instability, $\delta f/f \sim 2\times10^{-15}$ in a 100s measurement time in a vacuum

12-31-14: Compete data analysis, test documentation, test environment documentation and final report
Success criterion would be publication of test results and reports.

Progress and Accomplishments

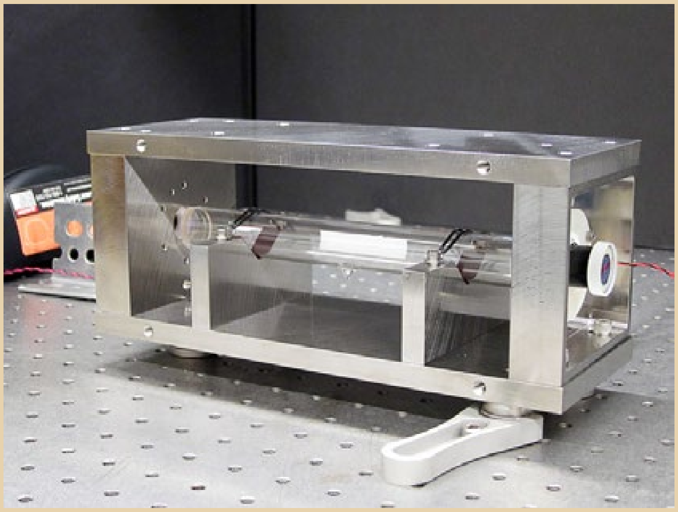

Figure 1: *Optical cell*

The first 6 months of the project has seen significant progress on setting up the bench-top version of the CO laser stabilization system, also known as the molecular clock. This work proceeded in two main phases: design and fabrication of the bench-top optical cell assembly and assembly of the associated opto-electronics.

The bench-top optical cell assembly is shown in Figure 1 and consists of a custom-built invar frame surrounding a CO gas cell and high finesse mirrors on either end attached to piezoelectric transducers. These mirrors act to amplify the absorption signal from the CO when the incoming laser light is in resonance with the cavity length. The most significant technical challenge for this assembly was to provide sufficient adjustment capability for aligning the optics without adding too many degrees of freedom for adjustment. The approach we have taken is to allow large adjustments in one plane and small in the orthogonal direction, with full rotation capability of critical elements. The rotation allows us to move any misalignments to the axis with large correction capability while the other axis retains fine tuning capability. The optical cell assembly is now in routine use for debugging the rest of the optical system.

Figure 2: *Optics setup*

The associated opto-electronics consist of multiple commercial optical components operating at a wavelength of 1565 nm and mounted on a highly stable optical table. In the section near the laser the components are fiber coupled, while near the optical cell they are free space coupled. A photo of the optical layout is shown in Figure 2.

We have encountered some unexpected difficulties with the fiber lasers procured for the experiment. The present model appears to be excessively sensitive to back reflections entering the laser output port. We recently received additional fiber-coupled optical isolators to alleviate this problem and are continuing to test. As a backup we have ordered a different model laser that is reputed to have less issues of this type. This laser will also provide the capability of operating at 1568 nm that is the optimum wavelength for the instrument.

We have achieved our first key milestone: turn on of the bench-top system by 6-1-13 and have progressed to the point where we can lock the cavity to the laser, the configuration used in the high-resolution spectroscopy we plan to demonstrate. A photo of the transmission signal from the TM_{00} mode is shown in Figure 3. The laser difficulty mentioned above manifests itself primarily as excessive low-frequency noise on the lock error signal. It does not appear to be a fundamental problem with the technology.

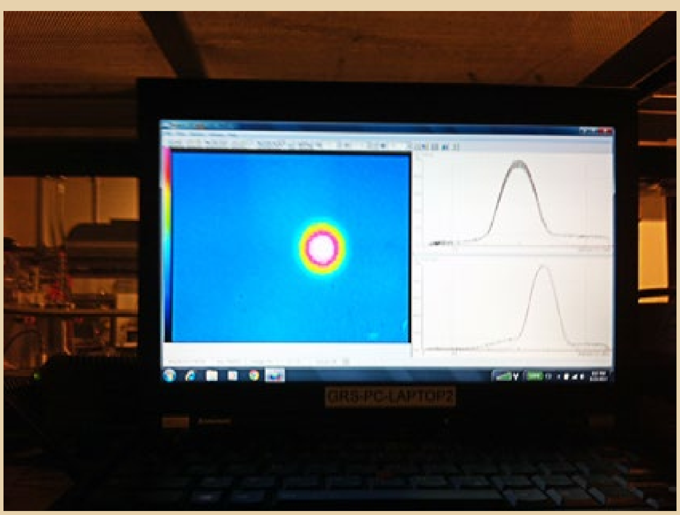

Figure 3: *Photo of resonant transmission of the TM_{00} mode through the cell*

We have also progressed with our second milestone, the initial turn-on of the optical cavity reference setup, due 7-1-13. We have the cavity assembled within a small vacuum system ready for hookup to the ancillary optics. This optics was developed earlier under separate funding and is available. It is not a pacing item at present and will be brought on line as time allows.

We have started on our third milestone, full bench-top operation with CO with the procurement of all components and the commencement of operations with CO. We have verified that the CO spectrum is as expected using a frequency comb spectrometer available in another laboratory.

Path Forward

The plan for the remaining work is along the lines set out in the proposal and is summarized briefly here.

The next major milestone is full bench-top operation with CO, scheduled for 9-1-13. We have the optical components to do this and are setting up the electronics. The task appears to be on schedule.

Completion of the flight prototype gas cell is the next milestone, due 1-1-14. The approach to be taken here is contingent on some optical loss measurements in the anti-reflective coatings of the existing gas cell. Theoretically the loss should be acceptable, but a measurement is needed to verify this. The measurements are scheduled for July. If the loss turns out to be too high, a decision will be needed on getting improved coatings or going to a new design that eliminates them.

Completion of the portable instrument is the next major milestone, scheduled for 3-1-14. It involves compressing the breadboard instrument layout and reconfiguring it for at least partial operation in a vacuum environment. A decision needs to be made at this point as to how much of the instrument would benefit from vacuum operation. Since a complete vacuum test is not needed to reach our goal of TRL4, we are considering the option of a hybrid vacuum/air test where only the gas cell and its immediate optics are in the vacuum. This has the advantage of allowing better thermal stability for the CO cell but avoids the complications of operating commercial electronics in a vacuum.

By 8-1-14 we expect to have completed the breadboard instrument performance testing and developed any enhancements necessary for retrofitting the portable instrument.

Effort will then be focused on frequency stability testing of the portable instrument with the vacuum system. This task is scheduled for completion by 11-1-14.

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Contact:
jlipa@stanford.edu

Adjustable X-ray optics with Sub-Arcsecond Imaging

Prepared by: Paul B. Reid (Smithsonian Astrophysical Observatory), Stuart McMuldroch (SAO)

Summary

Adjustable X-ray optics with sub-arcsecond imaging is an Astrophysics Research and Analysis (APRA) program that began in February 2013 and is scheduled to run through the end of FY15. This program follows an earlier APRA on the development of adjustable X-ray optics. This program seeks to develop bimorph adjustable grazing incidence X-ray mirrors to achieve 0.5 arcsecond (arcsec) imaging while also achieving extremely lightweight per unit collecting area (e.g., ~ 250 kg/m^2 compared to a value for *Chandra* of ~ 20,000 kg/m^2). Our technology will enable large-area high-resolution imaging X-ray telescope mission concepts such as the Square Meter Arc-second Resolution Telescope for X-rays (SMART-X)[1]. SMART-X will study the early Universe (growth of structure, merger history of black holes), as well as feedback and evolution of matter and energy.

Our technology eliminates the figure errors and unwanted distortions usually inherent in thin lightweight mirrors. We use a thin (1–1.5 µm) film of the piezoelectric material lead zirconate titanate (PZT) sputtered as a continuous film on the back of thin (0.4 mm) thermally formed glass Wolter-I mirror segments. (A continuous ground electrode is first applied to the back surface.) A pattern of independently addressable platinum (Pt) electrodes is deposited on top of the PZT layer forming individual piezo cells. Applying a low (< 10V) direct current (DC) voltage between a cell's top electrode and the ground electrode creates an electric field that produces a local strain in the piezo material parallel to the mirror surface. This strain causes localized bending in the mirror, called an *influence function*. By supplying an optimally chosen voltage to each of the individual cells, one can change the amplitude of each influence function to minimize figure errors in the mirror thereby improving imaging performance. This allows us to correct mirror figure errors from fabrication, distortions introduced during mounting, along with any gravity release errors. Figure correction is made once on the ground during a calibration step post-mirror mounting. Depositing an insulating layer on top of the piezo electrodes allows us to integrate strain gauges and electronics into each pixel; strain gauges provide precise feedback facilitating any on-orbit figure correction, should it be needed, while integrated control electronics reduces system complexity by enabling row-column addressing of each piezo cell. Having the ability to adjust and correct the figure of thin mirror segments, increase their performance from the 10 arcsec resolution level to 0.5 arcsec. We have shown through simulations improvements from ~ 7 arcsec half-power diameter (HPD) to < 0.5 arcsec HPD using exemplar mirror figure data and modeled influence functions[2]).

Besides the adjustable optics and SMART-X teams at the Smithsonian Astrophysical Observatory (SAO), significant contributors to the adjustable optics team are our colleagues at The Pennsylvania State University (PSU) Materials Research Laboratory and NASA Marshall Space Flight Center (MSFC). Dr. Susan Trolier-McKinstry at PSU, supported by Dr. Rudeger (Derek) H.T. Wilke, and Dr. Raegan Johnson-Wilke, develops the PZT processes. At MSFC, Dr. Stephen O'Dell and Dr. Brian Ramsey support metrology, analysis activities, and will lead X-ray testing.

A major milestone was achieved early this year–the successful deposition and testing of PZT on curved (cylindrical) test mirrors. The principle results are:

- PZT of satisfactory thickness uniformity can be deposited, and the piezo cell electrode pattern can be lithographically printed on the convex side of the cylindrical mirror segment,
- Piezo cell performance–piezo gain, or amplitude displacement as a function of applied voltage–matches that of PZT on flat test mirrors, and

- Measured influence function shapes agree with models to within metrology error, and the displacement performance is repeatable and stable to within metrology error.

Background

SMART-X will be capable of addressing almost all of the *International X-ray Observatory* (IXO) science goals–growth of supermassive black holes (SMBH) and strong gravity effects; evolution of large-scale structure and detection of the warm-hot interstellar medium (WHIM); active galactic nuclei (AGN) feedback and cycles of matter and energy. In many areas, SMART-X transcends the scope of IXO. It will be able to carry out surveys to the *Chandra* deep fields depth over 10 deg^2; study galaxy assembly processes to z = 2.5; and track the evolution of group-sized objects, including those hosting the first quasars, to z = 6; and open new opportunities in the time domain and high-resolution spectroscopy.

Over the past few years we have developed the concept of the adjustable-optic X-ray telescope. The challenge is to develop the optics to a high level of technical readiness over the next several years to provide *Chandra*-like 0.5-arcsec HPD angular resolution with IXO-like area (2.3m^2 at 1 keV, or ~ 30 times *Chandra*). This is a tremendous increase (a factor of four increase in area from Palomar to Keck was considered a breakthrough).

The baseline plan for SMART-X optics uses slumped glass mirror segments with deposited piezoelectric actuators energized to correct mirror figure errors from 10 arcsec HPD (achieved for IXO and the *Advanced X-ray Spectroscopic Imaging Observatory*, or AXSIO)[3] to < 0.5-arcsec HPD. The slumped glass mirror segments developed for IXO/AXSIO represent the current state-of-the-art in lightweight optics. (Another approach to develop adjustable X-ray optics relied upon gluing individual, thick [0.2 mm] ceramic piezoelectric actuators to thin mirrors. This resulted in large 'print-thru' errors in mirror figure[4]). Our approach builds upon the mirror development for IXO/AXSIO, both in terms of the thermally formed substrates, as well as mirror alignment and mounting. The addition of the piezoelectric layer is essentially just a single (multi-) deposition step in the mirror fabrication process. Our approach resolves the two main problems with lightweight slumped glass mirrors: (1) it corrects for the low-frequency figure errors that result from a combination of mandrel and thermal forming errors, and (2) it corrects after the fact for deformations introduced in coating and mounting thin, flexible mirrors. Additionally, the ability to make an on-orbit correction of mirror figure is critical for telescopes with apertures larger than can be tested with full aperture on the ground (i.e., larger than *Chandra*).

Our development plan progresses in a natural and stepwise way. In a prior APRA, we demonstrated the ability to deposit working PZT on flat mirrors, and showed that performance was repeatable, predictable, and could be modeled (i.e., deterministic)[5,6,7,8]. Additionally, we also showed that, using modeled influence functions (a good proxy for measured ones) with exemplar data (based upon interferometric measurements of IXO slumped mirrors), it was feasible to correct performance to ~ 0.5-arcsec HPD[2]. Our development plan for this program is to (a) demonstrate the process maps directly to conical mirror segments, and verify sub-arcsec performance by testing in X-rays a pair of mirrors aligned, mounted, and figure corrected. As parallel activities, we are investigating PZT lifetime through both accelerated and real-time lifetime testing, and improving yield (fraction of good piezo cells).

Objectives and Milestones

SAO started the project in January 2013 and has subsequently made substantial progress against the baseline plan. We are on or ahead of schedule for all tasks. At proposal award, we had shown our processes were repeatable and met our model expectations for flat test pieces. We had also shown we could deposit piezo material on curved surfaces but had not yet formed functioning adjusters. Since then we have successfully created piezo adjusters on cylindrical glass pieces and introduced controlled figure distortions that are deterministic, repeatable, and that match our model predictions. Figure 1 shows the annotated baseline schedule from our proposal:

Below we expound on some of the top-level descriptions listed in the schedule:

- We are placing on hold task 3–Deposition of PZT on nickel/cobalt (Ni/Co) replicas. Earlier efforts gave too large a figure error on Ni/Co segments (as opposed to full shells) due to electroplating stresses. Given the present level of success with thermally formed glass and the aforementioned difficulty with Ni/Co, we feel it prudent to concentrate on a single substrate material.

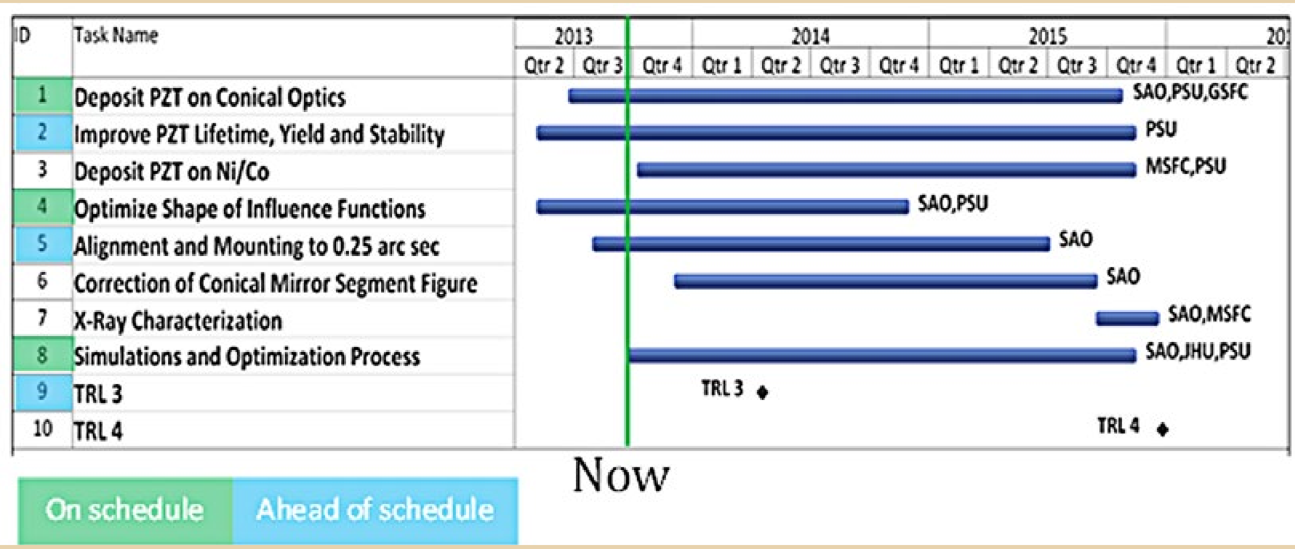

Figure 1: *Project schedule showing tasks are on track or ahead of schedule.*

- Task 4–Optimize shape of influence functions–refers to selecting piezo cell sizes, shapes, and layouts (rectangular array, interleaved, honeycomb, etc.) that produce the best shape influence functions for correcting representative mirror figure errors.
- Task 8–Simulations and optimization–improving the optimization process that finds the optimal set of piezo cell voltages to best correct the mirror figure error. This task includes investigating different optimizers (mathematical processes) and merit functions (what the optimizer minimizes).
- Technology Readiness Level 3 (TRL 3) and TRL 4–Our internal definition of TRL 3 is the demonstration of PZT deposition on cylindrical mirror segments with performance similar to that on flat test mirrors, with repeatable and deterministic (i.e., modelable) influence functions, along with simulations showing correction of representative mirror figure errors to ~ 0.5 arcsec or less. Our internal definition of TRL 4 is the demonstration of an aligned, mounted pair of adjustable conical mirror segments with corrected figure, tested in X-rays under full aperture illumination, and demonstrating sub-arcsec performance consistent with predictions.

Progress and Accomplishments

Significant progress was made since the program start in January ’13. PZT was successfully deposited on the back (convex) side of a 100 mm × 100 mm cylindrical test mirror segment with 220 mm radius of curvature. The film is 1.0 µm thick. 1 cm × 1 cm Pt electrodes were successfully printed on the test segment. The mirror size is the maximum that fits in the PSU sputtering chamber used for PZT deposition. A photograph of the mirror is shown in Figure 2. Hysteresis curves were measured for the piezo cells and showed piezo gain (average deflection per volt) of 0.15 µm/volt that both meets requirements and is comparable to that obtained on flat samples (0.1 µm/Volt). Repeatability and stability of influence functions were consistent with metrology noise of 20 nm, rms. Influence functions were measured with our optical profilometer and agreed with models to within the metrology noise (i.e., better than 20 nm rms point-by-point difference). An example of a profile through the center of an influence function comparing finite element model to profilometer measurement is shown in Figure 3. The conclusion we draw from these results is that (1) it is possible to do all the deposition and lithography steps required on the convex side of a cylinder, and (2) there are no noticeable piezoelectric or mechanical performance impacts in putting the piezo on the convex side of a curved element relative to putting it on a flat element.

We examined whether there was any improvement in piezoelectric performance as a function of depositing the PZT at an elevated subtrate temperature. Prior research has shown that different substrate temperatures affect the three-dimensional microstructure of thin film growth. This can result in a difference in piezoelectric coefficient (i.e., larger piezo gain). A flat test mirror was prepared at a 150°C substrate temperature (versus the standard processing we have used at room temperature). A comparison of piezo gain between the two samples showed no statistically significant differences in gain. As a result, we will continue to deposit the PZT at [the easier] room temperature.

Accelerated lifetime testing is being performed at PSU. The impacts of manganese (Mn) or niobium (Nb) doping are being investigated, but only preliminary results are available to date. Real-time

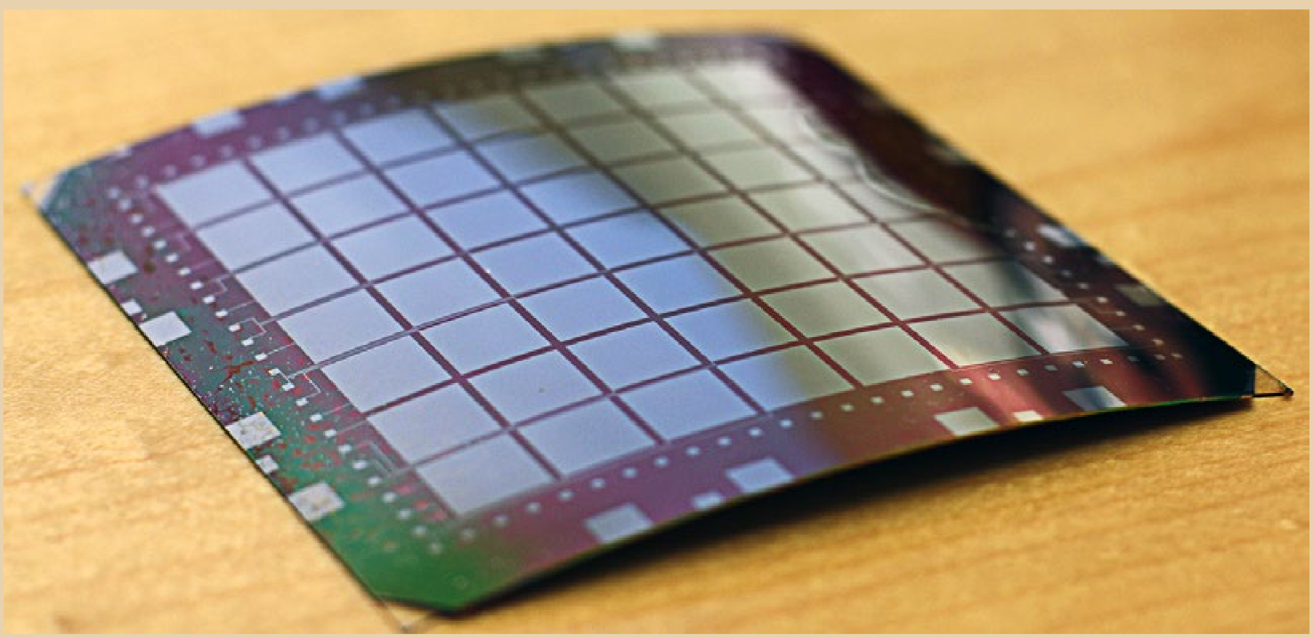

Figure 2: *Cylindrical mirror segment with 1 micro-meter thick piezoelectric film and 1 cm × 1 cm Pt electrode pattern.*

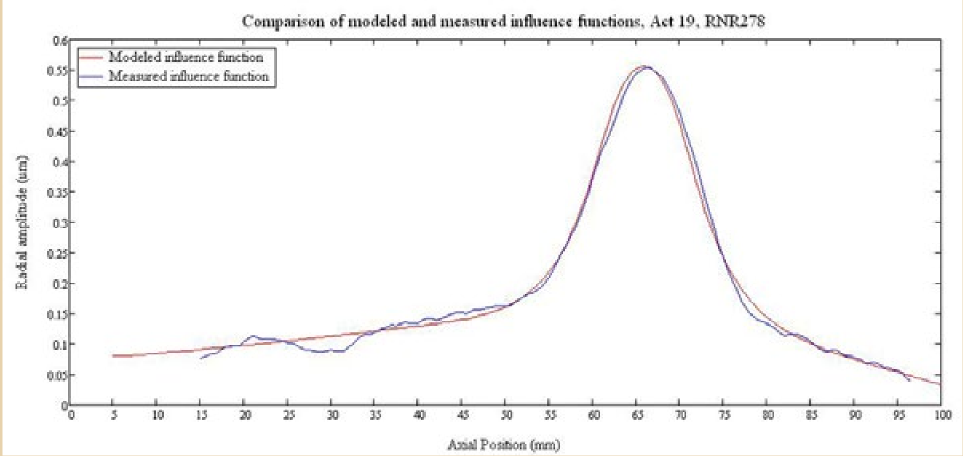

***Figure 3:** Comparison of modeled and measured influence function on a cylindrical test mirror.*

lifetime testing will be conducted at SAO. Test fixtures have been designed and are being built. A test plan has been developed. Under the plan, adjustable test mirrors will be exposed to vacuum, thermal cycling to telescope survival temperatures (-10 to + 40°C, unpowered), and radiation (cobalt 60 (Co^{60}) as a gamma radiation source and americium 241 (Am^{241}) as an alpha particle source). [Note: earlier studies[9] show no expected sensitivity of PZT to radiation for our intended application and reasonable on-orbit times (< 30–100 years).]

Simulation capabilities are being improved through the incorporation of two different optimizers. We have been using a Singular Value Decomposition (SVD) least squares optimizer, but with artificially incorporated bounds on the solution (this basically "spoils" the property of SVD, which in an unconstrained, unbounded case, mathematically must find the global optimum). We are now working with a bounded, constrained, least square optimization routine developed for radio astronomy, and we are also developing a simulated annealing optimizer. In both cases, we will be able to include bounds and constraints in a more natural way, obtaining a more "reliable" solution. We will also vary the size, shape, and layout of piezo cells to change the shape of the influence functions. We will also examine the sensitivity of our solutions to different merit functions (i.e., slope versus amplitude, etc.).

Path Forward

- Alignment and mounting of next generation PZT coated conical optics (Tasks 1 and 5)–Alignment efforts have begun. Our requirement is to align a pair of conical mirror segments to < 0.35 arcsec rms diameter, for the combination of residual coma and focus errors (this is the error magnitude in the SMART-X top-level error budget). Preliminary alignment of a hyperbola to a parabola is in progress. We are incorporating lessons learned from our Optical Assembly Pathfinder (OAP) experiences from *Constellation-X* (Con-X)/IXO. Over the coming year, we will incorporate an optical coarse alignment procedure (replacing the mechanical one presently in place), and develop an optical alignment raytrace model (a "double pass" model with the X-ray optics, Centroid Detector Assembly alignment metrology, Hartmann mask, and retroreflectors), to assist in generating a fuller understanding of the alignment process and data. We anticipate requiring modifications in our current design for supporting the mirrors during alignment: designed to be a kinematic support system for alignment, the supports appear to be somewhat non-kinematic. We will correct this by reducing the system friction. Finally, we will incorporate an improved mounting system (for bonding), including coefficient of thermal expansion matching between the mirror and its housing to mitigate thermally induced deformations and misalignments. All these improvements will support mounting the next generation of PZT coated conical optics currently under development prior to characterization and X-ray testing (Task 7).

- Figure correction of conical mirrors (Tasks 1, 4, 6, and 8)–We have received the first of our conical thermal forming mandrels, and the second mandrel is being shipped. This will give us the capability to make conical mirror segments rather than cylindrical mirror segments. (Finite element modeling indicates no difference is expected in influence functions, which is why we started with the easier to purchase, less expensive, cylindrical mandrels). We have purchased (on internal funds) a Shack-Hartmann wavefront sensor (WFS) for influence function and mirror figure measurements. This will provide higher-fidelity metrology than our optical profilometer. We will design, select, and purchase a cylindrical lens to serve as a refractive null corrector for conical (and cylindrical) mirror segments to enable nearly full aperture metrology with the WFS. We are also incorporating a 128-channel piezo cell controller, which will for the first time allow us to independently, under computer control, set the voltages for each piezo cell. (Previously, we have supplied the same voltage to multiple cells.) The combination of the improved metrology and the multichannel controller will enable us, for the first time, to correct figure errors in a mirror, flat or conical. Additionally, we will incorporate lessons learned in our influence function optimization simulation to design new electrode patterns for conical mirrors that will result in improved figure correction capability.

- Yield and lifetime (Task 2)–Accelerated lifetime testing will continue at PSU, with the incorporation of Mn or Nb dopants. The primary effort at this point will be to understand any failure mechanisms so as to be able to properly scale for piezo cell area from the smaller test structures. At present, lifetimes, scaled to our nominal operating conditions but not scaled for piezo cell area, range from 1,000 to 10,000 years. Examination of the piezoelectric microstructure and additional accelerated lifetime test conditions will be used to determine the cause of the eventual failures. Yield improvements are being worked in several ways. First, we are investigating aluminum oxide (Al_2O_3) as the insulating layer between piezo electrodes and strain gauges to prevent the shorting of the strain gauges to the piezo electrodes. Second, we are examining the stability and quality of the PZT sputter targets (which vary from vendor to vendor) used for deposition. We are also examining a technique for pre-cleaning the sputter target prior to sputtering. Lastly, we are making sure that we fully implement for conical pieces enhanced contamination control procedures to increase the yield to 100%. With respect to real-time lifetime testing described previously, we expect to complete the six test samples and begin lifetime testing in the coming year. These samples will remain under test until either failure or the 2020 Decadal (and beyond). Measurement of sample stability and performance will make use of the deposited strain gauges (which will be calibrated optically). In this way, measurement of piezo performance can be done without breaking vacuum or otherwise disturbing the sample mirrors.

- Miscellaneous–SAO continues to show strong institutional support for the adjustable X-ray optics program, providing funds for both internal research and development activities in addition to a 3-year postdoctoral fellowship (the Leon Van Speybroeck Fellowship in X-ray Optics). The independent research and development (IR&D) funds have helped us advance ahead of schedule, reducing overall project risk. The efforts of the first postdoctoral fellow, who will start August 1, 2013, will continue to increase the chance of success even in the absence of other future internal funding.

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Contact:
pried@cfa.harvard.edu

New PCOS SAT for 2014 Start
Advanced Antenna-Coupled Superconducting Detector Arrays for CMB Polarimetry

Abstract submitted by: James Bock (JPL)

We propose to develop advanced, high-sensitivity millimeter-wave detector arrays for measuring the polarization of the cosmic microwave background (CMB). The arrays are based on planar antennas that provide beam collimation, polarization analysis, and spectral band definition in a compact lithographed format that eliminates discrete fore-optics such as lenses and feedhorns. The antennas are coupled to transition-edge superconducting bolometers, read out with multiplexed Superconducting Quantum Interference Design (SQUID) current amplifiers. This development is directed to advance the technology readiness of the Inflation Probe mission in NASA's Physics of the Cosmos (PCOS) Program. The superconducting sensors and readouts developed in this Program share common technologies with NASA X-ray and Far-Infrared detector applications. The Inflation Probe is a fourth-generation CMB satellite that will measure the polarization of the CMB to astrophysical limits, characterizing the inflationary polarization signal, mapping large-scale structure based on polarization induced by gravitational lensing, and mapping galactic magnetic fields through measurements of polarized dust emission. The inflationary polarization signal is produced by a background of gravitational waves from the epoch of inflation, an exponential expansion of space-time in the early universe, with an amplitude that depends on the physical mechanism producing inflation. The inflationary polarization signal may be distinguished by its unique 'B-mode' vector properties from polarization from the density variations that predominantly source CMB detectors that will be needed for space-borne technology readiness. We will: (1) extend our antenna designs to frequencies 40-220 GHz that will be needed for precise removal of polarized galactic emission; (2) carry out precise polarized beam matching characterization measurements on a representative crossed-Dragone telescope; (3) develop two dual-band antenna designs that maximize use of available focal plane area; (4) test particle susceptibility to interactions with a thermally engineered detector frame at array level with SQUID readouts; (5) test the low-frequency noise properties of a microwave resonator-multiplexed radio frequency SQUID readout, a technique which offers potential resource advantages for space. Successful development elements will be independently field-demonstrated in sub-orbital and ground-based experiments.

Contact:
James.J.Bock@jpl.nasa.gov

Appendix C
Acronyms, Chemical Abbreviations, and Units

Acronyms

ADC . . . . Analog-to-Digital Converter
AEGIS . . . . . . Astrophysics Experiment for Grating and Imaging Spectroscopy
AIP . . . . *Astrophysics Implementation Plan*
AGN . . . . Active Galactic Nuclei
ALD . . . . Atomic Layer Deposition
APRA . . . . . . Astronomy and Physics Research and Analysis
ASCA . . . . . . *Advanced Satellite for Cosmology and Astrophysics*
ASIC . . . . Application Specific Integrated Circuit
ATHENA . . . . Advanced Telescope for High-Energy Astrophysics
ATHENA+ . . . Advanced Telescope for High-Energy Astrophysics plus
AXSIO . . . . . Advanced X-ray Spectroscopic Imaging Observatory
BESSY. . . . . . Berliner Elektronenspeicherring-Gesellschaft fur Synchrotronstrahlung
BI . . . . Back Illuminated
BOX . . . . Buried Oxide
CAT . . . . Critical Angle Transmission
CATXGS . . . . Critical Angle Transmission X-ray Grating Spectrometer
CCD . . . . Charge-coupled Device
CDA . . . . Centroid Detector Assembly
CDM . . . . Code Division Multiplexing
CFRP . . . . . . Carbon Fiber Reinforced Plastic
CMB . . . . Cosmic Microwave Background
CMM. . . . . . . Coordinate Measuring Machine
CMNT . . . . . . Colloid Micro-Newton Thruster
CMOS . . . . . . Complementary Metal-Oxide Semiconductor
Co-I . . . . Co-Investigator
Con-X . . . . . . *Constellation-X*
COTS . . . . . . Commercial Off The Shelf
CST. . . . . Community Science Team
CY . . . . Calendar Year
ddr . . . . Delta-Delta-Radius
DC . . . . Direct Current
DFB . . . . Distributed Feedback
DOF . . . . Degrees of Freedom
DM . . . . Demonstration Model
DPLL. . . . . . . Digital Phase Locked Loop
DRIE. . . . . . . Deep Reactive Ion Etching
eLISA . . . . . . evolved Lisa Interferometer Space Antenna
EBIT . . . . Electron Beam Ion Trap
ECL. . . . . External Cavity Laser
ESA. . . . . European Space Agency
ETU . . . . Engineering Test Unit
EUV . . . . Extreme Ultraviolet
FEM . . . . Finite Element Model
FI . . . . Front Illuminated
FWHM . . . . . Full Width Half Maximum
FY . . . . Fiscal Year

GPS . . . . Global Positioning System
GRACE-II . . . Gravity Recovery and Climate Experiment-II
GRACE FO . . Gravity Recovery and Climate Experiment Follow-On
GRS . . . . Gravitational Reference Sensor
GRU . . . . Gravity Reference Unit
GSFC . . . . . . Goddard Space Flight Center
GWO . . . . . . Gravitational Wave Observatory
HERO . . . . . . High Energy Replicated Optics
HETGS . . . . . High-Energy Transmission Grating Spectrometer
HPD . . . . Half-power Diameter
HQ . . . . Headquarters
IR . . . . Infrared
IR&D . . . . . . Independent Research and Development
IXO. . . . . *International X-ray Observatory*
JPL . . . . Jet Propulsion Laboratory
L1 . . . . Level 1
L2 . . . . Level 2
LATOR . . . . . Laser Astrometric Test of Relativity
LHP . . . . Loop Heat Pipe
LIDAR . . . . . . Light Detection And Ranging
LIMAS . . . . . . LISA Instrument Metrology and Avionics System
LISA . . . . Laser Interferometer Space Antenna
LSF . . . . Line Spread Function
LTP . . . . Long Trace Profilometer
LPF . . . . *LISA Pathfinder*
MEMS . . . . . . Micro-Electrical-Mechanical Systems
MEOP . . . . . . Maximum Expected Operating Pressure
MIT. . . . . Massachusetts Institute of Technology
MKI . . . . MIT Kavli Institute
MKID . . . . . . Microwave Kinetic Inductance Detector
MOU. . . . . . . Memorandum of Understanding
MSFC . . . . . . Marshall Space Flight Center
N-CAL . . . . . . Notional Calorimeter X-ray Mission XMS
N-XGS. . . . . . Notional X-ray Grating Spectrometer
NAC . . . . NASA Advisory Council
NEP . . . . Noise Equivalent Power
NGO . . . . New Gravitational-wave Observatory
NISP . . . . Near Infrared Spectrometer Photometer
NIST . . . . National Institute of Standards and Technology
NPR . . . . NASA Procedural Requirements
NPRO . . . . . . Non-planar Ring Oscillator
NRC . . . . National Research Council
NuSTAR . . . . *Nuclear Spectroscopic Telescope Array*
NWNH . . . . . *New Worlds, New Horizons in Astronomy and Astrophysics*, a report released by the National Research Council in 2010
OAP . . . . Optical Assembly Pathfinder
OBF . . . . Optical Blocking Filters
OCT . . . . Office of the Chief Technologist
OP-XGS . . . . Off-Plane X-ray Grating Spectrometer
OSIRIS-REx . . *Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer*

P/V . . . . Peak to Valley
PARCS. . . . . . Primary Atomic Reference Clock in Space
PATR. . . . . . . *Program Annual Technology Report*
PCOS . . . . . . Physics of the Cosmos
PhysPAG . . . . Physics of the Cosmos Program Analysis Group
PI . . . . Principal Investigator
PO . . . . Program Office
POEM . . . . . . Principle of Equivalence Measurement
PSA. . . . . Point Source Assembly
PSF . . . . Point Spread Function
PSU . . . . Pennsylvania State University
PTB . . . . Physikalisch Technische Bundesanstalt
QuITE. . . . . . Quantum Interferometer Test of the Equivalence principle
RACE . . . . . . Rubidium Atomic Clock Experiment
REXIS . . . . . . Regolith X-ray Imaging Spectrometer
RF. . . . . Radio Frequency
RFI . . . . Request for Information
RIN. . . . . Relative Intensity Noise
ROSES . . . . . Research Opportunities in Space and Earth Science
RRO . . . . Relaxation Oscillation
RTF. . . . . Roman Technology Fellowship
SAO . . . . Smithsonian Astrophysical Observatory
SAT. . . . . Strategic Astrophysics Technology
SBIR . . . . Small Business Innovative Research
SEM . . . . Scanning Electron Microscope
SHS. . . . . Shack-Hartmann Sensor
SIM. . . . . Space Interferometry Mission
SLF . . . . Stray Light Facility
SMART-X . . . Square Meter, Arcsecond Resolution X-ray Telescope
SMBH . . . . . . Supermassive Black Hole
SMD . . . . Science Mission Directorate
S/N. . . . . Signal to Noise
SNR . . . . Signal to Noise Ratio
SOI . . . . Silicon-on-Insulator
SQUID . . . . . Superconducting Quantum Interference Device
SR&T . . . . . . Supporting Research and Technology
ST7 . . . . Space Technology 7
STAR. . . . . . . Space-Time Asymmetry Research
STUFF. . . . . . Space Test of Universality of Free Fall
SVD . . . . Singular Value Decomposition
SXS. . . . . Soft X-ray Spectrometer
TDI. . . . . Time Domain Interferomery
TDM . . . . Time-Division Multiplexing
TDR . . . . Technology Development Roadmap
TechSAG . . . . Technology Science Analysis Group
TES. . . . . Transition-Edge Sensor
TLS . . . . Two Level System
TMB . . . . Technology Management Board
TPCOS . . . . . Technology Development for Physics of the Cosmos Missions
TRL. . . . . Technology Readiness Level

UK . . . . United Kingdom
ULE . . . . Ultra Low Expansion
UV . . . . Ultraviolet
WFI . . . . Wife-Field Imager
WFIRST. . . . . Wide-Field Infrared Survey Telescope
WFS . . . . Wavefront Sensor
WFXT . . . . . . Wide Field X-ray Telescope
WHIM. . . . . . Warm-Hot Intergalactic Medium
WHIMex . . . . Warm-Hot Intergalactic Medium Explorer
XGS . . . . X-ray Grating Spectrometer
XMM-Newton *X-ray Multi-mirror Mission*
XMS . . . . X-ray Microcalorimeter Spectrometer
XEUS . . . . . . X-ray Evolving Universe Spectroscopy

Chemical Abbreviations

aSi . . . . Amorphous Silicon
Al . . . . Aluminum
Al_2O_3. . . . . . . Aluminum Oxide
Am^{241} . . . . . . Americum 241
Au . . . . Gold
Be. . . . . Beryllium
Bi/Au . . . . . . Bismuth Gold
BOX . . . . Buried Oxide
C . . . . Carbon
CO . . . . Carbon monoxide
Fe . . . . Iron
HF . . . . Hydrofluoric Acid
HfO_2 . . . . Hafnium Oxide
KOH . . . . Potassium Hydroxide
Mg . . . . Magnesium
Mn . . . . Manganese
Mo/Au . . . . . Molybdenum Gold
N . . . . Nitrogen
Nb . . . . Niobium
$Nb/SiO_2/Nb$. . Niobium/Silicon Oxide/Niobium
Ne . . . . Neon
Ni/Co . . . . . . Nickel/Cobalt
O . . . . Oxygen
PMN . . . . Lead Magnesium Niobate
Pt . . . . Platinum
PZT . . . . Lead Zirconate Titanate
Si . . . . Silicon
SiC . . . . Silicon Carbide
SiO_2 . . . . Silicon Dioxide
TiN . . . . Titanium Nitride
YAG . . . . Yttrium Aluminum Garnet

Units

arcsec . . . . . . arcseconds
atm . . . . atmospheres
cc/s. . . . . cubic centimeters per second
cm . . . . centimeters
cm^2 . . . . square centimeters
cps . . . . counts per second
C . . . . Celsius
° . . . . degrees
f . . . . frequency
GHz . . . . Gigahertz
Hz . . . . hertz
k. . . . . thousand
keV. . . . . kiloelectron volt
kg. . . . . kilogram
kHz . . . . kilohertz
kW . . . . kilowatt
K . . . . Kelvin
λ. . . . . wavelength
m . . . . meters
m^2. . . . . square meters
M . . . . million
Mbits . . . . . . megabits
MHz . . . . megahertz
mm. . . . . millimeters
mm^2 . . . . square millimeters
μm . . . . micron (micrometer)
μN . . . . micro-Newton
nm . . . . nanometers
pW . . . . picowatts
rms. . . . . root mean square
s . . . . seconds
T_c . . . . transition temperature
V . . . . volts
v^2 . . . . velocity squared
W . . . . watt
z. . . . . redshift